WORLD METEOROLOGICAL ORGANIZATION

INSTRUMENTS AND OBSERVING METHODS

REPORT No. 67

WMO SOLID PRECIPITATION MEASUREMENT INTERCOMPARISON

FINAL REPORT

by

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NOTE

FOREWORD

The *WMO Solid Precipitation Measurement Intercomparison* was started in the northern hemisphere winter of 1986/87. The field work was carried out in 13 Member countries for seven years. The Intercomparison was the result of Recommendation 17 of the ninth session of the *Commission for Instruments and Methods of Observation (CIMO-IX).*

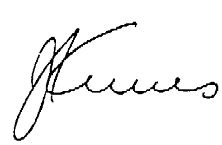
As in previous WMO intercomparisons of rain gauges, the main objective of this test was to assess national methods of measuring **solid precipitation** against methods whose accuracy and reliability were known. It included past and current procedures, automated systems and new methods of observation. The experiment was designed to determine especially wind related errors, and wetting and evaporative losses in national methods of measuring solid precipitation. The aim was to derive standard methods for adjusting solid precipitation measurements and to introduce a reference method of solid precipitation measurement for general use to calibrate any type of precipitation gauge.

The report is a consolidation of data and information from the most challenging intercomparison organized by WMO so far to determine the *in situ* performance characteristics of instruments. Various types of national gauges were compared at 26 test sites in different climatic regions during at least 5 winter seasons against a commonly agreed reference design which was not previously used internationally. According to the goal of the test, the magnitude of the systematic errors in the measurement of solid precipitation is now clearly documented. This is very important for research in the field of climate change. Furthermore, methods for adjusting current and historical archive data have been derived which Members can test and, if needed, adapt to their own equipment and conditions. Although this intercomparison provides valuable information on how best to improve the measurements of not only solid precipitation but also of rain, one must continue to address the problem of determining the required algorithm for correcting data containing systematic errors to which all measurements may be subject. Specific attention should be given to identification of problems in measuring precipitation with automatic gauges.

I should like to place on record the gratitude of CIMO to the managements, the national Project Leaders, the numerous scientists, and the operational staffs of all participating Members which were actively involved in this Intercomparison. The contributors came not only from the national services but also from other institutions that operated some of the test sites.

I also should like to acknowledge the significant work done by the members of the International Organizing Committee (IOC) responsible for the preparation and proper conduct of the trial as well as for determining the best procedures for evaluation of the results and their presentation. Finally, I express my great appreciation to Dr. B.E. Goodison (Atmospheric Environment Service of Canada), the Chairman of the IOC and the Project Leader of the whole Intercomparison for his dedicated work and his efforts in bringing together all the national data needed for this report and for ensuring that they be evaluated and presented in the very clear manner that can be seen in this comprehensive report. In addition to this I would like to thank the staff of AES involved in this work for the significant support they provided in the evaluation of national test results and for the preparation of this report.

I am confident that Members of WMO and others will find this report very useful, especially for improving the measurement of solid precipitation. It should contribute to the homogeneity of national data sets so that a better regional and global compatibility of the long-term data series might be achieved.



(Dr. J. Kruus)
President of the Commision for
Instruments and Methods Observation

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TABLE OF CONTENTS

		PAGE
ACKNOWLEDGEMENTS		
EXECUTIVE SUMMARY		**i**
CHAPTER 1	**BACKGROUND**	**1**
1.1	INTRODUCTION	1
1.2	HISTORY OF PRECIPITATION MEASUREMENT INTERCOMPARISONS	1
1.3	HISTORY OF DFIR	5
1.4	THE WORKING NETWORK REFERENCE GAUGE	5
1.6	CONCLUSIONS	6
CHAPTER 2	**METHODOLOGY**	**7**
2.1	INTRODUCTION	7
2.2	ORGANIZATION OF THE INTERCOMPARISON	7
2.3	DATA COLLECTION AND OBSERVATION PROCEDURES	9
2.4	DATA ANALYSIS	12
CHAPTER 3	**SUMMARY DESCRIPTION OF SITES, INSTRUMENTS AND DATA ARCHIVE**	**17**
3.1	SUMMARY OF SITE DESCRIPTIONS AND INSTRUMENTS	17
3.2	SUMMARY OF DATA ARCHIVE	17
CHAPTER 4	**RESULTS AND DISCUSSION**	**25**
4.1	INTRODUCTION	25
4.2	SITES AND DATA SOURCES	25
4.3	METHODS OF DATA ANALYSIS	25
4.4	RUSSIAN TRETYAKOV PRECIPITATION GAUGE	28
4.5	HELLMANN GAUGE	31
4.6	CANADIAN NIPHER SNOW GAUGE	34
4.7	NWS 8” STANDARD NON-RECORDING GAUGE	37
4.8	SUMMARY	39
4.9	DISCUSSION	46

		PAGE
CHAPTER 5	**AUTOMATION OF WINTER PRECIPITATION MEASUREMENTS**	**51**
5.1	INTRODUCTION	51
5.2	CANADA	51
5.3	FINLAND	53
5.4	GERMANY	55
5.5	JAPAN	55
5.6	SUMMARY	57
CHAPTER 6	**CONCLUSIONS AND RECOMMENDATIONS**	**58**
6.1	CONCLUSIONS	58
6.2	RECOMMENDATIONS	59
CHAPTER 7	**DEMONSTRATION AND IMPLEMENTATIONS OF THE RESULTS**	**61**
7.1	INTRODUCTION	61
7.2	CANADA: ADJUSTMENT OF PRECIPITATION ARCHIVE FOR THE NORTHWEST TERRITORIES (NWT)	61
7.3	DENMARK: AN OPERATIONAL SYSTEM FOR CORRECTING PRECIPITATION FOR THE AERODYNAMIC EFFECT	65
7.4	GERMANY: APPLICATION OF PRECIPITATION CORRECTION, GERMAN METEOROLOGICAL SERVICE, BUSINESS UNIT HYDROMETEOROLOGY	68
7.5	NORWAY: OPERATIONAL CORRECTION OF MEASURED PRECIPITATION	70
7.6	U.S.A.: APPLICATIONS OF THE WIND-BIAS ASSESSMENTS TO PRECIPITATION DATA IN USA AND GLOBAL ARCHIVES	73
REFERENCES		**77**
BIBLIOGRAPHY		**83**
GLOSSARY		**87**
ANNEXES		

ACKNOWLEDGEMENTS

The WMO Solid Precipitation Measurement Intercomparison has been successfully completed through the contribution, dedication and commitment of many individuals and agencies. The Intercomparison was unique, with 16 countries participating at over 25 sites. The tireless work of participants who established and operated sites over a number of years, analyzed the data and contributed to writing reports and papers is gratefully acknowledged. The people who had direct contact with the Organizing Committee are listed below. In addition, there were numerous observers at the experimental sites whose dedication to acquiring quality data was essential for the success of the Intercomparison. Thanks is extended to the agencies which provided staff to work on this study and who funded the establishment and operation of sites. I extend special thanks to my own agency, the Atmospheric Environment Service, Canada, for its support of this Intercomparison, especially for the special funding required to establish the digital data base for the study. Thanks are due to John Metcalfe for overseeing the preparation of this data base.

The support of the President, Executive and members of CIMO throughout this Intercomparison is acknowledged. We would not have succeeded without their on-going guidance, questions and suggestions. Thanks to my colleagues on the International Organizing Committee of the Intercomparison: Boris Sevruk, Valentin Golubev, and Thilo Günther for their on-going support. The preparation of the report has been a major undertaking; it would not have been possible without the dedicated work of Paul Louie and Daqing Yang. I trust that it meets Members' expectations.

Finally, I wish to extend special thanks to the WMO Secretariat who made sure that we stayed on course and addressed the issues. Klaus Schulze, and his predecessor Stephan Klemm, ensured our meetings were focussed and relevant; they brought their own special expertise to the problems being discussed; they made sure that all countries' concerns were considered. The Intercomparison would not have succeeded without their guidance. Thank you.

Barry Goodison
Chairman, International Organizing Committee
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EXECUTIVE SUMMARY

Introduction

In the spring of 1985, the International Workshop on Correction of Precipitation Measurement was held in Zurich, Switzerland. One of the conclusions was a recommendation to the WMO to organize a Solid Precipitation Measurement Intercomparison. Such a study would also complement the WMO Pit Gauge Intercomparison for liquid precipitation (Sevruk and Hamon, 1984). The WMO Solid Precipitation Measurement Intercomparison was initiated after approval by CIMO-IX in 1985. The International Organizing Committee (IOC) for the Intercomparison was established consisting originally of B. Dahlstrom (Sweden), B. Goodison (Canada), and B. Sevruk (Switzerland). B. Goodison was elected Chairman. The terms of reference for the WMO Solid Precipitation Measurement Intercomparison were established at the first meeting of IOC in Norrkoping, Sweden in December 1985 (WMO/CIMO, 1985). There have been seven meetings of the IOC; current members are B. Goodison, B. Sevruk, V. Golubev (Russian Federation) and Th. Günther (Germany). The following experts have participated from time to time in the meetings throughout the experimental period and in the successful implementation, conduct, and reporting on the experiment: D. Yang, China; J. Metcalfe, Canada; E. Elomaa, Finland; P. Allerrup and H. Madsen, Denmark; E. Førland, Norway; D. Legates, U.S.A.; and J. Milkovic, Croatia.

Field studies for the WMO Solid Precipitation Measurement Intercomparison were started by some countries during the 1986/87 winter and the last official field season was 1992/93, allowing most countries to collect data during five winter seasons; some sites have continued to operate with reduced programs. The goal was to assess national methods of measuring solid precipitation against methods whose accuracy and reliability were known, including past and current procedures, automated systems and new methods of observation. The Intercomparison was especially designed to:

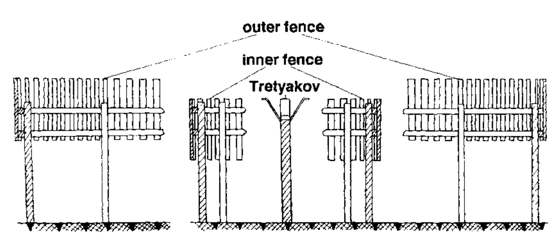
a) determine wind related errors in national methods of measuring solid precipitation, including consideration of wetting and evaporative losses;
b) derive standard methods for adjusting solid precipitation measurements; and
c) introduce a reference method of solid precipitation measurement for general use to calibrate any type of precipitation gauge.

Countries which participated, operated the reference standards, and submitted complete data summaries for analysis were: Canada, China, Croatia, Denmark, Finland, Germany, Japan, Norway, Russian Federation, Sweden, Switzerland and the United States. Other countries collecting comparative measurements for at least one winter included India, Romania, Slovakia and the United Kingdom. Table 1 provides a summary of the participating countries and the sites operated. Experimental results were obtained from 26 sites in 13 countries.

Reference standard for this Intercomparison

For this Intercomparison determination of the reference standard designed to measure snowfall precipitation was critical. After reviewing all possible methods (bush shield, double fence shield, forest clearing, snow board measurement, dual gauge approach, etc.) the IOC designated the octagonal vertical double fence shield (with manual Tretyakov gauge) as the Double Fence Intercomparison Reference (DFIR) (Figure 1). It is acknowledged that a gauge situated in a natural bush shelter would provide the best estimate of "ground true" precipitation and is considered to be the primary standard. However, since natural bush sheltering was not available in all climatic regions which were to be studied, an artificial shield was selected. The DFIR is a practical secondary standard and its ongoing assessment as a reference is recommended.

Figure 1 Cross section of WMO Double Fence Intercomparison Reference (DFIR)



The hydrological station at Valdai (Russian Federation) was the only site where the DFIR was assessed against gauges situated in bushes (kept at gauge height), which is deemed to provide the best estimate of "ground true". Precipitation totals, as summarized in Table 2 for November 1991 to March 1992, show the average differences between the DFIR, the bush gauge, and some of the other gauges operated at Valdai.

The measurements show the need to adjust the DFIR to the value of the bush gauge to account for the effect of wind and other environmental factors (e.g. temperature). Errors in measurement using the DFIR and adjustment procedures are given in Golubev (1986), WMO/CMIO (1992) and Yang *et al*.,1993).

Table 1 Summary of Participating Countries

Country	No. of Sites	Years of Data	National Gauge(s)	DFIR	Country Report(s)
Canada	6	6	Canadian Nipher shielded gauge	Yes	Yes
Croatia	1	3	Hellmann	Yes	No
China	1	6	Chinese Standard	Yes	Yes
Denmark, Finland, Norway, Sweden	1	6	Hellmann (Denmark) Wild (Finland) Tretyakov (Finland) H&H 90 (Finland) Norwegian Standard Swedish Standard	Yes	Yes (Denmark & Finland)
Germany	1	7	Hellmann	Yes	Yes
India	4	2	Indian Standard	No	No
Japan	2	3	RT-1, RT-3, RT-4	Yes	Yes
Slovakia	1	7	METRA 886	No	Yes
Switzerland	1	2	tested Belfort gauge	Yes	Yes
Romania	1	3	Romanian IMC	Yes	No
Russia Federation	1	14	Tretyakov	Yes	Yes
United Kingdom	2	3	UK Met Office Standard Mk 2	No	No
United States	4	6	NWS 8 inch Belfort Universal	Yes	Yes

Table 2 Precipitation totals (rain and snow) measured by different gauges at Valdai, Russia, November 1991-March 1992 (WMO/CIMO, 1992)

Gauge type	Total Precip (mm)	% of bush total
Tretyakov in bushes	367	100
DFIR (Tretyakov)	339	92
DFIR (Canadian Nipher)	342	93
Canadian Nipher shielded	314	86
Tretyakov	258	70
8" USA Alter shielded	273	75
8" USA unshielded	208	57

Determining systematic errors in the measurement

The systematic errors in the measurement of solid precipitation were determined in the Intercomparison quantitatively for over 20 different precipitation gauge and shield combinations. Experimental results confirmed that solid precipitation measurements must be adjusted for wetting loss (for volumetric measurements), evaporation loss and for wind induced undercatch before the actual precipitation at ground level can be estimated. Studies in precipitation physics have shown that the falling velocity of snowflakes depends on their shape which is a temperature phenomenon. Since the total wind effect depends on the shape of snowflakes, air temperature at screen or upper air levels can also be used as a variable in adjusting precipitation gauge measurements. Systematic losses varied by type of precipitation (snow, mixed snow and rain, and rain).

Evaporation from manual gauges can significantly contribute to the systematic undermeasurement of solid precipitation. Aaltonen et al. (1993) reported on the comprehensive assessment by Finland on evaporation loss. Average daily losses varied by gauge type and time of year. Evaporation loss was a problem in the late spring with gauges which did not use a funnel in the bucket. This is common for most gauges used to measure snow in the winter. Evaporative losses from the gauge in April of over 0.8 mm/day were measured. Losses during winter were much less than that recorded during comparable spring and summer comparisons, and ranged from 0.1-0.2 mm/day. These losses, however, are cumulative. Many gauges install a funnel for summer (rainfall) measurements, helping to reduce potential evaporation loss.

Wetting loss is another cumulative systematic loss from manual gauges which varies with precipitation type and gauge type, and the number of times the gauge is emptied. Average wetting loss for some gauges can be up to 0.3 mm per observation. Countries using manual gauges for solid precipitation measurement have determined the average wetting loss for their National gauge. At synoptic stations where precipitation is frequent and measured every six hours, this can become a very significant amount. At some Canadian stations, for example, wetting loss was calculated to be 15-20 per cent of the measured winter precipitation.

Data from all Intercomparison sites confirmed that solid precipitation measurements must be adjusted to account for errors and biases. The results confirmed that wind speed was the most important environmental factor contributing to the systematic undermeasurment of solid precipitation. Countries operating a reference gauge (DFIR) with corresponding wind data were able to develop adjustment equations for their National gauges. Deviations from the DFIR measurement varied according to gauge type and precipitation type (snow, mixed snow and rain, and rain). The derived catch ratio equations for the four most widely used non recording gauges for solid precipitation measurement in the world (the Russian Tretyakov Gauge, the Hellmann Gauge, the Canadian Nipher Gauge, and the US NWS 8" standard gauge) are presented in Table 3. The analysis was based on the combined international data set collected by the WMO Solid Precipitation Measurement Intercomparison project. For all gauges and at all sites, it was confirmed that wind was the most dominant environmental variable affecting the gauge catch efficiency. Temperature had a much smaller overall affect on the catch ratio, and was found to be more important for mixed precipitation than for snow. A graphical comparison of the catch ratio equations for snow is shown in Figure 2. These results show that the catch efficiency for snow of the four most widely used gauges can vary greatly, for example, from ~20% up to ~70% at 6 m/s wind speed. As expected, shielded gauges generally performed better than unshielded gauges.

Standard procedures were used to derive the catch ratio of different gauge types in relation to the DFIR. Some countries have already tested, and are applying, algorithms for adjusting precipitation measurements and archived data for climatological and hydrological applications. This report provides the catch ratio equations which can be adapted for precipitation adjustment procedures. One must be very careful when analyzing ratios and differences between gauges and applying catch ratios for adjustment. Small absolute differences between gauges and the reference gauge (DFIR) could create significant large variations in the catch ratios depending on the total measured (e.g. a 0.2 mm difference of Tretyakov gauge vs. DFIR with a DFIR catch of 1.0 mm gives a ratio of 80% versus 96% for a 5.0mm event). To minimize this effect, daily totals when the DFIR measurement was greater than 3.0mm were used for the statistical analyses (e.g. Table 3). The benefits of analyzing the correction factor and applying those algorithms are also discussed. The effect of averaging wind speed and temperature in different ways is shown to have a significant effect on the adjusted estimate" of precipitation, especially over short time intervals. It is clear that in order to achieve data compatibility when using different gauge types and shielding during all weather conditions, large adjustments to the actual measurements will be necessary. Since shielded gauges catch more than their unshielded counterparts, gauges should be shielded either naturally (e.g. forest clearing) or artificially (e.g. Alter, Canadian Nipher type, Tretyakov wind shield) to minimize the adverse effect of wind.

Other issues identified by the intercomparison study

The Intercomparison study and the subsequent development of adjustment procedures for gauge measurements of solid precipitation also identified other issues which must be addressed. Using the results of the experiment, procedures are proposed to adjust precipitation measurements for many different gauges for wind induced errors and losses due to wetting and evaporation. Wind speed at gauge height is one of the required variables in the adjustment procedure; it can be measured or derived using a mean wind speed reduction procedure. This is a very site dependent value and estimation will require a good knowledge of the station and gauge location, hence a good metadata record. At new automatic stations, the measurement of wind speed at gauge height is encouraged.

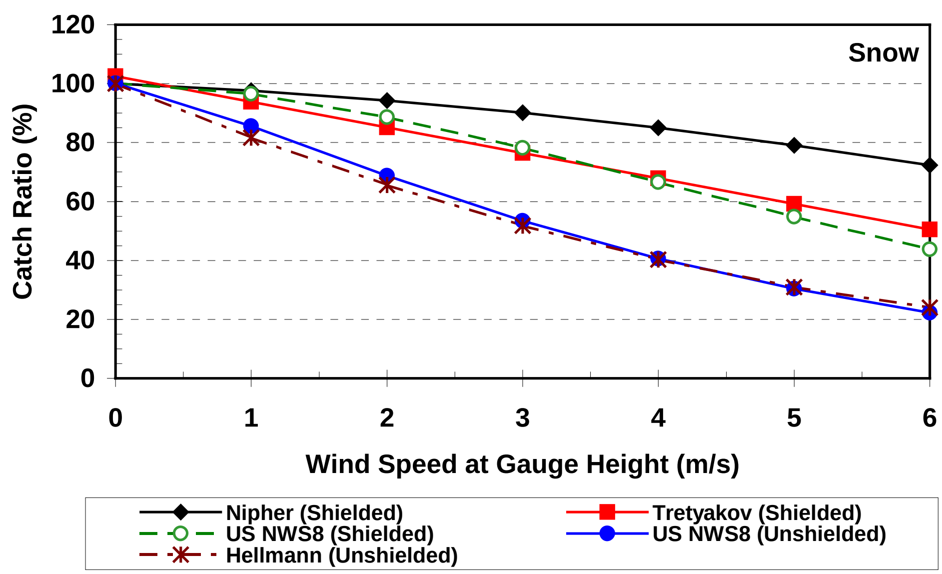
Wetting loss associated with manual gauge measurements is cumulative and depends on the number of times the gauge is emptied; it can become a very large value for the year. The adjustment of data on a daily basis seems logical, but precipitation measurements may be made every six hours, twice per day or only once per day, depending on the type of station. Each country archives its data differently and the exact number of times the gauge was emptied may not be retrievable from the historical digital archives. Wetting loss is an average value which could be added to the measurement at the time of observation. Use of a digital balance to weigh the contents of simple manual gauges, hence eliminating the need for adjusting for wetting loss, is a reliable alternative, but for most National Services it would be too expensive to implement. The adjustment for wetting loss at the time of observation is feasible, but would require a change in observing and reporting procedures by Member countries.

Table 3 Regression equations for catch ratio versus wind and temperature for Nipher, Tretyakov, US NWS8 and Hellmann gauges

Gauge	Catch Ratio versus Wind and Temperature	n	r^2	SE
	Snow			
Nipher	$CR_{NIPHER} = 100.00 - 0.44*W_s^2 - 1.98*W_s$	241	0.40	11.05
Tretyakov	$CR_{Tretyakov} = 103.11 - 8.67 * W_s + 0.30 * T_{max}$	381	0.66	10.84
US NWS 8"_Sh	$CR_{NWS\ 8\text{-}Alter\ Shield} = \exp(4.61 - 0.04*W_s^{1.75})$	107	0.72	9.77
US NWS 8"_Unsh	$CR_{NWS8\text{-}unshield} = \exp(4.61 - 0.16*W_s^{1.28})$	55	0.77	9.41
Hellmann	$CR_{Hellmann,\ unsh.} = 100.00 + 1.13*W_s^2 - 19.45*W_s$	172	0.75	11.97
	Mixed			
Nipher	$CR_{NIPHER} = 97.29 - 3.18*W_s + 0.58* T_{max} - 0.67*T_{min}$	177	0.38	8.02
Tretyakov	$CR_{Tretyakov} = 96.99 - 4.46 *W_s + 0.88 * T_{max} + 0.22*T_{min}$	433	0.46	9.15
US NWS 8"_Sh	$CR_{Alter\ Shield} = 101.04 - 5.62*W_s$	75	0.59	7.56
US NWS 8"_Unsh	$CR_{Unshield} = 100.77 - 8.34*W_s$	59	0.37	13.66
Hellmann	$CR_{Hellmann,\ unsh.} = 96.63 + 0.41*W_s^2 - 9.84*W_s + 5.95 * T_{mean}$	285	0.48	15.14

W_s = Wind Speed (m/s) at Gauge Height   T = Air Temperature (^oC)   n = Number of observations
r^2 = Coefficient of Determination   SE = Standard Error or Estimate

Figure 2 Plot of Catch Ratios versus Wind based on best fit regression equations shown in Table 3 for snow; the Tretyakov curve was plotted for T_{max} = -2.0 ^oC.



In testing adjustment procedures on its digital archive, Canada identified the additional challenge of quantifying trace precipitation. Currently, trace precipitation is recorded and archived as a “trace”, but is assigned a zero value in the computation of daily, monthly or annual precipitation totals. Some Canadian Arctic stations have reported over 80 per cent of all precipitation observations as trace amounts (over 1000 observations per year). Recognizing that there are losses for wetting, trace amounts can be a measurable amount, ranging from 0.0 to 0.15 mm or more, per observation. Trace precipitation must be considered as a non-zero value when adjusting precipitation data, with the assigned value varying according to the method of observation and climatic conditions. It is not a problem with recording gauges. Distinguishing between whether an event is “measurable” or just a “few flurries” is important; the use of two categories in the reporting of trace precipitation should be considered. Review of this issue by countries where trace precipitation is frequently recorded is warranted.

The WMO Solid Precipitation Measurement Intercomparison included some of the automatic gauges currently in use in some countries. Experiences of countries testing precipitation gauges suitable for measuring solid precipitation at automatic stations are presented. Although wind-induced errors negatively affect gauge catch, as for National non-recording gauges, there are several other problems which contribute to the serious undermeasurement of solid precipitation. Problems with both weighing and heated devices were identified. Heated gauges, including heated tipping bucket gauges, have been used in many countries. Finland and Germany reported a large undercatch by unshielded heated gauges, caused by the wind and the evaporation of melting snow. In Finland, the performance of heated tipping buckets was found to be very poor. Heated gauges are not recommended for use in measuring solid precipitation in regions were temperatures fall below $0^{o}C$ for prolonged periods of time.

Automatic weighing gauges are another alternative and were assessed in Canada, Finland and the United States. One serious operational problem with recording weighing gauges is that wet snow or freezing rain can stick to the inside of the orifice of the gauge and does not fall into the bucket to be weighed until some time later, often after an increase in ambient air temperature. There can be other complications, such as gauges catching blowing snow, differentiation of the type of precipitation and wind-induced oscillation of the weighing mechanism (wind pumping). These problems affect real-time interpretation and use of the data as well as the application of an appropriate procedure to adjust the measurement for systematic errors. The adjustment of weighing gauge data on an hourly or daily basis may be more difficult than on longer time periods, such as with monthly climatological summaries. Ancillary data from the automatic weather station, such as air temperature, wind at gauge height, present weather, or snow depth will be useful in accurately interpreting and adjusting the precipitation measurements from automatic gauges.

Conclusions and recommendations

The goal and objectives of the experiment were achieved. A quality controlled digital database of all intercomparison data submitted by participants for the period up to April 1993 has been prepared. The database is currently maintained by Canada and will be made available to interested Members and other researchers in accordance to WMO policy on the access to research data sets from Intercomparison projects. It is clear that in order to achieve data compatibility when using different gauge types and shielding during all weather conditions, adjustments to the actual measurements will be necessary. Since shielded gauges catch more than their unshielded counterparts, gauges should be shielded either naturally (e.g. forest clearing) or artificially (e.g. Alter, Canadian Nipher type, Tretyakov wind shield) to minimize the adverse effect of wind. However, even when using shielded gauges, adjustment of the measurements will still be necessary. Examples of the effect that adjustments have on archived data, nationally and globally, have been included to show Members that adjusting precipitation for systematic errors and biases is both feasible and essential.

At this time, the IOC is not recommending that a single precipitation gauge be adopted by all Members for the measurement of solid precipitation. Instead, Members should review the results of the Intercomparison for their National gauge and decide on the most appropriate action to address the errors in precipitation measurement within their country.

Specific conclusions and recommendations on the measurement and adjustment of solid precipitation prepared by the IOC and participants in the Intercomparison include:

1. Acceptance of the Double Fence Intercomparison Reference (DFIR) as a reference for the measurement of solid precipitation;

2. Methods to adjust solid precipitation measurements for systematic errors should be tested and implemented on current and archived precipitation data for use by Members[1]; creation of any national adjusted precipitation archive of historical data must be kept as a separate file from the original archive of observations;

3. Based on national reports, there should be a review of the observation, recording and archiving of "trace" precipitation so that it is treated as a non-zero quantity;

4. There should be a review of the frequency of blowing snow events during precipitation and how precipitation measurement during such events should be treated;

5. Automatic weather stations should also measure wind speed at gauge height; and

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1) Generally limited to mean wind speeds at gauge height during precipitation of < 6 m/s for the adjustment algorithms proposed in this report.

6. Heated automatic gauges are not recommended for the measurement of solid precipitation, based on results of tests in this Intercomparison.

To apply any adjustment procedures, it is recognized that a digital metadata archive which includes detailed site descriptions of gauge exposure, gauge configuration, changes in method of observation and data processing algorithms used to create the adjusted archive of precipitation would be extremely valuable.

The Intercomparison also found that equipment provided was not always to specifications. Hence it is further recommended that:

7. Users should calibrate and check the actual specifications of gauges when delivered which also might include the mechanical dimensions, tightness, orifice dimensions, etc. before field installation.

The Organizing Committee recognizes that all possible climatic conditions were not evaluated in the Intercomparison. Hence it is recognized that:

8. Members may validate the recommended Intercomparison adjustment algorithms when applying them to their data, especially for very cold regions not sampled in the Intercomparison; and

9. Members may establish National Precipitation Centres to facilitate necessary ongoing studies on precipitation measurement such as: new gauges and observational procedures, assessment of gauges for use at automatic stations, quantification of trace precipitation, assessment of blowing snow on measurements, further development and validation of adjustment models under more extreme wind and lower temperature conditions, etc.

The accuracy of methods of precipitation measurements currently used by the Members does not meet - in any way - the WMO requirements. The application of adjustments for precipitation data sets for systematic errors due to the adverse effect of wind, wetting and evaporation will improve significantly the quality of precipitation time series. Adjustment procedures and reference measurements have been developed and evaluated. The application of these procedures for different types of precipitation gauges tested during the WMO Intercomparison has been assessed in various countries, as summarized in the Report and contained in the Annex. Members are urged to test the application of these procedures on their precipitation observations and to continue to further develop them.

****

1. BACKGROUND

1.1 INTRODUCTION

The measurement of solid precipitation is recognized as a long standing problem and one that is far more difficult than the measurement of liquid precipitation. Snow measurement using precipitation gauges has been shown to have systematic losses of up to 100% caused by wind, wetting and evaporation effects and depending on the type of precipitation gauge and the observation site. The Commission for Instruments and Methods of Observation (CIMO) and the Commission for Hydrology (CHy) have been aware of the problem for many years and as required have appointed rapporteurs or working groups to address specific problems on the measurement of liquid and solid precipitation.

In 1970 the Executive Committee decided that CIMO should re-establish the Working Group on Measurement of Precipitation to conduct an international comparison of national precipitation gauges with a reference pit gauge for point rainfall measurement. Fifty-nine stations in 22 countries participated in the intercomparison between 1972 and 1976. The results of this intercomparison were published in the Instruments and Observing Methods Report No. 17. At the same time, the CIMO Working Group on Measurement of Precipitation initiated a programme to obtain information on national measurement techniques for solid precipitation (Sevruk and Hamon, 1984). Twenty-two countries responded to a questionnaire on methods to measure snowfall, on the efficiency of the methods, and on techniques to yield better results.

Consequently, at CIMO-VI (1973), a recommendation was passed for the comparison of gauges for the measurement of snowfall. CIMO and CHy representatives supported this proposal. A preliminary report of their findings was presented at CIMO-VII (1977). Unlike the pit gauge comparison a commonly accepted reference gauge or reference method for measuring solid precipitation was not available for this comparison. Although the comparison did not result in the definition of a standard reference, it did demonstrate that there were procedures available for a more accurate measurement of snowfall.

Members who participated in the comparison, or who have conducted their own studies on measurement of solid precipitation, have made considerable progress on this problem. Many of these results are included in the more comprehensive discussion on methods of Correction for Systematic Error in Point Precipitation Measurement (Sevruk, 1982).

At the International Workshop on the Correction of Precipitation Measurement (Zurich, 1985), papers revealed that an important number of very significant investigations on point precipitation measurements have been carried out at the national level in many countries (Sevruk, 1986). Based on results from such investigations and comparisons, various countries are already making or at least envisaging increased use of national point precipitation corrections on an operational basis. In addition, recognizing the needs expressed by CHy for more accurate solid precipitation data to allow better planning of water use and also as important input for hydrological models, water balances and for the estimation of evapotranspiration, CIMO-IX (1985) recommended that an international comparison of current national methods of measuring solid precipitation, including those suitable for use at automatic weather stations, should be conducted in order to reduce the problems of snow measurements.

Countries which participated, operated the reference standard and have submitted complete data summaries for analysis were: Canada, China, Croatia, Denmark, Finland, Germany, Japan, Norway, Russian Federation, Sweden, Switzerland, and the United States. Other countries collecting and submitting comparative data for at least one winter included Bulgaria, India, Romania and Slovakia, and the United Kingdom. This report documents the methodology, site description, data collection, archive and analyses, and summarizes the results from the participating Countries.

The remainder of this chapter presents a history on precipitation measurement intercomparison. A detailed discussion on the physics of precipitation gauges by B. Sevruk, is given in Annex 1.A.

1.2 HISTORY OF PRECIPITATION MEASUREMENT INTERCOMPARISONS

Precipitation gauges of different construction as installed at the same site near to each other frequently measure different precipitation amounts. The reason is the systematic error of precipitation measurement, particularly the wind-induced loss. Its magnitude depends considerably on the construction parameters of a particular type of gauge. Since there are more than 50 types of gauge used all around the world at present (Sevruk and Klemm, l989), the global precipitation data sets are hardly compatible. Precipitation totals between countries show systematic differences, and the isohyets at the borders of countries using different types of national standard gauges do not coincide. To eliminate this effect, the performance of precipitation gauges has to be checked and the precipitation measurements adjusted. To check the performance and to develop adjustment procedures for systematic error, the WMO recommends the carrying out of intercomparison measurements using the WMO standard references such as the pit gauge for rain and DFIR for snow, as shown further in this report. This section reviews the history of the WMO international precipitation measurement intercomparisons and the chronology of DFIR.

Table 1.2.1 WMO International Precipitation Measurement Intercomparisons

	INTERCOMPARISON		
	I	**II**	**III**
Subject	**Precipitation**	**Rain**	**Snow**
Time period	1960-1975	1972-1976	1986-1993
Purpose	Reduction coefficients between the catches of various types of national gauges	Rain catch differences between the various types of national gauges and the pit gauge. Correction procedures.	Determine wind-induced error. Derive standard correction procedures. (Wetting and evaporation losses considered)
Reference standard (See Fig. 1)	International Reference Precipitation Gauge, IRPG, consisting of Mk 2 gauge[1] elevated 1 m above ground and equipped with the Alter wind shield	Pit gauge consisting of Mk 2 gauge[1] installed in a pit, the orifice flush with the ground and surrounded by anti-splash grid	Double-Fence International Reference (DFIR) consisting of the shielded Tretyakov gauge[2] encircled by two octagonal lath-fences[3]
Participants	Belgium, Czechoslovakia, Hungary, Israel, USA, Russia	Basic stations: 22 countries. Evaluation stations: Australia, Denmark, Finland, USA	Canada, China, Croatia, Denmark, Finland, Germany, Japan, Norway, Romania, Russian Federation, Slovakia, Sweden, Switzerland, UK, and USA.
Results	Non-conclusive	Wind-induced loss depends on wind speed, rain intensity and the type of gauge. It amounts on average to 3% (up to 20 %) and to 4 - 6 % if wetting and evaporation losses are accounted for.	Wind-induced loss depends on wind speed, temperature and the type of gauge. Non-shielded gauges show greater losses as shielded ones (up to 80 % vs. 40 % for wind speed of 5 m/s and temperature greater than -8^{o}C).
Reference	Poncelet (1959) Struzer (1971)	Sevruk and Hamon (1984)	Goodison et al. (1989a)

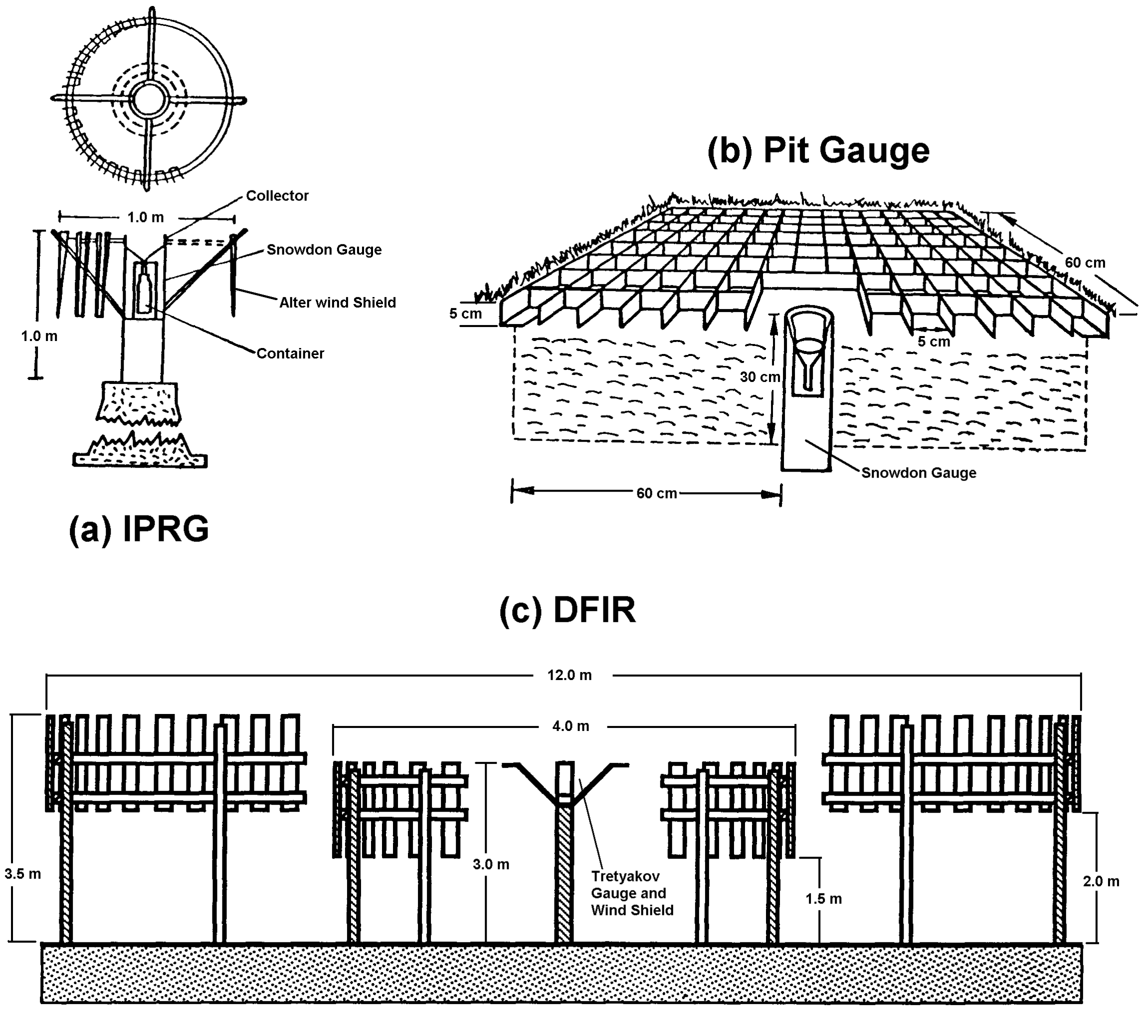
1 British Meteorological Office standard gauge of Snowdon type
2 The Tretyakov gauge is the Russian standard gauge
3 The diameter of inner fence is 4 m and of the outer fence is 12 m. The respective heights are 3 and 3.5 m above ground. The Tretyakov gauge without fence is the secondary standard.

An extensive review of history of precipitation measurement especially of the systematic measurement error with numerous references is given in a report by Sevruk (1981). A short, selected chronology of the wind-induced loss, starting back to 1769 can be found in the WMO publications by Sevruk (1982) and Sevruk and Hamon (1984). An excellent source of references up to 1972 is the WMO Annotated Bibliography on Precipitation Measurement Instruments by Rodda (1973). The development of DFIR was reviewed by Golubev (1979). Table 1.2.1 gives an outline of the WMO intercomparison measurements of precipitation and Figure 1.2.1 shows the WMO reference standards of precipitation measurements.

The intercomparison of precipitation measurements were used through centuries to develop better precipitation gauges. They are documented particularly during the last two centuries, since Heberden (1769) has published his famous treatise on rain measurements. The first intercomparisons were probably carried out even earlier at the very beginning of precipitation measurement at the end of the 17th century. As can be traced by comparing comments and pictures in the literature, it seems that intercomparisons at that time were more of a qualitative nature. The reason might be the evident need to improve the relative simple and unsatisfactory design of the first precipitation gauges. They showed excessive evaporation and wetting losses. In any case, the second generation of precipitation gauges appearing during the 18th century was better suited for more accurate measurements. The body of a gauge was build in a more compact form. For instance, the long flexible tube which was sometimes used to connect the separated collector with the container and caused considerable wetting losses was successively replaced by the funnel with a short outflow, placed immediately above the inflow of the container. The container consisted of a glass or earthware bottle with a small inflow opening or was made from a glass tube of small diameter. The tube was calibrated so that even small amounts of precipitation could be directly read out with a satisfying accuracy.

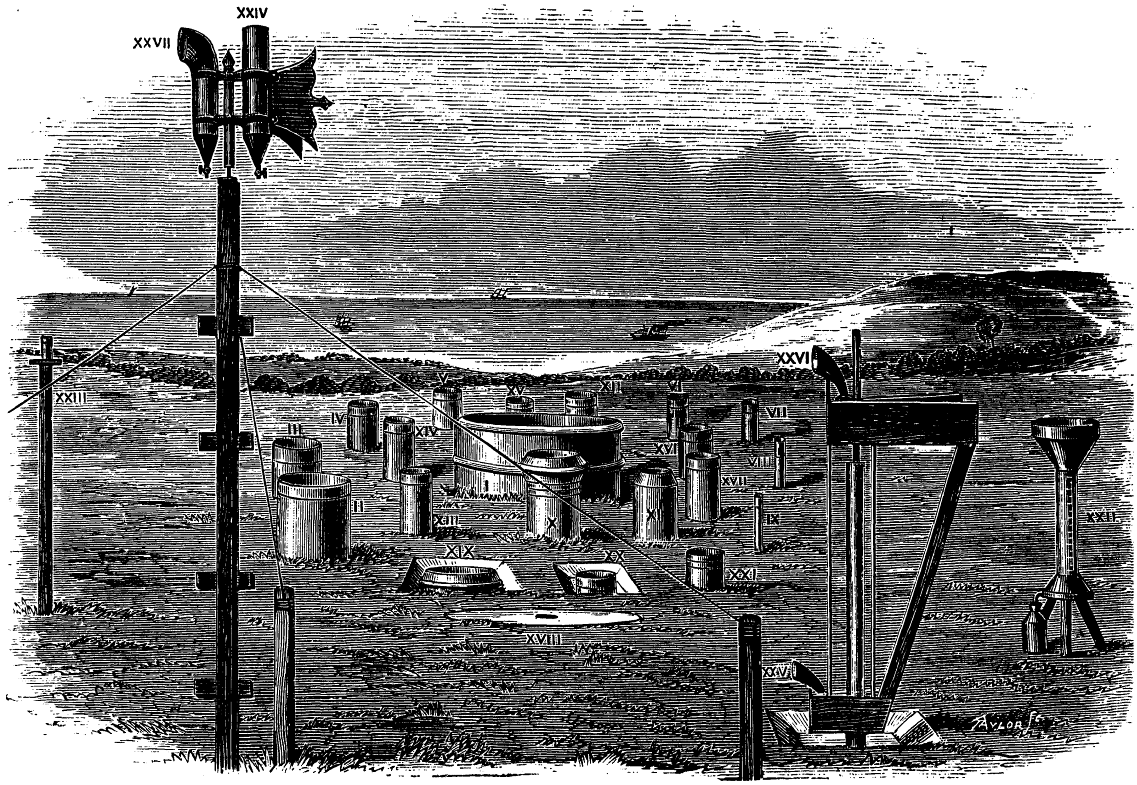
Later in the 19th century, the collector and the container were inserted into a protective can. Owing to such improvements, the evaporation and wetting losses could be considerably reduced.

Figure 1.2.1 Standard reference gauges as used during international precipitation measurement intercomparisons. Clockwise: (a) International Precipitation Reference Gauge, IPRG (Poncelet, I959); (b) the pit gauge, and (c) the Double-Fence International Reference.



Intercomparison measurements carried out in the 19th century demonstrated that different types of precipitation gauges measured different precipitation amounts. This was why the national meteorological services decided to use only one type of a gauge over the state territory as the national standard. To select such a gauge type, intercomparison measurements were organized on a national base. The more of less qualitative intercomparisons as usually made prior to this time by an individual observer in the manner: "... and there was snow on the ground but nothing in the gauge..." were replaced by a planned systematic action including more observers and different sites and involving some scientific aspects. Usually, the gauges made of different materials and having different shapes were placed near to each other and simultaneously measured to select the most suitable one. Alternately, gauges of the same type were installed in various heights above ground or under different environmental conditions (e.g. open areas, forest clearings or edges, etc.). The gauge types or installations showing most precipitation were considered to be the best. The most successful intercomparison of this type was organized in Britain by G. J. Symons in the second half of the last century. Figure 1.2.2 shows an example of an intercomparison site. The observers were educated persons such as priests and retired officers who were interested in the science and published regularly their reports in the year-books of British Rainfall. Since then, many national intercomparisons were organized, the best ones in the former USSR, in the 1960s by L. R. Struzer. The primary aim was to acquire more accurate hydrological balances through adjustments of precipitation measurements. Based on the results of these intercomparisons, the Soviet scientists developed for the first time in history, adjustment procedures for all components of the systematic error of precipitation measurement for operational use including the losses due to wind, wetting and evaporation and also due to the excess of measured precipitation during blowing snow events. Thus besides W. Heberden and the Belgian scientists L. Poncelet as mentioned below, the names of Symons and Struzer represent the milestones in the history of precipitation measurement research.

Figure 1.2.2 The view of the intercomparison site at Hawskers, according to Stow (1871).



1.2.1 The first international intercomparison

The first international intercomparison was initiated by Poncelet (1959) and organized jointly by the WMO and the International Association of Hydrological Sciences (IAHS). Its object was to obtain reduction coefficients between the catches of various types of national gauges. The Snowdon gauge (British Meteorological Office, Mk 2 gauge), was chosen as the International Reference Precipitation Gauge (IRPG). It was elevated 1.0 meter above the ground and equipped with the Alter wind shield (Figure 1.2.1a). Such a gauge, however, is still subject to a considerable extent, to the wind field deformation and consequently does not show the true amount of precipitation. This could be why the first international intercomparisons failed in the final analysis as pointed out by Struzer (l971) but its results have been used to develop the first map of corrected global precipitation (UNESCO, l978).

1.2.2 The second international intercomparison

The idea of the second WMO intercomparison was conceived at Versailles (France) in 1969. Its object was to evaluate wind correction factors for rainfall and to correct systematic errors in different parts of the world using the pit gauge as the WMO standard reference. Such a gauge is installed in a pit so that its orifice is flush with the ground. It is surrounded by a special metal or plastic grid preventing in-splash as shown in Figure 1.2.1b. It is interesting to note that pit gauges were already used in the last century as can be seen from Figure 1.2.2. Pit gauges are hardly affected by wind, and if corrected for wetting and evaporation losses they give reliable results as showed by Sevruk (l981) who reviewed papers on intercomparison measurements of various types of pit gauges and anti-splash surfaces including results from 24 experimental sites. The differences in catches of pit gauges amounted on average to ± 1% if wetting losses were accounted for and to ± 2% if no corrections for wetting were applied. The second WMO intercomparison started in 1972 and ended in 1976. It included 60 gauge sites in 22 countries. The results were published by the WMO (Sevruk and Hamon, 1984). They showed that rainfall as measured by the standard gauges elevated above ground is subject to the systematic error due to wind, wetting and evaporation, which is of an order of magnitude of 4 - 6% depending on the gauge type and the latitude and altitude of gauge site. This error can be corrected using an empirical model based on meteorological variables such as wind speed and the intensity of precipitation. The results indicated in which countries or regions these corrections are most important. Moreover the procedures available to introduce the corrections into the standard practices of precipitation measurements were developed.

1.2.3 The third international intercomparison

The pit gauge is not suitable to measure snowfall and it was necessary to select some other instrument as a standard reference if solid precipitation measurements have to be corrected. From the numerous snowfall measurement techniques as developed in the last hundred years, the precipitation gauges as shielded by fences appeared to be most promising for the operational use. In the 1970s, the WMO planned to organize a solid precipitation measurement intercomparison. A fence encircling a shielded gauge as developed in the USA (Wyoming shield) was suggested as the reference. For the lack of interest of the WMO Members this intercomparison was not realized. It was started more than 10 years later as recommended by the participants of the WMO International Workshop on Correction of Precipitation Measurement held in Zurich in 1985. The Organizing Committee for this intercomparison decided to use the Russian double fence as international reference standard, DFIR (see Figure 1.2.1c). This fence consists of the shielded Tretyakov gauge encircled by two octagonal lath-fences having the diameter of 4 and 12 m and the respective heights of 3 and 3.5 m. The Tretyakov gauge without fence was recommended to be used as the working reference. The aim of the WMO Solid Precipitation Measurement Intercomparison is to determine wind-induced error of different national standard gauges and to derive adjustment procedures considering wetting and evaporation losses. As noted in the Introduction, some 16 countries participated at some level in this intercomparison.

1.3 HISTORY OF DFIR

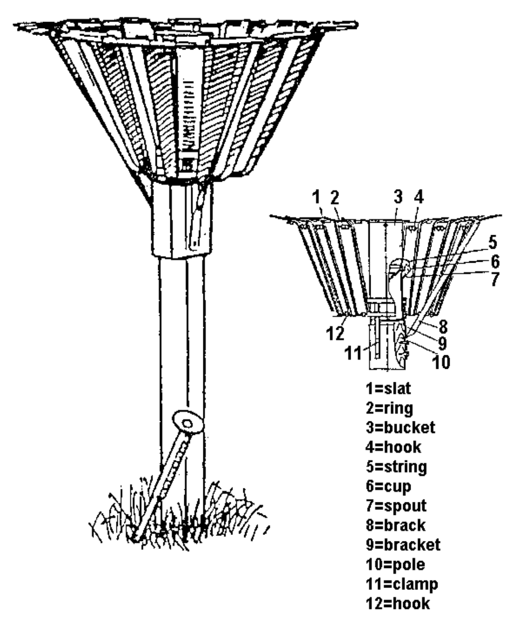
The development of fences as a protection of precipitation gauges against wind can be traced back to the Swiss meteorologist Heinrich Wild in the second half of the last century and to the Russian scientist G.I. Orlov approximately 60 years later. H. Wild was working in Russia and he installed in 1879, a single square snow fence, 5 x 5 m and 2.5 m high around the gauge. The gauge was situated in the center at a level of 1 m above ground. Such a gauge showed considerably more snow than an unshielded one (Wild, 1885). The idea of a double-fence can be attributed to Orlov (1946). He used such a fence probably for the first time in l936 in Russia. It was an octagonal double-fence 2.5 m high. The diameter of the inner fence was 4 m and of the outer one 12 m. The height of the gauge orifice was 1.7 m above ground, that was 0.8 m below the top of the fence. Golubev (1986) tested three different types of such fences during 1965-1972 in the Valdai experimental base situated midway between St. Petersburg and Moscow. He used the so called "bush gauge" as a reference which consisted of a gauge surrounded by a bush cut up to the level of the gauge orifice over an area of approximately 100x100 m. The DFIR catch varied from 92 to 96% of the actual snowfall. Based on his results, the Organizing Committee selected the present type of the DFIR as the WMO reference standard for solid precipitation measurement.

Fences of similar design were also developed and tested in the USA in the 1960s and it is referred to in studies by Richard (1972) and Larson (1986). Sevruk (1992) reviewed results of intercomparison measurement with the "Wyoming shield" as mentioned above. This fence has been tested in various modifications in the USA, Canada and Russia and showed a slightly worse performance than the DFIR. It is still used in the USA.

1.4 THE WORKING NETWORK REFERENCE GAUGE

The Tretyakov precipitation gauge (Figure 1.3.1) which is a part of the DFIR has been introduced in the former USSR at the end of the 1950s. It is still the national standard for countries which occupy the territory of the former USSR. Because the Tretyakov precipitation gauge has the most complete documentation of its performance for a wide range of climatic conditions for the measurement of solid precipitation, it was designated as the Working Network Reference gauge for this Intercomparison.

Figure 1.3.1 Tretyakov Gauge with wind shield, designated as the secondary or Working Network Reference gauge for WMO Solid Precipitation Measurement Intercomparison



1.5 CONCLUSIONS

The importance of intercomparison measurements of precipitation is stressed by the fact that they are used to check the performance of precipitation gauges and to develop adjustment procedures for systematic error of precipitation measurement. Moreover they are the basic source of the knowledge on the physical properties of precipitation gauges. In addition, intercomparison measurements of precipitation are carried out in many countries at present and they are the main methodical approach to be applied in the planned national and regional precipitation centers. Despite the increased use of wind tunnel experiments and computational fluid dynamic to study the physics of precipitation gauges and to derive adjustment procedures for systematic errors, it seems that field intercomparison measurements continue to be the main tool in precipitation measurement investigations and that this situation is not likely to be changed very soon.

2. METHODOLOGY

2.1 INTRODUCTION

The methodology and procedures used in the WMO Solid Precipitation Measurement Intercomparison study were set at the first session of its International Organizing Committee held at Norrkoping, Sweden on 16-20 December 1985. They were designed with the following study objectives in mind:

1. To determine the wind related errors in national methods of solid precipitation measurements including consideration of wetting and evaporation losses;

2. To derive standard methods for adjusting solid precipitation measurements;

3. To introduce a reference method of solid precipitation measurement for general use to calibrate any type of precipitation gauge including automatic gauges; and

4. To establish a complete solid precipitation data set with all necessary information for research (and eventually exchange) purposes.

All methods currently in operational use to measure solid precipitation (primarily in the form of snowfall) in the participating country were to be included in the Intercomparison. Such methods may be manual (e.g. non-recording precipitation gauges, ruler measurements of depth to estimate snow water equivalent) or automatic (e.g. recording precipitation gauges). Countries may have also compared other methods, such as snow pillows, snow lysimeters or nuclear, gamma and cosmic gauges.

It was recommended that all participants take this opportunity to test new techniques developed in their country for measuring solid precipitation, particularly those suitable for use at automatic weather stations. This might include new automatic precipitation gauges (e.g. heated, weighing) automatic snow depth sensors or ground based radar. Installation and observational procedures followed national standards.

Because of the growing importance of the determination of the exact amount of precipitation for acid precipitation and snowmelt shock potential studies, this Intercomparison provided an excellent opportunity to assess the accuracy of national methods currently used to measure solid precipitation for such studies (e.g. precipitation chemistry samplers). Again, installation and observational requirements followed current national standards.

2.2 ORGANIZATION OF THE INTERCOMPARISON

2.2.1 Place, date and duration of the Intercomparison

The WMO Solid Precipitation Measurement Intercomparison was carried out by the interested Members according to the procedures outlined in this report. The study lasted five years and was started in November 1986 in countries in the Northern Hemisphere and in May 1987 in the Southern Hemisphere.

2.2.2 Reference method

Since conventional precipitation gauges, elevated above the ground disturb the wind field around and over the gauge orifice, various shielding devices and other techniques have been developed to minimize this adverse wind effect. Such methods generally allow for more accurate snowfall measurements. They are listed below in order of their performance as reported in the literature:

- Bush-shield: bush encircling the gauge and cut-off regularly to the level of the gauge orifice

- Double-fence: large octagonal or twelve-sided, vertical or inclined lath fences encircling the gauge. The diameter of the outer fence is 6-12 m and that of the inner fence 3-4 m

- Forest clearing: the distance of the trees from the gauge is roughly equal to the height of the trees

- Snow board measurement: during periods where no snow drifting or blowing occurs taking into account the melting and evaporation of snow

- Dual gauge approach: two adjacent gauges, one shielded and the other one unshielded

Some adjustment procedures which have been developed for several gauges were published in WMO - No. 589 (see Sevruk, 1982). Such procedures allowed for the estimation of the actual snowfall at gauge sites where wind speed and temperature data were available.

Considering the above mentioned methods in detail the committee came to the conclusion to designate the following method as the reference for this Intercomparison and named as the Double Fence Intercomparison Reference (DFIR):

> *The octagonal vertical double-fence inscribed into circles 12 m and 4 m in diameter, with the outer fence 3.5 m high and the inner fence 3.0 m high surrounding a Tretyakov precipitation gauge mounted at a height of 3.0 m. In the outer fence there is a gap of 2.0 m and in the inner fence of 1.5 m between the ground and the bottom of the fences (see Figure 1.2.1 and Annex 2.B)*

Bush shields and forest clearings as noted above have been used in the past as methods for reference measurements for specific studies. It was recognized that such sites may not be available in all climatic regions for this Intercomparison. Where such sites are available, participants were encouraged to conduct comparisons between measurements using the DFIR and corresponding measurements at such sheltered locations (as described in Annex 2.A). The Tretyakov precipitation gauge (described in Figure 1.3.1 and Annex 2.C), having the most complete documentation of its performance for a wide range of climatic conditions for the measurement of solid precipitation was designated as the Working Network Reference gauge for this Intercomparison. Participating Members were kindly requested to contact the Finnish Meteorological Service for obtaining Tretyakov precipitation gauges for the intercomparison study.

NOTE: At sites not subject to drifting or blowing snow conditions, the snow water equivalent of solid precipitation may be determined from measurements made on a snow board (see WMO Guide to Hydrological Procedures, WMO No. 168, Vol. 1, 1981 p. 2.1-2).

2.2.3 Types of stations

For the Intercomparison, all participating Members were requested to operate at least one Evaluation Station and they may also choose to operate one or more Basic Station. These station types are described below:

(a) Evaluation Station - most intensively instrumented for the purpose of analyzing in detail the differences in snowfall catch between all national methods of measuring solid precipitation and the Double Fence Intercomparison Reference (DFIR) and the Working Network Reference. Such stations should be established to represent the different climatological and physiographic regions in a country; and

(b) Basic Station - instrumented with the minimum amount of equipment to assess the performance and accuracy of national methods of measuring solid precipitation relative to the working-Network Reference.

It was deemed desirable for Evaluation Stations to be located at existing synoptic or other observing stations to take advantage of the complete observing program at such stations. Basic Stations should be located at sites where a complete program of national methods of measuring solid precipitation can be conducted.

In carrying out the Intercomparison, the manner of installation of gauges and other observing equipment was required to agree with the instructions and specifications provided. The manner of observation of the Intercomparison Reference and Network Reference described in Annex 2.B and 2.C was required to be followed, but the measurements with the official national methods followed the practice specified in the appropriate national handbook or its equivalent.

2.2.4 Intercomparison site documentation and instrumentation

All sites used in the Intercomparison were required to be described according to Annex 2.D. A copy of each site description was required to be submitted to the Secretariat of WMO and to Dr. B. Goodison (Canada) for inclusion in the report.

For Evaluation Stations, the instrumentation consisted of the followings:

(a) One Double Fence Intercomparison Reference (DFIR) with a Tretyakov gauge shall be installed according to Annex 2.B;

(b) One national gauge equipped with the national standard windshield or with a shield similar to the bridled Alter shield or the Tretyakov shield (Annex 2.C);

(c) One national gauge without shield;

(d) One Tretyakov precipitation gauge (Complete drawings and specifications of this gauge and wind-shield are shown in Annex 2.C);

(e) One snow-board for case studies;

(f) One thermometer screen or other standard national weather shelter for housing a thermo-hygrograph or recording temperature and humidity sensing system;

(g) One recording thermo-hygrograph or recording temperature and humidity sensing system (minimum hourly resolution);

(h) Wind recorder for wind speed and direction, with speed measured a height of orifices and at the national standard height (10 m); storm mean wind speed and direction required;

(i) One double fence shield with national gauge or recording gauge installed in the centre; and

(j) Other equipment being tested by Members for their own purposes.

For Basic stations, the instrumentation was the same as for the Evaluation Station except (a), and (i) were not required.

2.2.5 Installation of equipment

The installation of instruments was as follows:

a) The required gauges were mounted on wooden posts or steel towers so that the orifices will remain at least 1 m above the vegetative cover or the deepest expected snow accumulation;

(b) For the required gauges, the unshielded gauges were installed in a row normal to the prevailing wind direction during snowfall events, at a distance of 7 - 9 m apart, the gauges with windshields should be installed in a row displaced 15 m downwind from the unshielded gauges and located 15 m apart;

(c) The windshields on the gauges were installed in conformity with specifications. (The bridled windshield and the free swinging windshield shall have the top of the leaves level with the gauge orifice and 12 mm above the gauge orifice, respectively);

(d) All gauge orifices and windshields were installed in a level position;

(e) The required wind speed and direction instruments were installed at the next grid position. The wind speed sensors were installed at the heights of the gauge orifices;

(f) The thermometer screen or other standard national weather shelter may be located away from the gauge site at a convenient nearby site; and

(g) The Double Fence intercomparison Reference (DFIR) were in line with gauges installed in (b) and (e) or downwind of (b) by at least 20 m. If more than one double fence shield is operated, they must be no less than 75 m apart, and preferably normal to the prevailing wind direction to avoid interference with each other.

2.3 DATA COLLECTION AND OBSERVATION PROCEDURES

2.3.1 Data Collection

The following meteorological variables were measured according to WMO procedures: precipitation, wind speed and direction, air temperature and relative humidity. Climatological data were provided from each station on a semi-daily and monthly basis (Table 2.E.1, Annex 2.E). Additional data for individual storm events were provided whenever possible (Table 2.F.1, Annex 2.F). All the participating Members were provided with sufficient number of forms shown in Annexes 2.E and 2.F.

The measured amount of snow was adjusted for wetting and evaporation losses (see sections 2.4.1 and 2.4.2). The values were classified according to the type of precipitation (Annexes 2.E and 2.F) as follows:

- snow
- snow with rain
- rain with snow
- freezing rain
- rain

The snowfall was briefly described by visual observation as follows:

- wet snow
- light snowfall
- snow storm (shower)
- blowing and drifting snow
- snow grains and pellets

<u>Notes:</u>

a) If there is a non-measurable amount of snow a trace should be recorded as 'T'. Duration of snowfall should be classified as short (less than 1 hour) continuous or intermittent.
b) Every day when drifting or blowing snow occurs, even without snowfall, should be clearly noted.

Monthly summary of precipitation for each gauge was divided according to the type of precipitation as follows:

- total precipitation
- snow
- mixed precipitation (snow with rain and rain with snow)

Duration of snow and mixed precipitation in the monthly total precipitation was also provided (Table 2.F.1 in Annex 2.F).

The following wind speed/direction data were provided:

- for each level of wind measurement above the ground the average wind speed during the actual observation period with snowfall. If snowfall occurs between observation times the average wind speed is to be compiled from the previous and the next (or current) observed wind speeds
- the predominant wind direction during the snowfall event as measured at the standard height
- monthly average during the snowfall periods (average of the above mentioned values)
- daily mean
- monthly mean

The following air temperature data were provided:

- average air temperature during the actual observation period with snowfall. If snowfall occurs between observation times the average temperature is to be computed from the previous and the next (or current) observed temperature
- monthly average during the snowfall periods (average of the above mentioned values)
- daily mean
- monthly mean
- daily maximum and minimum

2.3.2 Additional procedures

At the second session of the International Organizing Committee held at Zagreb, Croatia on 19-23 October, 1987, some improvements of procedures were recommended. These include:

a) All participants of the Intercomparison were requested to check that the orifice of all gauges is level (horizontal). This should be checked at the beginning and end of the winter season and monthly checks were recommended. A gauge which is out-of-level by 3^{o} can lead to errors of $\pm$5%, depending on wind direction during snowfall. Elevated gauges may be particularly subject to out-of-levelness.

b) When measuring more than one gauge with the same measuring graduate (e.g. DFIR Tretyakov and Tretyakov), it was recommended that the measuring graduate is wetted before making the first measurement. This will provide comparable measurements for both gauges.

c) Members were reminded to instruct observers to check that collectors are dry before they are replaced in the gauge. This may be done visually. This should only be a problem if observations are made frequently (e.g. every 3 hours).

d) Members were asked to note that wind speed is measured at the height of the gauge orifice. Thus, for the DFIR, wind speed should be measured at 3.0 m above the ground.

e) The Finnish report noted that observers were draining gauges quite individually, some of them waiting until the last drop and some pouring like a teapot. The spout of some Tretyakov gauges was found to be welded so deep that the gauge was sent fully empty by a single overturning. It was recommended that all participants check their gauges for this potential problem.

f) Members were reminded that gauges should be covered with their lids during transport.

g) On some types of recording precipitation gauges, snow may adhere to the walls of the orifice and not enter the weighing bucket at the time of falling. Sometimes the snow may not fall into the weighing bucket until the next day. This can cause a problem in comparing gauge catch. The measured amount should be entered on the daily summary on the day that it was measured by the gauge. If it is known that the timing is incorrect, a note should be made under comments. The correct total precipitation should be entered on the event summary.

h) Depth of snow on the ground should be measured at each observation and included on the daily summary in a separate column.

i) Members will find that wetting losses will vary for each collector, for each gauge type and possibly by precipitation amount. Laboratory experiments for 0.5 mm and 5.0 mm amount of water were conducted by Finland. Wetting losses may change over time as the gauge ages and the surface roughness of the collector changes. It was recommended that tests for wetting losses should be repeated about three years after the first test.

j) Evaporation losses were considered to be significant, especially late in the winter season. These varied by gauge type. Section 2.4.2 gives the procedure for recording these losses.

k) The Intercomparison was concerned with falling snow but not dew (frost) ice, fog etc. which may condense in the gauge. Occurrence of the latter should be clearly noted in the comments. If the duration of such events is known, the number of hours should be recorded. It is realized that not all stations can provide this information.

l) The Committee discussed the need to know something about the homogeneity of the observing site. Using the same gauge, will the same amount of precipitation be measured everywhere on the site? Members were requested to operate concurrently at least one and preferably two additional national standard gauges at different locations at the evaluation station for one year to assess homogeneity of the intercomparison field. A method for the evaluation of homogeneity is given in Annex 2.G.

m) It has been noted that information on the type of clouds (cumulus, stratus, cumulonimbus, etc.) during snow events would be useful additional information. Members were urged to include such information if it is available.

n) A participating Member noted that if the amount of snow in a gauge is large (at least 1/3 full), the observer could also sketch the shape of the snow surface in the gauge. Such information may be used to evaluate the influence of wind (e.g. blow out) or freezing phenomena on the measurements of each type of instrument. This also provides additional information on the homogeneity of the site.

o) Wet snow can adhere to the sides and tops of gauges or on the edge of the orifice. It may or may not fall in the gauges the observer may have to decide what snow to include in the observation and what to exclude. Such events should be clearly noted in the comments and observers were encouraged to sketch such observations for future reference in the analysis.

p) All Members were asked to provide details of their anemometers (name, manufacturer, technical specifications, threshold starting speed, accuracy etc.) on their site description form. Measurements from different anemometers can vary widely. The need for an intercomparison of wind sensors used in the experiment was to be considered by the Committee. The above details will be of value in the Intercomparison.

2.4 DATA ANALYSIS

To understand the reason for the difference (if any) in catch between national methods of measuring solid precipitation and the intercomparison reference and ultimately "true" snowfall precipitation, the factor responsible for the difference must be investigated within each country and preferably within different climatological regions. All data collected by Members and provided in the forms shown in Tables 2.E.1 and 2.F.1 (see Annexes 2.E and 2.F) were submitted to the Secretariat of WMO and to Dr. B. Goodison (Canada), Chairman of the Organizing Committee for analyses. It was expected that Members also conducted analyses of their own data. Although, the primary factor to be assessed was the effect of wind, wetting and evaporation losses were also considered. Members using heated snow gauges were requested to conduct special investigations to assess the magnitude of losses due to evaporation during normal operation of this gauge. Members were also encouraged to conduct specific studies to determine the magnitude of errors associated with blowing snow (in-blowing and out-blowing) and to determine the average value for trace amounts of snowfall.

A full discussion of the systematic errors of precipitation measurements is given in Annex 1.A: Physics of precipitation gauges by B. Sevruk. Some procedures for processing and analyzing the data to determine systematic errors have been suggested in the following sections.

2.4.1 Adjust versus correct

Both terms “adjust” and “correct” have been used for describing computational procedures to account for the systematic errors inherent in precipitation measurement. Although the term “correct” has been used more commonly, the term “adjust” is the preferred terminology since it does not imply that the resulting precipitation value is the exact “ground truth” value. Because of the many authors contributing to this report, these two terms have been used interchangeably.

2.4.2 Wetting losses for snow

The wetting loss from each intercomparison gauge which was measured by the volumetric method should be estimated by weighing the collector immediately after the melted snow has been poured out from the collector and after the collector has dried completely. The difference between the wet and dry collector, in mm, gives the wetting loss per snowfall event. An average from 40 measurements can be used as a constant for a given collector (see Table 2.4.1 below).

The conversion of grams to millimeters of water depth can be made considering 1 g of water equals 1000 mm^3 as follows:

wetting loss = 10*(difference in weight in g)/(gauge orifice area in cm^2)

<u>Notes:</u>

a) The gauge orifice area refers to the actual measured orifice of a given gauge.
b) If all precipitation measurements are made by a weighing method, no adjustment for wetting loss is required.

Table 2.4.1 WETTING LOSSES FOR SNOW GAUGE TYPE:

No.	**P**	**P_1**	**No.**	**P**	**P_1**
	(mm)	**(mm)**		**(mm)**	**(mm)**
1			4		
2			5		
3			6		

P_1 = difference between the weights of wet and dry precipitation collector (mm)
P = measured precipitation (mm)

2.4.3 Evaporation losses of precipitation gauges for snow

The evaporation loss should be estimated by weighing the collector immediately after the cessation of snowfall and at the time of observation and recorded in a form shown in Table 2.4.2. The difference between the weights, in mm, gives the evaporation loss. No snowfall should occur between the two weightings.

Table 2.4.2 EVAPORATION LOSSES FOR SNOWFALL GAUGE TYPE:

No	Year	Month	Day	Duration of evaporation		P_2 (mm)	Weather
				Begin	End		

P_2 = difference between the weight of precipitation gauge immediately after the snowfall and at the time of observation

2.4.4 Adjustment procedures for the effects of wind and temperature.

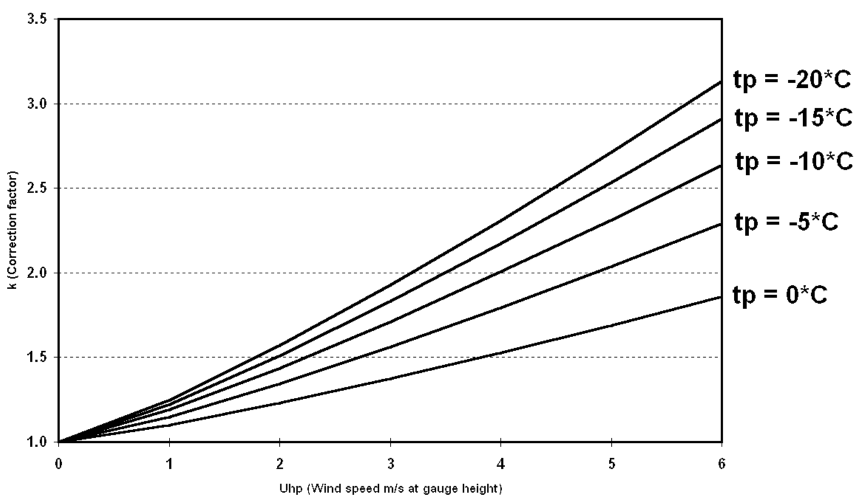
For most precipitation gauges, wind is the most important environmental factor contributing to the under measurement of solid precipitation. Studies in precipitation physics have also shown that the fall velocity of snowflakes depends on their shape which is a temperature phenomenon. This makes it possible to use air temperature as a parameter for the structure of solid precipitation. To study the effect of wind and temperature in the measurement of solid precipitation by ordinary precipitation gauges, researchers have represented the ratio of actual precipitation P_a to observed precipitation P_m as a function of the wind speed, u_{hp}, at the gauge orifice level and the air temperature, t_p, at the time of occurrence, thus:

$$k = P_a / P_m = f\,(u_{hp}, t_p)$$

A review of previous work on adjustment procedures based on empirical relationships of k with wind and temperature developed for the measurement of solid precipitation by specific gauges have been reported by Sevruk (1982). An example of such a relationship for the solid precipitation measured by the Tretyakov gauge developed by Braslavskiy, et al (1975) is given below and shown in Figure 2.4.1:

$$k = 1 + u_{hp}^{1.2}\,(0.35 - 0.25 \exp(0.045\, t_p)$$

Figure 2.4.1 Relationship of correction factor (k) with wind (u_{hp}) and temperature (t_p) for the solid precipitation measured by the Tretyakov gauge developed by Braslavskiy, et al (1975)



2.4.5 Adjustment of DFIR for wind effects

The need to adjust the DFIR measurement to the "true" value of the bush gauge for the effect of wind was discussed by Golubev (1989), since a comparison of DFIR and the bush gauge data at Valdai, Russia, indicated a systematic difference between the primary and secondary standards. Golubev (1989) proposed an adjustment procedure which included meteorological measurements of wind speed, atmospheric pressure, air temperature and humidity. More recent work by Yang, *et al* (1993) based on regression analysis indicated that the most statistically significant factor in the adjustment of the DFIR was the wind speed during the storms. The full report by Yang, *et al* (1993) can be found in Annex 2.H. The Sixth Session of WMO Organizing Committee of the Intercomparison (WMO/CIMO, 1993) recommended that the adjustment equations by Yang, *et al* (1993) given below be applied to all DFIR data before analyzing the catch of national gauges with respect to the DFIR where W_S is the wind speed at 3 metres in m/s during storm:

<u>Dry Snow:</u>

$$BUSH/DFIR(\%) = 100+1.89*W_S+6.54E\text{-}4*W_S^3+6.54E\text{-}5*W_S^5, \qquad (N=52, R^2=0.37)$$

<u>Wet Snow:</u>

$$BUSH/DFIR(\%) = \exp(4.54+0.032*W_S), \qquad (N=36, R^2=0.43)$$

<u>Blowing Snow:</u>

$$BUSH/DFIR(\%) = 100.62+0.897*W_S+0.067*W_S^3, \qquad (N=54, R^2=0.37)$$

<u>Rain with Snow:</u>

$$BUSH/DFIR(\%) = 101.67+0.254*W_S^2, \qquad (N=39, R^2=0.38)$$

<u>Snow with Rain:</u>

$$BUSH/DFIR(\%) = 98.97+2.30*W_S, \qquad (N=43, R^2=0.34)$$

<u>Rain:</u>

$$BUSH/DFIR(\%) = 100.35+1.667*W_S-2.40E\text{-}3*W_S^3, \qquad (N=120, R^2=0.22)$$

A re-evaluation of the adjustment procedures, developed by Yang, *et al* (1993), was recommended at the 7th Session of the International Organizing Committee of the WMO project, since more intercomparison data were collected at Valdai hydrological research station in Russia.

Similar statistical methods were used to analyze the intercomparison data. The results indicated that wind is the only factor affecting the DFIR catch of snow and mixed precipitation. For rainfall observation, there is no statistically significant correlation between wind speed and the ratio of Bush/DFIR. Figure 2.4.4 shows the best fit curves obtained by mean of the least square estimation. The regression equations are given below:

<u>Snow:</u>

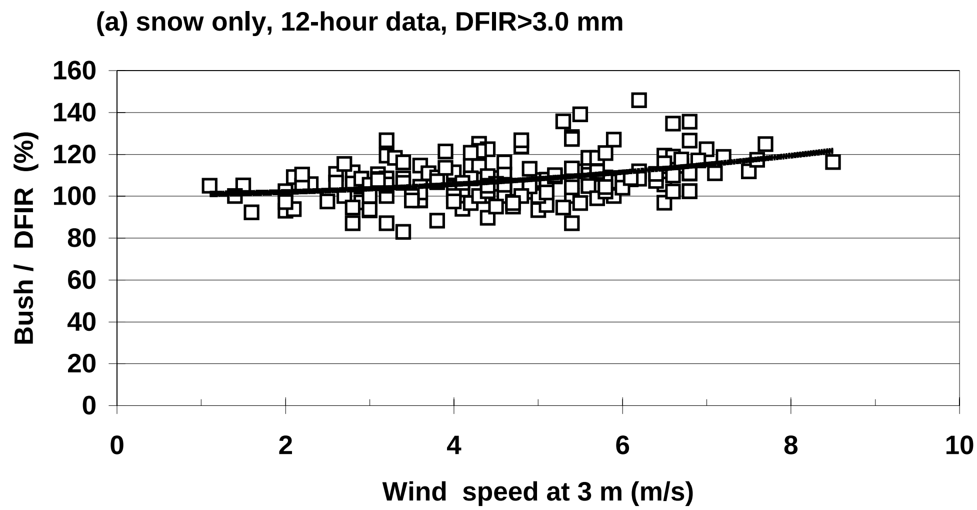
$$BUSH/DFIR(\%)=100+0.439*Ws+0.246*Ws^2, \quad (N=183, R^2= 0.151)$$

<u>Mixed precipitation</u>:

$$BUSH/DFIR(\%)=100+0.194*Ws+0.222*Ws^2, \quad (N=63, R^2= 0.093)$$

Comparisons of the results show that for snow the adjustment equations generally agree very well, with the difference of the catch ratios of the DFIR less than 5% for all the wind speeds. For mixed precipitation the new adjustment equation indicates a slightly higher catch ratio (2-8%), particularly for wind speed over 5m/s at gauge height (Figure 2.4.5).

It is recommended the new adjustment equations for snow and mixed precipitation be used in future studies. No adjustment is needed for rain measurements of the DFIR.



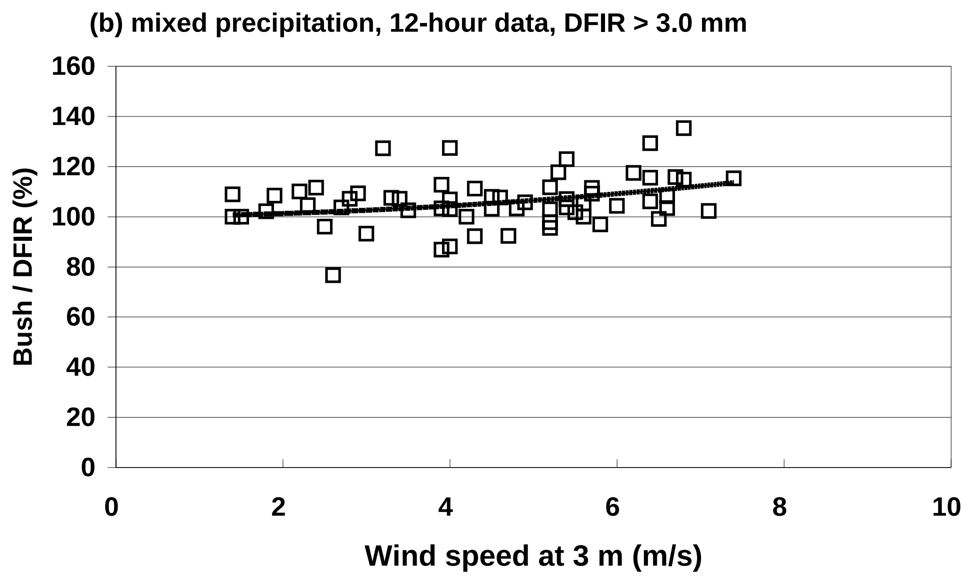


Figure 2.4.4. Ratio of the bush gauge to the DFIR as a function of wind speed at the DFIR height of 3 meters, for (a) snow and (b) mixed precipitation.

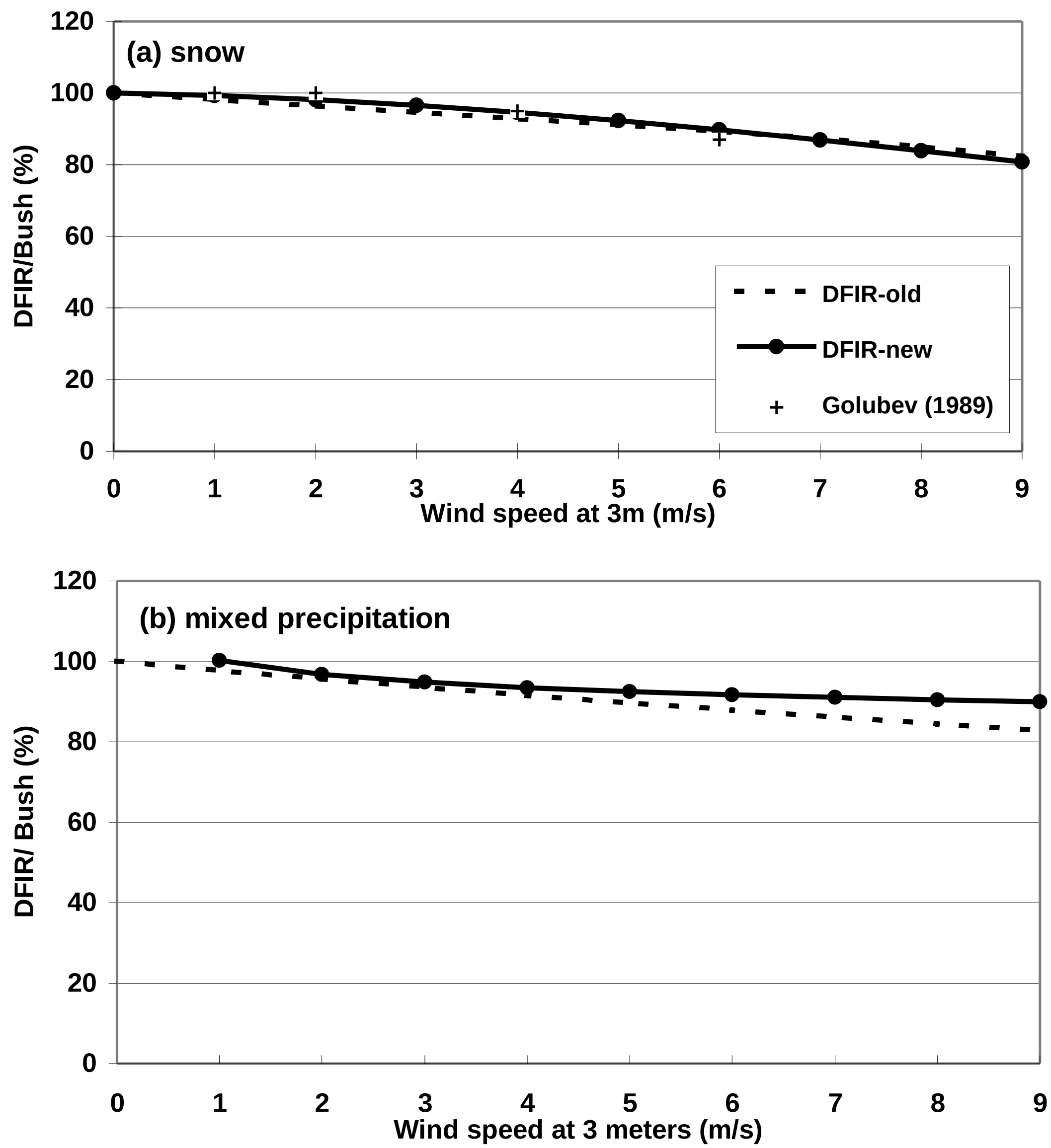


Figure 2.4.5. Comparison of the adjustment equations for wind-induced undercatch of the DFIR, (a) snow and (b) mixed precipitation.

3. SUMMARY DESCRIPTION OF SITES, INSTRUMENTS AND DATA ARCHIVE

3.1 SUMMARY OF SITE DESCRIPTIONS AND INSTRUMENTS

The site and instrumentation documentation requirements for Intercomparison stations have been described in Chapter 2. Countries which participated, operated the reference standard and have submitted site and instrumentation documentation were: Canada, China, Croatia, Finland (including Denmark, Norway and Sweden), Germany, Japan, Switzerland, Russian Federation, and the United States. Other countries collecting and submitting comparative data for at least one winter included India, Romania and Slovakia, and the United Kingdom. Figure 3.1 shows the site locations and Table 3.1 provides a summary of the site and instrument descriptions received. More detail reports provided by some countries are included in Annex 3.

3.2 SUMMARY OF DATA ARCHIVE

The WMO Solid Precipitation Measurement Intercomparison data archive consists of two components. For the first component, the data were compiled by the participating countries on observation forms. There were two forms used: a daily and monthly climatological summary form (see Section 2.3 and Annex 2.E) and a snow event duration form (see Section 2.3 and Annex 2.F). These two forms when completed, constituted the original paper archive of data collected during the Intercomparison.

For the second component, a PC compatible digital archive was created from the original paper archive. The digital archive consists of a spreadsheet format (MS Excel .xls or Lotus .wk1) that duplicates the original observation forms. An example of the digital data for Valdai, Russia is shown in Annex 4 Table 4.A.1. To assist the archive user in identifying the information located in each column of the paper or digital archive, WMO Solid Precipitation Gauge Logs were developed for both event and observation data sets. An example of a Precipitation Gauge log for observations is shown in Annex 4 Tables 4.A.2, it documents the type of data found in each cell of a spreadsheet by site. Each site was given a two letter identifier. This identifier followed by the year and month was used to label files in the digital archive. For example, EB88-04 is East Baltic (Canada) for April, 1988.

Every effort was made to insure that the digital archive contained valid information. After a data set was transferred from the paper archive to the digital archive, a hard copy print out was sent to the participating countries for review and verification. Errors or omissions which were identified by the participants were then corrected and the digital archive was updated. The final status of the WMO Solid Precipitation Measurement Intercomparison data archive is shown in Table 3.2. This table lists the participating countries from which paper archive data was received; the start and stop dates for which continuous daily, monthly or event data were collected; the status of the digital archive, event data and event archive; and an indication whether the digital archive was reviewed and checked by the participating country.

The availability of data from the WMO Solid Precipitation Measurement Intercomparison data archive to researchers will be in accordance with WMO policy on the access to research data sets from intercomparison projects.

Figure 3.1 WMO Solid Precipitation Intercomparison Sites

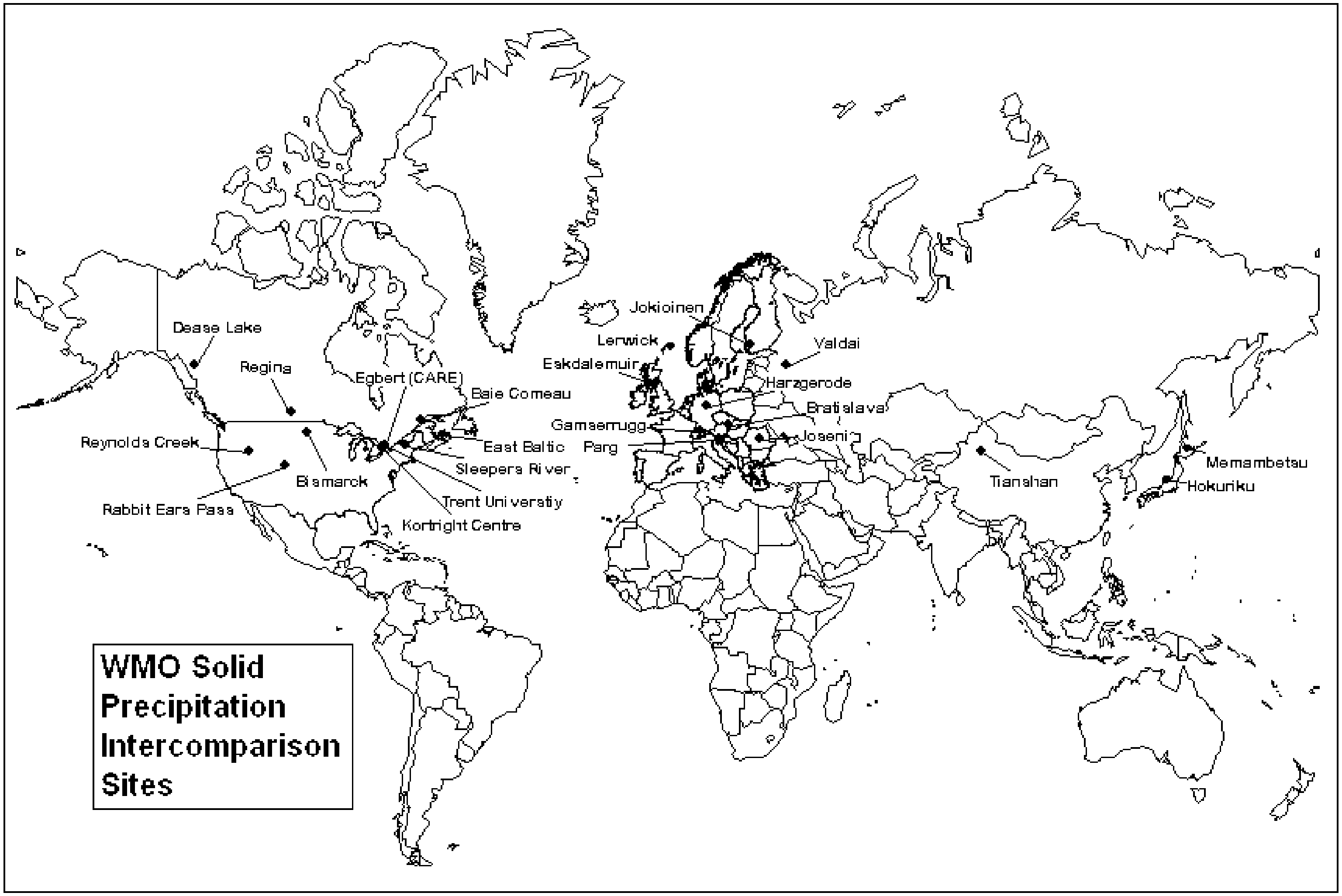


Table 3.1 Siting and instrumental information at WMO Intercomparison sites.

Station	***Climate & Exposure***	***DFIR***	***National Gauge***	***Obs. Method***	***Wind***	***Other Gauges / Wind Shields***	***Obs. Period***
Canada							
Dease Lake, B.C. 58°5'N 130°00'W 816m	T_a=-1.3°C P_a=405.9mm S_a=204.6 W_a=2.1m/s Exp=cleared area 600mx1000m	3m	Nipher snow gauge, AES Type-B rain gauge	volume	10m, 3m & 2m	unshielded Universal recording gauge, Alter shielded Universal gauge, large Nipher shielded Universal gauge, Snow Ruler, Acoustic Snow Depth Sensor	Dec87 to Apr93
Regina, Saskatchewan 50°26'N 104°40'W 577m	T_a=2.2°C P_a=384mm S_a=116mm W_a=6m/s Exp=flat open	3m	Nipher snow gauge, AES Type-B rain gauge	weight	10m, 3m & 2m	Tretyakov, unshielded Nipher, large Nipher shielded PTPR, Alter shielded Sacremento gauge, Alter shielded Stand-pipe gauge, Snow Ruler, Acoustic Snow Depth Sensor	Mar87 to Apr92
Kortright Centre, Ontario 43°51'N 79°36'W 208m	T_a=7.3 °C P_a=762mm S_a=131mm W_a=5m/s Exp=slightly rolling	3m	Nipher snow gauge, AES Type-B rain gauge	volume	10m, 3m & 2m	Tretyakov, unshielded Nipher, unshielded Universal recording gauge, DFIR with Universal gauge, Alter shielded Universal Gauge, Large Nipher shielded Universal gauge, unshielded Belfort Punch Tape Precipitation Recorder, Alter shielded Belfort PTPR, Snow Ruler, Acoustic Snow Depth Sensor	Jan87 to Mar91
Trent Universtiy, (Peterborough) Ontario 44°21'N 78°17W 230m	T_a= 6.3 °C P_a=797.7mm S_a=161.7mm W_a=3m/s Exp= open level field	3m	Nipher snow gauge, AES Type-B rain gauge	volume	10m, 3m & 2m	Tretyakov, large Nipher shielded Universal gauge, Snow Ruler	Dec86 to Mar91
Baie Comeau, Quebec 49°08'N 68°12W 21m	T_a=1.6°C P_a=987.6mm S_a=367.8mm W_a= Exp=flat open grass in valley	3m	Nipher snow gauge, AES type-B rain gauge	volume	10m, 3m & 2m	large Nipher shielded Universal gauge, Snow Ruler, Acoustic Snow Depth Sensor	Dec87 to Apr92
East Baltic, PEI 46°26'N 62°10W 61m	T_a= 5.4°C P_a=1012.7mm S_a=197.2mm W_a=5m/s Exp=flat grass farm land	3m	Nipher snow gauge, AES type-B rain gauge	volume	10m, 3m & 2m	large Nipher shielded Universal gauge, Alter shielded Belfort PTPR, Snow Ruler, Acoustic Snow Depth Sensor,	Dec87 to Apr92
Egbert, Ontario 44°13'N 79°47W 252m	T_a=6.5°C P_a=968.5mm S_a=154mm W_a= Exp=rolling open farmland	3m	Nipher snow gauge, AES type-B rain gauge	volume	10m, 3m & 2m	large Nipher shielded Universal gauge, Alter shielded Belfort PTPR, Snow Ruler, Acoustic Snow Depth Sensor	Nov90 to present

T_a=annual mean temp; P_a=annual total precipitation (mm); S_a=annual total snowfall (mm);
W_a=annual mean wind speed (m/s); Exp=site exposure.

Table 3.1 Siting and instrumental information at WMO Intercomparison sites (continued).

Station	*Climate & Exposure*	*DFIR*	*National Gauge*	*Obs. Method*	*Wind*	*Other Gauges / Wind Shields*	*Obs. Period*
China							
Tianshan 43° 4'N 87° 9'E 34720m	T_a= -5.4°C P_a= 420mm S_a= W_a=n/a Exp= 200m x 300m site in a river valley	2.5m	Chinese standard precipitation gauge	Volume	no wind data at site	Hellmann, Chinese recording gauge	Jun87 to Apr92
Croatia							
Parg 45°36N 14°38'E 863m	T_a=7.0 °C P_a=1885.6mm S_a= W_a=1.09m/s Exp=top on small hill surrounded by rounded mountains 10 Km away	3m	Hellmann Unshielded at 2m	volume	11.2m	Tretyakov, Double fence surrounding a Hellmann gauge (2m) , Hellmann unshielded at 2.25m and 2.66m, Hellmann Tretyakov wind shield	Jan87 to Apr89
FINLAND (including DENMARK, NORWAY, and Sweden)							
Jokioinen 60°49'N 23°29'E 104m	T_a= 3.9°C P_a=582mm S_a=138mm W_a=3.9m/s Exp=flat ground surrounded by cultivated fields; some shading forest in the sector SW to W	3m	Tretyakov, Danish Hellmann, Norwegian Standard, Swedish standard (SMHI)	volume and weight	10m, 6m, 4m, 3.5m & 2m	Tretyakov (unshielded), Hungarian Hellmann, Wild (Nipher-shielded and unshielded), Canadian Nipher, Finnish prototype, H&H 90 in Tretyakov shield, Geonor recording gauge, Geonor in the DFIR, Danish tipping bucket (heated), RIMCO (heated), Frieddrick's tipping bucket (heated), pit gauge.	Feb87 to Apr93
Germany							
Harzgerode 51°39'N 11°08'E 404m	T_a= 6.8°C P_a=635mm S_a= W_a=3.2m/s Exp=flat plateau with surrounding area of open fields	3m	Hellmann at 2m, unshielded	volume	3m	Hellmann (shielded), Tretyakov, Polish Hellmann, Canadian Nipher, Metra, Automatic gauge (AFMS)	Dec86 to Mar93
Japan							
Hokuriku 37°7'N 138°17'E 11m	T_a= °C P_a= S_a= W_a= Exp=	3.5m	RT-4	weight	5.5m	RT-1 unshielded	Jan93 to Mar93; Jan97 to Mar97
Memambetsu Hokkaido 43°55'N 144°11'E 39 m	T_a= 6.2°C P_a=757mm S_a=- W_a=2.2m/s Exp=	3m	RT-4 at 1.5m, Shielded	weight	10m & 2m	RT-4 unshielded, RT-3 unshielded, Weight rain / Snow gauge shielded	Dec88 to Mar91
Romania							
Joseni 45°36'N 14°38'E 750m	T_a= °C P_a= S_a= W_a= Exp=	3m	Tretyakov at 2m, shielded	volume	8m, 10m & 15m	unshielded Tretyakov	Dec86 to Mar89

T_a=annual mean temp; P_a=annual total precipitation (mm); S_a=annual total snowfall (mm); W_a=annual mean wind speed (m/s); Exp=site exposure.

Table 3.1 Siting and instrumental information at WMO Intercomparison sites (continued).

Station	Climate & Exposure	DFIR	National Gauge	Obs. Method	Wind	Other Gauges / Wind Shields	Obs. Period
Russian Federation							
Valdai 57°59'N 33°15'E 194m	T_a=3.4 °C P_a=800mm S_a=140mm W_a=4m/s Exp= flat, open	3m	Tretyakov at 2m, shielded	volume and weight	3m & 2m	Tretyakov in bush, Tretyakov unshielded, wild rain gauge , WMO rain gauge, Germany Hellmann, Polish Hellmann, Hungarian Hellmann, Canadian Nipher, USA NWS8" shielded and unshielded	Oct70 to Apr95
Slovakia							
Bratislava 48°10'N 17°7'E 286m	T_a= 9.3 °C P_a= 661mm S_a= W_a= 4.6m/s Exp= partially protected	N/A	Metra 866 at 1m	volume	10m	Hungarian Hellmann, Tretyakov, WMO Snowden IP	Nov86 to Mar93
Switzerland							
Gamserrugg 47°12'N 9°21'E 2074m	T_a= °C P_a= 1301mm S_a= W_a= Exp= very exposed, on top of Gamserrugg, flat 800x800m	3.5m	Belfort gauge	weight	3m	Belfort Gauge inside DFIR	Oct91
United Kingdom							
Eskdalemuir Observatory 55°19'N 3°12'E 242m	T_a= °C P_a= S_a= W_a= Exp=	N/A	U.K. Met. Office Standard MK-2 gauge unshielded	weight	0.3m, 2m & 10m	Tretyakov at 2m, unshielded	Dec.88 to Apr.91
Lerwick Observatory 60°48'N 1°11'E 82m	T_a= °C P_a= S_a= W_a= Exp=	N/A	U.K. Met. Office Standard MK-2 gauge unshielded	weight	0.3m, 2m & 10m	Tretyakov at 2m, unshielded	Nov.88 to Apr.91
United States of America							
Bismarck, North Dakota 46°46'N 100°45'W 502m	T_a= 5.3 °C P_a=393mm S_a=67mm W_a=4.8m/s Exp = open unobstructed	3m	Alter-shielded Belfort gauge	weight	6.1m, 3m & 1.4m	Belfort unshielded, Belfort with Wyoming fence, Belfort with DFIR, Tretyakov shielded, Aerochem Metrics	Nov.88 to Apr.91
Rabbit Ears Pass, Colorado 40°23' N 106°38'W 2925m	T_a= °C P_a= S_a= W_a= Exp=	3m	Alter-shielded Belfort gauge	weight	10m and 3m	Belfort unshielded, Belfort with Wyoming fence, Belfort with DFIR, Canadian Nipher, Tretyakov shielded and unshielded, Tretyakov with Wyoming fence, snow boards	Nov.89 to Apr.93
Reynolds Creek, Idaho 43°12'N 116°45'W 1193m	T_a=8.4 °C P_a= 284mm S_a= W_a= 2.3m/s Exp=gently sloping, sagebrush covered range land	3m	NWS 8" non-recording gauge at 1.0m, unshielded	weight	9.14m , 3m & 2m	Tretyakov, Alter-shielded Belfort, Canadian Nipher, Belfort with Wyoming fence, dual gauge system.	Nov.87 to Feb.92
Sleepers River, (Danville) Vermont 44°29'N 72°10'W 552m	T_a= 3.9°C P_a=1092mm S_a=254mm W_a=1.3m/s Exp= open	3m	NWS 8" non-recording gauge at 1.8m, Alter-shielded	volume	3m	Alter-shielded and unshielded Belfort, Tretyakov, snow boards	Dec.86 to Apr.92

T_a=annual mean temp; P_a=annual total precipitation (mm); S_a=annual total snowfall (mm); W_a=annual mean wind speed (m/s); Exp=site exposure.

Table 3.2 WMO Solid Precipitation Measurement Intercomparison Digital Archive Summary

Country/ Site	Data Received	Data Archived	Event Summary	Event Archived	Archive Reviewed
Canada					
Dease Lake(Airport)	11/87 - 03/88	yes	yes	yes	yes
	10/88 - 04/89	yes	yes	yes	yes
	10/89 - 03/90	yes	yes	yes	yes
	11/90 - 04/91	yes	yes	yes	yes
	10/91 - 04/92	yes	yes	yes	yes
	10/92 - 04/93	yes	yes	yes	yes
Regina(Airport)	03/87 - 04/87	yes	yes	yes	yes
	11/87 - 04/88	yes	yes	yes	yes
	01/89 - 03/89	yes	yes	yes	yes
	11/89 - 03/90	yes	yes	yes	yes
	11/90 - 04/91	yes	yes	yes	yes
	11/91 - 04/92	yes	yes	yes	yes
Kortright Centre	01/87 - 04/87	yes	yes	yes	yes
	12/87 - 03/88	yes	yes	yes	yes
	12/88 - 03/89	yes	yes	yes	yes
	12/89 - 03/90	yes	yes	yes	yes
	12/90 - 03/91	yes	yes	yes	yes
Peterborough(Trent)	12/86 - 03/87	yes	yes	yes	yes
	11/87 - 03/88	yes	yes	yes	yes
	12/88 - 03/89	yes	yes	yes	yes
	11/89 - 03/90	yes	yes	yes	yes
	11/90 - 03/91	yes	yes	yes	yes
Baie Comeau	12/88 - 04/89	yes	yes	yes	yes
(Airport)	10/89 - 04/90	yes	yes	yes	yes
	11/90 - 04/91	yes	yes	yes	yes
	11/91 - 04/92	yes	yes	yes	yes
	11/92 - 04/93	yes	yes	yes	yes
East Baltic	12/87 - 03/88	yes	yes	yes	yes
(Climate)	11/88 - 04/89	yes	yes	yes	yes
	11/89 - 04/90	yes	yes	yes	yes
	12/90 - 03/91	yes	yes	yes	yes
	12/91 - 04/92	yes	yes	yes	yes
China					
Tianshan	06/87 - 11/87	no	yes	yes	yes
	01/88 - 12/88	no	yes	yes	yes
	01/89 - 07/89	no	yes	yes	yes
	05/90 - 08/90	yes	yes	yes	yes
	05/91 - 09/91	yes	yes	yes	yes
	05/92 - 08/92	yes	yes	yes	yes
Croatia					
Parg	01/87 - 04/87	yes	yes	yes	yes
	10/87 - 04/88	yes	yes	yes	yes
	10/88 - 04/89	yes	yes	yes	yes
Finland					
(Denmark,Norway,Sweden)					
Jokioinen	02/87 - 04/87	yes	no	no	yes
	12/87 - 04/88	yes	no	no	yes
	10/88 - 04/93	yes	no	no	yes

Table 3.2 WMO Solid Precipitation Measurement Intercomparison Digital Archive Summary (continued)

Country/Site	Data Received	Data Archived	Event Summary	Event Archived	Archive Reviewed
Germany					
Harzgerode	12/86 - 03/87	yes	yes	yes	yes
	12/87 - 03/88	yes	yes	yes	yes
	12/88 - 03/89	yes	yes	yes	yes
	12/89 - 03/90	yes	yes	yes	yes
	12/90 - 03/91	yes	yes	yes	yes
	12/91 - 03/92	yes	yes	yes	yes
	12/92 - 03/93	yes	yes	yes	yes
India					
Bhang(Manali)	12/86 - 04/87	no	yes	no	no
	12/87 - 04/88	no	yes	no	no
Solang Nala(H.P.)	12/86 - 04/87	no	yes	no	no
	12/87 - 04/88	no	yes	no	no
Kothi(H.P.)	12/86 - 04/87	no	yes	no	no
	12/87 - 04/88	no	yes	no	no
Verinag	12/86 - 04/87	no	yes	no	no
	12/87 - 04/88	no	yes	no	no
Japan					
Memanbetu (JMA)	12/88 - 04/89	yes	no	no	yes
	11/89 - 05/90	yes	no	no	yes
	11/90 - 03/91	yes	no	no	yes
Hokuriku (JIRCAS)	01/93 - 03/93	yes	yes	yes	yes
	01/97 - 03/97	yes	yes	yes	yes
Romania					
Joseni	12/86 - 03/87	yes	no	no	no
	11/87 - 03/88	yes	no	no	no
	11/88 - 03/89	yes	no	no	no
Russian Federation					
Valdai	10/70 - 05/71	yes	no	no	yes
	10/71 - 05/72	yes	no	no	yes
	09/72 - 05/73	yes	no	no	yes
	09/73 - 05/74	yes	no	no	yes
	10/74 - 04/75	yes	no	no	yes
	10/75 - 04/76	yes	no	no	yes
	10/76 - 04/77	yes	no	no	yes
	10/77 - 05/78	yes	no	no	yes
	10/78 - 12/78	yes	no	no	yes
	11/88 - 04/89	yes	no	no	yes
	11/89 - 04/90	yes	no	no	yes
	10/90 - 04/91	yes	no	no	yes
	02/92 - 04/92	yes	no	no	yes
	10/92 - 02/93	yes	no	no	yes

Table 3.2 WMO Solid Precipitation Measurement Intercomparison Digital Archive Summary (continued)

Country/Site	Data Received	Data Archived	Event Summary	Event Archived	Archive Reviewed
Slovakia					
Bratislavia Koliba	11/86 - 04/87	yes	yes	yes	yes
	12/87 - 04/88	yes	yes	yes	yes
	11/88 - 04/89	yes	yes	yes	yes
	11/89 - 03/90	yes	yes	yes	yes
	11/90 - 05/91	yes	yes	yes	yes
	11/91 - 04/92	yes	yes	yes	yes
	10/92 - 03/93	yes	yes	yes	yes
Switzerland					
Gamserrugg	10/91 - 03/92	yes	no	no	yes
	10/92 - 03/93	yes	no	no	yes
United Kingdom					
Eskdalemuir	12/88 - 04/89	yes	no	no	yes
	01/90 - 04/90	yes	no	no	yes
	11/90 - 02/91	yes	no	no	yes
Lerwick	11/88 - 04/89	yes	no	no	yes
	11/89 - 04/90	yes	no	no	yes
	11/90 - 04/91	yes	no	no	yes
United States					
Danville(CRREL)	12/86 - 03/87	yes	no	no	yes
	12/87 - 03/88	yes	no	no	yes
	11/88 - 04/89	yes	no	no	yes
	12/89 - 04/90	yes	no	no	yes
	12/90 - 03/91	yes	no	no	yes
	12/91 - 04/92	yes	no	no	yes
Reynolds Creek(USDA)	11/87 - 04/88	yes	yes	yes	yes
	11/88 - 03/89	yes	yes	yes	yes
	11/89 - 03/90	yes	yes	yes	yes
	11/90 - 03/91	yes	yes	yes	yes
	11/91 - 02/92	yes	yes	yes	yes
	11/92 - 03/93	no	yes	no	no
Bismarck(USGS)	11/88 - 03/89	yes	yes	yes	yes
	11/89 - 04/90	yes	yes	yes	yes
	11/90 - 04/91	yes	yes	yes	yes
Rabbit Ear’s Pass	12/89 - 04/90	no	yes	yes	yes
(USGS)	01/91 - 05/91	no	yes	yes	yes
	10/91 - 04/92	no	yes	yes	yes
	11/92 - 04/93	no	yes	yes	yes

4. RESULTS AND DISCUSSION

4.1 INTRODUCTION

This Intercomparison offered an excellent opportunity for participating Countries to assess the accuracy of their national gauges against an international reference. Countries participating in the Intercomparison were encouraged to analyze their data sets and provide the results to the International Organizing Committee. National reports have been submitted by the following countries: Canada, China, Denmark and Finland (includes national gauges for Norway and Sweden), Germany, Japan, and the United States. A summary of these Country reports for their respective national gauge only and the complete Country reports, which also include the full analyses of national gauges and other gauges tested at some sites, can be found in Annex 5.

This chapter presents intercomparison results for several national gauges using the combined international data set collected by the WMO Solid Precipitation Measurement Intercomparison project. The first two sections provide site information, data sources and methods of data analysis. In the sections following, intercomparison results for the Russian Tretyakov Gauge, the Hellmann Gauge, the Canadian Nipher Gauge, and the US NWS 8” standard non-recording gauge are presented. These four gauges, perhaps the most widely used non recording gauges for solid precipitation measurement in the world, were operated at several sites and in different countries, hence in differing climatic regions.

4.2 SITES AND DATA SOURCES

Table 4.2.1 summarizes the site and instrument information (gauge height, shielding information, anemometer height, method and time of observation, and observation period) at the Intercomparison stations which operated the DFIR and other national precipitation gauges, such as the Tretyakov gauge, Hellmann gauge, Canadian Nipher gauge and the US NWS 8” standard gauge, depending on the national requirements of the participating countries. Installation of the DFIR, the national gauges, and other observing equipment and the associated observational procedures followed the experiment guidelines documented in WMO/CIMO (1985). More detailed descriptions of each site and its associated instrumentation have been provided in Annex 3 (the relevant sections for each station are referenced in Table 4.2.1).

For the analysis in the following sections, the climatological data sets from each of the stations were used and snow, mixed precipitation, and rain data were considered. The observation period for each station is given in Table 4.2.1 and varies from 6-hourly to daily. Temperature and wind data were averaged over the appropriate observing period for each station.

4.3 METHODS OF DATA ANALYSIS

The methods of analysis of the intercomparison data were established initially by the International Organizing Committee for the WMO Intercomparison (WMO/CIMO, 1985) and subsequently modified or updated at the regular session meetings for the Intercomparison (WMO/CIMO, 1993). In this chapter, data analysis follows the procedures outlined by WMO/CIMO (1993). Adjustment of the data for known biases are conducted prior to determining the relation of gauge catch to environmental factors. These include errors due to wetting loss, evaporation loss, undercatch of the DFIR, the effect of blowing snow on gauge measurement and any adjustment of wind speed to gauge height (if wind was measured at some other height).

For most precipitation gauges, wind speed is the dominant environmental factor contributing to the under measurement of solid precipitation. The trajectories of precipitation particles become distorted in a wind through the displacement and acceleration of wind flow over the top of the gauge caused by the aerodynamic blockage of the gauge body. The lighter particles are carried beyond the gauge opening, resulting in a reduced catch. The extent of reduction depends on the falling velocity of particles, wind speed and the aerodynamic properties (drag of the air) of a particular type of gauge. For the same gauge, the reduction is smaller for big raindrops, but several times greater for light snow and the reduction in catch increases with increasing wind speed.

Studies in precipitation physics have shown that the falling velocity of snowflakes depends on their shape which in turn depends on the temperature. Since the total wind effect depends on the shape of snowflakes, air temperature at screen or upper air levels can also be used as a variable for precipitation gauge adjustment.

4.3.1 Adjustment of the data for known biases

Systematic errors are errors in precipitation gauge measurement that introduce a preferred bias into the observations. Some examples of systematic under-estimation biases include the wind-induced undercatch, wetting and evaporative losses, out-splashing effects, friction of the recording pen, high intensity rainfall with tipping bucket gauges, and the treatment of traces as no precipitation.

The systematic errors in the measurement of solid precipitation were determined in the intercomparison quantitatively for over 20 different precipitation gauge and shield combinations. Data from all experiment sites confirm that solid precipitation measurements must be adjusted to account for errors and biases. These biases and methods for their adjustment are listed below:

4.3.1.1 Wind speed at gauge height

To adjust gauge measurements for any wind induced bias, wind speed at gauge height during the time of precipitation is required. If the wind is not measured at gauge height, then the station wind speed, which is typically located at 10 m above ground surface, can be used to estimated the wind at gauge orifice height (h) using the following formula:

$$U_h = [\log (h/z_o) / (\log (H/z_o))] \times U_H \qquad (4.3.1)$$

where:

- U_h wind speed at the height of the gauge orifice
- h height (m) of gauge orifice above ground
- z_o roughness length: 0.01 m for winter and 0.03m for summer
- H height (m) of the wind speed measuring instrument above ground, normally at 10 m
- U_H wind speed measured at the height H above ground.

4.3.1.2 Wetting Loss

The wetting loss from each intercomparison gauge which was measured using the volumetric method should be estimated by weighing the collector immediately after the melted snow has been poured out from the collector and then after the collector has dried completely. The difference between the wet and dry collector, in mm, gives the wetting loss per snowfall observation. This is a cumulative loss and varies with precipitation and gauge type; its magnitude is also a function of the number of times the gauge is emptied. Average wetting loss for some gauges can be up to 0.3 mm per observation. Participating countries using manual gauges for solid precipitation measurement have determined the average wetting loss for their national gauge. At synoptic stations where precipitation is measured every six hours, this can become a very significant amount. For example, at some Canadian stations, wetting loss was calculated to be 15-20 per cent of the measured winter precipitation (Metcalfe and Goodison, 1993).

4.3.1.3 Evaporation loss

This is the water lost by evaporation of the contents in the gauge before the observation is made. Evaporation loss from manual gauges can be a significant contributor to the systematic under measurement of solid precipitation. Aaltonen et al. (1993) reported on a comprehensive assessment by Finland on evaporation losses and found that average daily losses varied by gauge type and time of year. Evaporation loss was a particular problem with gauges which had no preventative funnel in the bucket, especially in late spring. Losses in April of over 0.8 mm/day were measured in some gauges. Losses during winter were much less than that recorded during comparable summer comparisons for rainfall, ranging from 0.1-0.2 mm/day.

4.3.1.4 Adjustment for wetting and evaporation losses

The general model for adjustment of systematic errors on precipitation measurements (Allerup, Madsen and Vejen 1997) is:

$$P_c = k(P_m + \sum \Delta P_{im}) \qquad (4.3.2)$$

where P_c is the adjusted or “true” amount of precipitation, P_m is the measured amount, $\Sigma\Delta P_{im}$ is the sum of various error sources among which wetting and evaporation losses are the most important and k is the correction factor due to wind induced undercatch.

The adjustment of the measured precipitation P_m for wetting and evaporation losses should be applied prior to any adjustment for the wind effect.

4.3.1.5 Variances in gauge design

Changes in the method and material used in the manufacture of gauges can be a source of error. For example, in late 1981, Canada started to use a fiberglass reinforced plastic Nipher shield as a replacement for the more expensive aluminum shield of the standard Canadian Nipher shielded snow gauge system. In the conversion of the shield from aluminum to fiberglass, there were two small, but possibly significant, design changes. The curvature of the outer surface was changed from an ellipse to a radius and the plane of the top surface of the shield was changed from a radial curve from the upper surface down to the outer lip to a flat surface (Metcalfe and Goodison, 1985). Testing of these gauges found that the average catch of the aluminum shielded gauge was greater than that of the fiberglass, with a bias of 0.17 mm at Broadview, Saskatchewan (continental climate) and 0.08 mm at Gander, Newfoundland (maritime climate). If only observations of 2.0 mm or greater were compared, the bias per observation was 0.40 mm at Broadview and 0.25 mm at Gander. Individual 6-hourly snowfall observations differed by as much as 1.2 mm at Broadview and 1.8 mm at Gander. It is reasonable to conclude then, that one should expect a difference in the catch efficiency of the two shields under blowing conditions. This factor was considered in the analysis of the Canadian Nipher gauge data and comparison of the current results with previous ones.

The orifice area of a gauge may differ from specifications and needs adjustment. This varies by gauge type and manufacturer. Finnish studies found, for example, Tretyakov gauges used in the experiment to be 1.47 per cent smaller than the nominal orifice area.

4.3.2 Other biases and considerations

4.3.2.1 Undercatch of the DFIR

The DFIR is considered as a secondary reference standard. The need to adjust the DFIR measurement to the "true" value of the bush gauge for the effect of wind was discussed by Golubev (1989), since a comparison of DFIR and the bush gauge data at Valdai, Russia, indicated a systematic difference between the primary and secondary standards. Golubev (1989) proposed an adjustment procedure which included meteorological measurements of wind speed, atmospheric pressure, air temperature and humidity. More recent work by Yang, *et al* (1993) based on regression analysis indicated that the most statistically significant factor in the adjustment of the DFIR was the wind speed during the storms. The full report by Yang, *et al* (1993) can be found in Annex 2.H. The Sixth Session of the International Organizing Committee of the WMO Intercomparison (WMO/CIMO, 1993) recommended that the adjustment equations by Yang, *et al* (1993) given Chapter 2, Section 2.4.4 be applied to all DFIR data before analyzing the catch of national gauges with respect to the DFIR.

4.3.2.2 Blowing snow

Blowing snow conditions are a special case when adjusting the DFIR data. Normally the flux of blowing snow will be greater at 1.0 m, 1.5 m or 2.0 m than at the 3.0 m height of the DFIR, and it is possible that under certain conditions, any gauge can catch some blowing snow. Since wind speeds are generally greater during blowing snow events, a larger adjustment for "undercatch" could be applied to a measured total already augmented by blowing snow. This problem would be most severe for gauges mounted close to the ground which are efficient in collecting snow passing over their orifice. Every effort was made to identify and eliminate blowing snow events in the Intercomparison data from subsequent analysis of gauge catch versus environmental factors, notably wind speed and temperature. It is recognized that blowing snow during a period or part of the precipitation event is a problem in some regions and will affect the actual precipitation measurements. This particular problem requires further investigation by Members for which it is a significant problems. Determining the amount of blowing snow caught by each gauge will be a challenge.

4.3.2.3 Data Combination

It is important to note that: (1) at all Intercomparison sites, the DFIR was installed and operated according to the same procedures (WMO/CIMO, 1985), resulting in a common standard at all the sites; national gauges were operated according to the countries national methods; (2) the DFIR measurements at the Intercomparison stations have been adjusted to the "true" precipitation using the same equations; and (3) when it is necessary to estimate daily mean wind speed at the height of the national gauge from wind measurement at different heights at the Intercomparison site, it is done using the same wind-profile technique. Thus, the Intercomparison data collected from different sites are compatible in terms of the catch ratio (measured precipitation/"true") for the same gauges, when wind speed at the gauge height is used in the analysis.

Table 4.2.1 WMO Intercomparison Stations with Tretyakov gauge, Nipher gauge, Helmann gauge, US NWS 8" gauge and DFIR Observations

Station	Lat. Lon. Elev.	Site Description reference	DFIR	National Gauges	Wind Sensors	Obs. Method/ Frequency	Obs. Period
Dease Lake, BC, Canada	58°46'N 130°00'W 816m	Annex 3.A	3m	Nipher at 2m	10m, 3m & 2m	volumetric 6 hourly	Nov87 to Apr93
Regina A, Sask, Canada	50°26'N 104°40'W 577m	Annex 3.A	3m	Tretyakov at 2m Nipher at 2m	10m, 3m & 2m	volumetric daily	Nov87 to Apr92
Kortright Centre, Ont. Canada	43°51'N 79°36'W 208m	Annex 3.A	3m	Tretyakov at 2m, Nipher at 2m	10m, 3m & 2m	volumetric daily	Jan87 to Mar91
Trent U, Peterborough Ont. Canada	44°21'N 78°17W 230m	Annex 3.A	3m	Tretyakov at 2m Nipher at 2m	10m, 3m & 2m	volumetric daily	Dec86 to Mar91
Baie Comeau, Que. Canada	49°00'N 68°12'E 21m	Annex 3.A	3m	Nipher at 2m	10m, 3m & 2m	volumetric daily	Dec88 to Apr93
East Baltic, PEI, Canada	46°26'N 62°10'W 61m	Annex 3.A	3m	Nipher at 2m	10m, 3m & 2m	volumetric daily	Dec87 to Apr92
Parg, Croatia	45°36N 14°38'E 863m	Annex 3.C	3m	Trteykov at 2m Hellmann at 2m	11.2m	volumetric	Jan87 to Apr89
Jokioinen, Finland	60°49'N 23°29'E 104m	Annex 3.D	3m	Tretyakov at 1.5m, Nipher at 1.5m, Hellmann at 1.5m	10m, 6m, 4m, 3.5m 2m	volumetric weighing 12 hourly	Oct88 to Mar93
Harzgerode, Germany	51°39'N 11°08'E 404m	Annex 3.E	3m	Tretyakov at 2m, Nipher at 2m, Hellmann at 1m	3m	volumetric daily	Dec86 to Mar93
Joseni, Romania	45°36'N 14°38'E 750m	Annex 3.G	3m	Tretyakov at 1.5m	15m, 10, & 8m	volumetric	Dec86 to Mar89
Valdai, Russia	57°59'N 33°15'E 194m	Annex 5.H	3m	Tretyakov at 2m, Nipher at 2m, Hellmann at 2m, US NWS 8" at 1m	3m & 2m	volumetric 12 hourly	Oct91 to Mar93
Bismarck ND, USA	46°46'N 100°45'W 502m	Annex 3.L	3m	Tretyakov at 1.4m	6.1m, 3m & 1.4m	weighing	Nov88 to Apr91
Danville, Vermont, USA	44°29'N 72°10'W 552m	Annex 3.L	3m	Tretyakov at 2m, US NWS 8" at 1.8m	3m	volumetric	Dec86 to Apr92
Reynolds Creek, Idaho, USA	43°12'N 116°45'W 1193m	Annex 3.L	3m	Tretyakov at 2m, Nipher at 2m, US NWS 8" at 1m	9.14m, 3m & 2m	weighing daily	Nov87 to Feb92

4.4 RUSSIAN TRETYAKOV PRECIPITATION GAUGE

The Tretyakov precipitation gauge which was the gauge used in the DFIR was introduced in the former USSR at the end of the 1950s. It is still the national standard for countries which occupy the territory of the former USSR.

This section, based on the WMO Intercomparison data compiled from 11 stations (Table 4.2.1), examines the accuracy of the Russian Tretyakov gauge measurements against the DFIR measurements for rain, snow and mixed precipitation. Daily precipitation measurements of both the DFIR and the Tretyakov gauge were used in this analysis and the relation of the gauge catch ratio to wind speed and temperature was investigated on a daily basis as well.

4.4.1 Average catch ratios

The average catch ratio of the Tretyakov gauge to the adjusted DFIR value for "true" precipitation varied by type of precipitation, mean daily wind speed on days with precipitation, and whether it was shielded or unshielded.

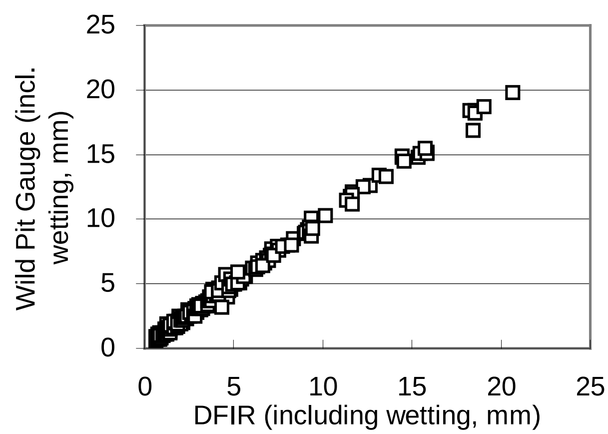


Figure 4.4.1 Comparison of daily pit gauge measurement of rain against DFIR at Jokioinen, Finland

Table 4.4.1 summarizes the average catch ratio for the shielded Tretyakov gauge as a function of the adjusted DFIR for different types of precipitation at the 11 WMO sites. Precipitation was classified as snow only, snow with rain, rain with snow and rain only. Although it was not an objective of this WMO project to study rainfall measurement using this gauge, Intercomparison results at Jokioinen in Finland demonstrated a very good agreement between rainfall measured by the DFIR and the pit gauge (accepted WMO standard for rainfall measurement) in a number of different seasons (see Figure 4.4.1). Hence, it was reasonable to accept the DFIR as a reference for rainfall measurement in this project, since most of the sites did not have a pit gauge or did not operate it in winter.

At most of the stations, the average catch ratio for the Tretyakov gauge is less for snow only than for mixed precipitation events. One may note that there are exceptions, but these are related to differences in the mean daily wind speed, or in sample size (e.g. few precipitation events). Average value of the catch ratio can be very misleading, since all storms are weighted equally, irrespective of wind speed, precipitation amount or other environmental conditions. Valdai and Jokioinen, which had extensive observing programs during a long "winter" period and even into the summer, exhibit the "expected" decease in the catch ratio from rain to snow. At some of the WMO sites, such as Danville and Parg, the average catch ratios of the shielded Tretyakov gauge varied little by precipitation type because of the very low average wind speeds on precipitation days. In some cases, mixed precipitation has a lower average catch than snow (e.g. Harzgerode), but the mean wind speed was greater during these events, so this result is not unexpected.

Table 4.4.1 shows that the average catch ratio of the shielded Tretyakov gauge varies for the same type of precipitation at the Intercomparison stations. The average catch ratios, ranging from 59-92% for snow and 72-97% for rain, change by type of precipitation. Investigation of the mean catch ratio of all observations at each site versus mean wind speed at gauge height during precipitation days shows that there is a general dependence of the mean catch ratio (C*R, %*) on mean wind speed (*Ws*) for snow only (Equation 4.4.1) and snow mixed with rain (Equation 4.4.2).

$$CR_{snow} = 101.9 - 10.3 * \underline{W}_{\underline{s}}, \quad (n=11, r^2=0.79), \qquad (4.4.1)$$

$$CR_{snow + rain} = 100.4 - 6.7 * \underline{W}_{\underline{s}}, \quad (n=11, r^2=0.60), \qquad (4.4.2)$$

For both cases, the mean gauge catch ratio decreases with increasing mean wind speed for precipitation days. For rain only and rain mixed with snow, there is no significant correlation between mean catch ratio and mean wind speed for precipitation days. It must be noted, however, that in all cases there is considerable scatter at any wind speed. Yet, it is very important to identify the relationship between the average catch ratio and mean wind speed for various types of precipitation, since there has been a tendency recently to use an averaged catch ratio for a gauge for different types of precipitation derived at a single site, to adjust the archived precipitation data for climatological and hydrological analyses. By not considering the varying effect of mean wind speed on the mean gauge catch, over-adjustment of the wind-induced error will occur for those stations with lower wind speed during precipitation than that at the intercomparison site. Under-adjustment of the wind-induced error will occur for those stations with higher wind speed during precipitation than that at the intercomparison site. To avoid the over-adjustment or under-adjustment of the wind-induced errors, a constant catch ratio (e.g. a constant adjustment factor) is not recommended for any gauge in any season. Instead, the relation of daily or event gauge catch as a function of corresponding daily mean or event mean wind speed should be applied to the gauge measured daily or for an event, since studies (Goodison, 1977; Goodison et al., 1981a,b) show that gauge catch varies by individual precipitation event.

Table 4.4.1 Summary of the Intercomparison of shielded Tretyakov gauge against the DFIR at 11 WMO sites.

	Snow				Snow/Rain				Rain/Snow				Rain			
Station	***Event***	***Ws***	***DFIR***	***Tret Catch***	***Event***	***Ws***	***DFIR***	***Tret Catch***	***Event***	***Ws***	***DFIR***	***Tret Catch***	***Event***	***Ws***	***DFIR***	***Tret Catch***
	(day)	*(m/s)*	*(mm)*	*(%)*	*(day)*	*(m/s)*	*(mm)*	*(%)*	*(day)*	*(m/s*	*(mm)*	*(%)*	*(day)*	*(m/s)*	*(mm)*	*(%)*
Valdai	304	4.1	1181.7	63.1	85	4.6	584.9	71.2	75	4.5	489.7	86.3	230	3.8	1259.2	91.4
Reynolds	50	2.5	105.6	84.4	27	3.8	71.4	88.5	8	4.4	29.3	85.4	40	2.7	206.4	92.0
Danville	157	1.5	1036.2	91.6	21	1.0	999.5	95.0	18	1.4	348.7	94.5	30	1.0	446.3	94.3
Jokioinen	334	2.6	740.9	67.2	149	3.1	405.6	72.5	131	2.9	414.3	84.5	567	2.5	1694.4	86.6
Harzgerode	42	3.0	112.7	72.2	53	3.9	110.2	78.5	127	4.2	538.8	82.4	172	4.2	475.3	81.3
Bismarck	32	3.3	94.6	65.4	16	3.1	53.3	67.8	-	-	-	-	3	3.3	9.3	71.6
Joseni	94	1.1	194.0	85.8	14	1.3	39.8	92.9	11	2.2	53.6	86.9	34	1.2	85.0	90.6
Parg	65	1.0	486.9	91.0	16	1.2	250.1	90.3	31	1.5	550.8	90.7	141	1.6	1573.8	88.2
Trent U	76	2.0	262.0	81.1	31	2.0	172.3	90.6	20	2.3	219.4	95.0	80	1.9	581.9	95.0
Regina	117	3.5	199.1	59.4	36	4.3	76.9	63.1	-	-	-	-	5	3.9	5.1	97.4
Kortright	107	2.5	274.7	83.1	25	2.7	198.4	85.3	1	4.2	31.9	91.8	64	2.3	342.6	90.0

4.4.2 Catch ratio versus wind speed

Studies have shown that gauge catch of precipitation, depending on both the environmental factors and the precipitation features, such as rainfall rate (Sevruk, 1982) and falling snow crystal type (Goodison et al., 1981a), can vary within each individual event of precipitation. In order to investigate the dependence of the Tretyakov gauge catch on environmental factors, daily data from the 11 WMO Intercomparison stations, representing a wide variety of climate, terrain and exposure, were compiled. One must be very careful when analyzing ratios and differences between gauges. Small absolute differences between the Tretyakov and DFIR gauges could create significant large variations in the catch ratios (e.g. a 0.2 mm difference of Tretyakov vs. DFIR with a DFIR catch of 1 mm gives a ratio of 80% versus 96% for a 5 mm event). To minimize this effect, the daily totals when the DFIR measurement was greater than 3.0 mm were used in the statistical analysis. The results confirm that wind speed is the most important factor for gauge catch when precipitation is classified as snow, snow with rain, rain with snow and rain. Air temperature has a secondary effect on gauge catch. A regression of the daily gauge catch ratio (C*R, %*) for the shielded Tretyakov gauge as a function of the daily wind speed (*Ws, m/s*) at gauge height and daily air temperature (T_{max}, T_{min} *and* T_{mean},*°C*) gave the best-fit regression equations for the different types of precipitation as follows:

<u>Snow:</u>

$CR = 103.10 - 8.67 * W_S + 0.30 * T_{max}$, (n = 394, r^2 = 0.66) (4.4.3)

<u>Snow and Rain:</u>

$CR = 98.56 - 6.19 * W_S + 0.90 * T_{max}$, (n = 204, r^2 = 0.57) (4.4.4)

<u>Rain and Snow:</u>

$CR = 98.13 - 3.17 * W_S + 0.60 * T_{mean}$, (n = 228, r^2 = 0.42) (4.4.5)

<u>All Mixed Precipitation</u>

$CR = 96.99 - 4.46 *W_S + 0.88 * T_{max} + 0.22*T_{min}$ (n=433, 0 r^2 =0.46) (4.4.6)

Figure 4.4.1 shows the derived shielded Tretyakov gauge catch ratio versus daily mean wind for a maximum air temperature of -10°C for snow. A wide range of wind speed has been sampled by the combined Intercomparison data sets in a variety of climatic regions; hence, the adjustment procedures derived from these data are more likely to be used successfully over a wide range of environmental conditions. Equations 4.4.3 to 4.4.6 suggest that gauge catch decreases with increasing wind speed on the precipitation day and increases with rising air temperature. However, compared to the wind influence, the effect of air temperature on the gauge catch of snow is small. For instance, an air temperature change of 10°C only results in a 3% change of the gauge catch whereas a wind speed increase of 1 m/s causes a 9% decrease of catch compared to the DFIR (Equation 4.4.3). For mixed precipitation, snow with rain and rain with snow, the effect of air temperature on the gauge catch is more significant and the wind effect becomes weaker. A 10°C change leads to a 9% and 6% catch change whereas a wind change of 1 m/s results in a 6% and 3% catch decrease (Equations 4.4.4 and 4.4.5), respectively.

A similar analysis of data for individual sites (as shown in the Country Reports in the Annex) or a combination of other than the 11 sites above, could result in different equations. It is critical, however, that a representative range of wind speed be sampled so that any derived equation can be applied to a range of sites with differing wind speeds.

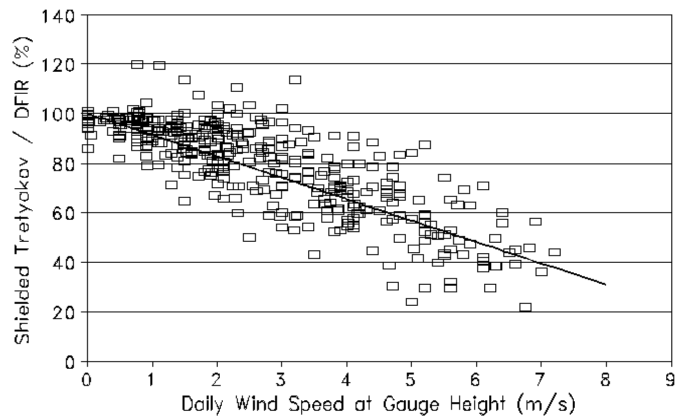


Figure 4.4.1 Shielded Tretyakov gauge catch (% of DFIR) of daily snow (DFIR > 3.0 mm) versus daily mean wind speed at the gauge orifice height at 11 WMO Intercomparison sites, Tmax = -10°C for the curve.

4.5 HELLMANN GAUGE

The Hellmann gauge is one of the most widely used precipitation gauges around the world. It is the standard gauge in 30 countries and the total number of the gauge is greater than 30,000. The Hellmann gauge is a non-recording gauge for both rain and snow measurement. It is about 43 cm high, with orifice area of 200 cm^2. There are various versions of the Hellmann gauges, such as German Hellmann, Danish Hellmann, Polish Hellmann and Hungarian Hellmann. The design of the different versions of the gauge are very similar (Sevruk and Klemm, 1989); they all have the same orifice area. A metal cross is installed in the Danish Hellmann gauge to prevent snow to be blown out of the gauge. In different countries, Hellmann gauges are placed at the height of 0.6 m to 1.5 m above the ground and in some countries they are equipped with a wind shield (such as Nipher shield and Tretyakov shield) at climate stations in mountain regions.

Many experimental studies on Hellmann gauges have been conducted and reported in the 1980's (Sevruk, 1981; 1982). Sevruk (1982) studied the wetting loss of the gauge. The Hellmann gauge was tested in the International comparison of National Precipitation Gauge with a Reference Pit Gauge (Sevruk and Hamon, 1984). The adjustment method for wind induced error in rainfall measurement has been reported by Sevruk and Hamon (1984) and the method has been used to adjust the archived precipitation in Switzerland (Sevruk et al., 1993).

During the WMO Intercomparison, Hellmann gauges were tested against the DFIR at Valdai in Russia, Jokioinen in Finland, Harzgerode in Germany and at Parg in Crotia (Table 4.2.1). In this section, various types of Hellmann gauges will be compared with the DFIR for different types of precipitation, with emphasis on snowfall observations.

4.5.1 Average catch ratios

Tables 4.5.1 through 4.5.4 summarize the average catch ratio for the unshielded and/or shielded Hellmann gauges of various version as a function of the adjusted DFIR for different type of precipitation at 4 WMO intercomparison sites.

Table 4.5.1 Summary (total and % of the DFIR) of daily observed precipitation for German Hellmann gauge (unshielded) at Valdai WMO Intercomparison station.

Type of Precip.	# Events (day)	Tmax (°c)	Tmin (°c)	Ws (@3m) (m/s)	DFIR	Unshielded Hellmann Gauge (German) (at 2m)	
Snow	136	-1.5	-4.2	4.5	729.9	386.6	(mm)
					100.0	53.0	(%)
Snow/Rain	45	1.0	-2.0	4.8	305.1	188.6	(mm)
					100.0	61.8	(%)
Rain/Snow	42	3.3	0.4	4.5	298.6	251.9	(mm)
					100.0	84.4	(%)
Rain	122	7.7	5.0	4.0	822.8	744.8	(mm)
					100.1	90.5	(%)

At the Valdai station, the German version of the Hellmann gauge was tested. The gauge was not shielded; it was mounted at 2 m above the ground. The average catch ratio for the Hellmann gauge ranged from 53% for snow to 90% for rain (Table 4.5.1).

At Jokioinen Finland, two unshielded Hellmann gauges, Hungarian and Danish versions, were installed at 1.5 m above the ground. Intercomparison shows that both gauges caught almost the same amount of snow precipitation (see Figure 4.5.1 for example); for rain, rain with snow and snow with rain, the catch ratio for the unshielded Hungarian Hellmann gauge is 3-4% higher than that for the unshielded Danish Hellmann gauge. For snow, the catch ratio of the Danish Hellmann gauge is a little higher (0.5%) than the Hungarian Hellmann gauge at the same site (Table 4.5.2). This may be due to the metal cross in the Danish Hellmann gauge, which reduces the amount of snow blown out of the gauge by high wind after the snowfall.

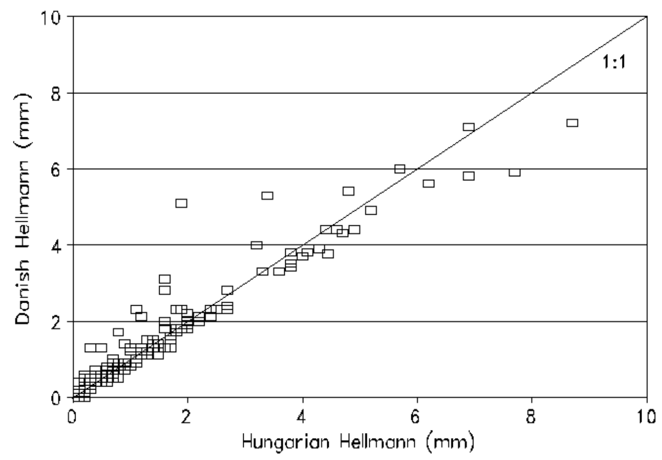


Figure 4.5.1 Comparison of Danish Hellmann gauge to Hungarian Helmman gauge for snow measurement at Jokioinen WMO Intercomparison station.

Table 4.5.2 Summary (total and % of the DFIR) of daily observed precipitation for Hungarian and Danish Hellmann gauges (unshielded) at Jokioinen WMO Intercomparison station

Type of Precip.	# Events (day)	Tmax (°c)	Tmin (°c)	Ws(@ 3m) (m/s)	DFIR	Hellmann Gauge (at 1.5m)		
						Hungarian	Danish	
Snow	266	-2.3	-6.0	2.7	620.2	263.2	264.8	(mm)
					100.0	42.4	42.7	(%)
Snow/Rain	150	1.0	-1.6	3.0	406.2	239.8	226.6	(mm)
					100.0	59.0	55.8	(%)
Rain/Snow	132	3.2	-0.1	2.9	414.8	336.9	320.4	(mm)
					100.0	81.2	77.2	(%)
Rain	526	11.3	7.0	2.4	1616.1	1456.6	1413.6	(mm)
					100.0	90.1	87.5	(%)

The Hellmann gauge is the national standard precipitation gauge in Germany. At the Harzgerode WMO station, the German Hellmann gauge with a Tretyakov wind shield and unshielded were placed at 1 m above the ground (standard height for this gauge in Germany) and tested against the DFIR for a number of years. The daily Intercomparison data are summarized in Table 4.5.3. The results indicate that on average, the unshielded German Hellmann gauge catches 60% of the DFIR for snow and 83% of the DFIR for rain, and the shielded German Hellmann gauge measures 77% of the DFIR for snow and 86% of the DFIR for rain. Thus, a Tretyakov wind shield is effective in increasing the average catch of the German Hellmann gauge.

Table 4.5.3 Summary (total and % of the DFIR) of daily observed precipitation for German Hellmann gauge (Tretyakov shielded or unshielded) at Harzgerode WMO Intercomparison station

Type of Precip.	# Events (day)	Tmax (°c)	Tmin (°c)	Ws(@ 3m) (m/s)	DFIR	Hellmann Gauge (at 1.0m)		
						Shielded	Unshielded	
Snow	42	-1.1	-6.3	3.0	112.7	87.2	67.3	(mm)
					100.0	77.4	59.7	(%)
snow/Rain	51	1.9	-2.8	3.9	156.9	122.7	107.7	(mm)
					100.0	78.2	68.6	(%)
Rain/Snow	97	4.7	-7.0	4.6	467.8	402.7	381.9	(mm)
					100.0	86.1	81.6	(%)
Rain	172	7.0	1.6	4.2	475.3	410.0	396.8	(mm)
					100.0	86.3	83.5	(%)

At the Parg WMO station in Crotia, two Hellmann gauges (version unknown) at 2 m above the ground, one with a Tretyakov wind shield and one unshielded, were compared. The average catch ratios of both the shielded and unshielded Hellmann gauges were much higher (85% for the unshielded and 89% for the shielded) compared to the other sites and they varied little by precipitation type because of very low wind speed on precipitation days (Table 4.5.4).

Table 4.5.4 Summary (total and % of the DFIR) of daily observed precipitation for Hellmann gauge (version unknown, Tretyakov shielded and unshielded) at Parg WMO Intercomparison station

Type of Precip.	# Events (day)	Tmax (°c)	Tmin (°c)	Ws(@ 3m) (m/s)	DFIR	Hellmann Gauge (at 2.0m)		
						shielded	Unshielded	
Snow	65	-1.4	-8.6	1.0	486.9	432.2	413.3	(mm)
					100.0	88.8	84.9	(%)
Snow/Rain	16	2.0	-3.5	1.2	250.1	225.1	219.7	(mm)
					100.0	90.0	87.8	(%)
Rain/Snow	31	4.8	-3.0	1.5	550.8	501.9	492.0	(mm)
					100.0	91.1	89.3	(%)
Rain	141	9.4	1.9	1.6	1573.8	1396.0	1368.0	(mm)
					100.0	88.7	86.9	(%)

4.5.2 Catch ratio versus wind speed

To determine the catch ratio versus wind relationship for the Hellmann gauges (of various versions with different shielding), regression analyses on the Intercomparison data when the DFIR measurment was greater than 3.0 mm, were conducted separately at the Jokioinen and Harzgerode WMO stations.

At Jokioinen, those data when the DFIR was greater than 3.0 mm were used for the analysis and the best-fit regression equations of the catch ratio (CR, %) of snow as a function of the wind speed (Ws, m/s) at the (Hungarian and Danish) Hellmann gauge height (1.5 m) were derived as follows (Ellomaa et al., 1993):

<u>Snow</u>

CR (Hungarian Hellmann) = $111.56 - 32.93 * W_S + 2.83 * W_S^2$, (n = 72, r^2 = 0.70) (4.5.1)

CR (Danish Hellmann) = $97.51 - 23.04 * W_S + 1.73\, W_S^2$, (n = 89, r^2 = 0.74) (4.5.2)

At Harzgerode, in addition to wind speed, air temperature, amount of gauge measured precipitation, duration and rate of precipitation were also considered in the regression analyses. For the German Hellmann gauges, wind speed (Ws) at gauge height (1.0 m) and temperature (T) were found statistically significant to the gauge catch of snow and the mixed precipitation (Günther, 1993).

<u>Snow:</u>

CR (German Hellmann, unsh.) = $103.8 - 14.8 * W_S + 2.4 * T_{mean}$, (n = 43, r^2 = 0.59) (4.5.3)

CR (German Hellmann, Tret.) = $116.8 - 13.4 * W_S + 1.9 * T_{mean}$, (n = 43, r^2 = 0.61) (4.5.4)

<u>Mixed precipitation:</u>

CR (German Hellmann, unsh.) = $92.1 - 6.9 * W_S + 6.0 * T_{mean}$, (n = 119, r^2 = 0.40) (4.5.5)

CR (German Hellmann, Tret.) = $97.0 - 5.4 * W_S + 3.7 * T_{mean}$, (n=119, r^2 = 0.31) (4.5.6)

Because of the difference of the gauge installation (such as gauge heights and wind shields) and of the wind data at the WMO Intercomparison sites, the above catch ratio-wind relations developed using single site data are basically site specific. They should not be applied to other stations in difference climate regions. However, as mentioned in the section 4.3.2, the WMO Intercomparison data collected from different sites are compatible in term of the catch ratio for the same gauge, when wind speed at the gauge height is used in analysis. The Intercomparison data for the unshielded Hellmann gauges were compiled from the 4 WMO sites and the wind speeds at the gauge heights were calculated by the logarithm wind profile and used to develop a more general catch ratio-wind relationship. Figure 4.5.2 shows the regression of the catch ratio (CR) of snow as a function of wind speed (Ws) for the unshielded Hellmann gauge for snow. As expected, the combined results (Equations 4.5.7and 4.5.8) are not always similar to those equations derived from the single station data.

A wide range of both wind speed and catch ratio has been sampled by the combined Intercomparison data, which were collected in a variety of climatic regions. The adjustment procedures derived from these data are more likely to be successfully used for a wide range of environmental conditions.

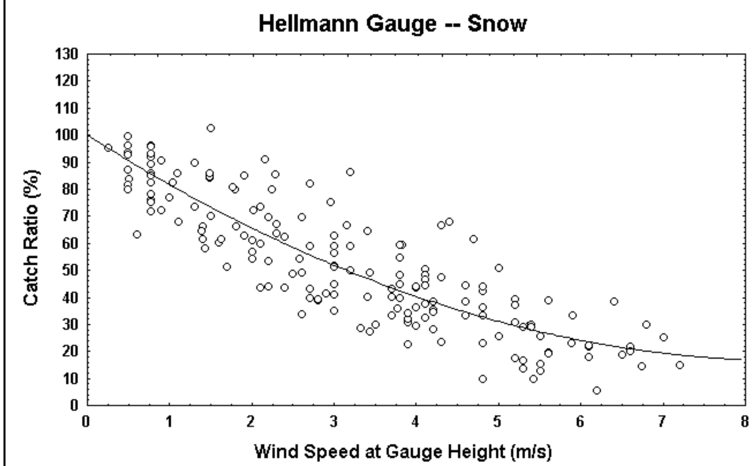


Figure 4.5.2 Catch ratio of snow as a function of wind speed at gauge height of the Hellmann gauge.

<u>Snow</u>

$CR = 100.00 + 1.13*W_s^2 - 19.45*W_s$, $(n = 172,\ r^2 = 0.75)$ (4.5.7)

<u>Mixed Precipitation</u>

$CR = 96.63 + 0.41*W_s^2 - 9.84*W_s + 5.95 * T_{mean}$, $(n = 285,\ r^2 = 0.48)$ (4.5.8)

4.6 CANADIAN NIPHER SNOW GAUGE

The Nipher Shielded Snow Gauge System is the national standard instrument system for measuring snowfall amount in terms of water equivalent in Canada. The measurement system consists of the snow collector which is a hollow metal cylinder gauge, 56 cm long and 12.7 cm in diameter. It is surrounded by a solid shield, made of spun aluminum or molded fiber glass, having the shape of an inverted bell. It is non-recording and requires at least daily observation. Snow caught in the collector is melted and poured out into a glass graduate for a volumetric measurement. The gauge is currently used at 300 stations in Canada, including principal observing stations and some standard climatological stations. The Nipher gauge is being replaced by automatic gauges as stations are automated.

In the WMO Intercomparison, 10 sites operated a Nipher gauge and a DFIR. Analyses of storm event data for the 6 intercomparison sites in Canada are presented in Annex 5.B. The analysis in the following sections will also include data from 4 other sites in Russia, Finland, Germany and the USA (Table 4.2.1). For the analysis in the following sections, the climatological data sets from each of the 10 stations were used and only snow and mixed precipitation were considered.

4.6.1 Average catch ratios

Table 4.6.1 provides a summary of the mean temperature, wind speeds, adjusted accumulated snow amounts for the Nipher and DFIR and the mean catch ratio for all 10 stations. As with the storm event data for the Canadian stations analyzed in Annex 5.B, only observations greater than 3.0 mm measured by the DFIR were included in this analysis. This reduced the problem of having small measurement differences between the two gauges producing quite variable ratios for small precipitation events.

4.6.2 Catch ratio versus wind speed

Scatter plots of catch ratio versus the wind speed at the height of the Nipher gauge for the non Canadian stations are presented in Figures 4.6.1(a) to (d). Scatter plots for the 6 Canadian stations are not shown here since they are similar in pattern (but with slightly greater scatter) as those shown for the event data analysis in Annex 5.B. The increase in scatter for the observation based data compared to the event based data is expected since the wind values for the observation based data may not coincide with the precipitation event.

Table 4.6.1 Data summary for 10 Intercomparison sites with Nipher and DFIR

Station	Period	# of Obs	Mean Tmax (^oC)	Mean Tmin (^oC)	Mean Wind Speed* at 2 m m/s	Total DFIR Adjusted (mm)	Total Nipher Adjusted (mm)	Mean Catch Ratio Nipher/DFIR (%)
Valdai, Russia	Oct.91to Mar.93	37	-1.3	-4.7	4.2	200.5	166.2	82.9
Jokioinen, Finland	Oct.88 to Mar.93	42	-1.8	-4.6	3.2	280.9	240.2	85.5
Harzgerode, Germany	Dec.86 to Mar.93	5	2.1	-1.5	3.7	46.9	43.1	91.9
Reynolds Creek, Idaho, USA	Nov.87 to Feb.92	14	3.1	-5.7	2.1	91.1	88.7	97.4
Dease Lake, BC, Canada	Nov.87 to Apr.93	44	-6.5	-9.3	1.8	209.6	199.9	95.4
Regina A, Sask, Canada	Nov.87 to Apr.92	18	-6.2	-14.5	3.6	97.2	83.3	85.7
Kortright Centre, Ont. Canada	Jan.87to Mar.91	22	-1.2	-10.4	2.3	179.6	175.8	97.8
Trent U, Peterborough Ont. Canada	Dec.86 to Mar.91	28	-2.2	-12.0	1.6	208.2	208.9	103.3
Baie Comeau, Que. Canada	Dec.88 to Apr.93	64	-3.7	-5.7	3.8	389.8	306.4	78.6
East Baltic, PEI, Canada	Dec.87 to Apr.92	64	-2.0	-7.5	2.7	491.7	466.1	94.8

*Note: for Jokioinen, Finland, the height of the Nipher gauge was 1.5 m thus the wind speed was also measured at 1.5 m.

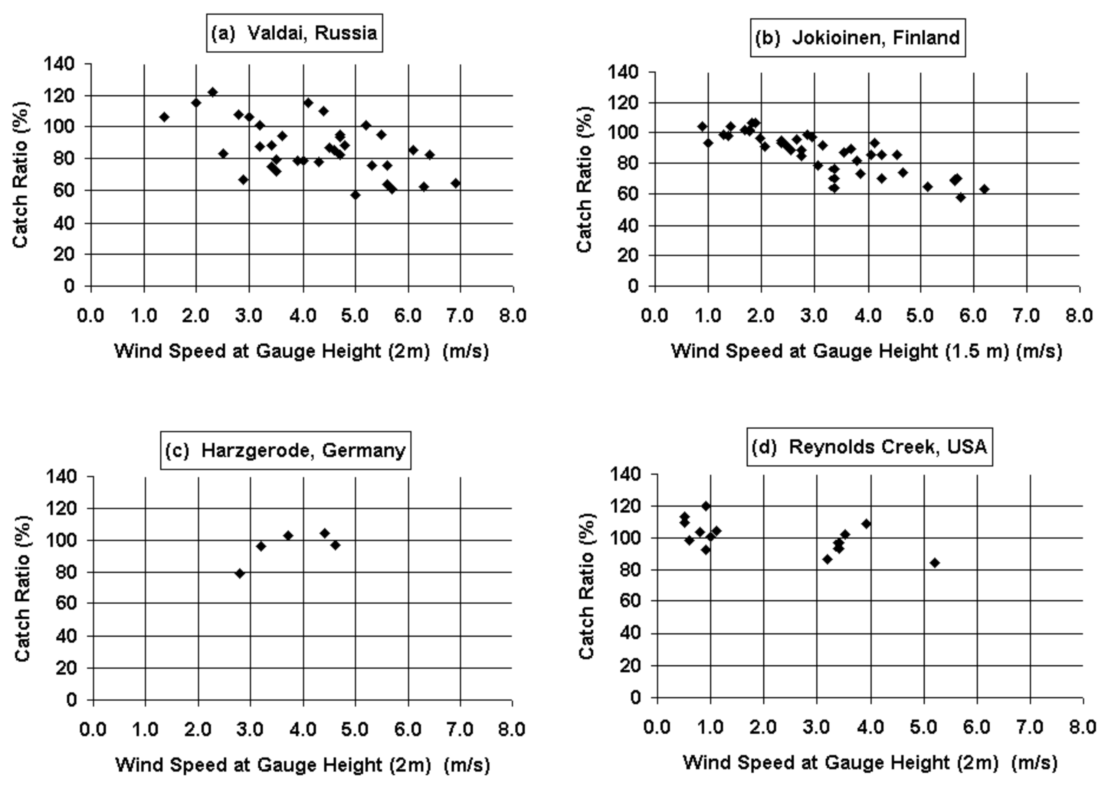


Figure 4.6.1 Scatter plots of Catch Ratio (Nipher/DFIR) for 4 WMO Intercomparison Stations for Snow when DFIR > 3.0 mm.

In screening these stations for analysis to establish catch ratio versus wind speed relationships, it was found that the daily data set from Trent U sampled a very limited range of wind speed. East Baltic had a good representation of wind speeds but local site obstructions and observing difficulties, especially related to blowing snow, limited the use of the data. The data from these two Canadian stations were not used in further analyses. The Harzgerode site in Germany was also not used since it only contributed 5 observations in a narrow wind speed range. The remaining 7 stations: Valdai, Jokionen, Reynolds Creek, Dease Lake, Regina, Kortright and Baie Comeau were used to develop the combined data set for analysis.

Regression analysis was applied to establish relationships for catch ratio versus wind speed and temperature for the combined 7 stations. For snow, the inclusion of temperature did not significantly improve the coefficient of determination (r^2). Thus for snow, the regression analysis was with wind only and the intercept set at 100% for zero wind speed (see Figure 4.6.2). Temperature was found to be a significant variable for mixed precipitation events. The resulting regression relationships are given below:

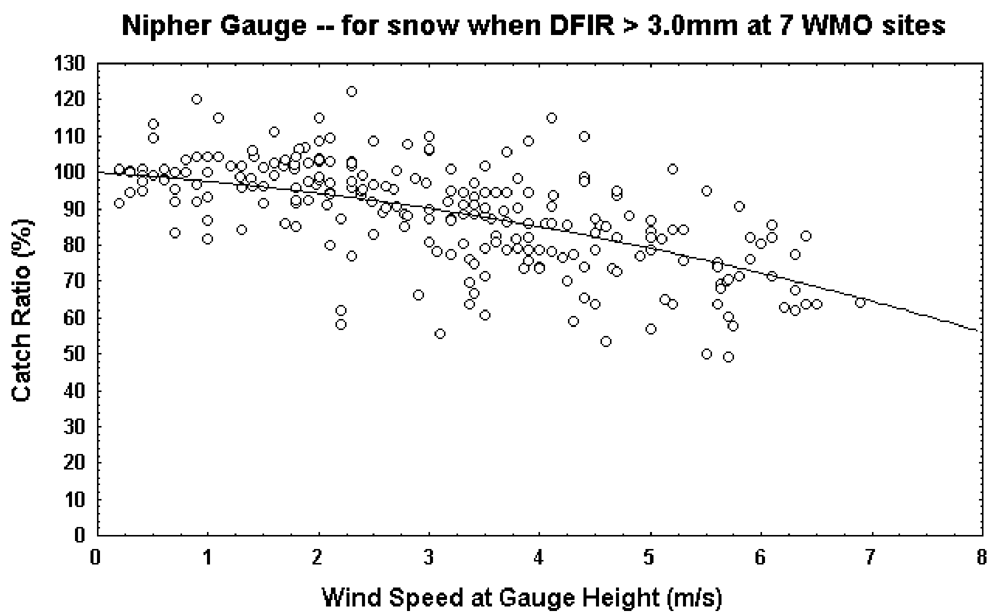


Figure 4.6.2 Regression analyses of Catch Ratio (Nipher/DFIR) versus Wind Speed at Gauge Height

<u>Snow</u>

$CR = 100.00 - 0.44*W_s^2 - 1.98*W_s$, (n = 241, r^2 = 0.40) (4.6.1)

<u>Mixed Precipitation</u>

$CR = 97.29 - 3.18*W_s + 0.58*T_{max} - 0.67*T_{min}$, (n = 177, r^2 = 0.38) (4.6.2)

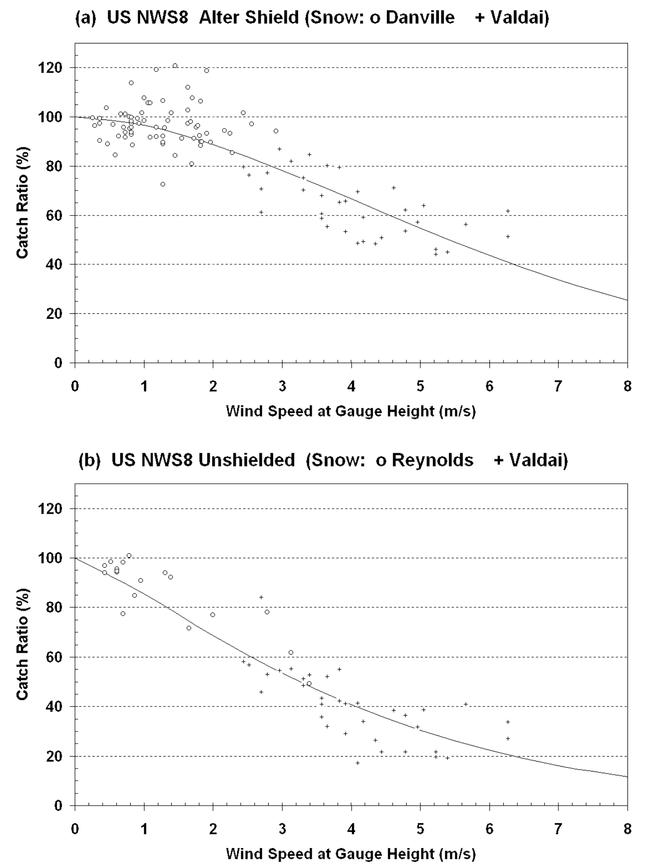
The results from the above analyses for the combined observation based data set for the 7 sites are similar to the results presented in Annex 5.B for the Canadian event based data set. These results again suggest that generally, the Nipher gauge's catch efficiency is at or close to 100% compared to the DFIR for wind speed up to 2 m/s at gauge height. The catch ratio decreases for wind speeds greater than 2 m/s to about 60% at a speed of 7.5 m/s. This decrease is slightly faster than the rate found with the event based analysis in Annex 5.B where the 60% catch ratio was reached at a wind speed of 8 m/s.

The catch characteristics of the Canadian Nipher Shielded Snow gauge appear to be similar to the WMO reference standard (DFIR) at low wind speeds when appropriate adjustments are made to minimize the known measurement biases. The results presented here and those in Annex 5.B were based on data from a wide range of climate conditions and wind speeds. They suggest that at mean storm wind speeds up to 2 m/s, no adjustment of the Canadian Nipher shielded snow gauge measurements except for wetting loss and design variance, is required to achieve the best estimate of actual snow or mixed precipitation. For mean storm wind speed greater than 2 m/s at gauge height, the catch efficiency of the Nipher gauge decreases and adjustments using the relationships established in Annex 5.B should be applied in addition to the adjustments for wetting loss and design variances. For data based on a fixed observation period as presented in above sections, there is more scatter in the catch ratio versus wind speed relationship. This is expected since the wind values may not be coincident with the precipitation event.

4.7 NWS 8" STANDARD NON-RECORDING GAUGE

The U.S. standard 8" non-recording gauge has been the official precipitation measuring instrument at climatological stations in the United States since the beginning of the US National Weather Service (U.S. Department of Commerce, 1963). Today this gauge is still widely used at 7,500 locations in the U.S. (Golubev et al., 1992a) and at about 1340 stations in other countries such as the Bahamas, Bangladesh, Saudi Arabia, Thailand and Philippines (Sevruk and Klemm, 1989). Relatively few of the NWS 8" standard gauges in the U.S. network are presently equipped with (Alter) wind shields, although it has been documented that an Alter shield can increase the catch of solid precipitation by tens of percent and rainfall by several percent (Larkin, 1947; Larson and Peck, 1974). Since 1940, the number of Alter-shielded gauges at U.S. Weather Bureau stations has been reduced from about 500 to less than 200 now (Karl et al., 1993a,b). The combination of precipitation records from shielded gauges with those from unshielded gauges results in inhomogeneous precipitation time-series and leads to incorrect spatial interpretations. Thus, use of such data for climatological and hydrological studies could be misleading.

Figure 4.7.1 Daily catch ratio (%) of the NWS 8" non-recording gauge to the DFIR as a function of daily wind speed (m/s) at the gauge height for (a) Alter-shielded, snow; (b) unshielded, snow



Many studies on the performance of the NWS 8" standard gauge have been done since the 1940's (Larkin, 1947; Black, 1954; Larson and Peck, 1974; Golubev et al., 1992a; Groisman and Easterling, 1994). From 1972 to 1976, the NWS 8" standard gauge was tested in the International Rainfall Comparison of National Precipitation Gauges with a Reference Pit Gauge (Sevruk and Hamon, 1984). Benson (1982) looked at the ability of this gauge to measure snowfall in Alaska, using a Wyoming shielded-gauge and snow surveys on arctic slopes as the references. Recently, Golubev et al. (1992a) reported some results of intercomparison data collected during the rainfall period of 1966 to 1969 at the Valdai Hydrological Research Station in Russia. Legates and DeLiberty (1993a) and Groisman and Easterling (1994) adjusted U.S. gauge measurements on a monthly basis by using monthly wind speed and air temperature to estimate adjustment factors.

This section compares the NWS 8" standard gauge measurements with those of the DFIR for rain, snow and mixed precipitation based on data compiled from 3 WMO Intercomparison stations (i.e. Valdai, Reynolds Creek and Danville) where the NWS 8" standard gauge and the DFIR were operated (Table 4.2.1).

4.7.1 Average catch ratios

The average catch ratio of the NWS 8" standard gauge to the adjusted DFIR value for "true" precipitation varied by the type of precipitation, mean daily wind speed on days with precipitation, and whether the gauge was shielded or unshielded.

At Valdai and Reynolds Creek, the average catch ratio for the NWS 8" standard gauge is less for snow than for rain. Average value of the catch ratio can be very misleading, however, since all storms are weighted equally, irrespective of wind speed, precipitation amount or other environmental conditions. Valdai, which had extensive observing programs during a long "winter" period and even into the summer, exhibits the "expected" decease in the catch ratio from rain to snow. At some of the WMO sites, such as Danville, the average catch ratios of the Alter-shielded NWS 8" standard gauge varied little by precipitation type because of the very low average wind speeds on precipitation days. In some cases, mixed precipitation has a lower average catch than snow (e.g. Reynolds), but the mean wind speed was greater during these events, so this result is not unexpected.

The beneficial effect of using a wind shield, the Alter shield in this case, on gauge catch is clearly shown by the difference between the average catch ratios of the shielded and the unshielded gauges at Valdai. The difference between the average catch ratios, clearly indicates the positive benefits of using a wind shield for snow and mixed precipitation measurements (Table 4.7.1).

Table 4.7.1 Summary (total and % of the DFIR) of daily observed precipitation for the NWS 8" standard gauge (with an Alter-shield or unshielded) at Valdai, Reynolds Creek and Danville WMO Intercomparison stations.

Type of Precip	**# Events (days)**	**Tmax (^oC)**	**Tmin (^oC)**	**Ws (@ 3m) (m/s)**		**DFIR**		**NWS 8" Alter shielded**	**NWS 8" Unshielded**	
(a) Valdai WMO site, October 1991 to March 1993										
Snow	154	-4.1	-	3.8		357.4		248.8	56.5	(mm)
						100.0		69.6	43.8	(%)
Mixed	73	0.7	-	4.5		463.9		361.4	303.4	(mm)
						100.0		77.9	65.4	(%)
Rain	108	10.0	-	3.6		434.5		400.8	386.0	(mm
						100.0		92.2	88.8	(%)
All	335	2.2	-	4.0		1255.8		1011.0	845.9	(mm)
						100.0		80.5	67.4	(%)
(b) Reynolds WMO site, November 1987 to March 1993										
Snow	50	2.6	-6.7	2.5		87.3		-	75.3	(mm)
						100.0		-	86.3	(%)
Mixed	27	7.3	-2.8	3.8		100.7		-	86.6	(mm)
						100.0		-	86.0	(%)
Rain	36	9.1	-0.3	2.8		183.4		-	170.2	(mm)
						100.0		-	92.8	(%)
All	113	6.3	-3.3	3.0		371.4		-	332.1	(mm)
						100.0		-	89.4	(%)
(c) Danville WMO site, December 1986 to April 1992										
Snow	158	-2.2	-11.6	1.5		1051.3		1018.4	-	(mm)
						100.0		96.9	-	(%)
Mixed	21	2.1	-8.6	1.0		650.8		624.8	-	(mm)
						100.0		96.0	-	(%)
Rain	22	6.4	-1.6	1.1		291.1		279.5	-	(mm)
						100.0		96.0	-	(%)
All	201	-2.6	-3.0	1.2		1993.2		1922.7	-	(mm)
						100.0		96.5	-	(%)

4.7.2 Catch ratio versus wind speed

To investigate the dependence of the NWS 8" standard gauge catch on environmental factors, combined daily data when the DFIR measurement was greater than 3.0 mm were used in the statistical analysis. The results confirm that wind speed is the most important factor for the gauge catch when precipitation is classified as snow, mixed precipitation, and rain. The best fit regression results of the daily gauge catch ratio (CR, %) for the shielded and unshielded NWS 8" standard gauge as a function of the daily wind speed (Ws, m/s) at gauge height for snow and mixed precipitation are given below.

The best fit regression relationships for snow and a scatter plot of the data are shown in Figure 4.7.1. A number of high catch ratios close to 120% appeared in Figure 4.7.1(a) for the lower wind speeds at Danville. Investigation indicated that these were wet snow events occurring at temperatures near the freezing point. It was quite possible the Tretyakov gauge orifice capped during large wet snow events since its orifice area was smaller than that of the NWS 8" standard gauge and an internal rim in the gauge allowed snow, particularly wet snow, to build up and cap the gauge.

Snow

$$CR_{Alter\ Shield} = \exp(4.61 - 0.04 * W_s^{1.75}), \quad (n = 108,\ r^2 = 0.72) \qquad (4.7.1)$$

$$CR_{Unshield} = \exp(4.61 - 0.16 * W_s^{1.28}), \quad (n = 55,\ r^2 = 0.77) \qquad (4.7.2)$$

Mixed Precipitation

$$CR_{Alter\ Shield} = 101.04 - 5.62*W_s, \qquad (n = 75, r^2 = 0.59) \qquad (4.7.3)$$

$$CR_{Unshield} = 100.77 - 8.34*W_s, \qquad (n = 59, r^2 = 0.37) \qquad (4.7.4)$$

4.8 SUMMARY

The results for the four most widely used non recording gauges for solid precipitation measurement in the world (the Russian Tretyakov Gauge, the Hellmann Gauge, the Canadian Nipher Gauge, and the US NWS 8" standard gauge) have been assessed. The analysis was based on the combined international data set collected by the WMO Solid Precipitation Measurement Intercomparison project.

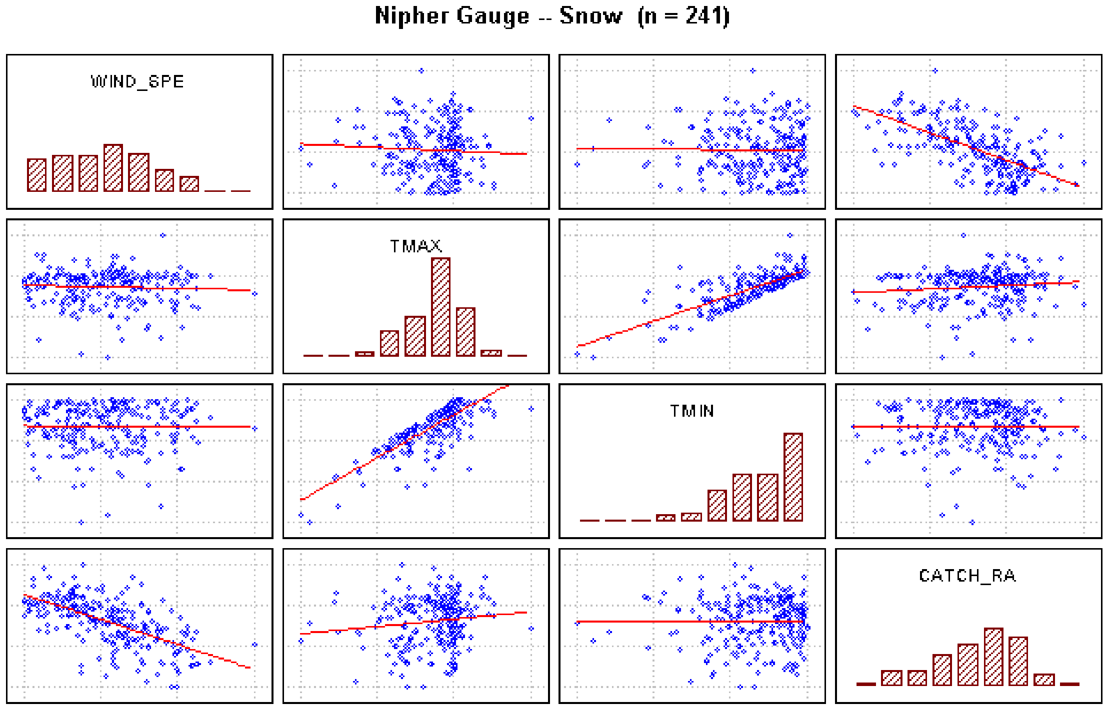
The methods of analysis followed the procedures outlined by WMO/CIMO (1993). Adjustment of the data for known biases was conducted prior to determining the relation of gauge catch to environmental factors. These included errors due to wetting loss, evaporation loss, undercatch of the DFIR, the effect of blowing snow on gauge measurement and any adjustment of wind speed to gauge height (if wind was measured at some other height). The climatological data sets from each of the stations were used. The observation period for each of the station varied from 6-hourly to daily. Temperature and wind data were averaged for the appropriate observation period for each station.

Regression analysis was used to develop relationships of catch ratio versus wind and temperature. Multiple linear regression (MLR) was applied for the initial screening of significant variables. These results are shown graphically in Figures 4.8.1 to 4.8.5 as multiple linear regression correlation matrices of the scatter plots of catch ratio versus wind and temperature for each of the four gauges. These graphs show the best linear fit of each variable pair and also the relative frequency distribution of each variable's data set.

For all gauges and at all sites, it was confirmed that wind is the most dominant environmental variable affecting the gauge catch efficiency. Temperature had a much smaller overall affect on the catch ratio, and was found to be more important for mixed precipitation than for snow. Using the MLR results as a guide, non linear regression analysis was applied to obtain improved fits where appropriate. In some cases, using a second order polynomial or exponential form of the wind variable improved the regression coefficient. The final regression equations (based on combining data from sites in different climatic regimes) for catch ratio versus wind and temperature for the four gauges are given in Table 4.81 and plotted in Figure 4.8.6.

Table 4.8.1 Regression equations for catch ratio versus wind and temperature for Nipher, Tretyakov, US NWS8" and Hellmann gauges

Gauge	Catch Ratio versus Wind and Temperature	n	r^2	SE
	Snow			
Nipher	$CR_{NIPHER} = 100.00 - 0.44*W_s^2 - 1.98*W_s$	241	0.40	11.05
Tretyakov	$CR_{Tretyakov} = 103.11 - 8.67 * W_s + 0.30 * T_{max}$	381	0.66	10.84
US NWS 8" Sh.	$CR_{NWS\ 8\text{-}Alter\ Shield} = \exp(4.61 - 0.04*W_s^{1.75})$	107	0.72	9.77
US NWS 8" Unsh.	$CR_{NWS8\text{-}unshield} = \exp(4.61 - 0.16*W_s^{1.28})$	55	0.77	9.41
Hellmann	$CR_{Hellmann,\ unsh.} = 100.00 + 1.13*W_s^2 - 19.45*W_s$	172	0.75	11.97
	Mixed			
Nipher	$CR_{NIPHER} = 97.29 - 3.18*W_s + 0.58* T_{max} - 0.67*T_{min}$	177	0.38	8.02
Tretyakov	$CR_{Tretyakov} = 96.99 - 4.46 *W_s + 0.88 * T_{max} + 0.22*T_{min}$	433	0.46	9.15
US NWS 8" Sh.	$CR_{Alter\ Shield} = 101.04 - 5.62*W_s$	75	0.59	7.56
US NWS 8" Unsh.	$CR_{Unshield} = 100.77 - 8.34*W_s$	59	0.37	13.66
Hellmann	$CR_{Hellmann,\ unsh.} = 96.63 + 0.41*W_s^2 - 9.84*W_s + 5.95 * T_{mean}$	285	0.48	15.14



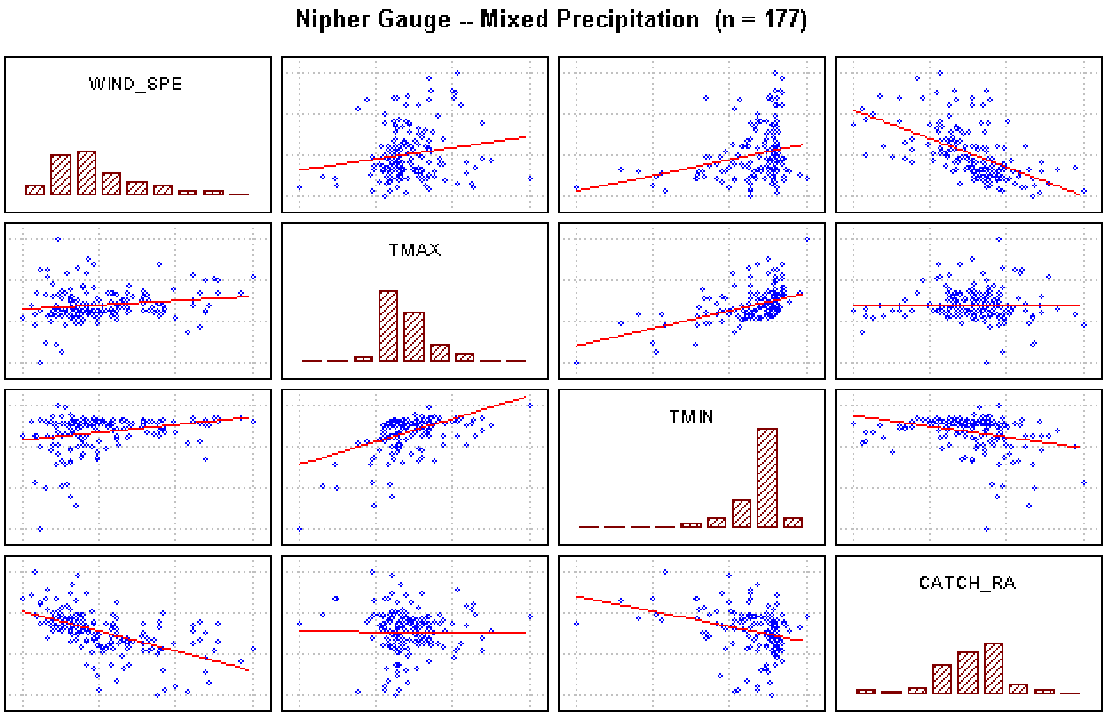


Figure 4.8.1 Multiple linear regression correlation matrix of scatter plots of Catch Ratio versus Wind and Temperature for Nipher Gauge

(These multiple linear regression correlation matrix of scatter plots were produce using STATISTICA for Windows Release 5.1, StatSoft, Inc., 2300 East 14th Street, Tulsa, OK, USA. The diagonal plots show the frequency distribution of all the variables. The scatter plots show the linear relationship between variable pairs. For example, the plot in the lower left hand corner shows the Catch Ratio (y-axis) versus the Wind Speed (x-axis).)

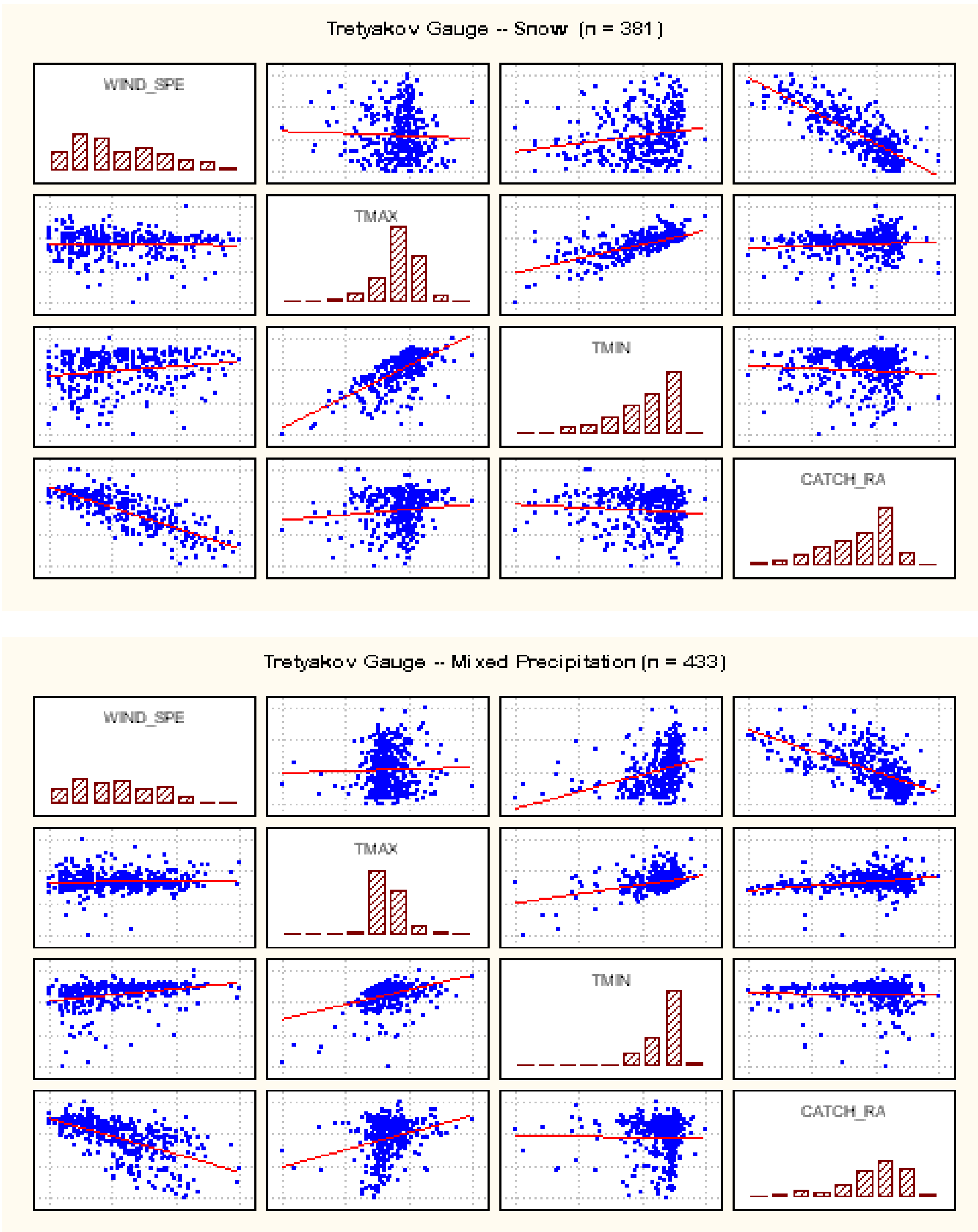
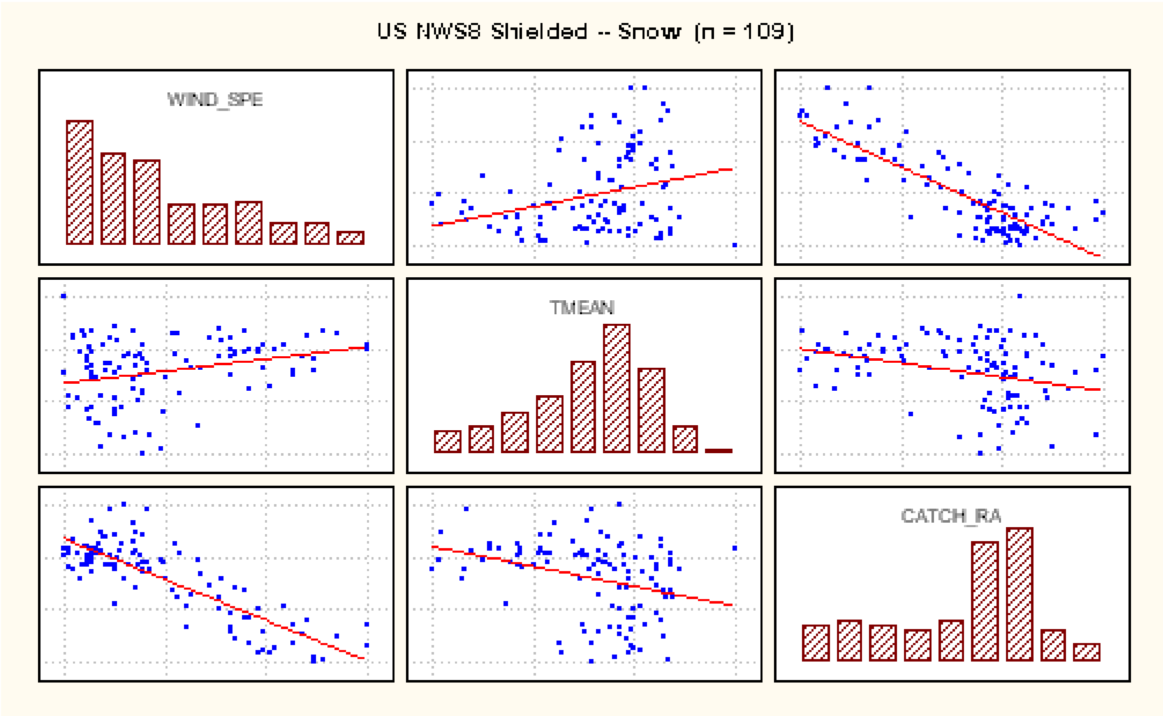


Figure 4.8.2 Multiple linear regression correlation matrix of scatter plots of Catch Ratio versus Wind and Temperature for Tretyakov Gauge



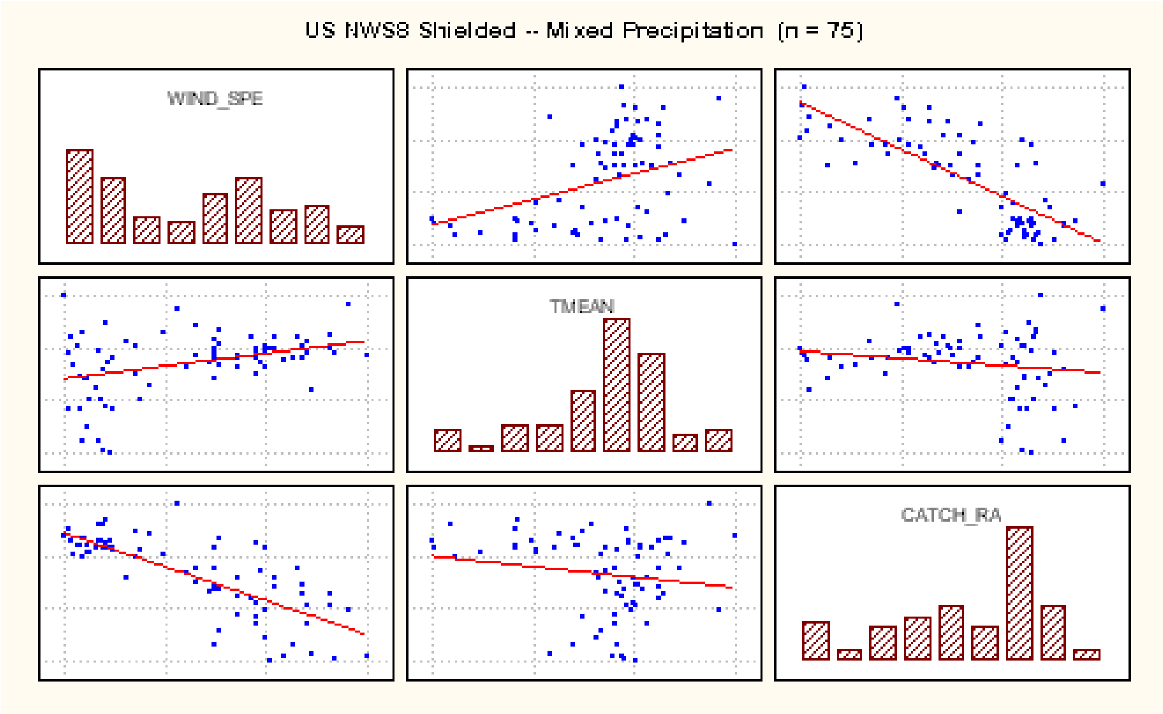


Figure 4.8.3 Multiple linear regression correlation matrix of scatter plots of Catch Ratio versus Wind and Temperature for US NWS8 Gauge with Alter Shield

Figure 4.8.4 Multiple linear regression correlation matrix of scatter plots of Catch Ratio versus Wind and Temperature for unshielded US NWS8 Gauge

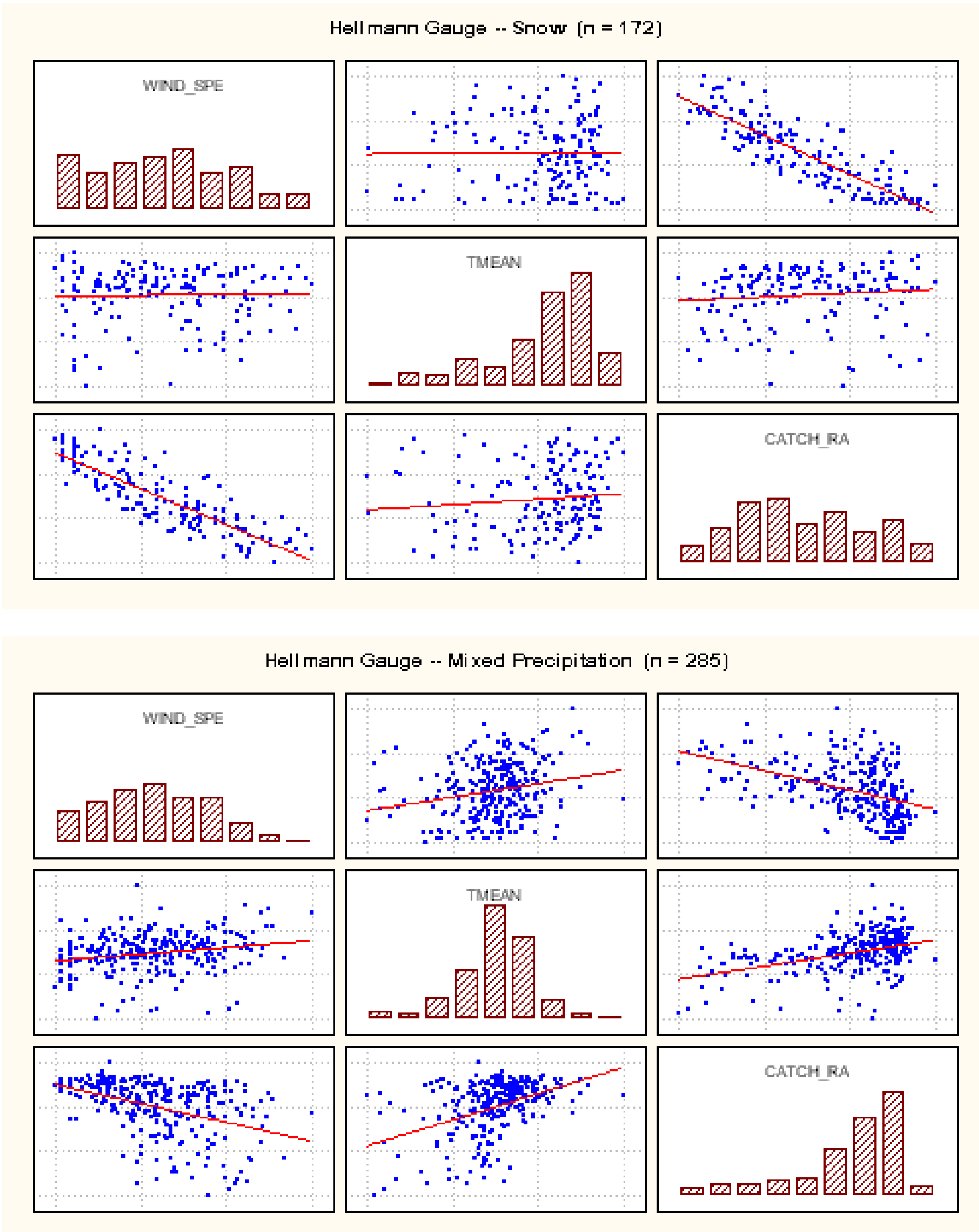


Figure 4.8.5 Multiple linear regression correlation matrix of scatter plots of Catch Ratio versus Wind and Temperature for unshielded Hellmann Gauge

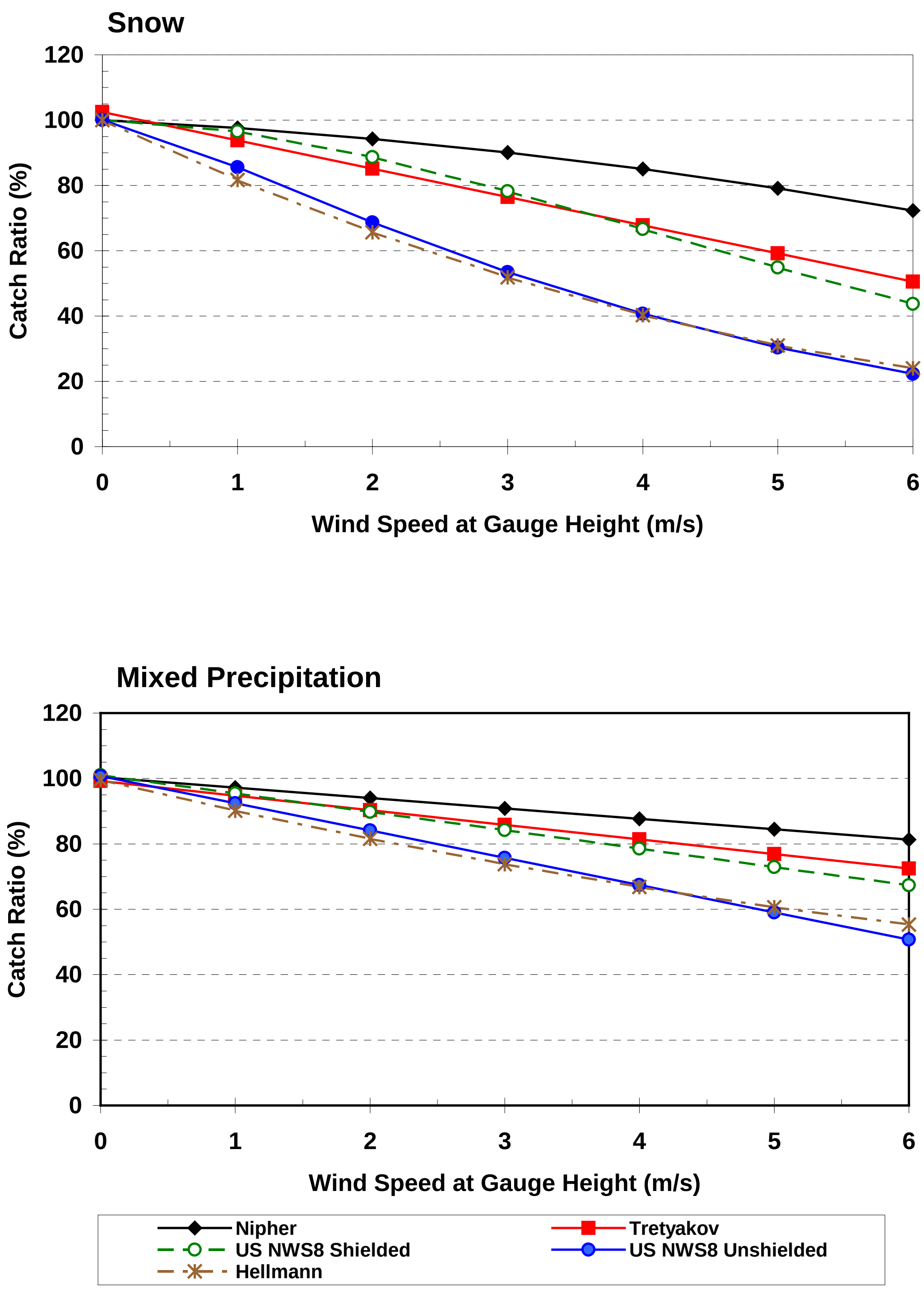


***Figure 4.8.6** Plots of Catch Ratios versus Wind based on best fit regression equations shown in Table 4.8.1. For snow, the Tretyakov curve was plotted for T_{max} = -2.0 °C. For the mixed precipitation plots, temperature variables were set as follows: T_{max} = 3.0 °C; T_{min} = -2.0 °C and T_{mean} = 0.5 °C.*

4.9 DISCUSSION

As noted in section 4.2, the methods of analysis of the intercomparison data were established initially by the International Organizing Committee for the WMO Intercomparison (WMO/CIMO, 1985) and were subsequently modified or updated at the regular session meetings for the Intercomparison (WMO/CIMO, 1993). The analyses in the preceding sections of this chapter and most of the analyses presented in the Country Reports in Annex 5 have generally followed these procedures. However, some countries have found it necessary to modify these procedures to meet their requirements. Denmark, in particular, have made several modifications to the established procedures for their analysis of the Jokioinen data set. The following is a discussion of the modifications that they made and their rationale for making these changes. There is also a very important discussion on the effect of averaging wind speed and temperature in different ways and the effect on the resulting estimate of “adjusted” precipitation.

4.9.1 Applying a DFIR > 3 mm minimum threshold to data sets

Most of the statistical analyses presented in this report was carried out only on observations exceeding 3.0 mm for DFIR. By applying this threshold, many observations were not included in the analysis. This constraint was set *a priori* by the protocol for the Intercomparison Study, but empirical investigations in Jokioinen have revealed that this limit is not necessary for conducting the statistical analyses. In fact, the effect of discrete values for the DFIR and the national gauges near zero precipitation turns out to be negligible, since the observed catch ratios (or adjustment values) show variances of the same magnitude for small precipitation values as for precipitation values satisfying the constraint: DFIR>3.0 mm. Accordingly, some of the analyses have been carried out applying this limit and some (e.g. the Jokioinen Field) have been undertaken applying lower limits so that maximum number of observations possible can be included.

4.9.2 Bush/DFIR adjustments

The Study Protocol has suggested that the DFIR-Bush transformation (Yang et al, 1993) be immediately implemented after collection of data in order to start data analysis from a level, where the bush reference emerge as the best and most 'true' precipitation value. The quality of this step, however, does depend on the quality and validity of the DFIR-bush transformation. It has been suggested that statistical modeling should preferably start from raw observations rather than observations that have already been subject to transformations. This should be especially considered if the impact of the transformation cannot be traced properly in subsequent analyses (e.g. analysis of the ratios: national gauge/ref, where ref is either DFIR or bush transformed reference). Furthermore, the suggested transformation DFIR to bush is complex in the sense that it is not possible to evaluate statistically, the consequences of implementing the DFIR-Bush transformation prior to analysis of the catch ratios (or correction factors) versus e.g. wind speed and temperature. Consequently, some of the statistical analyses presented use the raw DFIR data as the reference in all analyses. In such cases, it was preferred to apply a DFIR-bush transformation after the construction of an adequate model for the directly observed ratios with DFIR and the national gauge observations as variables.

4.9.3 Catch ratio versus correction factor

The relation between national gauge (NG) measurements and the reference DFIR can be studied either from statistical analysis on the catch ratio, CR= P_{NG}/P_{DFIR}, or from the correction factor, CF= P_{DFIR}/ P_{NG}. Although the calculation and analysis of the catch ratio, P_{NG}/P_{DFIR}, is more common, the analysis and application of the correction factor, P_{DFIR}/ P_{NG}, has certain advantages over the catch ratio.

First, whenever one has to adjust an observed P_{NG} value, the procedures leading to the adjusted amount of precipitation is: P_{NG}/CR (divide by CR), in case of catch ratio, and P_{NG}*CF (multiply by CF) in case of correction factor. If CR's and CF's are statistically modeled, for example, as a function of wind speed, W and temperature T, (i.e. CR(W,T) and CF(W,T)), then any subsequent multiplicative use of the estimated CR's or CF's is statistically simple. However, the use of the inverse 1/CR immediately gives rise to statistical problems, assuming that CR, and not CR^{-1} is the variable, which is modeled in the first place with W, T as independent variables. Second, there is no one-to-one mathematical transformation between adjustments obtained by the two approaches. In fact, parameter estimates, confidence limits etc. cannot be directly transferred between the two procedures.

For the purpose of intercomparing national gauges against the reference DFIR, it is preferable to use catch ratios (CR) since it provides a comparison of the relative catch efficiency of the national gauge against the reference. This is the convention used in this Intercomparison. For the purpose of developing adjusting procedures to adjust systematic errors in gauge measurements, it is preferable to use the correction factor (CF) which should be derived independently.

4.9.4 Log transformation of ratios

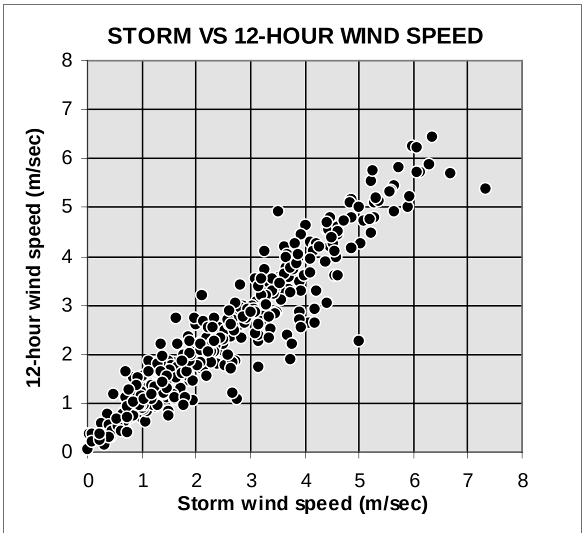
The scales on which the relation between DFIR and the national gauge values are studied are ratio scales, valid in both versions of the adjustment procedures, using either catch ratio CR or the correction factor CF. Although no consensus was established prior to analysis of the field data, a logarithmic transformation of the CR or CF's is likely to produce stable variances (homoscedasticity) which is preferable for most of the statistical analyses undertaken. In fact, direct modeling of the CR's in relation to wind speed W and temperature T run the risk of biased results and inaccurate confidence limits. A range of regression analyses has been used in this Report and the Country Reports, some of which have applied the logarithmic transformation to the ratios before further analysis.

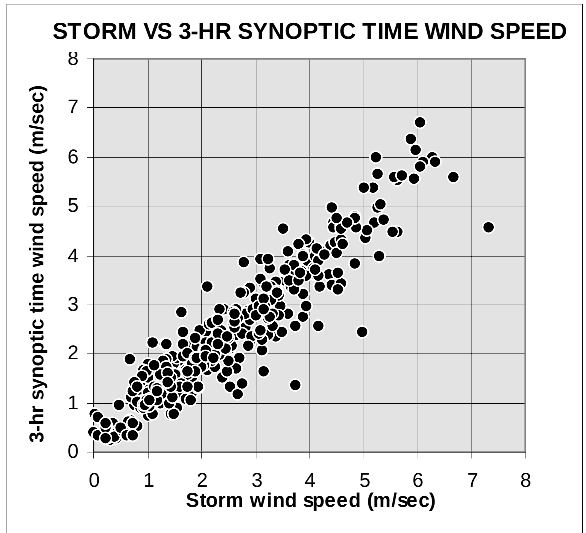
4.9.5 The effect of how averages of wind speed and temperature are estimated

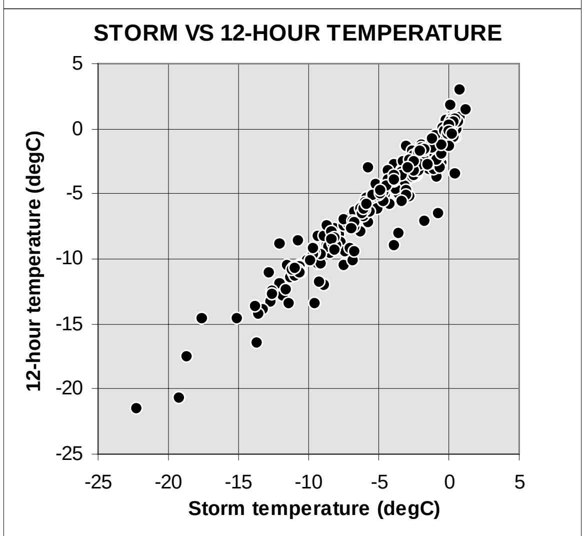
One could argue that data of wind speed and temperature should be provided on such a fine time scale that storm averages could be estimated as accurately as possible. In the experimental field at Jokioinen, Finland, wind speed W and temperature T were measured every 10 minute making it possible to quite accurately estimate storm averages. But most often, such conditions are not met "in the true world"; thus it is valuable to analyse the effect of using averages that have been estimated by other means. With increasing automation, data sampled over short time intervals is becoming more commonly available.

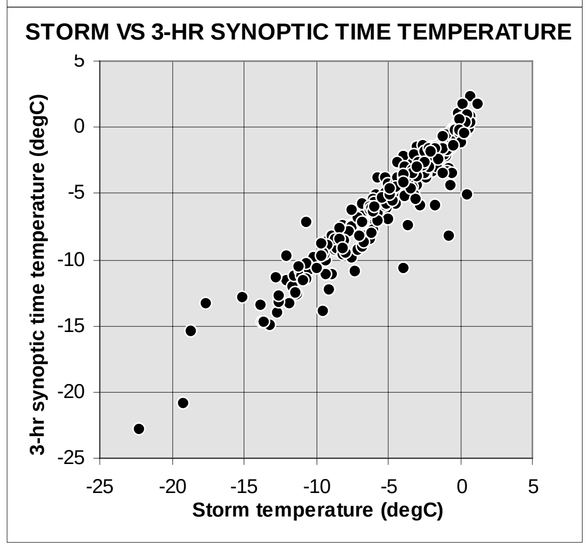
The Jokioinen dataset can be used to assess the effect of averaging. Wind speed and temperature averages for snow events were estimated as: (1) storm average, (2) 12-hour averages, and (3) averages using 3-hourly observations, only, but (4) average temperature was also estimated as the average of the period maximum and minimum temperature, hereafter denoted by T_{extr}. Graphs of storm average versus 12-hour, 3-hourly and max/min average is shown in Figure 4.9.1. A substantial spread is seen in all five examples; most of the points are concentrated in a thick band around the identity (1:1) line, but with some quite extreme outliers. This just illustrates the fact that wind speed and temperature can vary considerably over shorter time periods, 12 hours in these cases, and that the averages are not always representative of the conditions during a precipitation event as noted earlier in the report.

Using outlier averages for the adjustment of precipitation can increase the inaccuracy of the adjusted estimate, especially for high wind speeds and low temperatures, due to the exponential behaviour of the model of the correction factor (see for example Figure 5.D.10 in Annex 5.D). All snowfall events in Jokioinen that have been measured by the Danish Hellmann gauge have been adjusted using six combinations of averages, i.e. W and T estimated as (1) storm average, (2) 12-hour average, (3) 3-hourly measurement average, and (1)-(3) but with T estimated by maximum and minimum temperature. Then adjusted precipitation sums were calculated for the whole experimental period 1987-1993 using the Danish adjustment model for solid precipitation and subsequently the results were compared with the sum measured by the DFIR reference gauge. Figure 4.9.2 shows that the storm averages performs best, but this is not surprising because the Danish adjustment model is based on storm data. It is interesting that 12-hour and 3-hourly data all results in a slight 4-5% underestimation of the total sum of snowfall. This is in accordance with the graphs in Figure 4.9.1 where there is a trend towards slightly underestimated averages, but the differences are in fact small over the 7-year period.









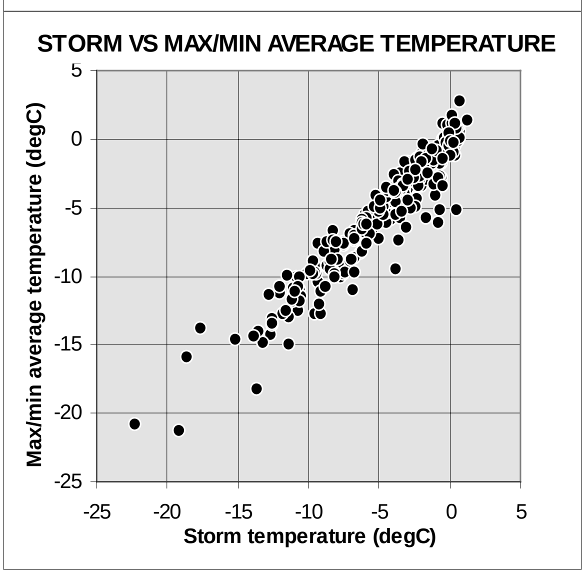


***Figure 4.9.1** Storm wind speed vs 12 hr data and 3 hr synoptic time data, and storm temperature vs 12 hr data, 3-hr synoptic time data and max/min average values. Jokioinen, Finland, 1987-1993.*

Table 4.9.1 shows a few examples showing adjustment of single events using the different average estimation methods. The cases have been randomly selected to illustrate the effect of using outliers of average wind speed and temperature. It is seen that the adjustment applied can differ considerably from that measured by the reference gauge (DFIR). Note, that the differences are not only an effect of using various averages, they are also due to inaccuracies on the adjustment model itself, i.e. the “build-in” differences between observed and predicted values. The event examples just illustrate the expected decrease in accuracy when adjusting precipitation on a smaller time scale. The differences between observed and predicted values are dampened when summing up on longer time scales as suggested by Figure 4.9.2. Thus working on a longer scale than just single events will lead to increased accuracy of the adjusted estimate from which, for example, water balance and climate studies can benefit.

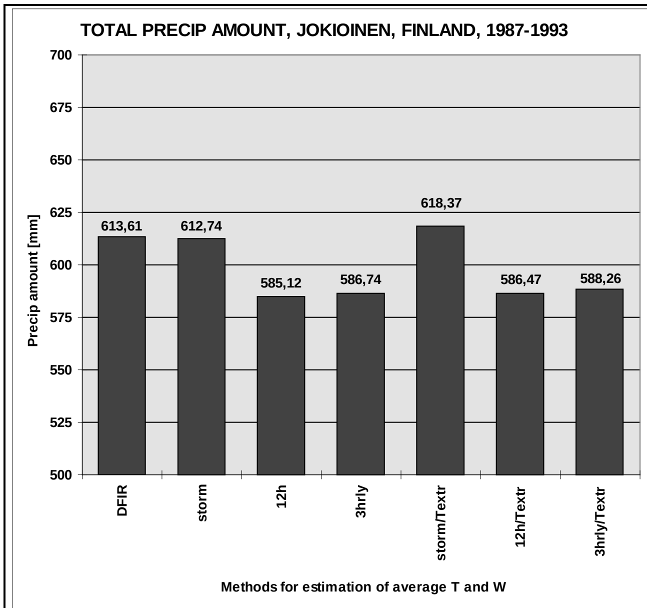


Figure 4.9.2 Adjusted snowfall amount measured by the Danish Hellmann gauge at Jokioinen, Finland, 1987-1993, using various methods of estimating average wind speed and temperature. DFIR=Tretyakov reference gauge, storm=adjustment using storm average of temperature T and wind speed W, 12h=using 12-hour averages, 3hrly=using average of 3 hourly measurements, Textr=average temperature from mean of maximum and minimum temperature. The figures above the columns are the total precipitation amount.

4.9.6 Systematic versus random errors and confidence limits on the adjustments

Several sources of errors occur when analyzing precipitation data by means of statistical models. This intercomparison study extends over very different geographical and climatological fields, which give rise to 'errors' of very different nature. Furthermore, a series of statistical models have been used which cannot be compared directly even within a common statistical framework.

The analyses presented in this Report have brought forward a number of suggestions as to the statistical modeling of catch ratios (or corrections factors) controlled by external variables, e.g. wind speed W and temperature T. This variety of analysis results needs to be further condensed using the complete international data set and a limited number of statistical analysis methods. As a simple example to illustrate the complexity of any gauge comparison problem, let us suppose that gauge (1) seems to suffer from strong sensitivity of the aerodynamic factors (systematic errors), leading to rather low values for the catch ratio, while gauge (2) shows catch ratios close to 100% (i.e. little systematic error) irrespective of the wind speed. Superficially, one would prefer gauge (2) to gauge (1). However, a scenario for preferring gauge (1) over the gauge (2) could be, that the confidence limits reflecting the level of random errors connected to the model, obtained from the statistical analysis show significantly greater width for the gauge (2) compared to gauge (1). Then a 'biased' gauge (1) would then be ranked higher than gauge (2) because its (systematic) bias can be very accurately estimated (low level of random error).

The distinction between random and systematic errors depends on the model under consideration, but several of the analyses put forward here are of the regression type. No attempt, however has been done to give priority to one specific gauge type or one specific type of adjustment procedure, this will be part of future analyses on the complete international data set.

Table 4.9.1. Examples of adjustment of measured and weighed precipitation (in mm) in Jokioinen, Finland, when using various methods for estimating temperature and wind speed averages. The adjustment method used is the Danish model that requires input of average temperature and wind speed. The precipitation has been measured manually every 12 hour by the Danish Hellmann gauge (D.Hellm.). The term 'extr' indicates that the average is estimated as a mean value of maximum and minimum temperature. The wind speed represents gauge level.

Event		**Average wind speed (m/sec)**			**Average air temperature (°C)**			
yyyy-mm-dd	period	storm	12h	3-hourly	extr.	storm	12h	3-hourly
1988-04-09	00-12	5,90	5,00	6,36	-1,95	-1,17	-1,54	-0,32
1988-12-21	00-12	3,15	1,73	1,64	-0,86	-3,70	-3,30	-3,28
1988-12-23	12-24	4,51	4,25	4,04	0,45	-3,47	-5,09	-5,20
1988-12-26	12-24	2,67	1,21	1,16	-11,81	-12,77	-13,32	-12,72
1989-12-10	12-24	5,19	4,76	5,36	-9,17	-9,66	-8,88	-11,15
1989-12-13	12-24	2,90	2,88	2,69	-13,24	-13,83	-14,96	-14,80
1990-01-11	12-24	2,78	2,92	3,23	-5,01	-5,78	-6,97	-7,25
1990-01-20	00-12	4,54	3,62	3,32	-6,04	-6,68	-5,48	-6,82
1990-04-02	12-24	2,09	2,07	2,45	-0,45	-0,04	-0,55	1,20
1991-01-10	12-24	4,17	2,92	2,56	-1,32	-1,37	-1,27	-1,19
1991-01-11	00-12	2,80	3,41	3,85	-3,17	-4,39	-5,12	-3,96
1992-01-14	00-12	3,79	3,75	3,49	-5,03	-5,04	-4,24	-5,26
1992-10-31	12-24	3,90	2,72	2,75	-3,02	-4,70	-3,71	-4,44
1993-02-20	00-12	4,28	4,20	4,03	-9,91	-10,17	-10,65	-9,54

Precipitation amount for the 12 events

Event		Precip.	Precip.	Precip. adjusted			Precip. adjusted, T_{extr} used		
yyyy-mm-dd	period	DFIR	D.Hellm	storm	12h	3-hourly	storm	12h	3-hourly
1988-04-09	00-12	3,12	0,77	3,43	2,57	3,75	3,04	2,45	3,40
1988-12-21	00-12	2,28	0,91	1,88	1,35	1,31	2,03	1,35	1,31
1988-12-23	12-24	1,00	0,40	1,09	1,23	1,25	1,45	1,34	1,25
1988-12-26	12-24	1,78	1,12	2,65	1,44	1,41	2,70	1,44	1,41
1989-12-10	12-24	4,67	0,44	2,54	2,21	2,65	2,87	2,40	3,07
1989-12-13	12-24	1,69	0,40	1,08	1,09	1,03	1,13	1,12	1,02
1990-01-11	12-24	2,65	1,21	2,53	2,70	3,10	2,67	2,81	3,13
1990-01-20	00-12	1,88	0,43	1,65	1,25	1,08	1,72	1,25	1,13
1990-04-02	12-24	6,01	3,79	5,98	5,91	6,54	5,84	5,81	6,31
1991-01-10	12-24	11,31	5,36	14,61	10,61	9,65	14,52	10,56	9,63
1991-01-11	00-12	2,41	1,19	2,39	2,97	3,49	2,44	2,92	3,33
1992-01-14	00-12	10,25	3,06	8,79	8,68	7,77	8,87	8,76	8,06
1992-10-31	12-24	7,38	4,00	10,92	8,14	8,02	11,60	8,09	8,16
1993-02-20	00-12	2,92	0,49	2,07	2,03	1,94	2,04	1,98	1,85
Event total:		59,35	23,57	61,59	52,18	52,99	62,90	52,26	53,08

5. AUTOMATION OF WINTER PRECIPITATION MEASUREMENTS

5.1 INTRODUCTION

With the increasing trend in many countries to replace manned observations with the use of automated meteorological and climatological systems and sensors, there is a need to evaluate the reliability and accuracy of these new techniques specifically with respect to winter precipitation measurement. During the WMO Intercomparison study, automatic gauges (including weighing and tipping bucket types) were tested at several evaluation stations in Canada, Finland, Germany, and Japan. The WMO Solid Precipitation Measurement Intercomparison project provided an opportunity to investigate, identify the problems, and provide solutions to some of the challenges of using automatic gauges for winter precipitation measurements. Based on the WMO Intercomparison data, problems with automatic systems were identified and initial adjustment procedures for automatic gauges for wind-induced errors were derived (see country reports in Annex 5). This chapter presents a brief summary of the intercomparison results for serval automatic precipitation gauges used in Canada, Finland, Germany, and Japan. It must be emphasized, however, that the measurement of precipitation, especially solid precipitation, using automatic devices still has many problems and challenges to be overcome before accurate and reliable measurements can be achieve for use in weather, climate, and hydrology.

5.2 CANADA

Canada established six evaluation stations for the Intercomparison, each site representing different climatic and physiographic regimes. A permanent national intercomparison station has been established at the Atmospheric Environment Service (AES) Centre for Atmospheric Research Experiments (CARE) at Egbert, Ontario where past, current and new Canadian methods of precipitation measurement and observation can be compared against international reference standards. At least one automatic precipitation gauge of the weighing type was operated at all of the Canadian evaluation sites (see Annex 3.A). Currently, the weighing-type precipitation gauges and the tipping bucket gauges are the most widely used instruments on automatic stations for the measurement of precipitation in Canada. The Canadian tipping bucket gauge is used only for measuring liquid precipitation. Non-intrusive type sensors which employ optical or small radar devices are being evaluated, but as yet have not been successfully calibrated for the measurement of winter precipitation. The Belfort Transmitting Precipitation Gauge (formerly called Fischer and Porter) combined with electro-optical encoder technology (Belfort model 3000) has proven to be the most suitable configuration for use on Canadian automatic recording systems.

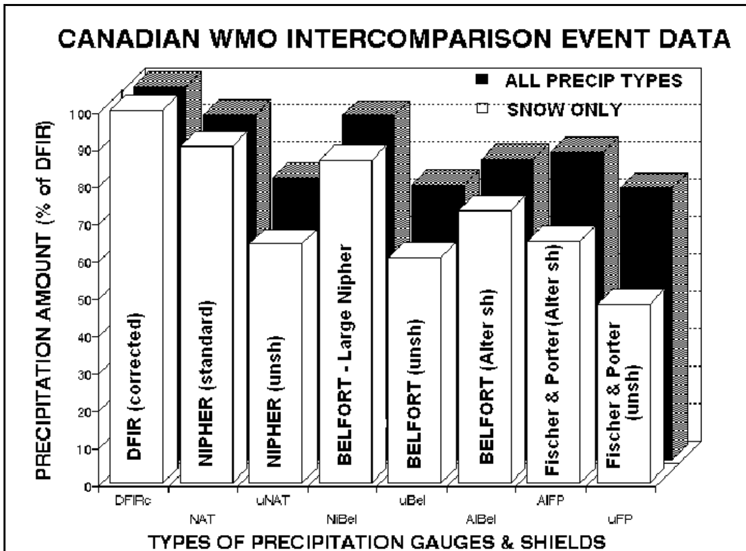


Figure 5.2.1 Mean annual accumulated winter precipitation greater than 5.0 mm, of different gauge types and shielding as a percentage of DFIR (adjusted) at the Canadian Evaluation Station at Kortright, Ontario from 1987-1991.

The goal of any automation plan should be not only to provide accurate precipitation measurements, but also to provide data which would be compatible with current national methods. In an effort to meet these needs, Environment Canada developed and tested a large Nipher-type shield suitable for use on 20.7 mm (8") orifice recording precipitation gauges. The large Nipher-type shield was constructed of fiberglass and designed to be compatible with the Canadian national standard Nipher snow gauge system. Results of field and wind tunnel tests (Goodison et al., 1983, 1992a) showed that the large Nipher-type shield can be used with recording gauges to provide monthly and annual precipitation measurements which are compatible with those obtained by the standard manual AES precipitation gauges. Figure 5.2.1 shows that over five winters (1987-1991), the large Nipher-type shielded Belfort gauge (NiBel) measured virtually the same as the national standard Nipher gauge (NAT) during all winter rain, snow and mixed events greater than 5.0 mm, at the Kortright Centre evaluation station. For snowfall events, the NiBel gauge caught 3% less than the NAT gauge. This shield provided a significant improvement in catch compared to similar gauges fitted with more commonly used shielding, i.e. unshielded (uBel, uFP) and Alter shielded (AlBel, AlFP).

One serious concern with recording weighing gauges is that wet snow or freezing rain can stick to the inside of the orifice of the gauge and not fall into the bucket to be weighed until some time later, often after an increase in ambient air temperature. This problem is notably amplified with the large Nipher-type shield which has its orifice extended 1.2 m above the gauge to accommodate the shield. Figure 5.2.2 shows precipitation observation results from two different automated data collection systems, i.e. GOES Data Collection Platform (DCP) and data logger (21X), compared to standard manned climate station observations at CARE. The auto-stations measured meteorological parameters hourly, but the climate station observations are performed twice daily, morning and afternoon. Both automatic systems used Belfort gauges with large Nipher shields to record precipitation totals. The climate station uses a standard Nipher gauge for snowfall and a Type B rain gauge for liquid precipitation. The average difference between the DCP and climate station precipitation observations is 0.04 mm; and between the 21X and climate is -0.02 mm. However, during the period Julian day 50 to 120, a seasonal period normally associated with mixed precipitation events, large daily differences, as much as 10 mm, are observed between the auto-stations and the manned climate station. A significant positive difference is usually followed, within 24 hours, by a similarly significant negative value, indicating the precipitation from the weighing gauge has fallen in at a later period.

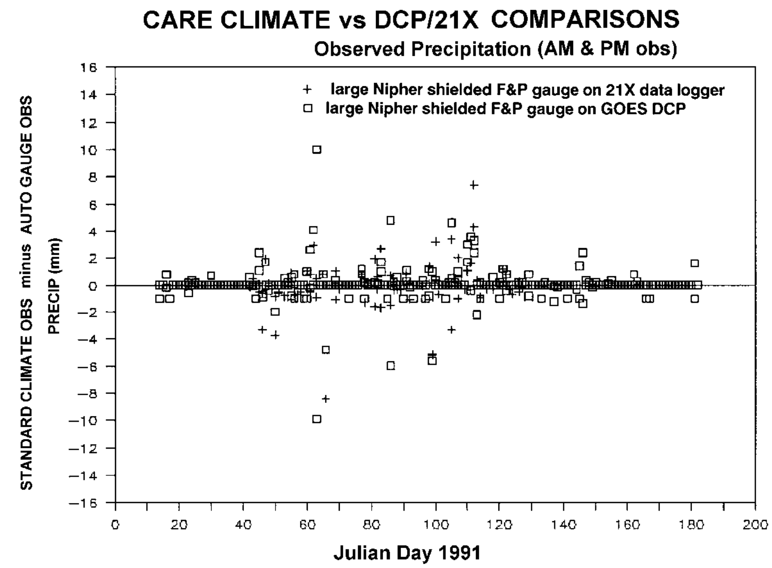


Figure 5.2.2 Difference between climate station and auto-station (DCP/21X) precipitation observations from January to June, 1991.

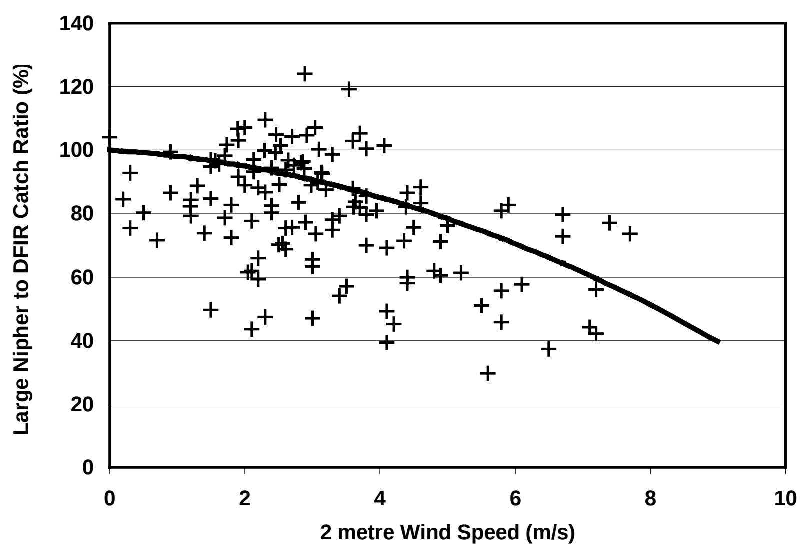


Figure 5.2.3 Comparison of catch ratios, large Nipher-type shielded weighing gauge to DFIR for snowfall events greater than 5.0 mm at all Canadian Evaluation Stations to the Catch Ratio curve for Canadian Nipher Shielded Snow Gauge derived in Section 4.6.

Other problems, such as the unwieldy size of the large Nipher-type shield, the effects of wind induced oscillation on the weighing mechanism, which is accentuated by the shield design, and the ability of the shield to cause the gauge to catch blowing snow (if mounted close to the ground) are all negative influences on the effectiveness of this shield. Figure 5.2.3 shows the ratio of large Nipher shielded weighing gauge to DFIR (i.e. "true" snowfall) for snowfall events greater than 5.0 mm as a function of mean storm wind speed at all Canadian evaluation stations. The data from the Belfort gauges were not adjusted for timing variations noted above, adding to potential variation in catch compared to the DFIR. The Catch Ratio curve derived for the standard national gauge (Nipher Snow Gauge System) in section 4.6 is plotted on the same graph. If the original assumption holds true, that is, simply scaling up the Nipher shield to fit weighing gauges provides similar catch characteristics, then this curve or one like it could be used to adjust large Nipher-type shielded gauges for wind induced error. However, for one or all of the reasons mentioned above the varied distribution in the event ratios determined during the Intercomparison for weighing gauges fitted with this shield makes this type of adjustment unreliable.

Concern over the recent promotion of heated tipping bucket gauges as a viable method of measuring solid precipitation in North America (Short, et al, 1991), led to the installation of a Lambrecht Model 1518 heated tipping bucket at CARE in 1990. Figure 5.2.4 shows some results of measurements taken with this gauge. A time series of accumulated precipitation measured with the WMO reference gauge (DFIR) and with the heated tipping bucket gauge for a period during 1991 is plotted along with hourly temperature. During warm periods, for example day 50 to 51, when rain is falling, both gauges catch similar amounts of precipitation. However, during cold periods, like days 45 to 48, when temperatures dipped to -20^{o}C, the heated tipping bucket severely under caught the DFIR. In total, over the entire period, the heated tipping bucket gauge caught less than a third of the actual amount of precipitation recorded by the DFIR.

In Canada, the use of weighing recording gauges is presently the most practical method of measuring annual precipitation at auto-stations. Heated tipping bucket gauges are not a feasible alternative to winter precipitation measurement in areas where temperatures fall below 0^{o}C for prolonged periods of time. The addition of the large Nipher-type shield on weighing gauges, particularly in windy environments, offers a viable method of minimizing catch errors, while providing measurements compatible with Canadian standard snow gauge observations. The use of an acoustic snow depth sensor in conjunction with precipitation gauge measurements has been found to be an effective tool in providing further information on type and timing of precipitation.

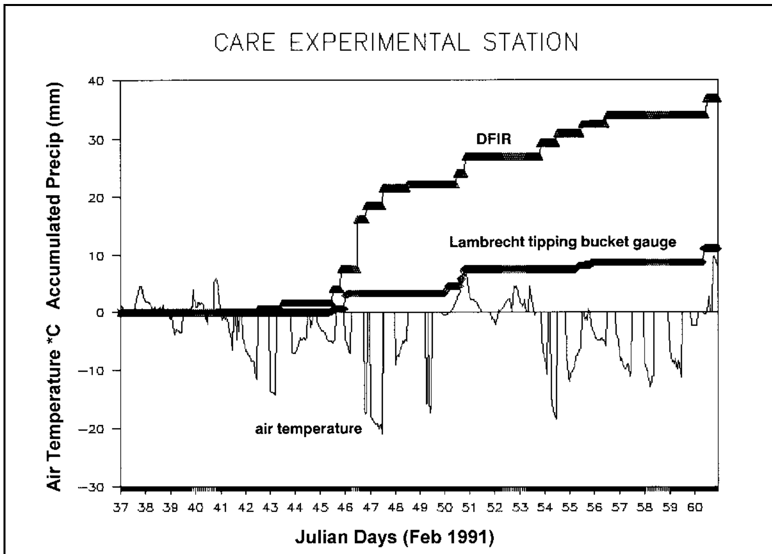


Figure 5.2.4 Difference between accumulated precipitation from WMO reference gauge (DFIR) and heated tipping bucket gauge at CARE during February 1991 along with hourly temperature.

Initial analysis of data from the Canadian WMO Intercomparison stations indicate that climatological summaries and event totals from a large Nipher-type shielded weighing recording gauge are similar to the WMO reference gauge (DFIR) and consistent with those from the Canadian standard Nipher shielded gauge. However, there is more scatter of the event data points about the regression line for the large Nipher shielded weighing gauge than for the standard Nipher gauge when plotted against wind speed. This is no doubt a reflection of the problems discussed above, particularly, the timing errors associated with freezing rain or wet snow events. The application of adjustment procedures for weighing gauge data on hourly or daily totals will certainly prove more difficult than adjusting data for longer time scales such as monthly climatological summaries.

5.3 FINLAND

The WMO solid precipitation intercomparison site at Jokioinen, Finland operated several automatic gauges. These included: Friedrich, Rain-o-matic-H, RIMCO, GEONOR, and FD12P. The first three are heated tipping bucket type gauges. The GEONOR is a weighing type gauge using a vibrating-wire strain sensor. The FD12P present weather sensor is a non-intrusive type gauge using a forward scatter visibility sensor to which a capacitive sensor based on the DRD11A Rain Detector has been added. More details on these auto gauges can be found in Annex 3.D

Some of operational problems experienced with these auto gauges included: tipping bucket blockages mainly in the autumn: Friedrich's bucket three times, RIMCO twice; the heating of RIMCO gauge was not sufficient on five occasions and once the measuring card was burnt; both GEONORs (I and II) had a faulty program at first and only from 1 Nov 1988 could the data be used in the analysis. Lightning damage required that the measuring component had to be changed twice for GEONOR I and once for GEONOR II. Birds have been found in the GEONOR buckets twice.

The data collecting system consisted of a PC-microcomputer, a line printer, interface cards and measuring transducers. The system was down 107 times and it has been stopped for maintenance 117 times. In total, the system recorded 299,857 ten minutes intervals starting in August 1987 and ending in May 1993. This means that the system worked on a level of 98.9 %.

The three heated auto gauges tested at Jokioinen (Friedrich, Rain-o-matic-H and RIMCO) showed great scatter in the one to one precipitation amounts for these gauges against the DFIR and their catch ratio versus wind speed relationships also have large scatter and relatively poor correlation. An example of these results for snow measurements with the Friedrich gauge is shown in Figure 5.3.1.

Despite the problems noted above with the GEONOR gauge, it did measure winter precipitation intensity in Finland for the first time at Jokioinen from 1989 to 1993. From 20,808 ten minutes cases during semi-daily snowfall, some 64% were classified into the intensity class of 0.00 mm/10 min. From 7,533 cases with greater intensity 50% were smaller than 0.035 mm/10 min. and 90% smaller than 0.16 mm/10 min. The greatest recorded intensity was 1.42 mm/10 min. This gauge system was found to have fairly good reliability with 92.6 % of the semi-daily DFIR data acceptably recorded with GEONOR I (Aaltonen et al. 1993).

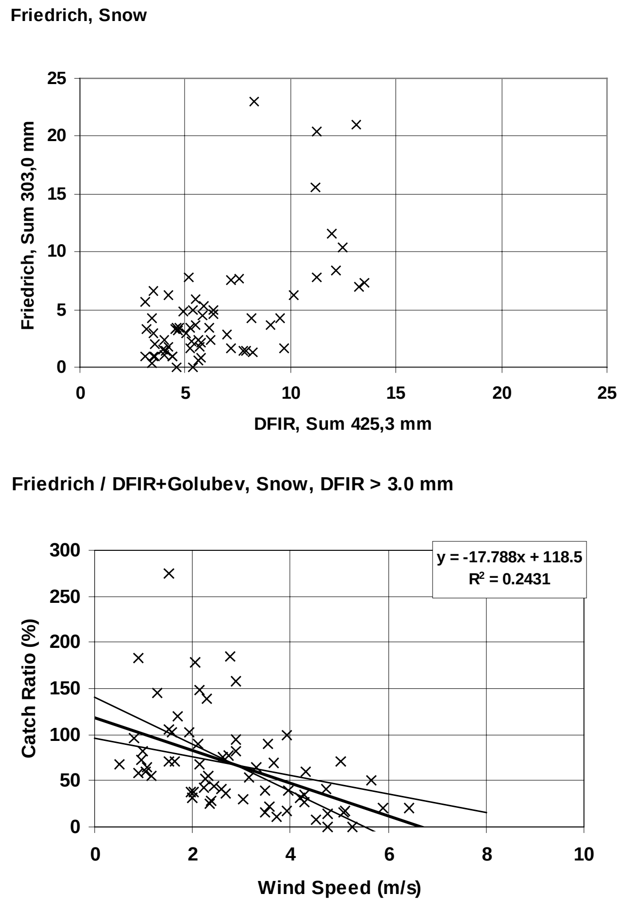


Figure 5.3.1 (top) One to one snow amounts of Friedrich gauge versus DFIR; (bottom) Catch ratio versus wind speed for Friedrich gauge

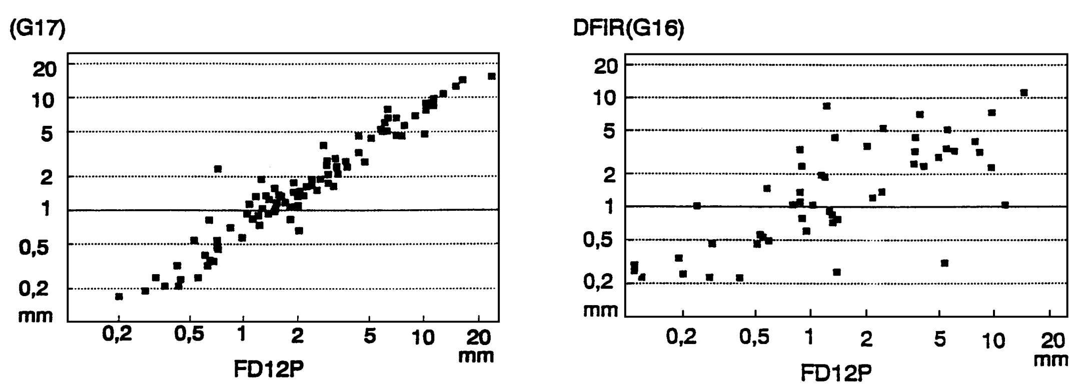


Figure 5.3.2 (Left) Sums of semi-daily rainfall (n=90) for 1 May 1993 to 30 Apr 1993 measured with pit gauge (G17, adjusted for wetting loss) and FD12P; (Right) Sums of semi-daily snowfall (n=54) for 1 May 1993 to 30 Apr 1993 measured with DFIR (G16, adjusted with Golubev's equation) and FD12P.

The FD12P present weather sensor showed good performance and a comparison of semi-daily adjusted sums of the pit-gauge and FD12P showed a fairly good agreement in rain but measurements in snowfall showed a rather big scatter (see Figure 5.3.2)

The results from the Jokioinen site found large undercatch of the heated tipping bucket type autogauges which is affected by wind speed and evaporation from melting snow. In general, the performance of the tipping bucket gauges was very poor and they cannot be recommended to be used for winter time precipitation measurement in Finland (Aaltonen et al. 1993).

5.4 GERMANY

The unshielded AFMS automatic gauge was one of the gauges tested in the WMO solid precipitation intercomparison site at Harzgerode, Germany. The precipitation total is determined by means of volume measurement in this gauge. The precipitation water collected in the funnel (200 cm^2) passes through a filter and a slanting channel into the measuring vessel which is made up of two connected vertical channels. When the precipitation total has reached 0.1 mm/m^2, an electric impulse is triggered in the measuring vessel by a needle electrode causing a brief opening of the valve which empties the measuring vessel. At the same time an impulse is given for the further processing of the measured value which represents the precipitation total of 0.1 mm. In order to measure solid precipitation, the collection funnel and the measuring vessel have been provided with an electronically controlled heating device (+2 ^oC).

Observations and measurements made at the Harzgerode Intercomparison site during the winter seasons 1986-1993 provided the basis for a more detailed analysis of gauge catch ratios measured by different gauge types. The first approach used the total gauge catch of each gauge type compared to the DFIR as a reference. The results showed that the AFMS Automatic gauge caught 42 % of the DFIR compared to the unshielded Hellmann gauge, at 47 % of DFIR, and the Tretyakov gauge at 61 % of the DFIR.

The analysis of the catch percentage separated for various classes of daily precipitation depth reveals the results shown in Table 5.4.1. There are no essential differentiations among the classes of higher precipitation (P $\geq$ 2.1 mm). The systematic losses of the unshielded Hellmann gauge is smaller for the classes of lower precipitation. Contrary to that there are significant higher losses with the Automatic gauge for the "low precipitation classes". The reason for that may be the increased evaporation losses caused by heating (cf. Figure 5.4.1).

Table 5.4.1 Daily totals of the catch percentage separated for various classes

	Hellmann, unshielded		AFMS Automatic gauge unshielded, volumetric	
	P $\leq$ 1.0 mm	P $\geq$ 1.1 mm	P $\leq$ 1.0 mm	P $\geq$ 1.1 mm
Snow only	60...78 %	44...53 %	27...30 %	38...48 %
Mixed precip	64...99 %	68...77 %	52...61 %	64...76 %

Relationships for catch ratio versus wind speed were developed for the AFMS automatic gauge at Harzgerode (see Figure 5.4.2). The high losses (low catch ratios) of the Automatic gauge in the case of small wind speeds are again most likely caused by the heating of the collecting funnel (Günther, 1993)

5.5 JAPAN

For the WMO solid precipitation intercomparison study at Hokuriku, Japan, all precipitation gauges used, including the DFIR were automatic gauges. The national gauges evaluated at this site included the RT-1, the RT-3 and the RT-4 precipitation gauges of Japan Meteorological Agency (JMA). The RT-1 is a simple tipping bucket gauge. JMA operates a model which has an electric heater which heats the air beneath the funnel. This gauge does not have a wind shield. JMA deploys this model to those few observatories where the probability of solid precipitation is low but not regarded to be zero.

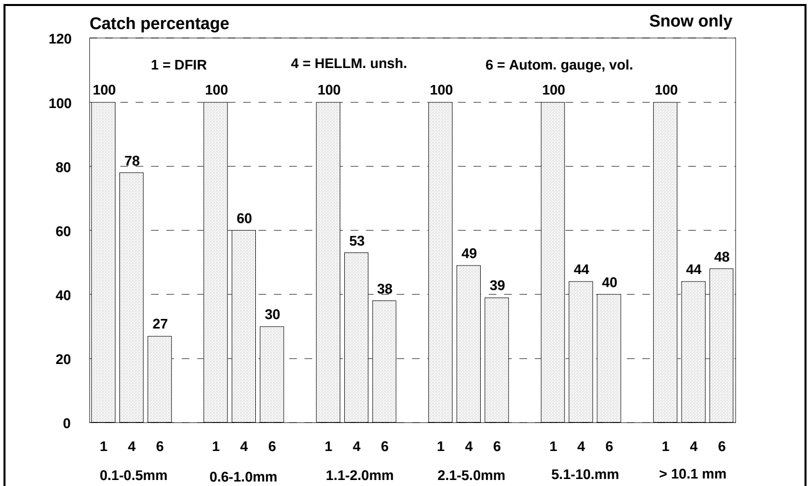


Figure 5.4.1 Catch percentage of the comparison gauges (4, 6) in various classes of depth of precipitation. Reference gauge (1) DFIR = 100 %

The RT-3 gauge has a thicker wall which is filled with warm water kept at 5°C. This gauge does not have a wind shield. JMA deploys this gauge to observatories where there is a higher probability for solid precipitation in winter.

The RT-4 gauge collects precipitation to the water reservoir installed in the orifice which is heated to 5°C. The collected precipitation water flows down to the measuring unit through the overflow drainage. The evaporation from the reservoir is reduced by an oil layer created over the water. This gauge has a cylindrical wind shield.

These three gauges all use the same tipping bucket mechanism with the resolution of 0.5 mm to measure the water amount. The physical characteristics of these gauges are given in Table 5.5.1. The height of gauge orifices was adjusted to 3.5 m above ground. JMA does not designate a standard height for precipitation gauges.

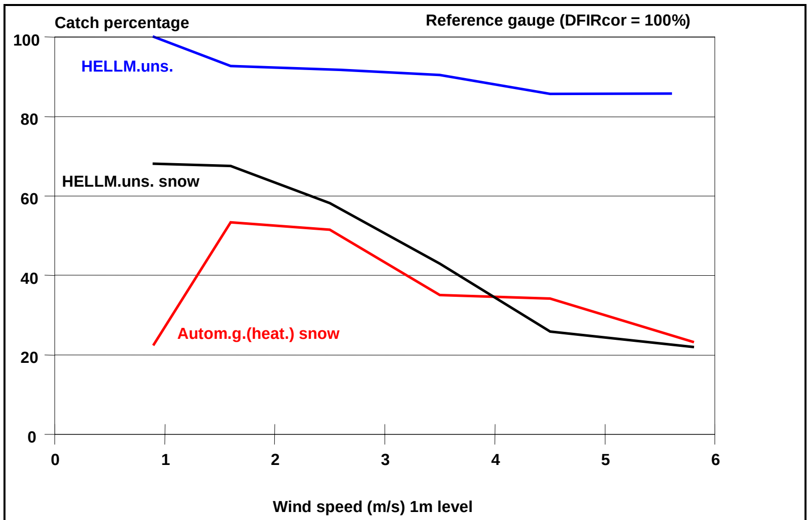


Figure 5.4.2 Catch percentage of comparison gauges dependent on wind speed (1 m level)

The DFIR installed at the station has been modified so that precipitation is able to be recorded continuously: the bottom of the Tretyakov Gauge is removed, and connected to a high precision automatic gauge via a metal tube 140 cm in length and 18 cm in diameter. Considering the snow depth in this area, the top of the outer fence, inner fence and the gauge were leveled to 400 cm, 350 cm and 350 cm above the ground, respectively, i.e., 50 cm higher than the standard DFIR.

Table 5.5.1 Physical characteristics of Instruments

Name	Type	Orifice area (cm^2)	Height above ground (cm)	Remarks
DFIR	modified Tretyakov	200	350	connected to automatic gauge
RT-1	tipping bucket	314	350	heated funnel
RT-3	tipping bucket	314	350	heated water jacket
RT-4	tipping bucket	314	350	heated water reservoir with wind shield

The intercomparison results reported from the Hokuriku site noted some problems with the operation of these gauges. The precipitation amounts at the beginning of an event were suspect if water adhesion to the inner gauge wall or wetting loss is not accounted for. Tests for the maximum water adhering capacity of gauges, were measured by spraying water to the walls. These tests found wetting loss values of: 0.53mm (Tretyakov), 0.07 mm (RT-1), 0.07 mm (RT-3), 0.25 mm (RT-4), 2.41 mm (automatic DFIR). The large value for the automatic DFIR is probably due to the long (140 cm) length of the extension tube. The probability of adhesion is expected to be low when both precipitating particles and gauge body are sufficiently cold but adhesion can occur at the station during mild conditions.

The current Japanese national gauges RT-3 and RT-4 are heated to a temperature lower than 5°C while the RT-1 may be higher since it is controlled more coarsely. The heating of these gauges may contribute to a large evaporation loss, particularly on the water adhering to the inner gauge walls. Although the maximum adhering capacity is small, i.e. 0.25 mm for the largest model, the effect of the evaporation loss on these gauges have not been fully tested. The ratio of total caught precipitation by RT-4 to that by Tretyakov for days on which solid precipitation is included is 0.92 under the condition that neither wetting loss by measuring nor evaporation loss by exposition are adjusted. This value includes the wind effect. This value would not suggest that this heated automatic gauge is inferior for snow measurement. However, further assessment is still necessary.

Snow accretion on non-heating gauges is a serious problem in this region of Japan. Accretion which had influenced observations occurred 5 days during the period from 13 January through 10 March 1997. In these cases, accretion occurred not only on wind shields, but on the cylinder as it covers the orifice (see Annex 5.G).

5.6 SUMMARY

Although the automation of winter precipitation gauges have been improving with technological advances, these improvements have mainly been in the measurement resolution of the caught precipitation and in the recording sub systems. Many of the systematic errors of precipitation measurement associated with environmental factors are still prevalent with automatic gauges and, in some cases, these errors may be increased.

The results reported above from the countries which included automatics gauges as part of their participation in the WMO solid precipitation measurement intercomparison study suggest the following conclusions and recommendations:

- Automatic gauges based on a tipping bucket type measuring sensor generally require a heating element to melt any solid precipitation prior to measurement. Three countries (Canada, Finland and Germany) which tested these type of gauges have expressed reservations on the use of heated tipping bucket type gauges for winter precipitation measurement due to suspected excessive evaporation loss. Japan reported relatively successful use of heated tipping bucket type gauges for winter precipitation measurement at their Hokuriku intercomparison site but they have indicated that further assessment is necessary.

- Weighing type recording gauges are presently the most practical method for measuring winter precipitation amount at automatic stations. Operational problems of weighing gauges which have been reported include: wet snow or freezing rain sticking to the inside of the orifice of the gauge and not falling into the bucket to be weighed until some time later (adversely affecting accurate timing of the precipitation event); gauges catching blowing snow; differentiation of the type of precipitation; and wind induced oscillation of the weighing mechanism. These problems affect real-time interpretation and use of the data as well as the application of an appropriate procedure to adjust the measurement for systematic errors. Continuing assessment of automatic precipitation gauges, their performance during all weather conditions and refinement of adjustment procedures is required.

- As with manual gauges, the catch efficiency of automatic gauges improves with the use of an appropriate wind shield. Adjustment procedures to adjust for systematic errors should be developed following similar procedures used with manual gauges. A wind sensor to measure the wind speed at the height of the gauge orifice is strongly recommended.

- The use of an acoustic snow depth sensor in conjunction with precipitation gauge measurements can be an effective tool in providing further information on type and timing of precipitation as well as snow accumulation.

It is becoming increasing evident that in any automation program, it is essential the requirements for environmental observations be clearly defined before the establishment of sensor specifications. The data requirements of a meteorologist may not be the same as a climatologist or hydrologist. Too often, instruments are used to infer measurements for which they were not designed. For example, the tipping bucket gauge was designed to provide information on rainfall rates. However, because it provides a high degree of resolution it is frequently used as a present weather sensor for lack of more appropriate devices. It has been demonstrated that the accuracy of tipping bucket gauges is highly variable (Adami and Da Deppo, 1985). Weighing gauges such as the Belfort Gauge, was designed to provide accumulated totals of precipitation, in remote areas, with a manufacturers stated measuring accuracy of +/- 3.8 mm. The addition of an optical encoder to a weighing gauge (Belfort 3000) now provides for resolution of precipitation totals to 0.1 mm. Field tests have shown however, that it is unreasonable to expect this type of gauge configuration to resolve precipitation totals to better than +/- 1.0 mm. The sensitivity of this gauge which is 0.6 mm, also precludes sampling at time intervals of less than one minute. Further, development of processing algorithms to derive precipitation from automatic gauges is still required.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

6.1.1 General

This Intercomparison offered an excellent opportunity for participating Members to assess the accuracy of their National precipitation gauges against an internationally recognized reference (DFIR). Experimental results from 26 sites in 13 countries confirmed that solid precipitation measurements must be adjusted for wetting loss (for volumetric measurements), evaporation loss and for wind induced undercatch before the actual precipitation at ground level can be estimated. Data from all Intercomparison sites confirmed that solid precipitation measurements must be adjusted to account for errors and biases. The results confirmed that wind speed was the most important environmental factor contributing to the systematic undermeasurment of solid precipitation.

Wind-induced undercatch, as well as the evaporation and wetting losses, were determined for all gauges tested and reported either in the combined analysis (multiple sites) or in the Country Reports or in both. The four most widely used non recording gauges for solid precipitation measurement (the Russian Tretyakov Gauge, the Hellmann Gauge, the Canadian Nipher Gauge, and the US NWS 8" standard gauge) were analyzed using the combined international data set collected by the WMO Solid Precipitation Measurement Intercomparison project. This analysis complements the Country Reports.

This study showed that the catch efficiency of different gauges can vary greatly, for example, from ~20% up to ~70% at 6 m/s wind speed. As expected, shielded gauges performed better than unshielded gauges. Standard procedures were used to derive the "catch ratio" of different gauge types in relation to the DFIR. Some countries have already tested, and are applying, algorithms for adjusting precipitation measurements and archived data for climatological and hydrological applications. This report provides the "catch ratio" equations that can be adapted for precipitation adjustment procedures. The benefits of analyzing the "correction factor" and applying those algorithms are also discussed. The effect of averaging wind speed and temperature in different ways is shown to have a significant effect on the "adjusted estimate" of precipitation, especially over short time intervals.

Experiences of countries testing precipitation gauges suitable for measuring solid precipitation at automatic stations are presented. Although wind-induced errors negatively affect gauge catch, as for National non-recording gauges, there are several other problems which contribute to the serious undermeasurement of solid precipitation. Problems with both weighing and heated devices are identified. It is clear that on-going assessment of methods to measure solid precipitation at automatic stations is essential, if accurate and reliable measurements are to be acquired for use for environmental information and prediction purposes including meteorological and hydrological forecasting, climatological analyses, and disaster management.

It is clear that in order to achieve data compatibility when using different gauge types and shielding during all weather conditions, adjustments to the actual measurements will be necessary. Since shielded gauges catch more than their unshielded counterparts, gauges should be shielded either naturally (e.g. forest clearing) or artificially (e.g. Alter, Canadian Nipher type, Tretyakov wind shield) to minimize the adverse effect of wind. However, even when using shielded gauges, adjustment of the measurements will still be necessary. Examples of the effect that adjustments have on archived data, nationally and globally, have been included to show Members that adjusting precipitation for systematic errors and biases is both feasible and essential.

6.1.2 Specific

Specific conclusions are:

1. The Double Fence Intercomparison Reference (DFIR) should be accepted as a secondary reference for the measurement of solid precipitation;

2. Methods to adjust solid precipitation measurements for systematic errors should be tested and implemented on current and archived precipitation data for use by Members[1)]; creation of any

[2)] Generally limited to mean wind speeds at gauge height during precipitation of < 6 m/s for the adjustment algorithms proposed in this report.

national adjusted precipitation archive of historical data must be kept as a separate file from the original archive of observations;

3. Based on national reports, there should be a review of the observation, recording and archiving of "trace" precipitation so that it is treated as a non-zero quantity;

4. There should be a review of the frequency of blowing snow events during precipitation and how precipitation measurement during such events should be treated;

5. Automatic weather stations should also measure wind speed at gauge height;

6. Heated automatic gauges are not recommended for the measurement of solid precipitation, based on results of tests in this Intercomparison.

To apply these adjustment procedures, or others which may be developed, it is recognized that a digital metadata archive which includes detailed site descriptions of gauge exposure, gauge configuration, unique observing procedures, changes in method of observation and data processing algorithms used to create the adjusted archive of precipitation would be extremely valuable.

The Intercomparison also found that equipment provided by manufacturers was not always to specifications. Hence it is further recommended that:

7. Users should calibrate and check the actual specifications of gauges when delivered which also might include the mechanical dimensions, tightness, orifice dimensions, etc. before field installation.

The Organizing Committee recognizes that all possible climatic conditions were not evaluated in the Intercomparison. Hence it is recognized that:

8. Members may validate the recommended Intercomparison adjustment algorithms when applying them to their data, especially for very cold regions not sampled in the Intercomparison.

6.2 RECOMMENDATIONS

6.2.1 Adjustment of precipitation observations

The accuracy of methods of precipitation measurements currently used by the Members does not meet - in any way - the WMO requirements. The application of adjustments for precipitation data sets for systematic errors due to the adverse effect of wind, wetting and evaporation will improve significantly the quality of precipitation time series. Adjustment procedures and reference measurements have been developed and evaluated. The application of these procedures for different types of precipitation gauges tested during the WMO Intercomparison has been assessed in various countries, as summarized in Chapter 7 and contained in the Annex. Members are urged to test the application of these procedures on their precipitation observations and to continue to further develop them.

6.2.2 Establishment of National Precipitation Centres

Considering the increased commercialization of national meteorological and hydrological services (NMHS), the requirement for guaranteeing a continuing high quality of measurements and the increased need for homogeneous data series, it is recommended that National Precipitation Centres be established by countries to facilitate ongoing studies on precipitation measurement such as: new gauges and observational procedures, assessment of gauges for use at automatic stations, quantification of trace precipitation, assessment of blowing snow on measurements, further development and validation of adjustment models under more extreme wind and lower temperature conditions, etc.

National Precipitation Centres would:

a) operate the WMO reference gauge configurations for rain (pit gauge) and snow (DFIR). Installation and operation will follow specifications of the WMO precipitation intercomparisons. A DFIR installation is not required when only rain is observed;

b) operate past, current, and new types of operational precipitation gauges or other methods of observation according to standard operating procedures and evaluate the accuracy and performance against WMO reference standards;

c) make auxiliary meteorological measurements which will allow development and application of precipitation adjustment procedures;

d) record, abstract, and provide quality controlled archived data in a readily acceptable format, preferably digital, of all precipitation intercomparison data; include the metadata describing the site, observing procedures, etc.;

e) agree to operate the evaluation station continuously for a minimum of ten years; and

f) facilitate the conduct of research studies on precipitation measurement.

These centres may provide calibration or verification of precipitation instruments, recommendations on national observation standards, and assessment on the impact of changes in observational methods on the homogeneity of precipitation time series in the region. They may also provide a reference standard for calibrating and validating radar or remote sensing observations of precipitation. Countries may wish to establish more than one centre in order to test gauges and observing procedures in more than one climatic region.

7. DEMONSTRATION AND IMPLEMENTATION OF THE RESULTS

7.1 INTRODUCTION

With results from the WMO Solid Precipitation Measurement Intercomparison, it is now possible to develop more accurate adjustment procedures for adjusting precipitation measurements from the most widely used National gauges. These include the Canadian Nipher shielded snow gauge system, the Russian Tretyakov gauge, the Hellmann gauge, and the US NWS eight inch gauge. The following sections provide examples of case studies which have applied these procedures to adjust precipitation records.

7.2 CANADA: ADJUSTMENT OF PRECIPITATION ARCHIVE FOR THE NORTHWEST TERRITORIES (NWT) *(J.R. Metcalfe, S. Ishida and B.E. Goodison, Climate Research Branch, Atmospheric Environment Service, Downsview, Ontario)*

The inherent nature of snow cover (eg. highly variable temporal and spatial structure related to land cover and terrain and redistribution by wind) and of snowfall (varying density, significant errors in gauge measurements due to wind, wetting and evaporative losses) make snow much more difficult to measure accurately than rainfall. In Canada, the problem of precipitation measurement is even more difficult since snowfall comprises about 30% of the total precipitation, and in northern regions, such as the Northwest Territories (NWT) of Canada, the snowfall component increases to 60 to 70% of the total annual precipitation, with snowfall potentially occurring in every month. The Atmospheric Environment Service (AES) has been actively involved both nationally and internationally in quantifying precipitation measurement errors and developing improved methods for snow measurement and analysis (e.g. Goodison 1978, 1981; Goodison and Louie, 1986; Goodison and Metcalfe, 1989, 1992a; Metcalfe and Goodison, 1993). Recently, the World Meteorological Organization (WMO) has completed the Solid Precipitation Measurement Intercomparison (Goodison et al., 1994) which has allowed Canada and other countries to define the systematic errors resulting from wind, wetting and trace amounts.

The Atmospheric Environment Service (AES) presently collects precipitation data at about 65 stations in the NWT. Water Survey of Canada measurements of the runoff from certain basins in the NWT located near selected AES stations have shown that runoff is greater than is reported falling on the basins. As a result AES, in collaboration with Indian and Northern Affairs Canada (DIAND), Water Resources Division, undertook the development of a adjusted historical precipitation archive for selected NWT stations based on the results from recent national and international precipitation intercomparison studies.

7.2.1 Canadian precipitation measurement methods

Currently in Canada, precipitation is measured at more than 2,400 AES co-operative climate stations, resulting in an average precipitation station density of 25 stations per 100,000 km^2. In the NWT, however, the density is closer to 2 stations per 100,000 km^2. Most stations still use non-recording or manual methods of measurement, with an observer making the measurements. The Type B rain gauge is used to measure rainfall at all of these stations; the Canadian Nipher Shielded Snow Gauge System is the standard AES instrument for measuring fresh snowfall water equivalent at about 300 (30 in NWT) of these stations. The remaining stations estimate snowfall precipitation from ruler measurements of the depth of freshly fallen snow and by assuming the density of fresh snow to be 100 kg m^{-3}. A more complete discussion on the AES network is given in Goodison et al. (1981), Goodison and Louie (1986) and Goodison and Metcalfe (1989).

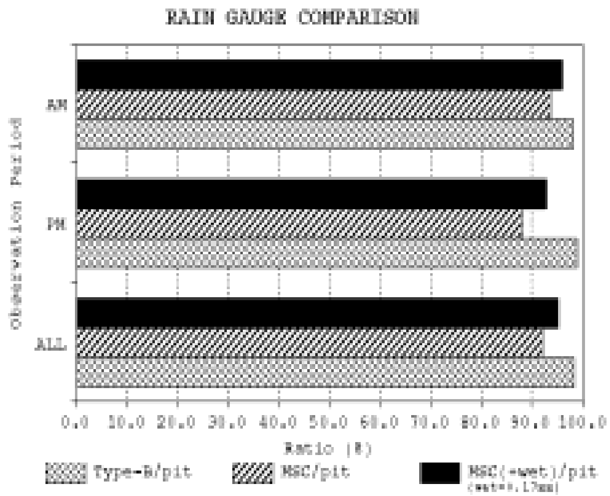
7.2.2 Rainfall measurement errors

The official rain gauge currently in use at AES stations is the Type-B rain gauge. It replaced the MSC rain gauge during the early 1970's. The MSC rain gauge had been used at AES stations since about 1920, and since the establishment of the AES stations in the NWT. Essentially, it was a cylindrical shaped gauge with a removable open top section. The area of the top opening was 64.5 cm^2 (10 square inches) and the orifice was mounted 30.5 cm (12 inches) above the ground surface. The funnel shaped device set into the top section directed water collected into cylindrical containers inside the rain gauge. To make the measurement, the inside containers were removed and their contents poured into a graduated cylinder. Prior to 1965 the gauge and both the inside containers were manufactured from copper; however, around 1965 a design change resulted in the primary inside container being fabricated from soft plastic. The Type-B gauge is 36 cm high, has an orifice area of 100 cm^2 and is mounted with the orifice 40 cm above the ground surface. The gauge has a collecting funnel and outer container made of high strength plastic which minimizes adhesion of rain water on the gauge surface, and a clear plastic inner container, graduated for direct reading. Details on installation, observation and maintenance of both gauges can be found in Instructions to Observers of the

Meteorological Service of Canada, 1931 and Technical Manual, AES Rain Gauge Type B System (TM 04-02-01) 1985.

Goodison and Louie (1986) reported that the difference in gauge catch for the MSC and Type-B rain gauges compared to pit gauge measurements at three test sites in Canada averaged 4% low for the MSC and 1% low for the Type-B. Although these tests provided some basic information on the magnitude of the systematic errors compared to the reference pit gauge for three climatic regions, no interpretation of the differences was attempted. Both gauges are mounted relatively low to the ground to reduce the effect of wind on gauge catch. The Type-B gauge was designed to minimize systematic errors, particularly losses due to adhesion of water to the gauge surface, evaporation between measurement periods and splash out. Ongoing intercomparison of AES rain gauges at the Centre for Atmospheric Research (CARE) near Toronto, Ontario confirms that the systematic difference between the Type-B gauge mounted at 40 cm and the pit gauge is about 2% lower at an open windy site (Figure 7.2.1).

Figure 7.2.1 Comparison of MSC and Type-B Rain Gauges to Pit Gauge at the Centre for Atmospheric Research Experiments during 1993, for morning, afternoon and all observations.



Wetting loss is defined as water subject to evaporation from the surface of the inner walls of the precipitation gauge after a precipitation event and water retained on the walls of the gauge and its containers after its emptying. Laboratory experiments and field investigations by Metcalfe and Routledge (1994) have shown that wetting and evaporative losses for the MSC gauge can be quite large. The average retention loss for the MSC gauge used prior to 1965 (i.e. all copper inserts) is 0.36 mm per observation. The average retention loss for the post 1965 period when the plastic insert was used was only 0.17 mm. Although it is estimated that evaporative losses can also be significant for this gauge, it is difficult to measure and for principal and synoptic stations it is probably small since observations are made at shorter intervals than at climatological stations. Figure 7.2.1 compares the catch of the MSC, with plastic insert, and Type-B rain gauges to the pit gauge at CARE and also shows the effect of adjusting the MSC gauge for wetting loss. Even with adjustment for wetting loss the MSC gauge measured an average of 5% below the pit gauge. CARE is a climate station which makes two observations a day (i.e. AM and PM). There is a noticeable difference in measured MSC totals compared to the pit gauge between morning and afternoon observations. The lower ratio for the PM observation could be due to evaporation but this has not been confirmed by any experimental studies.

7.2.3 Snowfall measurement errors

Prior to 1960, all AES stations relied on snow ruler measurements to estimate fresh snowfall precipitation. Where snow has fallen since the last observation, the snow depth is measured using a ruler, which currently is one metre long and graduated every 0.2 cm. Prior to 1978 the rulers were 36 inches long, with graduations every 0.2 of an inch. Presently, snowfall is read to the nearest 0.2 cm; less than 0.1 cm is recorded as a trace. The snowfall water equivalent is then estimated assuming the density of fresh snow to be 100 kg m^{-3}. Goodison (1981) and Goodison and Metcalfe (1981) showed that this method can be subject to substantial error. For an individual event the error depends on the magnitude of the deviation of the true density from 100 kg m^{-3}, on the representativeness of both the site and the depth measurements and the time of the observation during the storm.

Goodison and Metcalfe (1981) reported on an experiment to measure fresh snowfall water equivalent at selected Canadian stations over a three year period. Seasonal average fresh snowfall densities ranged from 70 to 165 kg m^{-3} across Canada. Recent results from Dease Lake, BC, an evaluation station in the WMO Intercomparison and a study site in the fresh snowfall experiment, produced a mean density of 81 kg m^{-3} which was calculated from comparative reference gauge/ruler ratios over five winter seasons. This value corresponded favourably to average densities of 71 to 84 kg m^{-3} determined in the previous study (Goodison and Metcalfe, 1981). Use of the standard 100 kg m^{-3} mean density at this station results in a 20%

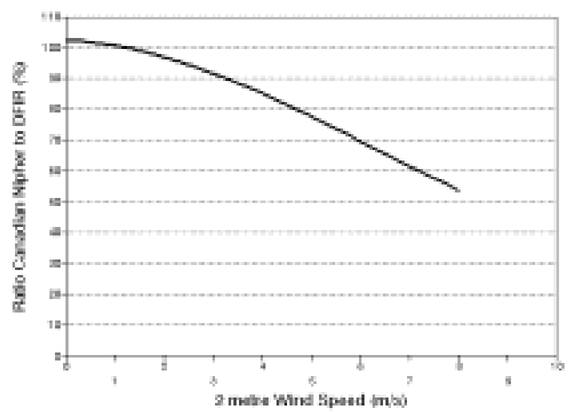
overestimation of winter precipitation. This is quite the opposite from most gauge measurements and from the common perception of most hydrologists.

The Canadian Nipher Shielded Snow Gauge System has been designated as the standard AES instrument for measuring snowfall amount as water equivalent. The accuracy of this snow gauge and others used in Canada was first defined by Goodison (1978). Results from the WMO Intercomparison indicate results similar to those found previously and show the catch of the Canadian Nipher shielded gauge to be almost the same as the WMO reference standard (Goodison and Metcalfe, 1992a).

The Canadian Nipher gauge is a non-recording gauge requiring the melted contents to be poured out into a measuring graduate. There is a wetting loss as the gauge always retains a certain amount of water which cannot be poured out. Previous field experimentation (Goodison, 1978) determined an average wetting loss for the Nipher gauge collector of 0.15 mm $\pm$ 0.02 mm. Recent studies (Goodison and Metcalfe, 1989b), as part of the WMO Intercomparison experiment, confirm these findings, with older collectors showing even greater wetting loss. This is a systematic error which occurs every time the contents are melted and poured out of the gauge.

The measurement of "trace amounts" of precipitation (<0.2 mm) using the Nipher gauge is also a concern. Some Arctic stations have reported over 80% of all precipitation observations as trace amounts. A trace is assigned a value of zero in the AES digital archive. Using techniques similar to those described above for resolving wetting loss, it was determined that a trace could be an actual measurable amount, the value of which lies between 0.0 mm and 0.15 mm. For adjustment purposes a trace reported in any 6-hour period is assigned a value of 0.07 mm. In the Arctic, where there is a high incidence of ice crystals reported, each trace is assigned an even lower value of 0.03 mm. Woo and Steer (1979) suggested similar values for Arctic trace rainfall.

Figure 7.2.3 Gauge catch ratio as a function of wind speed for the Canadian Nipher Shielded Snow Gauge System.



Many investigators have indicated that wind is a major cause of error in precipitation gauge measurements (Goodison et al., 1981). The effect of wind on gauge catch can be reduced by the use of naturally sheltered locations, or by using artificial shielding. Goodison (1978) showed that for most gauges, the mean ratio of gauge catch to "true precipitation" as a function of wind speed decreases exponentially with increasing wind speed. The Canadian Nipher gauge was an exception. The unique design of the Canadian Nipher shield minimizes disturbance of the airflow over the gauge and eliminates updrafts over the orifice. This results in an improved catch by the gauge, for wind speeds up to 7 ms^{-1}, measured at gauge height, relative to other shielded and unshielded gauges (Goodison et al, 1983). Results from the WMO Intercomparison, shown in Figure 7.2.3, confirm Goodison's findings but show the catch efficiency of the Nipher to be generally lower than that reported by Goodison (1978). Considering that two quite different methods of determining "true precipitation" were used and that the WMO Intercomparison involved sites in several different climatic regions, the results from these two studies are quite comparable.

7.2.4 AES precipitation archive adjustments

Information in the AES archive is stored as separate elements. For precipitation, the quality controlled elements which are archived include: each 6 hour precipitation measurement; 24 hour rainfall (i.e. millimeters of rainfall from rain gauge measurement); 24 hour snowfall (i.e. centimeters of fresh snowfall depth from ruler measurement); and, 24 hour precipitation total (i.e. millimeters of water equivalent from either, or both rain gauge and Nipher gauge measurement). Since the type of precipitation for each six hour amount is not identified it is impossible to determine accurately the gauge used to make measurements when mixed precipitation (i.e. rain and snow) occurs. This prevents assigning the exact wetting loss adjustment for gauge type during these events. In cases such as these, if the 24 hour snowfall is not greater than 50% of the 24 hour precipitation total (i.e. rainfall is greater than snowfall) then no adjustment is applied to the 6 hour precipitation values for wetting loss or wind induced error. Six hour trace amounts, for rain and/or snow are identified as trace, but are given an absolute value of zero in the archive when calculating monthly precipitation totals. These events are assigned a value of .07 mm or in the case of Arctic stations .03 mm. No further adjustment is applied to trace events.

For wind speed, the element used is the reported hourly wind speed measured as a two minute average recorded on the hour. From these, the mean wind speed for the 6 hour period corresponding to the time of the precipitation observation is determined. The station wind speed, which is typically located at 10 m above ground surface, is then estimated for a Nipher gauge orifice height of 1.5 m according to the following formulae:

$$U_{hp} = (1 - 0.024\,\mu)\, U_H\, (\log (h / z_o)) \;/\; (\log (H / z_o)) \qquad (7.2.1)$$

where:

- U_{hp} wind speed at the height of the gauge orifice
- h height of gauge orifice above ground, Nipher = 1.5 m
- z_o roughness length: 0.01 m for winter
- H height of the station anemometer above ground, normally 10 m
- U_H wind speed measured at the height H above ground
- μ average vertical angle of obstacles around the gauge

The latter (μ) depends on the exposure of the gauge site and is based on a technique for classifying exposure of a site as recommended by Sevruk (1994) using station descriptions stored in the AES archives.

In order to adjust snow water equivalent (SWE) measurement at AES stations for periods prior to Nipher gauge measurements, a mean density is calculated based on the ratio of adjusted Nipher gauge measurement to snowfall measurement for storms of 5.0 mm or greater during the period of record when snow ruler and gauge measurements were made coincidentally. This calculated density is then used to go back and adjust the 24 hour precipitation total amounts prior to gauge measurement. To adjust AES stations which have only snow ruler measurements (i.e. no Nipher gauge) average regional densities based on the above procedure will be used to interpolate new average station density. Table 7.2.1 shows average snow densities for different climatic regions within the NWT derived by this method.

Table 7.2.1 Mean snowfall densities used to calculate SWE from ruler measurements of snow depth.

High Arctic	108 kg m^{-3}
NWT barrens (east of longitude 110)	145 kg m^{-3}
NWT barrens (west of longitude 110)	137 kg m^{-3}
Mackenzie (delta area)	106 kg m^{-3}
Mackenzie (Norman Wells to Great Slave Lake)	112 kg m^{-3}
Baffin Island	125 kg m^{-3}

7.2.5 Summary

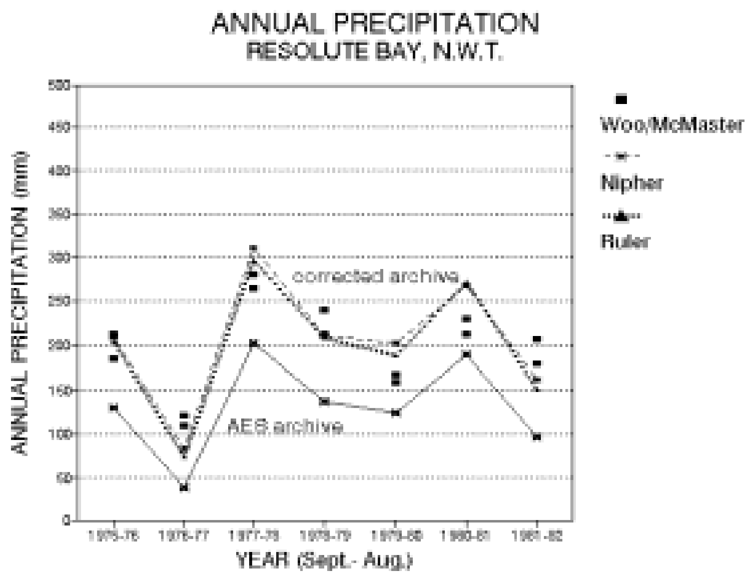
Figure 7.2.3 compares the present archived annual total precipitation measured at Resolute Bay, NWT with the adjusted total obtained using the above method. Plotted along with these are adjusted annual precipitation amounts based on special snow surveys reported by Woo et al. (1983). Both the adjusted annual precipitation and the snow course totals exhibit good agreement.

Most important, however, is that both methods indicate that actual annual precipitation is 50 - 100% greater than measured at this station. Similar increases resulted when precipitation adjustments were made at other Arctic stations. Increases in adjusted annual precipitation totals were less dramatic for other NWT stations located south of 65^{o} N. For example, at Yellowknife adjustments increased average annual precipitation by 26% and at Norman Wells by 19%. Both these sites are more sheltered than Resolute and the effect of wind on gauge catch is less.

The primary reason for the larger differences between measured and adjusted precipitation at High Arctic stations is the number of traces recorded annually at these locations. At Resolute Bay the average number of traces recorded each year has continued to increase from around 300 in 1950 to well over 700 in 1993. A large number of these trace observations are a result of the occurrence of ice crystals. There is some speculation that this trend in ice crystal occurrence may be directly or indirectly related to a systematic increase in Arctic haze and to changes in the Arctic winter boundary layer (Bradley et al., 1993).

The major source of water in NWT basins is precipitation. To estimate flows and to regulate the construction of holding ponds, accurate input values of all environmental parameters to the water balance equation must be available to users in both industry and government. The adjustment of six hourly archived precipitation measurements for known systematic errors will provide significantly improved estimates of actual precipitation than are currently available. It is anticipated that anomalies currently existing between various hydrologic data sets will be minimized after adjustment of the precipitation archive.

Figure 7.2.3 Comparison of AES archived annual total precipitation, adjusted annual total precipitation from gauge and ruler measurements and annual precipitation estimates (range) from special snow survey data (Woo et al., 1983) at Resolute Bay, NWT.



7.3 DENMARK: AN OPERATIONAL SYSTEM FOR CORRECTING PRECIPITATION FOR THE AERODYNAMIC EFFECT *(Danish Meteorological Institute)*

During the past years models have been developed at DMI for correcting all types of precipitation for the aerodynamic effect on point precipitation measurements. The increasing interest in monitoring groundwater researches in Denmark has motivated the development of a system that can estimate corrected values of measured precipitation including accuracy on the estimate. Recently, correction models have been implemented in a system that can correct precipitation measured at all rain gauge stations in Denmark operationally as well as for old data.

7.3.1 Required variables

For the correction to be carried out averages during precipitation of the following variables are required: (1) wind speed and precipitation intensity for liquid precipitation (Allerup and Madsen, 1980, 1986), wind speed and temperature for solid precipitation, and wind speed, temperature and precipitation intensity for mixed precipitation (Allerup, Madsen and Vejen, 1997). In practice, to estimate these averages as accurate as possible it is necessary to know various meteorological and station describing variables: (1) duration of precipitation to estimate precipitation intensity, (2) wind speed that normally is measured at 10m so it has to be reduced to gauge level, (3) air temperature, (4) snow depth, (5) precipitation type and time of precipitation to apply the appropriate correction model and to estimate the snow percentage for the event, (6) wind direction and height of obstacles surrounding the gauge for estimation of shelter effect. Also, the losses due to wetting and evaporation loss must be known. All these variables are measured or known as tabular values. It is important that the temporal resolution of the climatological variables are as good as possible at an adequately number of stations and that the shelter is well described at all rain gauge stations.

7.3.2 Basic station network

At present the variables mentioned above are not available at one single type of station in Denmark; some are measured at synoptic stations every 3 hours while others are measured hourly at automatical stations. This imply practical difficulties, which have not been solved fully in this preliminary version of the system. At least in the principle, all required variables should be measured at all rain gauge stations, but naturally this is not met. In the present Danish station network, all required variables except precipitation type and snow depth are recorded hourly at approximately 15 automatical climatic stations. At 50 synoptic stations the most of the variables are measured every 3-hour but duration of precipitation is not known.

In the correction system Denmark is divided up into small regions each having a basic station in the center. Automatic stations have been chosen as basic stations because most of the required variables have been measured continuously there for the last 10 years. The variables not measured at these stations have to be taken from the closest non-basic station, normally a synoptic station. The basic stations, evenly distributed all over the country, are assumed representative of certain hydrographic regions, and these are divided by the Thiessen polygon technique giving the basic station to be placed in the centre (Figure 7.3.1). The values measured by a basic station are then extrapolated to all rain gauge stations within the region. The precipitation type is taken from a nearby synoptic station. The regionalization works quite well primarily because Denmark is a flat country with the highest “mountain” reaching 173 m, but on a smaller scale the very variable coastline can influence the wind speed and thereby the correction pattern in a quite complex manner.

There are implicit problems in this scheme. For example, it is not an easy task to handle a situation where the basic station was complete dry but precipitation occurred at some manual precipitation stations within the region. This is normal in convective weather conditions. Thus the representativeness of the correction values applied to the rain gauge stations is very sensitive to the temporal and spatial resolution of those stations that measures the climatological variables. It is planned that future versions of the system shall use spatially and temporally interpolated values of the variables.

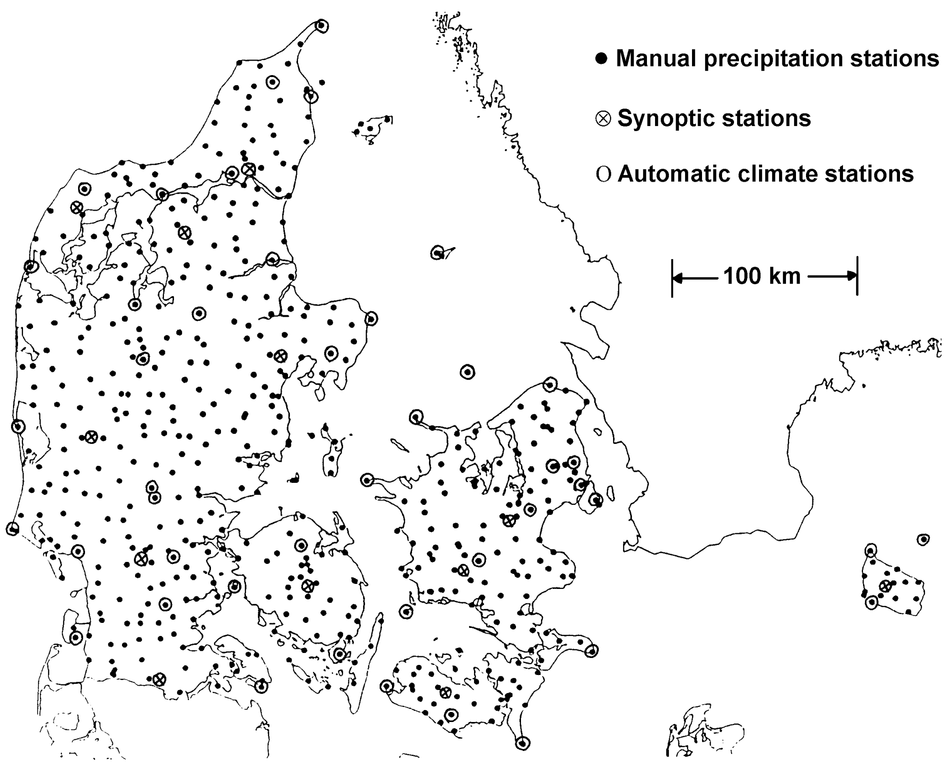


Figure 7.3.1 The station network; basic stations (automatic climate stations), synoptic and manual precipitation stations.

The basic stations must be stable through time for continuity reasons but even for good stations periods with data interruptions can happen. Data with satisfactory temporal resolution and an adequate measuring program have only existed for a rather restricted period of time; while some of the 6-hour synoptic stations have existed for at least 30 years ore more, 3 hourly measurements just started in the mid-eighties, and the automatic climatic stations have only existed for 8-10 years. This results in a homogeneity break in the time series when shifting from one basic station to another, so it is impossible to divide Denmark into hydrographic regions without introducing errors in the system. Changes in the station network influence the representativity of the regions and it might be very complicated to compare correction estimates for different periods. Because the temporal resolution of older data is poorer than the newer ones the accuracy of the correction estimate decreases back in time.

7.3.3 Correcting daily precipitation

All precipitation measurements within each region are corrected by using the variables from the basic station. The correction is carried out by running through five steps; (1) quality control, (2) control of basic stations, e.g. identifying interrupted stations and finding good substitutes, (3) estimating storm averages of all required variables at each one of the basic stations, wetting loss is given by tabular values, (4) allocating a basic station to each one of the precipitation stations, (5) correcting measured precipitation using variables from the basic stations and taking the local shelter conditions into account.

Finally, the accuracy of the corrections is evaluated. Inaccuracies are due to; (1) temporal and spatial resolution of measurements, i.e. representativity of the measurements for the conditions during precipitation, (2) measuring inaccuracies, (3) inaccuracy on the correction itself, by 1×the standard deviation the inaccuracy of the correction factor is ±8% on the model for solid precipitation and ±6% on the liquid model, and (4) estimation methods. The accuracy is linked to the duration of an event as well as the spatial and temporal variations of temperature, wind speed and intensity of the precipitation system (the synoptic situation), i.e. on the one side how good the measurements represents the conditions during precipitation and on the other how good a basic station represents the spatial variations within the hydrographic upland.

7.3.4 Examples

Table 7.3.1 and Figure 7.3.2 show the result of corrections of precipitation for the aerodynamic effect for the period 1979-1995, for selected years and on average at one manual precipitation station. A nearby synoptic station has been used as basic station. As a result of the correction the annual amount of precipitation was increased by about 153 mm or 23.3%. The main reason was that some quite large corrections on events occurred during 6-7 snow rich winters. For example, compare the very snow rich winter 1979 with the record mild winter 1990; the corrections were very large in January-February 1979 where 71-72% of the precipitation was snow. Thus the changes in the precipitation climate in Denmark are largest in the winter season, 68.8% more precipitation in February but only 10.5% more in august. The interannual variations are largest in the winter months but are much lesser in the summer. The combination "snow, large wind speeds and low temperatures" leads to large corrections, while large rain intensity and low wind speed only rise the liquid precipitation amount by a small figure. So changes in temperature normals will have large impact on measured precipitation amount and lead to a significant fictive change in the precipitation climate.

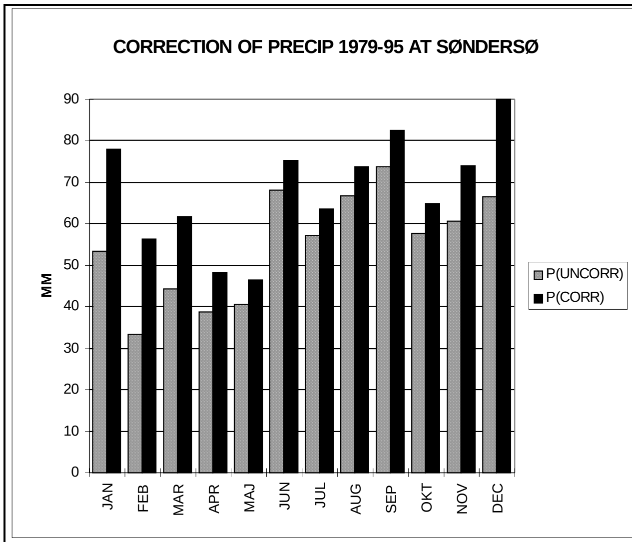


Figure 7.3.2 Correction of precipitation at Søndersø

Table 7.3.1 Measured (P_m) and corrected precipitation amount (P_{corr}), percentage change (Δ%), average temperature (T) and average wind speed during precipitation (V_g), and snow percentage pcst at the manual rain gauge station Soendersoe (WMO no 30240) for selected years, and averages for the period 1979-1995.

Year	par	J	F	M	A	M	J	J	A	S	O	N	D	Annual
1979	P_m	32.0	25.1	74.2	40.1	58.8	30.0	48.9	65.0	25.1	8.6	94.5	128.5	630.8
	P_{corr}	61.3	57.3	128.1	48.9	68.9	34.1	57.7	72.1	29.7	10.1	112.3	190.6	871.1
	Δ%	91.7	128.4	72.6	21.9	17.2	13.6	18.1	10.9	18.1	17.6	18.8	48.3	38.1
	T	-2.1	-2.2	1.7	4.6	9.0	14.0	13.7	13.2	12.2	9.7	4.5	3.2	.
	v_g	3.8	3.8	4.4	3.5	3.3	2.3	3.8	3.9	4.2	4.3	4.7	4.4	.
	pcts	0.72	0.71	0.35	0.01	0.05	0.00	0.00	0.00	0.00	0.00	0.02	0.29	.
1990	P_m	46.5	34.6	38.5	45.5	50.0	51.3	44.6	38.9	116.7	75.5	56.9	34.5	633.5
	P_{korr}	55.0	41.7	49.5	52.4	55.6	57.1	49.8	44.3	127.7	83.6	67.6	43.7	727.9
	Δ%	18.3	20.6	28.5	15.1	11.2	11.2	11.7	13.9	9.4	10.8	18.8	26.7	14.9
	T	5.2	5.9	6.2	6.9	11.1	15.8	15.6	16.3	11.6	10.9	6.0	2.8	.
	v_g	4.4	5.5	5.6	4.3	2.3	1.8	3.5	2.7	3.4	4.3	2.7	3.7	.
	pcts	0.00	0.03	0.04	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.19	.
Average 1979-1995	P_m	53.3	33.4	44.4	38.8	40.7	68.2	57.1	66.7	73.6	57.6	60.7	66.6	659.1
	P_{korr}	78.0	56.3	61.6	48.3	46.4	75.3	63.6	73.7	82.6	65.0	74.1	89.9	812.4
	Δ%	46.3	68.8	39.0	24.6	14.0	10.5	11.4	10.5	12.3	12.9	22.0	35.1	23.3

It will be interesting to study a corrected precipitation climatology when long data records have been corrected. If we suppose that the annual precipitation normal generally will increase by 153 mm Denmark will get about 6400 mio. m^3 more water than is believed. Obviously, this would be very important for various strategies and considerations on water balance and ground water resources. Because of the often very large corrections in winter months correction of measured precipitation is necessary for a more accurate estimation of snow package water equivalence, so that runoff in rivers could be watched and, if necessary, flood warnings be issued better than now when snowmelt begins. Also, use of a corrected precipitation climatology will have large and unpredictable impact on climate prediction models. Increasing air temperature would lead to a fictive increase in precipitation amount. Furthermore, because amount of snowfall among other things is linked to air temperature, snowmelt and albedo and thereby influence the energy balance at the Earth's surface and of the atmosphere, climate prediction studies should be revised.

7.3.5 Discussion and concluding remarks

In this preliminary version of an operational precipitation correction system, the estimations are based on some simplifications; (1) at present, it is impossible to find stations in the network that measure all required variables for the correction to be carried out, (2) the temporal resolution of some meteorological measurements is relatively poor, and (3) the assumption that the basic stations are representative of large areas results in inaccuracies despite the rather homogeneous topography. Also, it has been assumed that daily averages of the essential climatological variables are temporarily representative for all the manual rain gauge stations within the hydrographic region they belong. For example, the different friction over land and sea areas can infer substantial regional wind speed differences and "damage" the corrections.

Thus the present system is only a rough approach, but future improvements are planned in order to get more representative and accurate estimates. Improvements could be such like; (1) install supplementary equipment at the basic stations to measure all required variables, (2) use weather radar data to estimate duration of precipitation at all precipitation stations as to improve the rain intensity estimate, (3) spatial interpolation of point measurements of wind speed, temperature and rain intensity, (4) use weather radar data to indicate the time the precipitation fell at the precipitation stations which should result in more representative wind speed and temperature averages during precipitation, (5) use of Dual Polarization radar data to indicate the precipitation type at the precipitation stations have great potentials, but problems with calibration and various sources of error have to be reduced.

7.4 GERMANY: APPLICATION OF PRECIPITATION CORRECTION

(*Th. Günther, Deutscher Wetterdienst, Business Unit Hydrometeorology, Division of Hydrometeorological Development and Application, Berlin)*

Within the Federal Republic of Germany the Business Unit Hydrometeorology of the Deutscher Wetterdienst is supplying corrected precipitation totals to a constantly increasing number of water management-related institutions. The basis is a correction procedure which takes account of wind-related errors and the losses caused by evaporation and wetting. Due to the lack of routine wind measurements at the precipitation stations the wind-related error is calculated by estimating the wind exposure of the station, categorized as exposed to well-sheltered, and by considering the type of precipitation. The general form of the equation used for these applications is:

$$P_{corr} = P_{\text{ measured}} + \Delta P; \quad DP = b{*}P^{e} \qquad (7.4.1)$$

The coefficients b and ε, represent the wind exposure for the site and the type of precipitation. Precipitation measurements are corrected on the basis of daily values, long-term mean values according to mean monthly and annual errors in per cent. For average station sites in the Federal Republic of Germany the resulting mean annual error is shown in Figure 7.4.1.

Corrected precipitation totals are mainly used for:

- long-term management of water resources
- framework planning in connection with water management
- management planning for lakes and reservoirs
- adjustment of navigable waterways.

A specific example of applying corrected data is the study of the hydrometeorological water budget for the extension of the Havel-Oder waterway to better supply Berlin. Figure 7.4.2 shows the mean evaporation totals and the measured and corrected precipitation totals. They demonstrate the different budgets (P-E) resulting by applying measured and corrected precipitation totals. It is obvious that the precipitation totals obtained using the Hellmann gauge (German National Standard) must to be corrected for water-management/water balance studies such as this.

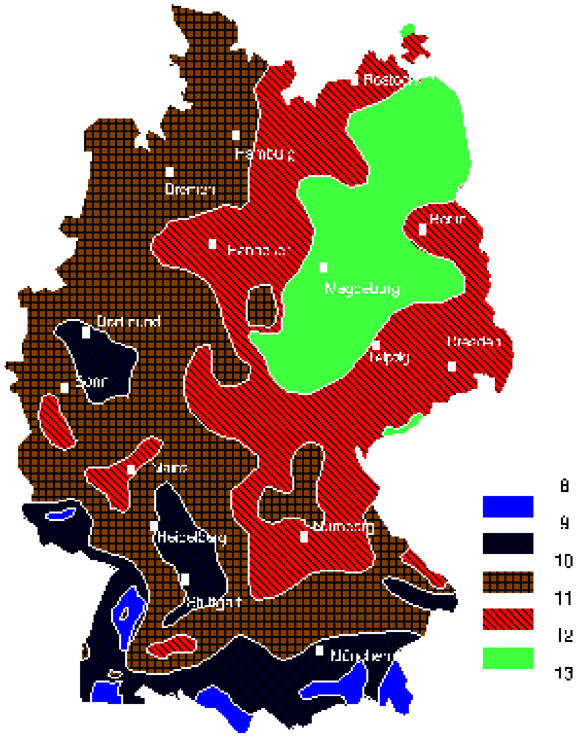
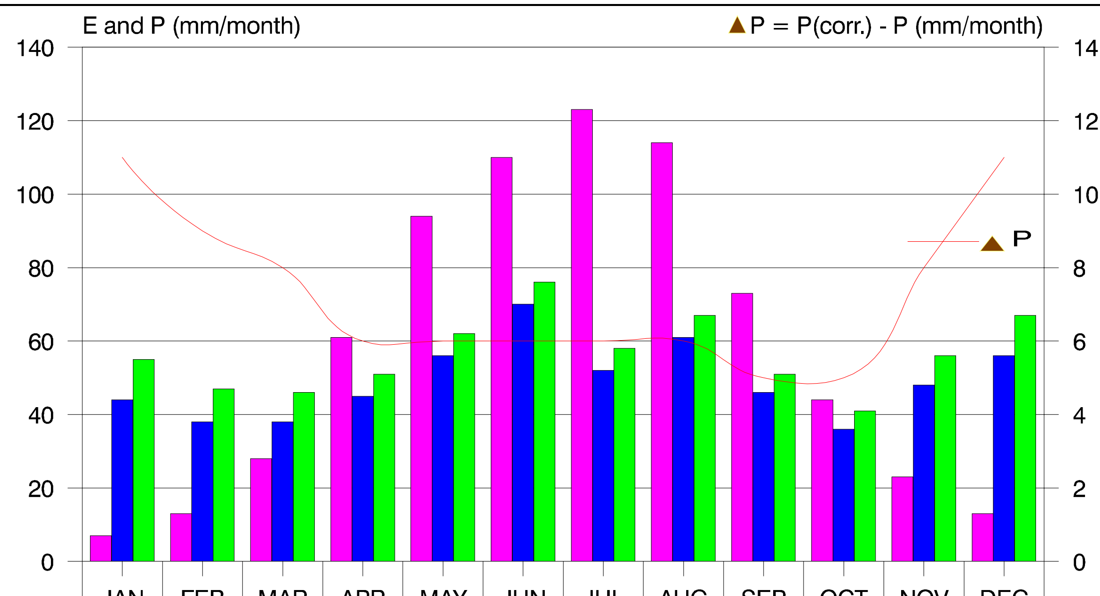


Figure 7.4.1 Mean correction (%) of the average annual precipitation total (1961/90) (for moderate wind-sheltered sizes)



	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
E	7	13	28	61	94	110	123	114	73	44	23	13
P	44	38	38	45	56	70	52	61	46	36	48	56
P(corr.)	55	47	46	51	62	76	58	67	51	41	56	67

Figure 7.4.2 Mean Monthly Evaporation (E) and Precipitation (P) of Havel-Oder Canal

7.5 NORWAY: OPERATIONAL CORRECTION OF MEASURED PRECIPITATION

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Two types of stations («Evaluation» and «Basic» stations, cf. Chapter 2.2.3) were suggested for the Intercomparison experiments. The Nordic countries co-operated in the operation of an Evaluation station in Jokioinen, Finland. As the weather conditions in the Norwegian Arctic areas are quite different from those in Jokioinen, the Norwegian Meteorological Institute established a «Basic station» in Ny-Ålesund, Spitsbergen (78 56N, 11 56E, 8 m a.s.l.) in order to make comparative analyses. At this Basic station, parallel measurements with a Norwegian (DNMI) gauge and a Tretyakov gauge were performed twice a day during the period July 1993 - August 1995. Hourly values of precipitation amount, temperature, wind speed (at gauge level), wind direction and humidity were recorded at an automatic weather station at the same site as the manual gauges. A detailed discussion of the results from the «Basic station» in Ny-Ålesund is presented by Hanssen-Bauer et al. (1996).

7.5.1 Aerodynamic correction factors for the Tretyakov gauge

As the Tretyakov gauge is to be used as a reference at Basic stations, a crucial issue is whether there exists a «Universal» method for estimating true precipitation based on this gauge. The shielded Tretyakov gauge was included in all WMO Evaluation stations (Chapter 2.2.4).

For operational purposes, the «true precipitation» $\mathbf{P_C}$ may be expressed as:

$$P_C = K \cdot (P_m + \Delta P_W + \Delta P_E), \qquad (7.5.1)$$

where **K** is the correction factor due to aerodynamic effects, $\mathbf{P_m}$ measured precipitation , $\Delta\mathbf{P_W}$ precipitation lost by wetting, and $\Delta\mathbf{P_E}$ precipitation lost by evaporation from the gauge.

By using the compiled Intercomparison dataset, (Yang, et al, 1995) developed a simplified equation for the daily gauge catch ratio (R) as a function of wind speed at gauge height (v_g). Assuming that the DFIR (adjusted to BUSH, cfr. Chapter 2.4.4) is representing the «true» precipitation, a simple correction factor based on the catch ratio for the compiled WMO dataset may thus be written as:

$$K_{TRET} = 1/R = 100/[\exp(4.605-0.06 \cdot v_g^{1.4})] \qquad (7.5.2)$$

Based on results from the Evaluation station in Finland, the solid precipitation correction factor for the Tretyakov gauge was found to be a function of wind speed (v_g) and temperature (T_g) (cf. Table 5.3.1):

$$K_{TRET} = \exp\{-0.04816 + 0.13383 \cdot v_g + 0.009064 \cdot T_g - 0.005147 \cdot v_g \cdot T_g\} \qquad (7.5.3)$$

Based on Russian data, Golubev & Bogdanova (1996) presented the following equation for snowfall:

$$K_{TRET} = 1 + \{0.35 - 0.25 \cdot \exp(0.045 \cdot T_g)\} \cdot v_g^{1.2} \qquad (7.5.4)$$

Figure 7.5.1 shows that the temperature-dependent correction models based on data from Finland (Equation 7.5.3) and Russia (Equation 7.5.4) are giving quite similar results for wind speeds below 5 m/s. For two temperature-independent models (based on resp. data from Canada (Goodison, 1977) and the compiled WMO Intercomparison dataset (Equation 7.5.2), Figure 7.5.1 indicates a good agreement between all models for temperatures around ^{0}C. However, the two temperature-independent models seem to underestimate the correction factor for precipitation falling at low temperatures. The reason is probably that the temperature-independent models are dominated by episodes with snowfall around 0 ^{o}C.

7.5.2 Estimating true precipitation at a Basic station

Both a Norwegian gauge and a Tretyakov gauge were included in the Evaluation station in Jokioinen, and coefficients for the correction factors are presented in Table 5.3.1. However it turned out that the catch ratio between the Norwegian and Tretyakov gauges, as a function of wind speed and temperature, was significantly different for Ny-Ålesund and Jokioinen. This may be due to micrometeorological wind gradients in the Jokioinen field, or that the correction models are different for different climatic regions (Hanssen-Bauer et al.,1996).

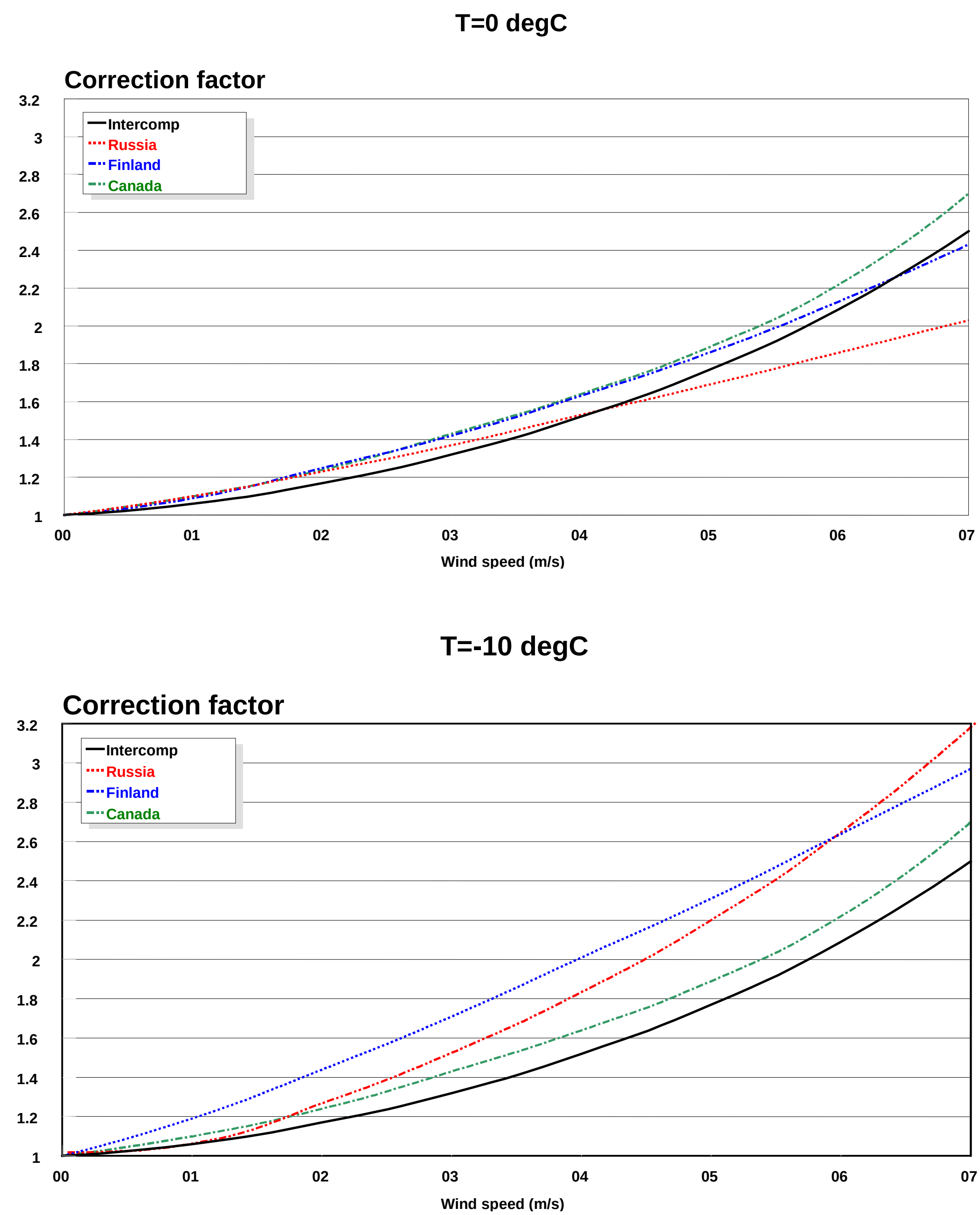


Figure 7.5.1 Correction factors for solid precipitation measured in shielded Tretyakov gauge

Based on the parallel measurements in Ny-Ålesund, Hanssen-Bauer et al (1996) concluded that the ratio between precipitation measured in the Tretyakov gauge and the Norwegian gauge could be described by:

for liquid precipitation (I is intensity in mm/h)

$$k_l = P_{TR} / P_{NOR} = \exp\{ 0.0096 \cdot v_g + 0.0060 \cdot \ln(I) \cdot v_g \} \qquad (7.5.5)$$

for solid precipitation

$$k_s = P_{TR} / P_{NOR} = \exp\{ 0.0150 \cdot v_g + 0.0020 \cdot T_g \cdot v_g \} \qquad (7.5.6)$$

for sleet and mixed precipitation, the ratio was described by:

$$k_m = (r_l \cdot k_l + r_s \cdot k_s) / (r_l + r_s) \qquad (7.5.7)$$

where r_l and r_s are the amounts of precipitation falling as rain and snow respectively.

For a Basic station, the correction factor for the Norwegian gauge may accordingly be estimated by:

$$K_{NOR} = P_{true}/P_{NOR} = P_{true}/P_{TRET} \cdot P_{TRET}/P_{NOR} = K_{TRET} \cdot k_i \qquad (7.5.8)$$

For solid precipitation, K_{TRET} is given by Equations 7.5.2, 7.5.3 or 7.5.4, and k_i by Equation 7.5.6. By combining Equations 7.5.3 and 7.5.6, the correction factor for the Norwegian gauge based on the «Basic station» concept is:

$$K_{NOR} = \exp\{-0.04816+0.14883 \cdot v_g+0.009064 \cdot T_g -0.007147 \cdot v_g \cdot T_g\} \qquad (7.5.9)$$

By using the Jokioinen coefficients for the Norwegian gauge (cf. Table 5.3.1), the correction factor is:

$$K_{NOR} = \exp\{-0.12159 + 0.18546 \cdot vg + 0.006918 \cdot Tg - 0.005254 \cdot vg \cdot Tg\} \quad (7.5.10)$$

By using Equation 9, the correction factor for solid precipitation in Ny-Ålesund during the period 1993-95 was estimated to 1.74. By combining Equations 7.5.4 and 7.6.6 the factor is 1.67. By using the Jokioinen coefficients for the Norwegian gauge (Equation 7.5.10), the correction factor was estimated to 1.84.

7.5.3 Measured and true precipitation in Ny-Ålesund, Spitsbergen

For solid precipitation, the «true» precipitation amount (P_C) was estimated by Equations 7.5.1 and 7.5.9. The liquid precipitation was corrected by a model including wind speed and rain intensity (Førland et al.,1996). Table 7.5.1 gives the total measured (ΣP_{nor}) and estimated true precipitation for different precipitation types. ΣP_{NOR} is precipitation corrected for wetting (ΔP_w) and evaporation (ΔP_E), and ΣP_C precipitation also corrected for aerodynamic effects. For solid precipitation, the estimated true precipitation is almost 190% of the measured, while the similar value for liquid precipitation is 115%.

Table 7.5.1 Observed and true precipitation in Ny-Ålesund during the period July 93 - Aug 95. (See text)

PRECIPITATION TYPE	N	ΣP_{nor} mm	ΣP_{NOR} mm	ΣP_C mm	$\Sigma PC / \Sigma Pnor$	$\Sigma PC / \Sigma PNOR$
LIQUID	148	325.9	348.1	375.4	1.15	1.08
SLEET/MIXED	64	276.9	286.5	400.2	1.45	1.40
SOLID	249	295.6	320.5	555.4	1.88	1.73
ALL	461	898.4	955.1	1331.0	1.48	1.39

In Ny-Ålesund, precipitation as rain or snow may occur in each month of the year. The monthly totals (Figure 7.5.2) of measured and corrected («true») precipitation, emphasise the large differences in corrections during summer respectively winter months. The seasonal ratios between true and measured precipitation varies from 1.26 for the summer season (Jun-Aug) to 1.70 for the winter season (Dec-Feb). If it is supposed that the seasonal ratios for the period 1993-95 are typical also for the normal period 1961-1990, the true normal annual precipitation would be 550 mm, i.e. 50% higher than the official uncorrected value.

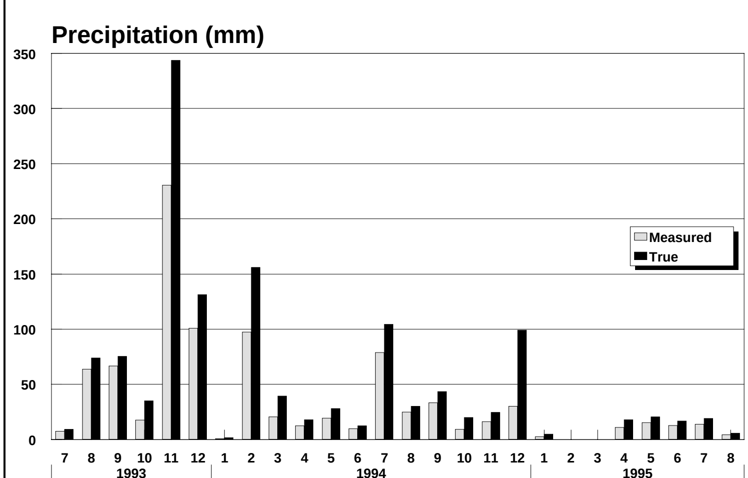


Figure 7.5.2 Monthly values of measured and «true» precipitation in Ny-Ålesund. (Note that values for February and March 1995 are missing).

7.5.4 Virtual changes in precipitation caused by temperature changes

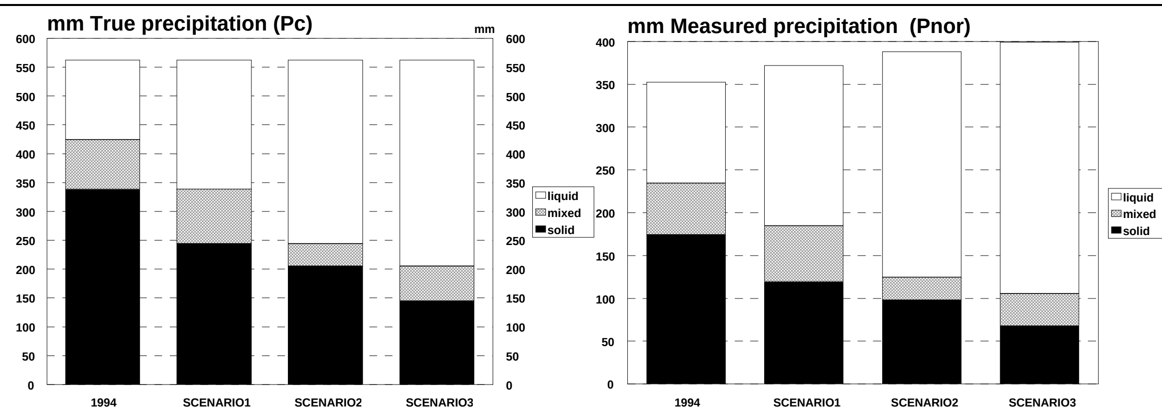
The correction factors for solid precipitation decrease when the temperature increases (cf. Equations 7.5.3, 7.5.4, 7.5.9 and 7.5.8). Further the correction factors for rain are smaller than for snow. i.e. if the temperature generally was increasing, such that the percentage of the annual precipitation falling as rain increased, the measured precipitation would increase even if the true precipitation was unchanged (Førland, 1994). Based on the results from the Basic station in Ny-Ålesund, it is possible to quantify this «virtual precipitation increase» by making some assumptions concerning the connection between temperature and precipitation type, and by using some simple temperature scenarios.

Based upon the latest IPCC scenarios (Kattenberg et al.,1996) three scenarios (+2, +4 and +6 ^{o}C) were suggested for the Norwegian Arctic areas. The same temperature increase was suggested for day and night, and it was assumed that the true precipitation and the wind speed during precipitation events are unchanged. As the annual values for 1994 were close to the 1961-90 normals, this year was used as model year. Figure 7.5.3a shows the 1994 true precipitation subdivided into solid, mixed and liquid precipitation for 1994 and for the three scenarios. The 1994 percentage of solid precipitation was 60, but a temperature increase of 6 ^{o}C would reduce it to 26. Likewise, the percentage of liquid precipitation would increase from 25 to 64.

Knowing the true precipitation and the precipitation type, Equation 7.5.9 in combination with estimates of wetting and evaporation losses, made it possible to estimate the precipitation which would have been measured during the different scenarios (Figure 7.5.3b). Totally the «measured» annual precipitation increases from the 1994 situation to scenario 3 (+6 ^{o}C) by almost 50 mm (13%), even if the true precipitation is constant.

The fictive increase in measured precipitation is partly due to the transition from snow via sleet and mixed precipitation to rain, but an additional effect is caused by different aerodynamic properties of snowflakes formed at different temperatures (Hanssen-Bauer et al.,1996).

The virtual addition to the annual precipitation will increase with increasing scenario temperature until all precipitation is liquid. The virtual addition for the whole year for scenarios 1, 2 and 3 are 6, 10 and 13% respectively. This increase, which is caused by changes in measuring errors alone, will be measured in addition to an eventual real increase in the precipitation which e.g. may be the consequence of the intensified hydrological cycle in a warmer atmosphere. According to IPCC-95 (Kattenberg et al., 1996), the expected **real** precipitation increase in the Norwegian Arctic connected to a doubling of the atmospheric CO_2 would be of the same magnitude as the expected ***virtual*** increase because of reduced measuring errors.



(a) **(b)**

Figure 7.5.3 (a): «True» (P_C); and (b): «Measured» (P_{nor}) precipitation distributed as solid, mixed and liquid precipitation for the year 1994 and for three temperature scenarios.

7.6 APPLICATIONS OF THE WIND-BIAS ASSESSMENTS TO PRECIPITATION DATA IN USA AND GLOBAL ARCHIVES

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While it has long been recognized that gauge-induced biases are significant and adversely affect precipitation measurements, these biases were largely ignored until recently. Research which is aimed at quantifying this bias, such as the WMO Solid Precipitation Measurement Intercomparison Project, has provided the necessary information by which this bias can be estimated and removed from precipitation data.

The results presented here have used the results of the WMO Solid Precipitation Measurement Intercomparison Project, or similar previous studies, to estimate the magnitude of the gauge-induced bias from precipitation time-series and/or averages. These bias-adjusted estimates subsequently have been used to provide more accurate precipitation climatologies which, for example, have been used as inputs to hydrologic models or evaluation fields for general circulation model simulations.

7.6.1 Global Precipitation Climatologies

Using long-term mean monthly precipitation measured at 24,635 independent terrestrial stations, a global climatology of precipitation at a 0.5 degree of latitude by 0.5 degree of longitude resolution was compiled by Legates (1987) and Legates and Willmott (1990). To assess the bias associated with precipitation gauge measurement resulting from the effect of the wind and wetting losses on the walls of the gauge, data from 17,986 terrestrial air temperature and 733 terrestrial wind speed stations were compiled.

Results indicated that mean annual terrestrial precipitation is 820 mm -- a value that is about 11 percent higher than other estimates that have been made in the previous twenty-five years. This increased precipitation results directly from the bias in the precipitation gauge measurement process. Zonally, precipitation estimates were greatly increased in the upper mid-and high latitudes but they were increased in the lower latitudes as well. Snowfall biases account for the underestimates in the upper mid- and high latitudes while enhanced spatial coverage increases precipitation estimates from South America, in particular.

The global precipitation climatology compiled by Legates (1987) and Legates and Willmott (1990) have been used in a variety of applications. These include validating general circulation model simulations of the present-day climate, evaluating the global hydrologic cycle, and providing a baseline estimate of precipitation for climate change studies. Future re-evaluations of this climatology will most certainly benefit from the more accurate assessments of wind-induced biases in precipitation gauge measurement that have resulted from the WMO Solid Precipitation Gauge Measurement Intercomparison.

7.6.2 Regional Precipitation Climatologies

Gauge-induced biases in monthly precipitation were estimated and removed from the 38-year time-series of precipitation (1950 through 1987) for 1,818 stations across the continental United States (Legates and DeLiberty, 1993a; 1993b). For this assessment, wind-induced biases and wetting losses were considered. These bias-adjusted estimates were obtained using site-specific information including wind speed, shelter-height air temperature, gauge orifice height, and gauge sheltering information. Differences in snowfall and rainfall biases are explicitly considered.

The largest biases in the measurement of winter precipitation occur over New England, Western New York and the Allegheny Mountains, the Pacific Northwest, Northern California, along the Colorado front range, the Bitterroots, and northwestern Wyoming (biases that exceed 18 mm per month). These patterns are expected since these regions experience either large winter snowfalls or considerable winter rainfalls. Biases decrease as winter snowfall and/or total precipitation decreases.

Maps of the bias in measured winter precipitation expressed as a percentage of the bias-adjusted precipitation show strikingly the pronounced effect of the wind on snowfall. These biases are particularly high because of the standard use of an unshielded precipitation gauge. In the central and eastern United States, there is a strong meridional gradient with increasing percentages toward the north. Largest percent errors exceed 30 percent and occur in the Northern Great Plains where wind speeds are high and snowfall predominates. Percent errors are lowest along the sunbelt states and the Pacific Coast owing to the decreased frequency of snowfall.

Summer biases are considerably lower than those of winter due to the lack of snowfall. Biases are less than 7 mm per month for the entire continental United States while percent biases are generally less than 6 percent. Percent biases are often high in the desert areas of California and Nevada but these represent small adjustments to very small precipitation totals.

These results indicate that precipitation gauge measurement biases are not trivial and must be considered if accurate and reliable precipitation estimates are to be obtained. In addition, these biases vary by season and can exhibit considerable intra-annual variability. Serious detrimental impacts therefore exist in studies which use unadjusted, biased data for monitoring climate change, environmental impact assessments, hydrological modeling of streamflow and runoff, and evaluations of snow cover including amount and spatial extent.

7.6.3 Local-Scale Hydrological Modeling

In a more recent study (Legates and Conly, 1995), the impact of precipitation measurement biases (both wind and wetting effects) on the calibration of hydrologic models was assessed. A seven-year time-series of precipitation for the Little Salt Creek River basin in eastern Nebraska was obtained and a hydrologic model was developed to represent the basin. Soils and land use/land cover data were obtained from the Nebraska Natural Resources Commission and county soil surveys. The hydrologic model used was the Simulator for Water Resources in Rural Basins (a derivative of the CREAMS model) which is a quasi-distributed model incorporating the Soil Conservation Service curve number technique for estimating infiltration, a crack flow model to simulate infiltration during dry soil conditions, separate evapotranspiration calculations from soil and vegetation, a crop growth model which simulates the seasonal growth of sorghum, wheat, and corn (grown on the basin), and a snow model to store snow on the surface and melt it as a function of energy availability.

The basin is a small, 113 km^2, watershed located in rural eastern Nebraska, just northeast of Lincoln. The basin is relatively long and narrow with minimal (<0.5%) urbanization. Snowfall characterizes winter precipitation and sufficient meteorological and hydrological data are readily available which are the rationale for choosing this watershed. Bias adjustments explicitly account for differences in rainfall and snowfall and are patterned after Legates and DeLiberty (1993a; 1993b) although the model here uses a daily time-series and adjustments are made on a daily basis. Biases were calculated using data obtained from the WMO Solid Precipitation Measurement Intercomparison.

Our hypothesis is that the calibration of hydrologic models satisfies two criteria: adjustment for uncertainties in model parameters and adjustment for gauge measurement biases. The first adjustment should be unsystematic (will not affect the mean) since the initial estimate of the curve number should be an unbiased estimate. The second adjustment, however, is systematic which serves to decrease the infiltration rate and provide more overland runoff. In reality, more runoff results from more precipitation (than is actually measured) but calibration serves to match the simulated and observed runoff. Thus, the simulation is correct after calibration but for the wrong reason. To test this hypothesis, we will run the hydrologic model, without calibration, using gauge measured and bias-adjusted precipitation inputs. If our hypothesis is correct, the simulated streamflow will be considerably less than the measured streamflow for the gauge measured precipitation but it will be of the same order of magnitude as the observed streamflow when the bias-adjusted precipitation is used.

Results indicate that a statistically significant improvement in the simulated streamflow resulted from adjusting the precipitation input for gauge measurement biases. Mean runoff for the seven year period was only 60% of the observed when the measured precipitation was used but was 97% of the observed when the bias-adjusted precipitation was substituted. The use of bias-adjusted precipitation measurements does not remove all of the error in the simulation, as expected, because uncertainty still exists in the model parameters. Thus, calibration is still necessary but results only in an addressing of model parameter uncertainties -- precipitation underestimation error has been properly addressed. Our hypothesis seems to be confirmed.

7.6.4 Conclusions

As a result of gauge bias assessments, such as the WMO Solid Precipitation Measurement Intercomparison, these and other studies have been better able to address the true precipitation climate. This research has proven and hopefully will continue to prove invaluable for both climatological and hydrological research.

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GLOSSARY

Accuracy/Reliability:

Since the gauge adjustment procedure will not result in an exact value but will introduce some degree of uncertainty into the adjusted estimates, it is imperative that the reported values include not just the adjusted estimate, but an interval in which the "real" value is expected to lie. It is proposed that 95% confidence limits be used since they are widely understood and recognized. This requires that some estimate of the goodness of fit of the correction factor be reported. It is also required that this "goodness-of-fit" be computed from an independent data set and not from the data which were used to specify the model parameters. Cross-validation can be used to obtain this independent data set.

Adjustment (correction) procedures:

Computational procedures developed to account for the systematic errors inherent in precipitation measurement. Although the term "correction" has been used more commonly, the term "adjustment" is the preferred terminology since it does not imply that the resulting precipitation value is the exact "ground truth" value. Because of the many authors contributing to this report, these two terms have been used interchangeably.

Automatic recording techniques:

Precipitation measurement techniques that involve mechanical (moving pens), electrical, or chemical procedures.

Blowing Snow:

Snow particles raised and stirred violently by the wind to moderate or great heights. Visibility is poor (6 miles or less) , and the sky may become obscured when the particles are raised to great heights.

Catch Ratio (R_c):

Ratio of the amount of precipitation caught by any gauge including the recorded amount and wetting loss (P_m) to the true precipitation (P_t). Mathematically,

$$R_c = \frac{P_m}{P_t}$$

Correction factor (k):

Ratio of the true precipitation (P_t) to the gauge measured precipitation adjusted for wetting losses (P_m). Mathematically,

$$k = \frac{P_t}{P_m} = \frac{1}{R_c} \quad ; \quad P_t = k * P_m$$

Deficit (D):

Ratio of the difference between the true precipitation (P_t) and the gauge measured precipitation (P_m) to the true precipitation. Mathematically,

$$D = \frac{(P_t - P_m)}{P_t} = 1 - R_c$$

Dry Snow:

Solid precipitation in the form of snow that normally falls in the absence of liquid precipitation at shelter-height air temperature less than -3^{o}C.

Evaporation loss:

This is the water lost by evaporation before the observation is made. Evaporation loss from manual gauges can be a significant contributor to the systematic under measurement of solid precipitation.

Gauge site exposure:

The exposure of the gauge site as to wind. To express the degree of protection of gauge site from the wind objectively and quantitatively, the average vertical angle of obstacles, a, can be applied. On the basis of assessments of a, a classification of gauge site exposure is possible (e.g., a distinction into open or exposed sites, partly open sites, partly protected sites, and protected sites).

Gauge undercatch: See deficit.

Mixed Precipitation:

Any combination of liquid (rain, drizzle), freezing (freezing rain, freezing drizzle) or solid precipitation falling during the observational period.

Precipitation Gauge:

An instrument designed to measure the amount of all forms of hydrometers, solid and liquid, that fall from the sky or through the atmosphere.

Rain Gauge:

An instrument designed to measure the amount of liquid precipitation only that falls from the sky or through the atmosphere.

Snow Gauge:

An instrument designed to measure the amount of solid precipitation that falls from the sky or through the atmosphere.

Solid Precipitation:

The solid products of the condensation of water vapour falling from clouds or deposited from air on the ground. For the purposes of this experiment solid precipitation includes snow, snow pellets, snow grains, ice pellets, hoar-frost and rime but excludes hail.

Snow is precipitation composed mainly of hexagonal ice crystals, mostly star shaped and usually clustered together to form snowflakes.

Snow Pellets are white, opaque balls of snow. They range from 2 to 5 mm in diameter and usually bounce when landing on a hard surface.

Snow grains are very small white and opaque grains of snow-like structure. The grains are somewhat flat or elongated. Their diameter is generally less than 1 mm. When they land on a hard surface they do not bounce or shatter. They usually fall in small quantities.

Ice Pellets are pellets of ice which form when raindrops freeze before reaching the ground. Ice pellets may also form when pellets of snow are covered by a thin layer of ice before reaching the ground. Ice pellets are 5 mm or less in diameter. They usually bounce and make a noise when landing on a hard surface.

Hoar-frost is a deposit of ice having a crystalline appearance generally assuming the form of scales, needles, feathers or fans, produced in a manner similar to dew, but at a temperature below 0^oC.

Rime is a deposit of ice composed of grains more or less separated by trapped air, sometimes adorned by crystalline branches.

Systematic Error:

An error in precipitation gauge measurement that introduces a preferred bias into the observations. Systematic underestimation biases include the wind-induced effect, wetting and evaporative losses, out-splashing effects, friction of the recording pen, high intensity rainfall with tipping bucket gauges, and the treatment of traces as no precipitation. Overestimation biases can be introduced by blowing snow and gauge design (e.g., the Canadian Nipher shield).

Random Error:

An error in precipitation gauge measurement that introduces no preferred bias into the observations. These biases include both observer and recording errors.

Wet snow:

Solid precipitation in the form of snow that normally falls in the absence of liquid precipitation at shelter-height air temperatures greater than or equal to -3^oC.

Wetting loss:

Water subject to evaporation from the surface of the inner walls of the precipitation gauge after a precipitation event and from the gauge after its emptying.

ANNEXES

TABLE OF CONTENTS

		PAGE
ANNEX 1	**PHYSICS OF PRECIPITATION GAUGES AND WIND-INDUCED MEASUREMENT ERROR**	**1**
ANNEX 1.A	PHYSICS OF PRECIPITATION GAUGES	1
ANNEX 1.B	INVESTIGATION OF WIND-INDUCED ERROR OF SNOW MEASUREMENTS USING NUMERICAL SIMULATION	11
ANNEX 2	**METHODOLOGY**	**17**
ANNEX 2.A	GENERAL DESCRIPTION OF THE SITE REQUIRED FOR THE INTERCOMPARISON	17
ANNEX 2.B	DESCRIPTION AND INSTALLATION INSTRUCTIONS FOR THE DOUBLE FENCE INTERCOMPARISON REFERENCE (DFIR)	17
ANNEX 2.C	SPECIFICATIONS AND DETAILS OF THE TRETYAKOV GAUGE (WORKING NETWORK REFERENCE)	19
ANNEX 2.D	STATION REPORT AND SITE DESCRIPTION	21
ANNEX 2.E	WMO SOLID PRECIPITATION MEASUREMENT INTERCOMPARISON CLIMATOLOGICAL DATA SUMMARY	22
ANNEX 2.F	WMO SOLID PRECIPITATION MEASUREMENT INTERCOMPARISON SNOW EVENT DURATION DATA	25
ANNEX 2.G	OBJECTIVE EVALUATION ON THE HOMOGENEITY OF A COMPARISON	27
ANNEX 2.H	ADJUSTMENT FOR UNDERCATCH OF THE DOUBLE FENCE INTERCOMPARISON REFERENCE (DFIR) GAUGE	29
ANNEX 3	**DESCRIPTION OF SITES AND INSTRUMENTS**	**37**
ANNEX 3.A	CANADA	37
ANNEX 3.B	CHINA	41
ANNEX 3.C	CROATIA	42
ANNEX 3.D	FINLAND (INCLUDING DENMARK, NORWAY AND SWEDEN)	50
ANNEX 3.E	GERMANY	66
ANNEX 3.F	JAPAN	75
ANNEX 3.G	ROMANIA	82
ANNEX 3.H	RUSSIAN FEDERATION	83
ANNEX 3.I	SLOVAKIA	84
ANNEX 3.J	SWITZERLAND	85
ANNEX 3.K	UNITED KINGDOM	86
ANNEX 3.L	UNITED STATES OF AMERICA	88
ANNEX 4	**DATA ARCHIVE EXAMPLES**	**91**
ANNEX 5	**COUNTRY REPORTS**	**97**
ANNEX 5.A	SUMMARY OF COUNTRY ANALYSIS AND RESULTS	97
ANNEX 5.B	CANADA	105
ANNEX 5.C	CHINA	113
ANNEX 5.D	DANISH METEOROLOGICAL INSTITUTE	116
ANNEX 5.E	FINNISH METEOROLOGICAL INSTITUTE	125
ANNEX 5.F	GERMANY	147
ANNEX 5.G	JAPAN	157
ANNEX 5.H	RUSSAIN FEDERATION	164
ANNEX 5.I	SLOVAKIA	201
ANNEX 5.J	SWITZERLAND	203
ANNEX 5.K	USA	206

ANNEX 1 PHYSICS OF PRECIPITATION GAUGES AND WIND-INDUCED MEASUREMENT ERROR

ANNEX 1.A PHYSICS OF PRECIPITATION GAUGES

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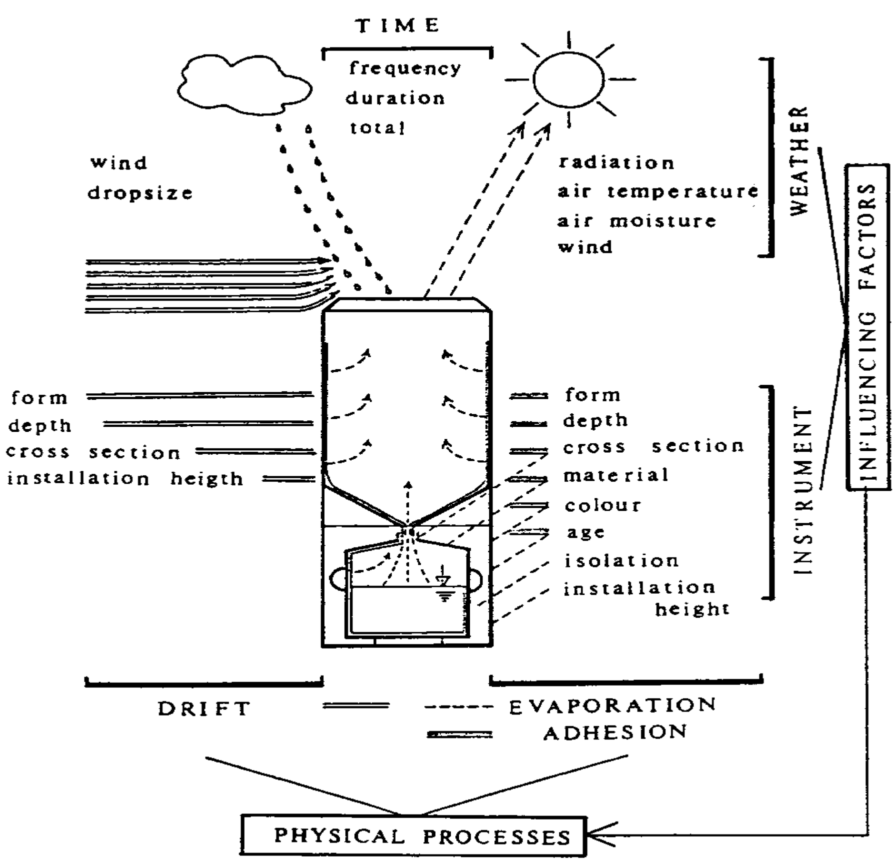
1. INTRODUCTION

As the development of accurate measuring instruments is limited by financial and physical constraints, the measurement of meteorological variables is carried out using less expensive and more common methods, simple instruments and uncomplicated arrangements. As a consequence, the meteorological observations are subject to systematic errors. These errors fill the gap between the "true" and measured values of a particular variable. They are caused when the physical characteristics of the instruments interfere with other variables involved in the measuring process, and depend on variables which include constructive parameters of instrument and weather conditions.

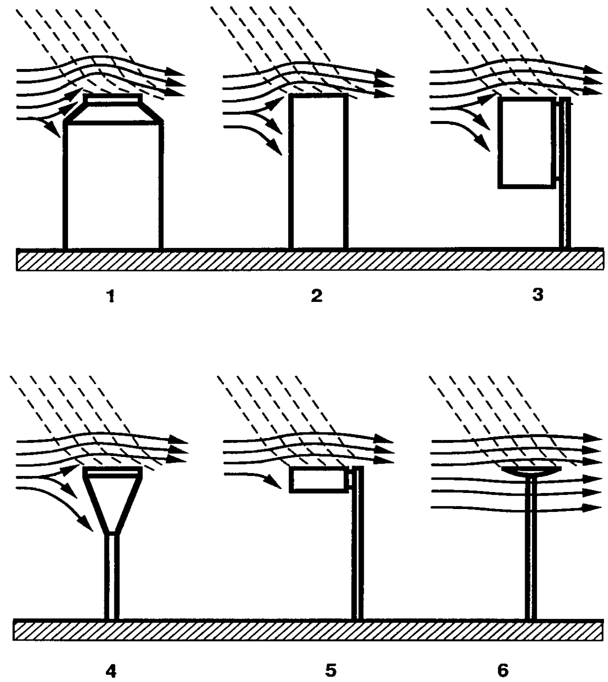
In the case of a common precipitation gauge, which mainly consists of an upright cylinder elevated above ground, the main interfering processes are the wind-field deformation above the gauge orifice, wetting of the inner surfaces of the gauge, evaporation of accumulated water in the gauge between the period of precipitation event and the time of observation, and splashing of raindrops or blowing of snow from and into the gauge. The first three processes and the influencing factors are shown in Figure 1.A.1: At the bottom are the respective, interfering physical processes; drift (wind-field deformation), (left), evaporation and adhesion (right) separated by the legend. In the centre are instrumental characteristics and in the upper part are most important weather variables.

Figure 1.A.1 Schematic representation of relevant physical processes and instrumental and weather variables affecting the basic components of systematic error of precipitation measurement; the wind-induced error, evaporative and wetting losses, according to Sevruk (l981).



The phenomenon of wind-induced error of precipitation measurement has attracted the attention of many scientists through the two last centuries. It is a very complex, physical matter. It includes the interaction of the body of a precipitation gauge with the wind flow and the solid and liquid particles falling through the air. The trajectories of particles become distorted in a wind through the displacement and acceleration of wind flow over the top of the gauge as caused by the aerodynamic blockage of the gauge body. The lighter particles are carried beyond the gauge opening, resulting in a reduced catch. The extent of reduction depends on the falling velocity of particles, wind speed and the aerodynamic properties (drag of the air) of a particular type of gauge. For the same gauge, the reduction is smaller for big raindrops but several times greater for light snow and it increases with increasing wind speed. This process of wind-induced error is described by a set of differential equations of fluid dynamics (three-phase flow; gas, liquid and solid phase) and is still not fully understood; in particular, the effect of turbulence has not been studied sufficiently.

Figure 1.A.2 Shapes of precipitation gauge body. The number 1 indicates the shape having the worst aerodynamic properties and the number 6 having the best ones. Arrows show the streamlines and the dashed lines the trajectories of precipitation particles.



A practical solution to the problem at hand would be to place the gauge in a pit with the orifice flush with the ground. However, for various reasons as discussed later, the gauges are elevated 20 to 200 cm above ground. The wind-induced loss amounts to 2-10% for rain and up to 80% for snow, and even more in the mountains. The diversity of error magnitudes is caused by many variables, as shown in Figure 1.A.1. Nevertheless, under the same environmental and observational conditions, the instrumental, constructive variables play the most important role. This is supported by the fact that precipitation amounts as measured at the same site by two gauges having different parameters are usually not the same. The better the aerodynamic properties of a gauge, the smaller the wind-induced error. In this context, the following gauge parameters are to be noted: the proportions and the shape of both gauge body and orifice rim. In addition, the use of wind shielding devices is one of the most critical factors.

The purpose of this contribution is to review the results of various kinds of studies into the physics of precipitation gauges, including both field intercomparison measurements and wind tunnel experiments. The focus is on the effects of precipitation gauge parameters on wind-induced error regarding practical applications such as the selection of suitable design criteria for different parts of the precipitation gauge, or the assessment of both reliability and possible error magnitude of a particular type of gauge. Last but not least, a more popular question is of interest concerning which gauge type is the best.

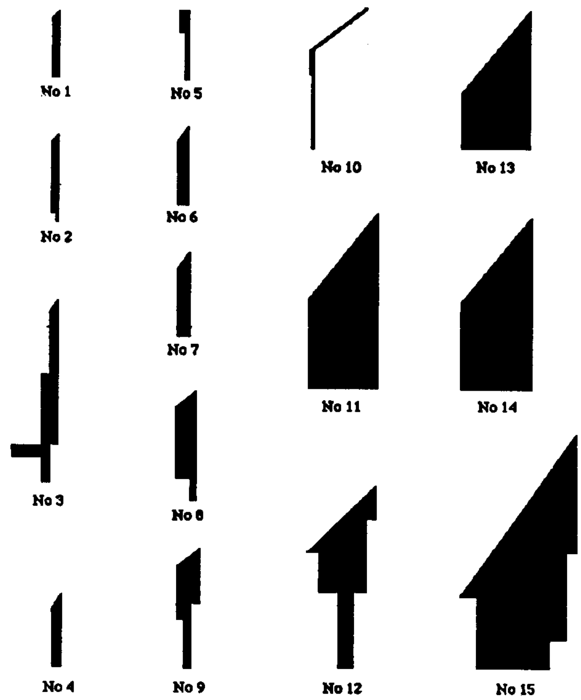
Updated information on the topic, shedding a good insight on the problem, can be found in Hall et al. (1993a,b) and Sevruk (1993) (see Culling, 1993), as well as in Sevruk et al. (1989, 1991, 1993), Nešpor (1993) and Nešpor et al. (1993).

2. CONSTRUCTIVE PARAMETERS OF GAUGES

From the point of view of fluid dynamics, the details of the shape and dimensions of a precipitation gauge are important variables responsible for the extent of the aerodynamic blockage effect of a gauge. Figure 1.A.2 shows various shapes of gauge body, whereby the gauge 1 has the worst and gauge 6 the best aerodynamic shape. Only a few gauge types used worldwide at present are of an aerodynamically more suitable conical shape and none have the best shape of a flat dish as shown in Figure 1.A.2 (gauge 6). The great majority of common precipitation gauges consists of an upright cylinder usually having the height/diameter ratio between 1.4 and 3.0 (gauges 2 and 3 in Figure 1.A.2). The height of most gauges varies from 20 to 70 cm (up to 90 cm) and the diameter from less than 10 to 25 cm. This represents a substantial bulk with rather worse aerodynamic properties. A few types of gauge are of combined form; upright cylinder over a funnel (gauge 4 in Figure 1.A.2), which is a slightly better form than the cylinder alone.

The most important constructive parameter regarding the wind-induced error seems to be the orifice rim used to reinforce the upper end of the gauge to prevent its deformation. It is a very sensitive part of the gauge immediately affecting the development of the wind field above the gauge orifice. Orifice rims differ in shape and thickness, depending on the type of gauge. Figure 1.A.3 shows various shapes and thicknesses of orifice rims used at present. A thin and simple sharp rim giving the best performance is not used at all. Slight deviations from the parameters of the orifice rim can cause considerable changes in characteristics of the wind field above the gauge orifice, and consequently different precipitation values.

Figure 1.A.3 Shapes and proportions of the precipitation gauge orifice rim. Note the differences in thickness. The thickest orifice rim is used on heated tipping-bucket gauges. It contains the heating device.

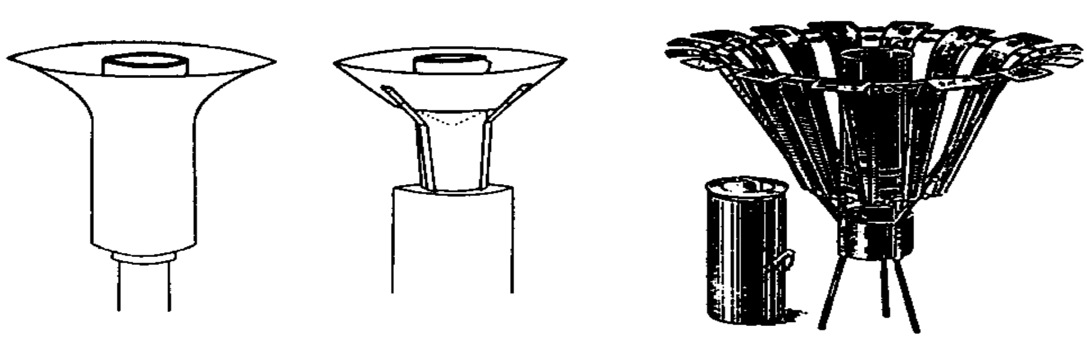


A further parameter to be noted is the wind shield, which is used to reduce wind speed at the level of gauge orifice. In Figure 1.A.4, three types of wind shield are presented.

It follows from the points set out above that aside from the pit gauge, the ideal model of elevated precipitation gauge should have a body in a shape of a flat plate, allowing for a small drag of air, as for instance, the inverted Frisbee as shown in Figure 1.A.2 (gauge 6). However, the pit gauge is not used by meteorological services and only occasionally by special agencies, and in addition it is not suitable for snowfall measurements. Moreover the flat, streamlined gauge has many problems caused by out-splashing, heating during the cold season, and ejection of precipitation which has already entered the gauge by a wind-driven circulating flow inside the gauge, etc. Therefore, with the exception of some experimental and special gauges, the body of almost all types of common gauges consists of a deep upright cylinder as shown in Figure 1.A.5. It is fixed on a pile or posed on the ground so that the gauge orifice is elevated above ground to be protected against in-splash and drifting snow. The installation height varies from 0.2 to 2.0 m and in the mountains even up to 4-5 m. The higher the gauge, the greater the wind speed and the resulting wind-induced error.

Other sources of systematic errors such as evaporative and wetting losses are less spectacular from the physical point of view and generally less consequential, particularly in the winter and for gauges having a fixed funnel and protected container.

Figure 1.A.4 Wind shields of various design. From the left; the Nipher rigid type as used in Canada and its shortened modification as used in Sweden and the Tretyakov semi-moving type as used in Russia.

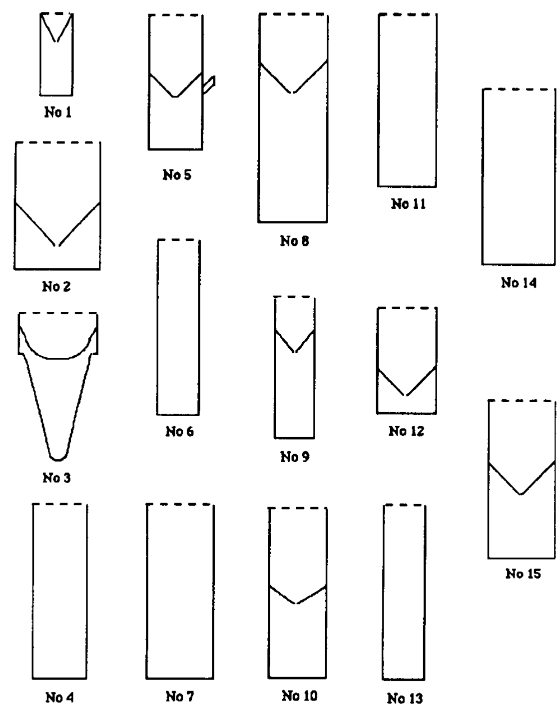


3. METHODS

3.1 Intercomparison measurements

To study the physical laws controlling the phenomenon of wind-induced error, four methods and their combinations can be applied. The first insights into the behaviour of precipitation gauges were acquired already during the period of initial measurement of precipitation in the 18th century, through more or less passive experiment by observation and deduction. The introduction of field intercomparisons of precipitation measurements by different types of installation and gauges in the 19th century represented a significant step forward. Further, in this century, the wind tunnel tests contributed a lot to develop more suitable, aerodynamic shapes of gauges and protective structures against wind such as wind shields and fences. Yet the greatest progress can be expected from the application of computational fluid dynamics used quite recently for the solutions of problems in science and in actual practice. Each of the above-mentioned methods has its merits, uncertainties and restrictions. This is why a verification of results by independent methods is still necessary and why a combination of more methods will probably yield best results.

Figure 1.A.5 Cross sections of commonly-used precipitation gauges.



Thanks to passive experiments, the construction of precipitation gauges was improved as early as the 18th century, particularly regarding the evaporation protection of accumulated water in the gauge. The main purpose of intercomparison measurements of precipitation in the last century was to select the best gauge and the most suitable conditions of installation. Gauges of different types were situated near each other at the same site. Generally speaking, the gauge showing more precipitation was considered to be better. Sometimes the reasons for the better or worse performance of a particular gauge were analyzed taking into account the different constructive parameters. Hence, the first ideas on the possible role of gauge parameters and their suitable design relative to the wind-induced error emerged. Because of a variety of construction parameters involved which might have different or even opposite effects on precipitation catch, the correct interpretation of the results of intercomparison measurements from gauges of various shapes, diameters, heights, etc. sometimes proved difficult. For instance, a shorter gauge collector can create, on the one hand, better aerodynamic conditions and at the same time the wetting losses also could be smaller, but on other hand, the reduced depth of collector can provoke out-splash, and in spite of the above-mentioned improvements, reduced gauge catch.

In view of the rather restricted possibilities of theoretical studies, the practical impact of intercomparison measurements can be still substantial. This is one of the reasons why they are used at present with success, for example to derive empirical relationships of various kinds. If they are strictly organized in a way that only one sensitive parameter as separated from the others is changed among the otherwise identical gauges, the physical reasons for the different performance or error magnitudes can be ascertained. If intercomparisons are supported by measurements of other meteorological parameters such as wind speed and intensity of precipitation and temperature, a statistical model can be derived describing the relative effect of a particular gauge parameter on the wind-induced error. And if the WMO reference measurements are included using the pit gauge for rain and a double fence (DFIR) for snow measurements, correction procedures for the wind-induced losses can be established for a particular type of gauge.

3.2 Wind-tunnel experiments

More theoretical background on the wind-induced error can be obtained from the results of wind tunnel experiments. In addition to the visualization of stream lines and the trajectories of particles, basic flow characteristics such as wind vectors (velocity and directions), intensity of turbulence and the replacement height over the gauge orifice can be measured under stable conditions. The measurements are made in sensitive positions such as the windward, leeward and the centre of gauge orifice using a pulsed-wire anemometer. The vertical and horizontal movement of the anemometer can be controlled automatically by a computer. In this way, the laws of wind field deformation can be studied. The simulation of particles and the measurement of gauge catch can also be arranged.

Wind tunnel experiments are more convenient than the field intercomparison measurements. In addition, they are able to not only confirm but also in part explain the results of the field intercomparison measurements.

3.3 Computational fluid dynamics

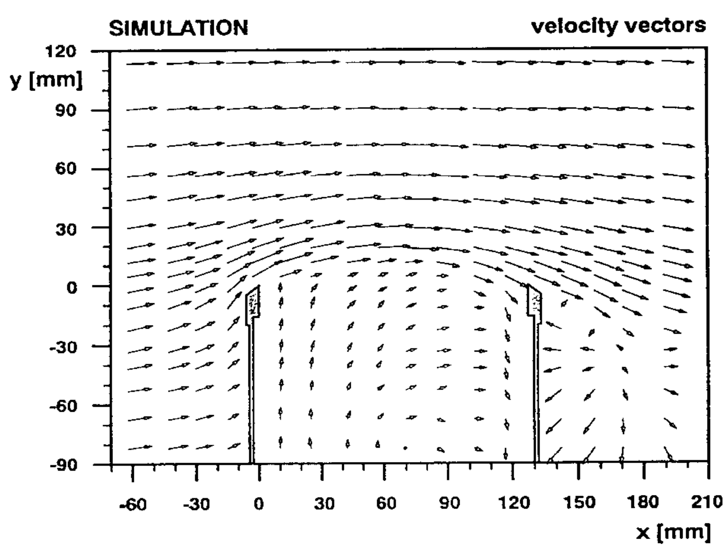
The real breakthrough in the study of the physics of precipitation gauges was achieved quite recently by applying the advanced simulation techniques of highly sophisticated, computerized fluid dynamics (Nešpor, 1996, 1997). This allows the experimental conditions to be changed immediately and in a very convenient manner. Moreover, the whole phenomenon of wind-induced error of precipitation measurement, including the particles, could be dealt with directly using the most advanced, mathematical formulas. A recent study using numerical simulation to investigate the wind-induced error of snow measurements by the Hellmann and ASTA precipitation gauges used in Switzerland is presented in Annex 1.B.

Unfortunately studies of this kind are rare. Part of the reason might be the lack of attractiveness of this subject to organizations having access to the expensive hardware and software required.

The absence of computer simulation studies of precipitation gauges and the inconclusive nature of many of the intercomparison measurements explains why the material as reviewed further in this report originates mainly from wind tunnel experiments and is not generally based on systematic studies. It is hoped that the gaps will be closed in the near future, resulting in a complete picture of precipitation gauge behaviour in wind during precipitation.

This review is divided into sections dealing separately with some characteristics of the wind field and the following precipitation gauge construction parameters: the body of a gauge, including the height/diameter ratio, the orifice diameter and thickness, as well as the shape and wind shield. An empirical model of the wind-induced error is also presented.

Figure 1.A.6 Wind field above the orifice of a common precipitation gauge (Mk2) based on flow simulation using the PHOENICS program. According to Nešpor (1993).



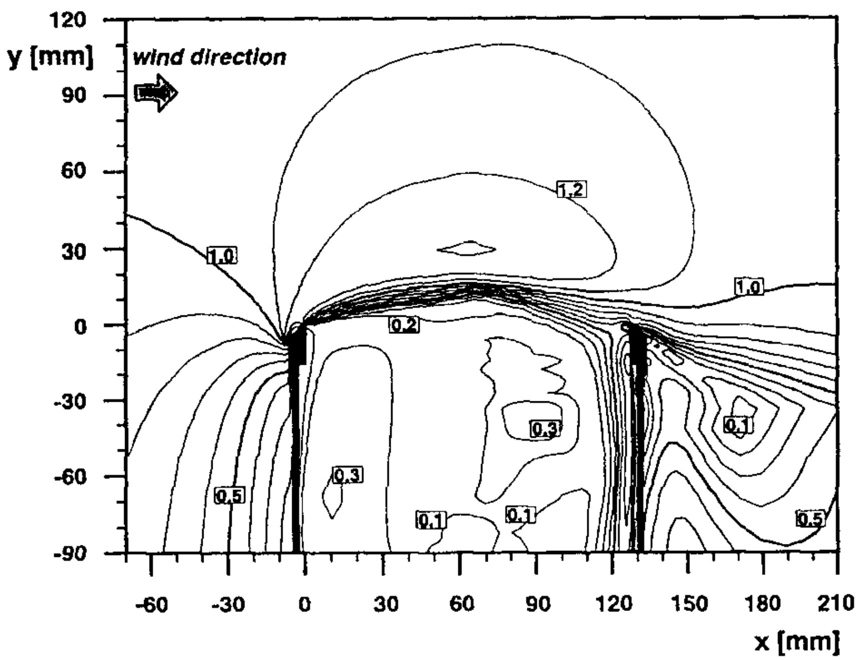
4. RESULTS AND DISCUSSIONS

4.1 Wind field characteristics

The wind field around a gauge is shown in Figure 1.A.6. The arrows indicate the vectors of wind speed, that is the direction and the speed of airflow. The airflow at the windward side of the gauge is directed upwards and is accelerated. Wind speed increases roughly up to the centre of the gauge orifice where the maximum increase of approximately 30% is obtained. At this point, the direction of airflow changes downwards and wind speed decreases, causing a wind-driven circulating flow inside the gauge and development of eddies in and behind the gauge, as shown in Figure 1.A.7, where the contour lines of normalized, horizontal component of wind speed are plotted.

The above mentioned Figures 1.A.6 and 1.A.7 refer to the UK Mk2 gauge. The profiles of normalized wind speed and intensity of turbulence situated windward and leeward of the gauge orifice and at the centre for two different gauges are shown in Figure 1.A.8. They provide a more detailed insight into the structure of the wind field above the gauge orifice. It can be seen, for instance, that in addition to the maximum wind speed increase, the height above the gauge at which it occurs differs considerably, not only between the types of gauges, but also between the profiles situated at different positions. The ratio of this height and orifice diameter is called displacement. The wind speed increase and displacement are the basic wind field characteristics used to evaluate the gauge performance. The smaller they are the better.

Figure 1.A.7 Contour lines of normalized, horizontal wind speed above the orifice of the Mk2 gauge as measured in a wind tunnel. According to Nešpor (1993).



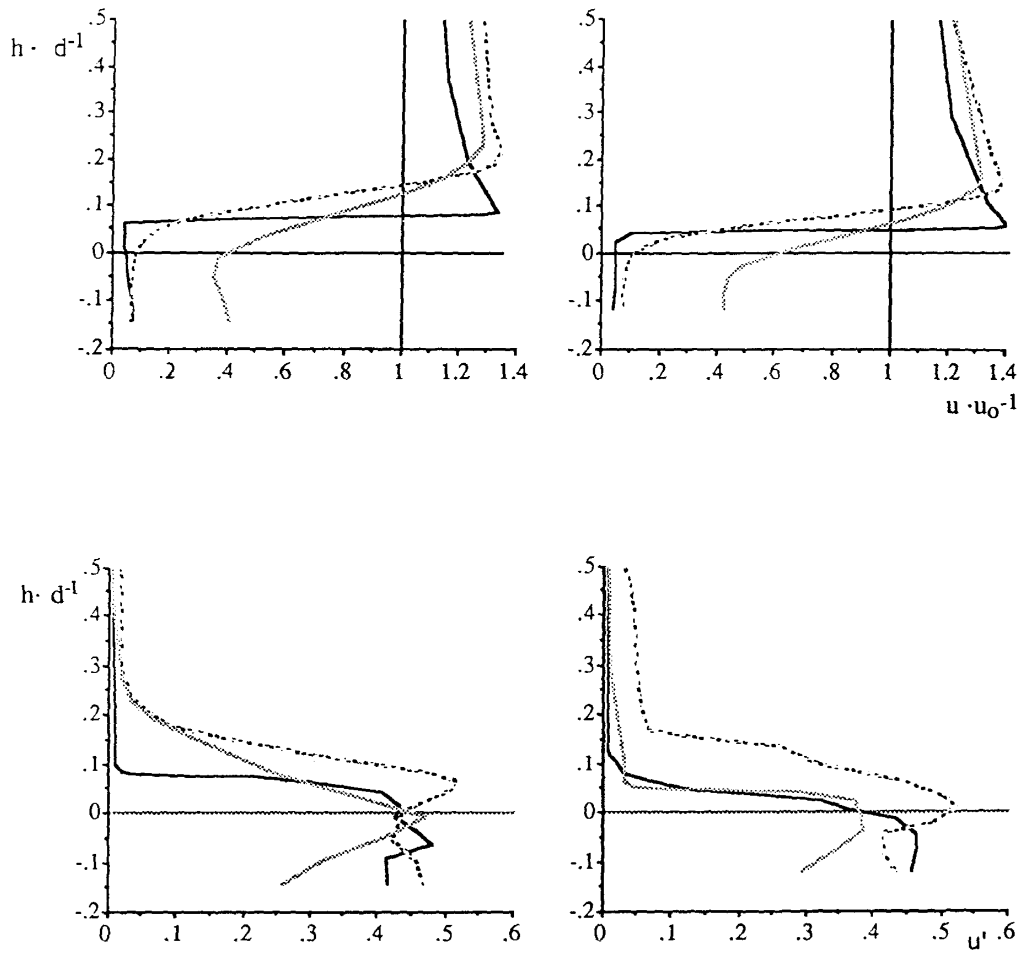
4.2 Height/diameter ratio

As pointed out by Sevruk et al. (1989), the increase of wind speed above the gauge orifice depends on the gauge type, that is on the construction parameters. One of these parameters, affecting the extent of the blocking of a gauge, is the ratio of cylindrical gauge height to the diameter. Hall et al. (1993a) investigated this ratio in the wind tunnel. They found a rapid increase of wind speed above the orifice centre with increasing ratio up to 0.5. Beyond this ratio value only a modest rate of increase was observed. The maximum increase of wind speed was 25%. Along with wind speed the displacement also increased. Its maximum value was 0.2.

4.3 Orifice area and rim thickness

Almost all types of gauge used worldwide at present have a height/diameter ratio greater than 0.5, and in most cases it varies between 1 and 3 (Sevruk and Klemm, 1989). In the light of the results by Hall et al. (1993a), mentioned earlier it seems firstly, that for a common type gauge the effect of the gauge orifice area on the wind speed increase is small. In fact, Figure 1.A.9 shows only a slight increase in the range of orifice area of 100 to 300 cm^2, particularly for gauges with a thin orifice rim, and no increase at all for gauges with a thick orifice rim. There is, however, evidence from intercomparison measurements that small orifice gauges (less than 70 cm^2!) catch more precipitation than large ones (Kalma *et al.*, 1969). Secondly, the maximum increase of wind speed above the centre of a common gauge is at least 25%. According to Sevruk et al. (1989), it was between 30 and 45% for seven types of national, standard gauges having height/diameter ratios from 1.5 to 3.2 and various sizes and shapes of orifice rim. This means that the additional wind speed increase exceeding the value of 25% was due to the orifice rim. Thickness of the rim in particular can have a serious effect on the wind speed increase, as shown in Figures 1.A.8 and 1.A.10. The maximum wind speed increases with increasing thickness of the gauge rim (Figure 1.A.10). The course of profiles of wind speed and intensity of turbulence for gauges with a thick or a thin rim is also different, as shown in Figure 1.A.8. Moreover, the displacement is greater for gauges with a thin rim as compared with gauges having a thick rim (Figure 1.A.8). It is clear that beside the thickness of orifice rim, its different shapes, as shown in Figure 1.A.3, have to be considered as a further, important parameter affecting the wind field characteristics. The respective studies have still not been conducted.

Figure 1.A.8 Comparison of normalized profiles of horizontal wind speed (above) and intensity of turbulence (below) over precipitation gauges with thin (left) and thick orifice rim (right), according to Sevruk et al. (1993). The solid line indicates the windward profile, dashed line the centre and dense point line the leeward profile: h is height above the orifice; u is profile wind speed and ù is turbulence intensity.



4.4 Shaping of gauge body

Different shapes of gauges are shown in Figure 1.A.2. A sloping shoulder below the gauge orifice, as can be seen for example on gauge 1, tends more to deflect the wind upwards than a common upright cylinder, thus increasing the vertical component of wind speed. Therefore it can cause larger wind-induced losses as compared with an upright cylinder gauge. According to Jones (1969), who evaluated field intercomparison measurements of gauges having a short and large sloping shoulder in the USA, the loss varied between 2 and 6%. In contrast, the gauge 4 in Figure 1.A.2, which has a shape of an inverted cone, tends to deflect the wind downwards from the orifice, and because of reduced wind speed above the gauge orifice, to reduce the loss. This was conformed either by field intercomparison measurements and wind tunnel tests or by numerical model simulation. As pointed out by Robinson and Rodda (1969), the maximum increase of wind speed above the centre of the orifice of such a gauge, consisting only of a shallow funnel, was 29% as compared with 37% for a cylindrical gauge (Mk2). The rain catch was larger than that of cylindrical gauges for light showers but smaller for heavy or prolonged rains, thus indicating that splashing was taking place. According to Folland (1988), a simple numerical model indicated more catch for a flat "champagne glass gauge" than for the cylindrical gauge. Conclusive results concerning the better performance of gauges having the more suitable, aerodynamic shape of an inverted Frisbee, as for example the gauge 6 in Figure 1.A.2, were obtained from the series of wind-tunnel experiments carried out in Warren Spring Laboratory in the UK by Hall et al. (1993a,b). The maximal increase of wind speed was 12% and the displacement was only 0.07.

Figure 1.A.9 The effect of orifice area, A, on the maximum wind speed increase, u_{max} above the centre. Solid line indicates the thick orifice rim and dashed line the thin one: u_o is the wind tunnel free wind speed.

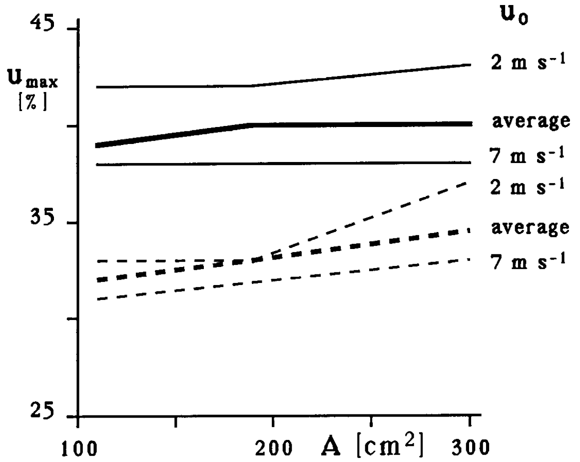


Figure 1.A.10. The effect of the thickness, D, of gauge orifice rim on the maximum increase, u_{max} of wind speed above the centre of orifice as measured in the wind tunnel. Various types of precipitation gauge were investigated as indicated by the legend (Tretyakov, Hellmann, Hungarian and ASTA). Three wind speeds, u_o,were used. Triangles indicate u_o = 2 ms^{-1}, crosses u_o = 3 ms^{-1} and points u_o = 7 ms^{-1}.

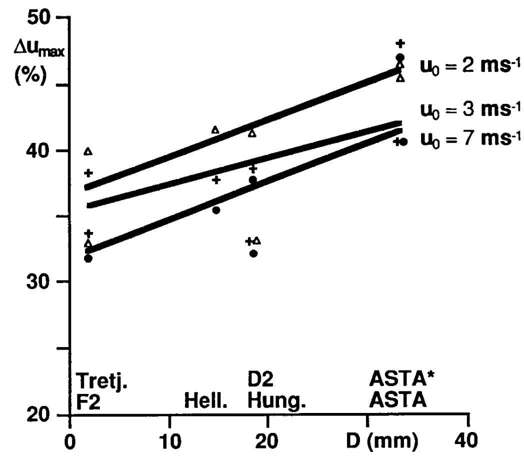
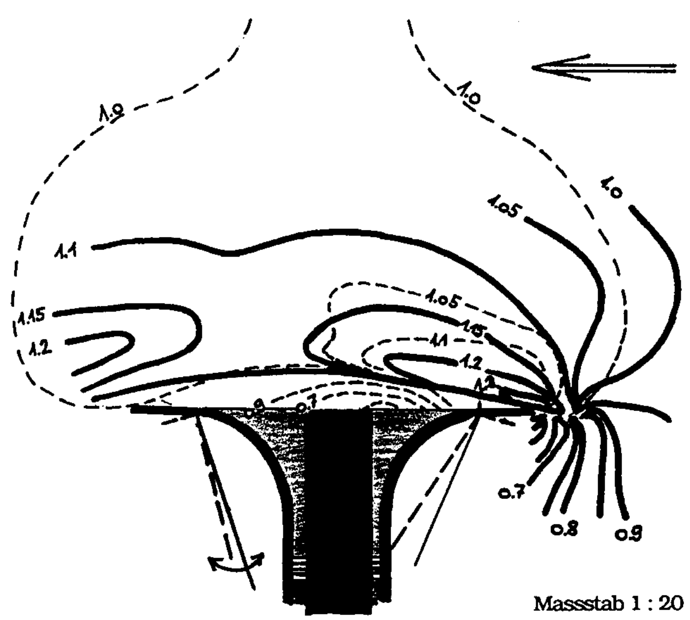


Figure 1.A.11 Comparison of contour lines of vertical component of wind speed above the orifice of a gauge protected by wind shield of the Nipher type and the Tretyakov type, according to Goodison et al. (1983) and Bolshakhov (1974), respectively. Solid lines indicate the contour lines of normalized wind speed for the Nipher wind shield and dashed lines for the Tretyakov one. The black column shows the precipitation gauge and the thick solid line the Nipher shield. The arrows on the bottom indicate the movement of the baffles of the Tretyakov wind shield and the arrow on the top indicates the wind direction. Wind speed was 3.5 m s^{-1} for the Nipher shield and 2.5 m s^{-1} for the Tretyakov one. Tammelin (1982) published similar picture for the Finnish gauge (Wild gauge). Contour lines of wind speed and intensity of turbulence for wind shields consisting of a flange with its upper surface mounted level with the rim of a gauge have been published by Lindroth (1991).



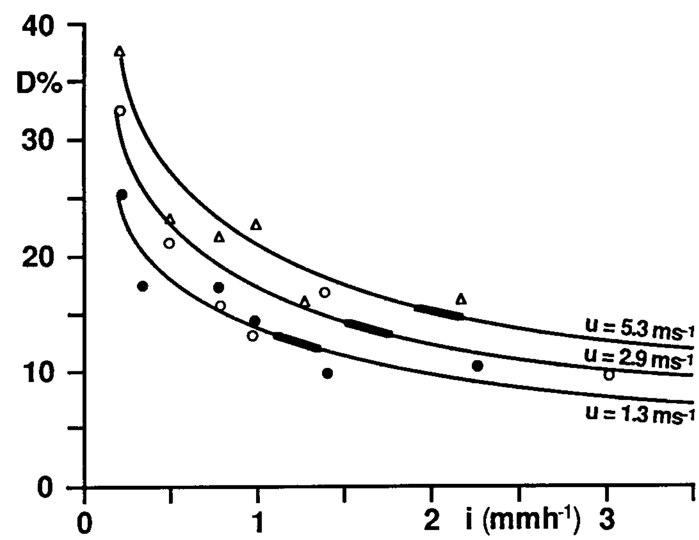
4.5 Wind shield

Wind shields help to displace the airflow around the gauge downwards. Moreover, they have a considerably larger diameter than the gauge, and in this way they reduce the height/diameter ratio. Consequently, wind speed increase above the gauge orifice is small. As shown in Figure 1.A.11, it does not exceed 15% above the gauge orifice centre. It looks as if the gauge is shifted leeward into the wind field of the wind shield, in the zone of lower wind speeds (cf. Figure 1.A.6). However, according to Hall et al. (1993a), who investigated different shapes of gauges and wind shields in the wind-tunnel, the shields do not reduce the displacement. The best results with almost no wind increase and no displacement were obtained from streamlined, i. e. shallow, Frisbee-like gauges equipped with a simple, rigid wind shield. This is a very promising development.

4.6 Empirical model of wind-induced error

The state-of-the-art of precipitation gauges from the aerodynamics point of view is that they have rather poor aerodynamic properties, and this situation will not change in the near future. Therefore, with regard to a considerable systematic error due to wind, the measured precipitation values have to be corrected. Since the correction procedures derived using the computational fluid dynamics are lacking, empirical models have been developed. A model of this type explaining the differences in wind-induced losses between two different types of gauges in terms of wind speed and intensity of rain is presented in Figure 1.A.12. The diagram incorporates 3 one-parameter curves relating the percentage difference to intensity for three wind speed intervals. The overall tendency of differences is obvious. They increase with increasing wind speed and decreasing intensity. Below a certain threshold value and despite the practically unchanged wind speed a sharp increase of differences exists with decreasing intensity for each wind speed interval. Above the threshold value there is only a slight effect of intensity and all three curves appear to run parallel. The reason for the considerable differences between the catches of two gauges could be the thicker orifice rim of a gauge showing less precipitation (Sevruk 1993).

Figure 1.A.12 The dependency of percentage difference, D%, between the precipitation values of different gauges on intensity, i, of precipitation and wind speed, u. Short and heavy lines indicate threshold values of intensity i, below which the difference starts to increase more sharply. According to Sevruk and Tettamanti (1993).



5. CONCLUSIONS

Precipitation measurement is subject to systematic errors. They are caused by the interference of physical characteristics of precipitation gauges with other variables accompanying the measurement process. The most important is the wind-induced error. To study the behaviour of a gauge in the wind more methods can be used. The greatest progress can be expected from the application of computational fluid dynamics. The knowledge of precipitation gauge physics assists the designer of new gauges and helps to assess the reliability and possible error magnitude of existing types of precipitation gauge.

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ANNEX 1.B INVESTIGATION OF WIND-INDUCED ERROR OF SNOW MEASUREMENTS USING NUMERICAL SIMULATION

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1. INTRODUCTION

In the present study investigations of the wind-induced error of snow measurements were concentrated on the Hellmann and ASTA precipitation gauges used in Switzerland. The study is a continuation of investigations of the wind-induced error of rain measurements presented in Nešpor (1996). In this reference the basic explanations, methods and procedures can be found. An additional information and complete results for rainfall and snowfall can be found in Nešpor (1997).

In general, the terminal velocities of solid precipitation particles are much smaller than those of water drops. In the present work terminal velocities of different solid particles were analyzed, parameterized and they were built in the computer code for computation of particle movement (Nešpor, 1997). Previous computations for liquid precipitation particles showed that the wind-induced error computed with the influence of turbulence on the particle movement can be up to four times larger compared to computations without the influence of turbulence (Nešpor, 1996). In the present computations the influence of turbulence on the particle movement was taken into account.

The computational results for snowfall (snow flakes) are presented in the form allowing fast determination of the 'true' precipitation intensity from the known measured intensity, wind speed and type of particle size distribution. The computational results are also compared with wind-induced error estimates obtained from available field measurements.

2. METHODS

2.1 Basic assumptions

All computations in the present study are based on the approach in Nešpor (1996, 1997). In this approach the computation of wind-induced error is subdivided into the following three steps:

- computation of the turbulent flow field around the precipitation gauge using a commercial software for fluid dynamic computations (PHOENICS);

- simulation of movement of precipitation particles in the computed flow field (determination of the partial wind-induced error as a function of the free-stream wind velocity and particle diameter); and

- integration of partial wind-induced errors over particle size distribution (determination of the integral wind-induced error as a function of the free-stream wind velocity, precipitation intensity and parameters of the particle distribution).

The computations and the subsequent wind-induced error estimations were based on the following basic assumptions:

- the motion of particles does not affect the air flow, therefore the air flow and the particle motion can be computed separately; and

- the moving particles do not influence each other, therefore their trajectories can be simulated individually.

The computation of the flow fields and particle trajectories were made for the air properties summarized in Table 1.B.1, the density of water ρ_w = 999.84 kg m^{-3} and the free-stream turbulence characterized by the turbulent kinematic viscosity equal the kinematic viscosity of the air. The flow fields around the precipitation gauges were computed using the κ - ε turbulence model and the particle trajectories were computed with the influence of turbulence on the particle movement (see Nešpor, 1996).

Table 1.B.1: Properties of the air used in the present computations. In the table T is the temperature, p is the pressure, ρ_h is the relative humidity, ρ_a is the density, μ_a is the dynamic viscosity, and ν_a is the kinematic viscosity.

T	*p*	ρ_h	ρ_a	μ_a	ν_a
[°C]	**[kPa]**	**[%]**	**[kg m^{-3}]**	**[kg m^{-1} s^{-1}]**	**[m^2 s^{-1}]**
0	101.325	50	1.292	1.718x10^{-5}	1.329x10^{-5}

2.2 Properties of snow crystals and particle size distribution

In the case of liquid precipitation particles (water drops) the shape and terminal velocities of particles are known, and the particle size distribution is also relatively well described. In the case of solid precipitation particles the situation is more complicated. In general, the form and properties of snow crystals depend on meteorological conditions (e.g. humidity, temperature). There is a large variety of natural snow crystals and their complete classification can be found in Magono and Lee (1966). In order to calculate trajectories of snow crystals it is important to know their properties (terminal velocity, mass, diameter and cross-sectional area). There are many articles about observed properties of snow crystals published until know, but a complete information is usually missing. A relatively complete description of properties of snow crystals can be found in Heymsfield and Kajikawa (1987), but there is no information about particle size distribution.

Muramoto et al. (1996) made an interesting study on the size and fall velocity of snow flakes by image processing technique. They results are based on measurements of a real snowfall event lasting 7.5 hours. Although they reported neither the type of snow crystals, nor the detailed type composition of snowfall, they measured the density and size distribution of snow flakes. The last two parameters together with the fall velocity are essential for the determination of the precipitation intensity and estimation of the integral wind-induced error.

The measured terminal velocities and particle size distribution of Muramoto et al. (1996) are in a good agreement with the results of Barthazy et al. (1996). Also in this case study the measurements were made on a real precipitation event which showed a well developed stratiform structure. In addition, the measured data of Muramoto et al. (1996) agree well with the typical range of terminal velocities and densities of snow particles (e.g. Locatelli and Hobbs, 1974; Hobbs, 1974; Goodison and Metcalfe, 1981; Sevruk, 1985). Therefore, the terminal velocities and particle size distribution of Muramoto et al. (1996) seem to be quite representative for an average snowfall.

The summary of measured properties of selected planar crystals, graupel and snow flakes are presented in Table 1.B.2. In the present study they were used to evaluate the partial wind-induced errors, and in the case of snow flakes also the integral wind-induced errors (Nešpor, 1997).

Table 1.B.2: Summary of measured particle data according to Heymsfield and Kajikawa (1987) (ice crystals) and Muramoto et al. (1996) (snow flakes). In the table the particle code is according to Magono and Lee (1966), T is the air temperature, D is the particle diameter, m is the particle mass, ω_T is the particle terminal velocity, and ρ_p is the particle density.

Code	**Description**	*T*	*D*	*m*	ω_T	ρ_p
		[°C]	**x10^{-3}[m]**	**x10^{-6}[kg]**	**[m s^{-1}]**	**[kg m^{-3}]**
P1e	dendrite	---	0.6-- 5.3	0.0007-- 0.108	0.13--0.43	20--100
R1d	rimmed stellar	---	0.7-- 5.3	0.0020-- 0.539	0.19--0.72	50--150
R2b	densely rimmed stellar	---	1.1-- 4.7	0.0310-- 0.905	0.43--1.43	100--130
R4b	lump graupel	$\geq$0.5	0.5-- 4.7	0.0390—17.200	0.70--4.40	210—630
		< 0.5	0.5-- 9.0	0.0140—68.000	0.47--4.65	89--350
R4c	conical graupel	$\geq$0.5	1.1-- 7.5	0.1650—110.000	1.07--5.70	210--630
		< 0.5	0.8-- 8.6	0.0580—53.700	0.64--4.08	89--350
---	snow flakes	---	0.5--15.0	0.0019—12.740	0.43--1.51	48--190

3. RESULTS

In contrast to water drops, ice crystals and snow flakes have a larger variety of forms and densities. Therefore, it was necessary to make larger modification in the code for particle trajectory computation. In the first step the partial wind-induced errors e_p were evaluated (Nešpor, 1997). The computations were concentrated on the Hellmann and ASTA precipitation gauges, and those solid particles for which a complete information about the particle shape, density (or mass), and terminal velocity was available (Heymsfield and Kajikawa, 1987; Muramoto et al. 1996).

The comparison of results for various ice crystals showed larger differences. Generally, the lower is the terminal velocity of the crystal, the larger is the partial wind-induced error e_p. The lighter dendrites had the highest partial error which was over 80% for wind velocity v_f = 1.0 m s^{-1}, and on the other hand the heavier lump graupel had the smallest error (Nešpor, 1997).

In order to estimate the integral wind-induced error the particle size distribution has to be known. A snowfall event can contain a variety of different types of ice crystals and snow flakes. This depends on the prevailing conditions at the place of particle origin, and in the layers of the atmosphere through which the particle passes on its way to the ground. Because of that it is very difficult to determine the solid precipitation particle distribution in type and size, and there is not enough literature about this topic published until now. A relative complete information about terminal velocities and distribution of snow flakes can be found in Muramoto et al. (1996). Although they do not describe the type distribution of particles, their data can be used to evaluate the partial error, and the integral wind-induced error as well.

The partial wind induced error for different diameters of snow flakes (Muramoto et al., 1996) was evaluated for wind velocities v_f = 0.5, 1.0, 1.5, 2.0 and 3.0 m s^{-1}. The computed values of e_p were fitted by the gamma probability density function (see Nešpor, 1996).

In the Ulbrich drop size distribution parameter κ determines the type of rain. The only parameter that depends on the rate of rainfall is Λ (Ulbrich, 1983). In the present computations it was supposed that this is valid also for the size distribution of snow flakes, and that snowfall intensities R can be evaluated from different parameters Λ. In the present computations the values of Λ varied between 350 and 1400. This corresponds to R between approximately 8.6 and 0.03 mm h^{-1}.

Similarly to water drops the integral wind-induced error for snow flakes increases with increasing wind velocity and decreasing snowfall intensity. In general, the errors for snow flakes are 5 to 10 times larger than the errors for water drops (Nešpor, 1997).

For the practical use it is convenient to express the rate of snowfall as:

$$R = \eta \, R_m \tag{3.1}$$

where R_m is the rate of snowfall measured by the gauge, and η is the multiplication factor. The integral wind-induced errors can be then recalculated to the form presented in Figure 1.B.1. These diagrams can be used for correction of measured snowfall amounts if the input parameters are known. The intercomparison of the two gauges shows that the ASTA gauge have a larger wind-induced error (larger η values) than the Hellmann gauge.

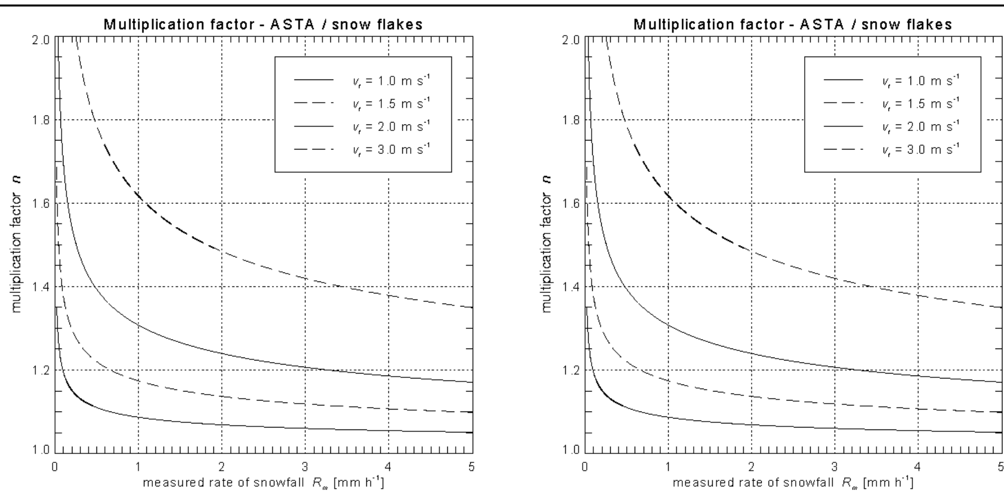

Figure 1.B.1: The multiplication factor h of the Hellmann (top) and ASTA (bottom) precipitation gauges is plotted as a function of the measured rate of snowfall R_m. The multiplication factors were derived from the computed integral wind-induced errors.

4. COMPARISON WITH MEASUREMENTS

The present comparison of computational results and field measurements of wind-induced error is based on the study of Günther (1993) which was actually a part of the WMO solid precipitation intercomparison project (e.g. WMO/CIMO, 1993). The wind-induced error was obtained from the difference between the Hellmann precipitation gauge elevated 1.0 m above the ground, and the reference measurement by the Double Fence Intercomparison Reference (DFIR) (see e.g. Yang et al., 1994). The original snowfall data measured in the period 1986--1993 in Herzgerode (Germany) were subdivided according to air temperature and fitted by lines. The solid line in Figure 1.B.2 represents the resulting fit for the air temperature of 0^oC. The points are computed integral errors for the snowfall intensity of 0.5 and 1.0 mm h^{-1}, respectively. Although snowfall intensities of measurements were not published, it can be expected that they were mostly between 0.5 and 1.0 mm h^{-1}. For example Maurer (1993) reported the mean snowfall intensity of approximately 0.8 mm h^{-1} for 56 precipitation events in the period of two years. Therefore, the intercomparison in Figure 1.B.2 shows good agreement between computations and field measurements. In addition, the computation results agree well also with the field results presented in Sevruk (1985). In this case the wind-induced error was obtained from the difference between elevated Hellmann precipitation gauges and snow samplers at seven locations in Switzerland.

5. CONCLUSIONS

The present study showed possibilities of estimation of the wind-induced error of precipitation measurements by a numerical simulation. The comparison of computational results with error estimates based on real field measurements showed good agreement. In principle, the computational results presented in the form of multiplication factor as a function of the measured rate of precipitation and wind speed (Figure 1.B.1) can be used for fast correction of measured precipitation amounts if the input parameters are known. Although for the snow the computations of integral wind-induced errors were based on one well documented precipitation event it seems that the measured parameters of the snow flakes are quite representative for an average snowfall (the typical range of densities and terminal velocities), and therefore, the resulting diagrams can be used more generally.

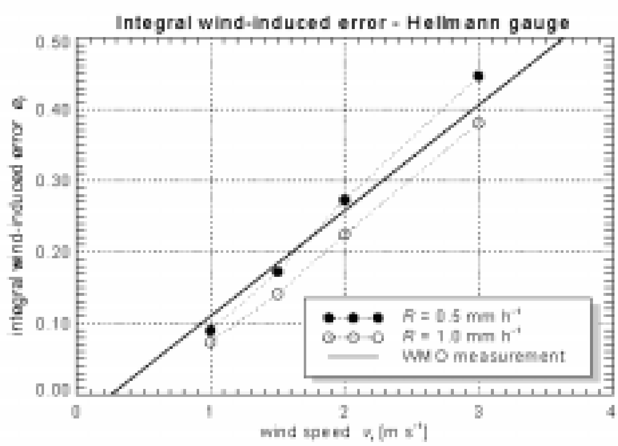

Figure 1.B.2: Comparison of the computed integral wind-induced error of snowfall with the relation based on measurements (Günther, 1993). The solid line approximates the measured data for the air temperature of 0^oC, the points represent computed values of integral wind-induced error for the snowfall intensity of 0.5 mm h^{-1} (filled points) and 1.0 mm h^{-1} (empty points).

The numerical simulation confirmed that there are differences between precipitation gauges. In general, the ASTA precipitation gauge shows higher wind-induced errors (higher multiplication factors η) than the Hellmann gauge. This is caused by the larger flow disturbance introduced by the ASTA gauge body. Furthermore, the computations confirmed that the wind-induced error depends strongly on the free-stream velocity at the level of the gauge orifice, and on the weight of precipitation particles. For the same free-stream velocity the lighter snow flakes show an integral wind-induced error 5 to 10 times larger than water drops. There are also differences between various snow crystals, and the lighter are the crystals, the higher is the wind-induced error (Nešpor, 1997).

But the presented procedure has its limits. They are mainly connected with the fact that the input parameters as the wind speed at the orifice level, rate of precipitation and particle size distribution are not known directly from measurements. There would be a possibility partially to eliminate this disadvantage by replacing the input parameters by some representative averages, but further investigations on real precipitation events are necessary. Specially in the case of snowfall the size distribution of particles and its variation with time is not known.

A further possible utilization of the presented procedure would be for checking the performance of different precipitation gauges, verification of existing and development of new correction procedures, investigation of the influence of different wind shields, and possibly improvement of the gauge shape.

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(B L A N K P A G E)

ANNEX 2 METHODOLOGY

ANNEX 2.A GENERAL DESCRIPTION OF THE SITE REQUIRED FOR THE INTERCOMPARISON

Open site shall be:

(a) flat for a distance of at least 300 m in all directions

(b) as free as possible from the influence of any obstacle such as bushes, trees and buildings that could cause a disturbance of the wind field over the site. No terrain feature shall extend to more than 5 degrees above the extended plane of the site and all objects shall be a distance of 20 times their height above the gauge orifice or their maximum horizontal dimensions. The height of objects above the horizon may be increased to 7 to 10 degrees where the obstacle is over 1 km away. In a case where these requirements cannot be met in all directions, the data obtained when the wind is blowing from these obstructed directions should be discarded

(c) uniform as to vegetative cover which should not exceed 30 cm in height

(d) fenced for protection from large animals in case any instruments are installed within reach. The fence should be constructed of small diameter wooden or steel posts and barbed wire (4 or 5 strands) with posts no closer than 20 times the post height above the height of any instrument and at least 5 m from any gauge

Notes: In cases when a forest clearing is used as an additional Intercomparison reference site, the gauge in the clearing shall be:

(a) in a forest of uniform height located in the vicinity of the open site, such that the angle from the gauge orifice to the top of the trees is between 300 and 450 (the distance from the gauge to the trees is not less than the height of the trees above the gauge)

(b) in a peripheral forest stand extending for at least 500 meters in all directions. (In case a site is lacking the specified border stand for a portion of the perimeter, data for wind blowing toward or away from the gauge in the direction of the inadequate forest protection should be discarded)

(c) Since the experiment will extend over 4 years and if the forest is not mature, allowance for growth of the trees during the study period must be considered

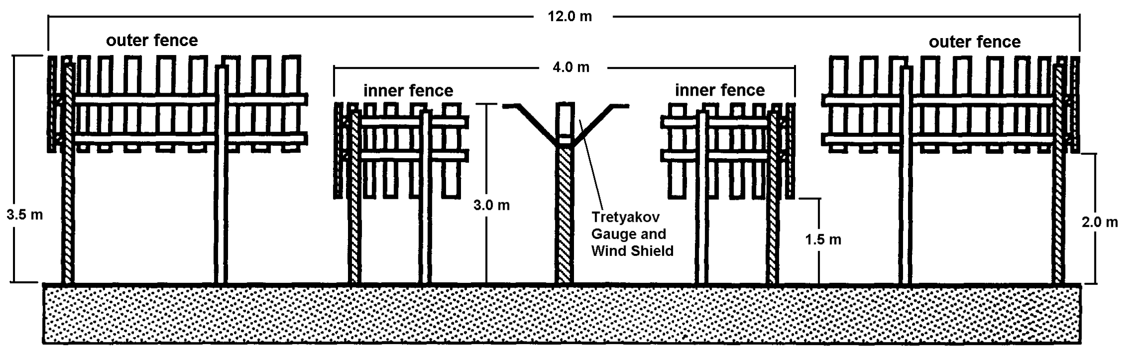
ANNEX 2.B DESCRIPTION AND INSTALLATION INSTRUCTIONS FOR THE DOUBLE FENCE INTERCOMPARISON REFERENCE(DFIR)

1. GENERAL DESCRIPTION

A double fence is used to attenuate wind effect at the level of the receiving surface of the Tretyakov gauge and to transform eddies with horizontal axes into eddies with vertical axes. The shield is a combination of two concentric octagonal fences. The outer fence (view from above) is an octagon inscribed into a circle 12 m in diameter. Every side of this octagon is 4.6 m long. The fence is 3.5 m high above the ground. The space between the lower edge of the laths and the ground in 2.0 m. To prevent the fence sides against sagging the supports are installed in the middle of the fence walls. The inner fence (view from above) is an octagon inscribed into a circle 4.0 m in diameter. The side of the inner octagon is 1.6 m long. The inner fence is 3.0 m high above the ground. The space between the lower edge of the fence and the ground is 1.5 m. Lath dimensions 150 cm long, 5 cm wide, 2.5 cm thick. The laths are spaced 5 cm from one another.

The Tretyakov gauge in placed in the centre of this double-fence installation in such a way that its receiving surface is 3.0 m above the ground. It is not recommended to install the receiving surface of the gauge higher than the upper edge of the laths of the inner fence and lower than 10 cm from this level. At the selection of the site for a double fence elevated topography is preferable; places subject to severe snow storm affects should be avoided.

Figure 2.B.1 Cross section of WMO Double Fence Intercomparison Reference (DFIR)



When the double fence is installed on a slope the height of outer and inner fences should be changed in a way that the planes of the upper and lower edges of outer and inner fences will be horizontal. Vertical dimensions (fence height and height of openings between laths) should correspond to the values shown in the Figure 2.B.1 in the cross-section area passing across the centre of the double-fence installation, perpendicular to the direction of the slope fall. If it is necessary to paint the fences, the paints should have low characteristics of albedo for short-wave radiation.

2. CONSTRUCTION OF DFIR USING WOOD DIMENSIONS AVAILABLE IN NORTH AMERICA

(Submitted by Canada)

2.1 Materials and tools required

Basic tools required for construction are: hammer, saw, level, line level, string, 8-foot step ladder (2), shovel, soil auger. Two people can assemble most of the shield; however, three will be needed to dig holes and install fence panels. Table 2.B.1 list the material required to construct one DFIR.

2.2 Construction

Snow fence sections are built in 1 inch x 2 inch x 150 cm slats are nailed, with 2 inch spacing, to 1 inch x 3 inch x 5 feet cross members for the inside fence. Slats are nailed, with 2 inch spacing, to 1 inch x 3 inch x 8 feet cross members to form the outside fence section. Pay particular attention to the length of slat above and below cross members. It is different for inside and outside fences. 1.5 inch nails or staples are used for construction of fence sections. In low snowfall areas it will not be necessary to build a gate section as one can duck under the fence for access to the gauge.

Pick a flat, level area approximately 40 ft in diameter to place the shield. To survey the area for positioning of 4 inch x 4 inch x 12 feet upright posts, a ball of string and some stakes are useful. Determine position of first post on outer fence and insert stake (point 1). From this point, run string diagonally across to its counterpart on the opposite side of outside fence 1200 cm away and drive in a stake (point 2). Determine and mark centre point of string. Insert a stake at the centre point. From centre point measure 600. cm and from point 1 measure 460 cm. At the intersection of these points put a stake (point 3). From point 3 run string across to point 4, 1200 cm away and 460 cm from point 2. Continue to do this until all 8 main outside fence post positions which form the octagon are marked. The centre point is now clearly established at the intersection of the strings. Measure out 200 cm from the centre along each string to determine the position of the 8 sides of the octagon between the 8 main posts (230 cm) resulting in a total number of 16 points for uprights on the outside fence.

Dig post holes (6 inch auger) and install 4 inch x 4 inch x 12 foot posts 100 cm, or approx. 30 inches, in the ground. Using string and line level an attempt should be made before back filling the holes to assure that the top of the inner and outer fences are level, especially if the ground slopes, before back filling the holes. Ensure upright 4 x 4's are vertical by using a level.

Install 8 inner fence panels and 16 outer fence panels as per diagram using 3 inch nails. Heavy wire may also be used in addition to nails to attach fence panels to uprights. Install 2 inch x 4 inch x 16 foot support posts from base of inside fence upright to top of outside fence upright to strengthen and support the fence as required. 2 x 4 x 12's may be used to support outside fence required. This extra support in not shown in diagram but may be required in areas of high winds. Guy wire may also be used to give additional support.

Tretyakov gauge is installed on centre post level with the top of the inner fence of the shield. When assembled, the DFIR will consist of two concentric octagonal rings of snow fence with a Tretyakov gauge mounted on a post in the centre. The bottom of the outer fence is 200 cm off the ground; the inner fence is 150 cm above the ground. The height of the outer fence is 3.5 m and the height of the tip of the inner fence is 3.0 m. There are 16 upright posts supporting 16 sections of fence in the outer ring and 8 uprights posts supporting 8 sections of fence in the inner ring. The diameter of the outer ring is 1200 cm and the diameter of the inner fence is 400 cm.

Table 2.B.1 List of materials required to construct Double-Fence Intercomparison Reference Shield (DFIR):

Description	**Units**	**Quantity of Order**
Pressure Treated Wood		
4 inch x 4 inch x 12 feet (16 outer uprights, 8 inner uprights, 1 centre = 25 required)	ea	25
3 inch x 1 inch x 8 feet (2 ea for outer fence section cross members (230 cm) = 32 required)	ea	35
3 inch x 1 inch x 10 feet (cut in half, 2 ea 5 ft or 160 cm for inner fence section cross members = 8 required)	ea	10
2 inch x 1 inch x 10 feet (cut in 150 cm lengths for fence section slats)	ea	300
2 inch x 4 inch x 16 feet (support posts as required)	ea	6
2 inch x 4 inch x 12 feet (support post as required)	ea	10
Nails		
1.5 inch galvanized spiral	lb	15
3.0 inch galvanized spiral	lb	8

Note: Some of the dimensions given above will have to be cut by the supplier from larger stock sizes (i.e. 1 x 6 cut to give three 1 x 2's). Some waste will occur due to imperfection in the wood when cut (i.e. knots). The quantities to order, given above, take into account this waste. Wood dimensions must be ordered in Imperial units resulting in the need to work with mixed units when building this shield. Imperial measurements are very close to the required metric dimensions specified. Use of pressure treated wood will eliminate the need to paint the shield to preserve the wood.

ANNEX 2.C SPECIFICATIONS AND DETAILS OF THE TRETYAKOV GAUGE (WORKING NETWORK REFERENCE)

1. GENERAL DESCRIPTION

The precipitation gauge has cylindrical casing (3) (see Fig.2.C.1) used to collect precipitation. Inside the casing there is a cone with a drain hole. In summer time, to reduce evaporation, the cone hole in covered with a funnel. Soldered to the casing externally is flute (7) to drain the collected precipitation. The flute in covered with cap (6) which in attached to the casing by chain (5). The casing in installed in bracket (9) and (11) which is secured by screws (12) to pole (10). To protect the casing against precipitation when it in carried over, the casing in closed with a cover. The gauge casing is placed inside a plate protection consisting Of fifteen plates (1) bent to a specific pattern. The upper ends Of the plates are bent outwards and must be aligned horizontally with the casing upper edge. Each protection plate has two cutouts with eyes to pass ring (2) which is attached to the pole together with the bracket by three braces (8). The protection plates are evenly spaced on the ring and successively fastened with hooks (4) and (13). The amount of precipitation collected in the casing is measured by a calibrated measuring glass. One division of the glass corresponds to 2 cm^2, which, with the casing receiving area of 200 cm^2, is equal to a precipitation layer of 0.1 mm.

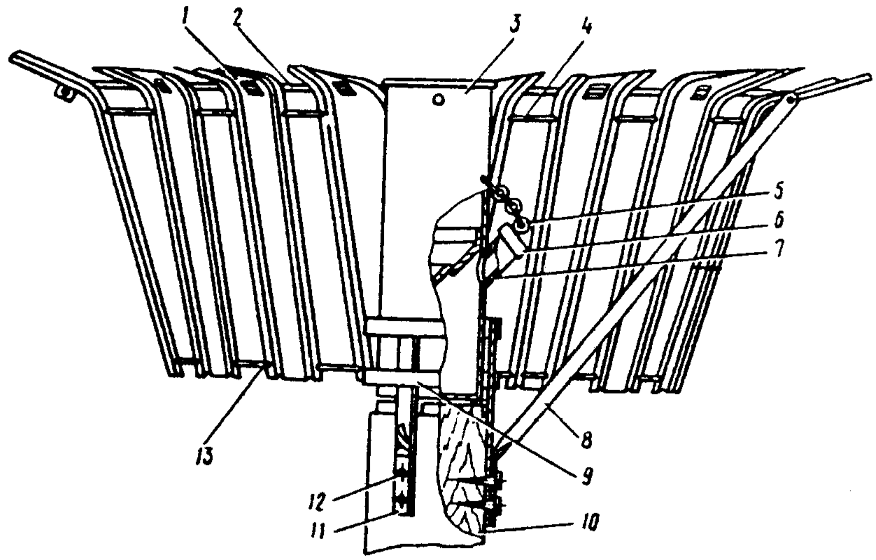


Fig. 2.C.1 Tretyakov Precipitation gauge
(1) plate; (2) protection ring; (3) casing; (4, 13) hooks; (5) chain; (6) cap; (7) flute; (8) brace; (9, 11) brackets; (10) pole; (12) screw

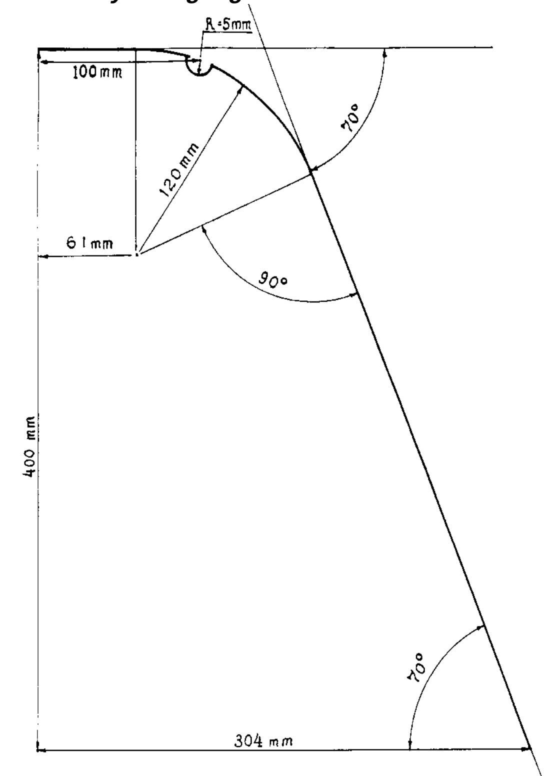
2. CONDITIONS FOR MAKING MEASUREMENTS

The Tretyakov precipitation gauge is installed on the plot for intercomparison on a special support such that the receiving surface of the gauge is 2 m above the ground surface and it is strictly horizontal.

The properly assembled precipitation gauge should meet the following requirements:

- the planed shield should be cone-shaped and the angle of plane declination should be 70^o to the horizon;
- the upper flanged edges of the planes should be horizontal to the surface and they should be at the same level with the upper edge of the receiving vessel, placed in the trivet;
- the shield planes should be fix to provide free vibrations under wind effect and to return to the initial position;
- the planes should be bent in such a way that this bend should correspond to the profile of a special pattern (see Figure 2.C.2); and
- the vessel for precipitation collection should be freely inserted into the trivet and easily taken away.

Figure 2.C.2 Pattern to verify the bond of plates in the Tretyakov gauge shield



In places where snow pack is deeper than 1 m, an additional support (or a pile) and a ladder should be available for precipitation gauge mounting. They should be 1 m higher than the support and the ladder applied in usual conditions. The precipitation gauge should be place on the additional support when mean depth of the snow pack exceeds 60 cm. In spring when snow pack depth will be less than 60 cm, the gauge should be placed on the main support.

All the changes in the installation of precipitation gauge should be registered.

3. OPERATION PROCEDURE AND MAINTENANCE

At an appointed time the observer brings a covered empty casing and replaces the installed one; then he takes off the cover and puts it on the removed casing. The casing in brought into a room where the collected precipitation in drained into the measuring glass (solid precipitation should be melted). The amount of precipitation (in mm) is equal to the number of glass divisions divided by ten. The readings are taken in terms of the glass whole divisions in the lower part of the water concave meniscus.

The gauge casing, when in use, should be regularly (at least twice a month) washed with hot water and checked for leakage. For this purpose, pour water into the casing up to the level where the flute is soldered in, wipe its outside dry and put the casing on a dry clean board or paper for 1 or 2 hours. In case of leakage, the leak point should be sealed. In winter, regularly clean the protection to remove snow.

It is necessary to check carefully that no snowdrifts are accumulated around the gauge. In case of snow-drifts they should be cut by a spade and taken away, care should be taken not to come to the installation too closely.

ANNEX 2.D STATION REPORT AND SITE DESCRIPTION

Type of site (open or protected).............................…………………………………………………........
Country...................................……………………………………………………………...........................
Station Name................................ Index No.................
Lat..................................... Long....................................
Elevation (m)...……..........
Nearest city... km.....……........
Description of surroundings (major topographic features, their effect on climate, prevailing wind, etc.)
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Instruments (type, gauge orifice area should be estimated for each gauge measuring the diameter in 4 directions model, height above ground for each instrument)
....………………………………………………………………....
....………………………………………………………………....
....………………………………………………………………....
....………………………………………………………………....
....………………………………………………………………....

The following should also be included with this reports

- topographic chart (1:100,000 recommended) showing location of station
- plan of local area (1:500 recommended)
- vertical angle of obstacles measured in degrees (3600 in 16 points of the wind rose to the distance of 300 m)
- four photographs of instrumented site

Station Name.................................... Index No.............

<u>Drawings and Dimensions of Official National Gauge*</u>

<u>Collector</u> **<u>Windshield</u>**

Attach drawings and dimensions of other gauges or instruments as might be appropriate

*Attach pictures

ANNEX 2.E WMO SOLID PRECIPITATION MEASUREMENT INTERCOMPARISON CLIMATOLOGICAL DATA SUMMARY

Table 2.E.1 WMO solid precipitation measurement intercomparison climatological data summary form

WMO SOLID PRECIPITATION MEASUREMENT INTERCOMPARISON
DAILY AND MONTHLY CLIMATOLOGICAL DATA SUMMARY

COUNTRY ____________ STATION ____________ MONTH ________ YEAR ________

DAY	TIME OF OBS	TEMP		PRED WIND DIR. (DEG.)	MEAN WIND SPEED (ms^{-1})				DEPTH NEW SNOW (cm)	PRECIPITATION AMOUNT, mm CORRECTED FOR WETTING AND EVAPORATION										TYPE OF PRECIP	TYPE OF SNOW	DUR. OF SNOW-FALL (HRS)	COMMENTS
		MAX °C	MIN °C		NAT. STAND	NAT. GAUGE HT.	DFIR	2 m		DFIR	TRET.	NAT. SH.	NAT. UNSH.	SNOW BOARD									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24

Explanation of WMO solid precipitation measurement intercomparison climatological data summary form

SECTION	TITLE	EXPLANATION
1	Day	Day of month
2	Time of observation	Time of day (GMT)
3	Max Temp	maximum (^{o}C) observed at time of observation
4	Min Temp	minimum (^{o}C) observed at time of observation
5	Predominant wind	predominant wind direction in degrees (DEG) to 16 points of the compass during the observation (e.g. N-360^{o}, NNE-22^{o}, NE-45^{o}, E-90^{o}, etc.)
6	Mean wind speed national standard	mean wind speed (m/s) during period since last observation measured from anemometer installed at height of national standard (e.g. 10 m)
7	Mean wind speed national gauge height	as above but at same height as national gauge
8	Mean wind speed DFIR gauge height	as above but at same height as DFIR gauge
9	Mean wind speed 2 m	as above but at 2 m
10	Depth new snow	depth of fresh snowfall depth deposited to nearest 0.2 cm during snow event period
11-20	Precipitation amount (measured by various gauges)	total precipitation measured for snow event period in mm. Precipitation amount reported is to include correction for wetting and evaporation losses. Trace amounts (less than a measurable amount of snow in the gauge) should be recorded as “T”
21	Type of Precipitation	Description of type according to following:

	Phenomena	Symbol
1.	Snow	S
2.	Snow with rain	SR
3.	Rain with snow	RS
4.	Freezing rain	ZR
5.	Rain	R

22	Type of Snow	Description of type of snow during the snow event period of observation or snow event according to following:

	Phenomena	Symbol
1.	wet snow	SR
2.	heavy snowfall	S+
3.	light snowfall	S--
4.	snow storm (shower)	SW
5.	drifting snow	DS
6.	blowing snow	BS
7.	snow grains or pellets	SG

23	Duration of snowfall	duration of snowfall during the period since last observation (in hours). Duration of snowfall should be classified as follows: c - for continuous, i - for intermittent
24	Comments:	observers should note special conditions which affect gauge measurement (i.e. blowing snow, “BS”). Weather at time of observation should be recorded. Problems of measurement should be recorded, for example: instrument failures gauges out-of-level leakage of gauge contents
25	Monthly summary precipitation totals	monthly sums of all daily precipitation totals (mm), including depth of new snow (cm) (columns 10-20)
	Mean temperature	monthly mean maximum and mean minimum temperatures derived from daily maximum and minimum temperatures (^{o}C) (columns 3-4)
	Mean wind speed	monthly mean wind speed derived from daily mean wind speeds (m/s) (columns 6-9)
	Predominant wind direction	predominant wind direction in degrees to 16 points of the compass during the month

ANNEX 2.F WMO SOLID PRECIPITATION MEASUREMENT INTERCOMPARISON SNOW EVENT DURATION DATA

Table 2.F.1 WMO solid precipitation measurement intercomparison snow event duration data form

WMO SOLID PRECIPITATION MEASUREMENT INTERCOMPARISON
SNOW EVENT DURATION DATA DURING THE WINTER SEASON

COUNTRY ____________

STATION ____________

SNOW EVENT PERIOD							TEMPERATURE			PRED. WIND DIR. (DEG.)	MEAN WIND SPEED (ms^{-1})				DEPTH NEW SNOW (cm)	PRECIPITATION TOTAL, mm CORRECTED FOR WETTING AND EVAPORATION										TYPE OF PRECIP	TYPE OF SNOW	COMMENTS
BEGINNING				ENDING																								
YEAR	MONTH	DAY	TIME	MONTH	DAY	TIME	MAX °C	MIN °C	MEAN °C		NAT. STAND	NAT. GAUGE HT	DFIR	2 m		DFIR	TRET.	NAT. SH	NAT. UNSH	SNOW BOARD								
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29

Explanation of WMO solid precipitation measurement intercomparison snow event duration data form

Note: a “Snow event period” is defined as a period of the time during which a discrete snowfall event occurs, resulting in a precipitation accumulation in the DFIR of $\geq$ 3 mm

SECTION	TITLE	EXPLANATION
1	Year	Year of observation
2,5	Month	Month of year for beginning and ending snow event period
3,6	Day	Day of month for beginning and ending of snow event
4,7	Time	Time of day (GMT) for beginning and ending of snow event period
8	Max Temp	maximum (^{o}C) observed during snow event period
9	Min Temp	minimum (^{o}C) observed during snow event period
10	Mean Temp	mean (^{o}C) observed during snow event period
11	Predominant wind	predominant wind direction in degrees (DEG) to 16 points of the compass during snowfall (e.g. N-360^{o}, NNE-22^{o}, NE-45^{o}, EN-90^{o}, etc.)
12	Mean wind speed national standard	mean wind speed (m/s) during snow event period measured from anemometer installed at height of national standard (e.g. 10 m)
13	Mean wind speed national gauge height	as above but at same height as national gauge
14	Mean wind speed DFIR gauge height	as above but at same height as DFIR gauge
15	Mean wind speed 2 m	as above but at 2 m
16	Depth new snow	depth of fresh snowfall depth deposited to nearest 0.2 cm during snow event period
17-26	Precipitation amount (measured by various gauges)	total precipitation measured for snow event period in mm. Precipitation amount reported is to include correction for wetting and evaporation losses. Trace amounts (less than a measurable amount of snow in the gauge) should be recorded as “T”
27	Type of Precipitation	Description of type according to following:

	Phenomena	Symbol
1.	Snow	S
2.	Snow with rain	SR
3.	Rain with snow	RS
4.	Freezing rain	ZR
5.	Rain	R

28	Type of Snow	Description of type of snow during the snow event period of observation or snow event according to following:

	Phenomena	Symbol
1.	wet snow	SR
2.	heavy snowfall	S+
3.	light snowfall	S--
4.	snow storm (shower)	SW
5.	drifting snow	DS
6.	blowing snow	BS
7.	snow grains or pellets	SG

-every day with drifting or blowing must be clearly noted
-duration of snowfall should be classified as follows:
c - for continuous, i - for intermittent

29	Comments:	observers should note special conditions which affect gauge measurement (i.e. blowing snow, "BS"). Weather at time of observation should be recorded. Problems of measurement should be recorded, for example: instrument failures gauges out-of-level leakage of gauge contents

ANNEX 2.G OBJECTIVE EVALUATION ON THE HOMOGENEITY OF A COMPARISON

As noted in Chapter 2, section 2.4.2, the Committee discussed the need to know something about the homogeneity of an observing site. Members were requested to operate concurrently at least one and preferably two additional national standard gauges at different locations at the evaluation station for one year to assess homogeneity of the intercomparison field.

A method for the evaluation of homogeneity was reported by Golubev (1985). He suggested that the reliability of precipitation data is dependent not only on the gauge design but also on observational methods, weather during and after precipitation, the type of precipitation and specific features of the site where precipitation gauges are compared. There is no need to describe all the requirements of a site selected for the intercomparison of precipitation gauges since some deviations would occur in practice. However, preference is given to a location with the following desirable characteristics:

- a relatively flat terrain
- a large enough area to allow for precipitation gauges to be spaced from each other at a distance sufficient to eliminate the effects of adjacent gauges and other obstacles surrounding the site
- any obstacles causing wind effects are far enough from the gauges to have minimum effect or are evenly distributed around the site.

Depending on the peculiarities of the terrain the orientation of a site may be quite different. Most of the gauges should be placed along the line perpendicular to prevailing storm winds. Instruments should be installed such that those with small horizontal dimensions are arranged in front of big and/or high instruments.

An objective characteristic of initial information quality obtained on a site is the measure of the relative error of this information. This statistic characteristic is computed on the basis of data of concurrent observations by two or more precipitation gauges of the same type. Therefore, it is desirable to install several additional national rain gauges at the ends of the site (or at most remote points, or along the line of the greatest deformations of the wind field) and to make about 100 concurrent precipitation measurements.

The measure of the relative error of initial data from of this observation series can be computed from the following equation:

$$\eta = \frac{\sigma_{\Delta p}}{\sigma_{\dot{p}}} = \frac{\sqrt{1-\bar{r}(o)}}{\sqrt{\bar{r}(o)}}$$

where:

σ_p random mean square-root error of initial data, in mm;

$\sigma_{\dot{p}}$ natural variability of the considered precipitation time series at the absence of random errors of observations, in mm;

$\bar{r}(o)$ mean coupled correlation coefficient for concurrent observation data obtained from the instruments of the same type.

If a site meets the requirements of intercomparison and the observation series is long enough, the following conditions will be followed:

(a) mean precipitation depth out of a number of concurrent observations by national (of the same type) gauges number 1, 2,... i will be practically the same, i.e.

$$\overline{P} \approx \overline{P}_1 \approx \overline{P}_2 \approx \ldots \approx \overline{P}_i$$

(b) mean root-square deviation of the observation series for every of such gauges will be approximately the same, i.e.

$$\sigma_p \approx \sigma_{p_1} \approx \sigma_{p2} \approx \ldots \approx \sigma_{pi}$$

Mean root-square deviation is computed from the following formula:

$$\sigma_{pi} = \sqrt{\frac{\sum (P_{ij} - \overline{P}_i)^2}{n-1}}$$

where

P_{ij} is total precipitation according to the i-th gauge for the j-th time interval;

$\overline{P}_i$ is mean precipitation depth according to the i-th precipitation gauge;

n is the number of time intervals for concurrent observations.

The natural variability of the considered precipitation series $(\sigma_{\dot{p}})$ is connected with mean root-square deviation (σ_p) by the following equation:

$$\sigma_p = \sigma_p \sqrt{\bar{r}(0)}$$

Thus, on the basis of a number of concurrent observations of precipitation (using one type of gauge) it is possible to evaluate not only the measure Of the random error of initial data (η), but its absolute value as well $(\sigma_{\Delta p})$:

$$\sigma_{\Delta p} = \sigma_p \sqrt{1 - \bar{r}(0)}$$

Later this data may be applied to evaluate accuracy characteristics of actual precipitation, computed in accordance with the selected (or developed) methods of correction.

The Table 2.G.1 below gives statistical parameters and the values of errors of initial data obtained at the Valdai site in Russia for 12-hour intervals. Observations were made on an open site by six Tretyakov gauges installed at the elevation of 2 m. Four gauges were placed at the corners of the square site of 100 m x 100 m and two gauges were placed in the centre of this site spaced 12 m from each other.

Table 2.G.1 Empirical (Sampling) Statistical Parameters and Mean Root-Square Errors of Initial Data

Total precipitation for 12-hour interval

STATISTICAL PARAMETERS & ERRORS	UNIT	RAIN	MIXED PRECIPITATION	SNOW
$\overline{P}$	mm	8.6	3.8	3.2
σ_p	mm	4.44	1.39	1.95
$\overline{r}(0)$		0.970	0.917	0.945
$\sigma_{\dot{p}}$	mm	4.38	1.33	1.90
η	mm	0.18	0.30	0.24
$\sigma_{\Delta p}$	mm	0.79	0.40	0.46
$\sigma_{\Delta p} / \overline{P} \bullet 100$	%	9	11	14

References

Golubev, V.S., 1985: *On the problem of actual precipitation measurement at the observation site*. Proc. International Workshop on the Correction of Precipitation Measurements, WMO/TD No. 104, WMO, Geneva, 60-64.

ANNEX 2.H ADJUSTMENT FOR UNDERCATCH OF THE DOUBLE FENCE INTERCOMPARISON REFERENCE (DFIR) GAUGE

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1. INTRODUCTION

For the WMO Solid Precipitation Measurement Intercomparison study to be successful, it was necessary to designate a reference standard for measuring snowfall precipitation against which all other measurements could be compared. After reviewing all possible practical methods of measuring "true" snowfall in a variety of climatic environments the organizing committee designated the octagonal vertical double fence (with Tretyakov gauge) as the Intercomparison Reference Gauge (Goodison et al.,1988). Golubev (1986) stated that even the DFIR measurements, compared to the shielded Tretyakov gauge measurements in a sheltered bush site at the Valdai hydrological research station in Russia, are adversely affected by wind speed. He developed a correction equation for the DFIR measurement which uses wind speed, atmospheric pressure, mean air temperature and mean air humidity to correct the DFIR measurement to the shielded bush site (Golubev, 1989). Analysis of the Golubev equation showed that for the same site, atmospheric pressure and humidity have little effect and the equation could be simplified to consideration of air temperature and wind speed only (Goodison and Metcalfe, 1992). To ensure the best possible results from the Intercomparison and to incorporate data recently collected at Valdai as part of the Intercomparison, it was felt necessary to re-assess the DFIR correction procedure. Using the Valdai twice daily observations from 1970 through 1990, this study investigates the relationship between the DFIR and the shielded Tretyakov gauge in the bush (bush gauge) and assesses the factors contributing to any significant differences between the two gauges.

2. SITE AND INSTRUMENTATION

The Valdai hydrological research station is situated on the flat shore of Valdai lake. There are two DFIR's installed at the station in an open area of 200x200m with no nearby significant obstructions. Approximately 300m from the open site is the "bush gauge" (Tretyakov gauge with wind shield) placed in 2-4m high shrubs in a three hectare area. Within the 12m diameter working area of the gauge the shrubs are cut routinely to the gauge height of 2m. This gauge has been accepted as the working reference for winter precipitation measurement at Valdai station since 1970.

The bush gauge is considered as the most appropriate reference, i.e. "true" measurement for solid precipitation at this time and is comparable to the pit gauge for measuring rainfall (WMO, 1991). The gauges in both the open and bush sites at Valdai are measured twice a day at 0800 and 2000 (local time). The contents of the gauges were both weighed and measured volumetrically to determine precipitation amount and over a period of time an average wetting loss was determined. Since 1966, a correction for wetting loss of the Tretyakov gauge has been added to every volumetric precipitation measurement and therefore no additional correction for this systematic loss is required.

Wind speed and direction were measured at 2m height before September 1989 and a linear equation was used to estimate the wind speed at the DFIR height of 3m. Since then, wind speed at 3m has been measured directly. Atmospheric pressure, air temperature and humidity were also measured at the site.

3. DATA ANALYSIS

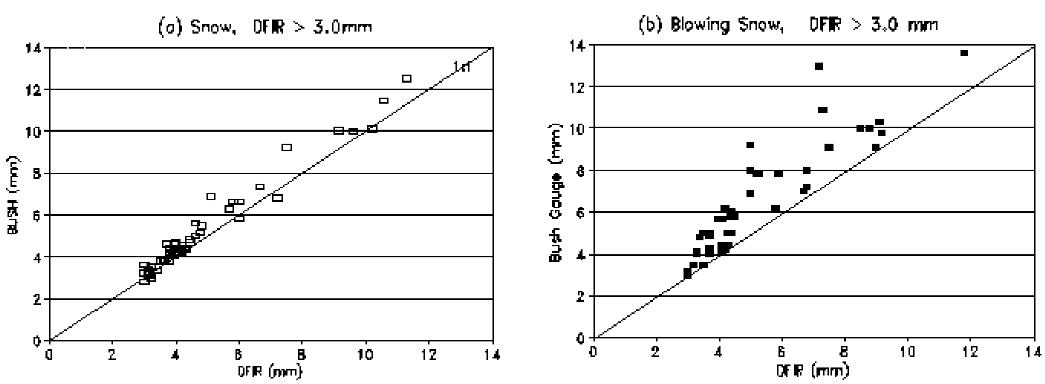
All of the Valdai precipitation data and auxiliary meteorological measurements measured from 1971 to 1978, and from 1988 to present have been submitted to the WMO Intercomparison international archive. Analysis focused on the gauge catch ratio of the DFIR to the "bush gauge" as a function of wind speed at the height of the DFIR. In order to minimize the scatter in the ratio of bush gauge to DFIR that could occur when assessing small absolute differences between gauges for small precipitation events, only amounts when the DFIR measurement was greater than 3.0mm were used in this analysis. For the period of October 1970 through April 1990, 368 twelve hour observations of precipitation greater than 3.0mm were recorded. The bush gauge measurements were found to be systematically higher than those of the DFIR for all types of precipitation. A strong linear relationship was found to exist between the two gauges except during blowing snow events (Figure 2.H.1a, b). On average, the bush gauge caught 6.4, 8.5 and 10.8% more than the DFIR for rain, rain and snow mixed and snow, respectively (Table 2.H.1).

Table 2.H.1 Summary of all twice daily observations at Valdai WMO Intercomparison site

Type of Precip	# Obs	Tx (^{o}c)	Tn (^{o}c)	Ws (m/s)	BUSH (mm)	DFIR (mm)	B/D (%)
Rain	122	7.7	5.0	4.0	822.8	773.0	106.4
Mix.	88	2.0	-0.9	4.6	606.7	559.2	108.5
Snow	158	-1.7	-4.4	4.7	825.4	744.7	110.8

Notes: Tx = mean maximum air temperature; Tn = mean minimum air temperature;
Ws = mean wind speed at 3 meters; B/D = BUSH / DFIR.

Figure 2.H.1. Bush gauge against the DFIR at Valdai WMO Intercomparison site.



Golubev (1992) analyzed winter precipitation totals for 35 months from November 1971 through December 1978, without consideration of blowing snow, and found that the DFIR at Valdai station gave 9% lower totals than the bush gauge. According to the report of WMO/CIMO (1985), types of snowfall occurrences should be described as light, moderate or heavy in intensity; wet snow, snow storm (shower), snow grains or pellets and every day with drifting or blowing snow was to be identified. Review of the original Valdai data observation sheets revealed that blowing snow was a serious problem at this site. There were 55 blowing snow cases in the total of 158 snow only events. Statistical analysis showed that blowing snow generally takes place at a wind speed above 5m/s at this location. For the blowing snow cases (Table 2.H.2), the ratio of bush/DFIR is about 10% higher for winds blowing from the two southern quadrants, i.e. from the direction of the lake, than from the northern quadrants. During blowing snow events, the bush gauge at 2m caught, on average, 18% more snow than the DFIR at 3m height, for all wind directions. However, the average ratio of bush to DFIR, over all wind directions, is only 107-108% for both wet snow and dry snow conditions. In dry snow cases, the ratio does not change much with wind direction, except that the lowest ratio does occur with the lowest mean wind speed. The lowest wind speed is from the northwest quadrant which is the location of a forested area. For the wet snow events, the highest ratio is associated with southwest winds and the lowest with northwest winds. It is notable that the average highest winds, from the northeast, do not lead to a corresponding higher catch ratio or conversely a lower snowfall gauge catch, for any of the conditions, i.e. dry snow, wet snow or blowing snow. This fact strongly indicates the important influence of not only wind speed but wind direction to precipitation gauge catch at the Valdai site.

Table 2.H.2 Summary of the snow only observations (DFIR > 3.0mm)

WD (deg)	*# event*	*Tx (^{o}c)*	*Tn (^{o}c)*	*Ws (m/s)*	*BUSH (mm)*	*DFIR (mm)*	*B/D (%)*
a) Dry Snow (Tmax < -2.0 ^{o}C)							
1 - 90	12	-4.3	-6.7	4.3	65.5	61.1	107.2
91-180	12	-2.9	-6.0	4.0	65.1	59.5	109.4
181-270	16	-1.1	-3.2	4.0	80.4	72.9	110.3
271-360	14	-2.2	-4.3	3.3	68.5	65.7	104.3
All Dir	54	-2.5	-4.9	3.9	279.4	259.1	107.8
b) Wet Snow (-2.0 ^{o}C < Tmax < +2.0 ^{o}C)							
1-90	3	0.8	-0.7	4.9	15.4	14.3	107.7
91-180	8	0.7	-0.5	4.2	37.2	32.8	113.4
181-270	21	0.6	-1.5	4.4	108.5	102.8	105.5
271-360	5	-0.3	-3.7	4.2	26.9	26.0	103.5
All Dir	37	0.5	-1.5	4.4	187.9	175.8	106.9
c) Blowing Snow							
1- 90	4	-2.2	-6.0	6.4	19.7	17.6	111.9
91-180	13	-2.8	-5.0	5.7	85.5	71.4	119.8
181-270	25	-2.5	-6.0	5.9	142.9	118.6	120.5
271-360	13	-3.1	-7.7	5.2	78.0	68.8	113.4
All Dir	55	-2.7	-6.1	5.7	326.1	276.4	118.0

Notes: WD = wind direction; Tx, Tn and B/D are the same as those in Table 2.H.1.

Regression analyses were conducted to assess the effect of wind speed, air temperature, relative humidity and atmospheric pressure as reported by Golubev (1989), but after separating the data set into the three classes given above and for rain and snow mixed and rain only. The analysis indicates that for dry snow, wet snow and blowing snow events, the bush/DFIR ratio does not relate significantly to surface air temperature, humidity or atmospheric pressure and the only statistically significant factor is the mean wind speed during the storm. Figures 2.H.2a to 2.H.2f show the best fit curves obtained by means of the least square estimation for the various types of precipitation. The equations for these are given below:

Dry Snow:

$$\text{BUSH/DFIR}(\%) = 100+1.89*W_S+6.54E\text{-}4*W_S^3+6.54E\text{-}5*W_S^5, \quad (N=52, R^2=0.37) \quad (1)$$

Wet Snow:

$$\text{BUSH/DFIR}(\%) = \exp(4.54+0.032*W_S), \quad (N=36, R^2=0.43) \quad (2)$$

Blowing Snow:

$$\text{BUSH/DFIR}(\%) = 100.62+0.897*W_S+0.067*W_S^3, \quad (N=54, R^2=0.37) \quad (3)$$

Rain with Snow:

$$\text{BUSH/DFIR}(\%) = 101.67+0.254*W_S^2, \quad (N=39, R^2=0.38) \quad (4)$$

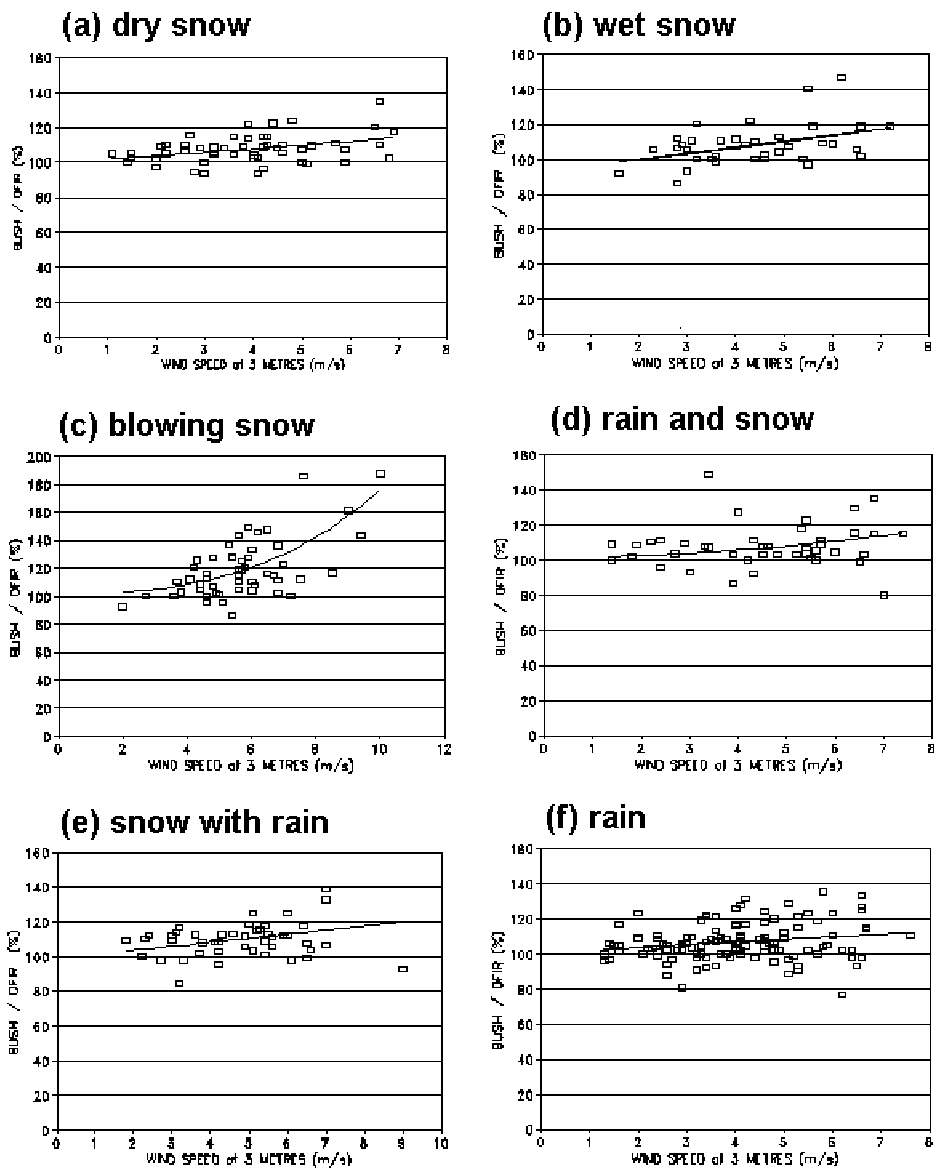
Snow with Rain:

$$\text{BUSH/DFIR}(\%) = 98.97+2.30*W_S, \quad (N=43, R^2=0.34) \quad (5)$$

Rain:

$$\text{BUSH/DFIR}(\%) = 100.35+1.667*W_S-2.40E\text{-}3*W_S^3, \quad (N=120, R^2=0.22) \quad (6)$$

Figure 2.H.2. Ratio of bush gauge to the DFIR as a function of wind speed at the DFIR height of 3 meters.



4. RESULTS

Table 2.H.3 compares the catch efficiency of the DFIR to the bush gauge, i.e. "true" measurement at Valdai, as reported by Golubev (1986) and the recent analysis using the precipitation types defined at the beginning of the intercomparison (WMO, 1985). Wind speed during the storm period is the most statistically significant variable affecting catch. While the catch of the DFIR when there is no wind is very close to true, it measures on average about 90% of "true" for winds of 6 m/s. The difference in catch ratio as a function of precipitation type at the same wind speed is small, being about 2% between dry snow and rain. This is an important point because it supports the use of the DFIR as a reference - ideally the DFIR would measure the same as the bush gauge for all types of precipitation.

One could argue that use of different correction equations for different types of precipitation is not necessary, especially considering the inherent scatter in the measurements. Since the intercomparison depends on the DFIR as the reference for all other gauges, even small systematic differences have to be accounted for. We recommend separating the data and using the proposed equations. More importantly, a correction for undercatch of the DFIR for wind speed must be done--it is not a constant systematic loss at all wind speeds. The authors also suggest that a correction using only wind speed, if the data are segregated by precipitation type, is adequate and that correction for incorporating factors such as atmospheric pressure and humidity are not required.

Table 2.H.3: Catch efficiency of the DFIR (%) for selected wind speeds based on Golubev (1986) and proposed equations

Wind Speed	DFIR (Gol)	DFIR DS	DFIR WS	DFIR S/R	DFIR R/S	DFIR R
1 m/s	100	98.1	103.3	98.8	98.1	98.0
2 m/s	100	96.4	100.0	96.6	97.4	96.6
4 m/s	95	92.8	93.9	92.4	94.6	93.6
6 m/s	87	89.3	88.0	88.7	90.3	91.0

Notes: DS = dry snow, WS = wet snow, R =rain, S/R = snow and rain, R/S = rain and snow.

Blowing snow conditions are a special case when correcting gauge data. Figure 2.H.2c shows that for all but four cases, the bush gauge caught the same or significantly more than the DFIR. It is the opinion of the authors that the bush gauge at Valdai over measured during these particular conditions. Therefore, correction of the DFIR when blowing snow is reported during the observation period (as opposed to after the ending of snowfall) using a separate equation for blowing snow (i.e. equation (3)) is not recommended. The measured DFIR can be corrected by using the dry snow equation.

The validity of correcting gauge data when blowing snow is reported during the snow event is also a question which users of precipitation data must decide. Certainly the flux of blowing snow is greater at 1.5 or 2 m than at the DFIR height of 3m, and it is possible that under certain conditions, any gauge can catch some blowing snow. Since wind speeds are generally greater during blowing snow events, a large correction "for undercatch" could be applied to a measured total already augmented by blowing snow. This problem could be most severe for gauges mounted close to the ground which are efficient in collecting snow passing over their orifice.

5. APPLICATION OF RESULTS

The affect of the correction on intercomparison event data is shown in Table 2.H.4. Equation (1) was applied to individual dry snow events > 3.0 mm for each Canadian Intercomparison site. The DFIR total is increased by 3% to 10%, depending on site exposure, regional climate and storm wind speed. It is not surprising to note that the largest correction corresponds to the station with the highest mean wind speed.

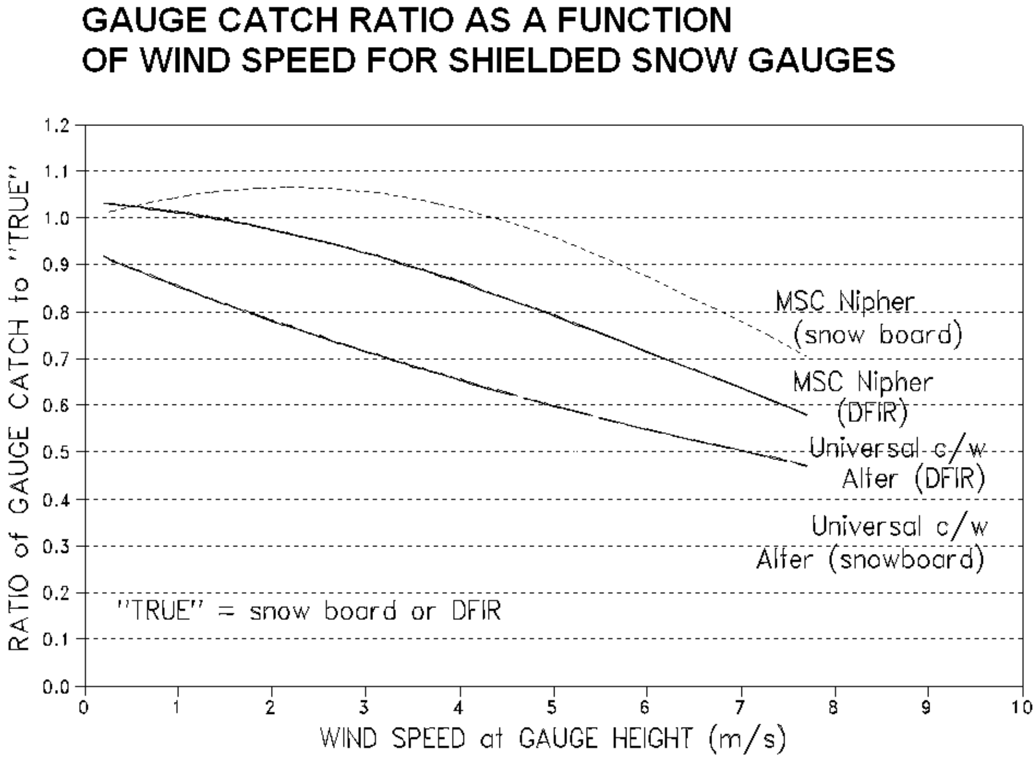
Table 2.H.4 Correction of dry snow measurement by the DFIR at 6 Canadian Intercomparison sites

Site	# of Events	Mean Temp (^{o}c)	Mean Wind (m/s)	DFIR1 (mm)	DFIR2 (mm)	D2/D1 (%)
Kortright	14	-5.5	2.7	148.4	156.9	105.7
Dease Lake	45	-11.0	1.7	380.7	393.2	103.3
Regina	21	-11.2	3.8	131.1	140.9	107.5
Trent	31	-8.2	2.2	208.1	216.8	104.2
Baie Comeau	48	-8.3	4.2	512.8	562.0	109.6
East Baltic	46	-6.8	4.6	638.4	699.3	109.5

Notes: DFIR1 = measured (including wetting loss),
DFIR2 = corrected for individual events,
D2/D1 = DFIR2 / DFIR1

The validity of using the DFIR as a reference for "true snowfall" was investigated by comparing correction curves developed in an earlier Canadian study (Goodison 1978) for two commonly used North American shielded precipitation gauges. Figure 2.H.3 shows the ratio of the Canadian Nipher Shielded Snow Gauge System and the Alter Shielded Universal (Belfort model 5915) gauge to corrected DFIR versus mean storm wind speed at gauge height. The data used is for events greater than 3.0 mm and was collected at both Canadian and United States Intercomparison stations. On the same graph the results obtained by Goodison (1978) for the ratio of the same two gauges to snowboard measurements at a single, sheltered site are also plotted for comparison. For wind speeds up to 2m/s, the results are similar, although Goodison's Nipher curve indicates a slight over measurement at this speed. While, at higher wind speeds, the current results indicate a catch ratio generally lower than that found in the earlier field study. Considering that two different methods of determining "true precipitation" were used and that the current Intercomparison involves sites in different climatic regions, the results from these two studies are quite compatible (Metcalfe and Goodison, 1993). Like the previous study, results from the Intercomparison indicate the Canadian Nipher Shielded gauge has a superior catch efficiency when compared to the Alter Shielded gauge.

Figure 2.H.3. Gauge catch ratio as a function of wind speed for shielded snow gauges.



6. SUMMARY

In terms of measurement accuracy, the bush gauge is the only reference available to check the DFIR in the field. At Valdai, blowing snow, mainly from the lake in the south, occurred during one-third of the snow events greater than 3.0 mm. On the average, the bush gauge over measures snowfall by 10% during blowing snow conditions. Even after eliminating, as much as possible, the snowfall observations during which blowing snow occurred, there remains a systematic difference between the measurements of the two gauges, that is, the bush gauge catches more snow than the DFIR. Therefore, the correction of the DFIR for wind induced loss is necessary in order to best represent true precipitation. The most important factor for the correction is mean wind speed during the storm. Atmospheric pressure, air temperature and humidity have little or no influence. The correction equations for different types of precipitation, presented in this paper, have been recommended to correct DFIR measurement for wind speed before comparative analysis with other gauge data (WMO/CIMO, 1993). Correction procedures like those demonstrated above will be developed for a large number of gauges, commonly used in many parts of the northern hemisphere, based on the DFIR as "true", to provide more accurate and representative spatial and temporal time series of solid precipitation measurements.

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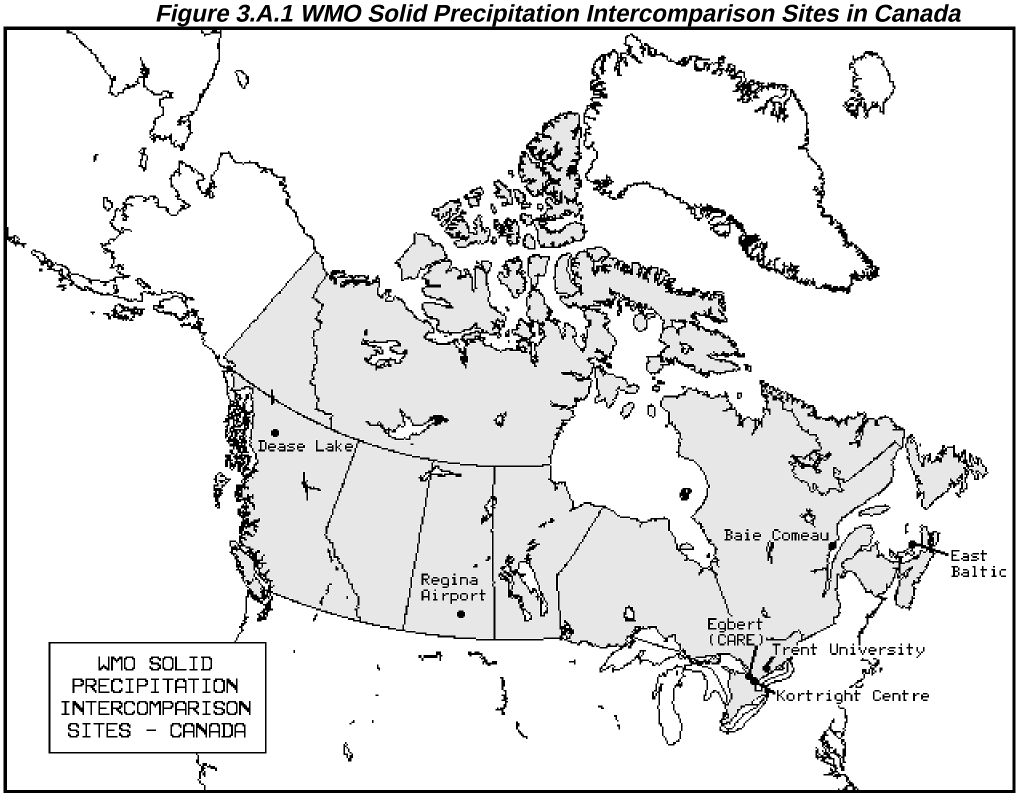
ANNEX 3 DESCRIPTION OF SITES AND INSTRUMENTS

ANNEX 3.A CANADA

1. INTRODUCTION

Canada established Evaluation stations for the Intercomparison at six sites across the country, representing different climatic and physiographic regimes (Figure 3.A.1). A permanent national intercomparison station has been established at the Atmospheric Environment Service (AES) Centre for Atmospheric Research Experiments (CARE) at Egbert, Ontario where past, current and new Canadian methods of precipitation measurement and observation can be compared against international reference standards. Table 3.A.1 summarizes the instruments being operated at each of the stations. All sites operate the DFIR (with Tretyakov gauge), the Canadian standard Nipher shielded snow gauge system, an AES Type-B rain gauge, a snow ruler and measure wind speed and direction (three levels), air temperature and humidity. Campbell-Scientific CR21X data loggers were used to record the data at various sampling intervals. Other precipitation gauges were operated at each site, depending on the measurement requirements to be tested for that region. Installation of the DFIR, precipitation gauges and other observing equipment and the observational procedures have followed those outlined in WMO (1986). A brief description of each site follows.

Figure 3.A.1 WMO Solid Precipitation Intercomparison Sites in Canada



2. DEASE LAKE

The Dease Lake, British Columbia site is located on the Pacific-Arctic Divide (58^o 5' N, 130^o 00' W) on the west side of Allen Lake and 4 km south of Dease Lake. The airstrip is 1.2 km west of the station. The elevation of the station is 816 meters above mean sea level and is situated in the Tanzilla Valley which is part of the Stikine Plateau. The closest peak is Tanzilla Butte, elevation 1530 m MSL, five miles to the southeast. The highest mountains are found in the Three Sisters Range approximately ten miles further southeast, with peaks up to 2290 m MSL. The area is heavily wooded up to 1220 m MSL.

To accommodate the intercomparison study, a natural clearing NE of the weather station was cleared exposing an area approximately 600 m long by 100 m wide. Predominant winds are along Allan Lake in a N, S direction. To the west stands a forest of coniferous trees 18-20 m high while on the east the land slopes down to Allan Lake covered by scrub brush. Winter precipitation averages 205 cm.

The AES operates a modified synoptic observing program at the Dease Lake weather office. Two full time observers man the station 365 days a year. Six-hourly precipitation totals are recorded daily from the standard AES gauges. Instrumentation at this site is listed in Table 3.A.1. An older style aluminum Nipher shielded snow gauge system is deployed at this station. Air temperature and station wind speed and direction at 15 meters were abstracted from station records. A Campbell Scientific CR2lx data logger was installed in the station office to collect recording gauge, wind speed and snow depth sensor readings. Observations in support of the intercomparison began December 1987.

Other precipitation gauges installed at this site by B.C. Hydro included two large capacity Belfort gauges (750 mm) one unshielded the other with an alter shield, and two standpipe type gauges with output to the data logger via a pressure transducer. The WMO monthly climatological and event forms were tabulated at the station. The observations are considered highly reliable.

3. REGINA AIRPORT

The Regina Airport site (50^{o} 26' N, 104^{o} 40' W) is at an elevation of 577 meters above mean sea level located in the southern portion of the province of Saskatchewan. The site is very typical of the flat, open topography found in Western Canada and the Arctic. The intercomparison area is situated in a field adjoining the airport and nearby the synoptic station. The area within a 32 km radius of the airport site is devoted to agriculture, the main crop being wheat.

The mean annual precipitation for Regina Airport is 384 mm of which 116 cm comes as snowfall. The prevailing wind direction during the winter months is SE with the average wind speed being approximately 6 m/s. The mean annual temperature for Regina is 2.2 ^{o} C with January having the coldest mean monthly temperature of -17.9 ^{o} C.

The Regina Airport is a synoptic weather office operated by the AES. Since about 1980 the Regina Airport has been the site of on-going assessment of precipitation gauge measurement accuracy on the prairies. A number of different types of precipitation gauges in common use in this environment were already installed at this site. Instrumentation at this site is listed in Table 3.A.1. The intercomparison observation program began in March 1987. Observation of manual gauges is performed daily at 1800 UTC. Data from the recording weighing gauges is abstracted from chart or tape daily by the observer. Daily average wind speed at 2 and 3 meters is recorded on a Campbell Scientific CR21 data logger. Supplementary observations such as snow depth daily maximum and minimum temperatures along with 10 meter wind speed and direction is taken from the official airport observation form. An AES designed and built acoustic snow depth sensor was also operated at this site during the 1987-88 winter season.

The WMO forms were completed at the station and both climatological and event forms were completed each year. The station was closed in the summer of 1992 due to airport construction.

4. KORTRIGHT CENTRE

The Kortright Centre for Conservation site (43^{o} 51' N, 79 ^{o} 36' W), near Kleinburg, Ontario is at an elevation of 208 meters above mean sea level. It is a 162 ha area owned and operated by the Metropolitan Toronto and Region Conservation Authority and is located just north of Toronto, Ontario on slightly rolling agricultural land (hay, grass).

The mean annual precipitation for this area (Toronto International Airport) is 762 mm. The average annual snowfall is 131 cm. January is the month in which most snow falls. Prevailing wind direction during winter storms is N and NW, with average speeds of 5 m/s. The mean annual daily temperature for this area is 7.3 ^{o}C with a January mean of -6.7 ^{o}C.

Instrumentation at this site is listed in Table 3.A.1. A contract station set up specifically to collect data in support of the WMO Intercomparison observations began January 1, 1987. Observations of non-recording gauges were performed daily at approximately 0800 hours LST. The Nipher shield used at this site was manufactured from black fiberglass. A snow board and ruler were used to measure fresh snowfall water equivalent, assuming a density of 100 kg/m^3. An AES type-B rain gauge was used to record rainfall totals for the observation period. Average snow depth at the site was also observed by taking the mean of several ruler measurements. Daily observations were recorded in a log book and later transferred to the WMO forms.

Other observations collected on the data logger included: average hourly air temperature and humidity, hourly average values of wind speed at 2, 3 and 10 meters, and mean wind vector direction at 10 meters and standard deviation of direction. An AES designed and manufactured Acoustic Snow Depth Sensor was also used to record hourly point snow depth near the wind mast.

TABLE 3.A.1 Instrumentation installed at Canadian Intercomparison stations

	Dease Lake A	**Regina A**	**Kortright Centre**	**Trent University**	**Bai Comeau A**	**East Baltic**	**C.A.R.E.**
Date Obs began	87/12	87/03	87/01	86/12	89/01	87/12	89/11
Date Obs end	93/04	92/04	91/03	91/03	93/04	92/04	
INSTRUMENTATION							
DFIR	x	x	x	x	x	x	x
Tretyakov Gauge		x	x	x			
Canadian Nipher Shielded Snow Gauge*	F	F,A	F	F	A	F	F
Unshielded Nipher		x	x				
Unshieded Universal Recording Weighing Gauge	x		x				
DFIR with Universal Gauge			x				
Alter shielded Universal Gauge	x		x				
Large Nipher Shielded Universal Gauge	x		x	x	x	x	x
Unshielded Belfort Punch Tape Precipitation Recorder			x				
Alter shielded Belfort PTPR			x				x
Large Nipher Shielded PTPR		x					
Alter shielded Sacremento Gauge		x					
Alter Shielded Stand-pipe Gauge		x					
Ruler Snow Depth*	x	x	x	x	x	x	x
Acoustic Snow Depth sensor	x	x	x		x	x	x
AES Standard Rain Gauge	x	x	x	x	x	x	x
Air Temperature / Humidity	x	x	x	x	x	x	x
Wind Speed / Direction	10,3,2m	10,3,2m	10,3,2m	10,3,2m	10,3,2m	10,3,2m	10,3,2m

*** = National Gauge; F = Fiberglass; A = Aluminum**

WMO forms were completed by Atmospheric Environment Service (AES) staff using an annual observers log book kept on station. Data logger information was collected approximately every three weeks on cassette tape to be used in completing climatological and event forms. The observations from this station are considered highly reliable. This station terminated operation at the end of August 1991.

5. TRENT UNIVERSITY

The Trent University site (44^{o} 21' N, 78^{o} 17' W) is located on the northern fringe of the community of Peterborough, Ontario. It is at an elevation of 230 meters above mean sea level in an area marked by glacial deposits (i.e. drumlins). The site is in an open and reasonably level natural grass field sufficiently distanced from any major topographical features. Prevailing winds for storm sequences since 1977 (Trent climate station) show NW, W and E tracks; all of these directions are unaffected by nearby topography.

Instrumentation at this site is listed in Table 3.A.1. A contract station set up specifically to collect data in support of the WMO Intercomparison observations began November 1, 1986. Manual observations were performed once a day at 1200 LST during the 1986-87 and 1987-88 winter seasons. The time of observation was changed to 1600 LST for the 1988-89 season. The time of observation for subsequent seasons (1889-90-91) was 0900 LST. Daily totals and averages were recorded on the Campbell-Scientific CR21X data logger at times corresponding to manual observation times.

Raw data were provided to AES each year, along with cassette tapes of 21X data collected throughout the season. WMO climatological and event forms were then completed by AES staff. The station was closed in the fall of 1991.

6. BAIE COMEAU

The Baie Comeau, Quebec site (49 ^{o} 0 08' N, 68 ^{o} 12' W) is at an elevation of 21 meters above mean sea level located at the Baie Comeau Airport near Pointe Lebel which is situated on a strip of land (Manicouagan Peninsula) 7 kms wide bounded by the Manicouagan River to the NE and the St. Lawrence River to the S and SW. The airport site is generally flat open grass land surrounded by forest. The St. Lawrence River valley is the major topographic feature affecting winds in this area. Predominant wind directions are along the valley in a SE-NW orientation.

The AES Quebec region operates a 24 hourly synoptic weather observing program at the Baie Comeau Airport site. The standard observing program in support of the intercomparison is similar to that of the Dease Lake station. Instrumentation at this site is listed in Table 3.A.1. The Nipher shielded snow gauge system in use here is also made of aluminum. A large Nipher shielded Belfort recording gauge, 2 and 3 meter wind speed sensors, an CSMAL01 ultrasonic depth sensor and a DFIR were installed near the station instrument compound for the intercomparison.

Air temperature and station wind speed and direction at 10 meters were abstracted from station records. A Campbell Scientific CR2lx data logger was installed in the field to collect recording gauge, wind speed and snow depth sensor readings. Observations in support of the intercomparison began December 1988. The observations from this station are considered to be highly reliable.

7. EAST BALTIC

The East Baltic, Prince Edward Island site (46^{o} 26' N, 62 ^{o} 10' W) is at an elevation of 61 meters above mean sea level near the northeast corner of P.E.I. on the Gulf of St. Lawrence. The instruments are installed on a grassed area SE of the observer's home. The surrounding country is generally flat agricultural land with tree-lines dividing individual sections of farmland. The Atlantic Region operates a climate station (temperature and precipitation) at this site. Predominate wind directions during winter storms are NW and SE and the mean annual snowfall for this area is 197 cm.

This site is the location of an AES Atlantic Region contract climate station. The climate station program consists of twice daily observations of maximum and minimum temperature and precipitation amount. Observation times are 0800 and 1700 LST. For rainfall a type-B rain gauge is used and for fresh snowfall, a ruler depth converted to water equivalent assuming a density of 100 kg/m^{-3} is applied.

Instrumentation at this site is listed in Table 3.A.1. All equipment, except the manual gauges were connected to a Campbell Scientific CR21X data logger. The logger was installed in the observer's home and was connected to a telephone line via a modem which can be accessed by a computer in the regional office observations in support of the intercomparison began December 1987.

Hourly data values were recorded on the logger for all sensors. The frequent occurrence of freezing rain events also played havoc with the timing of the weighing gauge increments. During the 1990-91 season a heat cable was installed around the orifice extension of the large Nipher shield in an attempt to reduce wet snow and freezing precipitation sticking to the sides and not being weighed. The raw data for the first season (1987-88) was sent to AES for compilation of the WMO forms. The station was closed in the summer of 1992.

8. EGBERT (CARE)

The Centre for Atmospheric Research Experiments (CARE) is located (44^{o} 13'N, 79^{o} 47'W) north-west of the village of Egbert, Ontario at an elevation of 252m. The area is generally rolling open farmland or pasture with some mixed coniferous and deciduous bush. This site is owned and operated by the Atmospheric Environment Service. Instrumentation at this site is listed in Table 3.A.1. The WMO precipitation standards, a pit gauge for rainfall and a double fence reference gauge (DFIR) for snowfall will be operated here on a long term basis to compare old and new instrumentation and methods of precipitation measurement.

A climate station is also located at this centre and operated by the AES Ontario region. Standard AES climate observations of temperature and precipitation are taken twice daily at 0800 and 1600 LST seven days a week by CARE staff.

A pit gauge was installed and observations began in June 1990. This gauge was designed following WMO guidelines for pit gauges and contains an AES Type-B rain gauge. The DFIR installed here began its observation program in November 1990. These two WMO standards will be operated seasonally one for rain the other for snowfall on a long term basis at this site.

ANNEX 3.B CHINA

1. TIANSHAN

The Urumqi River originates on the north slope of Chinese Tianshan and flows northward to the city of Urumqi, the capital of Xinjiang Autonomous Region. The headwaters of this river lie within the zone of alpine permafrost where the surface cover is dominated by tundra vegetation, rock outcrops, felsenmeer and glaciers. A study basin was selected in the Dry Cirque, a south-facing non-glacierized watershed, 1.5 km long and 1 km wide, surrounded by peaks of about 4300 m elevation on its western, northern and eastern flanks. Most slopes are steep and many parts of the basin are covered by coarse gravel. A hydrometric station was set up at the basin outlet (3804 m asl) and controls a drainage area of 1.68 km^2.

The climate of this area is typically continental, with a mean annual air temperature of -5.4 ^oC and mean annual precipitation of 420 mm at the Daxigou climatic station (43.06^o N, 86.50^o E; 3539 m asl). Eighty percent of annual precipitation is concentrated in the period of May through August and because of the high altitude of the study area, 43% and 35% of the summer precipitation occur as wet snow and snow mixed with rain respectively. Therefore, measuring precipitation in this area mostly deals with snow problems. Air temperature, precipitation and relative humidity have been measured routinely with Chinese standard instruments including the Chinese standard precipitation gauge at this station since May 1982.

A second weather station was set up near the centre of the basin where precipitation was observed by a Belfort recording gauge. In the fall of 1989, 42 snow stakes in 8 rows were installed between 3800 and 3900m asl in the Dry Cirque. In the following 3 winter seasons, snow depth was measured at each stake every seven to ten days. A snow-density profile was measured in snowpits between stake row C and D with a sampler of 100 cm^3 and a spring balance of 5 g resolution. Three to five samples were measured at each depth interval to reduce the relative error in the density measurement.

In July 1987, an intercomparison site for precipitation measurement was selected at the flat bottom (43.06^o N, 87.15^o E; 3720m a.s.l.), surrounded by mountain peaks in south and north directions, of the river valley in front of glacier No.1, which is situated 1 km south of the Dry Cirque. The instruments were installed as follows:

a) Chinese standard precipitation (rain and snow) gauge. It is a cylinder of galvanized iron, 65cm long and 20cm in diameter. The standard elevation of the gauge's orifice is 0.7 m, and no wind shield is used even in snowfall measurement. Two Chinese standard gauge were mounted at 0.7m and 2m at the site.
b) Hellmann gauge. One unshielded Hellmann (Switzerland) gauge was placed at 2m high above the ground during July to August 1987.
c) DFIR. A DFIR was set up at 2.5m high since the maximum snow depth in winter was less than 1m generally (Yang, et al., 1990). A Chinese standard gauge shielded with a Tretyakov wind shield was placed in the center of the double fences.
d) Screen. Air temperature and relative humidity were recorded automatically.

All the gauges at this site were measured by volumetric method at 8:00 am each day. Unfortunately, wind speed measurement at this site was not available.

ANNEX 3.C CROATIA

COMPARISON OF SNOW GAUGE MEASUREMENTS IN YUGOSLAVIA

Janja Milkovic

1. INTRODUCTION

This report describes instruments and methods used during the comparison of precipitation gauge measurements at Parg (Lat. =45^{o} 36' N, Long. =14^{o} 38' E), Yugoslavia. The comparison is a part of the Solid Precipitation Measurement Intercomparison organized by the Commission for Instruments and Methods of Observations of the World Meteorological Organization (CIMO/WMC). The Hellmann gauge is used as the standard precipitation gauge in Yugoslavia. This type of gauge is being compared, over a time period of five years, with different types of snow gauges to determine the systematic error in national methods of solid precipitation measurements. The report also presents some results of the previous comparison carried out in Yugoslavia as well as the preliminary results of the WMO Intercomparison.

Figure 3.C.1. The position of various rain gauge types at Zavizan in use up to June 1964 (Kirigin, 1973)

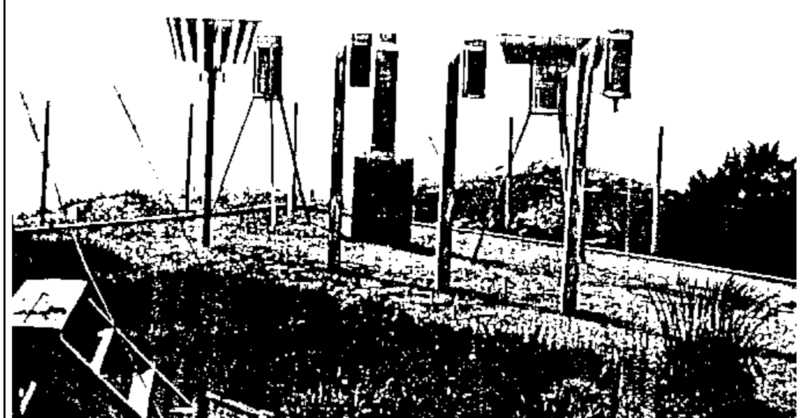


Figure 3.C.2. The position of various rain gauge types at Zavizan since 1964 (Kirigin, 1972a)

The first results of comparison between shielded and unshielded gauges have already been carried out in our country and were published in 1972. It was suggested that we use the shielded rain gauge instead of the national standard unshielded one, especially in the mountainous regions. This intercomparison offers an excellent opportunity to assess the accuracy of the national standard unshielded gauge as well as methods against an international reference. Therefore, when the Secretary-General of the WMO asked in his letter of March 12, 1986 that the WMO member countries inform the WMO Secretariat of their intention of participating in this Intercomparison, Yugoslavia replied positively, and started with preparatory work.

Having some experience in dealing with these topics, the Hydrometeorological Institute of Croatia assumed the responsibility for this Intercomparison. The evaluation station is the meteorological station Parg (WMO No 13114, Lat. =45^{o} 36' N, Long. =14^{o} 38' E, Elev.= 863 m) instead of Zavizan, where a similar comparison has been carried out since 1955, as we had intended earlier. We had to change the intercomparison site due to a lack of space for all required instruments at Zavizan.

2. PREVIOUS COMPARISONS IN YUGOSLAVIA

According to the WMO Climatology Commission Instructions (Washington, 1953) measurements by rain gauges of various constructions were commenced at the end of 1955. Since then such measurements have been carried out at several meteorological stations in the mountainous region of Croatia: Zavizan (1594 m), Baske 0starije (924 m) and Puntijarka (980 m).

The first special measurements by different types of rain gauges began on October 1, 1955 at Zavizan. Zavizan is situated on the mountain Velebit (a 165 km long barrier between the Adriatic sea and the inland) about 7.5 km from the Adriatic sea. Different types of rain gauges have been placed inside a relatively narrow and horizontal area belonging to the meteorological station and located on the southern slope under the peak Vucjak (1645 m). Between four and seven different rain gauges have been operated since October 1955. All gauges, except the storage gauge, were mounted at a height of 2 m above the ground and during the winter a snow cross was inserted into the upper container. The storage gauge (with Nipher shield) was mounted at a height of 4 m above the ground. Unfortunately the data are not completely homogeneous due to changes of the rain gauges positions (Kirigin, 1972a, 1972b, 1973). Namely, in June 1964, the gauges displaced 2 - 7 m westward in relation to the previous position (Figure 3.C.1 -3.C.2).

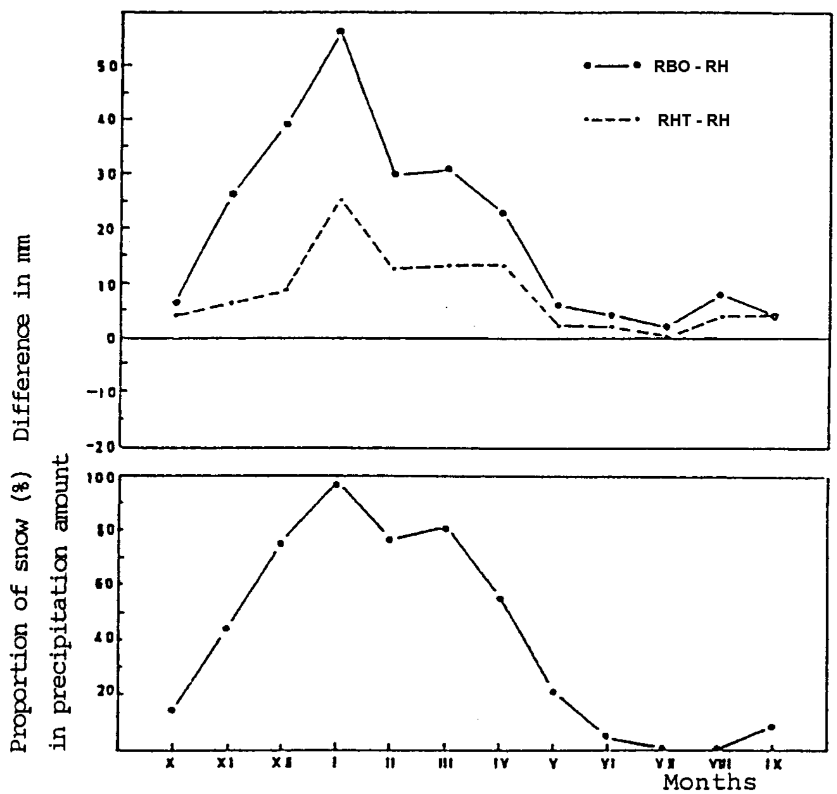


Figure 3.C.3. Mean monthly differences (in mm) of precipitation amounts between the shielded mountain gauge (RBO), the unshielded rain gauge of the totalizer type (RHT) and the ordinary unshielded Hellmann gauge (RH) by analogy with the proportion of snow (%) in precipitation amount at Zavizan, form 1955/56 to 1963/64 (Kirigin, 1972b)

Two shielded and two unshielded gauges have been operated since 1969 at Zavizan. The shielded gauges are the mountain rain gauge with the Nipher shield (its orifice area is 500 cm^2) and the rain gauge with the Wolfle shield (its orifice area is 200 cm^2). The unshielded gauges are the ordinary Hellmann gauge and the mountain rain gauge (the same type mentioned above, but without a wind shield). The results of the comparison between these shielded and unshielded gauges have been summarized by Kirigin (l959; 1972a; 1972b) and Mileta Cikos (1987). They have shown, among other things, that the greatest differences of the mean monthly precipitation amounts between shielded and unshielded gauges occurred in the cold part of the year, from November to April (Figure 3.C.3). The deficit of the unshielded mountain gauge have been from 15.1 to 33%, and for the ordinary unshielded Hellmann gauge from 10 to 29.3%, in relation to the precipitation amount caught by the shielded mountain gauge (Kirigin, 1972a). These results have also suggested that we use the shielded rain gauge instead of the national standard unshielded one, especially in the mountainous regions, however we did not use it.

Up until now, in comparisons and analyses carried out in our country, it has not been taken into account the sheltered measuring site as well as the proportion of snowfall in precipitation amount. There were not adequate wind data especially at the height of the gauge rim. In future these facts should also be included in the research.

3. CLIMATE OF PARG

According to the Koppen climate classification system there are two types of climate in Croatia. They are the humid mesothermal climate and the humid microthermal climate. Most of Croatia belongs to the zone of humid mesothermal climate (Hydrometeorological Institute, Zagreb 1971: Climatic data of Croatia). The coldest month has an average temperature of under 18^o C but above -3^o C. At least one month has an average temperature above 10^o C. Parg is situated in the mountainous region of Croatia (Gorski Kotar, Figure 3.C.4). The orography of Gorski Kotar is very well developed and there is a lot of woods. It is generally at 700 - 800 m above sea level (up to more than 1500 m). Parg also belongs to this zone of climate (Table 3.C.1).

The second type of climate, humid microthermal climate, exists only in the mountainous region above 1200 m. In this zone the mean temperature of the warmest month is at least 10^o C and the mean temperature of the coldest month below -3^{o}C.

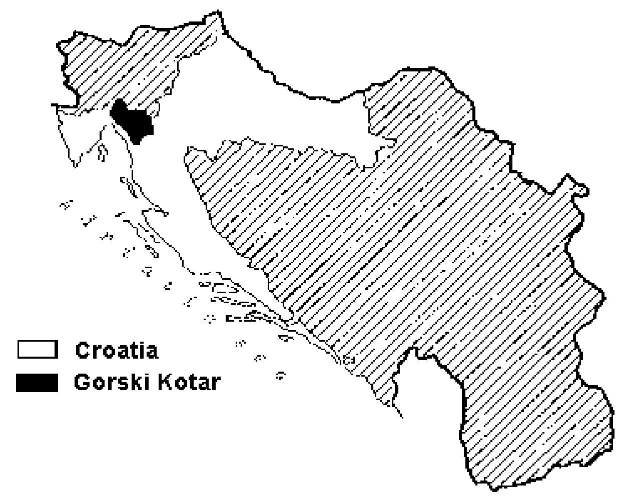


Figure 3.C.4 Position of Gorski Kotar in Yugoslavia

Table 3.C.1 Monthly values of climate parameters for Parq

Climate Parameter	Month												
	1	2	3	4	5	6	7	8	9	10	11	12	Year
Atm Press at Stn level (hPa)	913.3	912.1	912.8	912.2	915.2	916.2	916.8	916.9	918.1	917.4	914.5	913.6	914.9
Air Temperature (^{o}C)													
mean monthly	-1.2	-1.0	1.7	5.7	10.6	14.2	16.2	15.5	12.4	7.8	3.3	-0.3	7.0
mean monthly max	1.2	2.7	6.0	10.7	15.7	19.3	21.7	21.1	17.7	12.2	6.5	2.9	11.5
mean monthly min	-3.2	-2.0	0.9	4.7	9.2	12.8	14.5	14.2	11.4	7.0	2.7	-1.1	5.9
absolute max	15.4	17.4	21.2	26.0	28.2	30.2	31.4	30.4	29.9	23.5	21.7	17.1	31.4
absolute min	-18.6	-23.2	-18.9	-10.0	-5.0	0.6	3.0	2.1	-1.8	-5.8	-12.2	-15.9	-23.2
Sunshine duration (hours)													
mean monthly sum	64.9	78.0	108.6	130.3	169.7	174.8	230.0	214.8	162.1	120.4	67.0	62.8	1583.4
Relative humidity (%)	85	82	78	75	74	76	75	78	84	85	88	88	81
Precipitation													
mean monthly (mm)	140.2	138.0	129.9	147.7	140.1	151.8	138.7	133.2	185.1	194.1	225.4	161.5	1885.6
rainy days ($\geq$ 1.0 mm)	13	12	12	13	13	13	10	10	10	10	13	13	142
Wind force (at 11.2 m, in Beaufort Scale)	1.9	2.1	2.1	2.6	2.1	2.2	1.9	1.7	1.7	1.9	1.9	1.8	2.0

3.1 Precipitation and snow cover

The annual course analysis shows that the maximum precipitation is in the cold part of the year (from October to December), commonly in November (Table 3.C.1). About 23% of the total annual precipitation falls as snow.

The snow cover is as can be expected from October to May. In the winter season there is an average of 29 days with a snow depth greater or equal to 30 cm. The maximum snow depth registered at Parg is 156 cm and there has not been a snowless winter.

Winds blow most frequently from the sector south-east to south at Parg (Figure 3.C.5). The same situation occurs in both parts of the year i.e. in the warm part (Figure 3.C.6) and in the cold part of the year (Figure 3.C.7 - 3.C.8).

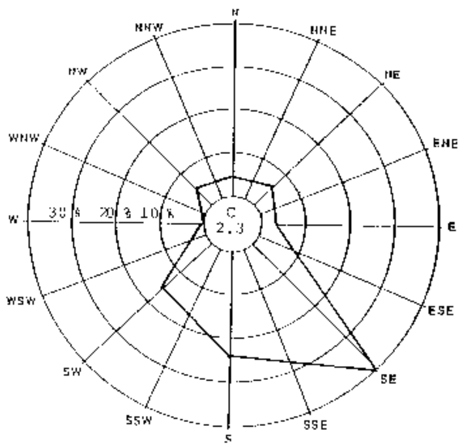


Figure 3.C.5. Mean annual wind rose for Parg (971-1980)

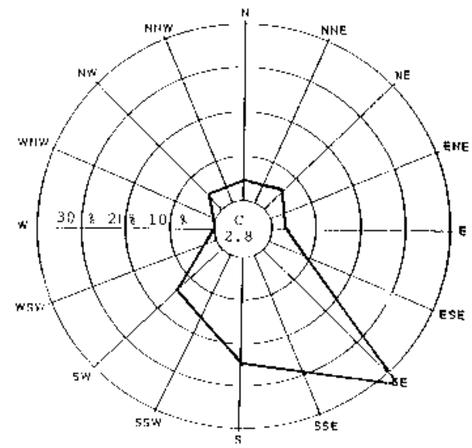


Figure 3.C.6. Mean wind rose for the warm part of the year (Parg, May - September, 1971-1980)

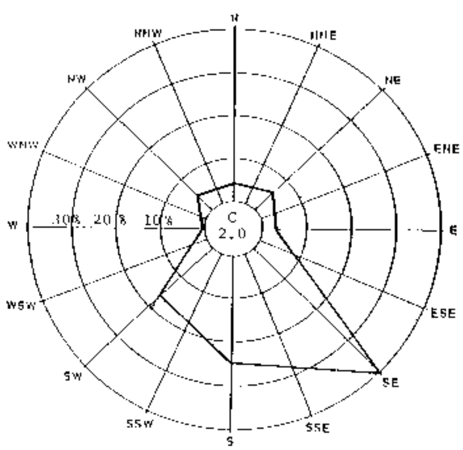


Figure 3.C.7. Mean wind rose for the cold part of the year (Parg, October - April, 1971-1980)

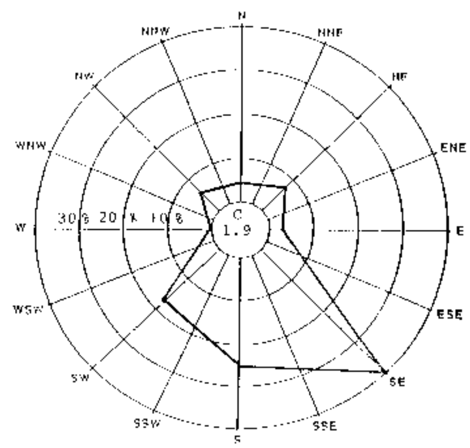


Figure 3.C.8. Mean wind rose for January (Parg, 1971-1980)

4. MEASURING SITE

4..1 Surroundings

The meteorological station at Parg (Lat. =45^{o} 36’ N, Long. =14^{o} 38’ E, Elev.= 863 m) is situated in the mountainous region of Croatia (Figure 3.C.4). The measuring site is situated at the top of a small hill Figure 3.C.9) above the small village of Parg (consisting of some 15 houses). The site is surrounded by rounded mountains about 10 km away. There is mountain range overtopping and protecting the measuring site from the western direction.

4.2 Intercomparison field

Figure 3.C.10 shows the location of gauges and other instruments in detail in the intercomparison field. The gauges were placed in two rows normally to the prevailing wind directions during snowfalls. In the first row

were placed the gauges with and without wind shields. Two Valdai double fences were placed in the second row 20 m downwind from the first row.

Vertical angles of obstacles (Figure 3.C.11) measured in degrees (360^{o} in 16 points of the wind rose to the distance of 300 m), give some idea of the openness of the field.

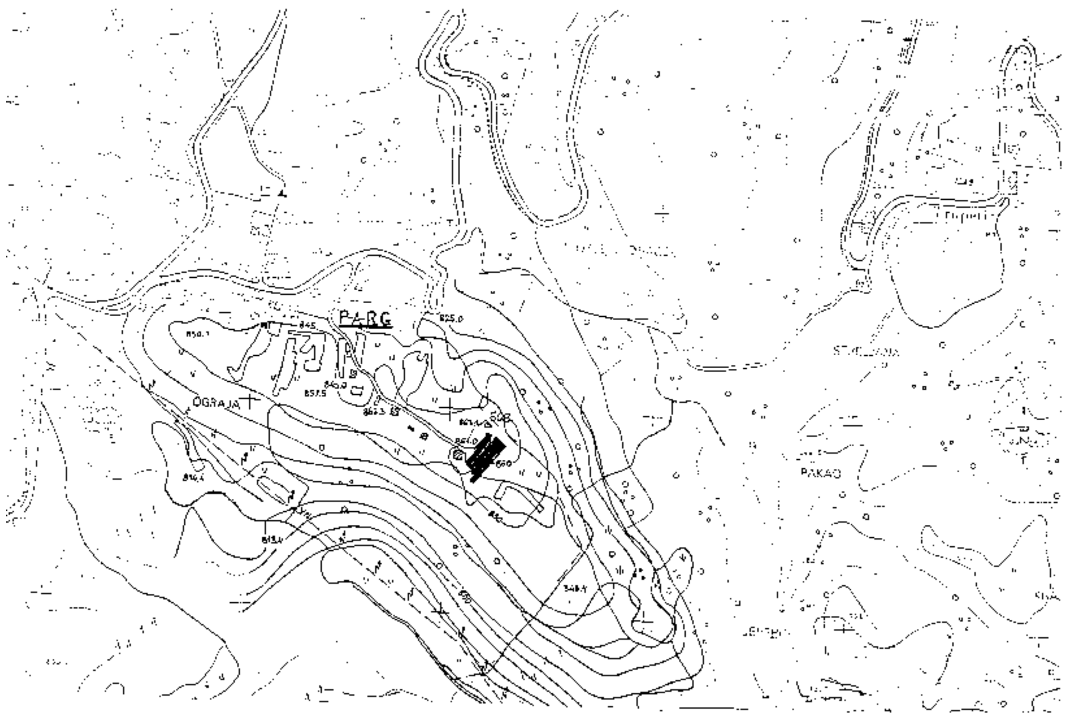


Figure 3.C.9. Map of local area at Parq

5. INSTRUMENTS

5.1 Gauges and shields

The gauges in the intercomparison field, as well as their height (in metres) above the ground (number in bracket) are marked as follows (Figure 3.C.10):

1 Hellmann gauge without wind shield (2m)
2 Hellmann gauge with Tretyakov type of wind shield (2m)
3 Tretyakov type of gauge with corresponding wind shield (2m)
4 Tretyakov type of gauge with wind shield in the Valdai double fence (3m)
5 Hellmann gauge without wind shield in the small wooden double fence (2m)
6 Hellmann gauge without wind shield (2.25 m)
7 Hellmann gauge without wind shield (2.66 m)

The measurements were started on January 1, 1987, when five gauges were available (gauges 1 to 5). The gauges, number 6 and 7, were started on January 1, 1988. These two additional national gauges were installed (by request of the Organizing Committee, Final report of the second session in Zagreb, 1987) to assess the homogeneity of the intercomparison field.

5.1.1 The Yugoslav standard precipitation gauge

The Hellmann gauge made of zinc, without wind shield, is used as the standard gauge in Yugoslavia (Figure 3.C.12a). The rim of this gauge is 1 m above the ground, except in the mountainous regions where it is 2 m above the ground. Its orifice area is 200 cm^2 . This type of gauge is operated throughout the whole year for both liquid and solid precipitation.

5.1.2 The Tretyakov gauge

Besides the Hellmann gauge there is also the Tretyakov gauge. Its orifice area is also 200 cm. Inside the casing there is a cone with a drain hole. In the summertime, to reduce evaporation, the cone hole is covered with a funnel. The gauge casing is placed inside a wind shield of 15 plates forming a cone with the upper ends of the plates bent outwards. The flat tops are leveled with the rim of the bucket (Figure 3.C.12b).

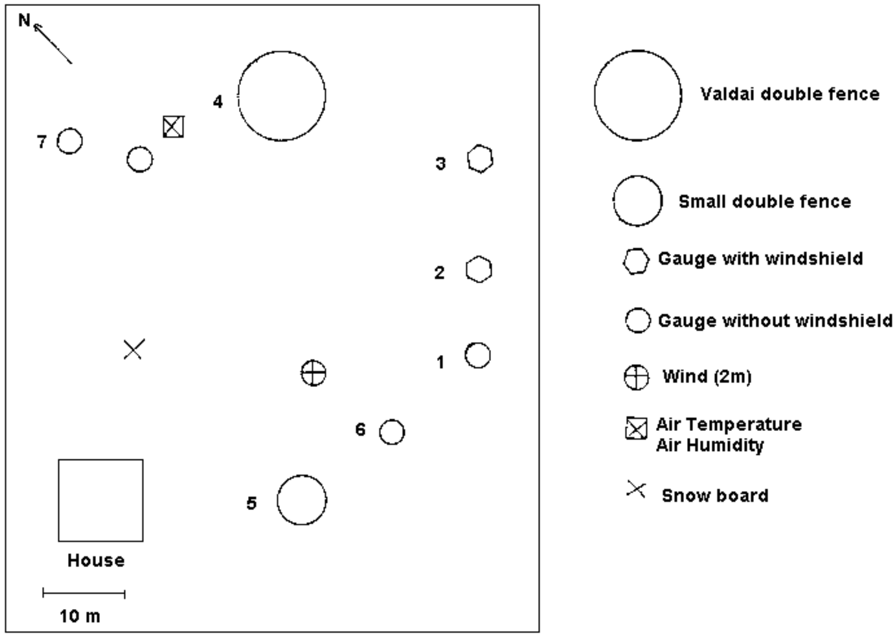


Figure 3.C.10 Location of gauges and other instruments in the intercomparison field

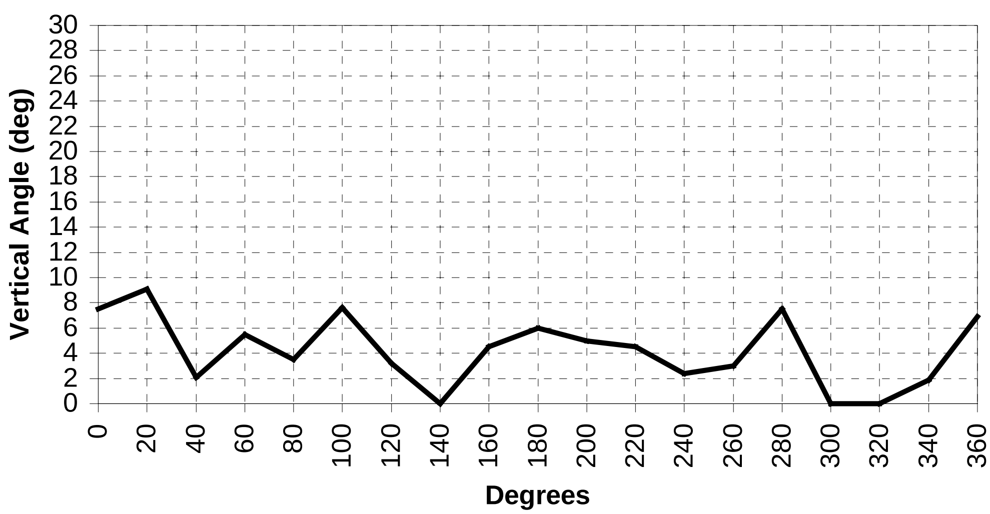
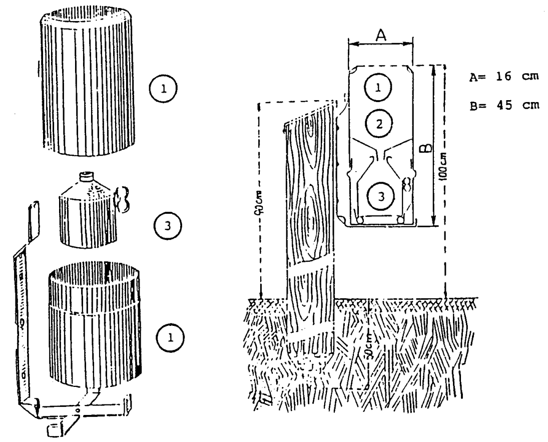


Figure 3.C.11. Vertical angles of obstacles measured by theodolite in degrees at a height of 1.5 m

5.1.3 Valdai wooden double fence

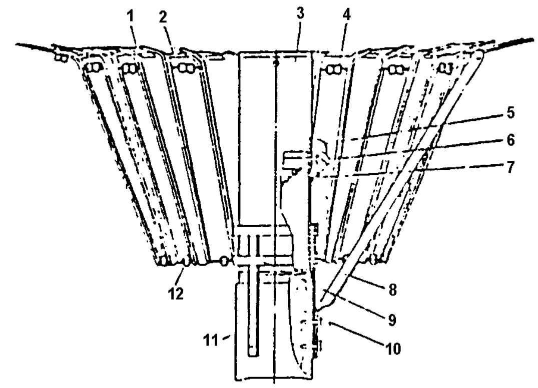
There are two wooden double fences. The first one is Double Fence Intercomparison Reference (DFIR) which was constructed according to the instructions of the Organizing Committee for the WMO Solid Precipitation Measurement Intercomparison.

The second double fence is smaller and lower than the DFIR. This is also an octagonal vertical double fence inscribed into a circle. It differs from the DFIR by the dimensions of the circles into which the fence is inscribed: the outer fence is inscribed into a circle of 6 m in diameter, the inner fence into a circle of 3 m in diameter. The outer fence is 2.5 m high, the inner fence is 2.0 m high. The fence is also made of wooden picket boards, 1.5 m high, 0.05 m wide in a such way, that there is a gap between the vertical bars of 0.05 m, i.e. equal to the width of the bars. In the outer fence there is a gap of 1 m height between the ground and the bottom of the picket boards. In the inner fence this gap is only 0.5 m high. The Hellmann gauge, without wind shield, is placed in the centre of the inner fence and the receiving surface of the gauge is 2 m above the ground (Figure 3.C.13).



1- casing; 2 - funnel for preventing evaporation;
3- container

Figure 3.C.12a. Yugoslav standard precipitation gauge (Hellmann)



1 - plate; 2 - protection ring; 3 - casing; 4, 12 - hooks; 5 - capron line ; 6 - cap; 7 - flute ; 8 - brace; 9 - bracket; 10 - pole; 11 - screw

Figure 3.C.12b . Tretyakov gauge

Figure 3.C.13. Small wooden double fence

6. OBSERVATIONS

Routine observations were started on January 1, 1987, when five gauges were available. Observations were made twice per day at 0600 and 1800 GMT.

The snow depth is measured, also twice per day, on the experimental field and water equivalent of snow is measured by weighing.

6.1 Wind data

Unfortunately there was no wind recorder at Parg. There was only a wind vane (11.2 m above the ground). From January 1, 1987 to June 15, 1987 there was also a remote anemometer (2 m above the ground). So the mean wind speed (ms^{-1}), at the height of the national standard, was assessed according to the Beaufort wind scale by the equation:

$$v = 0.863N\sqrt{B^3}$$

where v is expressed in metres per second and *B* is the corresponding Beaufort number.

6.2 Wetting and evaporation losses

Wetting and evaporation losses have not yet been determined, and the precipitation amounts have not been corrected for these losses.

ANNEX 3. D FINLAND (INCLUDING DENMARK, NORWAY AND SWEDEN)

DESCRIPTION OF SITE AND INSTRUMENTATION FOR JOKIOINEN, FINLAND

1. INTRODUCTION

The errors inherent with precipitation measurement were identified already during the 18th century and a lot of field investigations have been operated in order to find suitable corrections (e.g. Heberden (1769), Hjeltström (1885), Sevruk (1982), Dahlström, et al (1986), etc.).

In 1986 WMO felt the need of an integrated effort to improve the quality of point precipitation measurements and decided to initiate an international intercomparison of snow measurements. The Nordic countries decided to make a co-ordinated contribution to this initiative and a test-field in Jokioinen, 100 km NW Helsinki, was established.

The Finnish Meteorological Institute has thus financed and been responsible for a comprehensive field measurement program. The work has continuously been co-ordinated between the Nordic countries by the Nordic Working Group on Precipitation. The main data collection has taken place during 1987 to 1993, but the test-field is still in operation, but with a reduction of the number of measurements.

The collected data sets represent a unique bank of information on the characteristics of both manual and automatic precipitation measurement devices. The methods for precipitation correction presented in this report are developed on the basis of the data from Jokioinen. For future research dealing with error correction of precipitation this data collection is expected to be of fundamental importance.

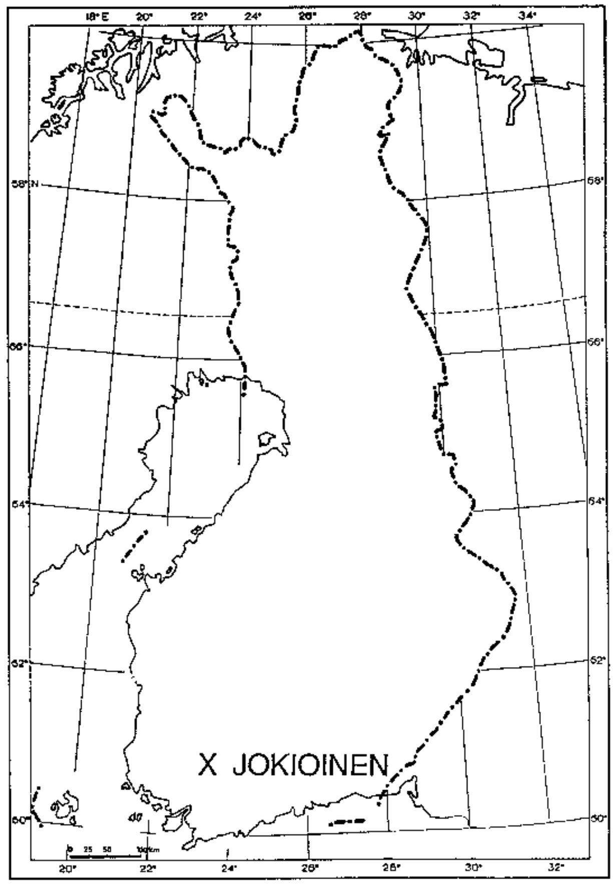


Figure 3.D.1 Meteorological observatory at Jokioinen, southwestern Finland (60° 49'N, 23° 29'E).

2. DESCRIPTION OF THE FIELD EXPERIMENTS IN FINLAND

An evaluation of possible comparison sites revealed that the most suitable site was in the neighbourhood of the Jokioinen meteorological observatory of the Finnish Meteorological Institute in the Southwestern part of Finland (60° 49'N, 23° 29'E) (See Figure 3.D.1).

2.1 Description of the site

The meteorological observatory at Jokioinen lies 104 m above mean sea level on a fairly flat ground surrounded mainly by cultivated fields. There are, however, some shading forests in the sector south-west to west close to the main building of the observatory (See Figure 3.D.2 and 3.D.4).

For the intercomparison the Valdai double-fences were placed in the western part of the field not to disturb other gauges, because snow falls mainly from the eastern and south-eastern sector. In the eastern-most row most of the gauges were without wind shields, whereas the gauges in the middle row were equipped with wind shield. Measurements in Finland has also been made in the summer-time and therefore a pit gauge has also been installed in the field. A cabin for manual measurements of amounts of precipitation and for automatic recording by a microcomputer was situated near the north-east corner of the field (See Figure 3.D.5).

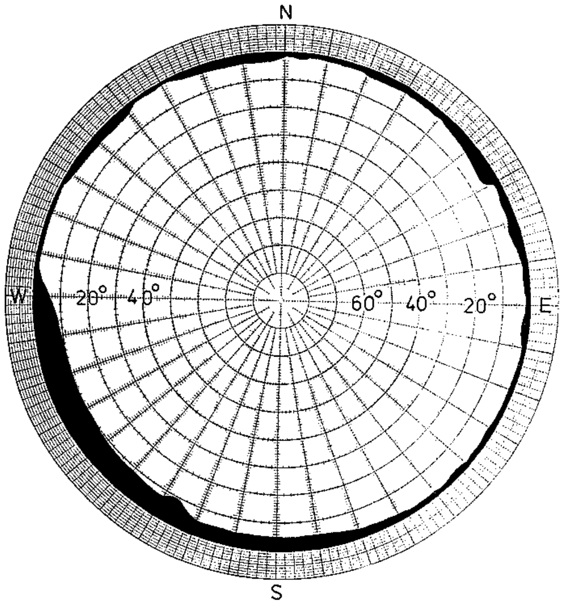


Figure 3.D.2. Horizon of the intercomparison field measured at a height of 1,5 m in the centre of the field.

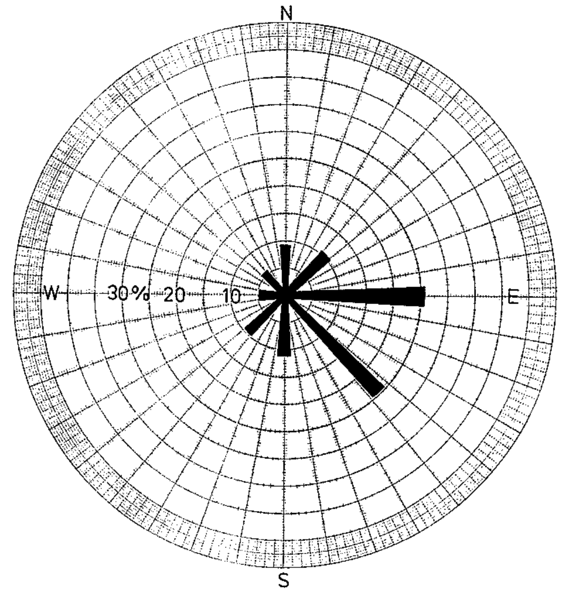


Figure 3.D.3. Mean annual distribution of solid precipitation versus different wind directions in Huittinen, 60 km NW of Jokioinen (1886 - 1935). (Korhonen 1942).

3. CLIMATE OF JOKIOINEN

In the area the mean length of the thaw free period is less than 60 days and the value of frost degree days is 620 - 799. The mean maximum snow depth is 40 - 69 cm and a snowless winter is fairly rare (recurrence interval over 20 years). The mean temperature drops below zero (the thermal winter begins) on the 15th of November and the thermal winter, on the average, lasts 142 days until 5 April (See Table 3.D.1).

Table 3.D.1. Climatological data for Jokioinen, Southwestern Finland, 1961 - 1990.

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Atmospheric pressure at mean sea level (hPa-1000)	12.4	14.6	12.8	12.9	15.5	12.3	11.0	11.7	11.2	12.3	9.3	9.9	12.1
Air temperature (°C)													
mean (t)	-7.5	-7.4	-3.5	2.4	9.4	14.3	15.8	14.2	9.4	4.7	-0.4	-4.9	3.9
mean daily maximum	-4.6	-4.1	0.4	6.8	15.0	19.7	20.9	19.1	13.4	7.7	1.7	-2.2	7.4
mean daily minimum	-11.2	-11.2	-7.7	-1.8	3.2	7.9	10.3	9.4	5.6	1.8	-3.0	-8.1	-0.5
absolute maximum	7.4	9.4	14.0	21.2	27.7	31.5	29.9	30.4	27.6	18.4	11.3	7.2	31.5
absolute minimum	-36.7	-39.3	-29.0	-20.9	-7.0	-3.1	0.8	-1.5	-8.8	-13.4	-24.5	-33.4	-39.3
Sunshine hours (%)	23	26	41	38	48	57	50	46	36	27	16	14	40
Global radiation (MJ/m2)	28	89	241	386	565	633	578	435	238	109	33	16	3350
Precipitation (mm)	36	24	25	32	35	46	80	83	65	58	55	42	582
Rainy days (>1.0 mm)	9	7	8	7	7	8	11	11	12	11	11	10	112
Potential evapotranspiration (mm)				61	112	108	82	38	20				
Precipitation deficit* (mm)				26	66	28	-1	-27	-38				
Mean relative humidity (%)	89	88	82	76	67	67	74	80	86	88	91	90	82
Snow depth on the 15th of each month (cm)	23	35	39	16							2	11	
Mean wind speed 30 m above ground (m/s)	3.9	3.8	4.0	4.9	3.9	3.7	3.5	3.4	3.6	4.0	4.1	4.0	3.9
Thermal seasons													
summer (t>10 °C)	length 114 days starting 23 May												
autumn (10>t>0 °C)	length 62 days starting 14 September												
winter (t<0 °C)	length 142 days starting 15 November												
spring (0<t<10 °C)	length 47 days starting 6 April												
Thermal growing season	length 167 days starting 28 April and ending 12 October												
	Sum of the effective growing temperature (t>5 °C) 1183 dd												

∗) Precipitation deficit = Potential evapotranspiration (PET) - precipitation (Ansalehto et al.,1985)

The lasting snow cover, on the average, settles at a temperature of - 4.2 °C when some 14 mm snow has fallen after the first snow cover. At Jokioinen the lasting snow cover settles on the 14th December and it disappears on the average on the 20th April and in the forests 7 to 11 days later. The total duration of temporary snow cover is on the average 16 days. The mean monthly precipitation increases from March until August and then gradually decreases towards the spring. About 30 % of the total annual precipitation falls as snow. The last snowfall occurs at about the same time as the forests free themselves from their winter snow cover, usually in early May but in extreme cases even in June.

Wind blows most frequently from the sector south to south-west. However, in southwestern Finland snow falls mostly (80 %) when winds are blowing from the eastern half (north-east-south) of the compass and most frequently (50 %) when they are from the sector east to south-east (See Figure 3.D.3).

During the intercomparison most of the winter months were milder than normal (See Table 3.D.2).

Table 3.D.2. Monthly mean air temperatures, precipitation sums, part of solid, days with rain and snow at Jokioinen 1987 - 1993. Normal values for the period 1961 -1990 are also included.

a) Air temperature (°C)

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
1987	-18,9	-7,9	-6,8	2,4	7,6	12,1	14,8	11,7	8,4	6,4	-0,7	-5,3	2,0
1988	-3,1	-4,3	-3,5	0,9	11,4	16,5	19,0	14,1	10,8	4,2	-3,9	-7,0	4,6
1989	-0,5	0,0	1,1	5,3	10,4	15,4	16,3	13,7	11,0	4,7	-0,1	-5,9	6,0
1990	-4,0	0,9	1,0	5,6	9,3	14,4	15,2	15,0	8,0	4,9	-1,9	-1,6	5,6
1991	-3,6	-7,5	-1,0	3,4	7,2	12,1	16,6	16,2	9,1	5,4	2,6	-1,6	4,9
1992	-2,1	-2,7	0,4	1,3	11,4	15,6	16,0	14,3	11,2	-0,6	-1,8	0,1	5,3
1993	-2,3	-3,4	-0,9	3,3	13,5	11,4	15,6	12,9	5,7	3,0	-3,6	-3,4	4,3
normal	-7,5	-7,4	-3,5	2,4	9,4	14,3	15,8	14,2	9,4	4,7	-0,5	-4,9	3,9

b) Precipitation (mm)

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
1987	18	32	13	5	38	81	68	83	120	43	38	36	572
1988	49	41	45	46	44	25	128	79	85	96	12	55	704
1989	33	61	40	40	41	30	85	92	51	49	69	47	637
1990	73	73	45	35	22	20	85	90	62	48	53	62	668
1991	69	16	31	14	29	69	55	92	80	49	81	34	619
1992	50	31	43	48	7	25	47	107	59	64	63	33	577
1993	56	16	29	29	1	56	107	136	13	51	3	61	558
normal	36	24	25	31	35	47	80	83	65	58	55	42	582

c) Part of solid precipitation to total precipitation (%)

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
1987	100	70	70	69	0	0	0	0	0	1	68	90	19
1988	57	75	92	57	0	0	0	0	0	11	83	88	28
1989	58	43	55	5	0	0	0	0	0	10	47	69	22
1990	68	44	50	43	3	0	0	0	0	12	64	74	31
1991	81	74	61	31	0	0	0	0	0	3	29	76	23
1992	69	73	76	56	3	0	0	0	0	48	54	38	33
1993	61	95	71	39	11	0	0	0	0	4	94	63	22
normal	81	78	73	44	4	0	0	0	1	11	38	68	24

d) Amount of precipitation days (precipitation have appeared regardless of precipitation amount)

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
1987	23	24	19	12	16	22	15	21	24	14	27	28	245
1988	26	27	28	20	12	20	18	26	22	20	24	29	272
1989	23	19	27	20	18	17	16	25	17	25	24	27	258
1990	31	25	24	18	16	12	22	16	26	14	24	26	254
1991	27	25	22	21	20	21	17	18	21	24	27	26	269
1992	22	26	27	26	13	10	18	27	30	26	27	24	266
1993	29	22	24	14	8	20	22	23	12	18	24	30	246
normal	26	22	21	18	16	16	19	19	21	21	25	26	250

e) Amount of solid precipitation days (snow have appeared regardless of precipitation amount)

Year	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	I-XII
1987	23	24	19	7	0	0	0	0	0	1	23	26	123
1988	22	27	28	13	0	0	0	0	0	8	19	27	144
1989	19	13	22	5	0	0	0	0	0	1	12	25	97
1990	31	17	17	6	1	0	0	0	0	3	19	22	116
1991	24	23	18	12	0	0	0	0	0	5	10	20	112
1992	18	22	22	20	1	0	0	0	0	5	16	7	139
1993	26	20	20	8	1	0	0	0	0	6	20	27	128
normal	25	21	19	12	2	0	0	0	1	5	16	23	122

Figure 3.D.4 Aerial photo of the intercomparison site

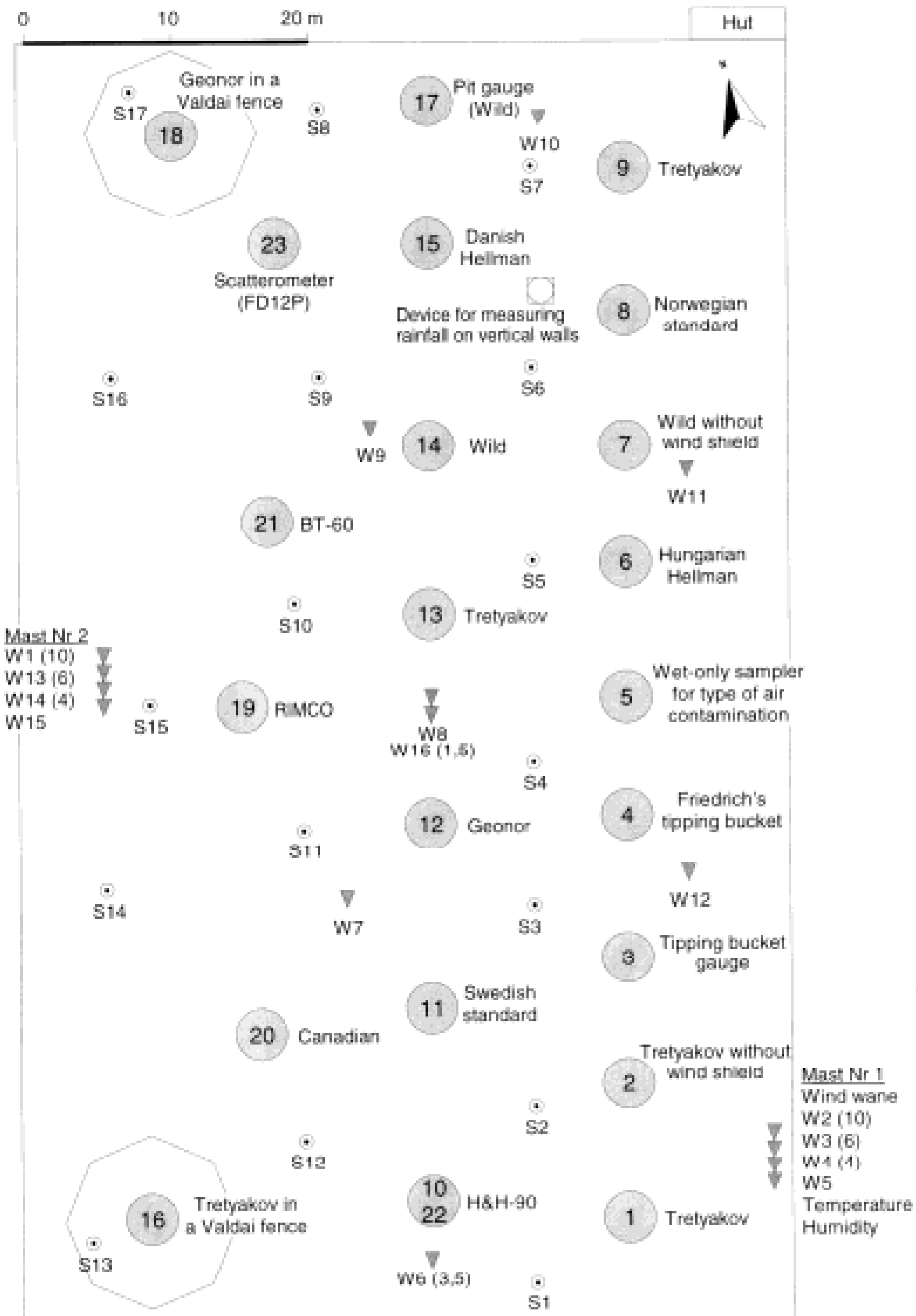


Figure 3.D.5 Location of instruments at the Jokioinen intercomparison site

4. DESCRIPTION OF THE INSTRUMENTS AND METHODS

4.1 Gauges and shields

Measurements were started on the 1st of February 1987. The following gauges were used during the experiment (Table 3.D.3).

Table 3.D.3 The gauges used at Jokioinen experimental field.

No	Gauge	Period	Comments
1	Tretyakov	01.02.1987 – 30.04.1993	with a funnel 1.5.-30.9.
2	Tretyakov	01.02.1987 – 30.04.1993	with a funnel 1.5.-30.9.
3	Wild, Tipping bucket	26.08.1987 – 30.09.1992	May–September
4	Friedrich	19.01.1988 – 30.09.1992	
5	Wilska	01.01.1989 – 30.04.1993	
6	Hungarian Hellmann	01.05.1988 – 30.04.1993	
7	Wild without a wind shield	01.02.1987 – 30.04.1993	
8	Norwegian	07.04.1987 – 30.04.1993	
9	Tretyakov	01.02.1987 – 30.04.1993	with a funnel 1.5.-30.9.
10	Finnish prototype	01.02.1987 – 24.02.1991	with a funnel 1.5.-30.9.
11	SMHI	01.02.1987 – 30.04.1993	with a funnel 1.5.-30.9.
12	Geonor	26.08.1987 – 30.04.1993	with a funnel 1.5.-30.9.
13	Tretyakov	01.02.1987 – 30.04.1993	with a funnel 1.5.-30.9.
14	Wild with a Nipher	01.02.1987 – 30.04.1993	
15	Danish Hellmann	06.02.1987 – 30.04.1993	with a snow cross 1.10.-30.4.
16	Tretyakov	01.02.1987 – 30.04.1993	
17	Wild, pit gauge	11.05.1987 – 30.09.1992	May–September
18	Geonor	26.08.1987 – 30.04.1993	
19	Rain-o-matic-H	21.02.1988 – 06.03.1990	
	RIMCO	06.03.1990 – 30.04.1993	
20	Canadian	23.02.1988 – 30.04.1993	
21	Tretyakov, BT-60	08.02.1990 – 30.04.1993	with a funnel 1.5.-30.9.
22	H&H-90	01.03.1991 – 30.04.1993	with a funnel 1.5.-30.9.
23	FD12P weather sensor	09.04.1992 – 30.04.1993	

4.1.1 Orifice area of the gauges

The area of each gauge orifice was measured using a precision ruler at angular intervals of 45 degrees, i.e. by taking four measurements of each diameter. The areas were then calculated using the diameters and the mean value of the four calculations has been used in the data analysis. The biggest difference of the gauge orifice area compared to the nominal value of the gauge was about 5 % (Table 3.D.4).

One should note that the orifice area of gauges no 8A and 8B (the old Norwegian standard gauge for snow measurements) was of square form while all the others are circular. The walls of the orifices of these Norwegian gauges also appeared to be slightly convex thus leading to measured orifice area larger than the nominal area. In the Table 3.D.4 the area of a small and short spout (area about 1.5 cm^2) of the gauges 4 (SMHI) and 10 (Finnish prototype) were not included in the measured area.

Table 3.D.4 Nominal and measured orifice areas of precipitaion gauges. Two units (A and B) of each manual gauge type were used alternately in the field.

Gauge		**Area**	**Ratio measured/nominal**		
no	name	(cm^2)	A	B	(A+B)/2
1	Tretyakov	200	0.9840	0.9940	0.9890
2	Tretyakov	200	0.9868	0.9922	0.9895
3	Wild, Tipping bucket	500	0.9472		
4	Friedrich	200	0.9976		
5	Nilu	300	1.0350	1.0163	1.0256
6	Hungarian Hellmann	200	1.0018	0.9912	0.9966
7	Wild without a wind shield	500	0.9908	0.9965	0.9936
8	Norwegian	225	1.0043	1.0120	1.0082
9	Tretyakov	200	0.9881	0.9834	0.9858
10	Finnish prototype	200	1.0018	1.0025	1.0022
11	SMHI	200	0.9906	0.9912	0.9909
13	Tretyakov	200	0.9750	0.9922	0.9836
14	Wild with a Nipher	500	0.9916	0.9827	0.9872
15	Danish Hellmann	200	0.9916	0.9940	0.9928
16	Tretyakov	200	0.9816	0.9860	0.9838
17	Wild, pit gauge	500	1.0020	0.9998	1.0009
18	Geonor	200	1.0136		
19	Rain-o-matic-H	200			
20	Canadian	125	1.0110	1.0142	1.0126
21	Tretyakov, BT-60	200	0.9916	0.9872	0.9894
22	H&H-90	200	0.9966	0.9912	0.9939

4.1.2 The gauges used in Finland since 1908 (No. 14, 1, 9, 13, 16, 22)

In Finland the Wild precipitation gauge with a Nipher wind shield was used, with minor variations, as the standard gauge in the period 1908 - 1981. The cylindrical bucket of the Wild gauge is made of 0.5 mm thick brass sheet. The orifice area is 500 cm^2 and its height 150 cm above the ground (Figure 3.C.6). Inside the bucket there is a fixed conical partition with a drain hole of 4 mm in diameter. The wind shield is a truncated cone of galvanized iron.

In 1982 the Wild gauge was replaced by the Tretyakov gauge (Figure 3.D.7). The cylindrical vessel is made of 0.5 mm thick galvanized iron with a lacquered grey outside surface. The orifice is 200 cm^2 and it is placed at a height of 150 cm above the ground. Inside the bucket there is a cone-shaped partition with a large drain hole. To reduce evaporation during summertime, the drain hole is covered with a shield consisting a funnel with a hole of 7 mm in diameter. The spout of the vessel is about 215 mm from the bottom of the bucket. The bucket is placed inside a wind shield made of 15 slats forming a cone with the upper edges of the slats bent outwards in an angle of 70 degrees to be horizontal. The slats are on a level with the rim of the bucket.

A new Finnish standard bucket was introduced into operation in all manual observation stations 1st January 1992. It is made of aluminum and covered inside with white teflon and is painted white outside. There is no spout in the bucket and the height of the bucket is the same as that of the Tretyakov bucket (40 cm) (Figure 3.D.8). In addition there is a Tretyakov gauge in a special 60 % transmitting wind shield (No. 21, BT-60), which has been used in earlier studies on precipitation measurement.

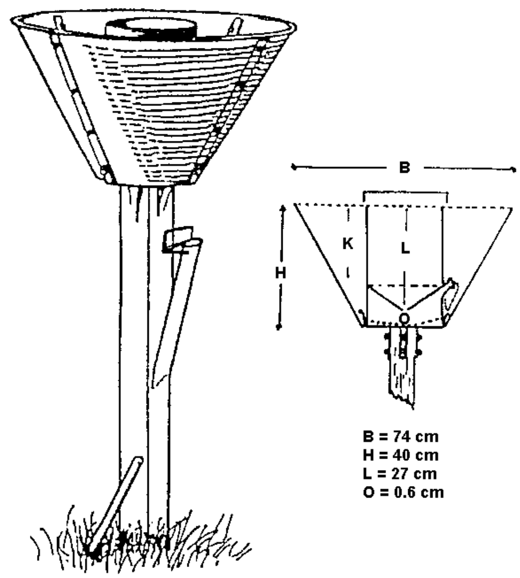


Figure 3.D.6. Wild precipitation gauge with a modified Nipher wind shield (Finnish standard gauge 1908-1981).

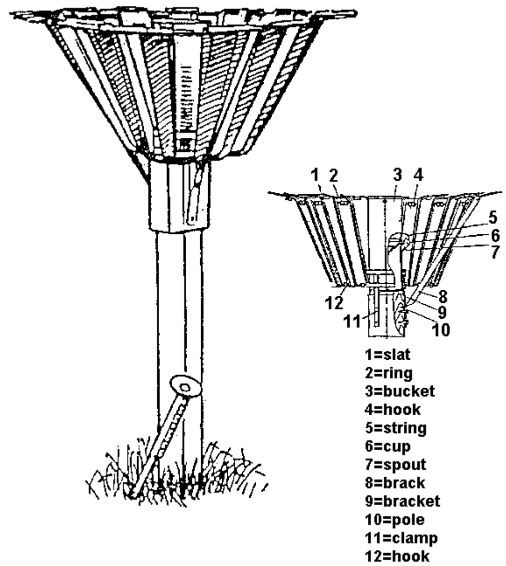


Figure 3.D.7. Tretyakov gauge (Finnish standard 1982-1991).

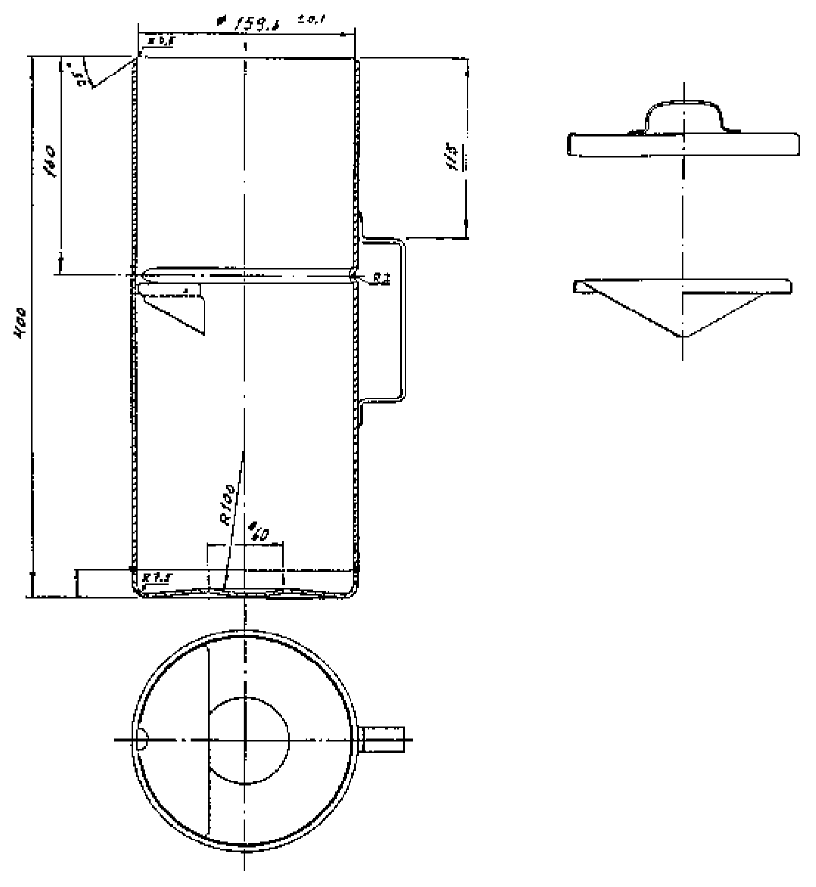


Figure 3.D.8. H&H-90 bucket used in a Tretyakov wind shield. Finnish standard 1992-

4.1.3 The NILU gauge (No. 5)

The NILU gauge is a wet-only type sampler used for air contamination. It is made of plastics and there is an iron double ring above the orifice to prevent birds from contaminating the bucket.

4.1.4 The pit gauge (No. 17)

The bucket used in the pit gauge is a Wild type one and it is placed in the middle of a 2 m^2 large pit covered with an iron crossing squared in 10 cm^2 intervals at the ground level.

4.1.5 The Danish Hellmann gauge (No. 15)

The Danish national precipitation gauge is a 200 cm^2 Hellmann gauge made of zinc, and the height of its orifice is 1.5 m above the ground (Figure 3.D.9). It consists of an upper part with a funnel shaped base and of a lower part with a container. In winter the gauge is provided with a metal ”snow-cross” put into the vessel for preventing snow blowing out of the gauge.

4.1.6 The old Norwegian standard gauge (No. 8)

The old Norwegian standard precipitation gauge (Figure 3.D.10) was used on all meteorological stations in Norway until 1981. Since 1982 the Norwegian Meteorological Institute (DNMI) is gradually introducing the Swedish standard gauge as the national standard.

4.1.7 The Swedish precipitation gauge (No. 11)

In Sweden the SMHI-gauge of anodized aluminum and surrounded by a wind shield is used (Figure 3.D.11). The orifice area is 200 cm^2 without a small and short spout near the upper edge of the gauge. During a warm season a funnel is inserted into the vessel to reduce evaporation.

4.1.8 Hungarian Hellmann (No. 6)

The Hungarian standard gauge is a Hellmann gauge similar to the Danish one except that no snow-cross is used during wintertime.

4.1.9 Canadian gauge (No. 20)

The bucket is made of copper and it is 520 mm deep. The collection bucket is placed in a Nipher wind shield made of the glass fiber with the orifice height (150 cm) and diameter of 610 mm (Figure 3.D.12).

4.1.10 Tipping bucket (No. 3)

The tipping bucket is made of an Wild gauge under which a tipping bucket with magnet and reed relay system has been installed. The resolution is 0.1 mm and it is not heated. This type of gauges without wind shield has been installed on agrometeorological automated weather stations in Finland and they are mainly used from May to September.

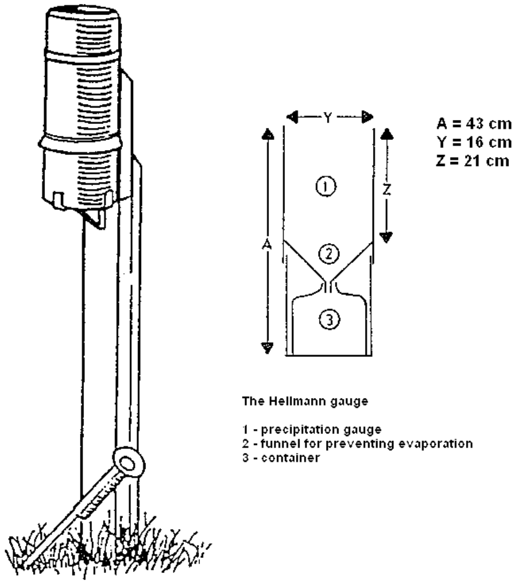


Figure 3.D.9. Danish standard precipitation gauge (Hellmann).

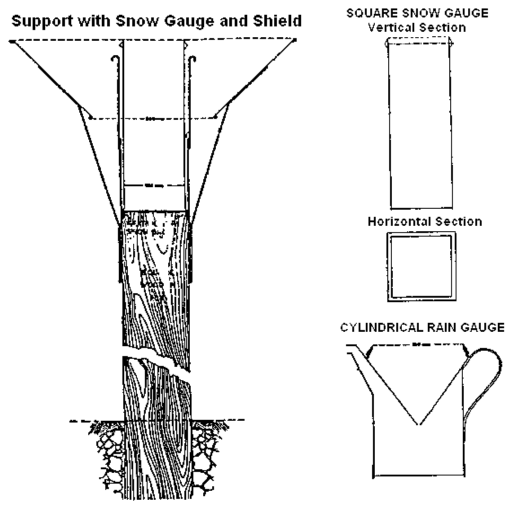


Figure 3.D.10. Norwegian standard gauge.

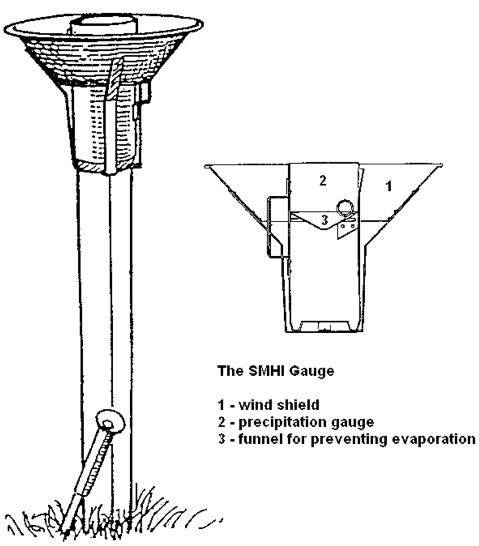


Figure 3.D.11. Swedish precipitation gauge.

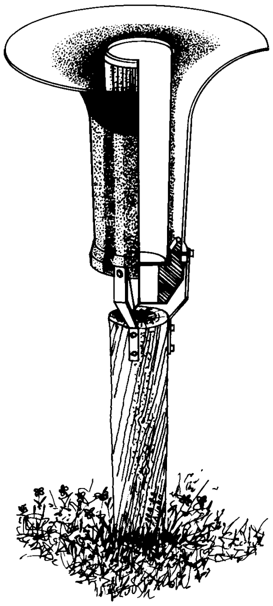


Figure 3.D.12. Canadian gauge with a Nipher wind shield

4.1.11 Friedrich's tipping bucket (No. 4)

The collection area of this heated gauge is 200 cm^2, resolution 0.1 mm, measurement range 0…15 mm/min, accuracy ±3% up to 4 mm/min intensity and operating temperatures -25°…+60° C. Heating power is 140 W. It has an electromechanical pulse counter, 5 digits with reset. The bucket is made of aluminum and it is presented in the Figure 3.D.13.

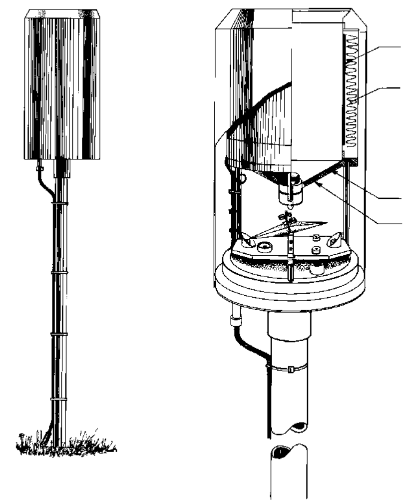


Figure 3.D.13. Friedrich's Tipping bucket. (Inha A.)

4.1.12 Rain and snow gauge GEONOR (No. 12 and 18)

This precipitation gauge is based on the vibrating-wire principle. The output of the vibrating-wire transducer is an alternating current (800…3500 Hz). The frequency is measured with a digital counter and precipitation can be calculated from a standard formula. The accuracy is 0…600 mm of the liquid water and sensitivity 0.1 mm. The accuracy is 0.1 % of full scale. Temperature range for operations is -25…+60° C with a temperature drift of 0.001 % of full scale/C.

To measure rain and snow precipitation the gauge used a standard 12 litres bucket mounted on three flexible supports. One sensors is sufficient provided that the gauge is carefully leveled to ensure equal load distribution. The electronics incorporate a filter for damping vibrations caused by wind loadings etc., to ensure stable readings. The GEONOR gauge is mounted using a universal 3-point mounting with a leveling system incorporated in the base.

When the gauge is used at sub-zero temperatures, an anti-freeze mixture must be poured into the bucket in order to melt the incoming snow and to prevent freezing. A solution of ethylene glycol and methanol is recommended. It is also essential to pour 0.4 litre of thin oil into the bucket to retard evaporation losses. ESSO UNIVIS J43 aero hydraulic oil (or equivalent) is recommended throughout the year. Around the gauge there is an Alter wind shield of U.S. Weather Bureau type (Figure 3.D.14).

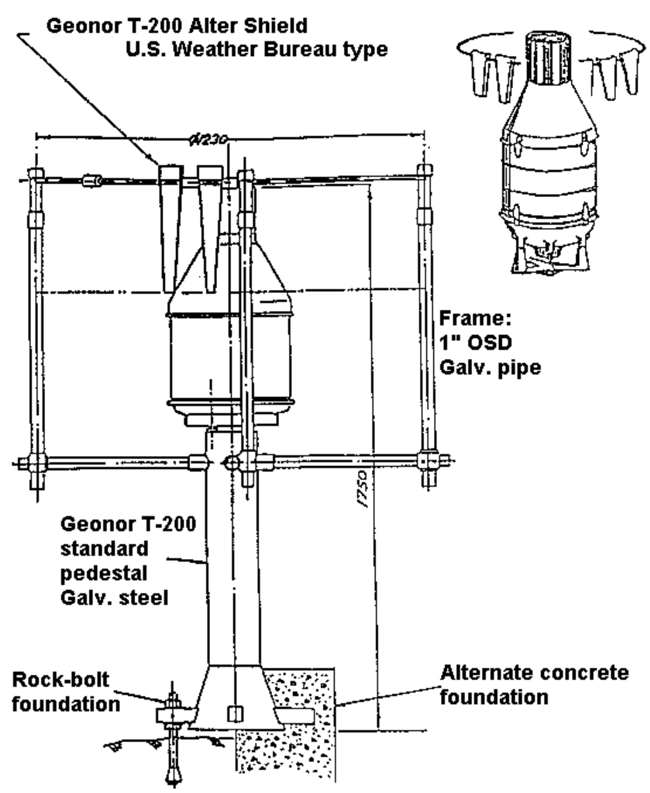


Figure 3.D.14. Geonor T-200 series.

4.1.13 RIMCO (No. 19)

An Australian made tipping bucket has on orifice of 200 cm^2 and is 380 cm high. The measuring height is 150 cm above the ground (Figure 3.D.15). It is normally heated using two 40 W lamps under the collector. The drainage hole is 2 mm in diameter and has been frozen. For the winter 1992-1993 the heating lamps were changed to be 80 watts each. The resolution of the tipping bucket is 0.1 mm.

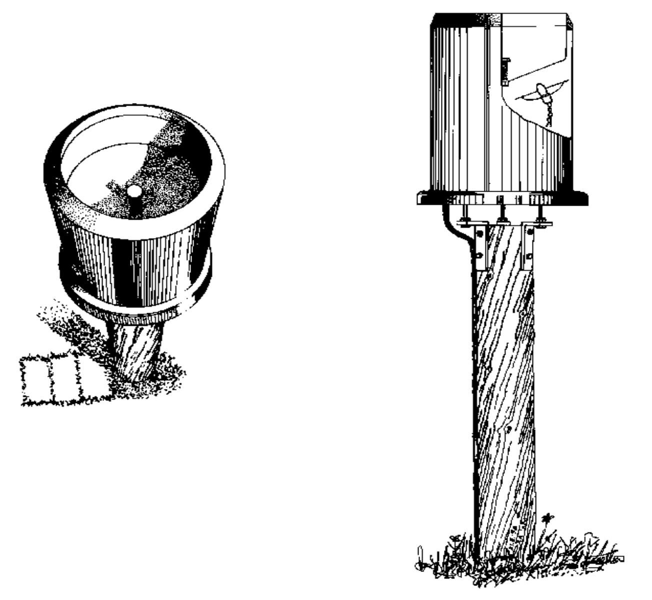


Figure 3.D.15. Rimco, a heated tipping bucket. (Inha A.).

4.1.14 FD 12P Weather sensor (No. 23)

This is a scatterometer with the operating principle of forward scatter at angle 33 degrees. Light source is a near-infrared Light Emitting Diode, peak radiated power is 100 mW, peak wavelength 875 nm, modulation frequency 2.3 kHz. Transmitter lens have a diameter of 72 mm. In addition there is a reference photodiode for light source control and backscatter photodiode for contamination measurement. Light receiving photodiode is of type PIN 6 DI, spectral response has its maximum at 850 nm, 0.55A/W.

The sensor is used mains supplied and it has a power consumption of 30 VA at maximum but 150 VA with an optional defrosting heaters. Serial data line may be used either as RSS-232-C level signals or interfaced via an optional data modem. Update interval of the sensor is 15 seconds.

The height of the instrument is 215 cm and it weights 35 kg and it is made of anodized aluminum and is natural grey. It can be operated in the following environmental conditions : -40...+50 °C, 0...100 % (RH), 60 m/s (wind speed). Direct and reflected sunlight into the light receiver must be avoided.

4.2 Other Measurements

4.2.1 Wind speed and direction

Wind speed is measured on the field on 10 separate spots (Figure 3.D.5). In 9 of the spots there is an anemometer at 2 m height and in the middle of the field there is an anemometer at 1.5 m, as well. Near the DFIR with a Tretyakov gauge there is an anemometer at 3.5 meter height. There are three masts on the field. In the masts 1 and 2 wind speed is measured at 4 levels: 2, 4, 6 and 10 m. Wind direction is measured at the top of the mast no 1 at 10 m height.

The WAA 15 3-cup optoelectric anemometers are used. They give 14 pulse per revolution. The pulse frequency is directly proportional to wind speed. A WAA 15 anemometer includes a heating element with a heating power of about 10 W. The accuracy is +/- 0.1 m/s with wind speed below 10 m/s and +/- 2 % at wind speed 10...75 m/s. The starting threshold speed is in general about 0.3...0.6 m/s according to the calibrations which have been done once a year. Some 20 % of the anemometers have greater figures after one year of operation.

Ten minutes mean and 2 seconds minimum and maximum wind speed have been recorded from the measurements made every 5 seconds. Wind direction is recorded as follows:

1. wind direction 10 min average weighted on wind speed
2. wind direction x-component 10 min average weighted on speed
3. wind direction y-component 10 min average weighted on speed
4. wind direction x-component variation
5. wind direction y-component variation.

4.2.2 Air temperature

Air temperature is measured at the mast no 1 at two meters height. The temperature transducer is a RTD PT-100 (1/DIN) platinum thermometer. The ohmic value of the RTD is measured with a voltage/current (4…20 mA / -40…+40 C) converter. The resolution os 0.01 C and maximum error +/- 0.2 C.

Air temperature is measured every 5 seconds and 10 min mean values are recorded.

4.2.3 Air humidity

Air humidity is measured at the mast no 1at two meters height. The transmitter is based on a Lambrecht “PERNIX” measuring element. It has a resistance 5-100-5 ohms, and the linear resistance alteration from 0 to 100 ohms corresponds to a humidity change from 0 to 100 %.

4.2.4 Measurement of snow cover

On the intercomparison field there are 10 (1987-1988) and 17 (1988-1993) snow stakes and snow depth is measured twice a day from the stakes no 3 and 6 (Figure 4). From all the stakes snow depth is measured on the 5th, 10th, 15th, 20th, 25th and 30th (31st, 28th, 29th) of each snow month.

Snow density and depth for water equivalent measurements were made at one point on the field on the 5th, 10th, 15th, 20th, 25th and 30th (31st, 28th, 29th) of each snow month.

4.2.5 Rain on/off

The rain on/off detector is based on capacitance measurement. Precipitation on the sensor surface increase its capacitance which is indicated as rain on. The sensor is equipped with
heating which switches on when the temperature decreases below +5 C and also when water drops fall on it. This allows the water to dry off fairly quickly (1…5 min) after the rain. The sensor is installed at the mast no 1 at the height of 2 meters.

4.3 Data collecting system of the auto gauges

The data collecting system measures and saves data automatically. The system consists of a PC-microcomputer, a line printer, interface cards and measuring transducers. The system is shown in Figure 3.D.16.

The main unit of the system is an IBM-compatible PC -microcomputer Osborne 5. Its specifications are as follows:

1. central processing unit: 8088, clock frequency is programmable 4.77/8 MHz
2. memory: 640 k bytes
3. monitor: CGA
4. interfaces: RS-232 serial interface, Centronix printer interface and 5 pcs IBM-PC compatible slots
5. clock: battery back-up.

The DT2805 converter board includes a low-level wide-range 12-bit analog to digital (A/D) converter system for 8 differential input channels. A programmable gain amplifier provides software selectable gains of 1, 10, 100 and 500. Which allow the user to accommodate a 20 mV to 10 V full scale range of input signal levels. Resolution with the lowest level is 6 μV. The DT2805 also includes two 12-bit digital to analog (D/A) converters, two 8-line digital I/O channels and an internal programmable clock.

The CTM-05 multifunction counter-timer and digital I/O board provides five 16-bit up/down counters. A 1 MHz crystal timebase with divider and separate general purpose 8 bit TTL input and output ports. The AMD-9513 system timing controller IC is used for all counting and timing functions.

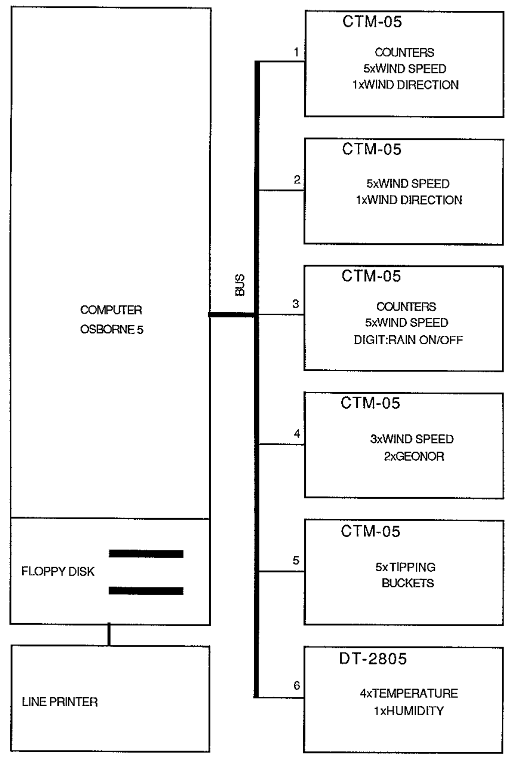


Figure 3.D.16. Block diagram of the measuring system.

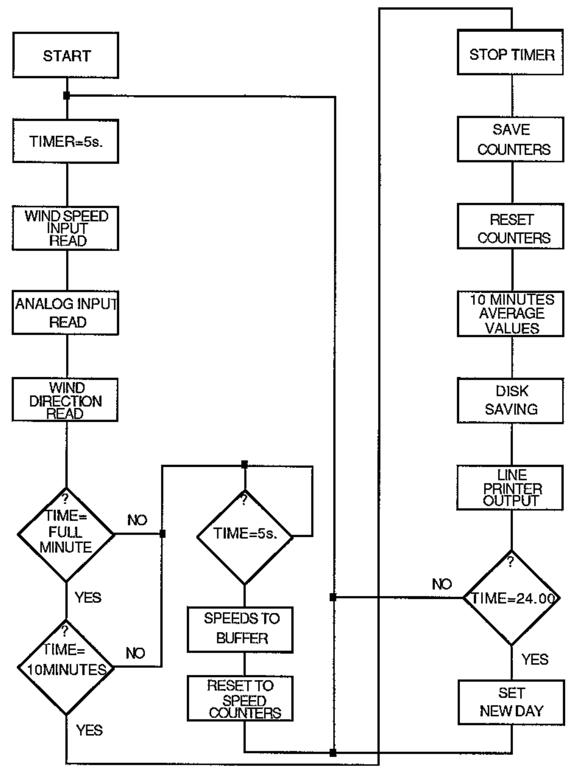


Figure 3.D.17. Program flow chart

Technical specifications of the measuring system are as follows:

1. power: 220 VAC
2. power consumption: 0.4 kW
3. temperature: 5…30 C
4. humidity: 5…90 %.

Analog transducers are connected direct to the system. Digital transducers are optically isolated from the interface cards.

The measuring software is developed using a Microsoft QuickBasic compiler. The program is specially made for this system. The program flow chart is shown in Figure 3.D.17. Because the program is done with Basic, possible changes are easy to make

4.4 Sampling Procedure

The observation cabin, the two Valdai double-fences and the posts of the gauges were erected before the end of January 1987.

The Valdai double fences were grounded to the depth of 70 cm, but that seemed to be too low a depth. During a ground frost melting period in 1988 the fences were very near to fall down because of strong NW-winds at Jokioinen.

In summertime the measuring site is grass covered. Pathways covered with concrete slabs connect the different gauges to the observation cabin and to other buildings of the observatory.

Routine observations were started on 1 February 1987 when nine gauges were available (Table 3.D.3). By the end of April the number of gauges was twelve. Observations are made at 00 and 12 hrs local time in order to suit the daily observation routine of the observatory.

The gauges were taken into the cabin and replaced by empty ones always in the same order. The gauges were not changed if the observer was convinced that there has been no precipitation or condensation since the preceding observation. A snowmobile was used for carrying the gauges in the wintertime and wheelbarrow in the summer. All gauges were covered with their lids during the transport. Snow was allowed to melt with lids on the gauges in the cabin.

The water equivalent of snow was measured both by measuring cylinders (volumetrically) and by weighing with a digital balance. In order to arrive at comparable results, the measuring cylinders were wetted before starting the measurements. Afterwards the empty gauges were allowed to dry thoroughly before bringing them back to the measuring site.

While using a digital balance for water equivalent measurements condensation of water on the cold gauges was a problem. Observers had to wait for some minutes before a reading can be taken (Figure 3.D.18) (Elomaa et al. 1989).

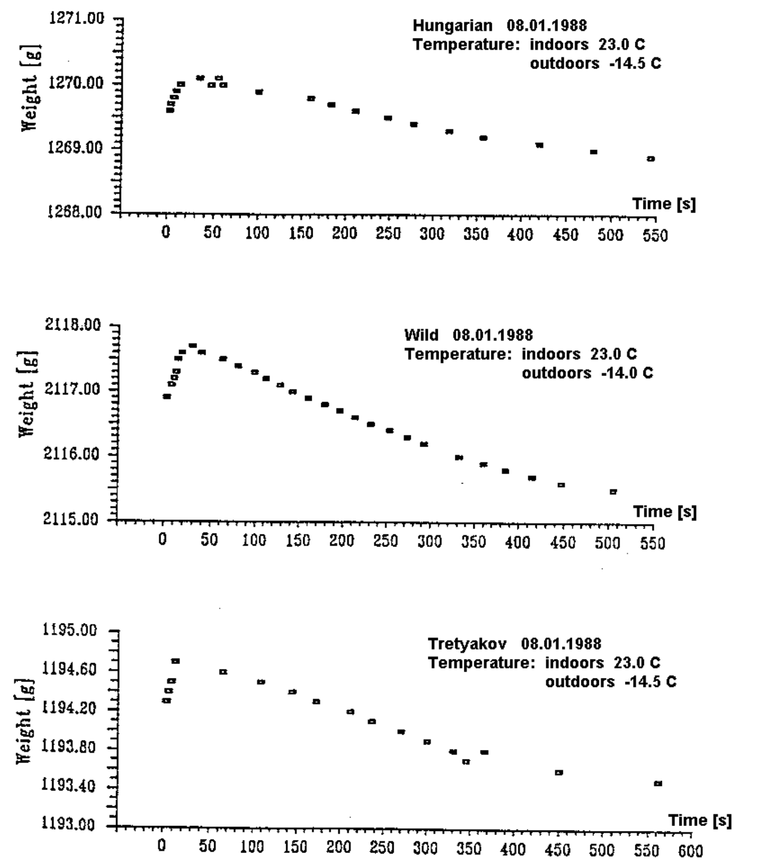


Figure 3.D.18. Change of a gauge weight after taken a gauge from the field into the observation cabin.

If the amount of snow in a gauge was rather large, say at least one third of the measuring capacity, the observer on duty also sketched on the measuring site the shape of the snow surface in the gauge. This information may be used in evaluating the influence of wind (e.g. blowing out of the gauge) or freezing phenomena on the measurements with each type of the gauge. The homogeneity of the measuring site may also be estimated in this way.

4.5 Supporting Observations

The following routine observations of the meteorological observatory supported the measurements on the intercomparison field:

1. synoptic weather observations every 3 hours including the height of cloud base
2. monitoring weather elements with a time resolution of 5 minutes
3. global radiation and net radiation measurements
4. soil temperature measurements
5. ground frost measurements
6. snow board measurements
7. wind speed and direction on the top of an instrument tower (about 30 m above the field)
8. radiosonde measurements giving PTU (air pressure, temperature and relative humidity) and upper wind data twice a day.

4.6 Special Experiments and Measurements

4.6.1 Wetting loss

Wetting loss can be taken as a difference between weighted and volumetrically measured precipitation. It was also measured separately for each type of the gauges. Three different amounts of water 0.5, 5.0 and 10.0 mm were at first poured and later on sprayed into each gauge during the tests.

The wetting loss depended only slightly on the amount of water sprayed into the buckets and varied from 0.1...0.3 mm/case on the average.

The wetting losses were measured at three different periods (1987, 1989 and 1992) according to the following procedure:

1. Each gauge was weighted empty, with a resolution of 0.1 gram, using an accurate digital balance (Reading A).
2. Certain amounts of water were measured for each gauge, using its own measuring glass. In the first series of observations 0.5 mm of water, in the second series 5.0 mm of water and in the third series 10.0 mm of water was used.
3. Each amount of water was poured (1987 and 1989) and sprayed (in 1992) into the respective gauge and left there for a time of about ten minutes. Then the water was poured out of each gauge in the same way as in a routine precipitation measurement.
4. Each gauge was then weighted again with the resolution of 0.1 gram (Reading B).
5. Each gauge was then left to dry without any cover at room temperature (about 20 C).
6. Some gauge with small orifices were dried by heating them with a heating device.
7. Each gauge was weighted again dry with a resolution of 0.1 gram (Reading C).
8. The difference D = B - C for each gauge were then calculated.
9. The difference D is the wetting loss for each gauge.
10. The above described procedure 1-9 was repeated 20 times for each gauge with a 0.5 mm amount of water.
11. The measuring procedure 1-9 was then repeated in the second series of observations with water amounts of 5.0 mm
12. The measuring procedure 1-9 was then repeated in the third series of observations with water amounts of 10.0 mm.
13. Wetting losses were calculated for each gauge and for the three water amounts.
14. The mean values of wetting losses with their standard deviations were then calculated and converted into millimeters of water.

4.6.2 Evaporation

Evaporation from the gauges was measured in the wintertime from snow and in the summertime from water in the gauges. Evaporation was measured using at first only two different type of gauges: WILD and TRETYAKOV and later on (since 1991) using also the following gauges: H&H-90 (no 22), SMHI (No 11), Danish Hellmann (no 15) and Norwegian gauge (No 8).
The daily procedure used was as follows:

1. Gauges were weighted dry (empty) with resolution of 0.1 gram (Reading A).
2. In the winter 1-2 cm of light snow was put into the gauges. In the summer 2.0 mm on paired days and 3.0 mm on odd days was poured into the gauges.
3. The gauges were weighted with the resolution of 0.1 gram (Reading B).
4. The gauges were kept outside on their own stands from 08 until 20 o'clock local time i.e. for 12 hours.
5. The gauges were weighted (in the case no precipitation had occurred) with a resolution of 0.1 gram (Reading C).
6. The difference D = B - C were calculated to indicate the evaporation of snow or water.
7. The results were converted into millimeters of water.

5. REFERENCES

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ANNEX 3.E GERMANY

HARZGERODE, GERMANY

Th. Günther, Deutscher Wetterdienst, Business Unit Hydrometeorology, Division of Hydrometeorological Development and Application, Berlin

1. DESCRIPTION OF SITE

Country:	Federal Republic of Germany	
Station Name:	Evaluation Station Harzgerode	
	Latitude:	51^{o} 39' N
	Longitude:	11^{o} 08' E
Type of site:	Open	
Elevation:	404 m a.s.l.	
Nearest town:	Harzgerode; Federal State Saxony-Anhalt	

1.1 Measuring site

The Evaluation Station Harzgerode is located on a flat plateau, 404 m a.s.l. Its location is shown in Figure 3.E.1. The surrounding area is characterized by open fields, mainly cultivated without woods (Figure 3.E.4). The border of the forest is at a distance of about 500 m SW to W of the station. SE of the station a sparsely built-up area - the out-skirts of Harzgerode - is located at a distance of 250 m to 300 m. Because of its open position, the station is exposed to wind (mean vertical angle of the visible horizon $\alpha < 5^{o}$, see the Table 3.E.3; Figure 3.E.5).

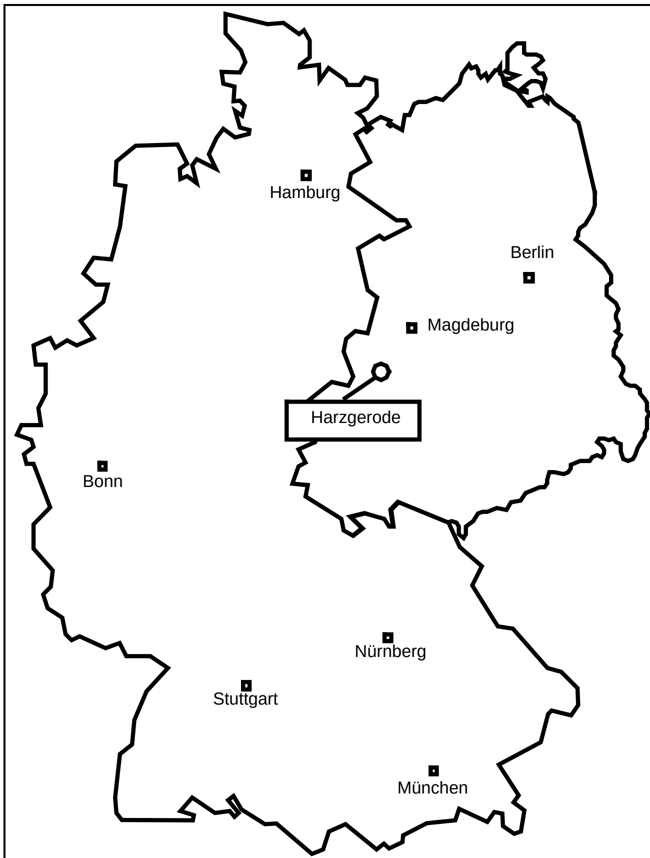


Figure 3.E.1 Map showing location of Harzgerode

The Double Fence Intercomparison Reference (DFIR) was erected in November 1986, and placed at the north-eastern part of the measuring field. Figure 3.E.6 gives the location of gauges and other instruments in the measuring field of the Harzgerode station.

1.2 Climate of Harzgerode

Germany belongs to the warm-moderate climate of west and central Europe, with precipitation in all seasons. The Harz Mountains are characterized by forests and plateaus between 400 and 600 m above sea level.

The average monthly precipitation total (1951-1980) for the Evaluation Station Harzgerode increases from February (44 mm) until June (71 mm) and then gradually decreases towards September (43 mm), followed by a slight increase up to a secondary maximum in December (Table 3.E.1). Monthly mean winter temperatures range from -1,8 ^{o}C (in January) to +1,6 ^{o}C (in March). About 20 % of the total annual precipitation is snow. The average maximum snow depth is 20 to 25 cm (January to March). The absolute maximum, i.e. 75 cm, was measured on 6 March 1970. On average from December to March snow fall ($\geq$ 0,1 mm) is observed on 10 to 12 days per month. During the winter season winds blow most frequently from South-South-West to West (Table 3.E.2, Figure 3.E.2), the average wind speed in the winter season is 4,5 ms^{-1} (15 m above ground, 1978-1987, Figure 3.E.3).

Table 3.E.1 Climatological data for Harzgerode / Germany 404 m a.s.l. (1951 - 1980)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year
Air temperature (^oC)													
mean	-1,8	-1,3	1,6	5,8	10,6	14,2	15.5	14,8	11,7	7,4	2,8	-0,3	6,8
mean monthly maximum	7,8	10,2	15,0	20,5	24,5	27,3	28,4	28,3	25,4	20,8	13,6	8,9	30,0
mean monthly minimum	-13,2	-12,3	-9,1	-3,9	-1,2	2,4	3,9	3,8	0,7	-2,3	-6,0	-11,1	-15,8
absolute minimum	-23,0	-24,3	-18,9	-9,5	-4,2	-1,4	1,4	1,7	-3,1	-7,1	-18,1	-23,6	-24,3
Sunshine hours (h)													
mean monthly total	40,8	69,0	113,7	154,3	195,5	205,5	196,1	186,3	152,2	114,4	51,1	34,9	1513,8
number of days < 1,0 h	3,8	3,5	3,3	2,8	1,9	2,3	2,0	2,0	2,5	3,7	5,5	5,2	38,5
number of days ≥ 10,0 h	-	-	1,0	4,9	8,0	8,2	7,3	6,4	3,2	0,1	-	-	39,1
Precipitation													
mean monthly total (mm)	48	44	48	49	59	71	64	62	43	46	47	54	635
mean daily maximum (mm)	10,1	12,3	13,7	14,5	17,1	20,7	20,9	16,9	13,4	14,7	12,8	12,3	36,3
absolute maximum (mm)	25,5	26,4	42,0	33,1	45,3	34,0	71,5	46,6	47,6	52,5	52,5	31,8	71,5
number of days ≥ 0,1 mm	18,0	16,0	15,8	15,3	15,2	14,1	13,8	14,8	13,6	14,1	16,5	18,0	185,2
number of days ≥ 1,0 mm	10,8	9,5	9,5	9,6	10,3	10,2	9,7	10,3	8,4	8,2	9,6	10,6	116,7
number of days ≥ 3,0 mm	5,1	3,9	5,0	5,1	6,1	6,6	5,9	6,2	4,1	4,3	5,3	5,8	63,4
number of days ≥ 10,0 mm	0,8	0,9	1,1	0,9	1,6	2,1	1,4	1,6	0,7	1,1	0,9	1,2	14,3
number of days ≥ 0,1 mm	12,8	11,0	9,1	5,2	0,6	-	-	-	-	0,5	5,0	9,7	53,9
Snow													
portion of snow (1951/65) (%)	66,4	68,3	52,3	20,8	3,3	-	-	-	-	-	17,4	54,8	
Snow depth													
mean monthly maximum (cm)	24,2	22,7	20,5	2,5	0,1	-	-	-	-	-	5,7	15,3	35,4
absolute maximum (cm)	55	64	75	15	1	-	-	-	-	-	34	40	75
number of days ≥ 1 cm	21,7	16,5	11,6	1,9	0,1	-	-	-	-	0,1	3,9	13,9	69,7
number of days ≥ 3 cm	19,3	14,3	10,0	1,3	-	-	-	-	-	-	3,1	11,6	59,6
number of days ≥ 10 cm	13,6	10,0	6,4	0,1	-	-	-	-	-	-	1,1	7,1	38,3
Relative humidity (%)	90	87	83	79	77	78	79	82	84	87	89	91	84
Vapour pressure	5,1	5,2	5,9	7,4	10,0	12,7	14,1	13,0	11,7	9,2	6,9	5,7	9,0

Table 3.E.2 Seasonal wind climate for Harzgerode

(a) Wind rose (%)

		30^o	60^o	90^o	120^o	150^o	180^o	210^o	240^o	270^o	300^o	330^o	360^o	calm
	Mean	4,9	4,3	3,5	2,7	2,5	4,1	11,6	24,5	14,7	4,6	5,6	6,4	10,6
XII, I, II	**Winter**	5,6	5,1	3,8	2,0	2,5	3,6	10,7	22,7	17,8	4,4	5,5	5,4	10,8
III, IV, V	**Spring**	7,1	6,4	4,4	3,9	3,2	4,4	10,5	18,8	12,3	4,1	6,1	8,2	10,6
VI, VII, VIII	**Summer**	4,4	3,1	2,8	2,3	1,9	3,3	10,2	24,5	15,2	5,9	7,2	7,9	11,3
IX, X, XI	**Autumn**	2,6	2,5	2,9	2,5	2,5	5,0	15,3	32,1	13,6	3,8	3,8	4,1	9,6
Nov, Dec, Jan, Feb, Mar		4,7	5,2	3,6	2,2	2,4	4,0	1,4	24,8	16,8	4,1	4,9	4,7	10,1

(b) Mean wind speed (m/s)

		30^o	60^o	90^o	120^o	150^o	180^o	210^o	240^o	270^o	300^o	330^o	360^o
	Mean	2,4	2,5	2,7	2,7	2,7	3,1	3,8	4.0	4,2	3,6	3,6	3,2
XII, I, II	**Winter**	2,5	2,1	2,7	2,4	2,6	3,0	4,0	4,6	4,8	4,2	4,1	3,5
III, IV, V	**Spring**	2,6	2,7	3,1	3,2	2,6	3,2	3,8	3,7	3,9	3,5	3,5	3,5
VI, VII, VIII	**Summer**	2,2	2,1	2,4	2,8	2,9	3,1	3,3	3,3	3,6	3,2	3,4	2,8
IX, X, XI	**Autumn**	2,4	2,4	2,6	2,4	2,6	3,1	4,2	4,2	4,2	3,6	3,6	3,0
Nov, Dec, Jan, Feb, Mar		2,5	2,4	2,8	2,5	2,6	3,2	4,2	4,6	4,8	3,9	4,0	3,4

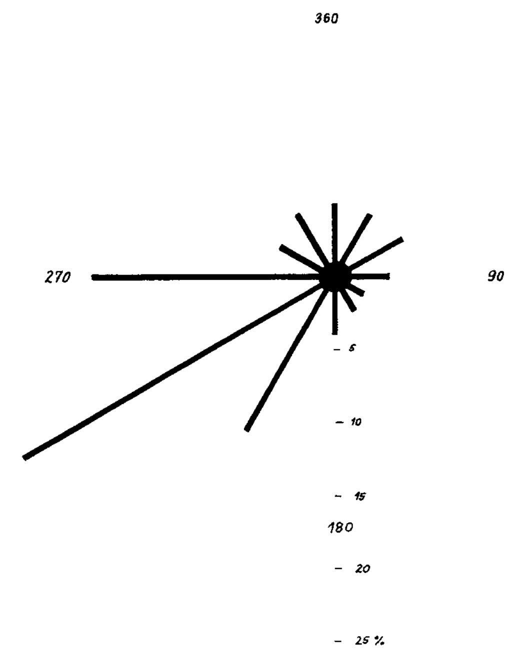


Figure 3.E.2   Wind rose for Harzgerode (1978-1987); Calm 10,1% ; November-March

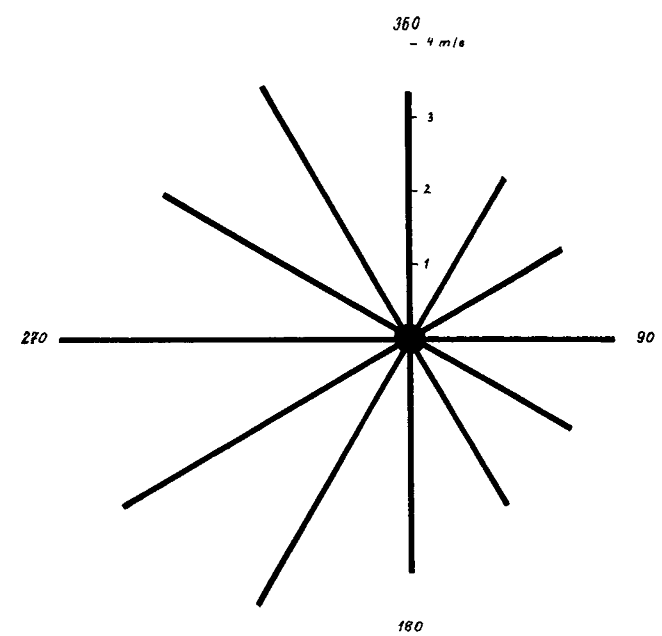


Figure 3.E.3 Wind rose for Harzgerode (1978-1987); Calm 10,1%; Wind speed (ms^{-1}); 15m above ground; November-March

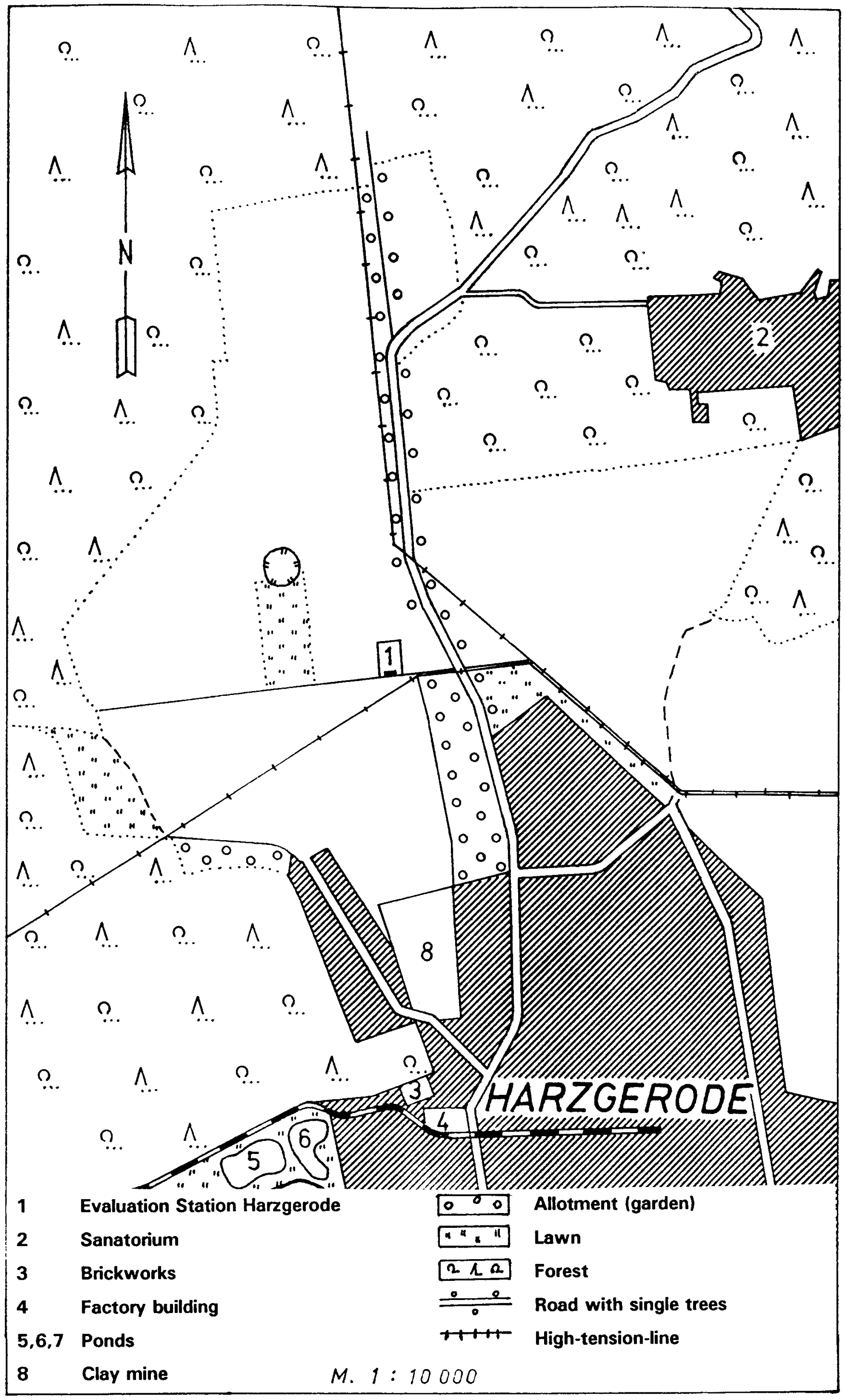


Figure 3.E.4 Map of Harzgerode site

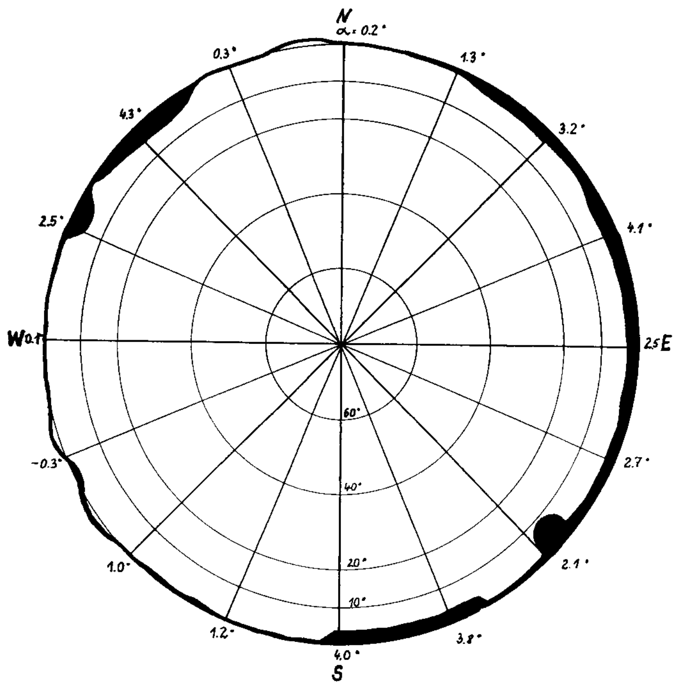


Figure 3.E.5 Evaluation Station Harzgerode/Germany;
α = vertical angle of obstacles (°) horizon of the intercomparison field

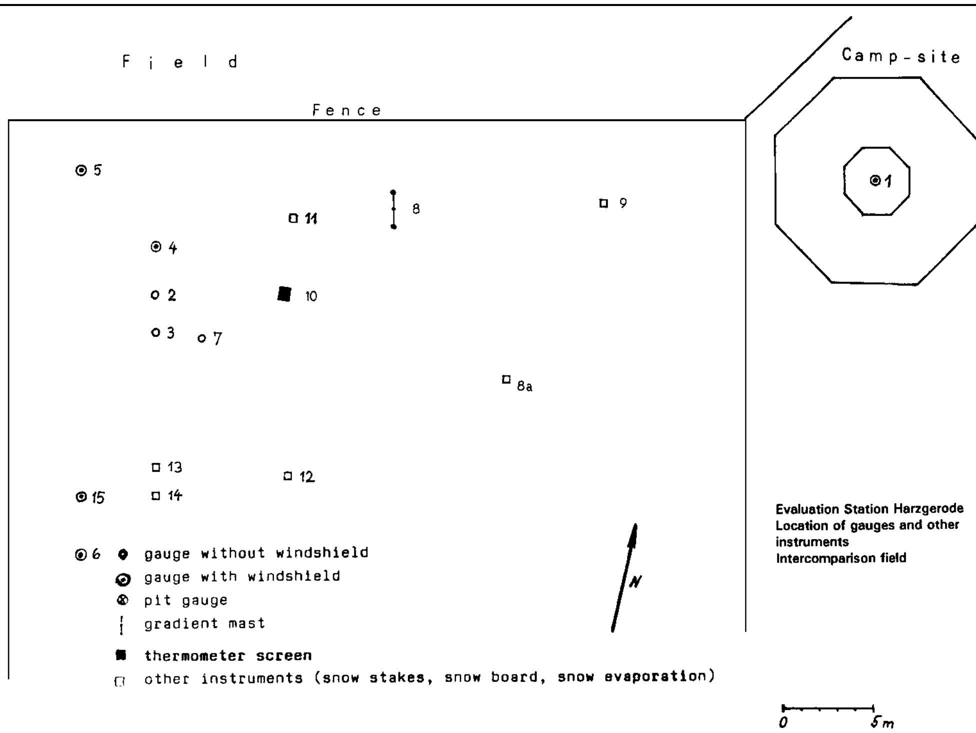


Figure 3.E.6 Evaluation Station Harzgerode; location of gauges and other instruments at the Intercomparison field

Table 3.E.3 Vertical angle of the horizon/obstacles measured in the centre of the field (360^o in 16 points of the wind rose)

Point of the wind rose	Vertical angle α (^{o})	Distance (m)
N (360^o)	1,3	450
NNE	2,4	360
NE (45^o)	3,2	170
ENE	3,3	110
E (90^o)	3,1	110
ESE	3,5	50 (single tree)
SE (135^o)	0,7	300
SSE	3,5	35 (Building of
S (180^o)	3,6	35 the station)
SSW	1,2	750
SW (225^o)	0,3	750
WSW	0,1	800
W (270^o)	0,2	800
WNW	3,0	240
NW (315^o)	4,4	280
NNW	0,3	700

2. INSTRUMENTS AND OBSERVATIONS

2.1 List of gauges

The intercomparison measurements were started on 1 December 1986. Table 3.E.4 lists the types of gauges (c.f. Figure 3.E.6) which have been included in the data archive:

Table 3.E.4 Gauges which have been included in the data archive:

Nr.	Type	Gauge orifice (cm^2)
1	Double Fence Intercomparison Reference(DFIR)	200
2	Hellmann gauge, unshielded National Standard	200
3	Automatic gauge, unshielded heated, volumetric (AFMS)	200
4	Hellmann gauge, shielded	200
5	Tretyakov, shielded	200
6	Precipitation gauge, Metra	500
7	Precipitation gauge, Hellmann Polish standard	200
15	Canadian Nipher shielded snow gauge	127

The orifice area of each gauge shown in Table 3.E.5 was measured using the following procedures:

- Measurement of the diameter of the orifice area with a precision ruler. Four measurements were made, at intervals of 45 degrees; the result is the mean from the individual measure-ments
- Production of a copy of the orifice area on paper, 4 measurements of the diameter of the orifice area with a precision ruler over the centre, at intervals of 45^o
- Determination of the orifice area by means of a polar-planimeter, mean from 2 measurements

Wetting losses were measured separately for each of the different gauge types according to the procedure given by Huovila et al (1988). Two different amounts of water, i.e. 0,5 and 5,0 mm, were poured into each gauge during the tests. Of all gauge types, the two replacement gauges were measured separately. The results of the measurements have been drawn up in Table 3.E.6. The results depict the maximal values, as this degree of wetting or drying out would hardly be attained in actual use.

Table 3.E.5 Nominal and measured orifice areas of precipitation gauges (A and B indicates the used duplicate gauges)

Gauge No.	Nominal area (cm^2)	Measured area (cm^2)			Ratio measured/nominal		
		Ruler on the spot	Ruler on sheet	Planimeter	Ruler on the spot	Ruler on sheet	Planimeter
1 A	200	198,75	199,95	201,1	0,9938	0,9998	1,0055
1 B	200	199,06	200,70	200,3	0,9953	1,0035	1,0015
2 A	200	199,00	200,31	199,5	0,9950	1,0016	0,9975
2 B	200	199,81	200,20	200,5	0,9991	1,0010	1,0025
3 A	200	199,62	199,20	198,7	0,9981	0,9960	0,9935
4 A	200	198,81	198,95	199,6	0,9941	0,9948	0,9980
4 B	200	198,81	199,95	200,5	0,9941	0,9998	1,0025
5 A	200	196,04	202,21	203,0	0,9802	1,0111	1,0150
5 B	200	197,03	203,72	203,4	0,9852	1,0186	1,0170
6 A	500	498,76	501,03	499,9	0,9975	1,0021	0,9998
6 B	500	498,68	499,44	498,0	0,9974	0,9989	0,9960
7 A	200	198,56	199,20	199,3	0,9928	0,9960	0,9965
7 B	200	199,06	199,20	199,5	0,9953	0,9960	0,9975
				Mean	**0,9937**	**1,0015**	**1,0018**

Table 3.E.6 Wetting losses (W) of different gauges with 0,5 mm and 5,0 mm water inputs

Type of gauge		Orifice area	Wetting loss (mm)	
		cm^2	0,5 mm	5,0 mm
DFIR	**1**	199,95	0,22	0,25
	2	200,70	0,20	0,22
Hellmann (unshield)	**1**	200,31	0,19	0,23
	2	200,20	0,19	0,21
Hellmann (shield)	**1**	198,95	0,19	0,25
	2	199,95	0,19	0,23
Tretyakov	**1**	202,21	0,22	0,28
	2	203,72	0,18	0,21
Metra	**1**	499,84	0,14	0,21
	2	499,44	0,13	0,19
Hellmann (Poland)	**1**	199,20	0,20	0,25
	2	199,20	0,20	0,22

In order to establish a complete data set with all necessary information for research purposes, especially for studying the wind related error in solid precipitation measurement, the following supporting observations have been carried out (c.f. Figure 3.E.6):

8, 8a Wind speed, gradient mast (0,65 m....7,00 m above ground)

9 Wind direction, mean wind speed (15 m above ground)

10 Air temperature, dew point (thermometer screen)

11 Snow depth, standard snow stakes, water equivalent of snow cover

12 Depth of fresh snow, standard snow stakes, water equivalent of fresh snow cover

13, 14 Evaporation from the snow cover (gauge, 3000 cm^2)

2.1.1 The Hellmann-gauge, unshielded

The Hellmann precipitation gauge without wind shield is the German National Standard. Its orifice area is 200 cm^2 and the height of its exposure is 1 m above the ground. The Hellmann gauge consists of an upper part with a funnel-shaped base and of a lower part with a collecting can each made of sheet zinc (Figure 3.E.7 and 3.E.8).

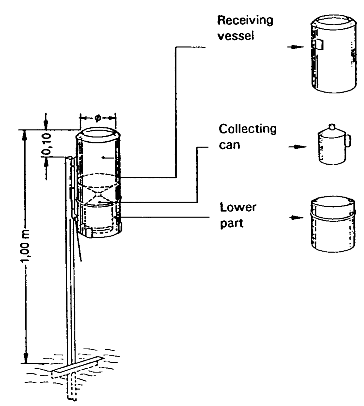


Figure 3.E.7 Diagram of Hellmann precipitation gauge, unshielded

Figure 3.E.8 Hellmann precipitation gauge, unshielded

2.1.2 Automatic gauge, ushielded (AFMS)

The precipitation total is determined by means of volume measurement. The precipitation water collected in the funnel (200 cm^2) passes through a filter and a slanting channel into the measuring vessel which is made up of two connected vertical channels. When the precipitation total has reached 0,1 mm/m^2, an electric impulse is triggered in the measuring vessel by a needle electrode causing a brief opening of the valve which empties the measuring vessel. At the same time an impulse is given for the further processing of the measured value which represents the precipitation total of 0,1 mm. In order to measure solid precipitation, the collection funnel and the measuring vessel have been provided with an electronically controlled heating device (+2 ^{o}C), (Figure 3.E.9 and 3.E.10).

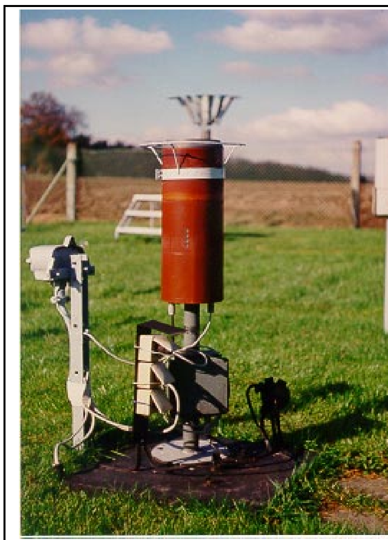


Figure 3.E.9

Figure 3.E.10

Automatic gauge (AFMS); Height of exposure: 1 m

Figure 3.E.11 Hellmann gauge, shielded

2.1.3 Hellmann gauge, shielded

The Hellmann gauge is surrounded by a modified Nipher wind shield (Figure 3.E.11). All other parts like the Hellmann standard gauge.

2.1.4 Double Fence Intercomparison Reference (DFIR)

The wooden DFIR was constructed in the experimental field according to the instructions given by the organizing committee for the WMO Solid Precipitation Measurement Intercomparison (Figure 3.E.12).

Figure 3.E.12 Double Fence Intercomparison Reference (DFIR)

ANNEX 3.F JAPAN

1. HOKURIKU, JAPAN

Type of site:	Open
Country:	Japan
Station Name:	TAKADA
Latitude:	37^{o} 06' 45" N
Longitude.	138^{o} 16' 31" E
Elevation:	11 m a.s.l.
Nearest city:	Joetsu City (2 km)

1.1 Description of surroundings

The station is located in a plain of about 200 km^2 in area northward open to the Japan sea (Figure 3.F1). The plain is surrounded by the mountain ranges. The distance from the site to the crest is 10 to 20k m, and the height is around 1000 m. The heighest summit nearby, 2462 m a.s.1., stands at 30 km south-west.

The station is about 6 km from the coast, and is surrounded by rice fields. The observation field is situated in the center of the experiment paddy field of the Hokuriku National Agricultural Experiment Station with an area of 133,000 m^2. Three sides, i.e. north, west, south, of the paddy field is private houses with trees and a road runs along its east side. Besides a 3-meter-high hut which is apart 35m north from Double Fence Intercomparison Reference Gauge (DFIR), there is no obstacles within the distance of 200m (see Table 3.F.1 for vertical angle of obstacles).

1.2 Climate

Due to the seasonal wind blown from the Siberian Air Mass and the warm current in the Japan Sea, the study site receives heavy amount of precipitation in winter. Figure 3.F.2 shows the record of maximum snow depth measured by the weather office adjacent to the station from 1922 to 1992. Because of its geographical location and elevation, the winter season in the study area is relatively warm, the winter three-month mean being 2.9^{o} C. Thus, a large year-to-year variation occurs in the relative percentage of solid precipitation. Figure 3.F.3 shows the wind climate during the intercomparison.

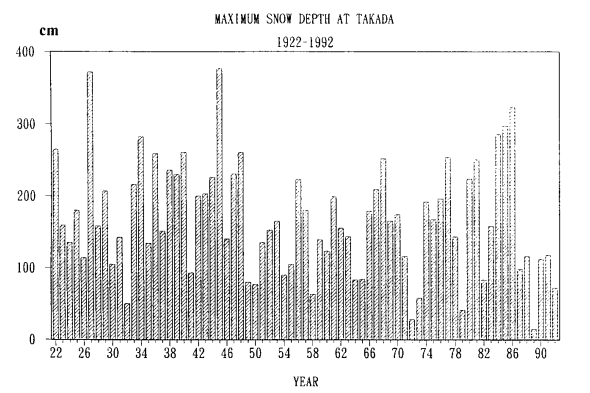


Figure 3.F.2 The record of maximum snow depth at Takada Weather Station from 1922 to 1992.

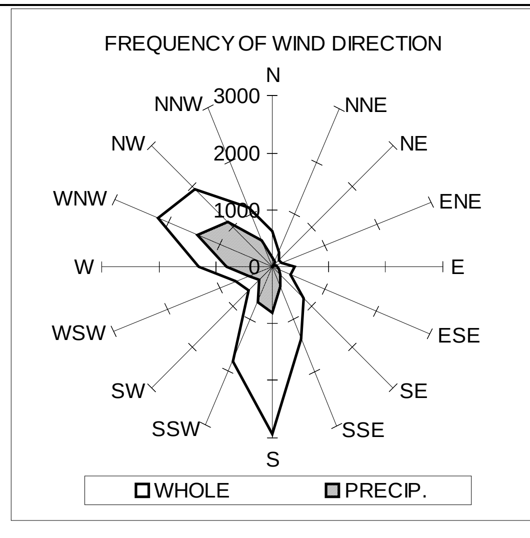


Figure 3.F.3 Histogram of wind direction frequency during intercomparison.

Table 3.F.1 Vertical angle of obstacles:

direction	angle(°)	major obstacle	direction	angle(°)	major obstacle
N	1	road bridge	S	3	tree
NNE	2	tree	SSW	3 1/2	tree
NE	1	road bank	SW	2	private house
ENE	1 V3	road bank	WSW	1 2/3	private house
E	5/6	road bank	W	5/6	private house
ESE	4	office building	WNW	1 1/2	institute building
SE	2 1/3	private house	NW	2 2/3	institute building
SSE	5/6	private house	NNW	1 1/3	institute building

1.3 Instrumentation

The national gauges evaluated this site included the RT-1, the RT-3 and the RT-4 precipitation gauges of Japan Meteorological Agency (JMA). RT-1 shown in Figure 3.F.4 is a simple tipping bucket gauge. JMA prepares a model which has an electric heater which heats the air beneath the funnel. This gauge does not have a wind shield. JMA deploys this model to those few observatories where the probability of solid precipitation is low but not regarded to be zero.

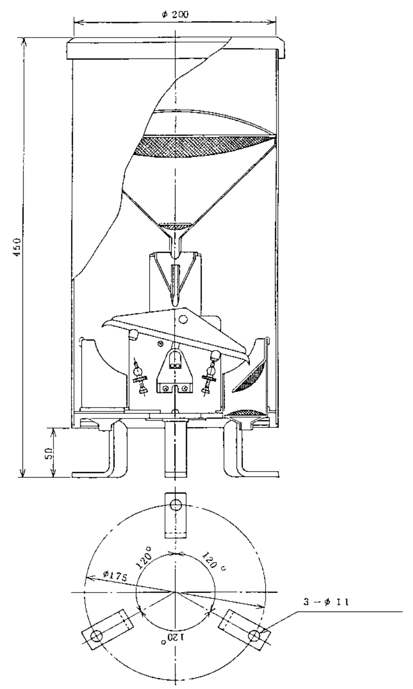


Figure 3.F 4 Structure of RT-1 gauge

RT-3 shown in Figure 3.F.5 has thicker wall in which hot water is filled. Hot water is kept to 5°C). This gauge does not have a wind shield. JMA deploys this type most of observatory where have a probability of solid precipitation in winter.

RT-4 shown in Figure 3.F.6 collects precipitation to the water reservoir installed in the orifice which is heated to 5°C. The water equivalent to the collected precipitation flows down to the measuring unit through the overflow drainage. The evaporation from the reservoir is protected by an oil layer created over the water. This gauge has a cylindrical wind shield.

These three gauges all use the same tipping bucket mechanism with the resolution of 0.5 mm to measure the water amount. The physical characteristics of these gauges are given in Table 3.F.2. The height of gauge orifices were adjusted to 3.5 m above ground. JMA does not designate the height of precipitation gauges.

Table 3.F.2 Physical characteristics of Instruments

Name	Type	Orifice area (cm^2)	Height above ground (cm)	Remarks
DFIR	modified Tretyakov	200	350	connected to automatic gauge
RT-1	tipping bucket	314	350	heated funnel
RT-3	tipping bucket	314	350	heated water jacket
RT-4	tipping bucket	314	350	heated water reservoir with wind shield

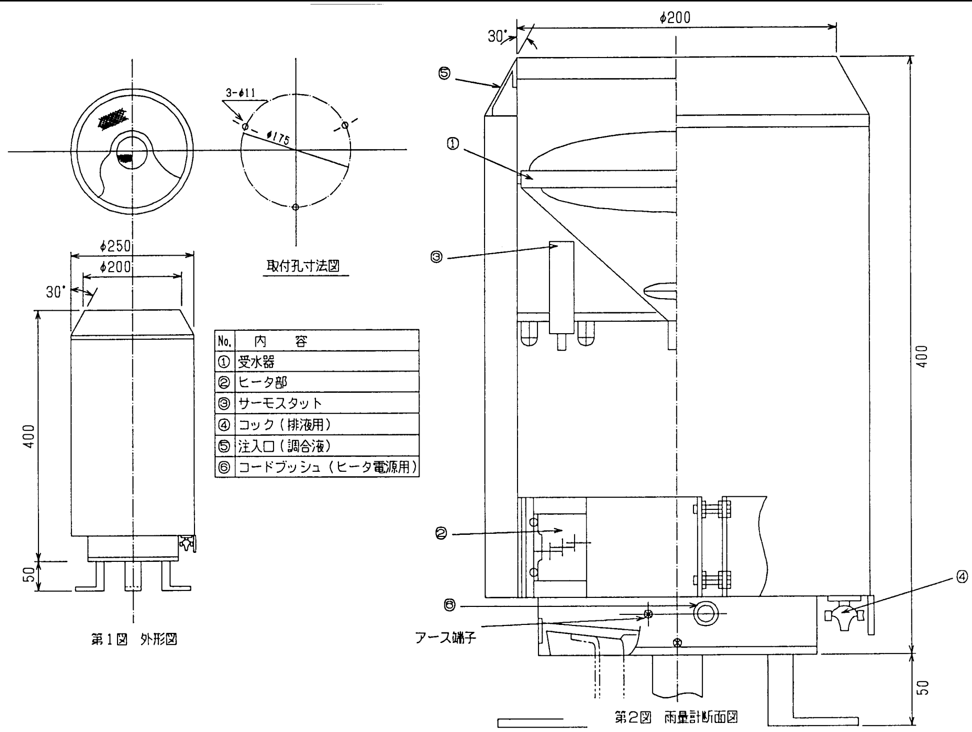


Figure 3.F.5 Structure of RT-3 gauge

A Tretyakov gauge was also set at 3.5 m above ground. The inclination of the wind shield panels of Tretyakov gauge and the automatic DFIR were set at 55º to horizon. Wind speed was measured with a windmill anemometer at 6.25m above the ground. The height of the air temperature sensor was set 1.5 m above snow surface and adjusted once a day. Snow depth was measured an automatic infrared snow depth gauge.

The DFIR installed at the station has been modified so as precipitation is able to be recorded continuously: the bottom of the Tretyakov Gauge is removed, and connected to a high precision automatic gauge via a metal tube of 140 cm in length and 18 cm in diameter (Figure 3.F.7). Considering the snow depth in this area (Figure 3.F.2), the top of the outer fence, inner fence and the gauge were leveled to 400 cm, 350 cm and 350 cm above the ground, respectively, i.e., 50 cm higher than usual DFIRs.

The instrumentation map of the station is shown in Figure 3.F.8. Photographs of the site are shown in figures 3.F.9 to 3.F.12.

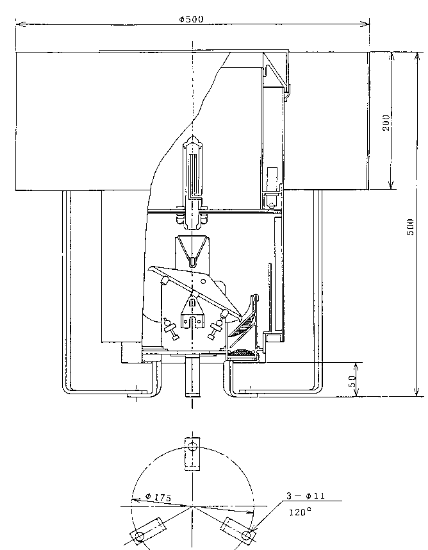


Figure 3.F.6 Structure of RT-4 gauge

Figure 3.F.7 Modified Tretyakov Gauge with a high-resolution automatic gauge in the double fence.

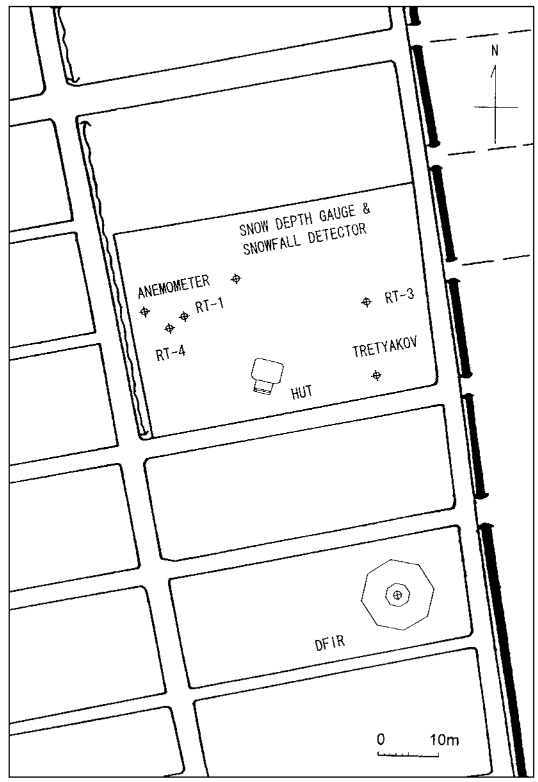


Figure 3.F.8 Disposition of instruments at evaluation site

Figures 3.F.9 to 3.F.12   Photographs of intercomparison site at the Hokuriku National Agricultural Experimental Station

2. MEMAMBETSU, HOKKAIDO, JAPAN

The Memambetsu station(43°55' N, 144°12' E, 39m MSL) is located on the east side of Hokkaido, the northern part of Japan. Abashiri is the nearest city of the station about 13km apart. The station is located in the area between two hills which extend from the south to the north with some 300m above MSL, and the distance from coast is about 12km. The Abashiri river goes north at the 1km west from the station and runs into the Lake Abashiri (34 km^2). The lake freezes in winter. Prevailing wind direction in winter is from WNW to NNW. In many snowing cases, wind direction is from NW to NNE. The maximum depth of snow cover during the cold season at the station is 102 cm on 2nd April 1975. The average maximum depth of snow cover from 1961 to 1990 is 65cm.

Climate of the Memambetsu station is shown in Table 3.F.3.

Table 3.F.3 Climate of the Memambetsu station (1961-1990)

monthly normals \ month	**Dec.**	**Jan.**	**Feb.**	**Mar.**
Air temperature (°C)	-4.9	-9.7	-9.2	-2.7
Mean daily max. temp.(°C)	0.7	-3.3	-3.1	1.6
Mean daily min. temp.(°C)	-9.8	-15.1	-15.3	-8.7
Relative humidity (%)	77.0	79.0	76.0	72.0
Wind speed (m/s)	2.1	2.1	2.0	2.4
Precipitation(mm)	36.0	47.0	28.0	45.0

The following instruments were operated from Dec. 1988 to Mar. 1991 and the location of the instruments are shown in Figure 3.F.13:

1) DFIR: Tretyakov gauge with doubled-fence (outer fence 12 m in diameter, inner fence 4m in diameter), 200cm^2 orifice area, 3 m height ;
2) overflow type rain/snow gauge with tipping bucket with shield, 314 cm^2 orifice area, 1.5 m height (RT-4, Figure 3.F.6) ;
3) overflow type rain/snow gauge with tipping bucket without shield, 314 cm^2 orifice area, 1.5 m height;
4) warm water rain/snow gauge with tipping bucket without shield, 314 cm^2 orifice area, 1.5 m height (RT-1, Figure 3.F.4);
5) weighing type rain/snow gauge with shield, 314 cm^2 orifice area, 1.5m height ;
6) snow measuring plate ;
7) snow scale ;
8) wind vane and anemometer, at 2 m height ;
9) wind vane and anemometer, at 10 m height;
10) thermometer and dew-point meter, at 1.5 m height.

There is no obstacle at the direction of prevailing wind. The vertical angle of obstacles in degrees is shown in Figure 3.F.14.

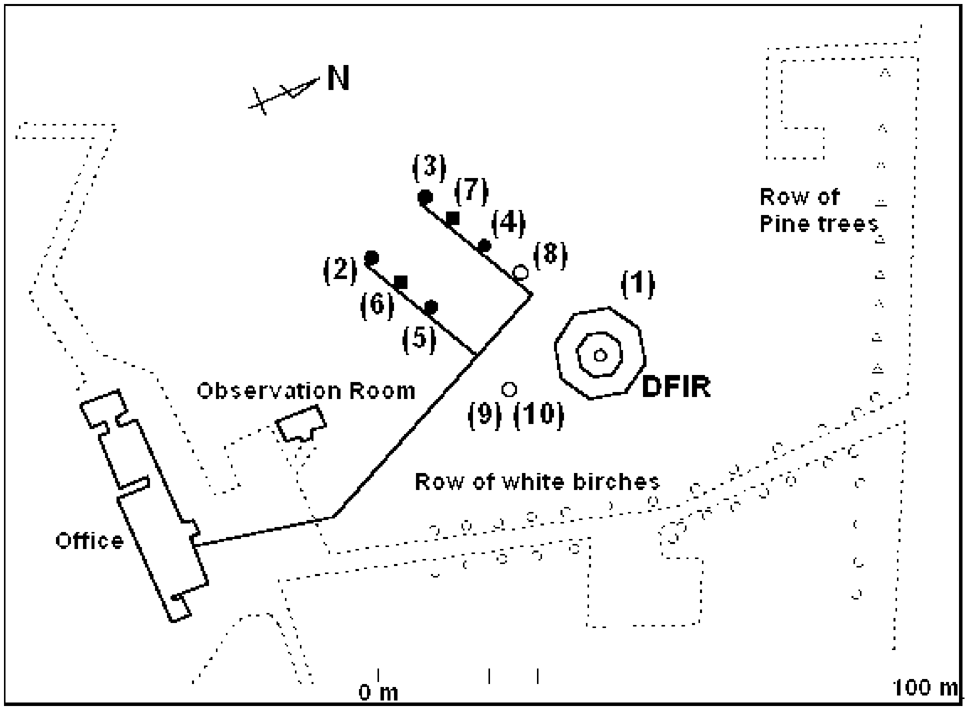


Figure 3.F.13   Location of the instruments at Memambetsu

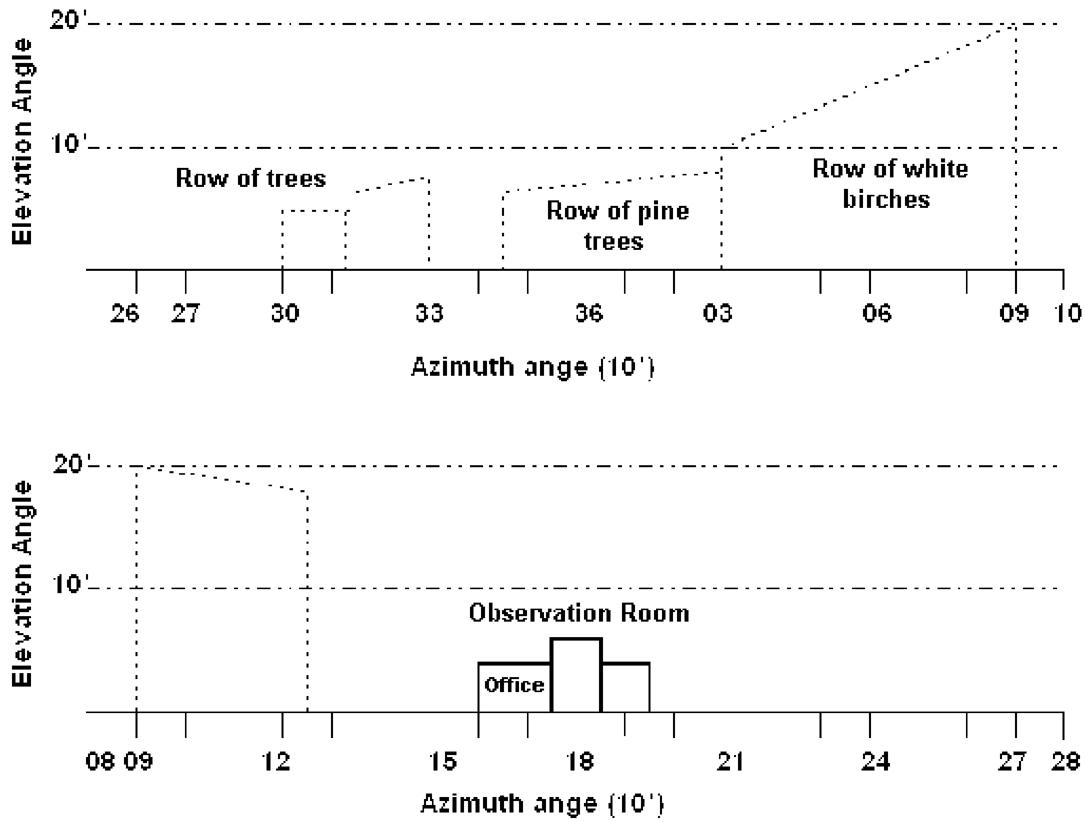


Figure 3.F.14   The vertical angle of obstacles at intercomparison field

ANNEX 3.G ROMANIA

1. JOSENI, ROMANIA

In 1986, Romania participated in the “Solid precipitation Measurement Intercomparison” initiated by WMO. By following the methods established during the first session of the WMO International Organising Committee of Solid Precipitation Measurements Intercomparison(WMO/CIMO, 1985), an evaluation station for the solid precipitation intercomparative measurements was established at the Joseni meteorological station.

The Joseni meteorological station (46°42’N, 25°40’W and 750m.a.s.l.) is located in the center of the Giurgeu depression. The general longitudinal direction of mountain chains surrounding the Giurgeu depression, which is perpendicular against the predominant western direction of the general atmospheric circulation, imposed some climatic peculiarities to the Joseni meteorological station. The predominant wind direction during the precipitation is NW. The wind speed is relatively low, which is characteristic for the areas. The low temperature in the area favors the occurrence of an average number of 35 snow days.

Precipitation accumulated during 12 hours (07GMT and 19GMT) were measured with five gauges:

- an IMC national precipitation gauge at 1.5m (which is a Hellmann type precipitation gauge with some modifications), unshielded for snow;
- an IMC precipitation gauge at 1.5m with a Tretyakov windshield;
- a Tretyakov precipitation gauge at 1.5m;
- an IMC precipitation gauge installed at 3m in the center of a double fence shield;
- a Tretyakov precipitation gauge at 3m in the center of the double fence shield (DFIR).

In addition to precipitation measurements, the necessary meteorological parameters were also measured, such as wind direction and speed at 10m, air temperature, relative humidity, etc.

ANNEX 3.H RUSSIAN FEDERATION

VALDAI HYDROLOGICAL RESEARCH STATION

The Valdai Hydrological Research Station (57.59^o N, 33.15^o E; 194 m) is situated on the flat shore of Valdai lake. Since the 1960's, many different gauge-and-shield combinations and national methods for precipitation measurement including vertical double wooden fences of various designs, Tretyakov shield, European Nipher shield, Hellmann gauge, Tretyakov gauge and Canadian Nipher snow gauge have been studied at this site. Since the fall of 1991, two NWS 8" standard gauges, one with an Alter shield and the other without, have been installed with their orifices 1 meter above the ground, which is the standard height for this gauge in the U.S. network. Approximately 300m from the open site is the "bush gauge" (Tretyakov gauge with a wind shield) placed in 2-4m high shrubs in a three hectare area. Within the 12m diameter working area of the bush gauge the shrubs are cut routinely to the gauge orifice height of 2m. This gauge has been accepted as the working reference for winter precipitation measurement at this station since 1970, since wind-induced errors are reduced to near zero by both the surrounding bush and the Tretyakov wind shield. The gauges both in the open and bush sites at Valdai are measured at 0800 and 2000 (local time). The contents of Tretyakov gauges were both weighed and measured volumetrically to determine precipitation amount and over a period of time an average wetting loss was determined. For the NWS 8" standard gauge at Valdai, the volumetric method was used for the measurements. Wind speed and direction were measured at 3m after September 1989. Atmospheric pressure, air temperature and humidity were also recorded.

The measurement of solid precipitation under the WMO comparisons programme at the MGI experimental station in Valdai, started from November 1988. A preceding period of observation from October 1, 1970 to 31 December 1978, corresponds most closely with the WMO programme for the intercomparison of current methods for solid precipitation measurement. These data cover 99 months of uninterrupted observations at 12 hours using the following instruments:

- Tretyakov gauge set up in a bush (the precipitation falls into a container which is partially filled with a calcium chloride solution and an oil transformer and is measured by the weighing method)
- Tretyakov gauge set up within double fences (the collection, storage and measurement of the precipitation are similar to those for the preceding gauge) - DFIR
- Tretyakov gauge (national standard since 1952)
- Rain gauge with a Nipher shield (national standard until 1952)
- Tretyakov gauge (without shield)
- Wild rain gauge
- Tretyakov gauge (weighing-type, calcium chloride and oil transformers
- Rain gauge with Nipher shield (similar to preceding instruments
- Tretyakov gauge (without shield, weighing-type, similar to preceding instrument)
- Wild rain gauge (measurement method similar to preceding instruments
- WMO rain gauge (IRPG) 2 m above ground
- Hellmann (GDR) rain gauge 2 m above ground
- Hellmann (Poland) rain gauge 2 m above ground
- Hellmann (Hungary) rain gauge 2 m above ground

In addition to the precipitation regime measurements carried out by the above instruments, the Valdai station also carried out studies of random and systematic errors in the initial data as well as preliminary assessments of the accuracy of the comparison's adopted standards. A more complete description of this site can be found in Annex 5.G which is the country report for the Russian Federation

ANNEX 3.I SLOVAKIA

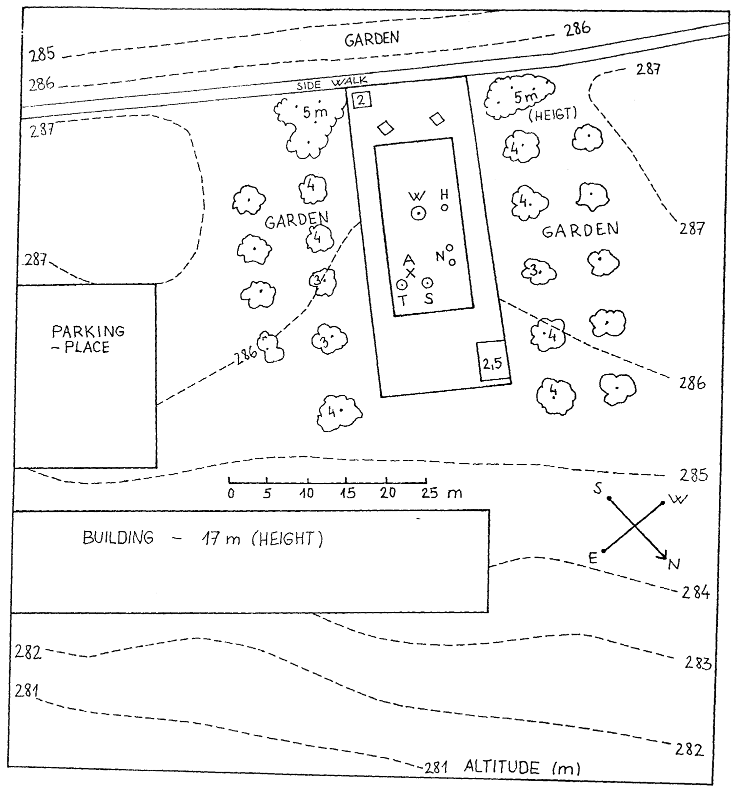
1. BRATISLAVA, KOLIBA

Type of Site:	partially protected
Country:	Slovakia
Station Name:	Bratislava, Koliba
Index No.:	11813
Latitude:	48.1686^{o} N
Longitude:	17.1106^{o} E
Elevation:	286 meters
Nearest City:	Bratislava

1.1 Description of Surroundings

Elevated site on the southern border of Small Carpathian Mountains 160 m above surrounding plain. Prevailing wind direction NW-27%, W-16%, calm-6%. Average wind velocity in height 10 m - 4.6 m/s. Number of days with wind velocity greater than 15 m/s is 86. Annual mean air temperature is 9.3^{o} C (July 19.8^{o} C ,January -2.6^{o} C). Annual precipitation total 661 mm (July 77 mm, February 40 mm). Number of days with 1 mm or more precipitation is 97, number of days with snow is 35. See Figure 3.H.1 and Table 3.H.1 for the location and list of instruments.

Figure 3.H.1 Plan of local area of Meteorological station at Bratislava, Koliba



Legend: A-Anemograph SIAP; T-Tretykov Gauge; N-National Gauge METRA 886; S- METRA 886 with wind shield; H-Hellmann Gauge; W-WMO Snowden Gauge IP

Table 3.H.1 List of gauges

Gauge	Height (m)	Gauge Diameter (cm^2)	Wind Shield
National standard METRA 886	1	500	with or without protection
Hellmann (Hungary)	1	200	without protection
Tretyakov (Russia)	2	200	with protection
WMO Snowden IP	1	5	with Alter protection

ANNEX 3.J SWITZERLAND

1. GAMSERRUGG

Observation site:	Top of Gamserrugg (District of St. Gall)
Altitude:	2074 m a.s.1.
Exposure:	Very exposed. It is on the highest point of Gamserrugg. The top of Gamserrugg is flat. It is a plateau with the dimensions of 800x800 m
Coordinates:	47°12’N and 09°21’E (Swiss Coordinates: 744 015 / 224 840)
Gauge:	Belfort-Gauge
Height of the orifice:	2.0 m above ground level
Data:	Since October, 5th 1991
Resolution:	Hourly basis
Contact:	Felix P. Blumer Swiss Federal Institute of Technology Zurich Department of Geography Hydrology Section Winterthurerstr. 190 CH-8057 Zurich

ANNEX 3.K UNITED KINGDOM

1. ESKDALEMUIR OBSERVATORY

Type of site:	Protected upland site
Country:	Scotland
WMO Index No.:	03162
Lat:	55 deg. 19 min. north.
Long:	3 deg. 12 min. west.
Elevation:	242 meters.
Nearest City:	Edinburgh, approx. 70 km to north; (town of Carlisle, approx. 30 km to south).

Eskdalemuir Observatory lies on a small, remote shoulder of moorland, about 30 meters above the upper reaches of the White Esk valley, in the Southern Uplands of Scotland. This shallow valley is approximately 0.4 km wide and lies immediately to the east of the observatory, the river flowing from north to south. The site itself slopes markedly from north-west to south-east and is sheltered by numerous trees and bushes around its perimeter. The surrounding area is very hilly, the immediate vicinity being open moorland, but extensive conifer plantations lie only 0.5 to 1 km distant both to east and west.

Although the upland location of Eskdalemuir Observatory earns it more snow than many U.K. sites, the temperate climate (with prevailing southwesterly winds), even here, produces some winters with little snow.

1.1 Instruments

Rain gauges:

1 Tretyakov, WITHOUT windshield, height 2 m, orifice 200 cm^2**,** (acting as the Working Network Reference)

3 U.K. Met.Office standard Mk 2 gauges, height 0.30 m, orifice 491 cm^2
- a) with turf wall, inner diameter 3 m, height 0.30 m
- b) unshielded
- c) spare unshielded (at other side of site)

N.B.

All measurements are by weight; therefore there is no wetting loss, but NO CORRECTIONS have been made for EVAPORATION.

Some of the forms contain data from other rain gauges. These data are solely for use of the U.K. Met. Office instrument development team and should be ignored by WMO.

Anemometers/wind vanes:

1 U.K. Met Office standard Mk 4 anemometer & wind vane, ht 10 m

2 Porton anemometers a) height 2 m
b) height 0.30 m

Thermometers: mercury-in-glass dry bulb in large Stevenson screen, height 1 m

2. LERWICK OBSERVATORY

Type of site:	Open, hill-top site
Country:	Shetlands Islands
WM0 Index No.:	03005
Lat:	60 deg. 48 min. north.
Long:	01 deg. 11 min. west
Elevation:	82 meters.
Nearest Town:	Lerwick, 2 km to northeast

The Shetland Islands lie to the north of Scotland, on the boundary between the northern North Sea and the Atlantic Ocean. They are thus exposed to the full force of the North Atlantic south-westerlies which, together with the relatively low altitude and the of a warm ocean current (the North Atlantic Drift), produce a mild but often stormy climate. Despite the high latitude, some winters have only small amounts of snow.

Lerwick lies roughly half way along the eastern coastline of the largest island, which is narrow (only 5 or 10 km from west to east) but elongated (covering some 4-0 minutes of latitude from north to south). Another much smaller island lies 1 km offshore, separated from Lerwick by the 7 km long Bressay Sound.

The observatory site lies on 6 flat terraces sloping gently upwards towards the south-east, with a steep drop to the sea 500 meters to the east. The surrounding area consists mainly of undulating, moorland with a hill, 174 meters above mean sea level, 2 km to the northwest of the site. In addition there is a reservoir, approx. 1.5 km N. -S. and 0.5 km E. - W, in close proximity to the west and northwest of the site, plus a small natural lake immediately to the south of the site.

2.1 Instruments

Rain gauges: (NO CORRECTIONS for evaporation/wetting losses)

1. Tretyakov, WITHOUT windshield, height 2 m, orifice 200 cm^2, (acting as the Working Network Reference)

2. UK Met.Office standard Mk 2 gauges, height 0.30 m orifice 491 cm^2
   - a) with turf wall, inner diameter 3 m, height 0.30 m
   - b) unshielded
   - c) spare unshielded (at other side of site)

Anemometers/wind vanes:

1. UK Met Office standard Mk 4 anemometer & wind vane, ht 10 m

2. Porton anemometers a) height 2 m
   b) height 0.30 m

Thermometers: 1 mercury-in-glass dry bulb in large Stevenson screen, height 1 m

ANNEX 3.L UNITED STATES OF AMERICA

1. BISMARCK, NORTH DAKOTA, USA

Type of Site:	open
Country:	United States
Station Name:	Bismarck
Latitude:	46 46’ 19"
Longitude:	100 45’ 39"
Elevation:	502 meters (1647 feet)
Nearest City:	Bismarck, North Dakota

1.1 Description of Surroundings

Bismarck is in south-central North Dakota, near the center of North America. The station is located at the National Weather Service Forecast Office which is at the Bismarck Municipal Airport. The station is approximately 2 miles southeast of the center of Bismarck. The station is on the east bank of the Missouri River in a shallow basin 7 miles wide and 11 miles long. The site is almost entirely surrounded by low-lying hills. The closest hills, 3 miles to the north and other hills 5 miles to the southeast, are about 200 to 300 feet high. West across the Missouri River the land is more hilly and 300 to 600 feet higher. The topographic features do not have significant effect on climate or prevailing winds.

1.2 Instruments

1. One Double Fence Intercomparison Reference (DFIR) having a Tretyakov gauge. The gauge’s orifice is 0.16 meter (6.3 inches) in diameter 0.02 square meter (36 square inches) in receiving areat and 3.0 meters (9.8 feet) above ground.

2. One national gauge equipped with the national standard windshield. The national gauge is the Belfort’s Universal Recording Rain Gauge model, 5-780. The gauge’s orifice is 0.203 meter (8.00 inches) in diameter, 0.13 square meter (50 square inches) receiving area., and 1.4 meters (4.6 feet) above ground. The national standard windshield is an Alter-Type Windshield.

3. One national gauge without windshield. The gauge is a Belfort’s Universal Transmitting Precipitation Gauge (model 5915) equipped with a Omnidata’s Datapod recorder (model DP111). The gauge’s orifice is 0.203 meters (8.00 inches) in diameter., 0.13 square meter (50 square inches) receiving area and 1.4 meters (4.6 feet) above ground.

4. One Tretyakov precipitation gauge. The gauge’s orifice is 0.16 meter (6.3 inches) in diameter, 0.02 square meter (31 square inches) in receiving area, and 1.4 meters (4.6 feet) above ground.

5. Temperature and humidity sensing system of the National Weather Service.

6. Wind speed and wind direction sensors. The wind sensors at national standard height of 6.1 meters (20 feet) are the National Weather Service’s instruments. The wind sensors at 6.1 meters are F-420C system, Electric Speed Indicator Co., Cleveland Ohio. Other wind speed and wind direction sensors are at 3.00 meters (9.8 feet) and a wind speed only sensor is at 1.4 meters (4.6 feet). The wind sensors at orifice heights of 3.0 and 1.4 meters (9.8 and 4.6 feet) are Met-One Wind Direction Sensor (model 024A) and Met-One Wind Speed Sensor (model 014A).

7. One double fence shield having national gauge installed in the center. The gauge is a Belfort’s Universal Transmitting Precipitation Gauge (model 5915) equipped with a Omnidata’s Datapod recorder (model DPlll). The gauge’s orifice is 0.203 meters (8.00 inches) in diameter 0.13 square meter (50 square inches) receiving area and 3.0 meters (9.8 feet) above ground.

8. One Aerochem Metrics model 301 automatic sensing wet/dry precipitation collector. The orifice is 0.293 meters (11.5 inches) in diameter 0.067 square meter (l04 square inches), and is 1.4 meters (55 inches) above the ground.

9. One national gauge with a Wyoming Windshield. The gauge is a Belfort's Universal Transmitting Precipitation Gauge (model 5915) equipped with a Omnidata's Datapod recorder (model DPlll). The gauge's orifice is 0.203 meters (8.00 inches) in diameter 0.13 square meter (50 square inches) receiving area and 1.4 meters (4.6 feet) above ground.

1.3 Daily and monthly data

The maximum and minimum air temperature (columns 3 and 4) are determined for each 12-hour period from hourly readings by the National Weather Service. The predominant wind direction (column 5) is determined for the 12-hour period from data that are recorded every 10 seconds by a data logger. Mean wind speed at national standard height (column 6) is determined for each 12-hour period from hourly readings by the National Weather Service. Mean wind speed at the orifice height of 1.4 meters (column 7) and the mean wind speed at the orifice height of 3.0 meters (column 8) are determined for the 12-hour period from data that are recorded every 10 seconds by a data logger. Precipitation for the DFIR gauge (column 11) and Tretyakov gauge (column 12) are determined by weighing method. Precipitation data for the national standard gauge (column 13) are provided by the National Weather Service. Precipitation data in column 14 are for the national standard gauge without a windshield. The official precipitation (column 16) is the precipitation that is published by the National Weather Service. The official precipitation is derived from their gauge data (column 13) but may have some adjustments. Precipitation from Aerochem Metrics gauge (column 17) is determined by weighing method. Precipitation data in column 18 are for the national standard gauge with a double fence windshield. Precipitation data in column 19 are for the national standard gauge with a Wyoming Windshield. Type of precipitation (column 21), type of snow (column 22), duration of snowfall (column 23), and comments (columns 24) are obtained from the National Weather Service's notes.

1.4 Event data

Information for the snow event period (columns 1-7) is obtained from the National Weather Service. The temperature data (columns 8, 9, and 10) are determined from National Weather Service's hourly observations for the period of the snow event. Predominant wind direction (column 11) is determined from hourly means recorded by the data logger for the event period. Mean wind speed at rational standard height (column 12) are determined from National Weather Service's hourly observations for the period of the snow event. Mean wind speed at the orifice height of 1.4 meters (column 13) and mean wind speed at the orifice height of 3.0 meters (column 14) are determined from hourly means recorded by the data logger for the event period. Precipitation data for DFIR (column 17), Tretyakov (column 18), national standard gauge with windshield (column 19), national standard gauge without windshield (column 20), National Weather Service published data (column 20), Aerochem Metrics (column 23), national standard gauge with double fence windshield (column 24), and national standard gauge with Wyoming Windshield are for the event periods.

2. RABBIT EARS PASS, COLORADO, USA

The study site is located in the headwaters of the Walton Creek drainage basin, near Rabbit Ears Pass, about 18 km southeast of Steamboat Springs, Colorado. The site is located in a large sub alpine meadow at an elevation of 2925 m. It is adjacent to a 2 km^2 research basin used to investigate the processes of snow accumulation and snowmelt on the hydrology of a sub alpine basin in the Rocky Mountain region. The site is unattended. Travel time to the site from the USGS office in Denver, Colorado is about 2.5 hr and from Steamboat Springs is about 0.5 hr.

Two precipitation gauges were used in this study. One was the Russian Tretyakov gauge which was selected by WMO as the index gauge to be used by all sites participating in this intercomparison study. The Tretyakov gauge is a manually measured gauge. Collected snow must be melted and poured into a graduated cylinder to measure gauge catch. An observer from Steamboat Springs was employed to measure the Tretyakov gauge catch at the end of each storm period.

The second gauge was the Universal Belfort precipitation gauge which uses a weighing bucket mechanism to measure gauge catch and a drum-chart to record the time trace of this measurement. The drum-chart recorder had a one week rotation time.

Each gauge type was installed in three different types of wind shields and with no shield. The three types of wind shields were a Double Fenced Intercomparison Reference (DFIR), a Wyoming, and an alter shield. A Canadian Nipher wind shield was also installed on a Universal Belfort gauge. The Nipher shielded gauge, however, was not installed in the study until January of 1991. In addition, the adjacent research watershed used an alter-shielded Universal Belfort gauge located in a small forested opening to measure precipitation.

This forested opening is located about 200 m from the study site and provided an additional measure for comparison.

3. REYNOLDS CREEK EXPERIMENTAL WATERSHED, IDAHO, USA

The Reynolds Creek Idaho site (43^o 12’ N, 116^o 45’ W; 1193 m) is located on gently sloping, sagebrush covered rangelands surrounded by rangelands and irrigated hay fields. In October 1987, a DFIR at 3m, a Tretyakov gauge at 2m, two Belfort Universal recording gauges at 1.30m with the Wyoming shield and Alter shield, respectively, Canadian Nipher Gauge at 2m, dual-gauge system (Larson, 1972) and one NWS 8" standard non-recording gauge without a wind shield at 1m were installed for the Intercomparison. All the manual gauges were measured by the weighing method in order to eliminate the wetting losses. Temperature, humidity, wind speed at 2m and 9.14m and wind direction at the higher level were recorded.

4. SLEEPERS RIVER RESEARCH WATERSHED, VERMONT, USA

The townline station (44.29 N, 72.10 W; 552 m) in the watershed north of Danville, Vermont, was established in 1967 as part of a cooperative snow hydrology project (Johnson and Anderson, 1968). The area is very flat, slightly sloping to the south. The station was located near the eastern edge of a 6 hectare clearing. To the west, the forest is about 185 m from the centre of the study site. The first 75 meters are generally free of vegetation protruding the winter snowcover. Beyond 75 m there are scattered clumps of small conifers. It is about 60 m from the centre of the site to the forest in both a northeasterly and southeasterly direction. The prevailing winds in the winter are from a westerly direction. This station was previously used to test the dual-gauge approach and to derive the precipitation profile by using a number of gauges at various heights (Larson, 1972). During the snow seasons of December 1986 to March 1992, a DFIR at 3 m, a Tretyakov gauge at 3 m, two Belfort Universal gauges with and without an Alter shield, respectively, and one Alter-shielded NWS 8" standard gauge at 1.83 m were operated for the Intercomparison (Bates et al., 1987). Precipitation was obtained using the volumetric technique for the manual gauges. Temperature, wind speed and wind direction were measured at 3 m.

THE DATA ARCHIVE

The digital archive consists of a spreadsheet format (MS Excel .xls or Lotus .wk1) that duplicates the original observation forms. An example of the digital data for Valdai, Russia is shown in Table 4.A.1. To assist the archive user in identifying the information located in each column of the paper or digital archive, WMO Solid Precipitation Gauge Logs were developed for both event and observation data sets. These logs shown as Tables 4.A.2 for the observation data set, document the type of data found in each cell of a spreadsheet by site. Each site was given a two letter identifier. This identifier followed by the year and month was used to label files in the digital archive. For example, EB88-04 is East Baltic (Canada) for April, 1988.

Table 4.A.1 Sample of data spreadsheet for Valdai, Russia from the Digital Archive

WMO Station:		Valdai, Russia												
				Temperature		Wind		Wind Speed (m/s)			Snow depth (cm)		Precipitation Amount (mm)	
Year	Month	Day	Time	(deg. C)		Dir.	Nat'l	Nat'l	DFIR	2 m	New	Ruler	DFIR	Tret
			GMT	max.	min.	(deg)	Std	Gge						
Col: 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
90-91	Dec 90	1	2000	-5.2	-8.7	202	.	.	4.1	4.0	.	.	0.5	0.4
90-91	Dec 90	2	800	-4.0	-6.2	247	.	.	3.5	3.4	.	.	0.1	0.1
90-91	Dec 90	2	2000	-2.8	-4.0	202	.	.	3.9	3.8	.	.	0.2	0.1
90-91	Dec 90	3	800	1.0	-3.7	180	.	.	6.0	5.6	.	.	1.7	1.2
90-91	Dec 90	3	2000	4.6	1.0	180	.	.	7.9	7.4	.	.	2.1	1.7
90-91	Dec 90	4	800	4.5	1.7	180	.	.	5.8	5.4	.	.	5.7	5.5
90-91	Dec 90	4	2000	2.7	0.9	180	.	.	5.2	4.9	.	.	1.3	1.2
90-91	Dec 90	5	800	1.4	0.5	180	.	.	3.3	3.1	.	.	2.0	1.8
90-91	Dec 90	5	2000	0.8	-0.6	202	.	.	3.0	2.8	.	.	2.4	2.3
90-91	Dec 90	6	800	-0.5	-3.6	270	.	.	2.4	2.2	.	.	1.1	0.9
90-91	Dec 90	6	2000	-3.5	-5.5	225	.	.	2.9	2.8	.	.	0.2	0.0
90-91	Dec 90	7	800	-4.9	-7.2	157	.	.	3.5	3.3	.	.	T	M
90-91	Dec 90	7	2000	-0.2	-6.7	157	.	.	4.0	3.7	.	.	0.5	0.3
90-91	Dec 90	8	800	0.8	-0.2	157	.	.	4.4	4.1	.	.	0.2	0.1
90-91	Dec 90	11	800	-3.9	-6.1	112	.	.	3.6	3.2	.	.	T	T
90-91	Dec 90	11	2000	-2.4	-4.0	90	.	.	3.4	3.2	.	.	1.8	1.5
90-91	Dec 90	12	800	0.3	-2.5	112	.	.	3.6	3.2	.	.	4.8	3.8
90-91	Dec 90	12	2000	1.3	0.3	112	.	.	5.3	4.5	.	.	0.6	0.7
90-91	Dec 90	13	800	1.3	0.4	90	.	.	3.6	3.3	.	.	0.7	0.7
90-91	Dec 90	13	2000	0.6	-1.9	112	.	.	4.2	3.8	.	.	0.7	0.7
90-91	Dec 90	14	800	-1.8	-2.4	112	.	.	1.3	1.3	.	.	1.1	1.1
90-91	Dec 90	14	2000	-1.5	-6.2	315	.	.	2.2	2.0	.	.	1.1	1.0
90-91	Dec 90	16	2000	-7.9	-12.1	225	.	.	2.2	2.2	.	.	0.4	0.3
90-91	Dec 90	17	800	-5.9	-8.0	337	.	.	M	2.1	.	.	T	T
90-91	Dec 90	17	2000	-5.9	-10.0	337	.	.	1.7	1.8	.	.	T	T
90-91	Dec 90	18	2000	-8.5	-9.0	202	.	.	3.3	3.3	.	.	T	T
90-91	Dec 90	19	2000	-9.6	-13.2	180	.	.	1.9	1.8	.	.	T	T
90-91	Dec 90	20	2000	-4.9	-7.6	135	.	.	3.9	3.7	.	.	T	T
90-91	Dec 90	21	800	-4.6	-5.4	135	.	.	4.7	4.4	.	.	1.0	0.4
90-91	Dec 90	21	2000	-2.8	-4.6	135	.	.	4.0	3.7	.	.	0.2	0.0
90-91	Dec 90	22	800	-3.3	-4.3	135	.	.	3.3	2.9	.	.	T	T
90-91	Dec 90	22	2000	-3.7	-7.3	90	.	.	2.0	1.8	.	.	0.6	0.4
90-91	Dec 90	23	2000	-4.8	-6.3	135	.	.	1.4	1.0	.	.	0.0	0.0
90-91	Dec 90	24	800	-5.3	-7.0	157	.	.	3.2	3.1	.	.	M	M
90-91	Dec 90	24	2000	-3.3	-5.3	180	.	.	4.3	4.3	.	.	T	T
90-91	Dec 90	25	800	-4.1	-5.1	180	.	.	3.9	3.7	.	.	T	T
90-91	Dec 90	28	2000	-2.1	-2.5	112	.	.	4.0	3.6	.	.	0.2	0.1
90-91	Dec 90	29	800	-0.6	-2.1	157	.	.	4.0	3.8	.	.	T	T
90-91	Dec 90	29	2000	0.4	-0.7	157	.	.	4.0	3.7	.	.	0.3	0.2
90-91	Dec 90	30	800	0.0	-2.4	112	.	.	4.5	4.2	.	.	0.9	0.6
90-91	Dec 90	30	2000	-0.1	-2.3	157	.	.	4.5	4.2	.	.	0.8	0.4
90-91	Dec 90	31	800	0.6	-0.1	202	.	.	4.9	4.7	.	.	0.6	0.5
90-91	Dec 90	31	2000	1.0	0.1	180	.	.	5.8	5.6	.	.	0.1	T
			Average	**-2.0**	**-4.2**				**3.8**	**3.5**			**33.9**	**28.0**

Table 4.A.1 Sample of data spreadsheet for Valdai, Russia from the Digital Archive (continued)

Month	Day	Time	Nat	Nat	Other	Other	Other	Other	Other	Other	Other	Other	Other	Other
		GMT	Shld	Unshld	1	2	3	4	5	6	7	8	9	10
Col: 2	3	4	16	17	18	19	20	21	22	23	24	25	26	27
Dec 90	1	2000	.	.	0.4	0.4	0.4	0.5	0.4	0.4	0.3	0.2	0.4	0.5
Dec 90	2	800	.	.	0.1	T	T	T	0.1	T	T	T	T	T
Dec 90	2	2000	.	.	0.2	0.2	0.2	0.2	0.2	0.2	T	T	0.2	0.2
Dec 90	3	800	.	.	1.6	1.6	1.0	1.3	1.4	1.0	0.9	0.7	1.2	1.4
Dec 90	3	2000	.	.	2.4	2.1	1.9	1.9	2.1	1.6	1.8	1.1	2.0	1.9
Dec 90	4	800	.	.	5.7	5.5	5.4	5.7	5.5	5.0	6.3	4.8	5.2	4.8
Dec 90	4	2000	.	.	1.0	1.2	1.2	1.3	1.2	1.2	1.2	1.1	1.1	1.0
Dec 90	5	800	.	.	1.6	1.9	1.7	1.8	1.8	1.7	2.0	1.5	1.6	1.7
Dec 90	5	2000	.	.	2.7	2.3	2.2	2.2	2.3	2.2	2.0	1.9	2.2	2.0
Dec 90	6	800	.	.	0.9	0.8	0.8	0.8	0.9	0.9	0.6	0.7	0.8	1.0
Dec 90	6	2000	.	.	0.2	0.1	0.1	0.1	0.1	0.0	0.1	0.0	0.2	0.3
Dec 90	7	800	.	.	T	M	T	M	T	M	M	M	M	T
Dec 90	7	2000	.	.	0.5	0.4	0.3	0.4	0.4	0.4	0.3	0.3	0.4	0.5
Dec 90	8	800	.	.	0.2	0.1	0.0	0.1	0.1	0.1	T	0.0	0.2	0.2
Dec 90	11	800	.	.	T	T	T	T	T	T	T	T	T	T
Dec 90	11	2000	.	.	1.9	1.3	1.4	1.6	1.6	1.5	0.6	1.1	1.8	1.9
Dec 90	12	800	.	.	4.7	3.5	3.7	3.9	3.6	3.2	1.8	2.5	4.4	4.8
Dec 90	12	2000	.	.	0.8	0.5	0.5	0.6	0.6	0.5	0.5	0.3	0.4	0.4
Dec 90	13	800	.	.	0.7	0.6	0.6	0.6	0.6	0.7	0.6	0.5	0.6	0.7
Dec 90	13	2000	.	.	0.8	0.6	0.6	0.6	0.6	0.5	0.4	0.5	0.8	0.8
Dec 90	14	800	.	.	1.1	1.0	1.1	1.1	1.1	1.0	0.8	0.8	1.1	1.1
Dec 90	14	2000	.	.	1.0	0.9	1.0	1.0	1.0	1.0	0.9	0.9	1.0	1.0
Dec 90	16	2000	.	.	0.4	0.3	0.2	0.3	0.3	0.2	0.2	0.2	0.4	0.4
Dec 90	17	800	.	.	T	T	T	T	T	T	M	T	T	T
Dec 90	17	2000	.	.	T	T	T	T	T	T	M	T	M	M
Dec 90	18	2000	.	.	T	T	T	T	T	T	T	T	T	T
Dec 90	19	2000	.	.	T	T	T	M	T	M	T	M	T	T
Dec 90	20	2000	.	.	T	T	T	T	T	T	M	T	T	T
Dec 90	21	800	.	.	1.1	0.6	0.4	0.6	0.7	0.4	0.0	0.3	1.0	1.1
Dec 90	21	2000	.	.	0.2	0.0	0.0	0.0	0.1	0.0	T	0.0	0.2	0.2
Dec 90	22	800	.	.	0.0	T	T	T	T	T	M	T	T	0.0
Dec 90	22	2000	.	.	0.5	0.3	0.3	0.4	0.4	0.4	0.1	0.3	0.6	0.7
Dec 90	23	2000	.	.	0.0	T	T	T	T	T	T	0.0	T	0.0
Dec 90	24	800	.	.	T	M	M	M	M	T	M	M	M	T
Dec 90	24	2000	.	.	T	T	T	T	T	T	T	T	T	T
Dec 90	25	800	.	.	T	M	T	T	T	T	M	T	T	T
Dec 90	28	2000	.	.	0.3	0.2	0.0	0.1	0.1	0.1	0.1	0.0	0.2	0.2
Dec 90	29	800	.	.	T	T	T	T	T	T	T	T	T	T
Dec 90	29	2000	.	.	0.3	0.2	0.1	0.3	0.2	0.1	0.1	0.1	0.4	0.4
Dec 90	30	800	.	.	1.1	0.4	0.4	0.6	0.5	0.5	0.0	0.3	0.8	1.0
Dec 90	30	2000	.	.	0.7	0.4	0.3	0.5	0.5	0.3	0.1	0.3	0.7	0.8
Dec 90	31	800	.	.	0.7	0.4	0.5	0.5	0.5	0.4	0.4	0.3	0.5	0.7
Dec 90	31	2000	.	.	0.1	T	T	T	T	T	M	T	0.1	0.2
		Totals	**0.0**	**0.0**	**33.9**	**27.8**	**26.3**	**29.0**	**28.9**	**25.5**	**22.1**	**20.7**	**30.5**	**31.9**

Table 4.A.1 Sample of data spreadsheet for Valdai, Russia from the Digital Archive (continued)

								Precip		
Month	Day	Time	Other	Other	Other	Precip	Snow	Event	Comments	Obs # / day
		GMT	11	12	13	Type	Type	(hrs.)		
Col: 2	3	4	28	29	30	31	32	33	34	35
Dec 90	1	2000	.	.	.	S	SW	7.0 i	.	.
Dec 90	2	800	.	.	.	S	SG	10.2 i	.	.
Dec 90	2	2000	.	.	.	S	SG	3.3 i	.	.
Dec 90	3	800	.	.	.	X	"SR,S"	5.5 i	.	.
Dec 90	3	2000	.	.	.	R	.	12.0 c	There was rainfall during the observation	.
Dec 90	4	800	.	.	.	R	.	3.8 c	.	.
Dec 90	4	2000	.	.	.	X	"RS,SR"	5.0 i	There was snowfall during the observation	.
Dec 90	5	800	.	.	.	X	"RS,SR"	6.8 i	.	.
Dec 90	5	2000	.	.	.	S	SR	7.4 i	There was snowfall during the observation	.
Dec 90	6	800	.	.	.	S	SW	12.0 c	There was light snowfall during the observation	.
Dec 90	6	2000	.	.	.	S	SW	6.0 i	.	.
Dec 90	7	800	.	.	.	S	S	1.6 i	.	.
Dec 90	7	2000	.	.	.	S	SG	8.1 c	.	.
Dec 90	8	800	.	.	.	S	SG	9.7 c	.	.
Dec 90	11	800	.	.	.	S	S	1.5 c	.	.
Dec 90	11	2000	.	.	.	S	S	12.0 c	There was snowfall during the observation	.
Dec 90	12	800	.	.	.	S	S	10.8 c	.	.
Dec 90	12	2000	.	.	.	X	SR	5.4 c	There was rainfall during the observation	.
Dec 90	13	800	.	.	.	X	"SR,SG"	6.5 i	.	.
Dec 90	13	2000	.	.	.	X	"SR,SG"	7.3 i	There was snowfall during the observation	.
Dec 90	14	800	.	.	.	S	S	9.8 c	.	.
Dec 90	14	2000	.	.	.	S	S	6.0 c	.	.
Dec 90	16	2000	.	.	.	S	SG	2.5 c	.	.
Dec 90	17	800	.	.	.	X	"RS,SG"	4.4 c	.	.
Dec 90	17	2000	.	.	.	S	SW	1.9 i	.	.
Dec 90	18	2000	.	.	.	X	ZR	6.3 c	.	.
Dec 90	19	2000	.	.	.	S	S	1.8 c	.	.
Dec 90	20	2000	.	.	.	S	S	1.2 c	.	.
Dec 90	21	800	.	.	.	S	S	6.4 i	There was light snowfall during the observation	.
Dec 90	21	2000	.	.	.	S	SG	4.3 c	.	.
Dec 90	22	800	.	.	.	S	S	5.4 i	There was light snowfall during the observation	.
Dec 90	22	2000	.	.	.	S	S	9.9 c	.	.
Dec 90	23	2000	.	.	.	S	SG	4.4 c	.	.
Dec 90	24	800	.	.	.	S	S	4.0 i	.	.
Dec 90	24	2000	.	.	.	S	S	2.1 i	.	.
Dec 90	25	800	.	.	.	X	"RS,SG"	6.2 c	.	.
Dec 90	28	2000	.	.	.	S	S	0.8 c	There was snowfall during the observation+AH24	.
Dec 90	29	800	.	.	.	S	S	2.8 i	.	.
Dec 90	29	2000	.	.	.	S	S	7.5 c	.	.
Dec 90	30	800	.	.	.	S	S	6.0 c	There was snowfall during the observation	.
Dec 90	30	2000	.	.	.	S	S	9.4 i	.	.
Dec 90	31	800	.	.	.	S	SW	2.7 i	.	.
Dec 90	31	2000	.	.	.	S	SW	1.4 i	.	.

The Column codes for Table 4.A.1 and Table 4.A.2 are given in Table 4.A.3. Columns 18 to 30 provide data for other gauges or other parameters at the site. This gauge type or parameter is determined by using Table 4.A.2 and Table 4.A. 4. For example, column 18 in Table 4.A.1 is “other 1”, going to column 18 in Table 4.A.2 and down to the row corresponding the Valdia, “USSR 01/88-12/90”, we find the Precipitation Gauge Code “4” which in Table 4.A.4 corresponds to the USSR Gauge with Bush Shield.

Table 4.A.2 WMO Solid Precipitation Gauge Log for Observations

WMO Station		1	2	3	4	5
		Year	**Month**	**Day**	**GMT Time**	**Max. Temp**
Baie-Comeau, Canada	**BC**	Year	Month	Day	GMT Time	Max. Temp
Baie-Comeau, Canada 01/90 - Present	**BC**	Year	Month	Day	GMT Time	Max. Temp
Bismarck, U.S.A.	**BZ**	Year	Month	Day	GMT Time	Max. Temp
Bratislava, C.S.F.R.	**CZ**	Year	Month	Day	GMT Time	Max. Temp
Dease Lake, Canada	**DL**	Year	Month	Day	GMT Time	Max. Temp
East Baltic, Canada	**EB**	Year	Month	Day	GMT Time	Max. Temp
Eskdalemuir, Scotland, U.K.	**ED**	Year	Month	Day	GMT Time	Max. Temp
Jokioinen, Finland	**FN**	Year	Month	Day	GMT Time	Max. Temp
Harzgerode, Germany 12/86 - 03/88	**GD**	Year	Month	Day	GMT Time	Max. Temp
Harzgerode, Germany 12/88 - 03/89	**GD**	Year	Month	Day	GMT Time	Max. Temp
Harzgerode, Germany 12/89 - 03/91	**GD**	Year	Month	Day	GMT Time	Max. Temp
Harzgerode, Germany 12/91 - Present	**GD**	Year	Month	Day	GMT Time	Max. Temp
Kortright, Canada	**KT**	Year	Month	Day	GMT Time	Max. Temp
Lerwick Observatory, U.K.	**LW**	Year	Month	Day	GMT Time	Max. Temp
Memanbetu, Japan	**JP**	Year	Month	Day	GMT Time	Max. Temp
Peterborough, Canada	**PT**	Year	Month	Day	GMT Time	Max. Temp
Regina, Canada	**RG**	Year	Month	Day	GMT Time	Max. Temp
Reynolds, U.S.A.	**RI**	Year	Month	Day	GMT Time	Max. Temp
Joseni, Romania	**BJ**	Year	Month	Day	GMT Time	Max. Temp
Tianshan, China	**TC**	Year	Month	Day	Beijing Time	Max. Temp
Valdai, USSR 01/70 - 12/78	**UR**	Year	Month	Day	Local Moscow	Max. Temp
Valdai, USSR 01/88 - 12/90	**UR**	Year	Month	Day	Local Moscow	Max. Temp
Danville, USA	**VT**	Year	Month	Day	GMT Time	Max. Temp
Parg, Croatia (YG)	**YG**	Year	Month	Day	GMT Time	Max. Temp

	6	7	8	9	10	11	12	13	14	15
	Min. Temp.	**Wind Dir. (Deg.)**	**Nat'l Std**	**Nat'l Gge**	**DFIR**	**2 m**	**New**	**Ruler**	**DFIR**	**Tret**
BC	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	-
BC	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	-
BZ	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
CZ	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	-	Tret
DL	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	-
EB	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	-
ED	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	-	Tret
FN	Min. Temp.	Wind @30m	Spd @30m	Wind@10m	Spd @10m	2 m	New	Ruler	DFIR	Tret
GD	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
GD	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
GD	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
GD	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
KT	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
LW	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	-	Tret
JP	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	-
PT	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
RG	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
RI	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
BJ	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
TC	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	-
UR	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
UR	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
VT	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret
YG	Min. Temp.	Wind Dir. (Deg.)	Nat'l Std	Nat'l Gge	DFIR	2 m	New	Ruler	DFIR	Tret

Table 4.A.2 WMO Solid Precipitation Gauge Log for Observations (continued)

	16	17	18	19	20	21	22	23	24	25	26
	Nat Shld	**Nat Unshld**	**Other**	**Other**	**Other**	**Other**	**Other**	**Other**	**Other**	**Other**	**Other**
BC	14	M	-	-	-	10	-	-	-	19	-
BC	14	M	-	18	-	10	-	-	23	19	-
BZ	9	12	-	-	-	-	-	-	-	-	-
CZ	Nat Shld	Nat Unshld		-	-	-	-	-	-	-	-
DL	14	Nat Unshld	34	12	9	10	-	-	23	19	-
EB	16	M	-	-	-	10	-	-	-	19	18
ED	44	45	34	88	-	-	-	-	-	-	-
FN	2	3	2	38	46	27	40	31	20	35	39
GD	47	47	34	-	-	-	-	-	-	-	-
GD	47	47	34	-	-	-	-	-	-	-	-
GD	47	47	34	-	-	-	-	-	-	-	-
GD	47	47	34	5	-	-	Cloud Type	-	-	-	-
KT	16	17	-	12	9	10	8	21	23	19	18
LW	44	45	34	45	-	-	-	-	-	-	-
JP	49	50	88	51	9	-	-	-	-	-	-
PT	16	M	-	-	-	10	-	-	-	-	18
RG	14	M	-	-	-	-	-	-	-	-	-
RI	9	43	34	-	-	-	-	-	-	-	-
BJ	Nat Shld	Nat Unshld	-	-	-	-	-	-	-	-	-
TC	Nat Shld	Nat Unshld	52	53	27	-		-	-	-	-
UR	Nat Shld	Nat Unshld	99	4	-	-	2	3	3	33	33
UR	Nat Shld	Nat Unshld	4	2	2	2	2	2	2	2	28
VT	Nat Shld	Nat Unshld	-	-	-	-	-	-	-	-	-
YG	Nat Shld	Nat Unshld	-	-	-	-	-	-	-	-	-

	27	28	29	30	31	32	33	34	35
	Other	**Other**	**Other**	**Other**	**Precip Type**	**Snow Type**	**Precip. Event (hrs)**	**Comments**	**Obs #/ Day**
BC	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
BC	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
BZ	9	42	8	11	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
CZ	29	30	6	27	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
DL	6	7	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
EB	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
ED	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
FN	26	32	14	1	Precip Type	Snow Type	Precip. Event (hrs)	25	24
GD	30	5	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
GD	30	5	28	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
GD	30	5	28	14	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
GD	48	30	28	14	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
KT	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
LW	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
JP	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
PT	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
RG	16	22	11	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
RI	14	11	12	9	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
BJ	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
TC	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
UR	40	40	47	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
UR	33	14	15	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
VT	43	9	9*	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day
YG	-	-	-	-	Precip Type	Snow Type	Precip. Event (hrs)	Comments	Obs #/ Day

Table 4.A.3 Explanation of Columns 1 through 17

Column	Definition	Column	Definition
1	Year	9	Wind Speed at National Gauge Height
2	Month	10	Wind Speed at DFIR Height
3	Day	11	Wind Speed at 2 meters
4	Time GMT	12	Fresh Snowfall Ruler Depth
5	Maximum Temperature for Day	13	Depth of Snow on Ground
6	Minimum Temperature for Day	14	Double Fence International Reference Gauge
7	Wind Direction at National Standard Height	15	Tretyakov Gauge (0-1 USSR)
8	Wind Speed at National Standard Height	16	National Standard Gauge
		17	National Standard Gauge without Shield

Table 4.A.4 Precipitation Gauge Codes

GAUGE	CODE
0-1 USSR H & H-90 (Tretyakov)	1
0-1 USSR with a wind shield (Tretyakov)	2
0-1 USSR without a wind shield (Tretyakov)	3
0-1 USSR Gauge with Bush Shield	4
Automatic Remote Transmitting Station (AFMS)	5
B.C. Transducer Standpipe Gauge with Alter Shield	6
B.C. Transducer Standpipe Gauge without Shield	7
Belfort Series 5915 in a Double Fence	8
Belfort Series 5915 with Alter shield	9
Belfort Series 5915 with Nipher shield	10
Belfort Series 5915 with Wyoming shield	11
Belfort Series 5915 without wind shield	12
BT-60	13
Canadian Nipher shielded Snow Gauge	14
Canadian Nipher shielded Snow Gauge in a Double Fence	15
Canadian Nipher shielded Snow Gauge Fixed at 2 metres	16
Canadian Nipher Snow Gauge without Shield	17
Canadian Type "B" Rain Gauge	18
CSC Acoustic Snow Depth Sensor	19
Finnish Prototype Gauge	20
Fischer and Porter Type Gauge with Alter Shield	21
Fischer and Porter Type Gauge with Nipher Shield	22
Fischer and Porter Type Gauge without Shield	23
Geonor Gauge	24
Geonor Gauge in a double fence	25

GAUGE	CODE
Hellman Gauge (Danish)	26
Hellman Gauge (Hungarian)	27
Hellman Gauge (Polish)	28
Metra Type 886 with Tretyakov wind shield (500 cm2)	29
Metra Type 886 without wind shield (500 cm2)	30
Norwegian Gauge	31
Pit Gauge	32
Rain gauge with Nipher Shield	33
Snowboard	34
Swedish Gauge (SMHI)	35
Tipping Bucket	36
Tipping Bucket (Danish)	37
Tipping Bucket (Friedrich's)	38
Wild with a Nipher a wind shield	39
Wild without a wind shield	40
Wilska Gauge	41
Aerochem Metrics Gauge	42
U.S. National Weather Service Precipitation Gauge	43
MK2 with a Turf Wall shield	44
MK2 without a wind shield	45
Danish Rimco (electric)	46
Hellman Gauge (German)	47
Automatic Gauge (daily totals)	48
Overflow type rain/snow gauge with tipping buckets with shield (Japan)	49
Overflow type rain/snow gauge with tipping buckets without shield (Japan)	50
Warm water rain/snow gauge with tipping buckets without shields (Japan)	51
Chinese Standard Gauge without Shield @ 0.7 m	52
Chinese Standard Gauge without Shield @ 2.0 m	53
* = alternate location	
UNDEFINED	88
Atmospheric pressure in millibars	99
MISSING	M

ANNEX 5 COUNTRY REPORTS

ANNEX 5.A SUMMARY OF COUNTRY ANALYSES AND RESULTS

1. INTRODUCTION

This Intercomparison offered an excellent opportunity for participating Countries to assess the accuracy of their national gauges against an international reference. Countries participating in the Intercomparison were encouraged to analyze their data sets and provide the results to the International Organizing Committee. Suggested methods for data analysis have been outlined in Chapter 2 and Annex 2. Country reports have been submitted by the following countries: Canada, China, Denmark, Finland (includes national gauges for Norway and Sweden), Germany, Japan, Russian Federation, Slovakia, Switzerland, and the United States. The following sections provide a summary of these Country reports for their respective national gauge only. The complete Country reports, which also include the full analyses of national gauges and other gauges tested at some sites, can be found in Annexes 5.C to 5.K.

2. SUMMARY OF COUNTRY ANALYSES

Ten countries provided Country reports with analyses and results. Seven countries: Canada, China, Denmark, Finland, Germany, Japan and the United States, provided a comparison of their National Gauge with the DFIR. Canada established evaluation stations for the intercomparison at six sites, representing different climatic and physiographic regimes. All sites operated the DFIR (with Tretyakov gauge), the Canadian standard Nipher shielded snow gauge system, an AES Type-B rain gauge, a snow ruler and measured wind speed and direction (three levels), air temperature and humidity. Other precipitation gauges were operated at each site, depending on the measurement requirements to be tested for that region. Combined event data from all six sites were used in the analysis. China had installed a DFIR for testing with their national gauge but unfortunately, did not have wind data at their site. They presented the correction equations for wind using snowboard data as the truth at a site very close to the DFIR. Denmark and Finland analyzed the data set from the same site (Jokioinen, Finland) but applied different techniques. Analyses for the Swedish and Norwegian Standard gauges were reported in the Danish and Finnish reports. The Finnish report also included an analysis for the Hungarian National gauge. A summary of these results showing how adjusted the measurements for the biases and their resulting wind adjustment equations are shown in Table 5.A.2 to 5.A.4.

For the remaining three countries who have submitted Country reports, the most comprehensive was the report from the Russian Federation. It provided a review of the experience of the former USSR on precipitation measurement intercomparisons and on systematic error correction. It also provided a good discussion on the assessment of the systematic and random errors of precipitation measurement for several gauges, including the Bush gauge (Valdai control system), DFIR, Tretyakov gauge and the pit gauge. The report presented intercomparison results of several national gauges versus the DFIR, such as the Canadian Nipher snow gauge, the US 8 inch standard non-recording gauge and the Hellmann gauge of various versions (Germany, Hungary and Poland). These results, however, were only presented in summary tables and plots with no correction equations.

The Country report from Slovakia presented results for shielded and unshielded Metra (their national gauge) versus the Tretyakov gauge (working network reference for this project) since there was no DFIR established for the site. The relationship between the daily catch ratio and environmental factors was investigated. Statistical analysis shows that daily catch ratio of snow for the unshielded Metra gauge does not change significantly with daily air temperature and daily mean wind speed is the only factor affecting the gauge catch. For mixed precipitation and rain, there is no statistically significant correlation between daily gauge catch and wind speed.

The Country report from Switzerland presented intercomparison results of a unshielded Belfort gauge versus the Belfort gauge in a DFIR-type shield at a windy alpine site. No national gauge was included in the intercomparison. The report presented a summary of the intercomparison events only, there was not enough data to develop a catch ratio versus wind relationship.

3. COMPARISON OF NATIONAL GAUGES VERSUS DFIR

A summary of the correction equations from the seven countries which operated a DFIR and provided equations for wind correction for their national gauges is presented in this section. For comparison purposes, the wind correction relationships given in Tables 5.A.2 and 5.A.3 were all expressed as equations for the Catch

Ratio ($P_{nat\ gauge}/P_{DFIR}$) in percent. Separate equations were given for snow and mixed precipitation when available. Most analyses were based on events $\geq$ 2.0 mm or 3.0 mm as measured by the DFIR. Notable exceptions were Japan which used events $\geq$ 10 mm and Denmark which used events $\geq$ 0.2mm.

With the exception of Japan and Denmark, the correction relationships for wind were developed using simple linear, multiple linear and non-linear regression analysis of catch ratio versus wind speed at gauge height to the first and second power. The Finnish analysis also included air temperature and humidity as independent variables, but only the wind speed was found to be statistically important. The German analysis included air temperature, depth of precipitation, duration of precipitation, and intensity of precipitation. They found the highest correlation for the German Hellmann unshielded gauge included wind, air temperature and precipitation duration as independent variables. However, since the equations which included precipitation duration only marginally improved the correlation over equations with only wind and temperature, only the latter are shown in Tables 5.A.2 and 5.A.3.

The Japanese analysis assumed the relationship between the Catch Ratio (CR) and wind (U) to obey the following relationship:

$$CR = 1/(1 + m*U)$$

The parameter “m” was used to fit the data for a particular gauge to minimize the standard error.

The Danish analysis assumed a simple bi-linear model for the correction factor ($P_{DFIR}/P_{nat\ gauge}$) using explicit values of wind speed (U) and temperature (T) in the following form:

$$\log (P_{DFIR}/P_{nat\ gauge}) = \beta_0 + \beta_1 U + \beta_2 T + \beta_3 U\,T$$

Regression analysis was used to estimate the coefficients β_0, β_1, β_2, and β_3 which are shown in Table 5.A.1 for the various Nordic gauges and the Canadian Nipher gauge.

Table 5.A.1 Estimated regression coefficients for the Danish model

Country/Gauge	β_0	β_1	β_2	β_3
Norway Std	-0.12159	0.18546	0.006918	-0.005254
Finland H&H 90	-0.07556	0.10999	0.012214	-0.007071
Sweden Std	-0.08871	0.16146	0.011276	-0.008770
Denmark Hellmann	0.04587	0.23677	0.017979	-0.015407
Canada Nipher	-0.11972	0.06758	0.00544	-0.003300
Tretyakov	-0.04816	0.13383	0.009064	-0.005147

A comparison of the Catch Ratios from the Danish analysis using an air temperature of -2.0°C and the corresponding results from the Finnish and Canadian analyses is shown in Table 5.A.4. The Danish results show significantly higher values of Catch Ratio for all gauges at low wind speeds and over catch at zero wind speed for all gauges except the Danish Hellmann gauge. However, for wind speeds from 3m/s to 6 m/s the maximum difference of the catch ratios is less than 5%. For the Danish Hellmann gauge, both methods of analysis produce virtually identical results.

The United States operated four sites of which two submitted reports. These two sites were Rabbits Ears Pass in Colorado and Reynolds Creek Experimental Watershed in Idaho. However, in both reports, the analysis of Catch Ratio versus wind relationship for their national gauges (NWS 8 inch, and Belfort Alter shielded and unshielded) showed a very poor correlation, with R^2 less than 0.3. For the Reynolds Creek site, the analysis indicated that there was no consistent relationship between any of the gauges and the DFIR catch as affected by wind speed. These results may be due to the small number of events, the fact that most events were not large and/or because wind speeds were generally low during the precipitation events.

Comparison of the Catch Ratios of National gauges for snow is shown in Table 5.A.5 and Figures 5.A.1 and 5.A.2 showing national gauges with wind shields and without wind shields respectively. This graph was derived from the Catch Ratio equations given in Table 5.A.2 and 5.A.3. Because of the poor correlation in the United State results, they were not included in the graphical comparison. The Danish results were also not included in the graphs but can be compared directly in Table 5.A.4.

4. SUMMARY OF RESULTS

The results from the Country reports showed that the catch efficiency of the various National gauges can vary from ~10% up to ~74% at 6 m/s wind speed. As expected, shielded gauges generally performed better than unshielded gauges. Wind and air temperature were found to be the most important variables for developing gauge Catch Ratio relationships with wind being the primary variable.

It is clear that in order to achieve data compatibility when using different gauge types and shielding during all weather conditions, large corrections to the actual measurements will be necessary. Since shielded gauges catch more than their unshielded counterparts, gauges should be shielded either naturally (e.g. forest clearing) or artificially (e.g. Alter, Canadian Nipher type, Tretyakov wind shield) to minimize the adverse effect of wind. However, one must be very careful when analyzing ratios and differences between gauges and applying catch ratios for correction. Small absolute differences between gauges and the reference gauge (DFIR) could create significant large variations in the catch ratios (e.g. a 0.2mm difference of Tretyakov gauge vs. DFIR with a DFIR catch of 1.0mm gives a ratio of 80% versus 96% for a 5.0mm event). To minimize this effect, only daily totals when the DFIR measurement is greater than 3.0mm are preferred for the statistical analyses.

The Danish and Finnish reports provided a comparison on the use of different analysis techniques. The Finnish analysis was based on using simple linear, multiple linear and non-linear regression analysis of catch ratio versus wind speed at gauge height to the first and second power, air temperature and humidity. The Danish analysis assumed a simple bi-linear model using explicit values of wind speed and air temperatures, and then using regression to fit to that model. Even though there were also differences in the way the data were screened and corrected for other biases prior to analysis, these two analyses provided very similar results for the higher wind speeds 3m/s to 6m/s. They differ at low wind speeds (< 2 m/s) with the Danish analysis producing significantly higher catch ratios and over catching at zero wind speed for most of the National Gauges.

Table 5.A.2 Summary of Country Analysis

Country:	**Canada**	**China**	**Finland (including Denmark, Norway and Sweden)**
No. of site:	6	1	1
National Gauge(s):	Canadian Nipher shielded snow gauge	Chinese Standard Gauge	Hellmann (Denmark), Wild (Finland), Tretyakov (Russia), H&H 90 (Finland), Norwegian Standard, Swedish Standard
Other Gauges tested:	Tretyakov, unshielded Nipher, unshielded Universal Gauge, DFIR with Universal gauge, Alter shielded Universal Gauge, Large Nipher shielded Universal gauge, unshielded Belfort Punch Tape Precipitation Recorder, Alter shielded Belfort PTPR	Hellmann; Chinese Recording Gauge	Tretykov (unshield), Hungarian Hellmann, Canadian Nipher, Geonor
Correction for Biases			
Wetting:	Nipher: 0.15mm/obs, DFIR: 0.20mm/obs	rain: 0.35mm/event snow: 0.30/event	0.1 to 0.3 mm/measurement measurement by weight to avoid error
Evaporation:	no	no	0.1 to 0.6 mm/day
Gauge Design:	corrected for Aluminum vs Fiberglass bias	no	corrected to nonimal gauge orifice area
DFIR vs Bush:	applied Yang et al (1993)	applied 5.7% correction	applied Yang et al (1993)
Blowing Snow:	events not used in analysis	events not used in analysis	not excluded but few cases suspected
Temperature:	no	no	not significant in Finnish Analysis but used in Danish Analysis
Wind:	analysis for events > 3.0mm; used combined data from 4 sites	no wind data at DFIR site	for snow only, DFIR > 3.0mm (semidaily measurements)
Snow Events:	$CR = 100.0 - 2.02*U - 0.387*U^2$ ($n=162$; $R^2=0.513$)	$CR = 100\ e^{-0.056*U}$ ($n=38$, $R^2= 0.56$) * snowboard as reference	Danish Hellmann: $CR = 97.51 - 23.04*U + 1.73*U^2$ ($n=89$, $R^2=0.742$) Tretyakov (shielded): $CR = 100.77- 9.28*U$ ($n=89$, $R^2 =0.766$) Tretaykov (unshielded): $CR =101.11-25.88*U+2.12*U^2$ ($n=89$, $R^2=0.744$) Finnish (H&H 90): $CR = 99.36 - 8.49*U$ ($n=33$, $R^2 =0.636$) Norweigian Standard: $CR = 98.18 - 11.27*U$ ($n=89$, $R^2=0.791$) Swedish Standard: $CR = 99.81 - 10.81*U$ ($n=89$, $R^2=0.795$) Hungarian Hellmann: $CR = 111.56 - 32.93*U + 2.83*U^2$ ($n=72$, $R^2=0.699$) Finland Wild with Nipher shield: $CR = 93.52 - 12.68*U$ ($n=89$, $R^2=0.800$)
Mixed Precip Events:	$CR= 100.0 - 1.49*U - 0.65* U^2$ ($n= 54$; $R^2=0.554$)		

Table 5.A.3 Summary of Country Analysis

Country:	Germany	Japan	United States of America
No. of site:	1	2	4
National Gauge(s):	Hellmann (unshielded)	RT-4 Recording Gauge RT-1 Recording Gauge	NWS 8 inch Standard non-recording gauge Universal Recording Gauge
Other Gauges tested:	Automatic (Hellmann shaped, heated, volumetric), Tretyakov, Hellmann (shield), Metra 500 cm^2, Hellman (Polish Standard), Canadian Nipher	RT-3 Recording Gauge	Belfort unshielded, Belfort with Alter shield, Wyoming fence and DFIR, Tretyakov gauge, Canadian Nipher gauge, dual gauge system
Correction for Biases			
Wetting:	Hellmann: 0.1mm/obs.	N/A	0.03mm/obs (rain) and 0.15mm/obs (snow) for the NWS 8" standard non-recording gauge, N/A for Belfort gauge.
Evaporation:	no	no	no
Gauge Design:	no	no	not specified
DFIR vs Bush:	applied Yang et al (1993)	applied Yang et al (1993)	not specified
Blowing Snow:	events not used in analysis	events not used in analysis	not specified
Temperature:	yes	no	no
Wind:	analysis for events > 2.0mm (daily measurements)	for wet snow events > 10.0mm	analysis for events > 3.0mm
Snow Events:	CR = 100.0*(1.038 - 0.148*U+0.024*T) (n=43; R^2=0.590)	Hokuriku RT-1: CR = 100/(1 + 0.17*U) (n=9 R^2= ??) RT-3: CR=100/(1 + 0.24*U) (n=7, R^2 = ??) RT-4: CR = 100/(1 + 0.14*U) (n= 23; R^2= ??)	Reynolds Creek, snow events Belfort (Alter): CR= 94.8-3.4*U (n=27, R^2=0.146) Belfort (unsh): CR=85.7-6.1*U (n=27, R^2=0.243) NWS 8" (unsh): CR= 97.2-4.5*U (n=27, R^2=0.265)
Mixed Precip Events:	CR= 100.0*(0.921 - 0.069*U+0.060*T) (n=119; R^2=0.400)		Reynolds Creek, Mix precip events Bellfort (Alter):CR=92.7+0.3*U (n=15, R^2=0.008) Belfort (unsh): CR=79.8+1.3*U (n=15, R^2=0.125) NWS 8" (unsh): CR= 93.5-0.1*U (n=15, R^2=0.0004)

Table 5.A.4 Comparison of Country Analysis

Country:	**Canada**	**Finnish Meteorological Institute (FMI)**	**Danish Meteorological Institute (DMI)**
No. of site:	6	1	1
National Gauge(s):	Canadian Nipher shielded gauge	Hellmann (Denmark), Wild (Finland), Tretyakov (Russia), H&H 90 (Finland), Norwegian Standard, Swedish Standard	Hellmann (Denmark), Wild (Finland), Tretyakov (Russia), H&H 90 (Finland), Norwegian Standard, Swedish Standard
Correction for Biases			
Wetting:	Nipher: 0.15mm/obs, DFIR: 0.20mm/obs	0.1 to 0.3 mm/measurement measurement by weight to avoid error	measurement by weight
Evaporation:	no	0.1 to 0.6 mm/day	no
Gauge Design:	corrected for Aluminum vs Fiberglass bias	Orifice area	no
DFIR vs Bush:	applied Yang et al (1993)	applied Yang et al (1993)	no
Blowing Snow:	events not used in analysis	not excluded but few cases suspected	included
Temperature:	no	no	yes
Wind:	analysis for events > 3.0mm; used combined data from 4 sites	for snow only, DFIR > 3.0mm (semidaily measurements)	for snow only, DFIR $\geq$ 0.2mm (semidaily measurements)

Gauge	**Canada Nipher**		**Finland H&H 90**		**Russia Tretyakov**		**Sweden Std**		**Norway Std**		**Denmark HM**	
Analysis	**Canada**	**DMI**		**DMI**	**FMI**	**DMI**	**FMI**	**DMI**	**FMI**	**DMI**	**FMI**	**DMI**
		T= -2^{o}C		T= -2^{o}C		T= -2^{o}C		T= -2^{o}C		T= -2^{o}C		T= -2^{o}C
Wind (m/s)												
0	100.0	114.0	99.4	110.5	100.5	106.9	99.8	111.8	98.2	114.5	97.5	99.0
1	97.6	105.8	90.9	97.6	91.1	92.5	89.0	93.5	86.9	94.1	76.2	75.8
2	94.4	98.2	82.4	86.2	81.6	80.1	78.2	78.1	75.6	77.4	58.4	58.0
3	90.5	91.2	73.9	76.2	72.2	69.3	67.4	65.3	64.4	63.6	44.0	44.4
4	85.7	84.7	65.4	67.3	62.8	60.0	56.6	54.6	53.1	52.3	33.0	34.0
5	80.2	78.6	56.9	59.4	53.4	52.0	45.8	45.7	41.8	43.0	25.6	26.0
6	73.9	73.0	48.4	52.5	44.0	45.0	35.0	38.2	30.6	35.3	21.6	19.9

Table 5.A.5 Catch Ratio (%) versus Wind Speed at orifice height of National Gauges versus DFIR (denote gauge with wind shield)*

Wind Speed (m/s)	Canada Nipher*	USA-Belfort Alter shield*	USA NWS8”	USA-Belfort (unsh)	Finland H&H-90*	Finland Wild*	Russian Tretyakov (sh)*	Russian Tretyakov (unsh)
0	100.0	94.8	97.2	85.7	99.4	93.5	100.8	101.1
1	97.6	91.4	92.7	79.6	90.9	80.8	91.5	77.4
2	94.4	88.0	88.2	73.5	82.4	68.2	82.2	57.8
3	90.5	84.6	83.7	67.4	73.9	55.5	72.9	42.6
4	85.7	81.2	79.2	61.3	65.4	42.8	63.7	31.5
5	80.2	77.8	74.7	55.2	56.9	30.1	54.4	24.7
6	73.9	74.4	70.2	49.1	48.4	17.4	45.1	22.2
	Norway Std*	**Sweden Std***	**Denmark Hellmann**	**Hungary Hellmann**	**Germany Hellmann**	**Japan RT-1**	**Japan RT-3**	**Japan RT-4***
0	98.2	99.8	97.5	111.6	99.0	100.0	100.0	100.0
1	86.9	89.0	76.2	81.5	84.2	85.5	80.6	87.7
2	75.6	78.2	58.4	57.0	69.4	74.6	67.6	78.1
3	64.4	67.4	44.0	38.2	54.6	66.2	58.1	70.4
4	53.1	56.6	33.0	25.1	39.8	59.5	51.0	64.1
5	41.8	45.8	25.6	17.7	25.0	54.1	45.5	58.8
6	30.6	35.0	21.6	15.9	10.2	49.5	41.0	54.3

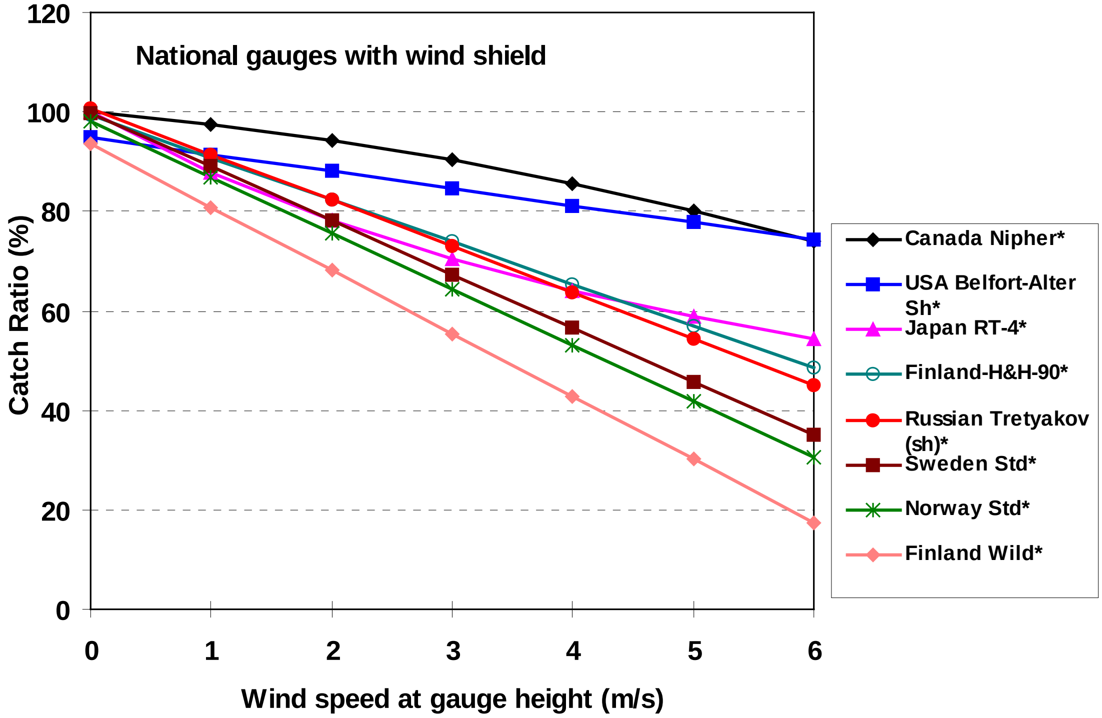


Figure 5.A.1 Comparison of Catch ratios for National gauges with wind shield for snow

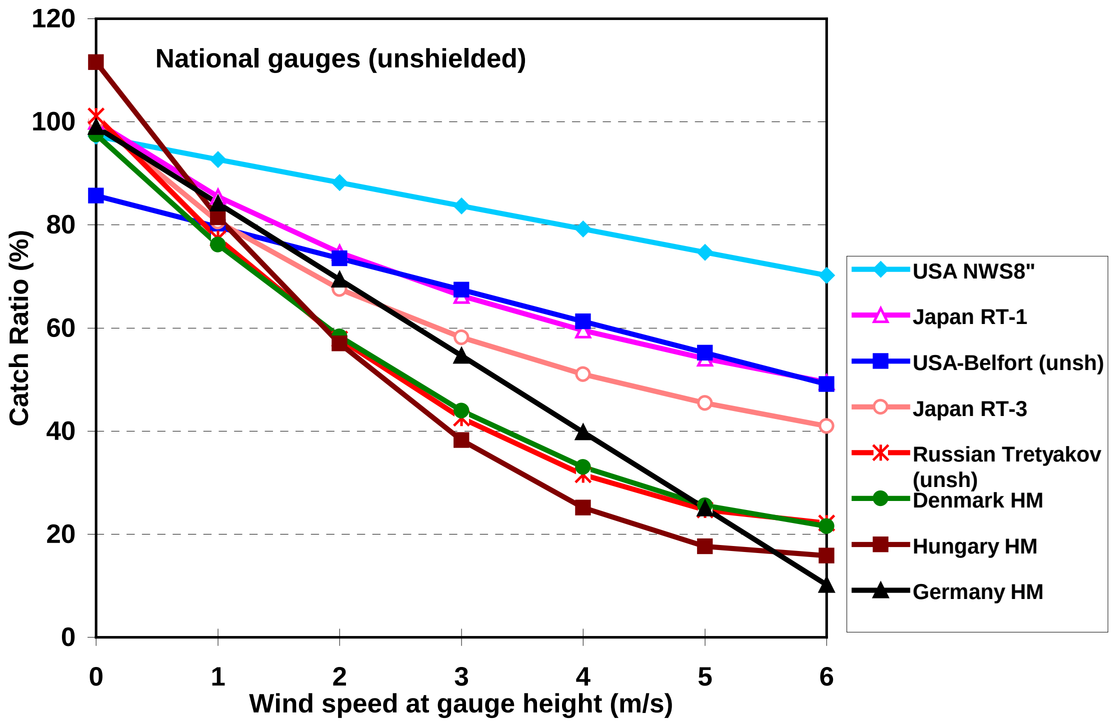


Figure 5.A.2 Comparison of Catch ratios for National gauges with no wind shield for snow

ANNEX 5.B CANADA

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1. INTRODUCTION

Canada established Evaluation stations for the Intercomparison at six sites across the country, representing different climatic and physiographic regimes. A permanent national intercomparison station has also been established at the AES Centre for Atmospheric Research Experiments (Egbert, Ontario) where past, current and new Canadian methods of precipitation measurement and observation can be compared against international reference standards. A description of these sites and a summary of the instruments being operated at each stations was given in Annex 3. All sites operated the DFIR (with Tretyakov gauge), the Canadian standard Nipher shielded snow gauge system, an AES Type-B rain gauge, a snow ruler and measured wind speed and direction (three levels), air temperature and humidity. Campbell-Scientific CR21X data loggers were used to record the data at various sampling intervals. Other precipitation gauges were operated at each site, depending on the measurement requirements to be tested for that region. Installation of the DFIR, precipitation gauges and other observing equipment and the observational procedures have followed those outlined in Chapter 2 and Annex 2. The following section presents the results for the Canadian standard Nipher shielded snow gauges from the six Canadian intercomparison sites.

2. CORRECTION OF DATA FOR BIASES

Prior to analyzing the catch of any national precipitation gauge in the WMO project, consideration must be given to wetting loss, evaporation loss, variances in gauge design, undercatch of the DFIR, the effect of blowing snow on gauge measurement and any adjustment of wind speed to gauge height (if wind was measured at some other height).

Wetting Loss: The Canadian Nipher shielded snow gauge and the USSR Tretyakov gauge are non-recording systems whose contents must be melted and poured out into a graduate for measurement by the observer. Both gauges retain a certain amount of water which cannot be poured out; this is known as the retention or wetting loss. Based on previous field experimentation, Goodison (1978) reported an average wetting loss for the Canadian Nipher snow gauge collector of 0.15mm +/-0.02mm. Although this is a systematic loss every time the contents are melted and poured out of the gauge, no correction for this error has been applied to the Canadian network data.

As recommended as part of the Intercomparison, wetting losses were assessed for both the Tretyakov and Nipher gauges. Procedures similar to those outlined by Huovila et al., (1988) were used to determine average retention or wetting losses for the different gauges. For both gauges, new collectors and collectors which had been in service for at least three years were tested. A series of 5 measurements of 0.5mm and 5.0mm of water were poured into each dry collector whose weight was known. The water was then poured back into the glass graduate and measured just like; or a routine precipitation measurement. The collectors were weighed again; the difference from the dry weight was the wetting loss, which was then converted into millimeters of water. The gauge collectors were dried, their weights recorded and the experiment repeated.

Figure 5.B.1 Wetting loss of different Nipher gauges with 0.5mm and 5.0mm water inputs. DL Dease Lake, KC - Kortright Centre.

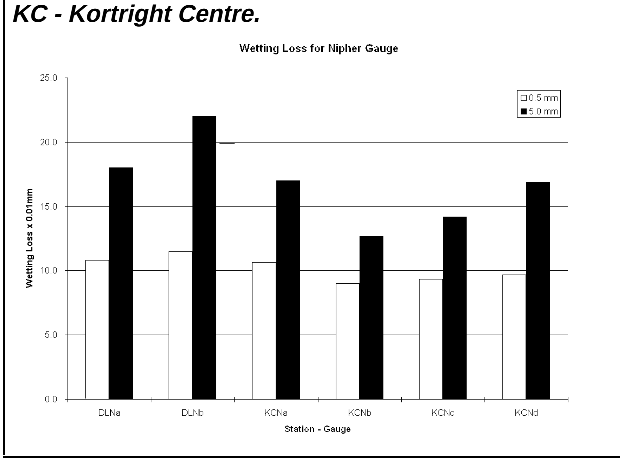
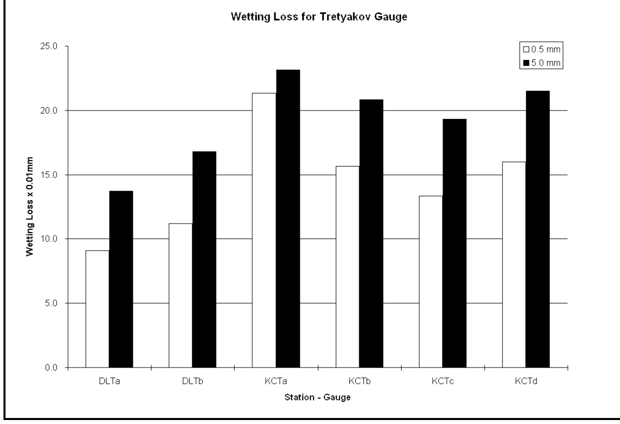


Figure 5.B.1 shows the wetting losses for six Nipher collectors. Average wetting losses are greater for the large events, although the percentage loss is much greater for small amounts of water. More significant is that the collectors at Dease Lake, which had been in service for many years, had a higher wetting loss than the collectors at the Kortright Centre which were three years old. However, these laboratory results are very similar to the average loss of 0.15mm determined from field trials reported previously by Goodison (1978). Measurements from the intercomparison stations have had a wetting loss correction applied depending on the age of the station collector, and the size of the measured amount.

Similarly, Figure 5.B.2 shows the wetting losses for the Tretyakov gauge. In this case, the collectors at Dease take had not been used while those at the Kortright Centre had been in service for three winters and were subject to paint peeling and rust. Its losses for the new collectors were similar to those reported by Huovila et al., (1988). As for the Nipher gauge, the losses for the older collectors were greater than for newer ones and they were slightly larger than the Finish results. Again, average wetting lose for each site has been applied to the gauge measurements. It is clear however, that wetting losses seem to increase as the collectors age with service, and for the Tretyakov an average lost of 0.20mm per observation could be expected.

Figure 5.B.2 Wetting lose of different Tretyakov gauges with 0.5mm and 5-Omm water inputs. DL Dease Lake, KC - Kortright Centre.



Evaporation loss: this is the water lost by evaporation before the observation is made. Unlike weighing recording gauges, no evaporation suppressant, such as light oil, is used in the manual gauge to minimize the evaporation loss. Comprehensive assessment of evaporation losses at the Finnish site indicated that average daily losses varied by gauge type and time of the year. Losses in summer of 0.30-0.80 mm/day and winter of 0.10-0.20 mm/day, respectively, for the Tretyakov gauge were found at Jokioinen in Finland during experiments to measure evaporation losses (Aaltonen et al., 1993).

Ideally, evaporation loss should be corrected before gauge catch analysis. However, because of its strong dependence on weather conditions, timing of precipitation compared to observation time and seasonal change which can be very site dependent, it was not possible to estimate the daily evaporation loss at the six Canadian Intercomparison stations, thus no correction was made for the potential daily evaporation loss from the Nipher or Tretyakov gauges.

Variances in gauge design: in late 1981 the Atmospheric Environment Service started to use a fiberglass reinforced plastic Nipher shield as a replacement for the more expensive aluminum shield of the standard Canadian Nipher shielded snow gauge system. Currently, only the fiberglass type can be purchased; but the observational network has both types in use. The previous field and wind tunnel investigations on gauge catch (Goodison, 1978) used the aluminum shield.

In the conversion of the shield from aluminum to fiberglass, there were two small, but possibly significant, design changes. The curvature of the outer surface was changed from an ellipse to a radius and the plane of the top surface of the shield was changed from a radial curve from the upper surface down to the outer lip to a flat surface (Metcalfe and Goodison, 1985). The question does arise whether the fiberglass shield has the same aerodynamic and catch characteristics as the aluminum shield. To assess this, co-located gauges of each type were operated for two years at two stations in Canada. Results are summarized in Metcalfe and Goodison (1985). The average catch of the aluminum shielded gauge was found to be greater than that of the fiberglass, with a bias of 0.17mm at Broadview, Saskatchewan (continental climate) and 0.08mm at Gander, Nfld (maritime climate). If only observations of 2.0mm or greater were compared, the bias per observation was 0.40mm at Broadview and 0.25mm at Gander. Individual 6-hourly snowfall observations differed by as a much as 1.2mm at Broadview and 1.8mm at Gander.

At Broadview only 2 of the 67 observations had the fiberglass shielded gauge measuring more then the aluminum shielded one. Statistical analysis of the Broadview data by van Wachem (1985) concluded that the mean measured snowfall precipitation caught by the two gauges was not significantly different. However, a difference test produced a statistically significant difference between the two types of shielded gauges. It is reasonable to conclude then, that one should expect a difference in the catch efficiency of the two shields under blowing conditions. This factor must be considered in the analysis of the Canadian Nipher gauge data and comparison of the current results with previous ones.

Undercatch of the DFIR: the DFIR is only considered as a secondary reference standard. At the moment, there is no accepted primary reference for measuring solid precipitation, but a gauge located in bushes which are kept cut to the height of the gauge is one reference method deemed to provide measurement close to "true" (WMO/CIMO, 1985). Yet such sites are not universally available and a secondary reference had to be chosen for the Intercomparison. The need to adjust the DFIR measurement to the "true" value of the bush gauge for the effect of wind was discussed by Golubev (1989), since a comparison of DFIR and the bush gauge data at Valdai, Russia, indicated a systematic difference between the primary and secondary standards. Golubev's proposed adjustment procedure included meteorological measurements of wind speed, atmospheric pressure, air temperature and humidity. More recent work by Yang, et al (1993) based on regression analysis indicated that the most statistically significant factor in the correction of the DFIR was the wind speed during the storms. A set of correction equations for the adjusting DFIR measurements to the "true" value of the bush gauge were developed by Yang, et al (1993) for the different types of precipitation. These are reported in detailed in Annex 2.H and have been recommended by the WMO Organizing Committee of the Intercomparison (WMO/CIMO, 1993) to be applied to all DFIR data before analyzing the catch of national gauges with respect to the DFIR. All DFIR measurements at the six intercomparison sites have been corrected to derive "true" values for this study.

Blowing snow: blowing snow conditions are a special case when correcting the DFIR data. Normally the flux of blowing snow will be greater at 1.0m, 1.5m or 2.0m than at the 3.0m height of the DFIR, and it is possible that under certain conditions, any gauge can catch some blowing snow. Since wind speeds are generally greater during blowing snow events, a larger correction for "undercatch" could be applied to a measured total already augmented by blowing snow. This problem would be most severe for gauges mounted close to the ground which are efficient in collecting snow passing over their orifice. Blowing snow events in the Intercomparison data were carefully identified and eliminated from subsequent analysis of gauge catch versus environmental factors, notably wind speed and temperature.

3. DATA ANALYSIS

The analysis presented in this section will be on “event” data, i.e. storm totals that may comprise of several observations. The appropriate corrections for wetting loss, undercatch of the DFIR and variances due to design change as noted in the previous section were applied and the precipitation events at each site were categorized into 4 type of events: Snow, Snow-Rain, Rain-Snow and Rain. Since the ratio of measurements from two gauges was the basis of the analysis, consideration was given to the fact that even small measurement differences between the two gauges could produce quite variable ratios for small precipitation events. To minimize this problem, it was decided to use only events greater than 3.0mm measured by the DFIR in the analysis of catch ratio (Nipher/DFIR) versus wind speed. Temperature and wind data were averaged over each event period and the catch ratios of Nipher/DFIR were computed for analysis. Table 5.B.1 provides a general summary of the relative catch of the Nipher to the DFIR for the six stations for their period of operation. As noted in this Table, the correction for wetting loss, undercatch of the DFIR and variances due to design change can be significant and must be applied consistently for both gauges.

Table 5.B.1 Summary of the mean wind speed and temperature, accumulated precipitation for the NIPHER gauges compared to the DFIR for the six stations. Means and accumulations are for all precipitation events > 3.0 mm.

DFIR1 = measured value | **NIPHER1 = measured value**
DFIR2 = DFIR1 corrected for wetting loss | **NIPHER2 = NIPHER1 corrected for wetting loss**
DFIR3 = DFIR2 corrected for wind | **NIPHER3 = NIPHER2 corrected for variance in gauge design**

SITE	No. of Events	Wind @ 2m (m/s)	Wind @ 3m (m/s)	Mean Temp (°C)	DFIR1 (mm)	DFIR2 (mm)	DFIR3 (mm)	NIPHER1 (mm)	NIPHER2 (mm)	NIPHER3 (mm)	NIPHER3 / DFIR3 (%)
Dease Lake											
Snow	70	1.5	1.8	-10.6	581.1	627.2	648.8	583.7	645.1	645.1	99
Snow-Rain	7	1.0	1.3	-1.0	43.3	46.3	47.3	40.9	44.9	44.9	95
Rain-Snow	0										
Rain	0										
Regina A											
Snow	21	3.6	3.9	-11.2	130.8	135.8	146.4	106.6	111.6	115.8	79
Snow-Rain	4	4.4	4.8	-3.7	19.5	20.1	22.1	15.8	16.4	16.9	77
Rain-Snow	1	2.3	2.4	0.6	5.6	5.8	5.9	4.4	4.6	4.7	79
Rain	0										
Kortright											
Snow	13	2.4	2.7	-9.1	132.5	135.5	143.1	129.3	132.3	134.9	94
Snow-Rain	15	2.3	2.6	-0.9	208.7	212.9	225.8	199.7	203.9	207.5	92
Rain-Snow	12	2.2	2.5	3.5	148.8	151.7	156.6	150.7	153.6	156.0	100
Rain	17	2.3	2.7	4.6	178.0	181.9	190.0	173.3	177.2	180.6	95

Table 5.B.1 (continued)

SITE	No. of Events	Wind @ 2m (m/s)	Wind @ 3m (m/s)	Mean Temp (°C)	DFIR1 (mm)	DFIR2 (mm)	DFIR3 (mm)	NIPHER1 (mm)	NIPHER2 (mm)	NIPHER3 (mm)	NIPHER3/DFIR3 (%)
Trent U											
Snow	31	1.8	2.2	-8.5	206.3	211.7	220.6	209.5	214.9	219.6	100
Snow-Rain	18	1.8	2.3	-1.8	222.4	226.6	236.1	231.6	235.8	239.4	101
Rain-Snow	20	1.7	2.3	-0.9	299.9	304.3	313.4	312.6	317.0	320.7	102
Rain	21	1.5	1.9	3.6	248.1	251.9	260.1	257.5	261.3	264.5	102
Baie Comeau											
Snow	59	4.1	4.3	-8.7	684.2	722.5	796.3	608.8	647.1	647.1	81
Snow-Rain	10	3.9	4.1	-1.7	136.3	142.2	154.8	109.5	115.4	115.4	75
Rain-Snow	7	3.8	4.1	-3.5	73.0	77.4	81.6	67.6	72.0	72.0	88
Rain	0										
East Baltic											
Snow	85	3.0	4.6	-7.0	967.1	992.9	1093.0	997.0	1022.8	1045.2	96
Snow-Rain	43	3.5	4.9	-2.9	764.9	781.7	860.5	743.2	760.0	774.6	90
Rain-Snow	6	2.7	4.2	-0.7	102.1	105.0	111.6	92.4	95.3	97.7	88
Rain	19	3.7	5.0	3.2	241.3	247.6	267.7	233.5	239.8	245.3	92

Figures 5.B.3(a) to (f) are scatter plots of the catch ratio of Nipher/DFIR versus the wind speed at gauge height (2 metres) for the six Canadian Intercomparison stations from west to east (see Figure 3.A.1 for locations). An examination of these scatter plots found some problems with the data set from two stations. The data set from Trent U (Figure 5.B.3d) had a very limited range of wind speed with almost 80 percent of all wind speeds found within the 1.0 to 2.5 m/s range and the average Catch Ratio did not appear to differ significantly from 100%. The data set for East Baltic (Figure 5.B.3f) had a good distribution of wind speeds but the scatter of the data points was significantly greater than all other stations. The data sets from these two stations were not used in further analyses.

For the remaining four stations, their data exhibited a good distribution of wind speeds and acceptable scatter. The data set for these four stations were combined into a single Canadian data set to maximize the range of wind speeds. Regression analysis was applied to establish relationships for catch ratio versus wind speed for each of the four precipitation categories. The regressions were force to have an intercept of 100% at zero wind speed. The Snow-Rain and Rain-Snow categories did not exhibit significantly different relationships and were therefore combined into a single mixed precipitation category. Since the Nipher Gauge in not use for rainfall measurements in Canada, the rainfall relationship is not presented. The resulting regression relationship for snow and mixed precipitation are shown in Figure 5.B.4 and the equations are:

Snow

$$NIPHER/DFIR(\%) = 100-0.39*W_S^2+2.02*W_S, \quad (N=162, R^2=0.51) \quad (1)$$

Mixed Precipitation

$$NIPHER/DFIR(\%) = 100-0.65*W_S^2-1.49*W_S, \quad (N=54, R^2=0.55) \quad (2)$$

where: W_S = wind speed at 2 metres (m/s)

Figure 5.B.3 Scatter plots of Catch Ratio of Nipher/DFIR vs Wind Speed at Gauge Height (2 metres) for the six Canadian Intercomparison stations for precipitation events > 3.0 mm. S=snow; SR=Snow-Rain, RS=Rain-Snow, and R=Rain

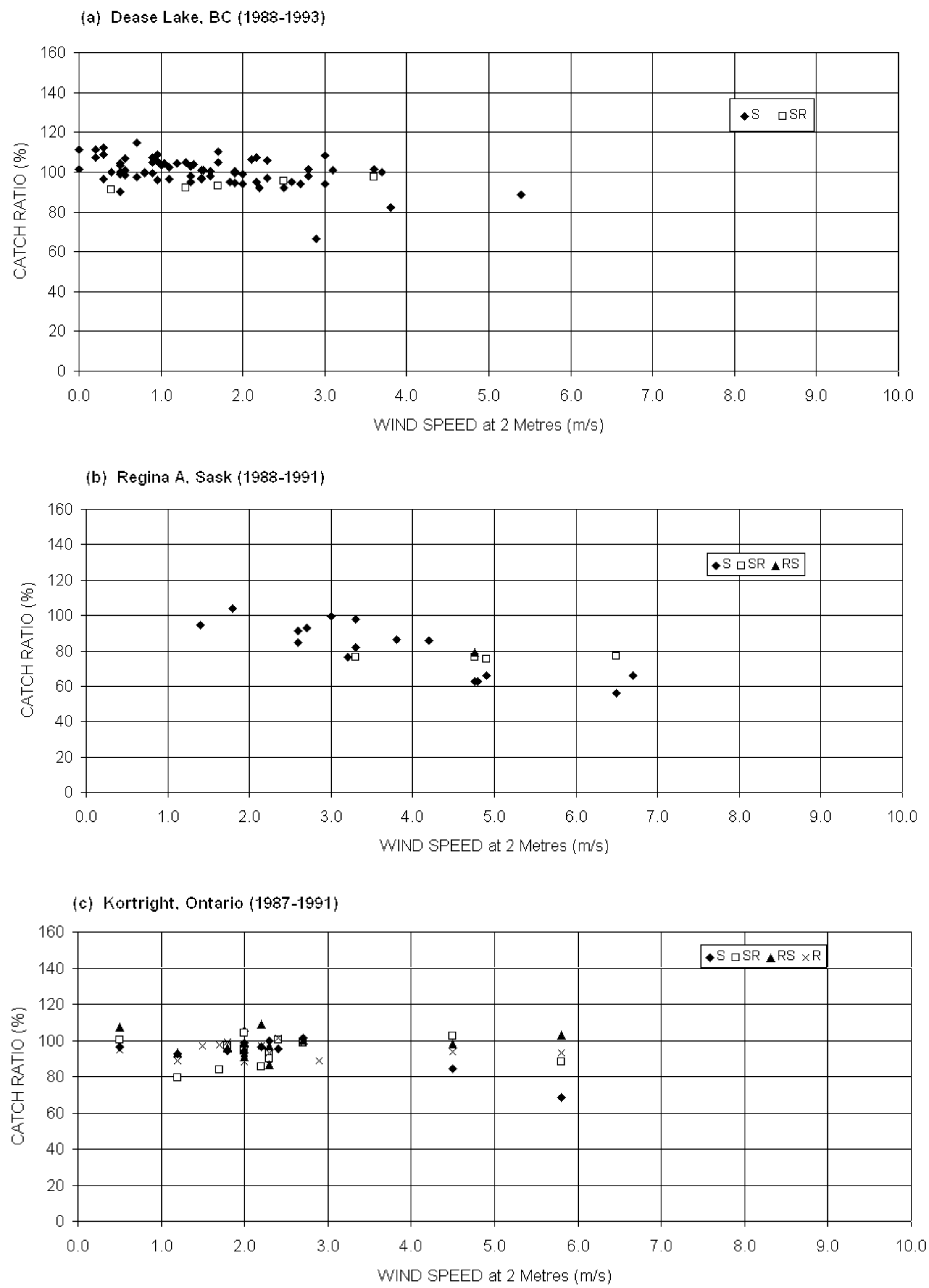
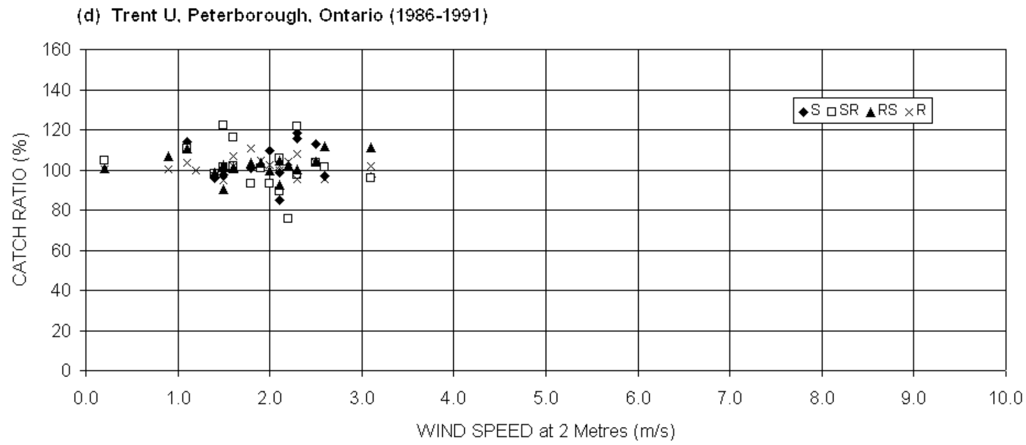
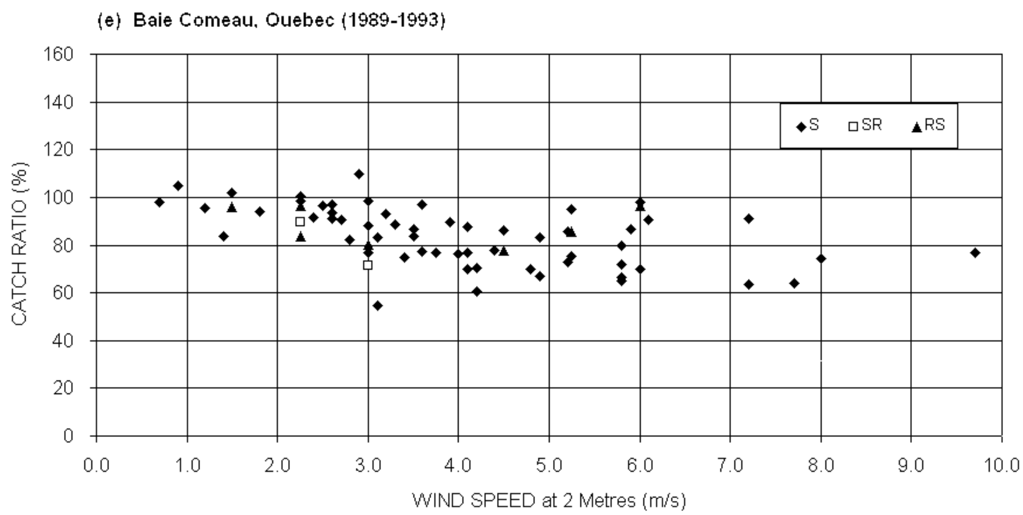


Figure 5.B.3 (Continued) Scatter plots of Catch Ratio of Nipher/DFIR vs Wind Speed at Gauge Height (2 metres) for the six Canadian Intercomparison stations for precipitation events > 3.0 mm. S =snow; SR=Snow-Rain, RS=Rain-Snow, and R=Rain





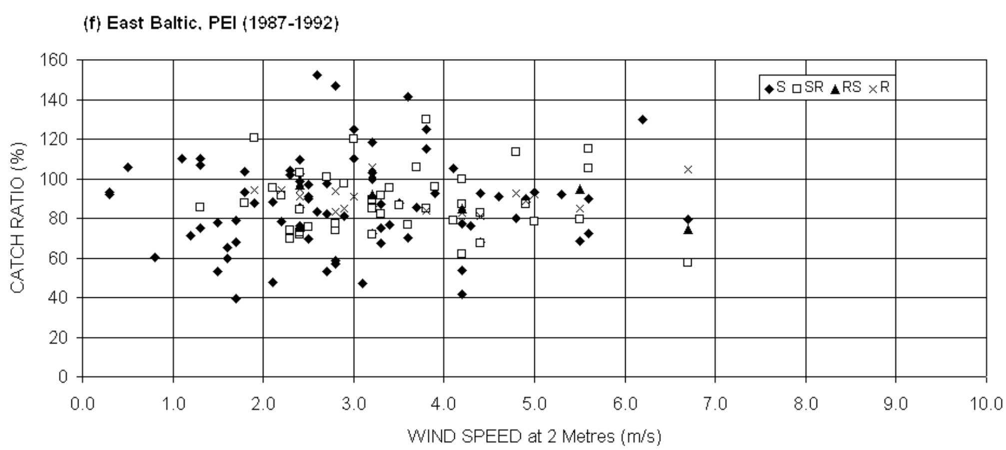
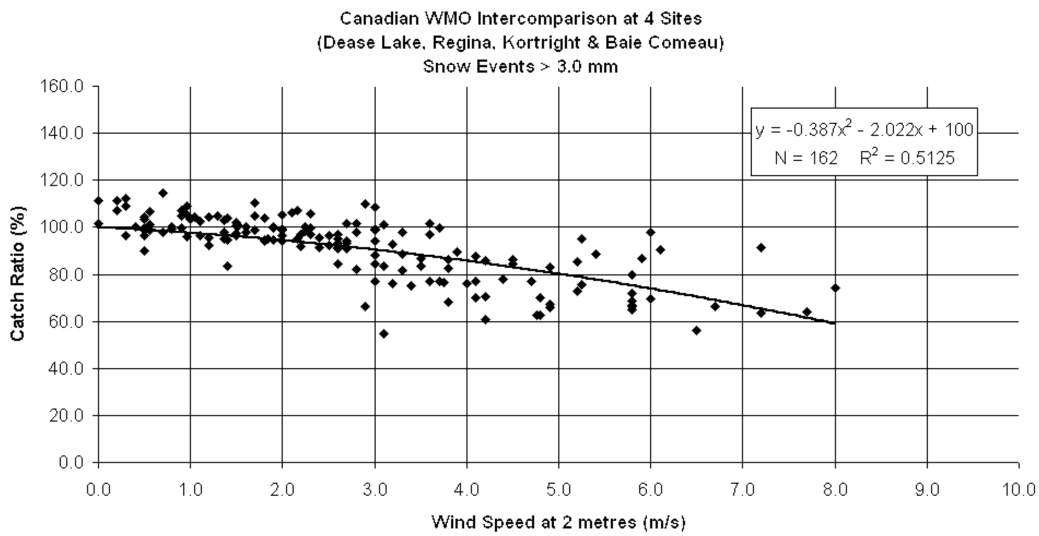
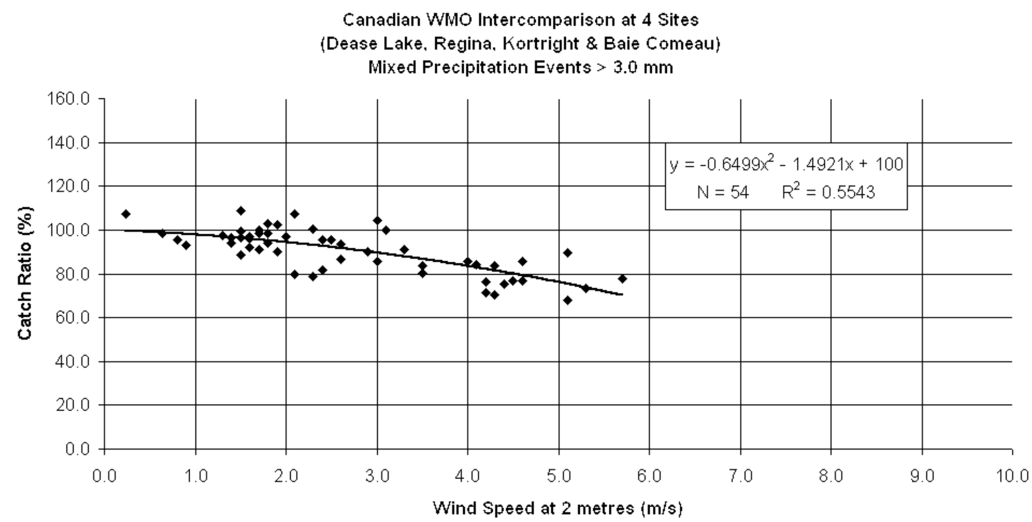


Figure 5.B.4 Regression analysis of Catch Ratio (NIPHER/DFIR) vs Wind Speed for 4 Canadian Intercomparion sites





4. DISCUSSION OF RESULTS

The results from the above analyses suggest that the Nipher gauge's catch efficiency is at or close to 100% compared to the DFIR for wind speed up to 2 m/s at the 2 m gauge height. The catch ratio decreases for wind speed greater than 2 m/s reducing to 60% at 8 m/s for snow events and 70% at 5.5 m/s for mixed precipitation events. A study by Goodison (1977) presented results for the catch ratio of the Nipher gauge compared to snowboard measurements as "true precipitation". In that study, the Nipher gauge was found to overmeasure snow for wind speeds up to 4 m/s. The current study also found some suggestion of overmeasurement at the lower wind speeds but not as pronounced as in the previous study. For the higher wind speeds, the current intercomparison show the catch efficiency of the Nipher to be slightly lower (60% compared to 68% at 8 m/s) than that reported by Goodison (1977; 1978). There are several possibilities for this: a different method of determining 'true' was used (corrected DFIR vs. snowboard in a sheltered site); the current Intercomparison includes more climatic regions and a greater range of wind speeds; and there has been a design change of the Nipher shielded gauge as noted in the previous section.

6. SUMMARY

The catch characteristics of the Canadian Nipher Shielded Snow gauge appears to be very similar to the WMO reference standard (DFIR) at low wind speeds. The current results which are based on data from a wide range climate conditions and wind speeds, suggest that at mean storm wind speeds up to 2m/s, no correction of the Canadian Nipher shielded snow gauge measurements except for wetting loss and design variance, is required to achieve the best estimate of actual snow or mixed precipitation. For mean storm wind speed greater than 2 m/s at gauge height, the catch efficiency of the Nipher gauge decreases and corrections using the relationships established above should be applied in addition to the corrections for wetting loss and design variances.

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ANNEX 5.C CHINA

TIANSHAN, CHINA

Daqing Yang and Ersi Kang, Lanzhou Institute of Glaciology and Geocryology, P.R. China.

1. RESULTS

During July 1987 through August 1991, 230 daily precipitation events greater than 2mm were collected at the intercomparison site at Tianshan, China (see site description in Annex 3.B). All gauge measurements were corrected for wetting loss, e.g. 0.35 mm/event for rainfall and 0.30 mm/event for snowfall, according to the wetting loss experiments of Chinese standard gauge (Yang, et al., 1989).

The accuracy of DFIR measurements is critically important for the intercomparison. Recently analysis of Russian Valdai intercomparison data at Canadian Climate Center (CCC) indicates the necessity of correcting DFIR measurements for the wind induced error (Yang, Metcalfe and Goodison, 1993). Unlike Golubev (1985a, 1985b) stated, the CCC study shows that the most important factor to the correction is mean wind speed during the storm and atmospheric pressure, air temperature and humidity have little or no influence. Unfortunately wind speed at Tianshan intercomparison site was not measured. Therefore, after investigating the similarity of wind pattern of nearby Daxigou climatic station to six Canadian intercomparison sites (Goodison and Metcalfe 1992a), the correction ratio of 5.7% at Kortright centre was applied to the snow event at Tianshan station and no wind correction was made to rain and mixed precipitation (Table 5.C.1).

Table 5.C.1 indicates that the catch ratio of the Chinese standard gauge (CSG) changes significantly with type of precipitation. For the dry snow cases, on the average, Chinese gauge at 0.7m catches 72.3% of the DFIR. Generally, the catch ratios of the Chinese gauge at 2m are 5 to 8% lower than that of the Chinese gauge at 0.7m. Hellmann gauge was involved in the intercomparison experiment during June through August 1987. In this period of wet snow and mixed precipitation domination, the measurement of Hellmann gauge was 2-5% higher than that of the CSG at 0.7m. The average catch ratio of Hellmann gauge to the DFIR was 92.3%, which was very close to rain and snow result for the same gauge at Harzgerode WMO site in Germany (Goodison and others, 1992b).

Table 5.C.1. Summary of WMO precipitation measurement intercomparison at Tianshan glaciological station, July 1987 through August 1991

Type of Precip	No. of Events	DFIR Total (mm)	Chinese Gauge at 0.7m		Chinese Gauge at 2m	
			Catch Ratio (%)	Total (mm)	Catch Ratio (%)	Total (mm)
Rain	13	123.8	95.82	117.3	90.78	129.2
Rain+Snow	67	427.8	89.03	389.4	81.04	480.5
Wet Snow	112	847.5	83.62	788.1	77.76	1013.5
Dry Snow	38	198.4	72.62	187.3	68.56	273.2
All Type	230	1597.5	84.24	1482.1	78.15	1896.4

Wind speed was not measured at the DFIR site during the intercomparison. Early experiment conducted in the same river basin, using snowboards as reference, resulted the following relation of catch ratio (CR) of snow versus wind speed (U) at gauge height (Yang, et al., 1989):

$$CR = 100\, e^{-0.056*U}, \quad (n= 38, R^2 = 0.56) \qquad (1)$$

Goodison (1981) and Woo, *et al* (1983) investigated the accuracy and compatibility of the Canadian snowfall and snow survey data in southern Ontario and in the high arctic basin, respectively. They found that Canadian snow gauge under-measured snowfall, and snow survey and gauge measurement were not compatible until gauge measurements were corrected for gauge catch variations and snow survey data were representative of basin land use. In our study area in China, wind speed during precipitation is generally low, with 80% of the annual precipitation occurring when daily wind speed is below 3 ms^{-1}. Thus, the spatial distribution of the freshly fallen snow is relatively even, allowing the calculation of water depth of new snowfall by snow survey at the basin stake network during the 1989-90 snow season.

Table 5.C.2 shows that the SWE of the new snow, measured after the cease of snowfall in order to eliminate snow sublimation of 0.1-0.3mm per day (Yang and Zhang, 1992), was always higher than the Chinese standard gauge measurement despite winter sublimation from the snow surface. Generally, the ratio of water

equivalent of newly fallen snow to Chinese standard gauge measurement is less variable for the heavy snow events. For these events, the Chinese standard gauge catches 62-88% of the SWE of new snow, and on average, the catch ratio of the Chinese standard gauge in Dry Cirque for dry snow is 73.2% (Table 5.3.2). This result implies the appropriate correction of the DFIR measurement for wind induced undercatch at the intercomparison site in front of glacier No.1.

Table 5.C.2. Comparison of SWE by snow survey at stake network and Chinese gauge measurement, Dry Cirque, 1989/90 winter

Period	New Snow Depth (cm)	New Snow Density	SWE (mm)	Gauge Measurement (mm)	
				Dry Cirque	Daxigou Station
Oct.06/Oct.16	9.0	0.125	11.3	10.0	10.9
Dec.23/Jan.01	2.2	0.120	2.6	1.0	1.2
Jan.12/Jan.20	1.5	0.100	1.5	0.5	0.7
Feb.14/Feb.20	1.1	0.100	1.1	1.6	2.8
Feb.26/Mar.05	2.1	0.100	2.1	2.1	2.7
Mar.19/Mar.26	6.4	0.135	8.6	6.0	6.3
Apr.16/Apr.22	13.8	0.137	18.9	16.1	17.8
Apr.23/May.04	28.4	0.118	33.5	21.0	21.1
Total	64.5	-	79.6	58.3	63.5
Mean	-	0.117	-	-	-

2. SUMMARY

The intercomparison demonstrates the mean catch ratio of the Chinese standard gauge for various type of precipitation, providing a possibility to approximately correct the measured precipitation in the high alpine areas. This correction is extremely important to the regional glaciological and hydrological studies. The intercomparison continued to the summer of 1994 and wind speed at DFIR height was measured in order to correct the daily and monthly precipitation data. In the late summer of 1994, the DFIR was moved down to the Daxigou climatic station, where precipitation, air temperature and wind speed at 10m have been measured since 1958. A pit gauge was set up for rainfall measurements in order to establish a regional precipitation center for long-term climatological and hydrological studies (WMO/CIMO, 1993). Chinese automatic rain gauge, Tretyakov wind shield, Belfort recording gauge and other new instruments were placed at the station. Weighing method was used to determine the average amount of trace precipitation, since trace precipitation occurs quite often in this area, for instance, 104 trace events were recorded in 1983.

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ANNEX 5.D DANISH METEOROLOGICAL INSTITUTE

DETAIL ANALYSIS OF JOKIOINEN, FINLAND DATA BY THE DANISH METEOROLOGICAL INSTITUTE

A STATISTICAL MODEL FOR CORRECTING SOLID PRECIPITATION

Peter Allerup, Henning Madsen and Flemming Vejen

1. INTRODUCTION

Observations of solid precipitation collected during the 6 winters 1987-93 in the experimental field at Jokioinen, Finland have been submitted to statistical analysis. These studies concern results from comparing the national precipitation gauges from the Nordic countries of Denmark, Finland, Norway and Sweden to a Tretyakov gauge with wind shield placed in a Valdai double fence. Further a Canadian gauge and three Tretyakov gauges with wind shield have been compared to this reference gauge, DFIR.

All data have been subjected to control and correction of syntax errors before the statistical analysis. This control has included missing records and wrong chronological order of records. After this first-hand control, a quality control of data, by comparing all data of measured amount of snow from the manual precipitation gauges to each other, has been undertaken, and the same procedure has been used for wind speed and temperature.

2. STATISTICAL ANALYSIS OF DATA

The aim of the statistical analysis is to set up statistic models for correcting solid precipitation considering wind speed and temperature during precipitation as controlling factors. The corrections concern the national precipitation gauges in Canada, Denmark (Hellmann), Finland (Finnish prototype +H&H-90), Norway (Norwegian standard gauge) and Sweden (Swedish standard gauge). All these gauges are shielded except the Danish one. Since the Tretyakov gauge is placed at all the WMO experimental fields, it will also be of interest to give a correction in relation to this gauge in order to compare those corrections to other corrections found for the other fields.

Due to the great amount of data, we have been compelled to use wind data from only one wind sensor - the best of the 8 sensors, and in the same way we have calculated precipitation duration on the basis of one recording precipitation gauge, the Geonor placed in a Valdai double fence. The wind speed having been measured at 2 m level has been reduced to precipitation gauge level (1.5m) considering the snow depth.

It should be emphasized, that the following statistical analysis were all done on observations passing the quality control and exceeding the limit 0.2 mm. This limit is lower compared to analysis limits applied elsewhere in the WMO study, but empirical investigations revealed, that the discretization effect on the observed catch ratios (or the inverse) is negligible, besides the fact, that many observations would be missing. This could in fact distort the construction of adequate statistical modelling.

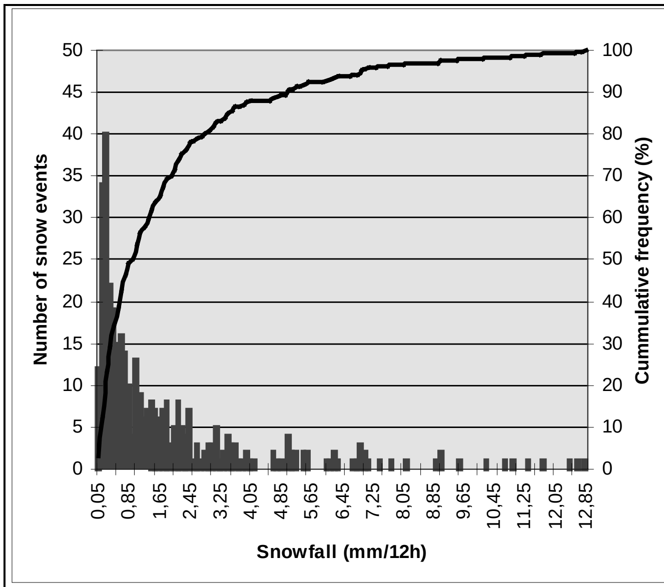

Figure 5.D.1 Frequency of semi-daily amount of snow at the reference gauge No. 16 (DFIR) for the period November 1987-March 1993.

It was recommended in the WMO protocols for the Intercomparison Study to transform the observed catch ratios: National gauge/DFIR (or the inverse correction factors) to a ratio between the national gauge and the so-called bush gauge (Golubev, 1992) before any statistical analysis be undertaken. The argument for this being, that the bush gauge could be considered to represent more accurately the "true" precipitation value. The following statistical analyses have not applied any transformation of this kind, because any subsequent statistical modelling would then be influenced by the quality of such a transformation. It is therefore preferred, to eventually imply a bush transformation after the construction of an adequate model for the directly observed ratios with DFIR and the national gauge observations as variables. The data include about 300 semi-daily precipitation values from the period November 1987 to March 1993 and all cases only concern snowfall, the values resulted from weighing - thus wetting errors are excluded. All values $\geq$ 0,2mm have been used. It can be mentioned, that some few cases with blowing snow probably have been included especially with the Canadian Nipher gauge, but we have, unfortunately, no information from the synoptic weather observations. Figure 5.D.1 shows the distribution of snowfall amounts measured at DFIR. About 50% of the cases are amounts $\geq$ 1.0 mm, and events below 3.0 mm amount to 80% of all cases.

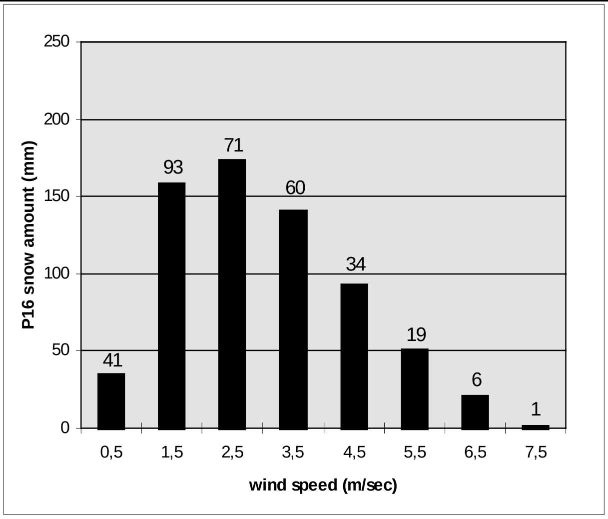

Figure 5.D.2 Amount of snow measured at the DFIR No. 16 distributed on wind speed. The number of semi-daily events are placed above the columns.

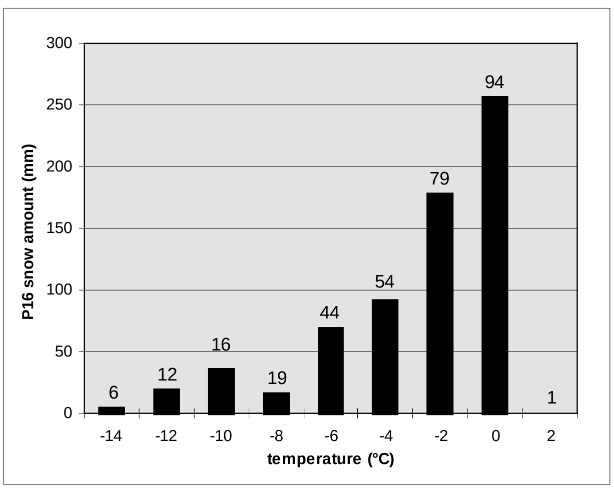

Figure 5.D.3 Amount of snow measured at the DFIR No. 16 distribution on temperature. The number of semi-daily events are placed above the columns.

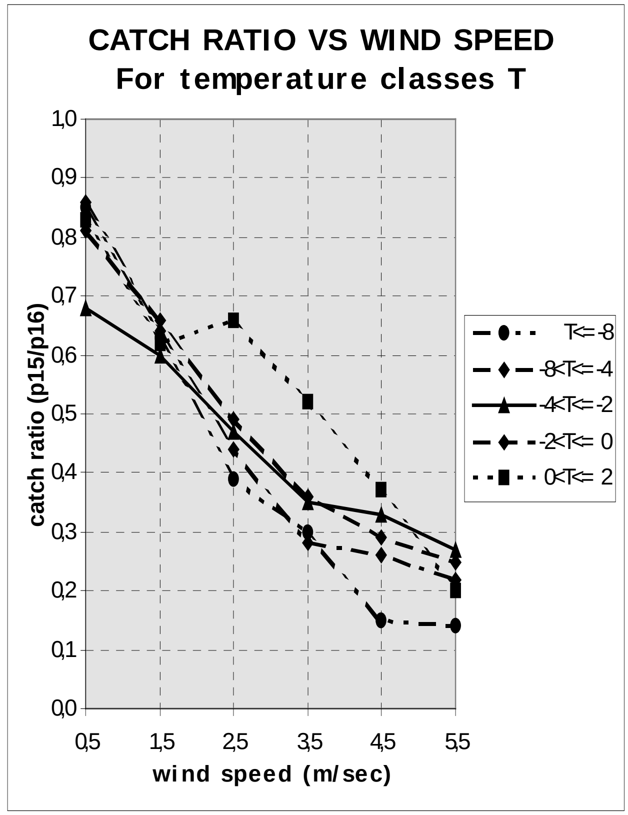

Figure 5.D.4 Catch ratio P_{16}/P_{15} concerning semi-daily measurements of snow for the Danish Hellmann gauge related to wind and temperature.

Ten minute values are taken from the Geonor to calculate the duration of precipitation for all the semi-daily values, and for the same periods 10 minute registrations from the wind and temperature mast are providing average values of wind speed and temperature. Furthermore synoptic weather observations give detailed information about precipitation types (rain, sleet snow etc.).

Wind speed and temperature are calculated as mean values for periods when snowfall have occurred. The wind and temperature conditions in the field during precipitation are illustrated on Figure 5.D.2 and 5.D.3. Figure 5.D.2 shows the amount of snow from the semi-daily values distributed according to wind speed. The wind speed is relatively small, viz. most of the semi-daily events (205) have occurred at wind below 3 m/s and recordings above 6 m/s is seldom. The temperature distribution appears from Figure 5.D.3 showing relatively high temperatures. Only few cases with temperature below -10^{o} C occur, and at 174 events the temperature have been above -3^{o} C.

The error of measurement of the precipitation gauge can be expressed in terms of the ratio P_n/P_r, the gauge catch considering the amount of precipitation, P_n measured at the national gauge in question and P_r being the precipitation measured at the reference gauge, DFIR.

The magnitude of the gauge ratio depends on wind speed. However, the ratio also depends on temperature (W.R. Hamon (1973), B.E. Goodison (1978), B Aune and E.J. Førland (1985), and B. Sevruk (1983)) since the final wind effect depends on the shape of snow flakes, which is dependent on temperature. The data have been divided in such a way, that the combinations of wind speed (V) and temperature (T) classes (V,T) represent the range of the observed wind speed and temperature. At the same time we also have insured, that every combination (V,T) are represented by a sufficient number of snowfall events in the interest of the subsequent statistical analysis, which appears from Table 5.D.1. On Figure 5.D.4 the catch ratio P_{15}/P_{16} for the Danish Hellmann gauge is related to wind speed and temperature. It can be seen very clearly, that the catch ratio decreases with increasing wind speed for all temperature classes. Generally, the ratio also decreases with decreasing temperature.

Figure 5.D.5 shows the catch ratio for all the manual gauges due to wind speed for one temperature class $0.0 \leq T < -2.0$. The results show decreasing ratios for all gauges up to a wind speed of 6 m/s (above this figure only few events are found). The unshielded Danish gauge (No. 15) catches a relatively small part of the snow compared to the other gauges.

In the following, a stochastic correction model is tested by studying the empirical structure between semi-daily values of snow P_j and P_{16}, measured at gauge No. j, and at the reference gauge DFIR No. 16 respectively. This structure is analysed for fixed combinations of wind speed and temperature and for each (V,T) combination a scatter plot of log P_{16} versus log P_j has been studied; one of these plots for 2.0 m/s $\leq$ V < 3.0 m/s and $-4.0^o < T \leq -2.0^o$ appears from Figure 5.D.6, This example is typical for all other (V,T) combinations and it is seen, what is fundamental for the following, that a linear structure emerge:

$$(1) \quad \log P_{16} = \alpha(V,T) + \beta(V,T) \log P_j$$

The linear relation is specified for fixed (V,T)-classes, and estimates of intercept $\alpha(V,T)$ and the slope $\beta(V,T)$ can be readily obtained through ordinary regression analysis techniques.

Table 5.D.1 Number of semi-daily measurements of snow 0.2mm for the Danish Hellmann gauge related to wind speed and temperature. Nov. 1987 to March 1993.

Temperature	**Wind speed V (m/sec) at gauge level**					
T (C^o)	$0 \leq V < 1.0$ $V_m = 0.58$	$1.0 \leq V < 2.0$ $V_m = 1.43$	$2.0 \leq V < 3.0$ $V_m = 2.41$	$3.0 \leq V < 4.0$ $V_m = 3.46$	$4.0 \leq V < 5.0$ $V_m = 4.41$	$V \geq 5.0$ $V_m = 5.55$
$0.0 < T \leq 2.0$ $T_m = 0.28$	4	5	9	6	5	6
$-2.0 < T \leq 0.0$ $T_m = 1.06$	8	29	24	16	5	5
$-4.0 < T \leq -2.0$ $T_m = 3.04$	9	23	14	13	3	1
$-8.0 < T \leq -4.0$ $T_m = 5.84$	9	15	8	12	9	2
$T \leq -8.0$ $T_m = -10.99$	8	8	6	3	2	3

Notice, that this linear structure is found adequate for <u>all</u> (V,T) combinations. Notice also, that the variable P_{16} emerge on the left hand side of (1) as the dependent variable in stead of P_j the national gauge. By this a direct access to analyzing the correction factor P_{16}/P_j is established in favor of the catch ratio P_j/P_{16}; the reason for choosing the correction factor instead of the catch ratio is, that after having estimated the correction factor P_{16}/P_j, this can immediately be applied (multiplied) to the observed P_j value in order to obtain the "true" reference P_{16} value. If the catch ratio is to be used, one has to apply (i.e. divide) observed P_j value by the catch ratio in order to get the P_{16} value.

There are, however clear and marked differences, seen from the statistical analysis point of view, between analyses studying the behavior of P_{16}/P_j compared to P_j/P_{16}; conclusions drawn from the one kind of analysis cannot be transferred to the other (parameter estimates, confidence limits etc.). If the statistical properties of the catch ratio itself are known by analysis one can, consequently, not apply this knowledge directly to calculations involving the **inverse** catch ratio.

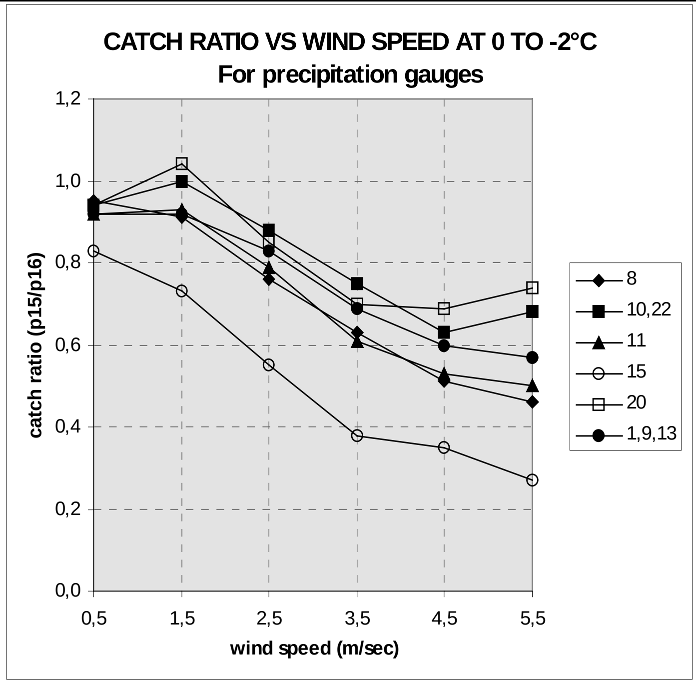

Figure 5.D.5 Catch ratio P_j/P_{16} concerning semi-daily measurements of snow related to wind speed for one temperature class 0.0°C≤T<-2.0°C for the 4 Nordic national gauges No. 15 (Denmark), No. 10+22 (Finland), No. 8 (Norway) and No. 11 (Sweden), and the Canadian gauge No. 20, and average of the Tretyakov gauges No. 1, 9 and 13.

In the first, preliminary analysis of the data from one gauge only it seemed, that (V,T) was dependent on wind speed V and temperature T in such a way, that the logarithmic difference log (P_{16}/P_j) between the two gauges could be modelled as a function f of wind speed, level of precipitation (log P_j) and temperature T in the following structure:

$$(2) \quad \log P_{16} / P_j = \alpha(V,T) + \beta(V,T) \cdot \log (P_j)$$

Although this model, analyzed through ordinary linear regression technique, showed good fit (R^2=0,55 on average) the structure of significant/insignificant contributions from wind speed (V), temperature (β(T)) and level of precipitation (log P_j) varied much across the different gauges. No distinct pattern emerged, and the model (2) was therefore abandoned.

The basic structure (1) - still valid - was used again, and more detailed studies of estimated $\alpha(V,T), \beta(V,T)$ - values (across all gauges) for varying wind speed (V) and temperature (T) led to the following hypothesis:

$$(3) \quad \alpha(V,T) = \eta_0 + \eta_1 V + \eta_2 T + \eta_3 VT$$
$$\beta(V,T) = 1, \text{ i.e. independence of } V,T$$

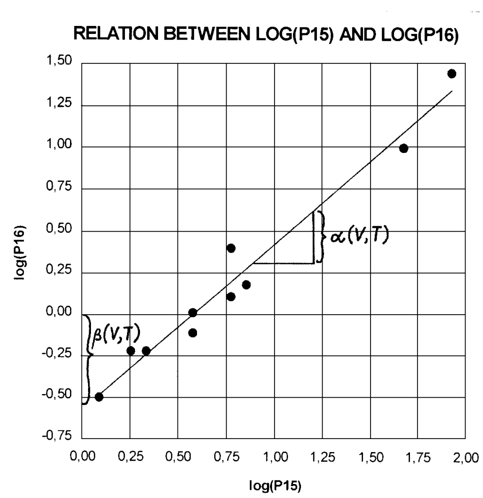

Figure 5.D.6 Scatter plot of log P_{16} versus log P_j for 2.0m/s≤V<3.0m/s and -4.0°C<T≤-2.0°C.

As a consequence, wind speed V and temperature T are now introduced <u>explicitly</u> in $\alpha(V,T)$ together with an interaction V T between V and T while $\beta(V,T)$ is set to unity. By this the correction P_{16}/P_j is independent of the level of precipitation P_j.

This model specification was tested successfully against all gauges with high values of the multiple correlation R^2, and no systematic deviations were found using residuals (Allerup, *et al*, 1996).

Accepting these tests, a final model was therefore proposed:

$$\text{(4)} \quad \log (P_{16} / P_j) = \beta_0 + \beta_1 V + \beta_2 T + \beta_3 VT$$

The model (4) represents a simple bi-linear model using explicit values of wind speed V and temperature T. Notice, that model (4) for any fixed value of temperature $T = T_0$ represents the type of model traditionally applied (see e.g. W.R. Hamon (1973)) to the differences between the reference gauge (P_{16}) and the gauge under analysis:

$$\text{(5)} \quad \log (P_{16} / P_j) = \underbrace{(\beta_0 + \beta_2 T_0)}_{\tau_0(T_0)} + \underbrace{\beta_1 + \beta_3 T_0}_{\tau_1(T_0)} \cdot V$$

Consequently a test of the bi-linear structure in model (4) can be done by estimating $\tau_0(T_0)$ and $\tau_1(T_0)$ in the model (5) for fixed T_0-values and, - using wind speed V as independent variable - subsequently study $\tau_0(T_0)$ and $\tau_1(T_0)$ as a function of T_0 to see if the relations are linear in T_0. An example of these analyses of structure is given by Figure 5.D.7, where log (P_{16}/P_j) - the left hand side of (5) - is plotted versus wind speed V for fixed temperature T = T_0 = -1.06 (cf. the grouping of temperature in Table 5.D.1).

The structure in Figure 5.D.7 is clearly linear and ordinary regression estimates of intercept τ_0=0.13341 and slope $\tau_1 = 0.17464$ can be obtained. The analysis in Figure 5.D.7 is repeated for all T_0 values (τ_0=-10.99,-5.84,-3.04,-1.06 and 0.28 cf. Table 5.D.1) and estimated intercepts and slope values for varying T_0 are obtained:

T_0	$\tau_0(T_0)$	$\tau_1(T_0)$
-10.99	-0.23483	0.23187
-5.84	-0.16064	0.19616
-3.04	-0.10907	0.17181
-1.06	-0.13341	0.17464
0.28	-0.08663	0.14346

The structure of model (5) requires, that $\tau_0 (T_0) = \beta_0 + \beta_2 T_0$ and $\tau_1 (T_0) = \beta_1 +$ are both linear functions of T_0. For gauge No. 8 the estimated τ_0, τ_1-values listed above are displayed in Figure 5.D.8 and 5.D.9 as functions of T_0. Similar graphs can be obtained from analysis of data from the other gauges, and it is concluded, that the postulated linear structures on τ_0 and τ_1 as functions of T_0 cannot be rejected.

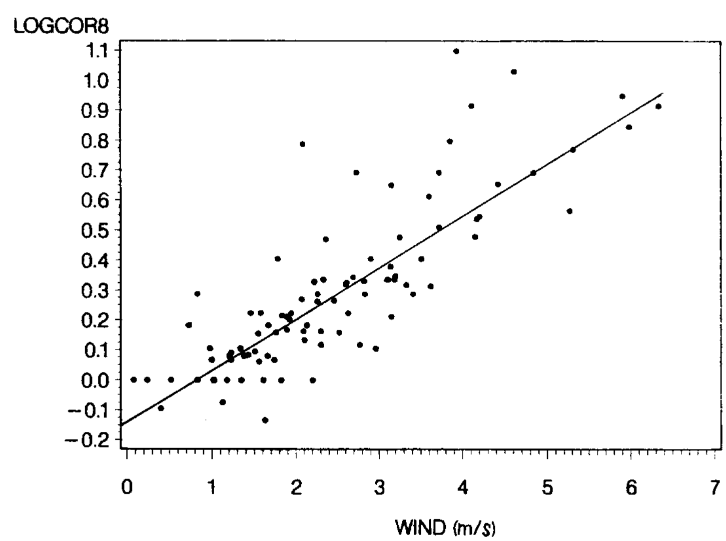

Figure 5.D.7 Logarithmic correction factors log(P_{16}/P_j) for the Norwegian gauge No. 8, plotted versus wind speed V for temperature T_0=-1.06.

Further statistical testing of the model (4) has been undertaken using analysis of residuals, analysis of multicollinarity, analysis of auto-correlation etc. A brief summary of the results of the regression analyses are presented in Table 5.D.2.

The values presented in Table 5.D.2 represents the directly estimated regression coefficients from the data. Further analysis may adjust these values slightly a.o. because predicted values of the correction factor P_{16}/P_j may depend on extreme combinations of V and T. These analyses will provide final estimates of the coefficients $\beta_0, \beta_1, \beta_2$, and β_3 and provide confidence bounds for the correction P_{16}/P_j as well.

It is, however, a strong impression from the analysis done so far, that the structure of the model (4) holds true for all gauges. Examples of estimated correction "surfaces" P_{16}/P_j as functions of wind speed V and temperature T are given below in Figure 5.D.10 (for these plots the estimated regression coefficients from Table 5.D.2 have been used).

Table 5.D.2 Estimated regression coefficients in the model (4)

Gauge No.	Country	β_0	β_1	β_2	β_3
8	Norway	-0.12159	0.18546	0.006918	-0.005254
10+22	Finland	-0.07556	0.10999	0.012214	-0.007071
11	Sweden	-0.08871	0.16146	0.011276	-0.008770
15	Denmark	-0.04587	0.23677	0.017979	-0.015407
20	Canada	-0.11972	0.06758	0.00544	-0.003300
1,9,13	Tretyakov	-0.04816	0.13383	0.009064	-0.005147

It appears from the figures, that the correction factor increases with increasing wind speed and decreasing temperature. The Canadian gauge No. 20 is seen to be the best one (cf. Figure 5.D.5) with a maximum value of the correction factor (wind speed 6 m/s and temperature -10^{o}C) below 2.00. On the other hand, for the unshielded Danish gauge No. 15 the maximum value is approximately 8.00.

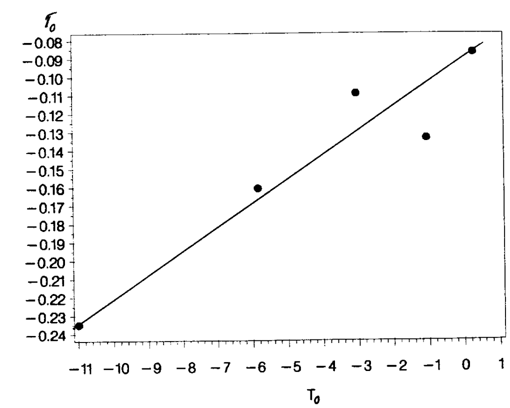

Figure 5.D.8 Estimated values of τ_0 as function of T_0 for gauge No. 8.

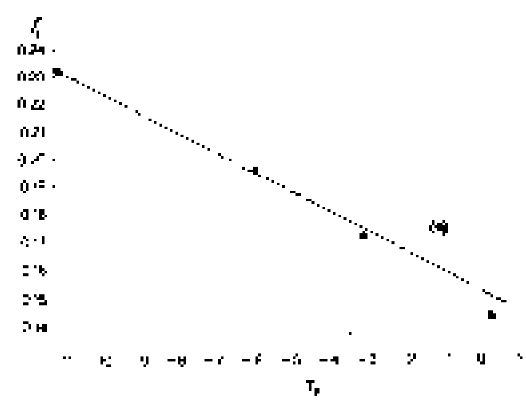

Figure 5.D.9 Estimated values of τ_1 as function of T_0 for gauge No. 8.

3. A CORRECTION MODEL FOR MIXED PRECIPITATION

Strictly speaking “true mixed precipitation” means that the precipitation type is reported as sleet or as a mixture of rain and snow. In the following, precipitation is classified as mixed precipitation when both snow and rain have been observed within the observation period. The mixed precipitation data are considered composed of solid and liquid precipitation in a relative proportion which must be estimated and, finally corrected according to the correction models for solid and liquid precipitation which have wind speed and temperature and wind speed and rain intensity as controlling factors, respectively.

The influence of temperature and rain intensity on the observed ratio P_{16}/P_{15} was more or less distinct, depending on the proportion pcts of snow in the mixed precipitation. This is not surprising when considering mixed precipitation as a true combination of two distinctly different components: rain and snow, each of which should be corrected individually. Figure 5.D.11 shows how the correction factor P_{16}/P_{15} vary (fixed values of wind speed V) in relation to pct=percentage snow of total precipitation. The expected level of correction P_{16}/P_{15} changes according to the proportion pcts of snow, attaining lowest values for low values of pcts (i.e. nearly pure rain), and the level of correction increases with increasing wind speed. It is expected that the observed correction values P_{16}/P_{15} near the left vertical axis in Figure 5.D.11 are well fitted by the model for liquid precipitation and *vice versa* for the model fitted P_{16}/P_{15}

values on the right vertical axis (where pcts ≈ 1 indicates nearly pure snow). The open points shown in Figure 5.D.11 are model expected corrections using average rain intensity (1.0 mm/hour) and average temperature (-2.0°C).

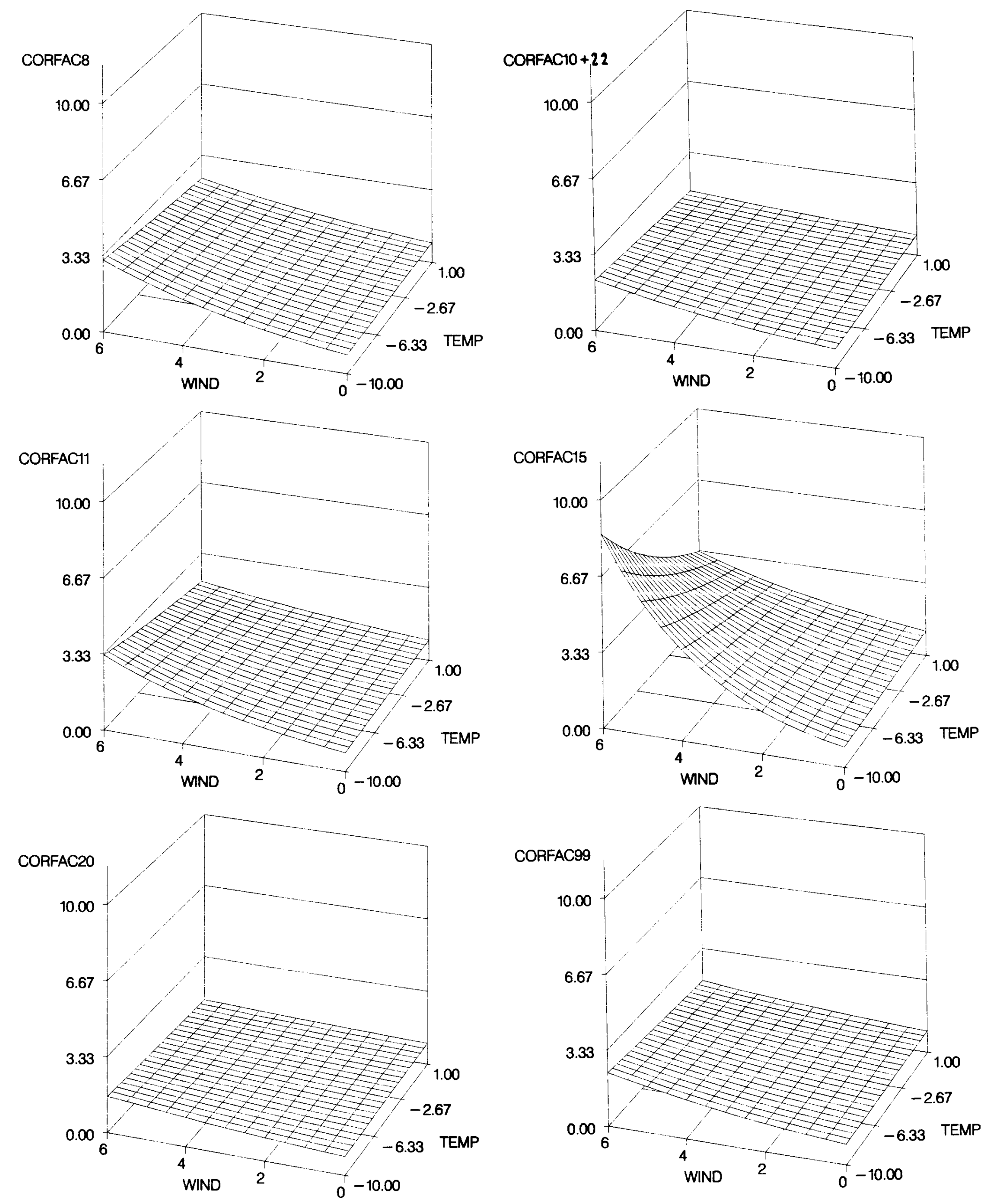

Figure 5.D.10 Estimated correction factors P_{16}/P_j (gauge No. j=8, 10+22, 11, 15, 20 and 99=average (9,11,13)) based on regression coefficients in mode (5) from Table 5.D.2 related to wind speed (m/s) at gauge level and temperature (°C).

When correcting mixed precipitation an appealing solution would be to correct the two sub quantities ΔS (mm snow) and ΔR (mm liquid precipitation) separately according to the correction models for solid and liquid precipitation. The main problem is to find good estimates of the proportion pcts of snow in actual total precipitation. Two different ways of calculating pcts have been examined; one method is based on the time (minutes) in which snow has been observed in relation to the total time of precipitation, the other is based on a classification of the current precipitation event, snow or rain, and subsequent adding up the amount measured in mm. It is clear, that the second method is providing the most accurate estimate; however it has been found empirically, that the far more easy obtainable estimate based on simple observations of the time (minutes) works satisfactory. The proposal is therefore to use this method in getting an estimate of pcts. If it is not possible in practical work to have access to such observations of due time, pcts can be roughly estimated from the temperature T.

In summary, mixed precipitation should be considered as two distinct components: rain and snow with proportion=pcts as snow. It should be corrected separately using the two separate statistical correction

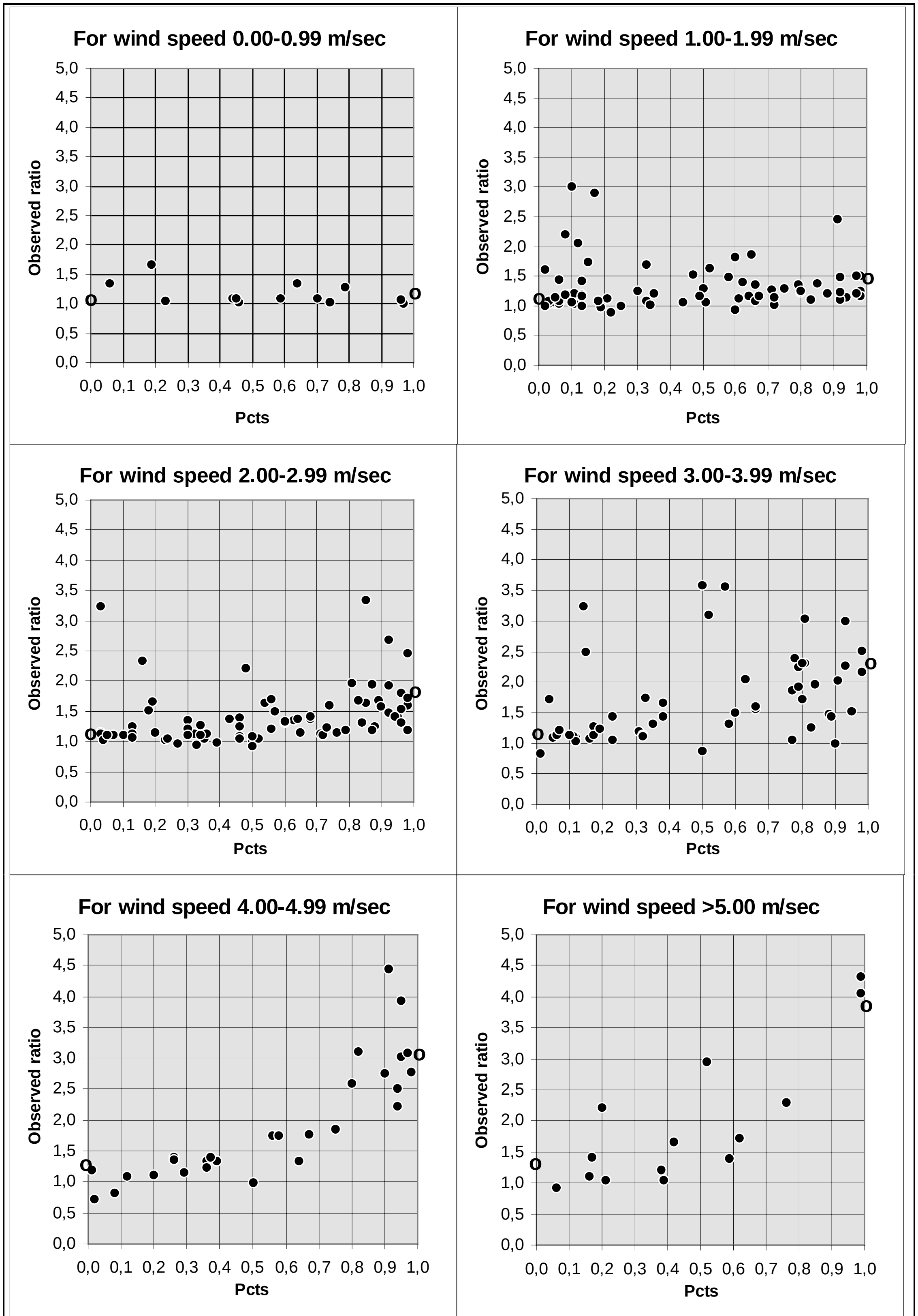

Figure 5.D.11 Variation of observed ratio P_{16}/P_{15} for fixed values of wind speed V in relation to percentage snow in the precipitation. Open black points are model expected corrections using <u>average</u> rain intensity (1.0 mm/hour) and average temperature (-2.0°C).

models for liquid and solid precipitation. This procedure yields a combined correction factor K, which is calculated as a weighted average as follows:

$$K = pcts \cdot \exp(\beta_0 + \beta_1 V + \beta_2 T + \beta_3 VT) + (1 - pcts) \cdot \exp(\gamma_0 + \gamma_1 V + \gamma_2 \log I_0 + \gamma_3 V \log I_0)$$

where percentage snow=pcts $\in$ [0,1].

4. CONCLUSIONS

A correction model for the aerodynamic influence on solid precipitation measurements has been constructed during the analysis of the Jokioinen data from the WMO Intercomparison for Solid Precipitation. It was found, that the correction factor for solid precipitation can be calculated using a bi-linear statistical model with wind speed and temperatures as explicit variables in the model. The model for mixed precipitation is at the present state based on linear simplifications (weighted average). Future work will improve the fit by introducing non-linear techniques.

5. REFERENCES

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ANNEX 5.E FINNISH METEOROLOGICAL INSTITUTE

ANALYSIS OF JOKIOINEN, FINLAND BY THE FINNISH METEOROLOGICAL INSTITUTE

1. PRECIPITATION EVENT CHARACTERISTICS DURING INTERCOMPARISON

During the intercomparison period 14 February 1988…31 March 1993 77.7 % of the time there were no precipitation, 9.2 % was snow and 7.6 % rain (Table 5.E.1).

Table 5.E.1. Different precipitation phenomena and their duration in Jokioinen 1.2.1987 to 1.5.1993.

Weather	Number of cases	Total duration (h)	Total duration (%)	Case duration (h) mean	Case duration (h) max
No precipitation					
Drifting or blowing snow	19	87.2	0.2	4.6	16.0
Thunder without precipitation	131	81.5	0.1	0.6	3.8
Not any precipitation phenomena	3866	42350.3	77.4	11.0	486.3
	4016	42519.0	77.7		
Precipitation					
Drizzle and snow grains	1	0.8		0.8	0.8
Hail	4	0.7		0.2	0.3
Small hail	7	0.6		0.1	0.2
Ice pellets	8	7.9		1.0	2.3
Snow hail	19	5.8		0.3	1.1
Drizzle and snow	30	27.6	0.1	0.9	4.3
Drizzle and rain	56	66.0	0.1	1.2	6.3
Ice crystals	61	157.5	0.3	2.6	9.3
Snow grains	252	707.5	1.3	2.8	16.7
Rain and snow	381	549.5	1.0	1.4	10.5
Drizzle	692	1486.4	2.7	2.1	35.4
Snow	2000	5046.0	9.2	2.5	43.0
Rain	3547	4170.8	7.6	1.2	89.3
	7058	12227.0	22.3		

2. Manual Gauges

During the winter months (October ... April) 1099 semi-daily measurements of precipitation were made with the gauges which have been with the intercomparison from the very beginning and 375 measurements with the new Finnish bucket H&H-90 which was used only from the 1st of March 1992. From all possible manual measurements only 4 have been lost. The reason was the fact that handling so many buckets in the sledge of a skido caused some problems.

Data for intercomparison (with the DFIR-reference corrected using the formula by Yang et al, 1993) includes 1034 cases of which 448 are snow fall, 253 snow and rain, 56 drizzle and 277 rain.

Orifice area of the gauges were measured and all the recordings were corrected to the nominal area of the buckets. It was found that the orifice area of the Tretyakov gauges used in the intercomparison was 1.47 % smaller than the nominal orifice area.

During the intercomparison buckets of the manual gauges were tinned to stop leakage as follows: one Norwegian and two Wild buckets once, both buckets of Danish Hellmann and Canadian gauge twice.

To avoid wetting error in the measurements the buckets were weighed with a digital balance. After taking buckets from outside into the measurement hut they must be dried because of the condensed water vapour onto their surfaces (Elomaa et al. 1989).

3. AUTO GAUGES

Tipping buckets were blocked several times, mainly in the autumn: Friedrich's bucket 3 times, RIMCO twice. In addition the heating of RIMCO gauge was not sufficient in 5 occasions and once the measuring card was burnt. Both GEONORs (I and II) had a faulty program at first and only from 1.11.1988 the data could not be used in the analysis. The measuring hybrid was once struck by lightning and must have been changed. In all hybrids were changed twice for GEONOR I and once for GEONOR II. Two birds have been found in GEONOR-buckets. In all 92.6 % of the semi-daily DFIR data was acceptably recorded with GEONOR I (gauge 18).

The data collecting system consisted of a PC-microcomputer, a line printer, interface cards and measuring transducers. The system collapsed in all 107 times and it has been stopped for maintenance 117 times. However, the system recorded 299,857 10 minutes intervals starting in August 1987 and ending in May 1993. This means that the system worked on a level of 98.9 %.

Later on a present weather sensor FD12P has been used on the same intercomparison field from May 1992 to April 1993. It is based on the FD12P Forward Scatter Visibility Sensor to which a capacitive sensor, based on the DRD11A Rain Detector, has been added (Lönnqvist & Nylander, 1992).

A comparison of semi-daily corrected sums of the pit-gauge and FD12P showed a fairly good agreement in rain but measurements in snow-fall showed a rather big scatter (Figures 5.E.1 and 5.E.2) (Aaltonen et al.,1993).

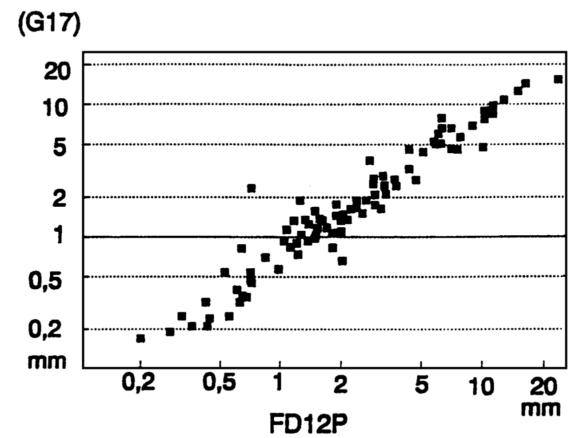

Figure 5.E.1 Sums of semi-daily rainfall (n=90) 1.5.1992…30.4.1993 measured with pit gauge (G17, corrected for wetting loss) and FD 12P.

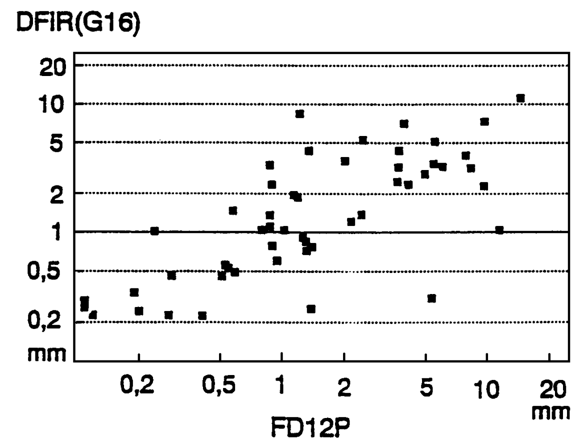

Figure 5.E.2 Sums of semi-daily snowfall (n=54) 1.5.1992…30.4.1993 measured with DFIR (G16, corrected with Golubev's equation) and FD 12P.

4. EVAPORATION AND WETTING LOSS FROM MANUAL GAUGES

Mean daily evaporation loss was studied with 6 different gauges and on rainless days it was as high as 0.87 mm/12h (Table 5.E.2). In April 1989 it was as high as 1.5 mm/12h from a Tretyakov gauge (Elomaa, et. al., 1992).

Wetting loss was determined as a difference of weighed and volumetrically measured precipitation. It was the smallest in snow-fall cases and the greatest in rain fall cases (Tables 5.E.3 ... 5.E.7).

Table 5.E.2 Mean daily evaporation loss, (mm/day), from different gauges for different months in 1989 ... 1993. n = number of observations, m = arithmetic mean, std = standard deviation, min = minimum and max = maximum values of daily evaporation loss.

a) H&H-90

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	12	16	35	43	39	37	39	27	26	25	6	17
m	0.18	0.17	0.30	0.81	0.22	0.16	0.18	0.10	0.04	0.20	0.11	0.14
std	0.19	0.13	0.18	0.38	0.18	0.12	0.11	0.08	0.04	0.14	0.07	0.20
min	0.02	0.02	0.04	0.04	0.01	0.02	0.04	0.04	0.00	0.03	0.05	0.00
max	0.73	0.49	0.88	1.65	0.86	0.62	0.59	0.36	0.18	0.64	0.24	0.83

b) Tretyakov

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	23	42	65	80	79	78	72	59	61	53	18	25
m	0.15	0.19	0.36	0.87	0.58	0.59	0.55	0.35	0.20	0.20	0.09	0.13
std	0.14	0.15	0.32	0.46	0.32	0.25	0.23	0.18	0.11	0.16	0.09	0.14
min	0.02	0.01	0.00	0.00	0.10	0.18	0.17	0.10	0.03	0.01	0.00	0.00
max	0.66	0.69	2.11	2.27	2.19	1.21	1.36	1.16	0.47	0.78	0.38	0.65

c) Wild

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	18	34	56	71	79	76	73	59	58	44	15	19
m	0.09	0.17	0.21	0.07	0.03	0.04	0.04	0.03	0.02	0.02	0.01	0.09
std	0.13	0.21	0.23	0.19	0.01	0.04	0.02	0.01	0.01	0.02	0.02	0.13
min	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00
max	0.54	1.09	1.06	1.08	0.08	0.38	0.20	0.10	0.09	0.14	0.06	0.49

d) Danish Hellmann

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	4	19	25	32	23	25	20	10	15	9	5	5
m	0.41	0.17	0.16	0.20	0.22	0.27	0.26	0.16	0.06	0.04	0.24	0.03
std	0.67	0.12	0.13	0.28	0.09	0.11	0.07	0.08	0.03	0.03	0.31	0.02
min	0.00	0.01	0.02	0.03	0.09	0.15	0.16	0.08	0.02	0.00	0.01	0.00
max	1.57	0.52	0.58	1.37	0.41	0.62	0.40	0.37	0.12	0.11	0.83	0.05

e) Swedish

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	6	18	26	32	23	25	20	10	15	13	5	8
m	0.17	0.14	0.21	0.56	0.33	0.44	0.36	0.30	0.08	0.17	0.08	0.09
std	0.21	0.10	0.12	0.26	0.16	0.15	0.11	0.20	0.05	0.10	0.05	0.09
min	0.01	0.02	0.02	0.05	0.13	0.20	0.18	0.17	0.00	0.08	0.05	0.02
max	0.63	0.41	0.48	1.24	0.65	0.91	0.67	0.86	0.17	0.47	0.18	0.31

f) Norwegian

month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	6	16	25	32	23	25	20	10	14	13	5	8
m	0.17	0.13	0.18	0.64	0.14	0.18	0.16	0.10	0.02	0.16	0.09	0.10
std	0.22	0.10	0.11	0.37	0.07	0.07	0.05	0.08	0.02	0.13	0.08	0.10
min	0.00	0.00	0.02	0.00	0.04	0.08	0.07	0.04	0.00	0.00	0.02	0.00
max	0.66	0.41	0.44	1.66	0.32	0.40	0.30	0.30	0.05	0.53	0.23	0.32

Table 5.E.3a   All snowfall cases 1987 - 1993 in winter (October - April). Reference is Tretyakov gauge with wind shield in a Valdai Double Fence Intercomparison Reference (DFIR, last row in table), which is corrected with wetting loss and Golubev's equation. Gauges are provided with wind shield if otherwise not mentioned and they are corrected with gauge orifice area. The gauge number in the brackets is the same as in picture 5. N is a number of cases (12 hour period). Precipitation sum (mm and % of the reference) is measured both by weighing (x) and volumetrically (y) and wetting loss is calculated from with them: 100*(x-y)/x (%) and (x-y)/N (mm/case).

Gauge	N	Weighed values		Volum. values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	200	288.92	59.3	272.78	56.5	5.6	0.08
H&H-90 (22)	121	231.16	75.0	224.54	73.6	2.9	0.06
Tretyakov without wind shield (2)	451	431.20	49.1	400.00	45.6	7.2	0.07
Tretyakov (1)	451	659.79	75.1	618.00	70.4	6.3	0.09
Tretyakov (9)	451	641.02	73.0	606.71	69.1	5.4	0.08
Tretyakov (13)	451	650.36	74.1	607.08	69.2	6.7	0.10
Wild without wind shield (7)	451	357.15	40.7	340.74	38.8	4.6	0.04
Wild (14)	451	503.88	57.4	495.95	56.5	1.6	0.02
Canadian (20)	255	491.99	82.3	466.32	78.6	5.2	0.10
Danish Hellmann (15)	451	428.31	48.8	384.69	43.8	10.2	0.10
Hungarian Hellmann (6)	310	322.42	46.5	302.51	44.0	6.2	0.06
Norwegian standard (8)	451	579.43	66.0	556.66	63.4	3.9	0.05
Swedish standard (11)	451	607.73	69.2	597.65	68.1	1.7	0.02
DFIR (16)	451	835.02	95.1	807.75	92.0	3.3	0.06
corrected with wetting loss and Yang	451	881.42	100.4	881.12	100.4	0.0	0.00
corrected with wetting loss and Golubev	451	878.23	100.0	877.84	100.0	0.0	0.00

Table 5.E.3b   As in Table 5.E.3a but only the cases where reference measurement > 3.00 mm.

Gauge	N	Weighed values		Volum. values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	57	198.93	56.2	193.37	54.6	2.8	0.10
H&H-90 (22)	37	165.75	72.1	163.59	71.2	1.3	0.06
Tretyakov without wind shield(2)	94	276.48	49.0	266.70	47.3	3.5	0.10
Tretyakov (1)	94	421.20	74.7	410.04	72.7	2.7	0.12
Tretyakov (9)	94	405.95	72.0	397.70	70.5	2.0	0.09
Tretyakov (13)	94	412.25	73.1	400.88	71.1	2.8	0.12
Wild without wind shield (7)	94	221.39	39.3	215.77	38.3	2.5	0.06
Wild (14)	94	315.27	55.9	312.35	55.4	0.9	0.03
Canadian (20)	68	338.28	79.4	324.59	76.2	4.1	0.20
Danish Hellmann (15)	94	268.48	47.6	255.12	45.2	5.0	0.14
Hungarian Hellmann (6)	76	214.18	44.2	208.04	42.9	2.9	0.08
Norwegian standard (8)	94	364.20	64.6	362.70	64.3	0.4	0.02
Swedish standard (11)	94	384.09	68.1	380.96	67.6	0.8	0.03
DFIR (16)	94	533.14	94.5	527.53	93.6	1.1	0.06
corrected with wetting loss and Yang	94	565.11	100.2	565.11	100.2	0.0	0.00
corrected with wetting loss and Golubev	94	563.93	100.0	563.90	100.0	0.0	0.00

Table 5.E.4a All rainfall cases 1987 - 1993 in winter (October - April). Reference is Tretyakov gauge with wind shield in a Valdai Double Fence Intercomparison Reference (DFIR, last row in table), which is corrected with wetting loss. Gauges are provided with wind shield if otherwise not mentioned and they are corrected with gauge orifice area. The gauge number in the brackets is the same as in picture 5. N is a number of cases (12 hour period). Precipitation sum (mm and % of the reference) is measured both by weighing (x) and volumetrically (y) and wetting loss is calculated from with them: 100*(x-y)/x (%) and (x-y)/N (mm/case).

Gauge	N	Weighed values		Volum. values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	156	321.74	92.6	301.60	87.5	6.3	0.13
H&H-90 (22)	125	252.89	97.1	236.83	91.6	6.4	0.13
Tretyakov without wind shield (2)	277	623.07	91.2	583.54	85.4	6.4	0.14
Tretyakov (1)	277	658.50	96.4	616.63	90.3	6.4	0.15
Tretyakov (9)	277	643.53	94.2	609.82	89.3	5.2	0.12
Tretyakov (13)	277	656.30	96.1	618.02	90.5	5.8	0.14
Wild without wind shield (7)	277	630.94	92.4	609.66	89.2	3.4	0.08
Wild (14)	277	638.00	93.4	625.04	91.5	2.0	0.05
Canadian (20)	219	492.91	96.6	459.04	90.1	6.9	0.16
Danish Hellmann (15)	277	625.05	91.5	586.50	85.8	6.2	0.14
Hungarian Hellmann (6)	240	574.77	95.2	542.88	89.8	5.6	0.13
Norwegian standard (8)	277	622.12	91.1	580.55	85.0	6.7	0.15
Swedish standard (11)	277	653.29	95.6	633.49	92.7	3.0	0.07
Pit gauge (17)	143	427.82	100.2	411.99	96.6	3.7	0.11
DFIR (16)	277	683.21	100.0	648.35	94.9	5.1	0.13
corrected for wetting loss	277	683.21	100.0	683.25	100.0	0.0	0.00

Table 5.E.4b As in Table 5.E.4a but only the cases where reference measurement > 3.00 mm.

Gauge	N	Weighed values		Volum. values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	44	220.43	95.1	214.30	92.6	2.8	0.14
H&H-90 (22)	29	159.72	97.9	155.58	95.6	2.6	0.14
Tretyakov without wind shield (2)	78	447.81	93.8	436.29	91.4	2.6	0.15
Tretyakov (1)	78	466.10	97.6	453.86	95.1	2.6	0.16
Tretyakov (9)	78	456.09	95.5	447.29	93.7	1.9	0.11
Tretyakov (13)	78	465.16	97.4	454.50	95.2	2.3	0.14
Wild without wind shield (7)	78	448.26	93.9	442.02	92.6	1.4	0.08
Wild (14)	78	449.26	94.1	445.61	93.3	0.8	0.05
Canadian (20)	61	337.83	97.3	325.42	93.7	3.7	0.20
Danish Hellmann (15)	78	445.58	93.3	433.71	90.8	2.7	0.15
Hungarian Hellmann (6)	72	414.57	95.5	405.41	93.2	2.2	0.13
Norwegian standard (8)	78	444.61	93.1	430.77	90.2	3.1	0.18
Swedish standard (11)	78	462.34	96.8	456.58	95.6	1.3	0.07
Pit gauge (17)	48	316.73	98.4	311.37	96.7	1.7	0.11
DFIR (16)	78	477.45	100.0	468.25	98.1	1.9	0.12
corrected for wetting loss	78	477.45	100.0	477.45	100.0	0.0	0.00

Table 5.E.5a All rain and snowfall cases 1987 - 1993 in winter (October - April). Reference is Tretyakov gauge with wind shield in a Valdai Double Fence Intercomparison Reference (DFIR, last row in table), which is corrected with wetting loss. Gauges are provided with wind shield if otherwise not mentioned and they are corrected with gauge orifice area. The gauge number in the brackets is the same as in picture 5. N is a number of cases (12 hour period). Precipitation sum (mm and % of the reference) is measured both by weighing (x) and volumetrically (y) and wetting loss is calculated from with them: 100*(x-y)/x (%) and (x-y)/N (mm/case).

Gauge	N	Weighed values		Volum. values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	143	341.84	81.0	324.92	77.6	5.0	0.12
H&H-90 (22)	91	226.74	92.5	216.37	89.3	4.6	0.11
Tretyakov without wind shield (2)	253	546.11	76.1	511.07	71.2	6.4	0.14
Tretyakov (1)	253	648.87	90.4	610.23	85.0	6.0	0.15
Tretyakov (9)	253	628.20	87.5	594.64	82.9	5.3	0.13
Tretyakov (13)	253	646.40	90.1	610.33	85.0	5.6	0.14
Wild without wind shield (7)	253	520.05	72.5	499.94	69.7	3.9	0.08
Wild with a Nipher (14)	253	558.86	77.9	546.97	76.2	2.1	0.05
Canadian (20)	184	500.64	94.0	471.42	88.8	5.8	0.16
Danish Hellmann (15)	252	539.88	75.3	494.94	69.0	8.3	0.18
Hungarian Hellmann (6)	208	490.35	78.7	459.29	73.9	6.3	0.15
Norwegian standard (8)	245	568.15	81.8	536.57	77.3	5.6	0.13
Swedish standard (11)	253	625.67	87.2	609.87	85.0	2.5	0.06
Pit gauge (17)	40	124.89	100.2	120.16	96.2	3.8	0.12
DFIR (16)	253	717.81	100.0	690.63	96.2	3.8	0.11
corrected for wetting loss	253	717.81	100.0	717.70	100.0	0.0	0.00

Table 5.E.5b As in Table 5.E.5a but only the cases where reference measurement > 3.00 mm.

Gauge	N	Weighed values		Volum. values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	52	253.67	81.5	248.50	80.2	2.0	0.10
H&H-90 (22)	30	157.12	91.9	153.25	90.6	2.5	0.13
Tretyakov without wind shield (2)	84	394.73	76.7	383.61	74.6	2.8	0.13
Tretyakov (1)	84	467.83	91.0	454.41	88.3	2.9	0.16
Tretyakov (9)	84	452.01	87.9	441.45	85.8	2.3	0.13
Tretyakov (13)	84	465.71	90.5	454.68	88.4	2.4	0.13
Wild without wind shield (7)	84	371.63	72.2	363.28	70.6	2.2	0.10
Wild (14)	84	398.51	77.5	393.89	76.6	1.2	0.06
Canadian (20)	66	367.78	94.4	352.72	90.7	4.1	0.23
Danish Hellmann (15)	84	386.18	75.1	368.63	71.7	4.5	0.21
Hungarian Hellmann (6)	74	360.20	78.3	347.90	75.7	3.4	0.17
Norwegian standard (8)	81	411.09	82.4	401.39	80.4	2.4	0.12
Swedish standard (11)	84	448.37	87.2	443.86	86.3	1.0	0.05
Pit gauge (17)	15	97.06	98.8	94.28	96.3	2.9	0.19
DFIR (16)	84	514.41	100.0	507.26	98.6	1.4	0.09
corrected for wetting loss	84	514.41	100.0	514.40	100.0	0.0	0.00

***Table 5.E.6a** All rainfall cases 1987 - 1993 in summer (May - September). Reference is pit gauge, which is corrected with wetting loss (last row in table). Gauges are provided with wind shield if otherwise not mentioned and they are corrected with gauge orifice area. The gauge number in the brackets is the same as in picture 5. N is a number of cases (12 hour period). Precipitation sum (mm and % of the reference) is measured both by weighing (x) and volumetrically (y) and wetting loss is calculated from with them: 100*(x-y)/x (%) and (x-y)/N (mm/case).*

Gauge	N	Wighted values		Volum. values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	267	828.42	95.0	795.87	91.5	3.9	0.12
H&H-90 (22)	178	566.37	96.7	546.06	93.3	3.6	0.11
Tretyakov without wind shield (2)	344	1093.19	93.2	1045.12	89.0	4.4	0.14
Tretyakov (1)	344	1129.28	96.2	1080.53	92.1	4.3	0.14
Tretyakov (9)	344	1119.51	95.4	1076.22	91.7	3.9	0.13
Tretyakov (13)	344	1132.82	96.5	1082.83	92.3	4.4	0.15
Wild without wind shield (7)	344	1116.31	95.1	1093.61	93.2	2.0	0.07
Wild (14)	344	1131.65	96.4	1121.32	95.5	0.9	0.03
Canadian (20)	344	1141.67	97.3	1100.76	93.8	3.6	0.12
Danish Hellmann (15)	344	1117.64	95.2	1094.80	93.3	2.0	0.07
Hungarian Hellmann (6)	344	1138.38	97.0	1106.80	94.3	2.8	0.09
Norwegian standard (8)	344	1140.21	97.2	1109.05	94.5	2.7	0.09
Swedish standard (11)	344	1122.22	95.6	1098.68	93.6	2.1	0.07
DFIR (16)	344	1159.10	98.8	1119.89	95.4	3.4	0.11
Pit gauge (17)	344	1173.59	100.0	1144.14	97.5	2.5	0.09
corrected wetting loss	344	1173.59	100.0	1173.72	100.0	0.0	0.00

***Table 5.E.6b** As in Table 5.E.6a but only the cases where reference measurement > 3.00 mm.*

Gauge	N	Wighted values		Volum. values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	95	645.31	97.3	633.02	95.6	1.9	0.13
H&H-90 (22)	63	443.05	98.7	435.19	97.2	1.8	0.13
Tretyakov without wind shield (2)	126	875.74	96.1	858.65	94.3	2.0	0.14
Tretyakov (1)	126	900.87	98.9	883.68	97.0	1.9	0.14
Tretyakov (9)	126	891.40	97.9	874.44	96.0	1.9	0.14
Tretyakov (13)	126	903.09	99.2	884.90	97.2	2.0	0.14
Wild without wind shield (7)	126	876.64	96.2	867.09	95.2	1.1	0.08
Wild (14)	126	885.69	97.2	881.75	96.8	0.4	0.03
Canadian (20)	126	917.14	100.7	890.91	97.8	2.9	0.21
Danish Hellmann (15)	126	886.91	97.4	877.33	96.3	1.1	0.08
Hungarian Hellmann (6)	126	896.88	98.5	886.00	97.3	1.2	0.09
Norwegian standard (8)	126	892.97	98.0	881.13	96.7	1.3	0.09
Swedish standard (11)	126	890.28	97.7	881.20	96.7	1.0	0.07
DFIR (16)	126	915.44	100.5	901.25	99.0	1.6	0.11
Pit gauge (17)	126	910.86	100.0	896.87	98.5	1.5	0.11
corrected wetting loss	126	910.85	100.0	910.85	100.0	0.0	0.00

Table 5.E.7 All drizzlefall cases 1987 - 1993 in winter (October - April). Reference is Tretyakov gauge with wind shield in a Valdai Double Fence Intercomparison Reference (DFIR, last row in table), which is corrected with wetting loss. Gauges are provided with wind shield if otherwise not mentioned and they are corrected with gauge orifice area. The gauge numbers in the brackets is the same as in picture 5. N is a number of cases (12 hour period). Precipitation sum (mm and % of the reference) is measured both by weighing (x) and volumetrically (y) and wetting loss is calculated from with them: 100*(x-y)/x (%) and (x-y)/N (mm/case).

Gauge	N	Weighed values		Volum. Values		Wetting loss	
		(mm)	(%)	(mm)	(%)	(%)	(mm/case)
BT-60 (21)	14	10.67	70.2	9.11	60.3	14.7	0.11
H&H-90 (22)	7	10.20	91.7	9.57	87.0	6.1	0.09
Tretyakov without wind shield (2)	56	37.97	68.6	32.33	58.4	14.9	0.10
Tretyakov (1)	56	49.39	89.2	41.83	75.5	15.3	0.14
Tretyakov (9)	56	47.35	85.5	40.59	73.3	14.3	0.12
Tretyakov (13)	56	48.98	88.4	41.84	75.6	14.6	0.13
Wild without wind shield (7)	56	35.48	64.1	32.09	57.9	9.6	0.06
Wild (14)	56	40.59	73.3	38.22	69.0	5.8	0.04
Canadian (20)	26	19.41	89.7	17.48	81.0	10.0	0.07
Danish Hellmann (15)	56	38.27	69.1	30.82	55.6	19.5	0.13
Hungarian Hellmann (6)	40	32.28	73.5	27.04	62.3	16.2	0.13
Norwegian standard (8)	54	42.73	77.7	35.39	64.4	17.2	0.14
Swedish standard (11)	56	46.49	84.0	43.39	78.4	6.7	0.06
Pit gauge (17)	7	8.13	102.9	7.60	94.3	6.5	0.08
DFIR (16)	56	55.37	100.0	49.39	89.2	10.8	0.11
corrected for wetting loss	56	55.37	100.0	55.38	100.0	0.0	0.00

5. Undercatch of the Gauges

The correction for undercatch due to wind for the reference gauge (DFIR) was calculated using a equations of Golubev (WMO/CIMO 1992),

$$\frac{\mathrm{BUSH}}{\mathrm{FDIR}}(\%) = 100 \times \left[1 + 0.005 \times u_3^{\,2} \left(\frac{P_a}{1000} \times \frac{273}{273 + T_a} \times \frac{P_a}{P_a + 0.4 \times e_a} \right)^2 \right] \qquad (1)$$

where P_a is the stations atmospheric pressure, T_a is surface dry air temperature, e_a is water vapour pressure and u_3 is wind speed at 3 meters height.

Undercatch of the gauges was from about 8% (Tretyakov) in DFIR to about 62% (Wild without windshield) for snowfall (Table 5.E.5), for rainfall from 3 to 15 % (Table 5.E.6), for drizzle from 6 to 38 % (Table 5.E.7) and for rain and snow (mixed) from 4 to 31 % (Table 5.E.8).

Catch ratio vs wind speed at gauge height was also calculated for different gauges for 12-hour periods with more than 3.0 mm snowfall (Figures 5.E.3 to 5.E.9). For the gauges with windshield linear equations were calculated and for the gauges without windshield equations of second power were applied. As a reference weighed values of DFIR gauge corrected with the equation by Yang et al (1993) were used.

The equations can be applied only up to the wind speed measured. One must note that wind speed values in the Figures 5.E.3 to 5.E.9 are those which were get by using the simple equation:

$$u = 0.1\,R, \qquad (2)$$

where u = wind speed (m/s) and R = pulse rate frequency of anemometers.

Wind tunnel tests per ASTM standard method D 5096-90 (ASTM Designation) at the fairly large wind tunnel at The Technical Research Centre in Finland showed the transfer function:

$$u(R) = 0.4054 + 0.09853\,R, \qquad (3)$$

where u(R) = wind speed using the transfer function.

Equation (3) provides an accuracy of $\pm$ 0.17 m/s compared to $\pm$ 0.5 m/s using equation (2). The transfer function given by equation (3) is for the Vaisala wind sensor WAA 15A and can be applied to model WAA 15 as well. No wind directions were deleted in the catch ratio calculations because wind speed during snowfall cases was very homogenous over the field (Figure 5.E.11). According to the regression models only the wind speed is statistically important variable, not air temperature and air humidity (Table 5.E.8).

Table 5.E.8 Different regression models in snow event (DFIR>3.0 mm) for different gauges and variables. Model: CatchRatio = $\beta_0 + \beta_1 \cdot W + \beta_2 \cdot W^2 + \beta_3 \cdot T + \beta_4 \cdot U$ where W = wind speed at gauge hight, T = temperature and U = humidity at 2 meters and β_0, β_1, β_2, β_3 and β_4 are the unknown parameters or the estimated regression coefficients. Other symbols in table: N = number of cases, m = the number of independent variables used in each model and R-square = the square multiple correlation coefficient.

Gauge and N	m	β_0	β_1	β_2	β_3	β_4	R^2
Tretyakov	1	100.77	-9.2841				0.7661
with wind shield	2	101.16	-9.1893		0.25685		0.7697
(G1)	2	101.86	-9.3064			-0.01181	0.7661
N = 89	3	105.72	-9.2624		0.30935	-0.04884	0.7708
Tretyakov	1	101.11	-25.884	2.1196			0.7438
without wind shield	2	103.25	-25.428	2.1284	1.3821		0.7946
(G2)	2	95.063	-25.794	2.1254		0.006641	0.7449
N = 89	3	113.78	-25.543	2.1194	1.5043	-0.11366	0.7973
Hungarian gauge	1	111.56	-32.927	2.8261			0.6991
(Hellmann)	2	115.61	-32.388	2.8232	2.2186		0.7812
(G6)	2	93.692	-32.370	2.7928		0.19599	0.7052
N = 72	3	126.56	-32.685	2.8429	2.3667	-0.11703	0.7830
Wild	1	107.47	-33.522	2.8839			0.6575
	2	111.24	-32.533	2.8213	2.3676		0.7441
(G7)	2	89.736	-33.247	2.8907		0.19512	0.6627
N = 89	3	121.51	-32.639	2.8142	2.4898	-0.11094	0.7456
Norwegian	1	98.178	-11.267				0.7909
standard gauge	2	99.174	-11.133		0.5464		0.8012
(G8)	2	87.278	-11.071			0.1196	0.7953
N = 89	3	93.524	-11.050		0.4796	0.0606	0.8022
Tretyakov	1	100.49	-9.4217				0.7988
with wind shield	2	101.35	-9.3536		0.4172		0.8069
(G9)	2	93.462	-9.3048			0.0774	0.8013
N = 89	3	98.616	-9.3146		0.3843	0.0293	0.8072
The Swedish	1	99.808	-10.807				0.7953
standard gauge	2	100.77	-10.586		0.6347		0.8107
(G11)	2	88.887	-10.623			0.1203	0.8003
N = 89	3	96.051	-10.527		0.5790	0.0511	0.8115
Tretyakov	1	100.93	-9.2405				0.7621
with wind shield	2	101.51	-9.1035		0.3839		0.7695
(G13)	2	95.163	-9.1214			0.0627	0.7638
N = 88	3	99.627	-9.0729		0.3629	0.0201	0.7697
Wild gauge with	1	93.519	-12.681				0.8000
a Nipher wind shield	2	95.045	-12.443		0.8782		0.8213
(G14)	2	77.120	-12.379			0.1795	0.8080
N = 89	3	87.263	-12.328		0.7868	0.0835	0.8228
Hellmann gauge,	1	97.507	-23.041	1.7257			0.7423
Danish standard	2	99.305	-22.558	1.6799	1.0748		0.7742
(G15)	2	88.048	-22.833	1.7180		0.10336	0.7449
N = 89	3	102.65	-22.613	1.6809	1.1149	-0.03582	0.7745
DFIR: Tretyakov	1	99.894	-1.7619				0.9994
in a Valdai fence	2	99.952	-1.7630			-0.00063	0.9994
(G16)	2	99.892	-1.7626		-0.00169		0.9994
N = 89	3	99.938	-1.7632		-0.00117	-0.00049	0.9994
Canadian gauge with	1	100.67	-6.8300				0.6685
a Nipher wind shield	2	97.012	-6.7670			0.0415	0.6698
(G20)	2	100.55	-6.8641		-0.0877		0.6691
N = 64	3	94.902	-6.8007		-0.1693	0.0627	0.6716
H&H-90	1	99.356	-8.4938				0.6362
with wind shield	2	101.14	-8.0107		1.4988		0.7023
(G22)	2	122.39	-8.6369			-0.2573	0.6426
N = 33	3	139.84	-8.2027		1.6461	-0.4305	0.7194

6. Precipitation Intensity

Precipitation intensity could be measured in Finland for the first time with a GEONOR gauges at Jokioinen from 1989 to 1993. From 20808 ten minutes cases during semi-daily snowfall some 64% were classified into the intensity class of 0.00 mm/10 min. From 7533 cases with greater intensity 50% were smaller than 0.035 and 90% smaller than 0.16 mm/10 min. (Figure 5.E.10). The greatest recorded intensity was 1.42 mm/10 min. (Aaltonen et al. 1993). Values were corrected for wind speed using Golubev's equation.

7. Results of the application of heated gauges

The heated gauges tested at Jokioinen were the Friedrich (4), Rain-o-matic-H (19) and RIMCO (19). Figures 5.E.12 and 5.E.13 show the great scatter in the one to one precipitation amounts for theses gauges against the DFIR. Figures 5.E.14 and 5.E.15 show the catch ratio versus wind speed relationships also with large scatter and relatively poor correlation. Some of the problems noted with these gauges were the blockage of their orifice several times during rainy conditions and the heating was many times insufficient in snow cases. The Rain-o-matic-H and RIMCO also showed more precipitation than the DFIR for rain because of some electrical circuit problems.

8. Closing Remarks

The wind speed range at Jokioinen was rather small. A more careful analysis of wetting corrections and the influence of temperature and wind speed on aerodynamic corrections of snowfall is needed.

A globally competent correction formula presumes also air pressure consideration. A global treatise perhaps also requires information on distribution of crystal structures during precipitation.

When implementing operational corrections the question of representativeness of gauges and their surroundings is to be addressed. It has also influence on the question of choosing the reference gauge, because the representativeness of the Valdai bush gauge as the intercomparison reference is not fully considered.

A more comprehensive national final report is under preparation. Measurements on the experimental field are still going on with a special attention to old precipitation gauges used in Finland (from 1749 …) and in Sweden.

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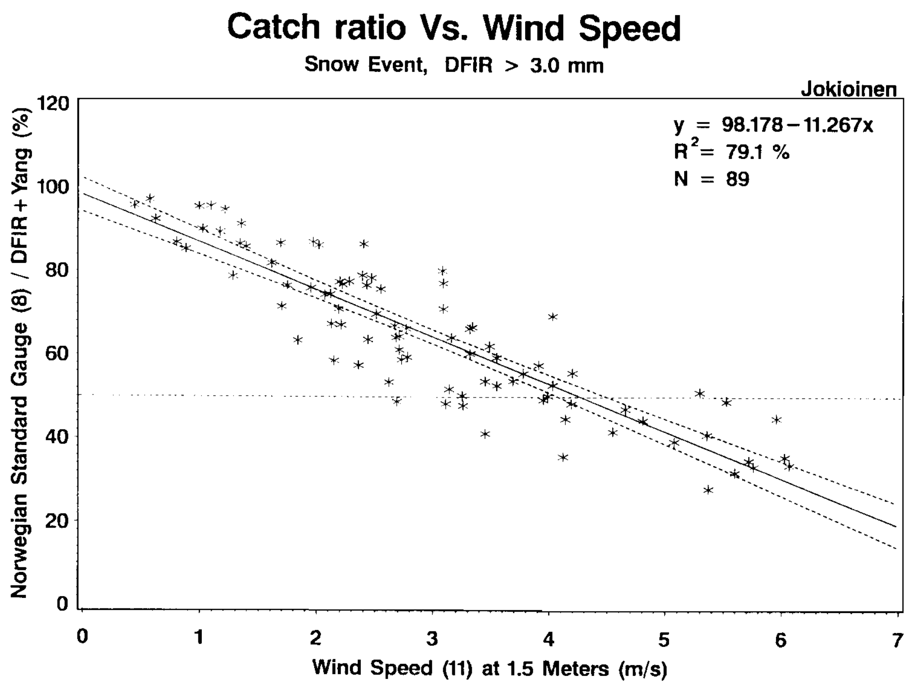


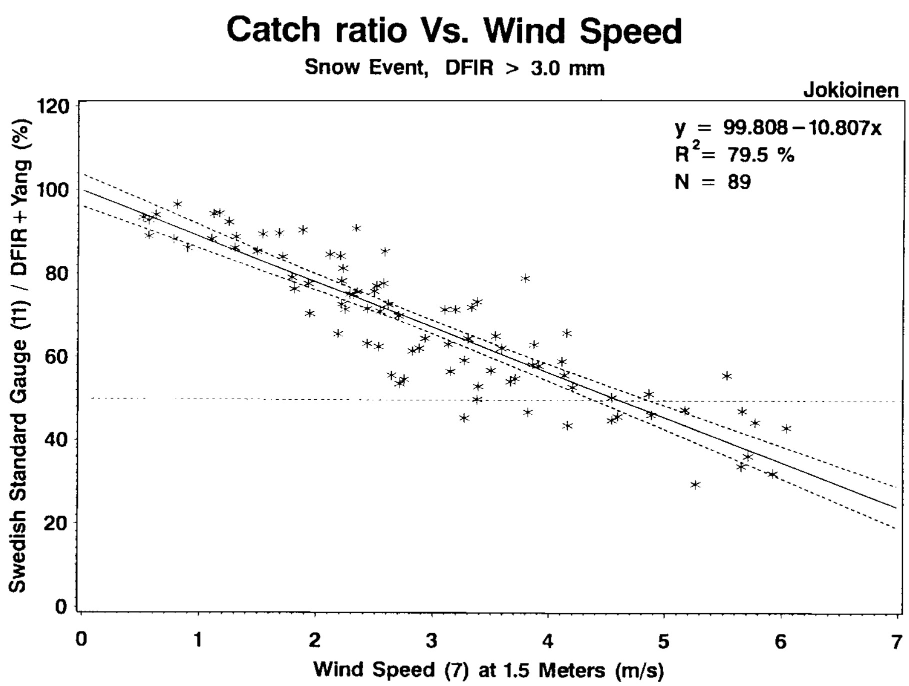
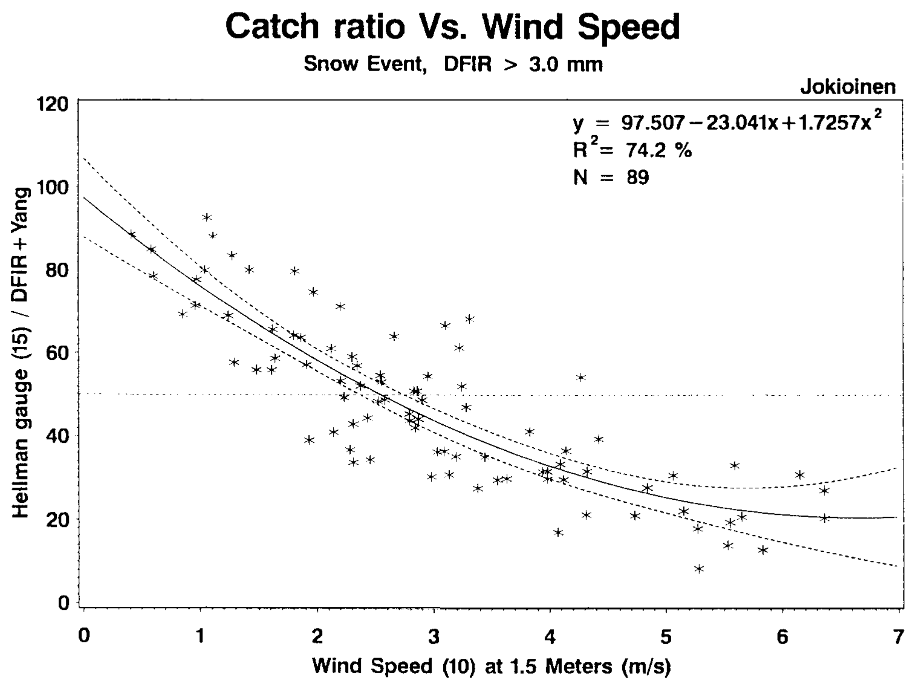


Figure 5.E.3 Catch ratio vs wind speed a gauge height for Norwegian standard gauge (8) and Swedish standard gauge (11) over DFIR corrected using Yang et al, 1993



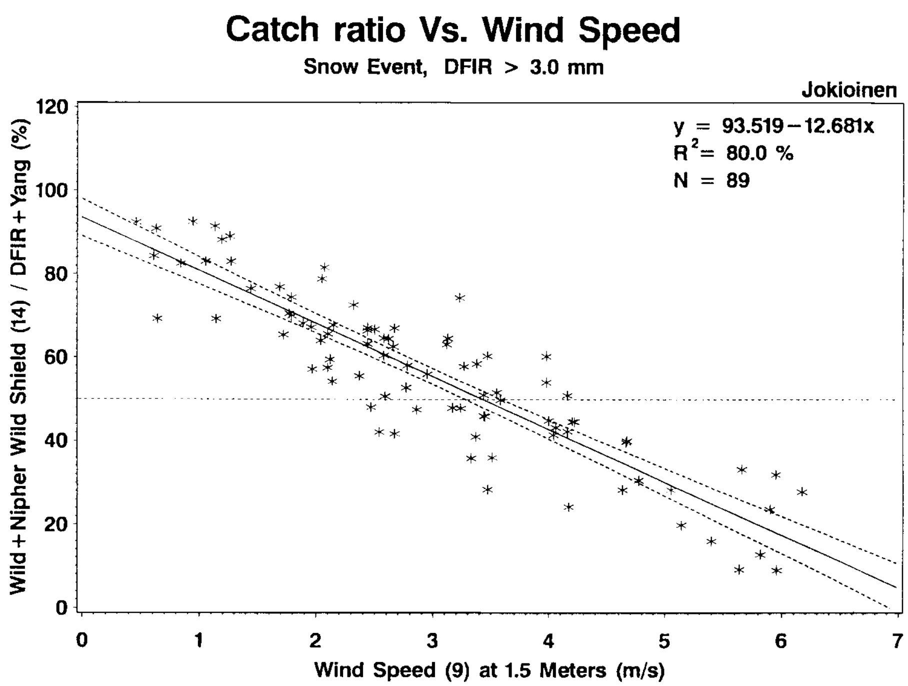
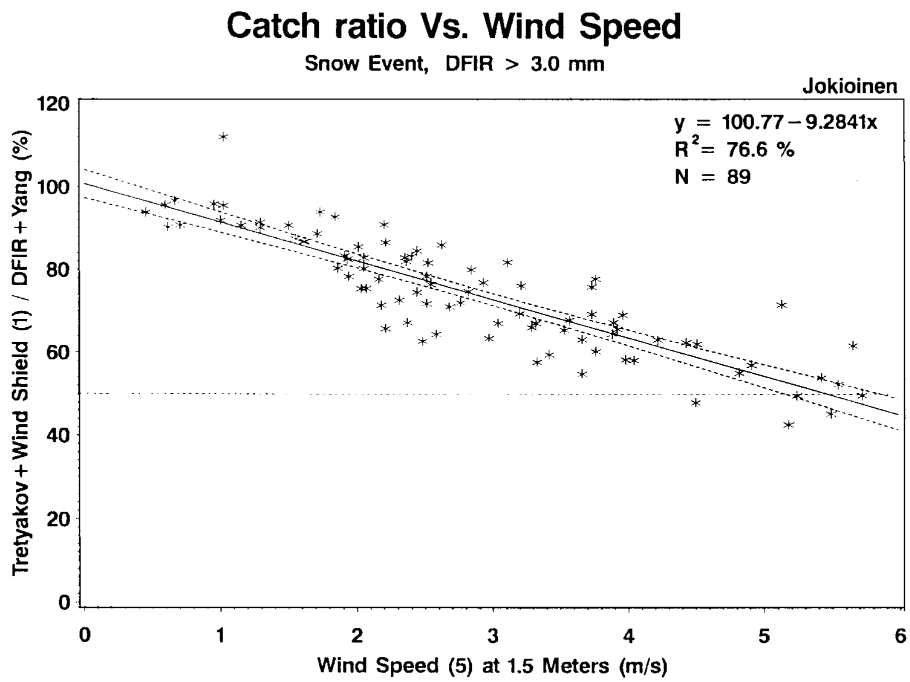


Figure 5.E.4 Catch ratio vs wind speed a gauge height for Hellmannn gauge (15) and Wild + Nipher Wild shield (14) over DFIR corrected using Yang et al, 1993



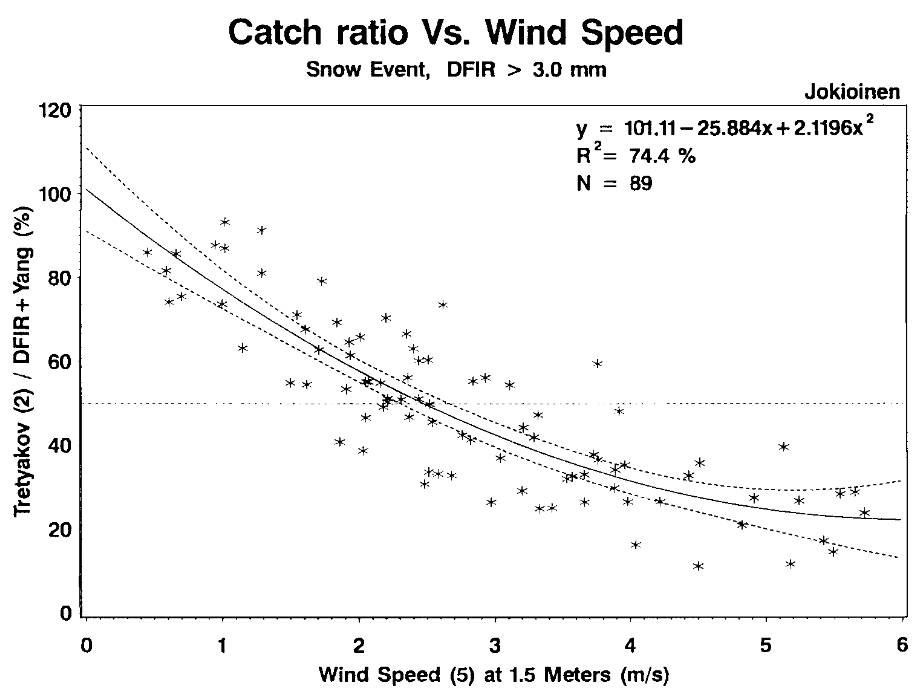


Figure 5.E.5 Catch ratio vs wind speed a gauge height for Tretyakov + wind shield (1) and Tretyakov gauge (2) over DFIR corrected using Yang et al, 1993

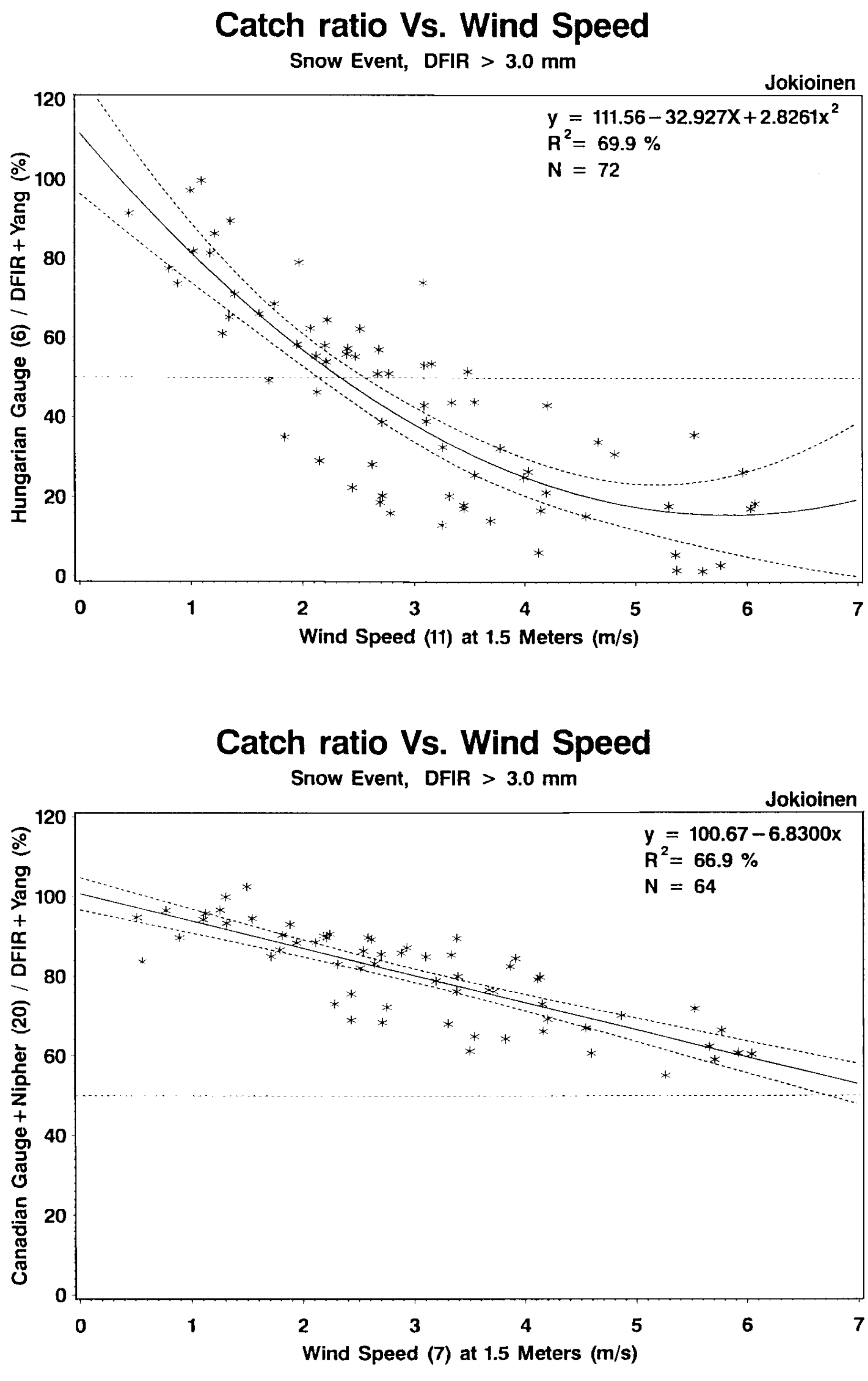
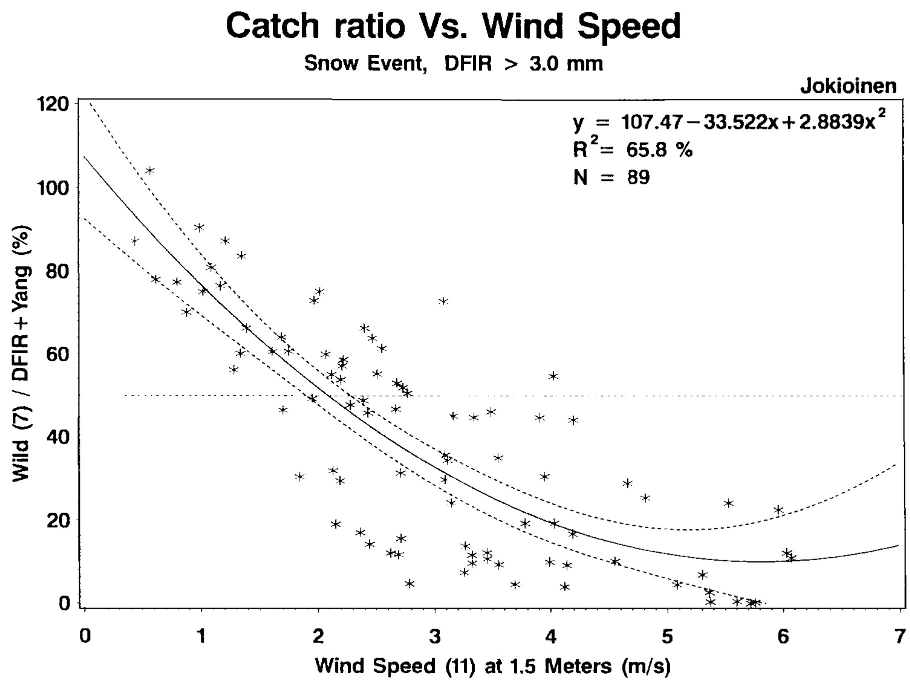


Figure 5.E.6 Catch ratio vs wind speed a gauge height for Hungarian gauge (6) and Canadian gauge + Nipher shield (20) over DFIR corrected using Yang et al, 1993



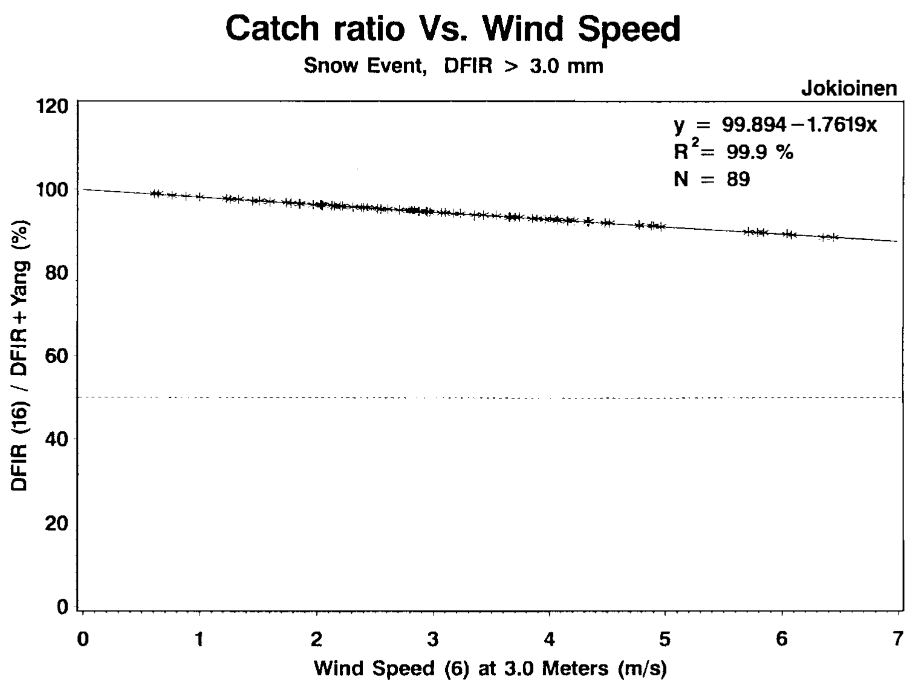
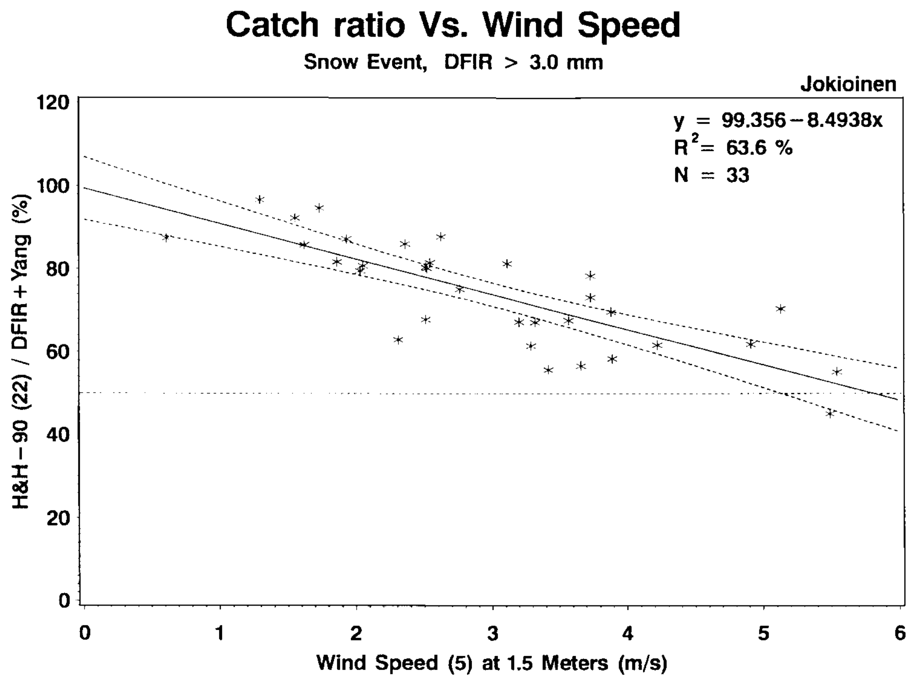


Figure 5.E.7 Catch ratio vs wind speed a gauge height for Wild gauge (7) and DFIR (16) over DFIR corrected using Yang et al, 1993



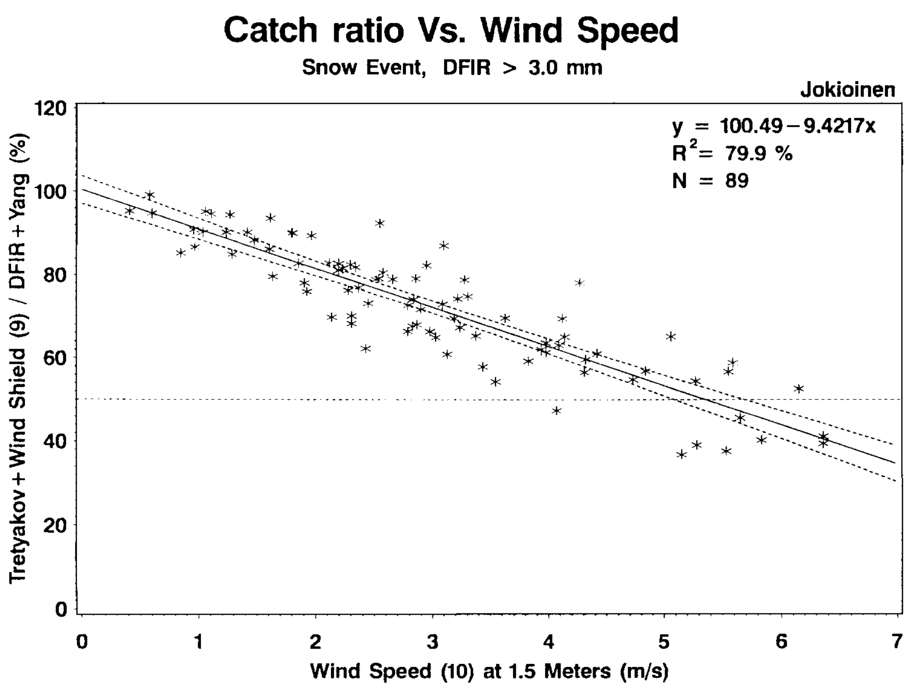


Figure 5.E.8 Catch ratio vs wind speed a gauge height for H&H-90 gauge (22) and Tretyakov + wind shield (9) over DFIR corrected using Yang et al, 1993

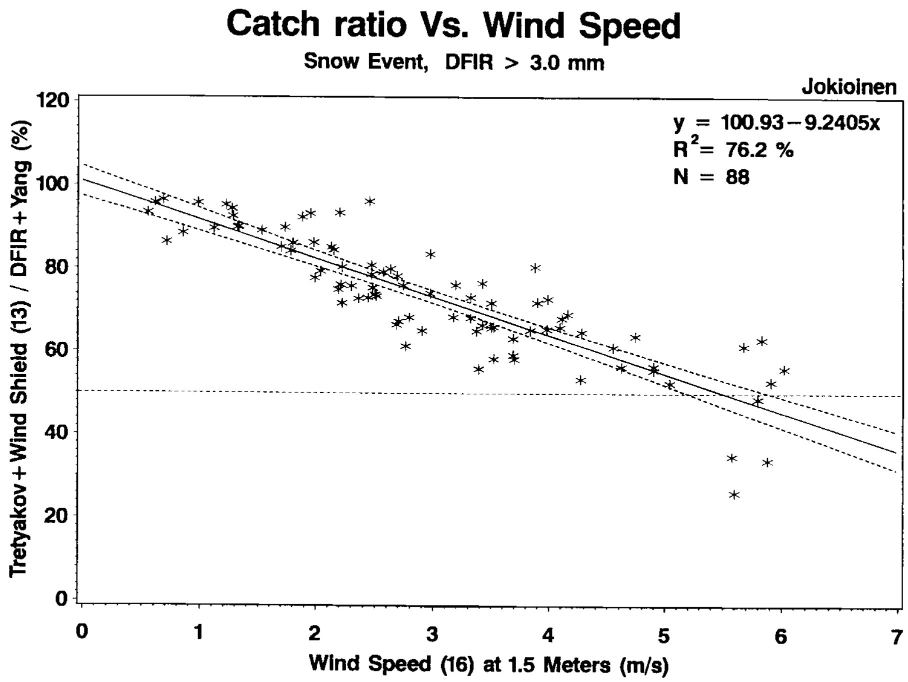


Figure 5.E.9 Catch ratio vs wind speed a gauge height for Tretyakov + wind shield (13) over DFIR corrected using Yang et al, 1993

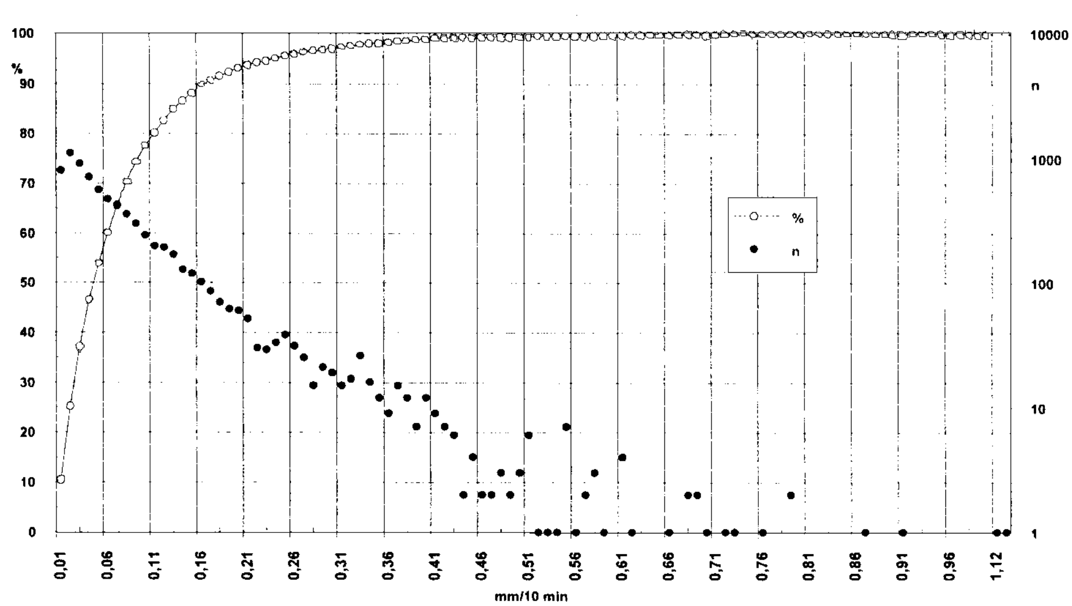


Figure 5.E.10 Number of observations in snowfall intensity classes (n) and cumulative frequency of the same classes (%)

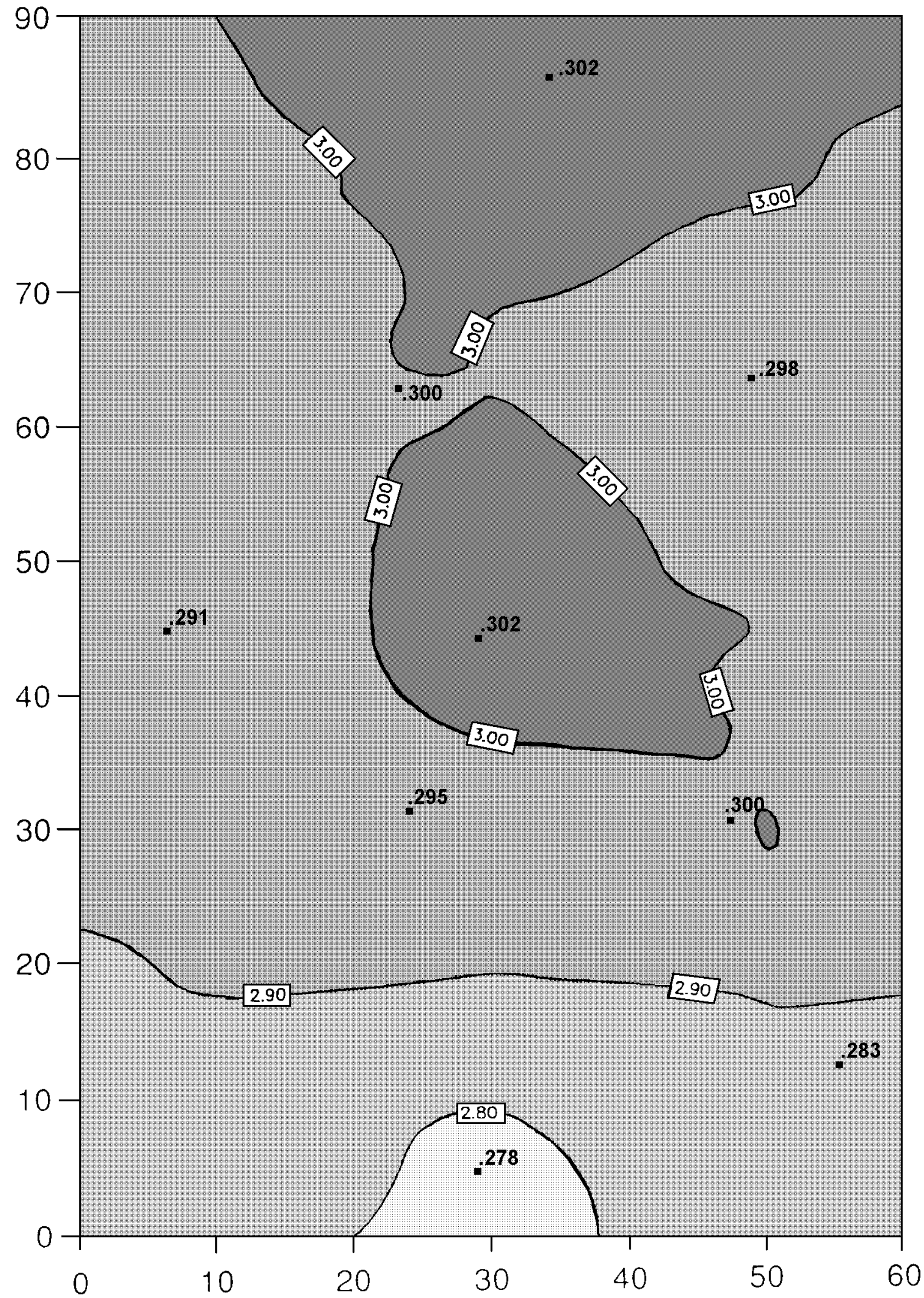
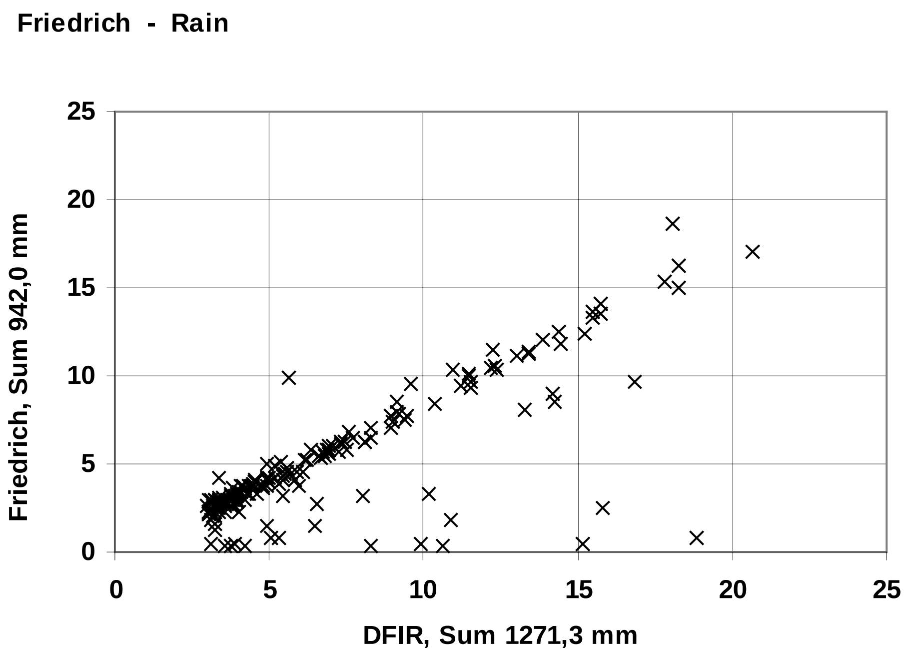


Figure 5.E.11 Wind speed during snowfall cases (> 3.0mm/12 hours) over the intercomparison field at 1.5 m height.



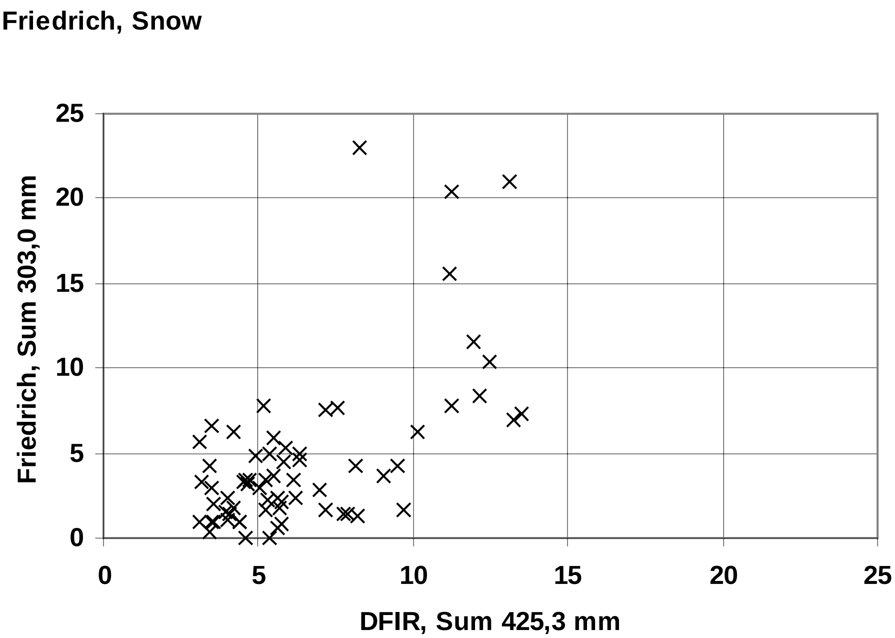


Figure 5.E.12   One to one rain and snow amounts of Friedrich gauge versus DFIR

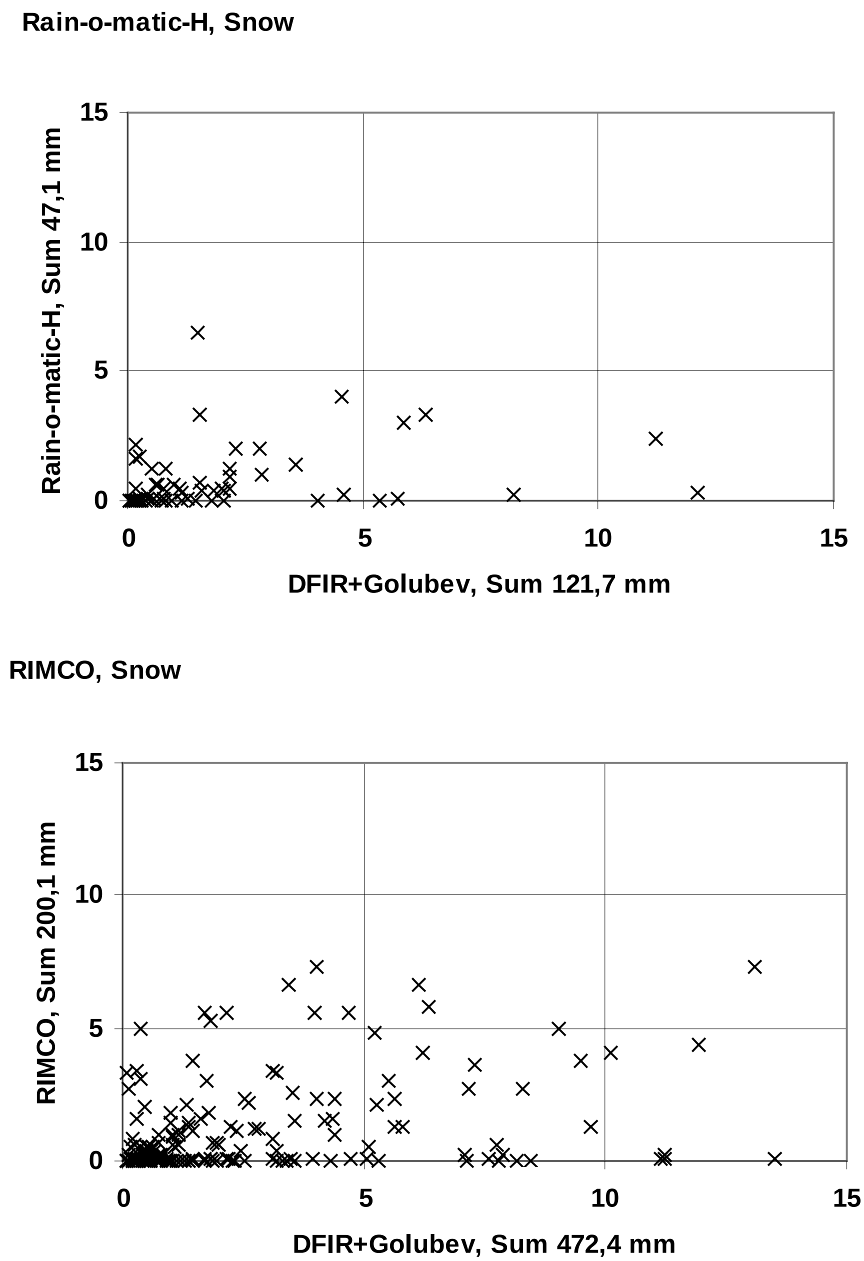
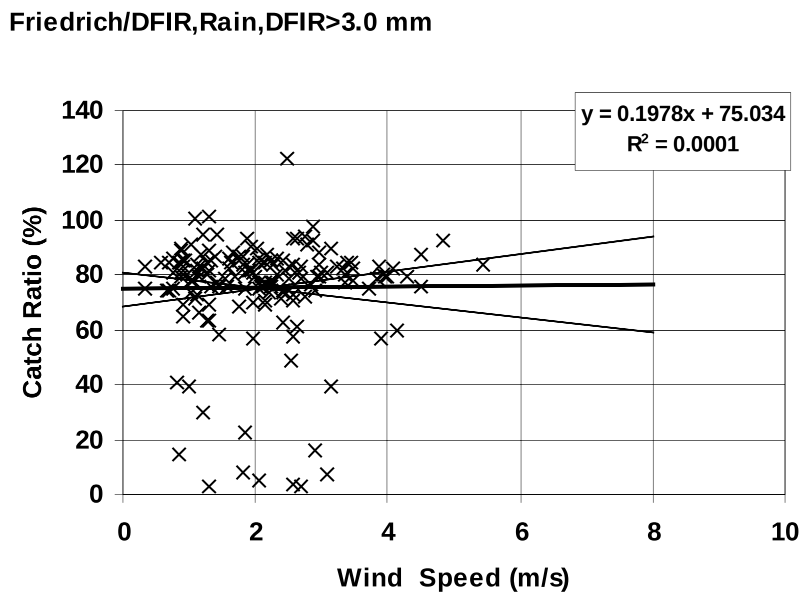


Figure 5.E.13 One to one snow amounts of Rain-o-matic-H and RIMCO gauges versus DFIR



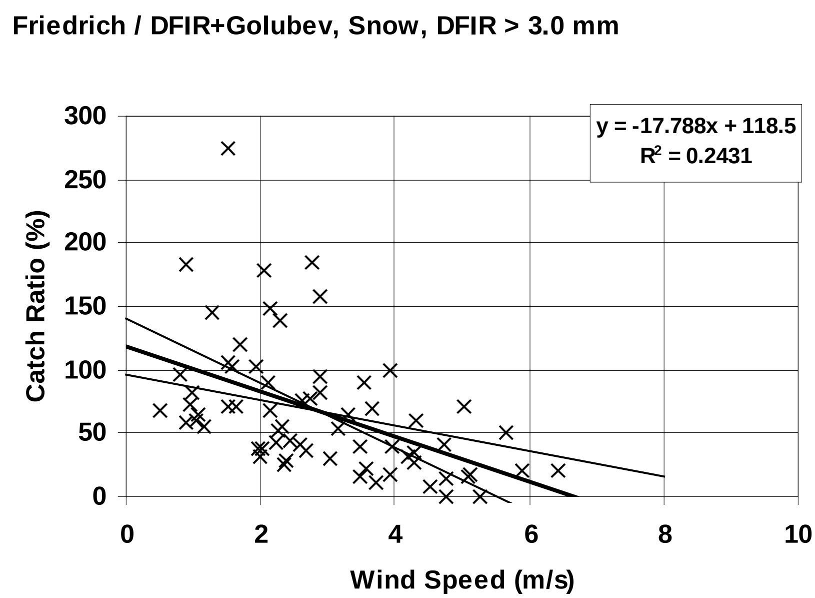
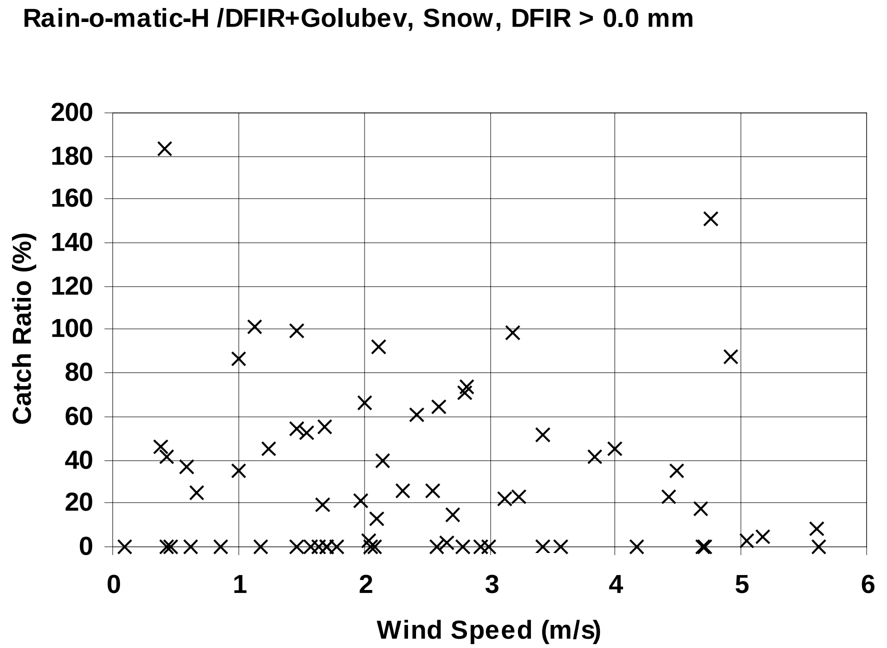


Figure 5.E.14 Catch ratio versus wind speed for Friedrich gauge



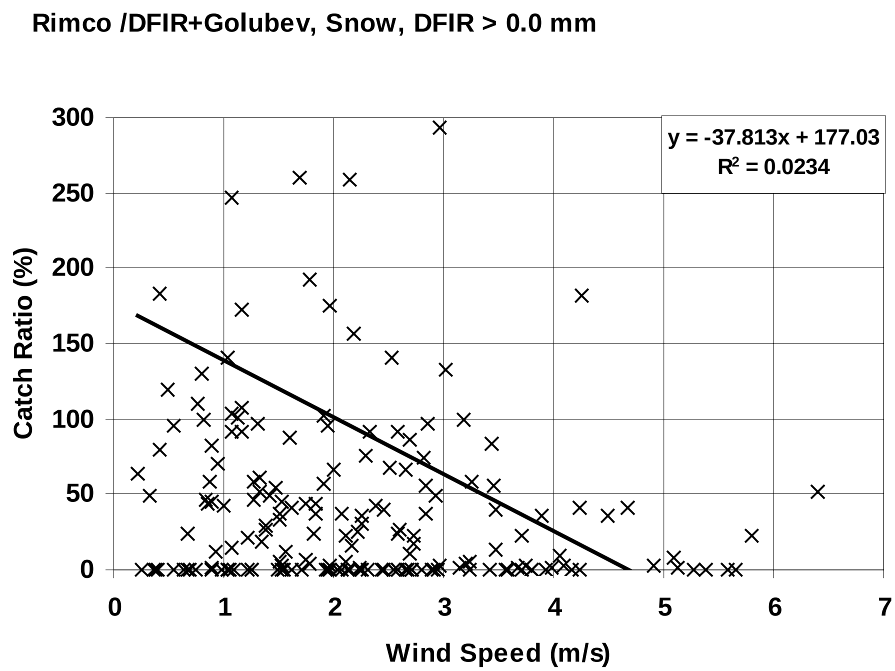


Figure 5.E.15   Catch ratio versus wind speed for Rain-o-matic-H and RIMCO gauges

ANNEX 5.F GERMANY

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GERMAN ANALYSIS AND RESULTS

1. INTRODUCTION

This chapter presents results of the statistical analysis on the basis of the seven year data set of the Evaluation Station Harzgerode/Germany (cf. Annex 3.E). This data set allowed a detailed investigation of the comparison of gauge catch ratio, especially the Hellmannn unshielded gauge (German National Standard), to the DFIR. As Hellmannn shaped gauges are used in several national services, the significant results presented here provide an idea of possible correction precedures and the magnitude of the necessary corrections to be taken into consideration in the services/countries concerned.

2. DATA BASIS

The intercomparison measurements at the Evaluation Station Harzgerode (51^{o}39'N, 11^{o}08'E) were started on 1 December 1986 with 12 different types of precipitation gauges. The following gauges have been included in this analysis (cf. Annex 3.E): Hellmannn, unshielded; Hellmannn, shielded; Automatic gauge, unshielded (volumetric, heated); Tretyakov, shielded; Gauge with 500 cm^2-orifice area, unshielded; Double Fence Intercomparison Reference (DFIR).

The German national standard precipitation gauge is a Hellmannn gauge without wind shield. Its orifice area is 200 cm^2 and the height of its exposure is 1 m above ground.

The following automatic and supporting observations have been carried out: hourly automatic recordings of precipitation, wind direction, profiles of wind speed on the comparison field on a fixed mast, air temperature and dew point. Additional data, e.g. on type of precipitation (S = Snow only, SR = Snow with rain, RS = rain with snow, R = rain), snow fall intensity, depth of fresh snow, water equivalent of fresh snow cover, are also included in the observation programme. The total data record comprises 532 days with precipitation in the winter seasons 1986 to 1993. In order to characterize the precipitation conditions during the period under review, the proportion (%) of the type of precipitation (S, SR, RS, R) and the various classes of depth of precipitation (S), as well as the precipitation totals (S) an the number of cases (S) in various classes of depth of precipitation, are shown in Figure 5.F.1.

3. WIND FIELD ANALYSIS AND CASE STUDIES OF SNOWFALLS

The assumption that the octagonal vertical double fence installed around the Tretyakov precipitation gauge should substantially reduce the wind was decisive for this method to be selected as the standard reference for snowfall intercomparisons. For the assessment and confirmation of this assumption the wind speeds at the exposure level of the reference precipitation gauge (3 m above ground) within the inner fence were compared with those outside the fence on the comparison field.

The measurements were made using a portable anemometer (Figure 5.F.2a) only on days without precipitation, in order to avoid any additional influence upon the precipitation measurement by the anemometer system.

The results of the wind measurements show that with higher wind speeds ($v \geq 5\ ms^{-1}$) the double fence shield reduces the wind speed by 65 to 75 per cent at the gauge height (Figure 5.F.3). A frequency analysis of more than 2300 measurements averaged over all wind speed classes and all wind directions, shows that the ratio (wind speed DFIR, point B/wind speed on the comparison field) nevertheless is still in 60 percent of all wind measurements a value of Q < 0,5, in 87 per cent Q < 0,6. This is sufficient evidence of the wind reducing effect of the double fence shield and at the same time showing its suitability as a reference instrument.

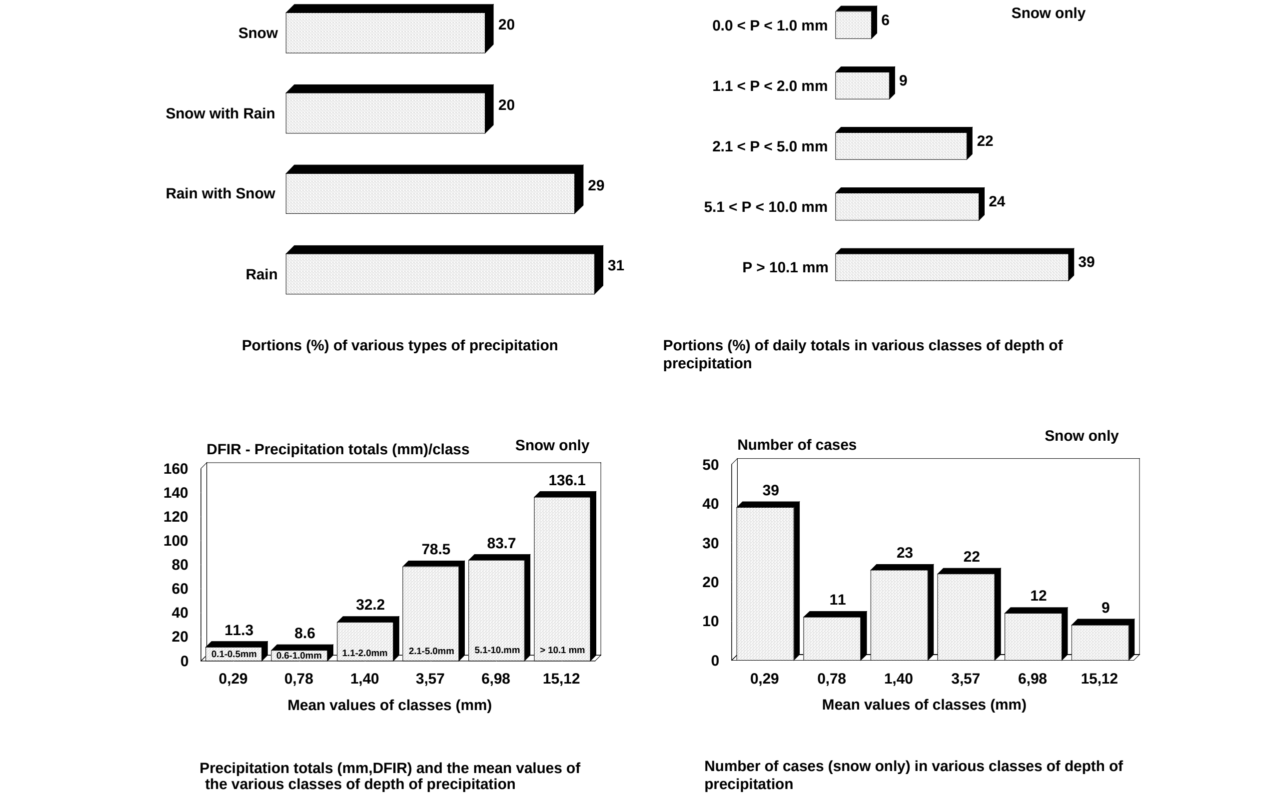

Figure 5.F.1 WMO Solid Precipitation Measurement Intercomparison; Evaluation Station Hargerode/Germany; Data basis, December-March, 1986-1993.

Interesting details as to the wind losses of different methods of solid precipitation measurements are already obtained from some selected case studies of snowfalls. In Figures 6.X.2c and 6.X.2d the results of five different types of precipitation gauges are compared with the DFIR for four event days. According to the prevailing wind conditions, the type of precipitation, the duration and depth of precipitation, we obtain rather varied results. With more or less identical precipitation depth, i.e. 24,0 mm and 23,9 mm measured in the DFIR, on 25 February 1988 with high wind speeds great differences were observed as compared with the DFIR and between the gauge types; whereas on 1 January 1987 with rather weak wind during snowfall the differences were only small (Figure 5.F.4). Two further instances are presented in Figure 5.F.5: extremely high catch differences during a prolonged snowfall event of low intensity with medium wind speed and low air temperature on 12 January 1987 - and very small catch differences on 19 March 1987 during showery snowfalls and very low wind speeds. Even these few selected examples reveal the complex nature of the problem of developing a correction procedure to be applied to daily solid precipitation measurements.

4. FINAL RESULTS OF THE COMPARISONS AND DISCUSSION

Günther and Richter (1986) reported on some previous results of investigations on the systematic errors in precipitation measurements made with the Hellmann gauge. Summarizing all types of precipitation (rain, snow with rain, snow) the wind effect produces an average annual loss of 13 per cent at wind exposed stations, and 7 per cent or 6 per cent at normal or sheltered stations. The average wind caused losses of snow precipitation are rather great, i.e. 90 per cent at exposed sites. At normal and sheltered sites the value was much smaller, i.e. 30 per cent and 25 per cent respectively. These results are, however, not yet reliable.

Observations and measurements made at the intercomparison site Harzgerode during the winter seasons 1986-1993 provide the basis for a more detailed analysis of gauge catch ratios measured by different gauge types in dependence on wind speed and taking into account type of precipitation, air temperature, depth, duration and intensity of precipitation.

In the first approach the total gauge catch of five different gauge types was obtained by adding all daily totals using the DFIR as a reference. The results are contained in Figure 5.F.6 and show for snow only precipitation, that the National standard, the unshielded Hellmann gauge, caught only 47 % of DFIR, the Automatic gauge (Hellmann shaped, heated, volumetric measurement) caught 42 % and the Tretyakov gauge caught 61 % of the DFIR.

The analysis of the catch percentage separated for various classes of daily precipitation depth reveals the results shown in Table 5.F.1.

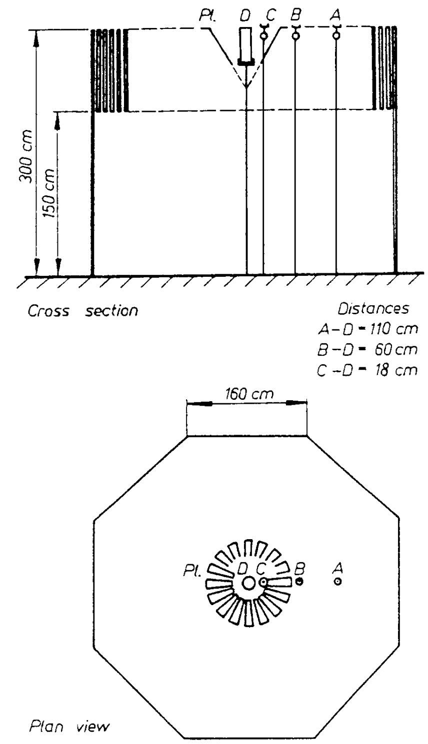

Figure 5.F.2 Wind speed measurements within the DFIR/Inner-fence; A, B, C, D: Anemometer stands (portable); PL: Tretyakov protection plates

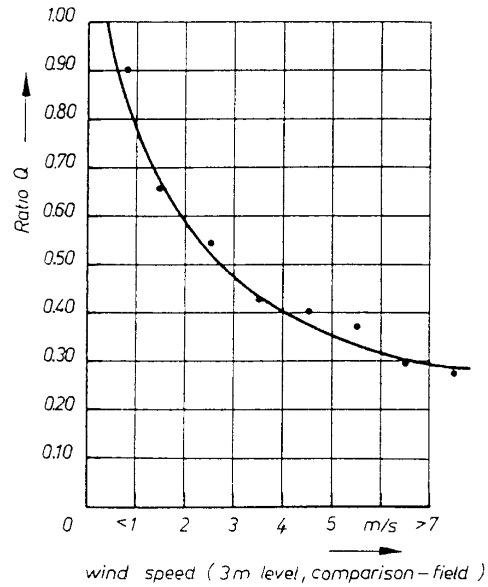

Figure 5.F.3 Ratio Q in dependence on the mean wind speed in the 3 m level

Q = wind speed/DFIR - Inner fence / wind speed/comparison field

$$Q = \frac{\text{wind speed/DFIR - Inner fence}}{\text{wind speed/comparison field}}$$

There are no essential differentiations among the classes of higher precipitation (P $\geq$ 2,1 mm). The systematic losses of the Hellmann unsh. gauge is smaller for the classes of lower precipitation. Contrary to that there are significant higher losses with the Automatic gauge for the "low precipitation classes". The reason for that may be the increased evaporation losses caused by heating (cf. Figure 5.F.7).

Table 5.F.1 Daily totals

	Hellmann, unsh.:		**Automatic gauge,vol.:**	
	P $\leq$ 1,0 mm	**P $\geq$ 1,1 mm**	**P $\leq$ 1,0 mm**	**P $\geq$ 1,1 mm**
Snow only	60...78 %	44...53 %	27...30 %	38...48 %
Mixed precip	64...99 %	68...77 %	52...61 %	64...76 %

According to the actually observed wind, the daily precipitation totals measured by the DFIR in mm and the catch percentage of the comparison gauge were further classified into six groups (i.e. 1 m/s steps) and averaged. Table 5.F.2 contains these results for different types of precipitation. There are remarkable differences between the DFIR and the unshielded Hellmann and the Automatic gauge respectively.

The catch percentage of the Hellmann unsh. gauge differs in dependence on wind speed in the case of "snow only precipitation" between 22 % (V1 $\geq$ 5 ms^{-1}) and 68 % (V1 = 1,1 to 2,0 ms^{-1}). The high losses of the Automatic gauge in the case of small wind speeds are probably caused by the heating of the collecting funnel (cf. Table 5.F.2, Figure 5.F.8).

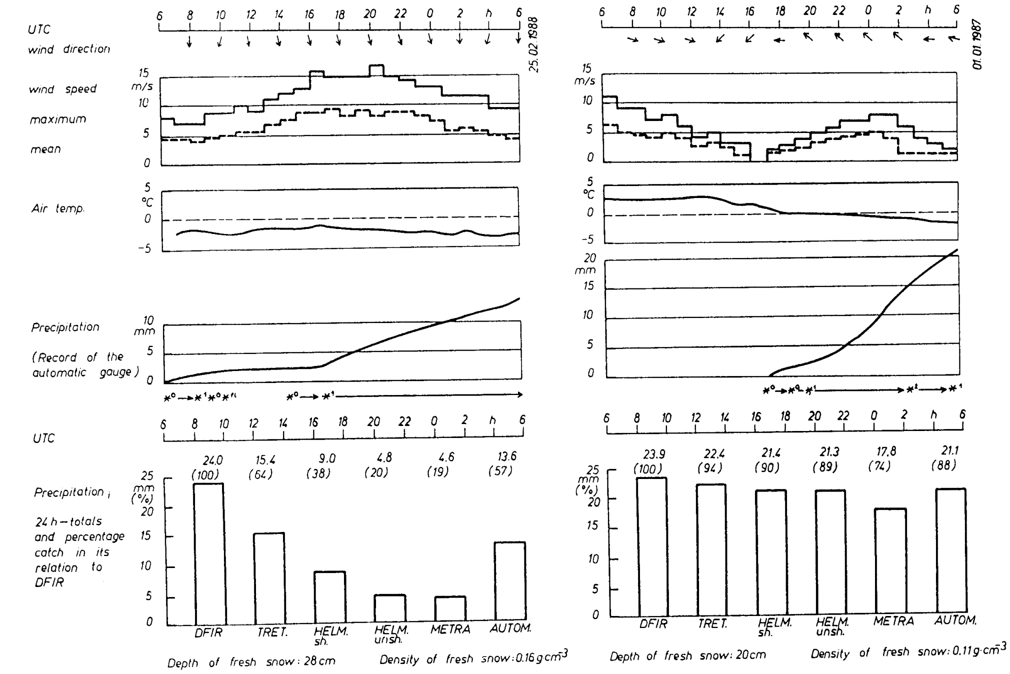

Figure 5.F.4 Case studies of snowfall events (01.01.87; 25.02.88). Gauge catch of five different gauge types compared to DFIR

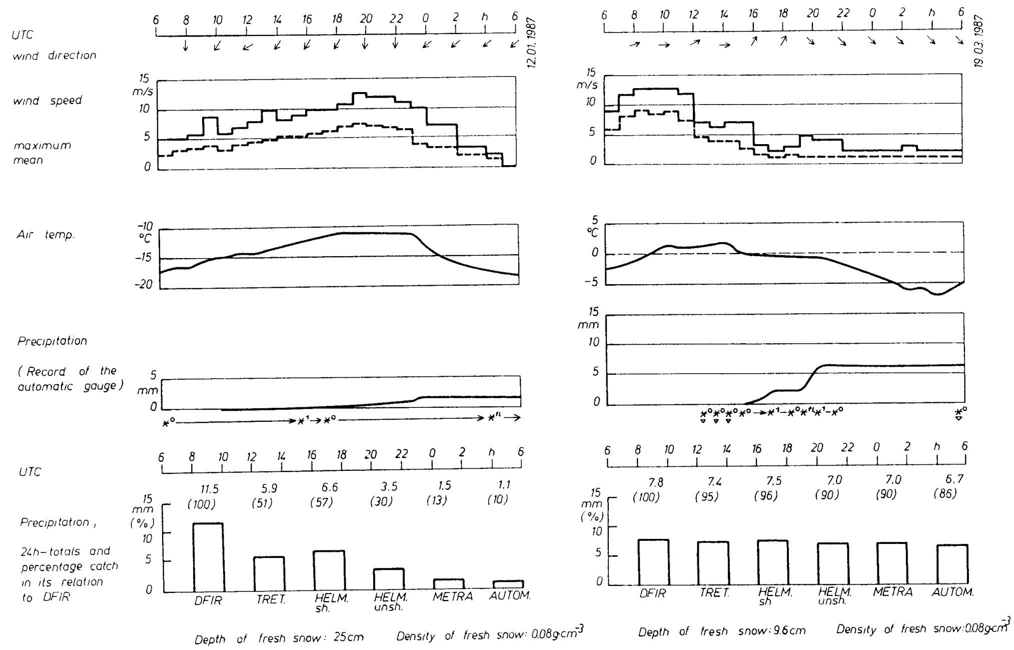

Figure 5.F.5 Case studies of snowfall events (11.01.87; 19.03.87). Gauge catch of five different gauge types compared to DFIR

Table 5.F.2 Catch percentage of the comparison gauges dependent on wind speed (1m level) and type of winter precipitation(included cases: Daily totals DFIR ≥ 3.0 mm)

Type of precipitation : Snow

Wind Speed (m/s)	No. of Cases	Mean Wind Speed (m/s)	DFIR Total (mm)	TRET/ DFIR (%)	HELLM Unsh/ DFIR (%)	HELLM Sh/DFIR (%)	Autom Gauge/ DFIR (%)	500cm²/ DFIR (%)
0.0-1.0	0							
1.1-2.0	7	1.5	54.0	86.1	67.6	86.9	59.3	60.4
2.1-3.0	6	2.6	59.9	71.3	56.1	69.6	55.3	50.6
3.1-4.0	12	3.6	70.1	49.2	41.7	61.9	34.0	32.8
4.1-5.0	8	4.5	79.0	49.6	25.8	43.2	35.2	21.5
5.1-20.0	3	5.8	16.4	32.9	22.0	45.1	23.2	17.7
0.0-20.0	36	3.4	279.4	60.2	44.1	62.1	43.1	37.9

Type of precipitation : Snow with rain

Wind Speed (m/s)	No. of Cases	Mean Wind Speed (m/s)	DFIR Total (mm)	TRET/ DFIR (%)	HELLM Unsh/ DFIR (%)	HELLM Sh/DFIR (%)	Autom Gauge/ DFIR (%)	500cm²/ DFIR (%)
0.0-1.0	1	.9	9.2	68.5	63.0	84.8	50.0	44.6
1.1-2.0	8	1.7	77.5	84.9	79.5	87.7	73.0	70.2
2.1-3.0	8	2.5	39.2	76.0	68.9	82.9	56.9	54.3
3.1-4.0	8	3.5	61.8	62.1	56.8	66.7	53.9	45.1
4.1-5.0	9	4.7	63.0	51.6	45.9	61.0	46.0	35.9
5.1-20.0	7	5.9	48.2	56.0	49.8	62.0	49.0	38.4
0.0-20.0	41	3.6	298.9	66.8	61.0	72.9	56.7	49.8

Type of precipitation : Rain with snow

	No. of Cases	Mean Wind Speed (m/s)	DFIR Total (mm)	TRET/ DFIR (%)	HELLM Unsh/ DFIR (%)	HELLM Sh/ DFIR (%)	Autom Gauge/ DFIR (%)	500cm²/ DFIR (%)
0.0-1.0	0							
1.1-2.0	5	1.6	27.9	90.7	84.6	90.7	74.6	78.9
2.1-3.0	8	2.6	44.1	86.6	84.8	89.3	79.1	77.1
3.1-4.0	19	3.6	141.3	82.7	81.5	84.3	79.1	75.6
4.1-5.0	14	4.5	106.7	82.9	85.5	86.9	84.3	75.3
5.1-20.0	11	6.0	119.8	83.1	79.1	85.6	80.5	70.5
0.0-20.0	57	4.0	439.8	83.8	82.3	86.2	80.5	74.5

Type of precipitation : Rain

Wind Speed (m/s)	No. of Cases	Mean Wind Speed (m/s	DFIR Total (mm)	TRET/ DFIR (%)	HELLM Unsh/ DFIR (%)	HELLM Sh/DFIR (%)	Autom Gauge/ DFIR (%)	500cm²/ DFIR (%)
0.0-1.0	0							
1.1-2.0	5	1.5	24.4	92.2	94.3	95.1	91.4	90.6
2.1-3.0	9	2.6	51.5	91.3	91.3	93.2	90.9	86.0
3.1-4.0	9	3.6	74.8	90.5	89.6	91.6	88.2	86.0
4.1-5.0	11	4.5	86.1	88.2	85.8	89.4	88.3	82.0
5.1-20.0	16	5.5	132.9	82.5	86.6	88.3	91.6	79.3
0.0-20.0	50	4.0	369.7	87.3	88.2	90.3	90.0	83.0

The results of a comparison of the daily values measured in the reference gauge (DFIR) and the standard Hellmann precipitation gauge stratified for the four types of precipitation S, SR, RS and R and five wind classes are portrayed in Figure 5.F.9. There is a clear contrast between the large wind losses for the precipitation types S and SR and the comparably lesser losses for the precipitation types RS and R (small differences in the ascent of the straight lines for the five classes of wind speed).

The final step was to determine the catch ratios for the comparison gauges as a function of relevant influential factors. The following catch ratios were included into the regression analysis:

Y1: HELLMANN, unsh./DFIR
Y2: HELLMANN, sh./DFIR
Y3: AFMS 2/DFIR
Y4: TRETYAKOV/DFIR

in relation to:

V1:	Wind speed (1 m level = gauge height)
T:	Air temperatur (2 m)
P:	Depth of precipitation
D:	Duration of precipitation
I:	Intensity of precipitation

for the types of precipitation SNOW ONLY (S), MIXED PRECIPITATION (SR, RS) and RAIN (R).

Starting with simple linear regressions multiple linear and non-linear regressions were finally calculated including two or three of the above listed variables (V1, T, P, D, I). From the total of more than 600 regression equations only those equations were listed in Tables 5.F.3 and 5.F.4 which have in each case the highest correlation coefficient r^2. Generally the multiple linear regression (three variables) yields the best results. The most important factor of influence is the mean wind speed (V1) which forms the decisive contribution to the correlation coefficient (r^2).

Table 5.F.3 Results of the regression analysis - SNOW ONLY

Totals per day (DFIR $\geq$ 2,0 mm); n = 43

Y1:	HELLMANN unsh. / DFIR	Y3:	AFMS2 / DFIR
Y2:	HELLMANN sh. / DFIR	Y4:	TRETYAKOV / DFIR
V1:	wind speed (1 m - level);		
P:	precipitation depth;	D:	precipitation duration;
T:	air temperature;	I:	intensity of precipitation

Y1 = -0,148 V1 + 0,024 T + 1,038	r^2 = 0,59
Y2 = -0,134 V1 + 0,019 T + 1,168	r^2 = 0,61
Y3 = -0,118 V1 + 0,028 T + 0,893	r^2 = 0,42
Y4 = -0,138 V1 + 0,015 T + 1,105	r^2 = 0,55
Y1 = -0,140 V1 + 0,018 T - 0,012 D + 1,159	r^2 = 0,66
Y2 = -0,131 V1 + 0,018 T - 0,007 P + 1,200	r^2 = 0,65
Y3 = -0,111 V1 + 0,026 T + 0,266 I + 0,732	r^2 = 0,59
Y4 = -0,136 V1 + 0,015 T + 0,105 I + 1,042	r^2 = 0,57

Table 5.F.4 Results of the regression analysis - MIXED PREC. (SR, RS)

Totals per day (DFIR $\geq$ 2,0 mm); n = 119

Y_i; V1; P; D; I; T see Table 5.F.3

Y1 = -0,069 V1 + 0,060 T + 0,921	r^2 = 0,40
Y2 = -0,054 V1 + 0,037 T + 0,970	r^2 = 0,31
Y3 = -0,045 V1 + 0,069 T + 0,768	r^2 = 0,38
Y4 = -0,064 V1 + 0,042 T + 0,940	r^2 = 0,34
Y1 = -0,070 V1 + 0,059 T - 0,004 D + 0,977	r^2 = 0,41
Y2 = -0,055 V1 + 0,036 T - 0,003 D + 1,019	r^2 = 0,33
Y3 = -0,048 V1 + 0,067 T + 0,068 I + 0,745	r^2 = 0,40
Y4 = -0,063 V1 + 0,043 T + 0,004 D + 0,879	r^2 = 0,36

The ratio $DFIR_{cor}$/HELLMANN unsh. can be used for the correction of the wind-induced losses of daily HELLMANN-gauge measured precipitation. The statistical analysis of the seven year winter data (Dec.-March) indicates that this correction ratio $DFIR_{cor}$/ HELLMANN unsh. relates significantly to the mean wind speed. The curves and regression equations (exponential) for the various types of precipitation - S, SR, RS and R - are given in Figure 5.F.10. Generally the correction ratio increases, as it is expected, with mean wind speed. Apart from this it is underlined by the results that separate correction equations for the different types of precipitation S, SR, R have to be derived. The correction ratios for the precipitation types RS and R on the contrary, differ only slightly and consequently could be combined in one regression equation.

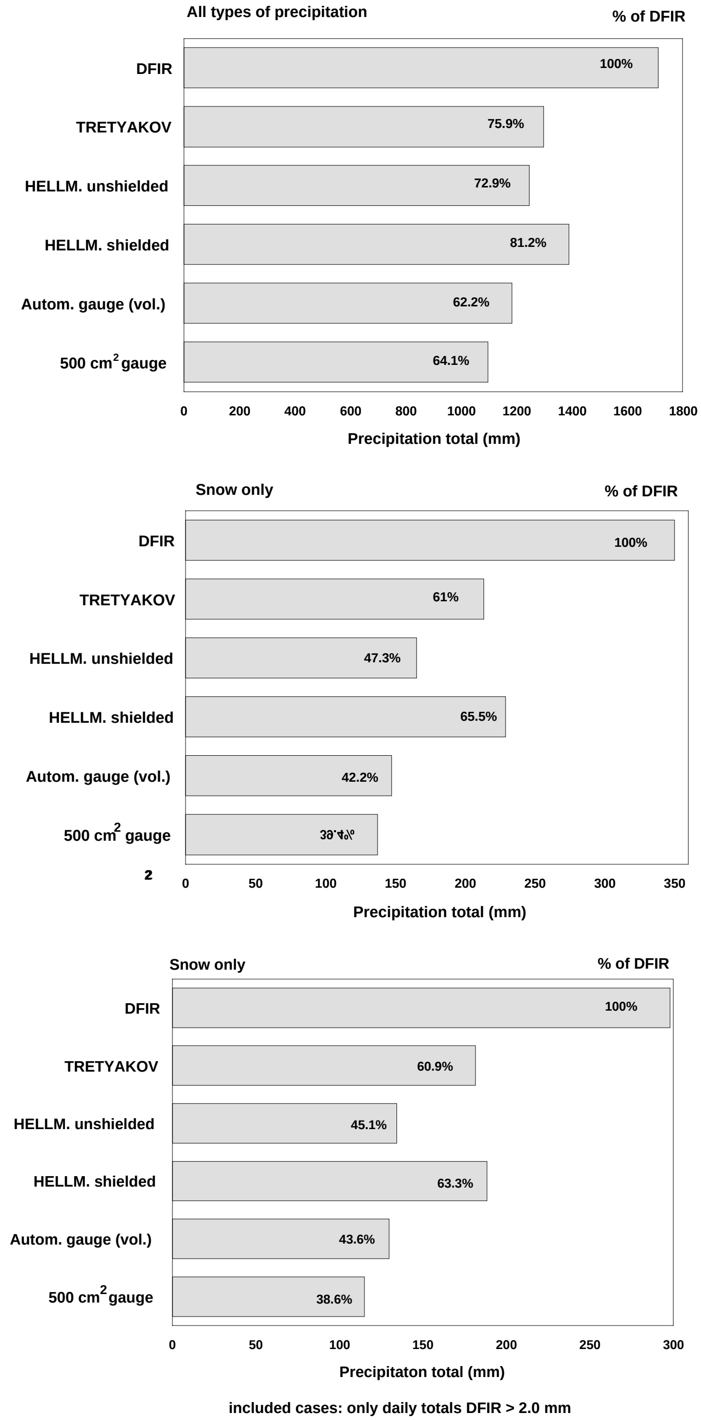

Figure 5.F.6 Precipitation totals and catch percentage of the comparison gauges. Reference gauge (1) DFIR = 100 %; December - March (1986-1993)

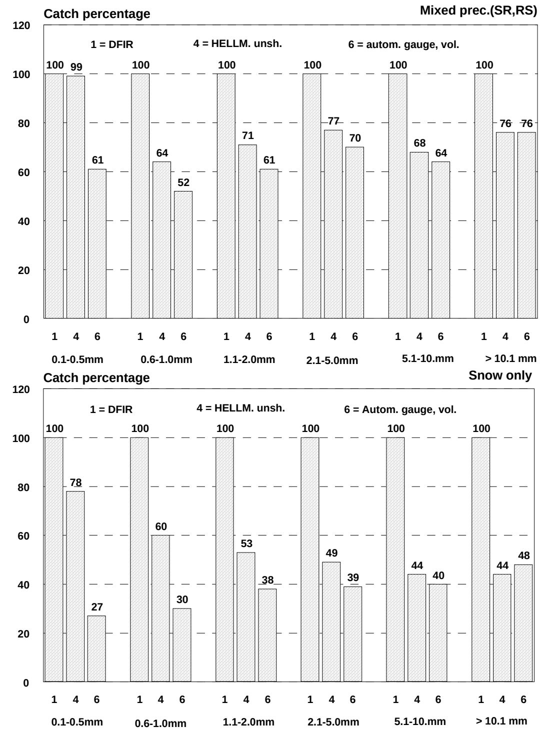

Figure 5.F.7 Catch percentage of the comparison gauges (4, 6) in various classes of depth of precipitation. Reference gauge (1) DFIR = 100 %

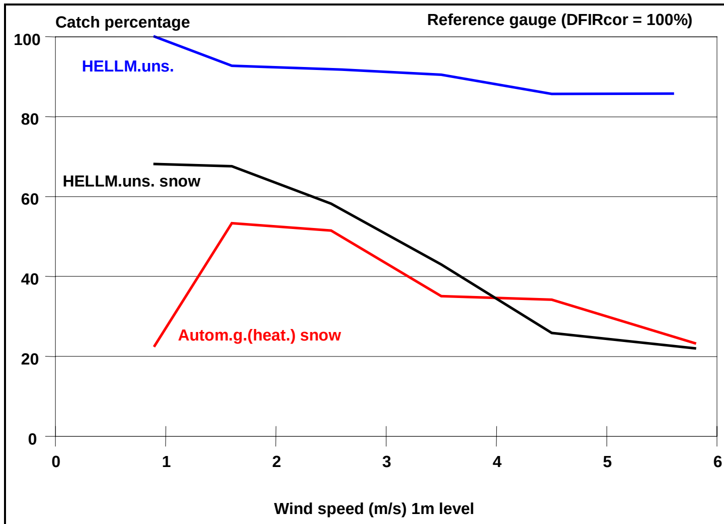

Figure 5.F.8 Catch percentage of comparison gauges dependent on wind speed (1 m level)

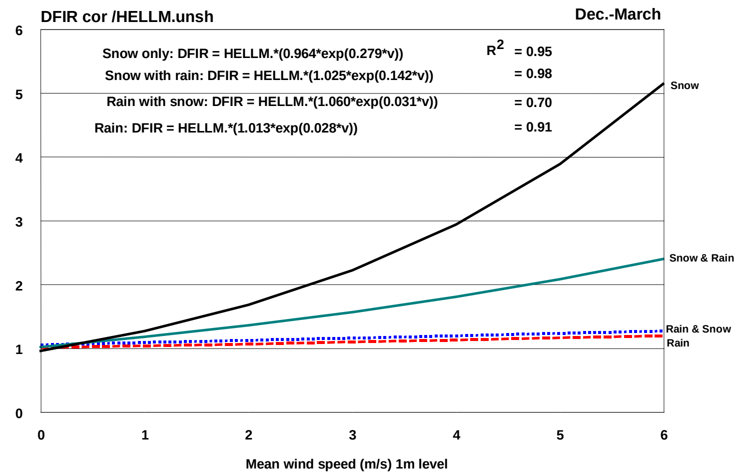

Figure 5.F.10 Correction ratio $DFIR_{cor}$/HELLMANN unsh. for winter precipitation dependent on wind speed

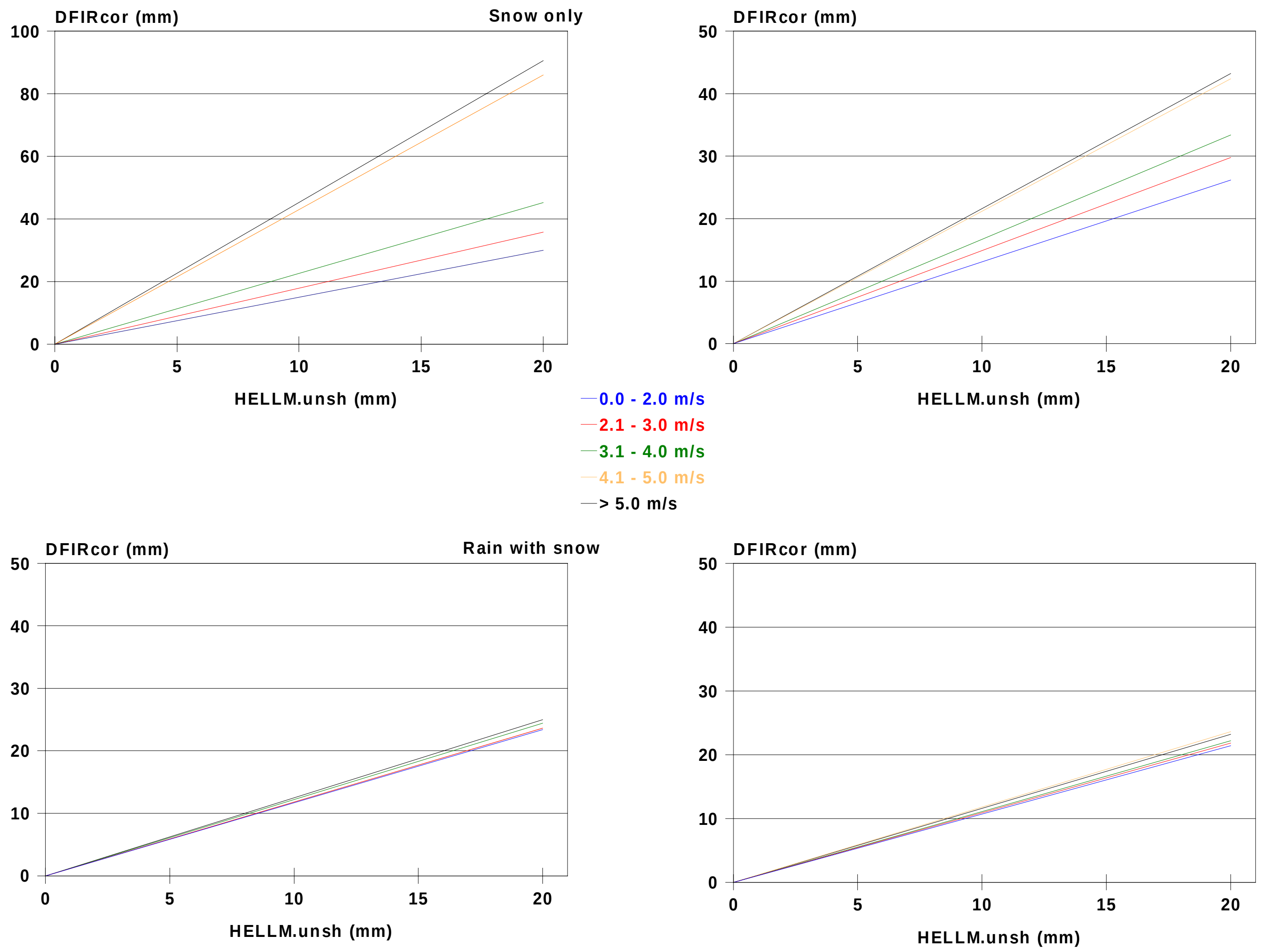

Figure 5.F.9 ***Comparison of daily totals of winter precipitation (mm)DFIR vs Hellmann, unsh. Dependent on wind speed (ms^{-1}, five classes; 1 m level)***

5. CONCLUSIONS

The results of the analysis confirm the predominant influence of the wind causing the HELLMANN-gauge catch deficiencies, especially in the case of solid precipitation. The correction of winter season precipitation measurements in Central Europe is rather a problem, because the types of precipitation vary frequently and within short intervals between snow and rain, particularly in flat regions.

From the above presented results the conclusion may be drawn that a correction procedure for multi-year annual or monthly precipitation totals has to take account not only of the type of precipitation (snow, mixed, rain) but also of the wind speed at least characterized by the wind exposition of the measuring site. An operational correction procedure for current monthly, daily or event values has to be taken into account as factors of influence mean wind speed and precipitation depth. Correction factors or regression equations should be derived separately for the different types of precipitation.

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ANNEX 5.G JAPAN

1. HOKURIKU, JAPAN (*Hiroyuki OHNO, Japan International Research Center for Agricultural Sciences; Kotaro YOKOYAMA, Yasuhiro KOMINAMI and Satoshi INOUE, Hokuriku National Agricultural Experiment Station, Japan)*

1.1 Site and Instrumentation

The evaluation station is located near the north-western coast of the middle of Honshu main island, Japan (37° 06' 45"N, 138° 16' 31" E), 11 m a.s.l. The station is about 6 km from the coast, and is surrounded by paddy fields. Due to the seasonal wind blown from the Siberian Air Mass and the warm current in the Japan Sea, the study site receives a large amount of precipitation in winter. Because of its geographical location and elevation, the winters of the study area are relatively warm, the winter three-month mean being 2.9°C. Thus, the ratio of solid precipitation to the winter precipitation varies largely year by year. Thunder storms and snow pellet are quite frequent in this season.

The DFIR installed at the station has been modified so that precipitation is able to be recorded continuously: the bottom of the Tretyakov Gauge is removed, and connected to a high precision automatic gauge via a metal tube 140 cm in length and 18 cm in diameter (see Annex 3.F). Considering the snow depth in this area, the top of the outer fence, inner fence and the gauge were leveled to 400 cm, 350 cm and 350 cm above the ground, respectively, i.e., 50 cm higher than the specification for the DFIR.

A Tretyakov gauge was also set at 3.5 m above ground. The inclination of the wind shield panels of Tretyakov gauge and the automatic DFIR were set at 55º to horizon. Wind speed was measured with a windmill anemometer at 6.25 m above the ground. The height of the air temperature sensor was set 1.5 m above snow surface and adjusted once a day. Snow depth was measured by an automatic infrared snow depth gauge.

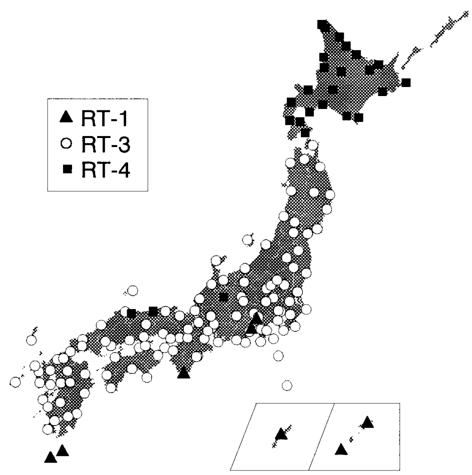

Figure 5.G.1 Location of RT-1, RT-3, and RT-4 gauges in Japan

The national gauges evaluated at this site are the RT-1, the RT-3 and the RT-4 precipitation gauges of the Japan Meteorological Agency (JMA). These three gauges (described in Annex 3.F) all use the same tipping bucket mechanism with the resolution of 0.5 mm to measure the water amount. The height of gauge orifices were adjusted to 3.5 m above ground. The map of deployment of these gauges in Japan is shown in Figure 5.G.1.

1.2 Data Collection

The data were collected from the experiments made in 1992-93 and 1996-97 winters. Measurement of Tretyakov gauge are made at 09:00 hour in local time every day. The correction of wetting loss and evaporation loss of Tretyakov gauge were made by means of adding the correction coefficients (0.2 mm/day and 0.9 mm/day, respectively) which had been obtained from recurrent observations. The gauges without heating were occasionally accreted with snow. A daily sketches of Tretyakov gauge are shown in Figures 5.G.4 and 5.G.5. Figure 5.G.3 shows a photograph of accreted snow on DFIR gauge on 31 Jan. 1997. In the case which accretion was not very serious, accreted snow was shaved to the gauge diameter and added to the caught precipitation. The signals out from automatic instruments were recorded every 10 minutes. The wind speed at national standard height (10 m) and gauge height (3.5 m) is estimated from observed wind speed (6.25 m) with the relationships which had been established from prior experiment. Depth of new snow was not measured. Types of precipitation is identified from manual observation, record of snow fall detector, and record of current weather at Takada Weather Station where 2 km apart from the station. The collected data have been included in the digital data archive of the International Organizing Committee.

1.3 Snow Catch Ratios of National Gauges

Snow catch ratios (*CR*) of national gauges versus DFIR were calculated. Snowing periods were extracted from the 10-minute basic data set. The snowing periods were extracted from the data set on the following criteria; (1) solid precipitation, (2) beginning of a event not included, (3) the period amount not less than 5 mm. Total amounts of precipitation during a period was regarded to a datum for regression analysis. 'True' period precipitation is estimated from the DFIR record and wind speed in 10-minutes step using a formula recommended by Yang et. al (1993). Among the formulae, the one for wet snow was adopted. The true precipitation is related to the period mean wind speed. Period mean wind speed (*U*) was calculated with weight of corresponding 10-minute DFIR record.

Following the previous work in Japan (Yoshida 1959), the relationships between *CR* and *U* was assumed to obey the following formula:

$$CR = \frac{1}{1+mU} \tag{1}$$

where *m* is a parameter assumed to be gauge dependent. As equation (1) indicates, those gauges that are affected more by wind have larger *m*. The relationship between catch ratio and wind speed and their regressed relationship are shown in Figure 5.G.2 The parameters and standard errors of the regression are tabulated in Table 5.G.1.

Table 5.G.1 Aerodynamic characteristics of the three gauges evaluated at Hokuriku National Agricultural Experiment Station (37º 06' 45" N, 138º 16' 31" E) in 1992/1993 winter.

GAUGE TYPE	EVENT BASIS		
	m 1)	*e* 2)	*n* 3)
RT-1	0.17	0.29	9
RT-3	0.24	0.24	7
RT-4	0.14	0.29	23

1) The parameter m [$m^{-1}s$] is the one defined in Eqn. (1) (see text) and estimated from the fitting as shown in Figure 5.G.2. 2) e stands for the standard error of the fitting. 3) number of events.

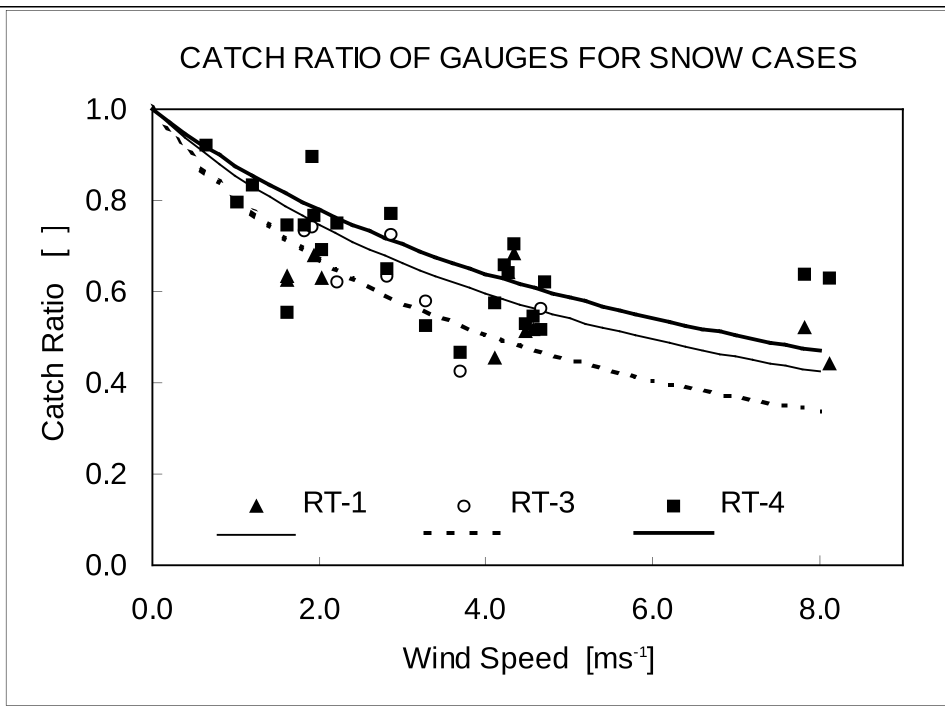

Figure 5.G.2 Relationship between catch ratio and wind speed for snow. A open circle, across hair and a solid circle indicate observed catch ratio of RT-1, RT-3, RT-4, respectively. Corresponding fitted curves are drawn in Thick broken line, thin solid line and thick solid line, respectively. The form of fitted curve defined by Eqn. (1)

1.4 Concluding Remarks

The reason why the beginning of events were eliminated is because the amount of precipitation caught and the amount measured (or weighed) often did not agree. This is due to adhesion of precipitation to the inner side to gauge wall. Tests for maximum water adhering capacity of gauges were measured by spraying water to the wall. These tests found adhesion loss values of: 0.53 mm (Tretyakov), 0.07 mm (RT-1), 0.07 mm (RT-3), 0.25 mm (RT-4), 2.41 mm (automatic DFIR). The probability of adhesion is expected to be low if both precipitating particles and gauge body are sufficiently cold, but adhesion can occur at the station during mild conditions.

Snow catch ratio of Japanese national gauges decrease as wind speed increase. They are about 60% when wind speed is 4 m/s. RT-4 has the smallest coefficient *m*, RT-1 has the next and RT-3 has the largest. It means the catch efficiency of the gauges is higher in this order. The shape of RT-3 is tapered at the top while that of RT-1 is almost a simple cylinder. The reason why RT-3 has a lower catch ratio than RT-1 may be due to its shape being aerodynamically inferior. The reason why RT-4, which has the same body shape with RT-3, has the best performance among the three is most likely due to the fact that only the RT-4 has a windshield

Although a heating automatic gauge which measure caught precipitation immediately is free from wetting loss caused by measuring and from evaporation loss caused by exposure after precipitation, it may have a larger evaporation loss from the heated wall. Current Japanese national gauges are this type. RT-3 and RT-4 are heated to the temperature lower than 5°C while RT-1 is controlled more coarsely. The heating of these gauges may contribute to a large evaporation loss, particularly on the water adhering to the inner gauge walls. Although the maximum adhering capacity is small, i.e. 0.25 mm for the largest model, the effect of evaporation loss on these gauges have not been fully tested. The ratio of total caught precipitation by RT-4 to that by Tretyakov for days on which solid precipitation is included is 0.92 under the condition that neither wetting loss by measuring nor evaporation loss by exposition are corrected. This value includes wind effect. This value would not suggest that this heating automatic gauge is inferior for snow measurement. However, further assessment is necessary.

Snow accretion on non-heating gauges is a serious problem in this region (see Figure 5.G.3). Accretion that had influenced observation occurred 5 days during the period from 13 January through 10 march 1997. In these cases, accretion occurred not only on wind shields, but on the cylinder as it covers the orifice. Figures 5.G.4 and 5.G.5 shows daily sketches of snow accretion on the Tretykov gauge for the period 23 Jan 97 to 10 Mar 97. Future intercomparisons should include procedures to deal with such conditions in warm and heavy snowing areas.

***Figure 5.G.3 Photograph of DFIR gauge on 31 Jan 1997. Snow accreted and covered the gauge*.**

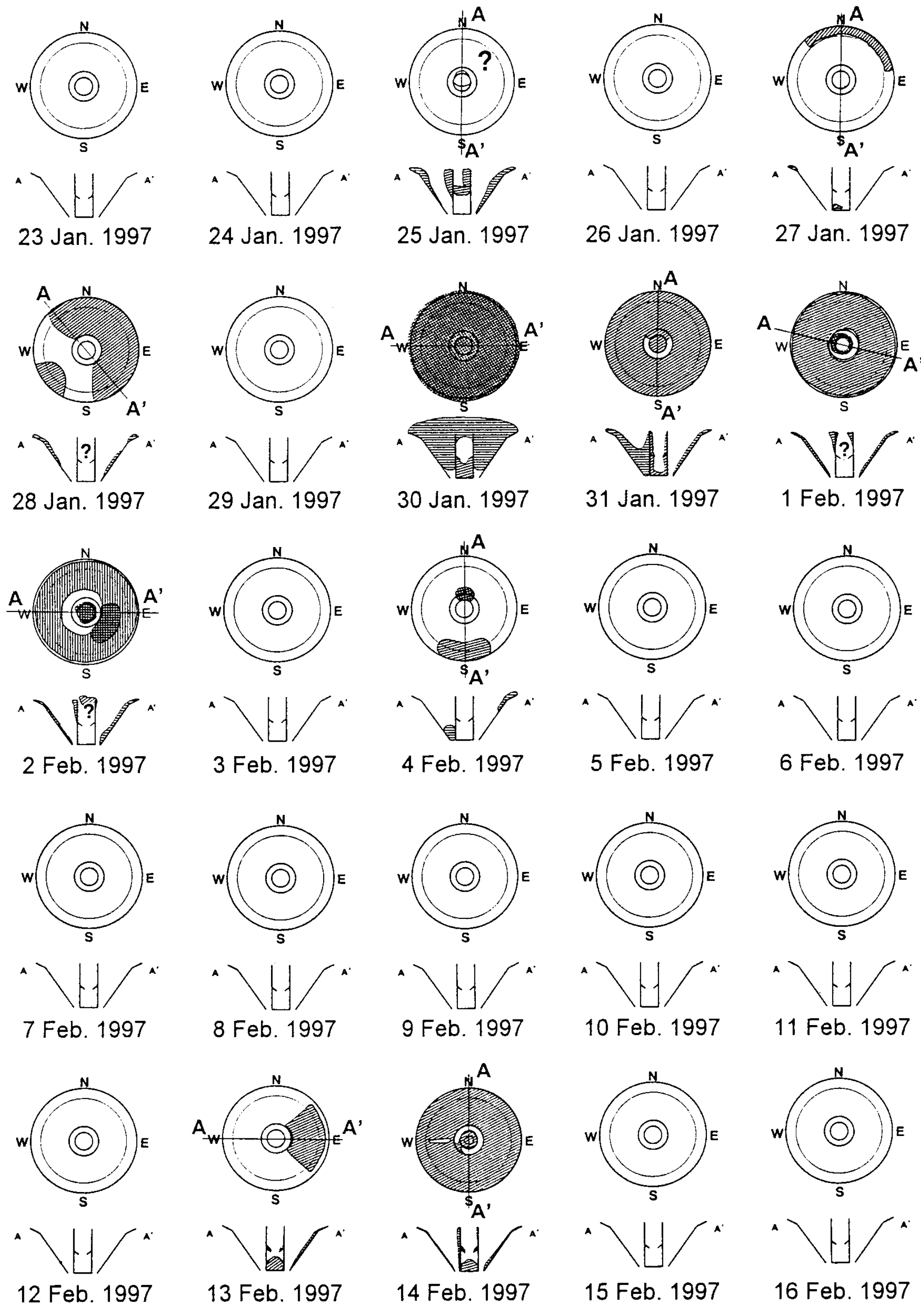

Figure 5.G.4 Daily sketch of snow accretion on Tretyakov gauge (23 Jan. - 16 Feb. 1997). Hatched area denotes snow accretion. Crosshatched area denotes the area snow accreted across wind shield panels.

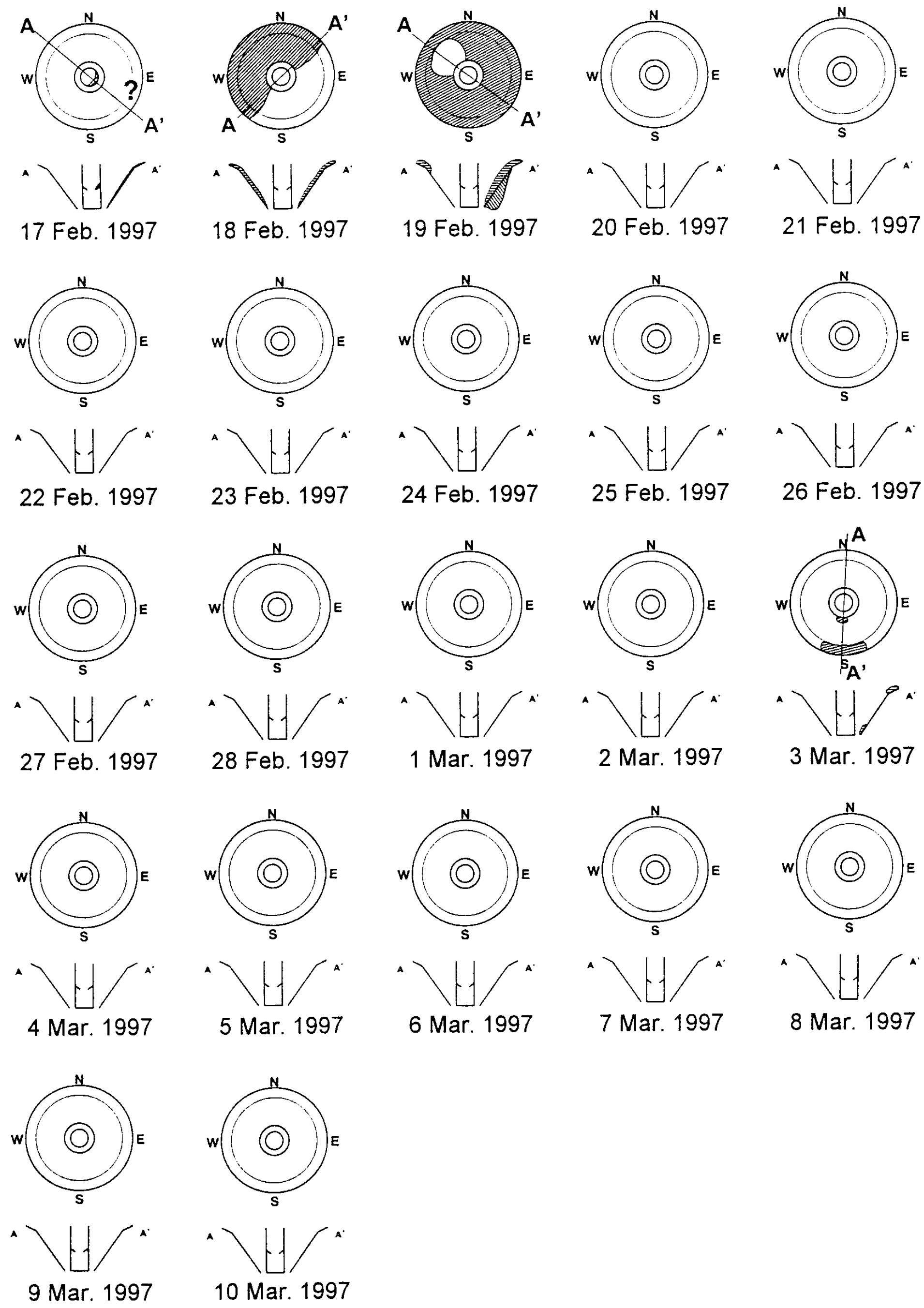

Figure 5.G.5 Daily sketch of snow accretion on Tretyakov gauge (17 Feb. - 10 Mar. 1997). Hatched area denotes snow accretion. Crosshatched area denotes the area snow accreted across wind shield panels.

2. MEMAMBETSU, JAPAN *(Masanori SHIRAKI, Observations Division, Japan Meteorological Agency)*

Table 5.G.2 shows the summary of the WMO solid precipitation measurement intercomparison from Feb. 1989 to Feb. 1991 at Memambetsu station in Japan.

Table 5.G.2 Summary of WMO precipitation measurement intercomparison at Memambetsu

year	month	No.of Data	DFIR amount	Overflow amount	(Shield) ratio	Overflow amount	ratio	Warm Water amount	ratio	Weighing amount	(Shield) ratio
89	2	27	17.3	7.0	0.40	6.0	0.35	2.5	0.14	8.0	0.46
89	3	30	87.8	39.0	0.44	21.5	0.24	29.5	0.34	65.9	0.75
89	4	29	81.9	52.5	0.64	57.0	0.70	55.0	0.67	57.9	0.71
89	11	29	85.2	68.0	0.80	70.5	0.83	47.0	0.55	70.5	0.83
89	12	30	43.1	25.0	0.58	25.5	0.59	11.0	0.26	29.2	0.68
90	1	30	60.0	29.5	0.49	25.0	0.42	17.5	0.29	38.0	0.63
90	2	28	23.8	13.5	0.57	14.0	0.59	11.0	0.46	16.2	0.68
90	3	29	60.3	48.0	0.80	38.0	0.63	28.5	0.47	56.9	0.94
90	4	30	75.9	65.5	0.86	66.0	0.87	65.0	0.86	70.9	0.93
90	5	31	79.0	73.5	0.93	76.5	0.97	71.5	0.91	73.9	0.94
90	11	28	72.0	71.5	0.99	71.0	0.99	71.0	0.99	73.4	1.02
90	12	31	46.3	36.5	0.79	33.0	0.71	32.5	0.70	41.4	0.89
91	1	31	45.7	21.0	0.46	15.5	0.34	14.5	0.32	30.6	0.67
91	2	28	69.2	20.5	0.30	14.0	0.20	21.0	0.30	46.0	0.66

Precipitation amount (unit: mm) and catch ratio of Japanese gauge /DFIR are shown in Table 5.G.3. In the case of rain (+ rain with snow), the catch ratios are from 0.82 to 0.90. And in the case of snow (+ snow with rain), their shields are effective.

Table 5.G.3 Precipitation amount and catch ratio at Memambetsu in winter

Prec.Type	Rain					Snow				
Instrument Type	DFIR	Overflow (Shield)	Overflow	Warm Water	Weighing (Shield)	DFIR	Overflow (Shield)	Overflow	Warm Water	Weighing (Shield)
amount	432.6	368.0	355.5	355.5	387.8	512.5	270.0	223.5	212.5	361.9
ratio		0.85	0.82	0.82	0.90		0.53	0.44	0.41	0.71

Scatter plots of catch ratio of Japanese gauge/DFIR vs wind speed (height: 2m and 10m) and daily mean temperature for daily precipitation >3mm are shown in Figures 5.G.6 - 5.G.8. The characteristics of catch ratio do not have evident relation to wind speed or temperature, so the regression equations are not calculated.

3. REFERENCES

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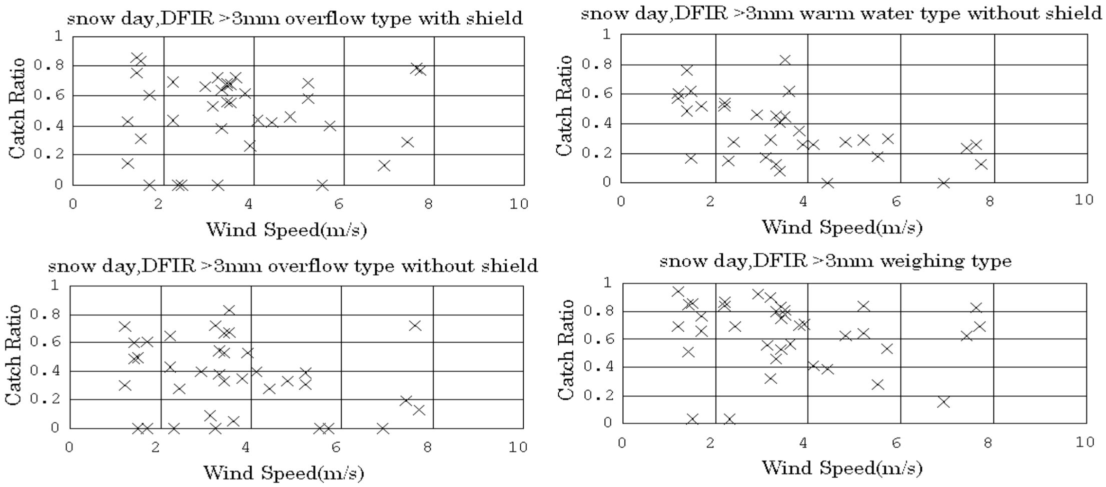

Figure 5.G.6 Catch Ratio Vs. Wind Speed (h: 10m)

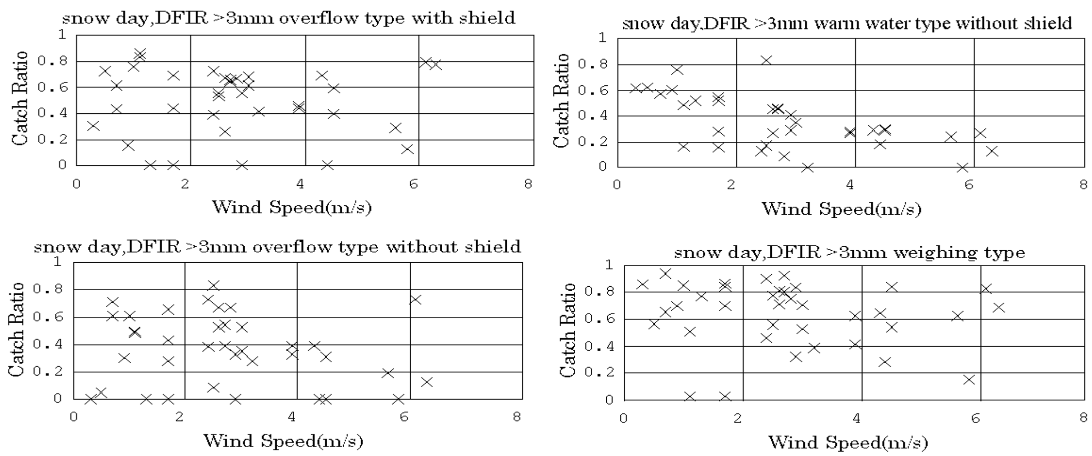

Figure 5.G.7 Catch Ratio Vs. Wind Speed (h: 2m)

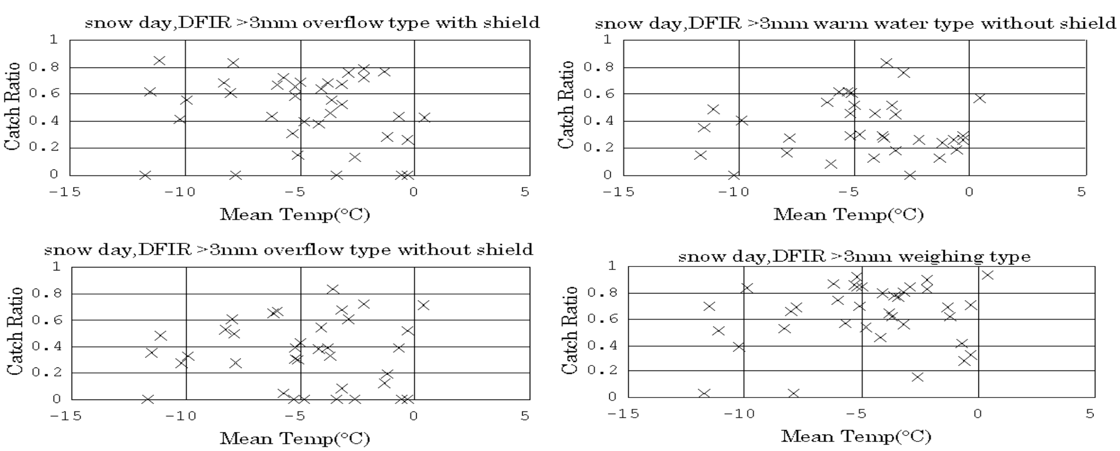

Figure 5.G.8 Catch Ratio Vs. Daily Mean Temperature

ANNEX 5.H RUSSIAN FEDERATION

COMPARISON OF PRECIPITATION MEASUREMENTS BY STANDARD GAUGES OF DIFFERENT COUNTRIES AT THE PRECIPITATION POLYGON IN VALDAI

Contribution of the Russian Federation to the WMO Solid Precipitation Measurement Intercomparison

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FOREWORD

As long ago as the XIXth century a general idea was formed that the precipitation measurement results obtained at the network of hydrometeorological stations contain considerable systematic errors. However, the level of the practical problems during that time made it possible to use of the observed data without any corrections. Later, many scientists and the national hydrometeorological services made their numerous attempts to get more reliable information on the actual amount of precipitation.

Here it is useful to pay attention to evolution of methodological problems in Russia which had been solved to improve methods for precipitation observations.

Before 1869 the instruments of different constructions were used for precipitation measurements in Russia, and the measurements were made at different changeable times, without common rules for observers. Academician G.I. Wild, Director of the Main Physical Observatory, prepared a single instruction on observations of precipitation common for all the meteorological stations in Russia and introduced it into practice in 1869 [1]. According to that instruction, a single rain gauge was used at the stations; it was a cylinder with orifice area of 500 cm^2; precipitation measurements were to be made at specified times. Later, G.I. Wild [2,3] carried out the careful studies of effect of the size, colour and height of orifice above land surface on the rain gauge readings. On the basis of these works, in 1883 the cylinder vessel was supplied by a special snow-cross inserted into the cylinder to protect the caught snow against blowing out. To increase the catching effect of solid precipitation it was recommended in 1887 to surround the cylinder by the Nipher wind shield. In the Russian version the Nipher shield was a solid metal over-head truncated cone (without a horizontal protective visor on the upper rim). During 1891-1894 this wind shield was installed at many stations. The rain gauge with the Nipher shield was used at the meteorological network up to 1948.

Improvement of technique for precipitation measurements during that period were mainly aimed at the elimination of negative wind effect on the catch and collection of solid precipitation in the gauge. Different variants of wind shields and vessels for rain and snow collection were tested. As a result the rain gauges with the Nipher shield were replaced by the precipitation gauges with the Tretyakov plate shield during 1952-1954 [4-7]. This instrument called as a precipitation gauge "0-1" is the main precipitation measuring instrument at the hydrometeorological stations of the Russian Federation until now.

A replacement of one measuring instrument for another one disturbed a homogeneity of precipitation series and created a new problem for climatologists associated with elimination of the resultant non-homogeneity of observation series. Therefore the long-term simultaneous precipitation measurements by the rain gauge and the precipitation gauge were made at many stations in different physiographic zones; it was also necessary to develop a special method to recover the homogeneity of the available series [7].

Although this work satisfied the needs of climatologists it could not satisfy the demands of hydrologists for precipitation data. To study water balance of river basins they needed data on the actual amount of precipitation onto the land surface. The practical needs and the level of knowledge did not allow to use of the network data without assessments of errors. Therefore it was emphasized that methods should be developed for measuring the actual amount of precipitation, and methods for correcting meteorological network data should be developed too.

The studies carried out in 1960s [8-20] made it possible to discover physical reasons of major errors of precipitation measurements, to establish quantitative estimates of a systematic component of measurement error and to develop the methods for the collected data correction. The methods of precipitation data correction developed at the different research institutes of the Hydrometeorological Service in the Former Soviet Union (FSU) did not provide homogeneous series of the corrected data. On the one hand, it was caused by the different levels of the basic data generalization, and on the other hand - by the different methods of the reference measurements of solid precipitation. During a preparation of the "Manual on the USSR Climate" and of the monograph "World Water Balance and Water Resources of the Earth" the correction method of monthly precipitation normals was applied [8-10]; this method was developed at the

Main Geophysical Observatory (MGO). To compute monthly water balances of river basins the correction method [11-14] developed at the State Hydrological Institute (SHI) was applied, and for correction of observation results in the regions with blizzards the correction method [15, 16] developed at the Arctic and Antarctic Research Institute (AARI) was used. Intercomparison and assessment of the errors of the reference data were not made.

Updated assessments of water and energy resources of the Earth and problems associated with prediction of their changes in case of different scenarios of global climate change expanded the problem of precipitation correction to the international level. At this stage the homogeneous and compatible observation data for the basins of seas and oceans, continents and the planet as a whole are required. Intercomparison of results of precipitation measurements by national methods and correction of the collected data are of the first priority at present. It is very important to select the only (reference) method of precipitation measurement which would satisfy the requirements that it should be valid, accurate and reliable. A long-term experience in methodological investigations and developments collected at the institutions of the Hydrometeorological Service of Russia, and in particular at the experimental laboratory of the SHI in Valdai [18-21], appeared to be useful for the international intercomparison of solid precipitation measurements.

1. INTRODUCTION

The World Meteorological Organization repeatedly conducted the intercomparisons of precipitation measurements by the national network gauges. This third intercomparison organized by the WMO differs from the previous intercomparisons not only by the fact that it is concentrated on solid precipitation of measurements but by the fact that for the first time the characteristics of accuracy and reliability of measurement results of the selected intercomparison reference have been determined.

Since this reference instrument was developed at the State Hydrological Institute and placed on the experimental precipitation site in Valdai, a complete description of the Valdai precipitation polygon, its brief history as well as the characteristics of the reference and routine precipitation measuring instruments tested at this site are given in Section 1 of this report. The assessments of the results of precipitation measurements by different gauges tested at the polygon according to the Program of the third intercomparison are discussed in Section 2 of the report. Section 3 describes a general model of precipitation data correction; the assessments of the accuracy characteristics of the corrected data obtained by the Intercomparison reference is given there; a conclusion is substantiated on the fitness of the corrected data for calibration of the results obtained by the standard national measuring instruments.

The accuracy assessment of the measurements by the Double Fence Intercomparison Reference and by the Working Network Reference Gauge has been carried out with the participation of Dr. D.A. Konovalov, chief of the Department of Metrology, SHI, and Yu. V. Tovmach, scientist from the SHI.

2. PRECIPITATION POLYGON

2.1 Brief History

The experimental precipitation polygon of the State Hydrological Institute was created in 1963 on the initiative of V.A. Ouryvaev, director of the SHI [28]. The polygon was designed to carry out long-term field testing of methods for precipitation measurements to study these methods, to estimate errors of obtained results and to improve precipitation observations at the network of runoff and hydrometeorological stations.

The creation of a stationary experimental polygon was based on numerous experiments carried out at the runoff stations and during the field observations made by different field teams of the Institute [22-27].

During the first years the observation program was aimed at the evaluation of relative differences in the readings of precipitation gauges. Therefore some instruments of the same type were installed at different heights above the ground, and some instruments of different types were placed at the same height. The instruments were tested on a meadow site open for any wind [18]. Then the experiments were aimed at a search of reference methods for precipitation measurements and at estimating systematic errors of different origin, such as wetting, evaporation, splashing and wind effect [19, 31, 34]. That time a bushy site was created where the gauges were protected against wind effect. Finally, when the required experimental data were collected, a development of methods for correcting the results of precipitation measurements obtained by the network instruments was initiated [20, 33].

Together with the national studies at this experimental polygon some studies were made according to the international programs. For example, during November 1972 - April 1975 on the request of the Administration of Water Management of Finland the Finnish rain gauges were tested. The polygon was used for the implementation of three international programs for intercomparison of precipitation measurements made under the aegis of the WMO.

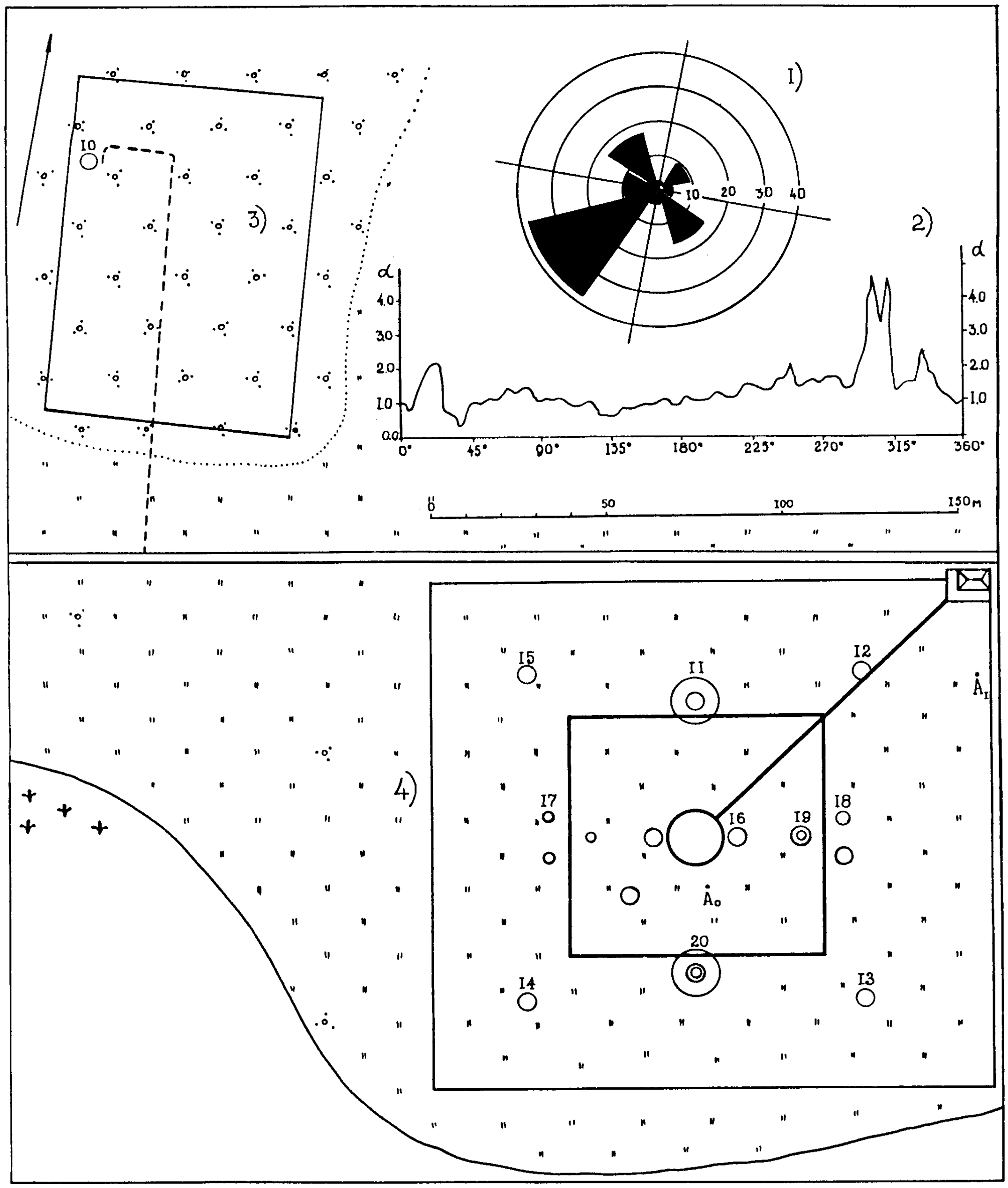


Figure 5.H.1 Valdai Evaluation Station: I) Windrose; 2) Vertical angle of obstacles; 3) Bushy site; 4) Meadow site

During the first intercomparison in 1963-1970 the assessments on monthly total precipitation by the Tretyakov precipitation gauge, by the Nipher shield rain gauge and by the pluviograph P-2 were obtained in comparison with the WMO Intermediate Reference Precipitation Gauge.

During the second WMO intercomparison (1970-1974) the major emphasis was focused on liquid precipitation. The World Meteorological Organization recommended to use the pit gauge as a reference for liquid precipitation. The pit gauges O-1M equipped with shields against splashing were used for reference measurements on the precipitation polygon.

The present (third) intercomparison is being made since 1988. The program of this intercomparison is aimed at the problem of solid precipitation measurements. The International Organizing Committee of the WMO recommended to use the results of measurements obtained by the Tretyakov precipitation gauge in the double fence shield, i.e. Double Fence Intercomparison Reference (DFIR), as the reference values.

The experience gained at the experimental precipitation polygon makes it possible to draw the following basic conclusions:

(1) Experimental precipitation sites designed for field studies of methods for precipitation measurements are expediently operated for a long-term period. Such sites should be created or maintained as the centres for secular studies; they should be operated according to the single international program of base observations.

(2) All the intercomparison references, from national reference to international one, should be used simultaneously and jointly to obtain simultaneous data to reflect different physiographic features as widely as possible.

(3) All the national methods for precipitation measurements, from the simplest ones applied in the past to updated and future methods, should be tested at such experimental sites .

2.2 Physiographic Characteristic of the Region

The experimental precipitation polygon is located on the west flat shore of the Valdai Lake, one kilometer north-eastward far from the outskirts of Valdai.

The geographic coordinates of the polygon:	57°59'N Lat.	38°15'E Long.
Elevation above sea level:	194 m.	

The study area is located in the north-western part of the East European Plain, in the centre of the Valdai Hills, in the middle between Moscow and St. Petersburg.

The Valdai Hills are characterized by a hilly moraine landscape where hills alternate with depressions. Predominant elevations is about 200 m above sea level.

The study area is located in the southern taiga zone where spruce and deciduous forests and pine woods mainly occur. The forested area occupies 75% of the region. Bushes occupy about 20% of the terrain.

The climate is weakly continental, rather humid. Mean annual air temperature is 3.4°C. July is the hottest month (mean monthly air temperature is 16.4°C), January is the coldest month (mean monthly temperature falls up to -9.7°C). Air temperature variations range within -46°C and +33°C. The duration of the warm period when air temperature is above 0°C is equal to 212 days. Total annual precipitation is about 800 mm. About 40% of this amount is lost as river runoff, while the remaining portion is lost for evaporation. Mean annual number of days with precipitation is equal to 207, 113 days out of this number occur in a warm period. Stable snow cover is usually observed from the third 10-day period in November to the second 10-day period in April. The highest snow pack is observed at the end of the first 10-day period in March and equals 71 cm. Concurrently, the maximum water equivalent of snow pack is observed (141 cm). In winter thaws often occur and they affect greatly on the snow cover parameters.

Within the Valdai Hills the southwestern winds prevail. Mean annual wind speed is about 4 m/s. The maximum wind speed is observed during winter months and equals 4.1-4.5 m/s on average. The minimum wind speed is observed during summer months (from 3.0 to 3.5 m/s). During some years mean wind speeds in winter months attain 6.7 m/s, while in summer months - 1.4 m/s. Wind speeds of 15 m/s and higher occur during two days a year. Repeatability of days with calm weather is equal to 8%.

2.3 Description of the Precipitation Polygon

The precipitation polygon consists of two sites: a meadow site and a bushy site. Their total area is about 5 hectares (Figure 5.H.1). Each of the sites is surrounded by a metal latticed fence 1.2 m high. The distance between the centres of these two sites is about 150 m.

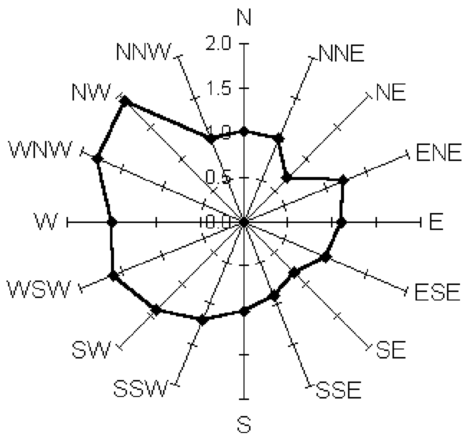


Figure 5.H.2 Vertical angles of obstacles relative to the meadow site centre.

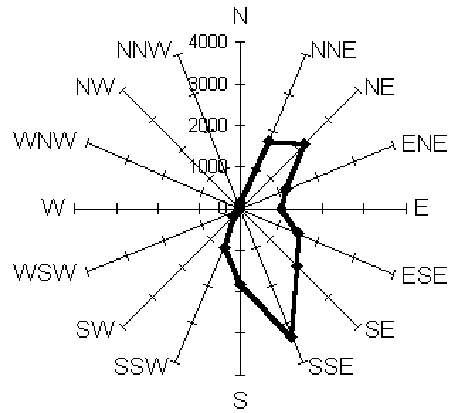


Figure 5.H.3 Length of the blizzard run at various wind directions.

2.3.1 Meadow site

The meadow site is located on the lake shore. The operational site part is 100 x 100 m in area and it is 25 m far from the latticed fence. The site surface is flat and it is less than 1.5 m above the lake water level during the low-water period. The grass cover during the warm period is regularly mowed. The average vertical angle of obstacles is equal to 1.4° and varies from 0.6° to 4.6° (Figure 5.H.2). The instruments on the site are exposed to winds of all directions.

Conditions for a formation of intensive (saturated) blizzard are available during the period of the stable snow cover at wind directions from NNE to SSW (Figure 5.H.3).

Wind speed distribution over heights in the centre of the site is described by the following logarithmic equation:

$$U_{z_1} = U_{z_2} \cdot \frac{\ln \frac{z_1}{z_0}}{\ln \frac{z_2}{z_0}}, \qquad (1)$$

where z_1 and z_2 are the heights of wind speed measurements, z_0 is a dynamic roughness parameter of the site. For period with a steady snow cover (November - March) the roughness parameter of the site is on average equal to 0.4 cm and when there is no snow on the site it equals 1.4 cm.

The results of wind speed measurements in the site centre may be translated to the whole operational area without any corrections. Mean square deviation of this translation is $\pm$ 0.3 m/s for the averaging interval of 10 minutes [18].

Precipitation is distributed over the site evenly, too. Characteristics of convergence computed from the

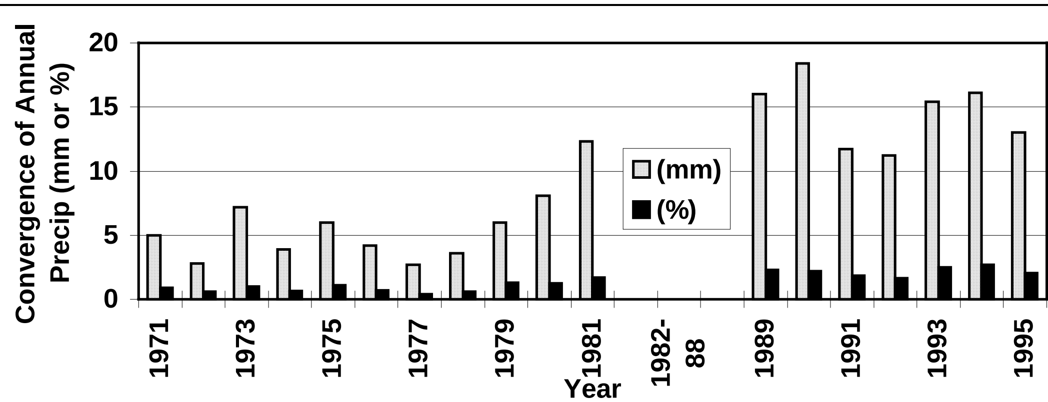


Figure 5.H.4 Characteristics of convergence of total annual precipitation for the meadow site of the polygon.

precipitation measurements by six precipitation gauges 0-1, out of which four gauges were located in the corners of the site and two instruments were located in the centre, are on average about ± 1-2% (Figure 5.H.4) that is in accordance with the technical specifications of these instruments.

2.3.2 Bushy site

The bushy site occupies an area north-westward from the meadow site (see Figure 5.H.1) and it is covered by leaf-bearing bushes up to 4 m high. Within the fenced territory 70 x 10 m in area the bushes are pruned (in autumn) at height of 2 m above the ground. The operational part of the site is located at distance of more than 50 m far from the nearest edge of the bushes.

Within the operational site part the mean bush density on the half of height is equal to 4 stems per 1 sq.m., and mean diameter of the shrub tops at height of 2 m above the ground is equal to 25 cm at minimum after the cutting in autumn. The maximum value of 50 cm on average the shrub top diameter is reached at the end of the warm period before the cutting.

The vertical angle of obstacles taken from the plane of the pruned bushes in direction to the tops of surrounding shrubs and individual trees varies all over around from 3.8° to 23.4° and on average it equals 10.5°; the angle of obstacles determined from the plane of the pruned bushes to the internal boundary between the transparent and non-transparent parts of the shrub tops is equal to 3.0° on average and it varies all over around from 0.8° to 10.2° (Figure 5.H.5).

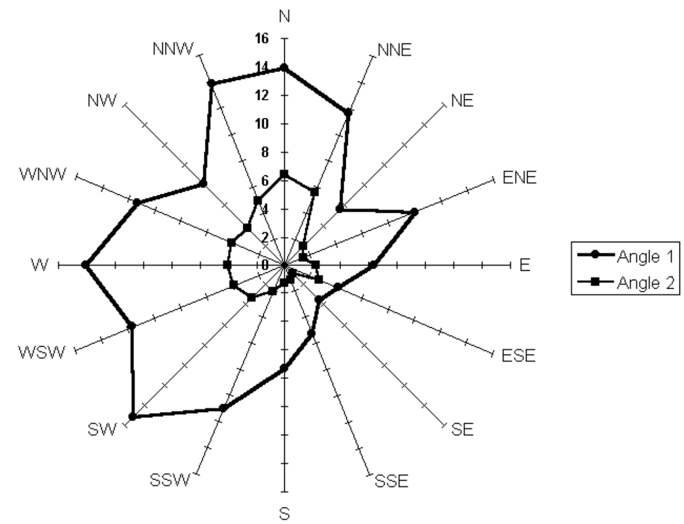


Figure 5.H.5 Vertical angles of obstacles relative to the bushy site centre, degrees
1- angle on the bush tops;
2 - angle to the internal boundary between the transparent and non-transparent parts of the shrub tops.

Aerodynamic parameters of the bushy site operational part are subject to changes during a year (Table 5.H.1).

Table 5.H.1 - Aerodynamic parameters of the bushy site

Period of year	Height of dynamic roughness layer, cm	Height of displacement layer, cm
November-April	41	136
May-October	33	148

2.4 Precipitation Measuring Instruments

The total number of instruments used at the Valdai precipitation experimental polygon since 1963 exceeded 100. It included the reference precipitation measuring instruments of all WMO intercomparisons as well as the national precipitation gauges of many countries [18,19]. The results of all measurements are stored in the Valdai Branch Archives of the SHI. Some observation data since 1965 have been published in annual issues of the "Observation Data of VRHL".

In 1988 the polygon was re-equipped for the Program of the third WMO Intercomparison - The WMO Solid Precipitation Measurement Intercomparison. 18 gauges from 6 countries were under operation at the site during 1988-1995(Table 5.H.2). The reference gauges of the two previous WMO intercomparisons were also included into this list of instruments, i.e. Intermediate Reference Precipitation Gauge (IRPG) and the pit gauge.

During that re-equipment some instruments were left on their places to provide the control for observation homogeneity and reliability. Those instruments were: two components (1 and 3) of the Valdai Control System (see section 2.4.1) and six Tretyakov precipitation gauges installed in the corners and in the centre of the meadow site (see Figure 5.H.1).

Table 5.H.2 - List of the gauges installed at the polygon during the third WMO Intercomparison. Valdai, 1988-1995

No.	Precipitation gauge	Orifice area, sm^2	Height, sm	Measurement technique	Period of testing	Gauge number in record book
1	VCS: Tretyakov gauges component 1 component 3	 200 200	 200 200	 volumetric volumetric	 11.88 - 12.95 01.91 - 12.95	 0 8
2	DFIR : Tretyakov gauge in double fence shield	200	300	volumetric	11.88 - 12.95	1
3	IRPG	200	200	volumetric	08.89 - 05.94	17
4	Pit gauge O-1M	200	10	volumetric	08.89 - 10.95	18
5	Tretyakov gauge	200	200	volumetric	11.88 - 12.95	2
6	Tretyakov gauge	200	200	volumetric	11.88 - 12.95	3
7	Tretyakov gauge	200	200	volumetric	11.88 - 12.95	4
8	Tretyakov gauge	200	200	volumetric	11.88 - 12.95	5
9	Tretyakov gauge	200	200	volumetric	11.88 - 12.95	6
10	Tretyakov gauge	200	200	volumetric	11.88 - 12.95	7
11	NSSGS: Nipher shielded snow gauge system (Canada)	127	200	volumetric	11.88 - 05.94	15
12	NSSGSdf: Canadian Nipher shielded snow gauge system in double fence shield	127	300	volumetric	11.88 - 05.94	16
13	USWB-8” unsh.: 8-inch gauge of the United State Weather Bureau, without shield	324	100	volumetric	09.91 - 12.95	20
14	USWB-8” sh.: 8-inch gauge of the United State Weather Bureau with Alter wind shield	324	100	volumetric	09.91 - 12.95	19
15	Hellmann gauge (Germany)	200	200	volumetric	11.88 - 12.95	10
16	Hellmann gauge (Poland)	200	200	volumetric	11.88 - 12.95	11
17	Hellmann gauge (Hungary)	200	200	volumetric	11.88 - 12.95	12
18	Rain gauge with Nipher shield (Russia)	500	200	volumetric	11.88 - 12.95	14

2.4.1 Valdai Control System for Precipitation Measurements

The Valdai Control System [31, 32] has been accepted as a reference for precipitation measurements on the Valdai experimental precipitation polygon; the components of this system are protected against wind better than the other instruments installed on the polygon.

The Valdai Control System (VCS) is located on the bushy site of the polygon and consists of three measuring components represented by the standard Tretyakov precipitation gauges, one of which is installed close to the bushes (component 1), the second one is installed in the centre of a round glade about 10 m in diameter (component 2), and the third component is installed on the glade of the same size but it is surrounded by an artificial wooden fence (component 3). The fence of the component 3 is a regular octagon inserted into a circle 4 m in diameter. The plates of the fence are 150 x 5 x 2.5 cm in size and fixed vertically at the distance of 5 cm from each other. The lower edge of the plates is 50 cm above the ground while the upper edge is 200 cm high above the land surface at the same level with the gauge orifice plane.

The measuring components of the VCS are placed in the centre of bushes more than 50 m far from the nearest edge of the forest. The distance between the VCS components does not exceed 20 m.

The measurements of precipitation by the component 1 were carried out using the weighing technique that excluded a necessity to introduce corrections compensating precipitation losses for wetting and evaporation. Measurements by the components 2 and 3 were made using the standard volumetric technique. The scale spacing of the balance and measuring glass were equivalent to 0.1 mm of water layer.

Since 1988 when the experimental precipitation polygon was re-equipped for the Program of the third WMO intercomparison the Tretyakov precipitation gauge placed among the bushes (component 1) was used as a reference for precipitation measurements at the polygon, and since 1991, when the component 3 was reconstructed, the VCS contained two components (1 and 3). Measurements by two components during the third intercomparison were made volumetrically.

2.4.2 Intercomparison References of the World Meteorological Organization

As noted above, the experimental precipitation polygon was operated during three international intercomparisons of precipitation measuring instruments under the aegis of the WMO. Therefore the precipitation reference gauges recommended by the WMO for these intercomparisons were installed and tested during a long period of time.

The Intermediate Reference Precipitation Gauge (IRPG) was used as a reference gauge for the first intercomparison. The IRPG was based on the UK rain gauge (Mk 2) and the Alter wind shield modified in accordance with the Warnick recommendations [29].

Since the second intercomparison was aimed at liquid precipitation measurements, the pit gauge [18] was taken as a reference rain gauge which was sufficiently studied and its reliability was proved. In accordance with recommendations [41], the pit gauge O-1M was installed at the Valdai precipitation polygon which was surrounded by a special shield of 3 x 3 m against splashing with meshes of 10 x 10 x 10 cm.

The third intercomparison (1986-1994) was aimed at solid precipitation measurements. This problem was of a great interest for hydrometeorologists because of a great wind effect on the catch and store of snow in the gauge. Investigations made at the SHI and in Valdai to restrict this effect had a long history by that time. As far back as 1964 at the polygon a double fence shield [18] was installed around the Tretyakov precipitation gauge, which was the national standard for precipitation measurements at the hydrometeorological station network. This shield and its modifications were developed and tested under the guidance of V.S. Golubev [21, 34] at the Valdai precipitation polygon. One of variants of the wind shield for precipitation gauge appeared to be applicable at the network of water balance stations [46, 59, 74].

In view of the fact that this precipitation system, i.e. the Tretyakov precipitation gauge surrounded by the double fence shield (Double Fence Intercomparison Reference), is universal, it was taken by the International Organizing Committee of the WMO as a precipitation measurement reference for the third intercomparison [75]. The standard installation of the Tretyakov precipitation gauge was recommended as a Working Network Reference Gauge for this intercomparison, because it provided the most complete results of quality assessments of solid precipitation measurements within a wide range of climate conditions as compared with other national precipitation gauges [75].

2.4.3 National Precipitation Gauges

During the period of operation of the experimental precipitation polygon (since 1963) precipitation was measured by different gauges from many countries. Three modifications of the Hellmann precipitation gauge applied in Germany, Hungary and Poland were operated for many years. During November 1972 - April 1975 the rain gauges of the National Service of Finland were tested. Different rain gauges applied in France and USA were tested too.

Two types of instruments, i.e. the land rain gauge of the Upsala University (Sweden) and the section rain gauge (China), were manufactured by the drafts in the experimental workshops of the SHI and tested at the polygon.

A complete list of precipitation gauges tested at the Valdai precipitation polygon is given in [18, 19].

2.5 Observations of Meteorological Components and Atmospheric Events

2.5.1 Wind Speed

Wind speed is observed directly at the polygon at heights of 2 and 3 m above the ground. Two contact anemometers M-92 are applied; these anemometers are fixed to a mast installed in the centre of the meadow site.

Three-cup current meter fixed to a vertical axis is a sensible component of the anemometer; the current meter is rotating in ball-bearings. The instrument is operating in open air at temperatures from -50°C to +50°C. Wind speeds from 0.6 up to 40 m/s can be measured. The instrumental error of the anemometer is equal to $\pm$(0.2+0.02U) m/s, where U is wind speed in m/s.

2.5.2 Other Meteorological Components and Atmospheric Events

Observations of other meteorological components and atmospheric events are performed at the "Valdai" operational meteorological station located 0.9 km southwestward the experimental precipitation polygon.

Before 31 December 1965 the meteorological components and atmospheric events were observed 4 times per day, each 6 hours. Since 1 January 1966 these observations are made 8 times per day, each 3 hours. The validity of translation of the meteorological station data to the precipitation polygon (except wind speed) is confirmed by the results of simultaneous observations carried out during warm periods in 1977-1980.

The following observation data are entered in the record book of the precipitation polygon from the observation register of the meteorological station:

maximum air temperature, °C;
minimum air temperature, °C;
air humidity, hPa;
saturation deficit, hPa;
atmospheric pressure, hPa;
wind direction, azimuth;
type of clouds;
types of precipitation and atmospheric events and duration, in hours.

3. COMPARISON OF PRECIPITATION MEASUREMENT RESULTS

The use of different reference gauges for liquid and solid precipitation measurements during the international intercomparisons rises a number of problems associated with both the interco-ordination of the obtained data and the assessment of accuracy characteristics of the measurement results. It was possible to solve these problems because of the continuous measurements by the VCS components and because of the availability of the long-term series of simultaneous measurements by the VCS and by all the reference gauges recommended by the WMO.

The experimental check made earlier [19, 31, 32] showed that the results of snow measurements using the VCS components are in a good agreement with the results of independent determinations of water equivalent increments in snow pack, and the results of rain measurements are in a good agreement with the readings of the pit gauge. It follows that the VCS observation data do not contain significant systematic errors and characterize quite reliably the amount of any kind of precipitation falling onto the land surface at the observation point (Figure 5.H.6).

Therefore the analysis of relative precipitation values obtained by the different gauges at the precipitation polygon and given in this report has been carried out in comparison with the VCS readings.

The first stage of the analysis was aimed at a discovery of possible disturbances in homogeneity of the collected data series when the precipitation polygon was rearranged in 1988. A check of the chronological graph of relative precipitation values for the Tretyakov precipitation gauges, which were left at the same places during a number of years, shows (Figure 5.H.7) that no significant disturbances in the homogeneity occurred. This conclusion is confirmed by the observation data obtained by the Tretyakov precipitation gauges in the double fence shields installed on the different places at the meadow site.

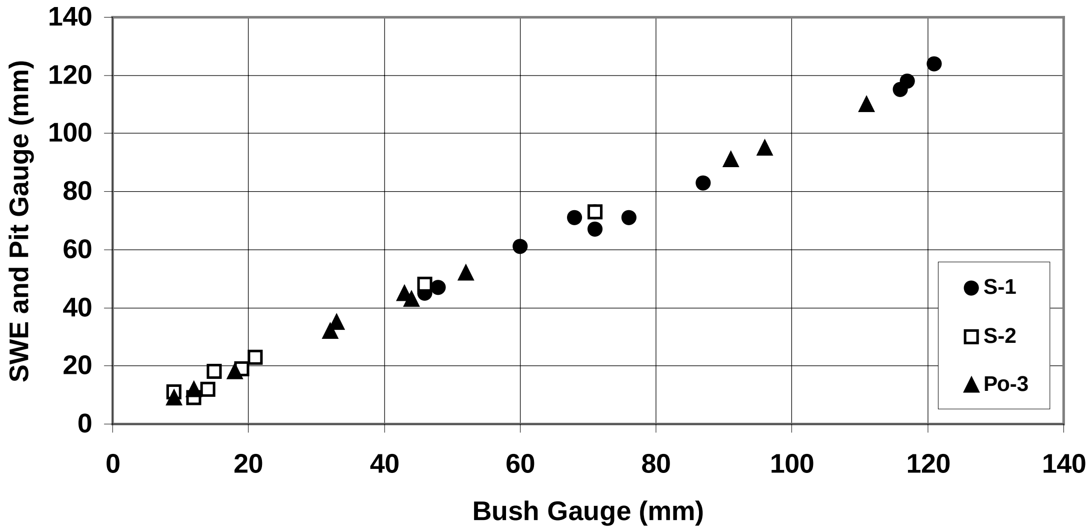


Figure 5.H.6 Interrelationship between the precipitation amount by the precipitation gauge installed among the bushes (P, mm) and the water equivalent of snow pack (S, mm), and the readings by the pit gauge (Po, mm).
S-1: water equivalent measurements of snow at the Valdai polygon;
S-2: water equivalent measurements of snow within the Sorot river basin;
Po-3: pit gauge readings at the Valdai polygon.

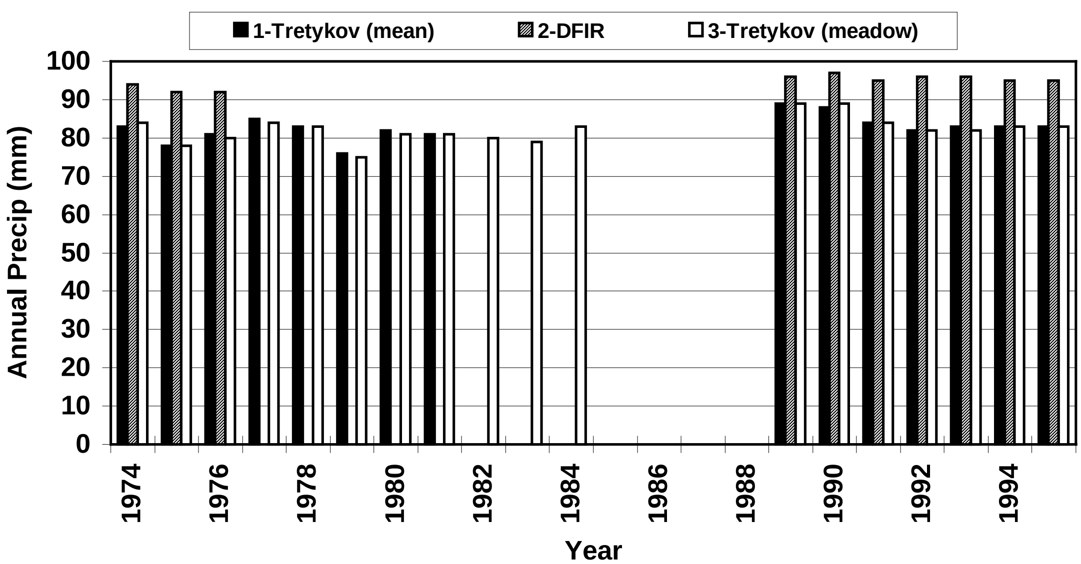


Figure 5.H.7 Chronological variations of relative values of total annual precipitation.
1 - mean value of total precipitation from 6 Tretyakov precipitation gauges;
2 - DFIR;
3 - one Tretyakov precipitation gauge installed in the centre of the meadow site.

The comparison of the relative precipitation values by the Tretyakov precipitation gauge in the double fence shield (DFIR), the Working Network Reference Gauge (WNRG), the Intermediate Reference Precipitation Gauge (IRPG) and the pit gauge (O-1M) carried out during the second stage of the analysis (Table 5.H.3) confirmed an agreement between the results of liquid precipitation observations obtained by the VCS and O-1M, and as a matter of fact these data require a random error of measurements to be established only.

The relative precipitation values obtained by the DFIR, WNRG and IRPG are essentially underestimated as compared with those obtained by the VCS and should be corrected for both cold and warm periods. Characteristics of systematic and random components of the measurement error should be established for these reference precipitation gauges.

Before these assessments are made, however, it is reasonable to consider the characteristics of the VCS accuracy because the problems of necessity and possibility of correction are closely connected with the correlation of errors of observation data obtained by the reference gauges and by the gauges under the comparison.

According to a criterion established by meteorologists [72], if the modulus of ratio of a systematic error to a random error equals 0.8 and greater, a correction making compensation for the systematic error should be introduced to the measurement results. The measurement results by the references should also meet the case, namely: the random error of reference measurements should be less than one of tested gauge measurements at least in 2.5 and more times.

Table 5.H.3 - Mean Long Term Relative Total Precipitation by the WMO Intercomparison References

Gauge	Monthly precipitation amounts, % of VCS											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
DFIR	86	92	94	98	93	94	94	95	92	93	92	89
WNRG	57	64	79	81	90	96	93	94	91	89	75	63
IRPG	49	53	60	74	91	94	92	94	90	83	64	54
O-1M (Pit)	-	-	-	-	107	96	99	99	99	-	-	-

A quality assessment of measurements by the national gauges and a conclusion on a fitness of the measurement results by the intercomparison references for calibration were made in accordance with these criteria

3.1 Errors of Precipitation Measurements by the Reference Gauges

3.1.1 Valdai Control System

The quality of precipitation measurement results by the VCS may be estimated by a random mean-root-square component of the error because as noted above the systematic component of the error may be neglected. It is shown in [72] that the absolute and relative values of the random measurement error for the VCS as a whole and for its particular components depend on the amount of precipitation and may be approximated by the exponential functions common for all kinds of precipitation (Figure 5.H.8, Table 5.H.4):

$$\sigma_{P_l} = cP^d \text{ , mm,} \qquad (2)$$

$$\sigma_{p_l} = 100cP^{d-1} \text{ , \% ,} \qquad (3)$$

where P is precipitation layer obtained by averaging the measurement results by three VCS components; c and d are the empirical parameters of the exponential formulas.

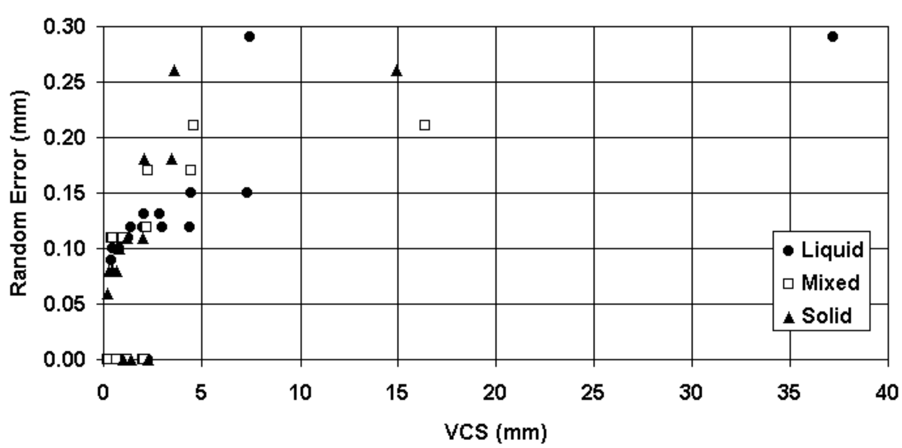


Figure 5.H.8 .Relationship between the random error of half-daily precipitation measured by the VCS and the amount of precipitation (P). Precipitation types: L - liquid; M - mixed; S - solid.

The results of measurements by the individual VCS components are characterized by several varying values of the random errors. The measurement results by the gauge placed on a small glade among the bushes (component 2) contain a maximum error, and the measurements by the instrument installed on a similar glade and in addition surrounded by a special shield (component 3) contain a minimum error. The error of precipitation measurement results obtained by the weighing gauge (component 1) installed close to bushes is intermediate [72].

Table 5.H.4 Results of the Assessment of Random Component of the Error of the Valdai Control System and Its Components at measuring Precipitation of Different Types

Precipitation type	**Period of summing**	**Depth of precipitation, max, mm**	**Number of events**	**Error of measurement, mm**			
				VCS	**VCS components**		
					1	**2**	**3**
solid	12 h	14,9	1705	0,16	0,16	0,18	0,13
mixed	12 h	16,4	375	0,17	0,19	0,21	0,12
rain	12 h	37,2	1727	0,16	0,20	0,14	0,14
total	decade	108,3	404	0,71	0,71	0,82	0,55
total	month	218,2	138	1,31	2,06	1,81	0,91

When analyzing the dependencies of the random error of half-daily precipitation obtained by the individual VCS components on the precipitation amount (Figure 5.H.9) it is possible to conclude that for the weighing gauge (component 1) the connection is the most close (Figure 5.H.9.2) and it hardly depends on the amount of precipitation. It is the most probable that the random error of the component 1 measurement results reflects metrological characteristics of the measuring instrument of mass. For the gauge with volumetric way of measurement (components 2 and 3) the dependence of the random error of measurements upon the amount of precipitation (Figure 5.H.9.3 and 5.H.9.4) is more significant. The scattering of points around the averaging line demonstrates a wide range of individual values of precipitation losses for wetting, and it shows no effect produced by introduction of averaged values of this error to individual measurements.

For 10-day and monthly total precipitation the random errors for the VCS are equal to $\pm$0.7 and $\pm$1.3 mm, respectively, which are equivalent in relative values to $\pm$3.3 and $\pm$2.1 % of the measured values. The absolute and relative values of random errors of the 10-day and monthly total precipitation depend on the total precipitation value. However, this relationship is rather climatic than statistical. The statistical nature of the errors of the 10-day and monthly total precipitation may be described by the following equation:

$$\sigma_{\sum P_i} = \pm\sqrt{\sum \sigma^2_{P_i}} \ , \qquad (4)$$

where $\sigma_{\sum P_i}$ is a root-mean-square deviation of random error of the total precipitation for 10-day or monthly period; $\sum \sigma^2_{P_i}$ is a sum of squares of random errors of individual measurements (12-hour) of total precipitation for 10-day or monthly period.

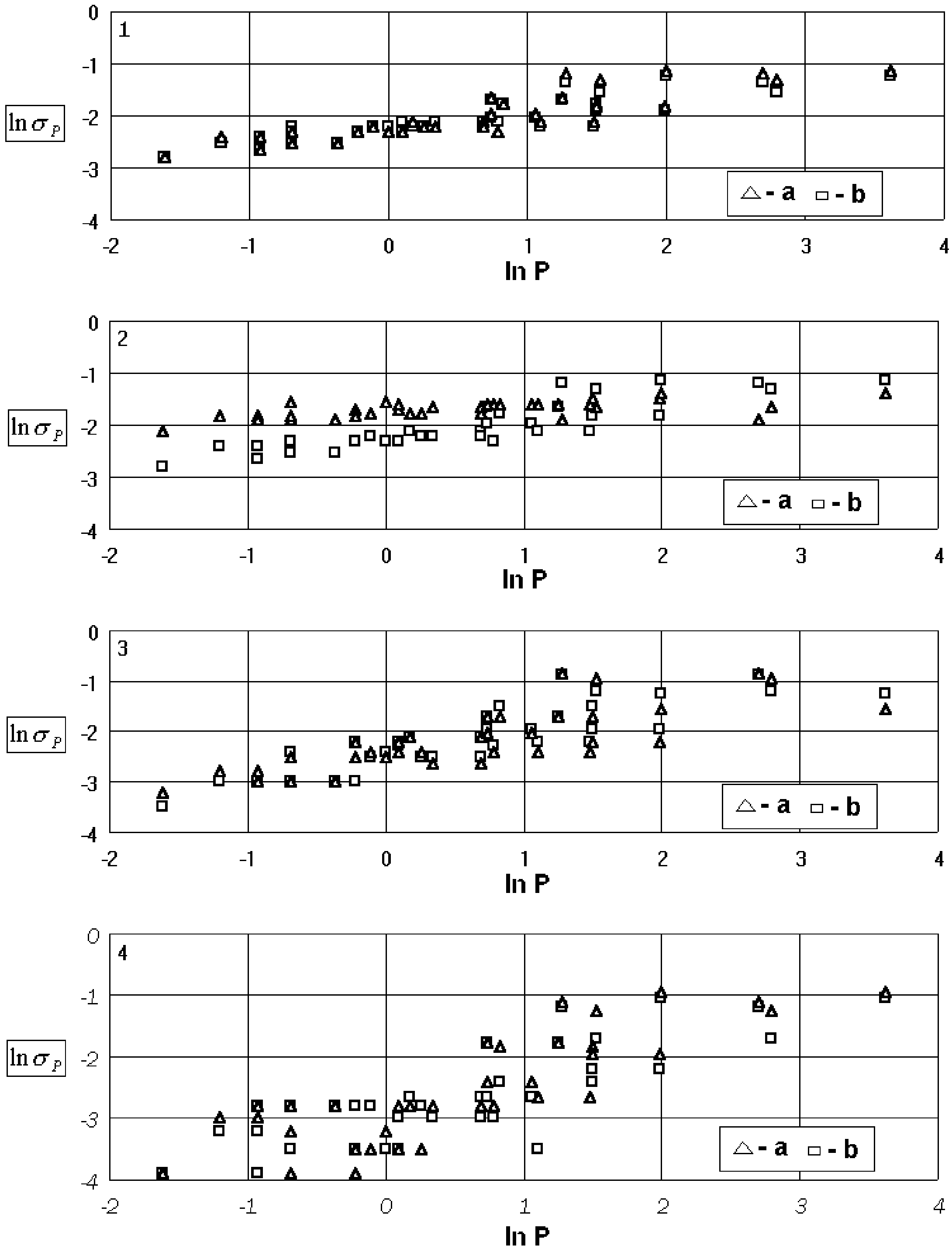


Figure 5.H.9 Dependence of the random error of half-daily precipitation measurements (ln σ_p) on the value of the measured depth (ln P).

1 - VCS as a whole; 2 - Component 1; 3 - Component 2; 4 - Component 3; Correction for wetting: a - not introduced; b - introduced

3.1.2 Double Fence Intercomparison Reference (DFIR)

The analysis of long-term observations by the VCS and by the solid precipitation intercomparison reference(see Table 5.H.3) shows that the data of measurements by the DFIR contain a significant systematic component of the error.

During a cold season the DFIR catches on average 9% less precipitation as compared with the VCS. The correlation coefficient of monthly precipitation amounts characterizing the statistical relations between the readings of the compared gauges is equal to 0.99. The random error is about 10%, and a ratio of the systematic error to the random error is equal to 0.95 [57] that points to the fact that it is necessary to correct the measurement results.

The assessments of the systematic error of the half-daily total precipitation shows that rain, mixed precipitation and snow measured by the DFIR is underestimated by 0.2 mm on average (Table 5.H.5). The random error is about twice higher than the systematic error and exceeds 0.4 mm.

When comparing the ratios of random errors of the measurement results by the DFIR (δP) and by the VCS (δP_{VCS}) it may be concluded that, according to the criterion established by meteorologists (see Section 2), the measurement results by the VCS may be accepted as reference ones for the control (calibration) of the DFIR readings.

Table 5.H.5 Assessment Results of Systematic (ΔP) and Random (δP) Components of Error of Measuring Half-daily Total Precipitation for the Intercomparison Reference (DFIR)

Precipitation type	ΔP, **mm**	$\pm\delta P$, **mm**	$\left\lvert \Delta P / \delta P \right\rvert$	$\left\lvert \delta P / \delta P_{VCS} \right\rvert$
Solid	-0.17	0.43	0.39	2.7
Mixed	-0.16	0.45	0.36	2.6
Liquid	-0.22	0.45	0.50	2.8

For all kinds of precipitation measured by the DFIR it is possible to see the certain relations between the absolute value of error and the precipitation amount (Figure 5.H.10).

A similar dependence is observed between the magnitude of the error and the wind speed (Figure 5.H.11).

A special feature of the considered dependencies is in the fact that there is no effect of the precipitation type, in its explicit form, on the magnitude of systematic and random errors.

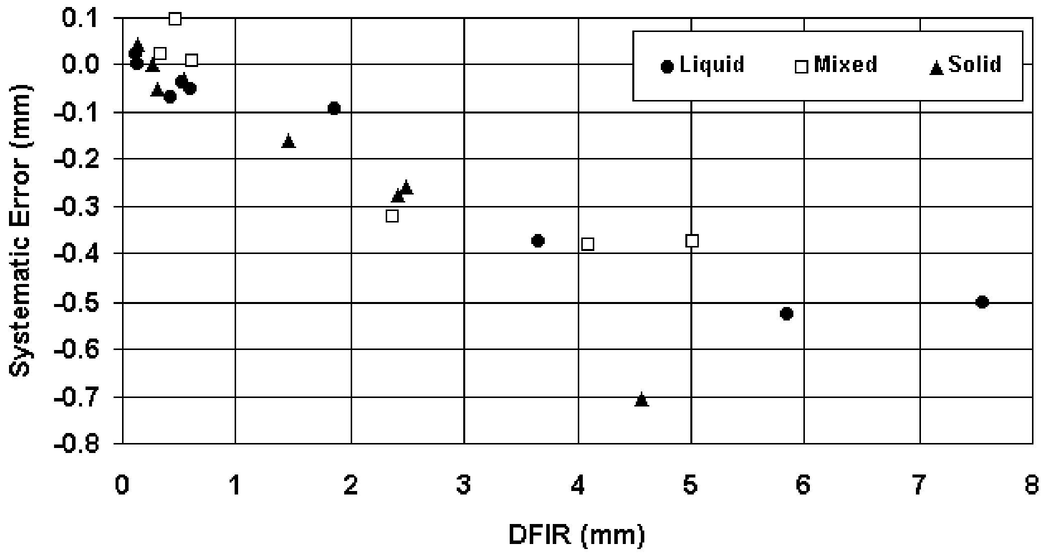
The modulus of ratio of systematic error to random error also depends on the amount of precipitation and wind speed (Figures 5.H.12 and 5.H.13).

As evident from the analysis of these dependencies, the correction of the measurement results by the DFIR (at measurements every 12 hours) may appear to be not effective for precipitation amounts less than 2.5 mm at the wind speeds lower than 4.5 m/s because the systematic component of error under these conditions is much less than the random component of error ($\left\lvert \Delta P / \delta P \right\rvert$ <0.8).

3.1.3 Tretyakov Precipitation Gauge (WNRG)

Precipitation measured by the Tretyakov precipitation gauge (WNRG) in winter is underestimated by 34% on average against the VCS. The correlation coefficient between the monthly precipitation amounts by the WNRG and the VCS equals 0.95. A ratio of systematic error to random one equals 1.5 [57]. In case of such characteristics of data the measurement results should be corrected to compensate the systematic error.

The estimates of systematic and random errors of half-daily precipitation amounts gives evidence to the fact that the solid, mixed and liquid precipitation measured by the WNRG is underestimated from 0.3 mm to 0.6 mm on average, and the random error for the different precipitation types ranges within 0.5-1 mm (Table 5.H.6).



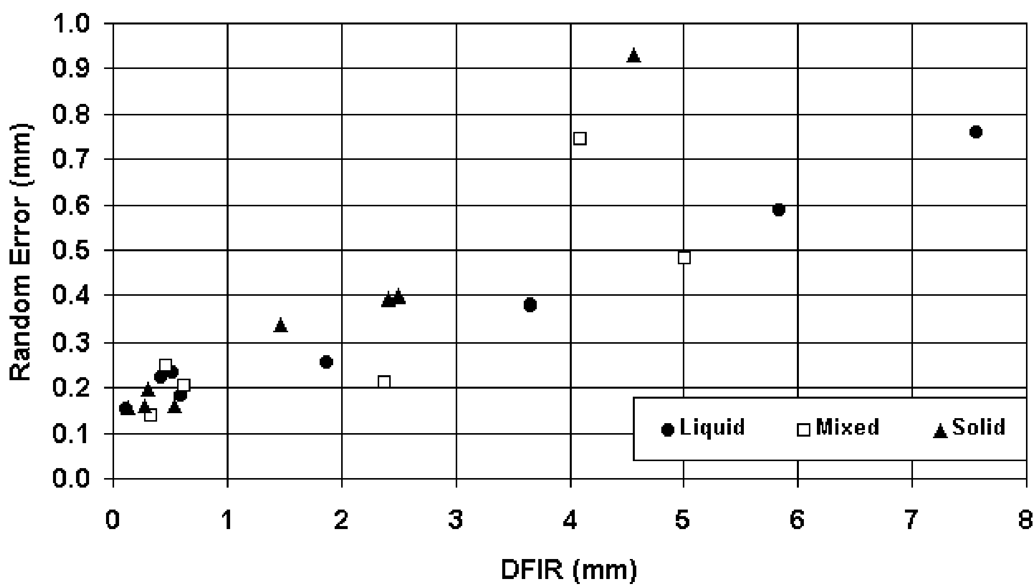


Figure 5.H.10 ***Dependence of measurement error upon the amount of precipitation (DFIR). Components of Error:***
1 - systematic; 2 - random. Types of precipitation: liquid - L, mixed - M, solid - S

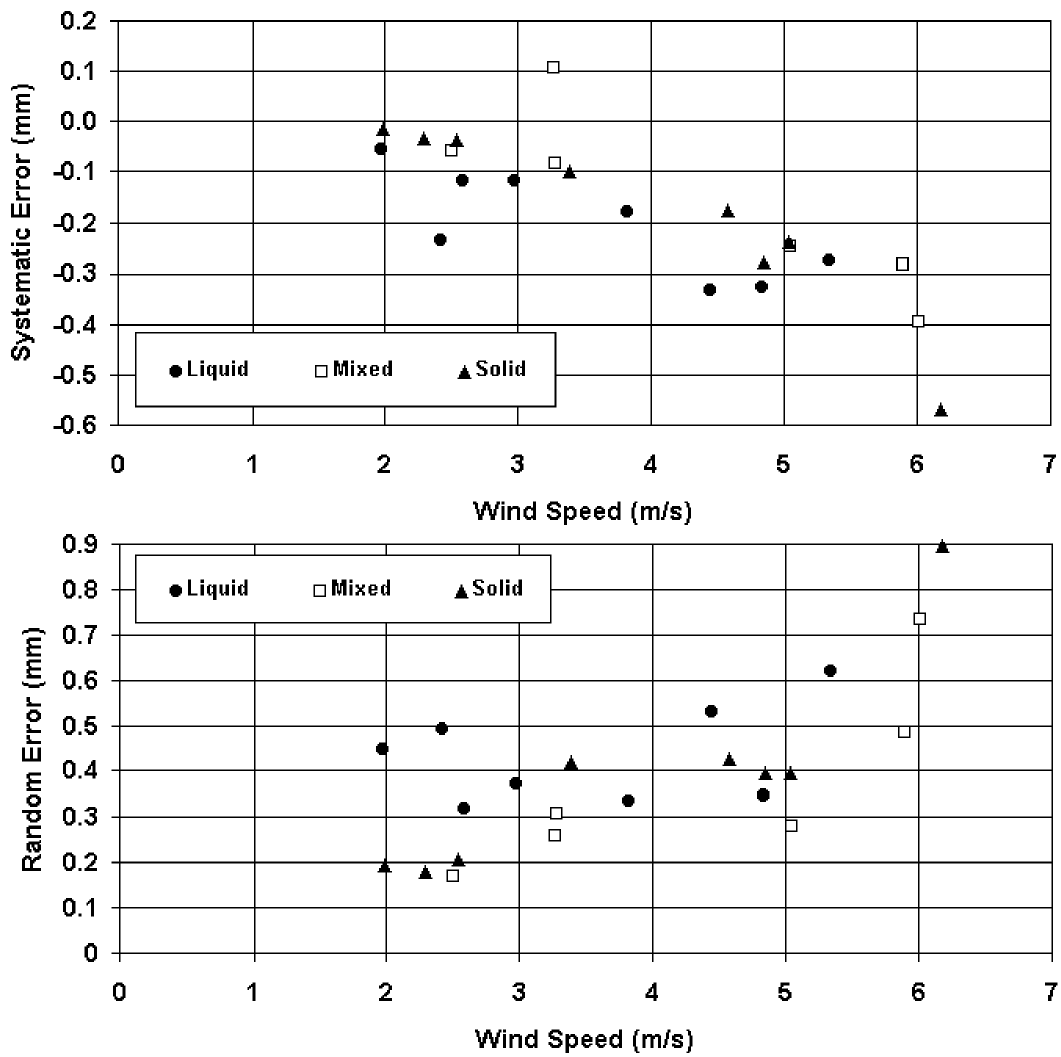


Figure 5.H.11 Dependence of the measurement error upon the wind speed (DFIR). Components of Error: 1 - systematic; 2 - random. Precipitation types: liquid - L, mixed - M, solid - S

Table 5.H.6 Assessment Results of Systematic (ΔP) and Random (δP) Components of Error of Half-daily Precipitation Amounts for the Working Intercomparison Reference (WNRG)

Precipitation type	ΔP, mm	$\pm\delta P$, mm	$\left\lvert \Delta P / \delta P \right\rvert$	$\left\lvert \delta P / \delta P_{VCS} \right\rvert$
Solid	-0.61	0.96	0.63	6.0
Mixed	-0.61	0.84	0.73	4.9
Liquid	-0.30	0.47	0.64	2.9

For all precipitation types measured by the WNRG there is a relation between the absolute values of systematic and random errors and the amount of precipitation and wind speed (Figures 5.H.14 and 5.H.15). The modulus of the ratio of systematic error to random error for the measurement results by the WNRG also depends on the amount of precipitation and the wind speed (Figures 5.H.16 and 5.H.17). As evident from the analysis of these dependencies, the correction of the results of measurements by the WNRG (at measurements very 12-hour) may be effective for precipitation amounts higher than 0.5 mm at the wind speed of 1 m/s and higher because the systematic error under such conditions is close to the random error and exceeds this error ($\Delta P / \delta P \approx\geq 1$).

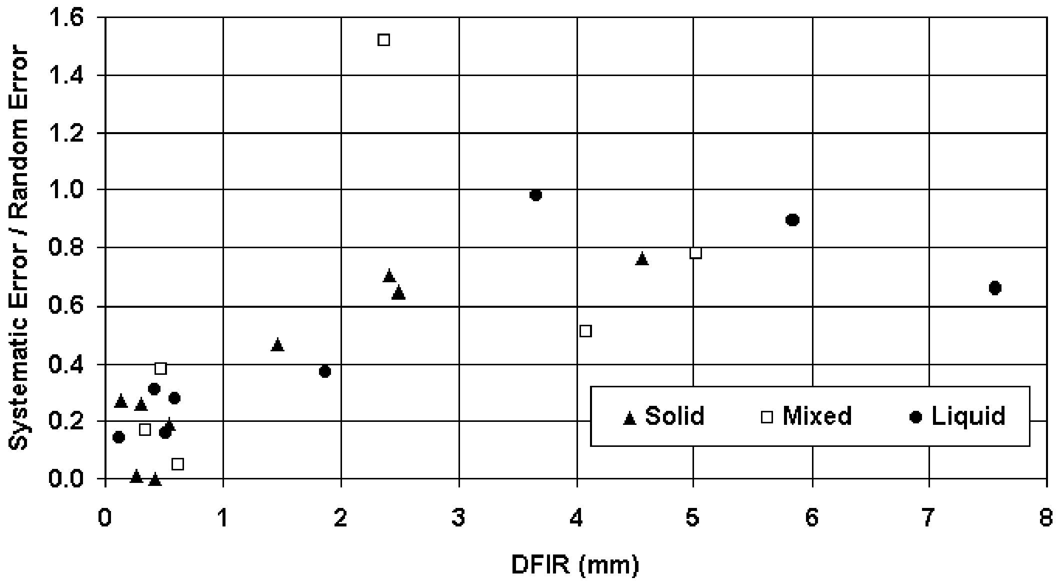


Figure 5.H.12 Dependence of the modulus of the ratio of systematic error to random one upon the precipitation amount. Precipitation types: liquid - L, mixed - M, solid - S

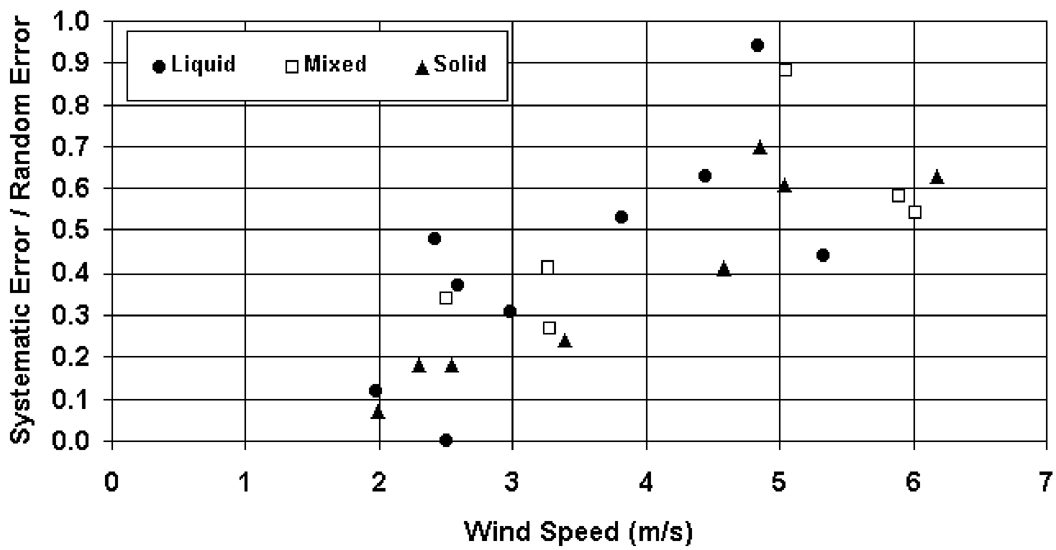


Figure 5.H.13 Dependence of the modulus of the ratio of systematic error of precipitation measurements to random error upon the wind speed (DFIR). Precipitation types: liquid - L, mixed - M, solid - S

3.1.4 Intermediate Reference Precipitation Gauge of the WMO (IRPG)

The results of precipitation measurements by the WMO intermediate reference precipitation gauge (IRPG) in winter are underestimated by 44% on average. The correlation coefficient of monthly precipitation totals between the IRPG and the VCS equals 0.94. The random error equals $\pm$26% on average, and the modulus of the ratio of systematic error to random error of precipitation measurements equals 1.7 [57].The monthly precipitation totals by the IRPG should be corrected by all means.

As evident from the analysis of the correlations of the random errors of the measurement results by the VCS and DFIR, WNRG and IRPG, the VCS may be used as the reference precipitation gauge for precipitation measuring instruments assigned by the WMO during the different periods as the reference gauges for intercomparison. The expediency and possibility of the correction of the results obtained by these gauges for 12-hour and 24-hour periods should be additionally investigated.

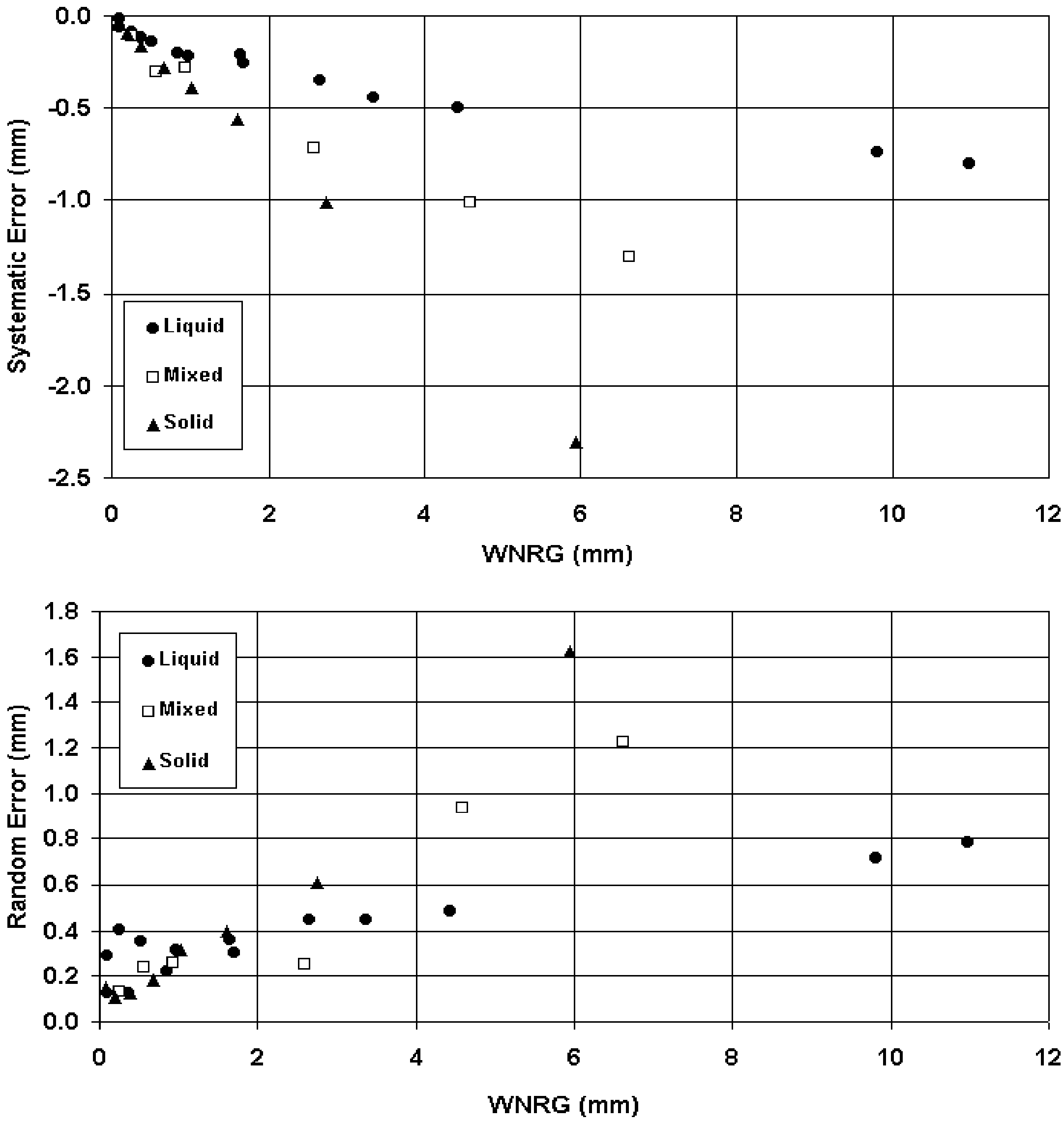


Figure 5.H.14 Dependence of the measurement error upon the precipitation amount. Components of Error: 1 - systematic, 2 - random. Precipitation types: liquid - L, mixed - M, solid - S

3.1.5 Pit Gauge

As evident from the comparison of the readings obtained by the pit gauge and the VCS given in the present report and in the previous publications [19], it is possible to conclude that their readings are in accordance with each other without any significant systematic differences. As the accuracy characteristics of the pit gauge data were not obtained by the methods independent on the VCS this issue should be specially studied in order to assess impartially the quality of the measurements by the pit gauges. This problem is not discussed in this report.

3.2 Errors of the Precipitation Measurement Results by the National Gauges

3.2.1 Nipher Shielded Snow Gauge System (NSSGS)

The Nipher shielded snow gauge system applied in Canada was installed on the precipitation polygon in two variants. One system was installed in usual way (NSSGS), the second one was surrounded by the double fence shield (NSSGSdf). The size and configuration of the fence shields around the Canadian system

(NSSGSdf) and the Tretyakov precipitation gauge (DFIR) corresponded to the standard accepted by the WMO [75].

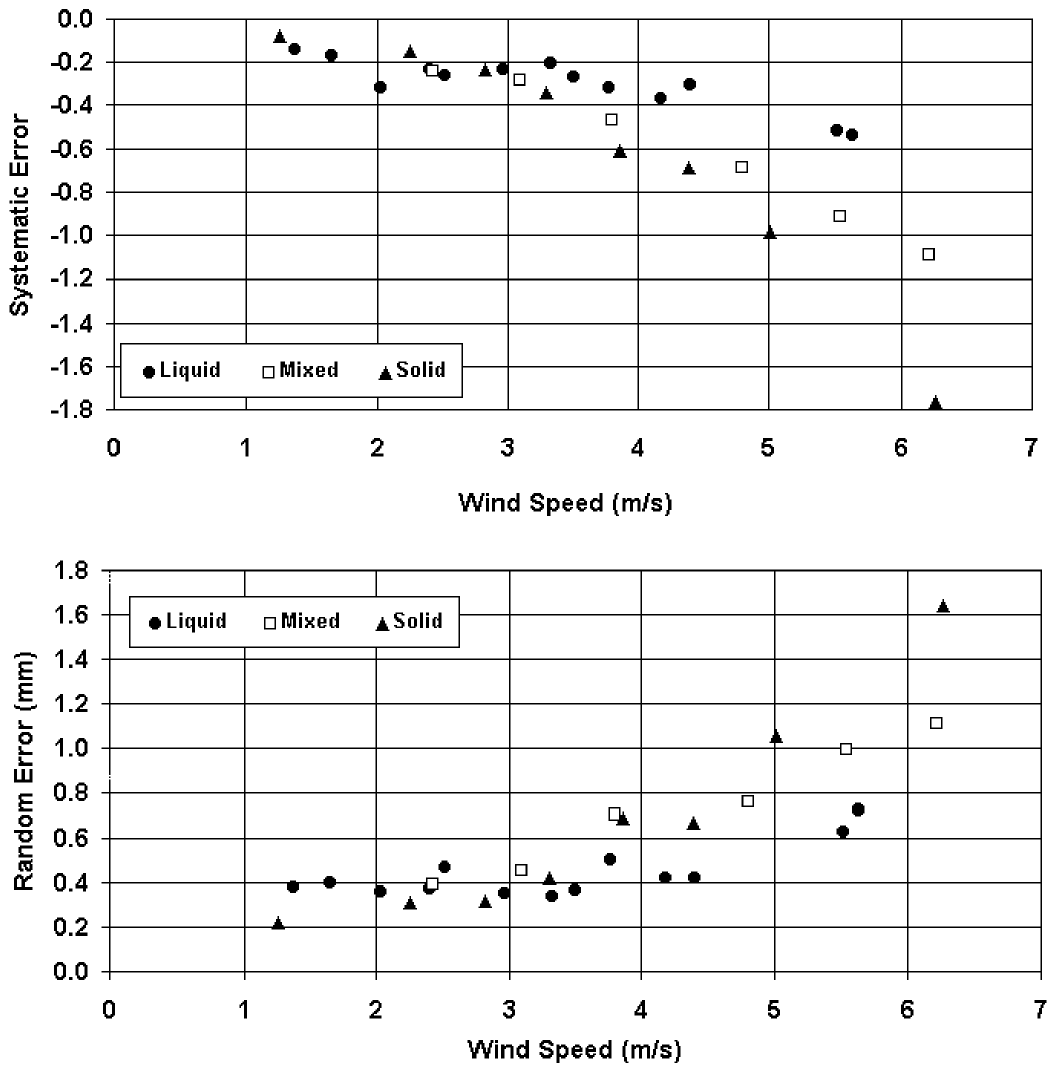


Figure 5.H.15 ***Dependence of the measurement error upon the wind speed (WNRG). Components of Error: 1 - systematic, 2 - random. Precipitation types: liquid - L, mixed - M, solid - S***

The experimental check demonstrated that the decreasing the wind speed within the fence shields above the orifices of the Tretyakov precipitation gauge and the Canadian System are practically the same at the Valdai polygon (Table 5.H.7).

The total amount of precipitation for a year caught by the Canadian System (NSSGS) is by 12% less as compared with the VCS (Table 5.H.8). Underestimation of liquid precipitation was about 7%, of mixed precipitation - about 13% and solid precipitation - 18% [58].

Table 5.H.7 Assessment Results of Wind Speed above the Precipitation Gauges Surrounded by the Double Fence Shields

Speed of forward airflow at 3 m	**Airflow speed in the shield centre above the Tretyakov gauge**		**Airflow speed in the shield centre above the Canadian System**	
U_3, **m/ s**	U_{DFIR} **, m/ s**	U_{DFIR}/U_3	$U_{NSSGSdf}$ **, m/s**	$U_{NSSGSdf}/U_3$
1.5	0.8	0.56	0.8	0.51
2.4	1.2	0.49	1.1	0.47
4.8	2.0	0.42	1.8	0.38
5.6	2.1	0.38	2.1	0.38
6.8	2.5	0.37	2.5	0.37

Table 5.H.8 Monthly Precipitation Totals by the Nipher Shielded Snow Gauge System

Gauge	Monthly precipitation totals in % of VCS											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
NSSGS	78	89	91	88	92	95	89	93	95	90	88	89
NSSGSdf	91	104	99	96	95	97	89	93	96	96	94	96

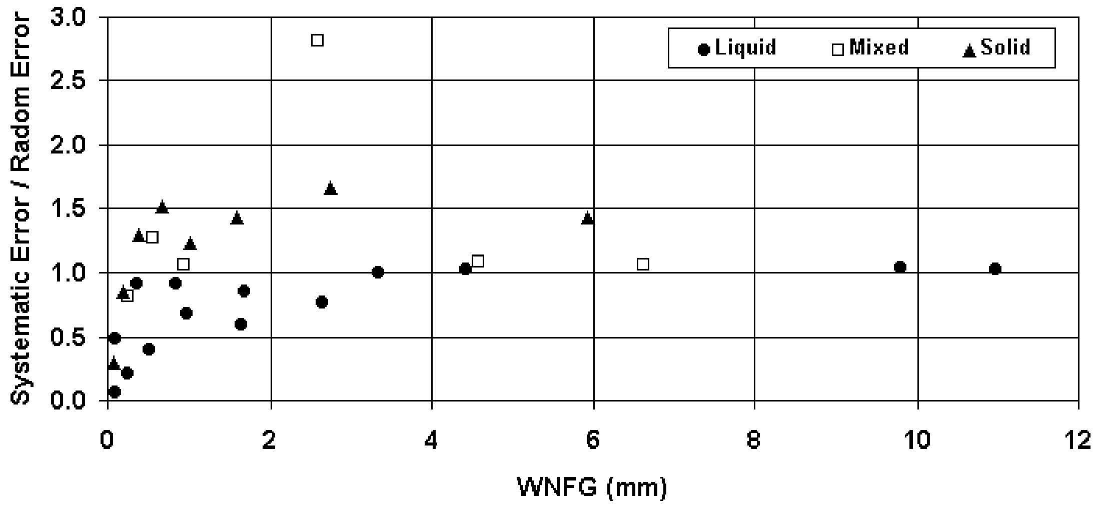


Figure 5.H.16 Dependence of the modulus of the ratio of systematic error to random error of precipitation measurements upon the precipitation amount (WNFG). Precipitation types: liquid - L, mixed - M, solid - S

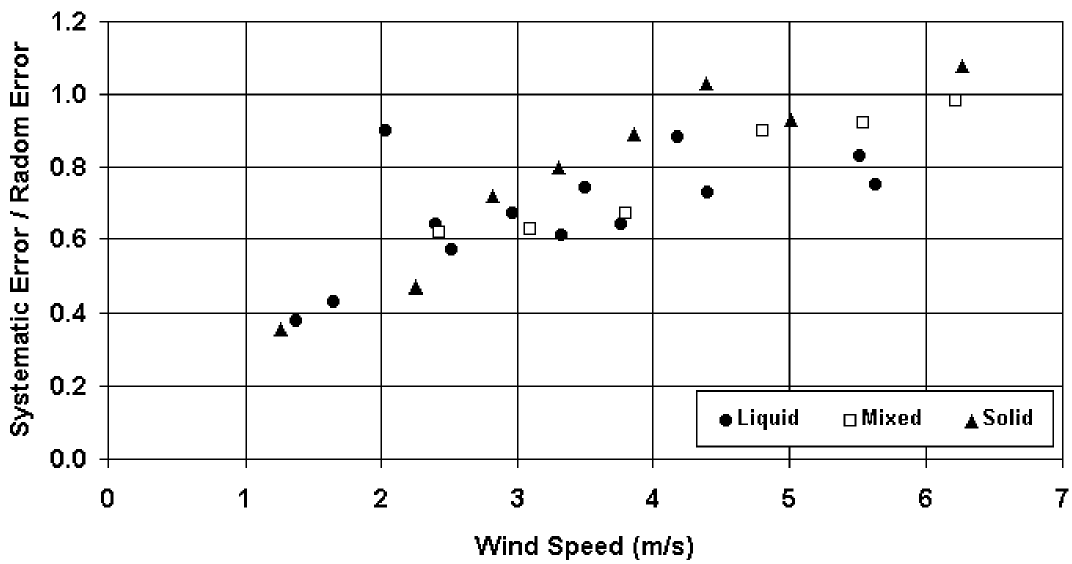


Figure 5.H.17 Dependence of the modulus of the ratio of systematic error to random error of precipitation measurements upon the wind speed (WNRG. Precipitation types: liquid - L, mixed - M, solid - S

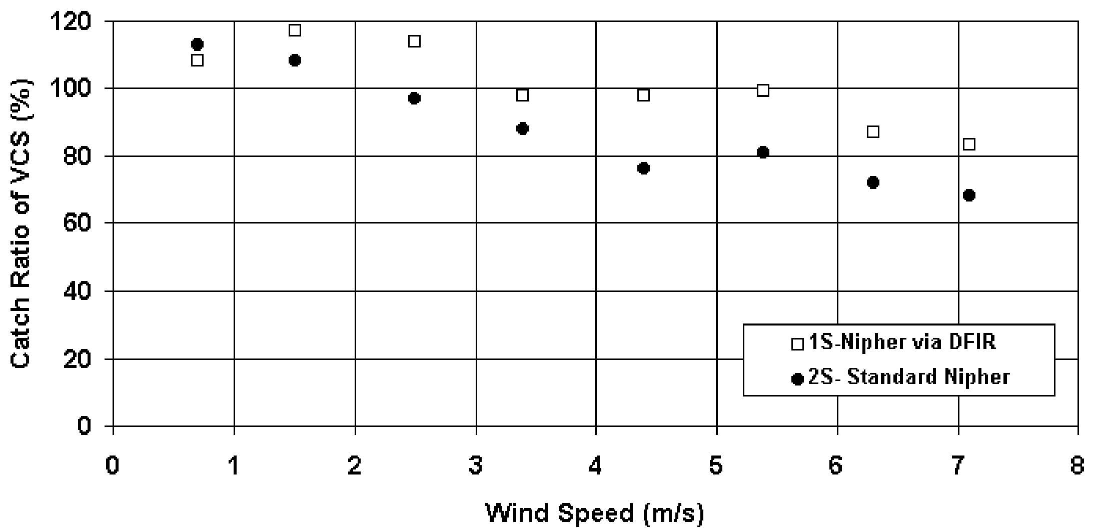


Figure 5.H.18 Amount of solid precipitation caught by the Canadian snow gauge system at different wind speeds
1S - Canadian System surrounded by the double fence shield (NSSGSdf);
2S - standard installation of the Canadian System (NSSGS).

During the observation period the Canadian snow gauge system installed within the double fence shield (NSSGSdf) caught practically the same amount of precipitation as measured by the DFIR, i.e almost 95% of the VCS readings; moreover, the solid precipitation was underestimated by 2%, mixed precipitation - by 8% and liquid precipitation was underestimated by 5%.

When the falling snow is dry at the wind speed lower than 3 m/s, the measurement results by the Canadian Systems as a rule are higher as compared with the data by the VCS. This is explained by the fact that at low wind speeds the snow flakes are stored on the horizontal part of the Nipher shield and when wind speed increases the snow flakes are blown away. At this, some snow flakes fall into the vessel for snow collection and thus making the amount of caught precipitation greater.

3.2.2 Precipitation Gauge of the US Weather Bureau (USWB-8")

Two precipitation gauges of the US Weather Bureau were tested at the precipitation polygon. The both instruments were installed at 1 m above the ground surface. One of the gauges was a cylinder vessel without any shield (USWB-8"unsh.), the second one was the same vessel surrounded by the Alter shield made of lathes (USWB-8"sh.). Proceeding from the obtained results it is possible to conclude that these two precipitation gauges underestimate the amount of precipitation especially in winter months (Table 5.H.9).

Table 5.H.9 Monthly Precipitation Totals by the US Precipitation Gauges

Gauge	**Monthly precipitation totals in % of VCS**											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
USWB-8"unsh.	52	39	64	69	82	91	86	91	90	74	55	54
USWB-8" sh.	70	70	80	82	88	96	92	90	93	78	72	74

In general the unshielded precipitation gauge (USWB-8"unsh.) caught precipitation for the comparison period by 65% less as compared with the VCS; at this, the solid precipitation was underestimated by 61%, mixed precipitation - by 36% and liquid precipitation - by 14%. The similar characteristics of the precipitation gauge surrounded by the Alter shield were much higher. Solid precipitation caught by the USWB-8"sh. precipitation gauge was underestimated by 34%, mixed precipitation - by 23% and liquid precipitation - by 10%. In general for the period of comparison this gauge caught 78% of precipitation as compared with the VCS.

During the analysis of the observation results obtained by the US Weather Bureau precipitation gauges for 24-hour intervals it was discovered that a systematic underestimation depended on the type of precipitation, wind speed and availability of a wind shield (Figure 5.H.19). The data obtained by the unshielded precipitation gauge were underestimated much more if compared with the data obtained by the shielded gauge. The relative underestimation of liquid precipitation is greater if compared with that of solid precipitation.

3.2.3 Standard Precipitation Gauges of Germany, Hungary and Poland

The precipitation gauges applied for regular observations of precipitation in Germany, Hungary and Poland were tested on the precipitation polygon for a long time period. In general these precipitation gauges are termed as a Hellmann precipitation gauge; however, this combination concerns the size of orifice area (200 cm^2), the depth of precipitation bucket (40 cm) and the shape of collector (cylinder). As to the other parameters, such as configuration of cross-section, angle of shear and width of ring restricting the orifice, size of container where the precipitation is stored, material, colour, technology of manufacturing etc., there are the significant differences which may affect the quality of the results. A comparison of the results obtained at the polygon (Table 5.H.10) shows that the Hellmann precipitation gauge made in Germany in winter catches precipitation by 3-6% more than the gauge made in Hungary. During the warm period the results by these precipitation gauges differ by 1%. The Hellmann precipitation gauge made in Poland during the warm period catches by 6% more precipitation as compared with the gauges made in Germany or in Hungary. A detailed examination of the orifice of the Polish precipitation gauge made it possible to discover that the ring restricting the gauge orifice was attached to the cylinder without a special hermetical sealing of separate surfaces (glue, welding or soldering). At the site where the ring was joint to the cylinder there was a narrow chin through which some portion of liquid precipitation might get into the funnel and then into the container. This fact was checked and confirmed by a special experiment with two instruments [43]. It is quite possible that it was a particular case. But it may be expected that the discovered defect may be found anywhere else because it was discovered at the joint of two details made from materials with different coefficients of thermal expansion.

In winter the results of measurements by the Hellmann precipitation gauges are on average underestimated by 56% (Germany and Poland) and by 58% (Hungary) as compared with the VCS. The correlation coefficient between the monthly precipitation totals by the VCS and by the Hellmann precipitation gauges is equal to 0.87 (Germany) and to 0.83 (Poland and Hungary). Random mean-square-root error of monthly totals by these gauges equals $\pm$ 32% (Germany), $\pm$ 33% (Poland) and $\pm$34% (Hungary). Modulus of the ratio of systematic error to random error equals 1.7 [57]. The monthly totals by these gauges should be corrected by all means.

Table 5.H.10 Mean Long Term Relative Values of Monthly Precipitation Totals by the Hellmann Precipitation Gauges

Gauge	**Monthly precipitation totals in % of VCS**											
	1	2	3	4	5	6	7	8	9	10	11	12
Hellmann gauge (Germany)	34	37	49	74	90	94	91	92	90	82	60	40
Hellmann gauge (Poland)	32	33	49	81	90	99	96	98	99	93	66	39
Hellmann gauge (Hungary)	29	34	43	75	89	94	92	93	91	82	60	37

The wind speed effect on the underestimation of precipitation by the Hellmann precipitation gauges is most evident (Figure 5.H.20), but for different types of precipitation there are some peculiarities related to the specific features of manufacturing precipitation gauges in different countries.

Liquid precipitation at low wind speeds is overestimated in the precipitation gauges of Poland and Hungary. In the Polish gauge the overestimation is explained by the effect of water penetration at the joint of the ring and cylinder. This was discussed above in detail. In the Hungarian gauge the overestimation may be explained by the effect of splashing out droplets when the droplets touch a very wide ring which restricts the orifice of the Hungarian gauge.

At the wind speeds exceeding 7 m/s solid precipitation is caught by the Hellmann precipitation gauge so poorly that, if a special centre cross is inserted into the collecting vessel (Germany), the amount of the caught precipitation does not exceed 10% of that caught by the VCS. An expediency and possibility of correcting 12-hour and 24-hour precipitation totals under such conditions require additional studies.

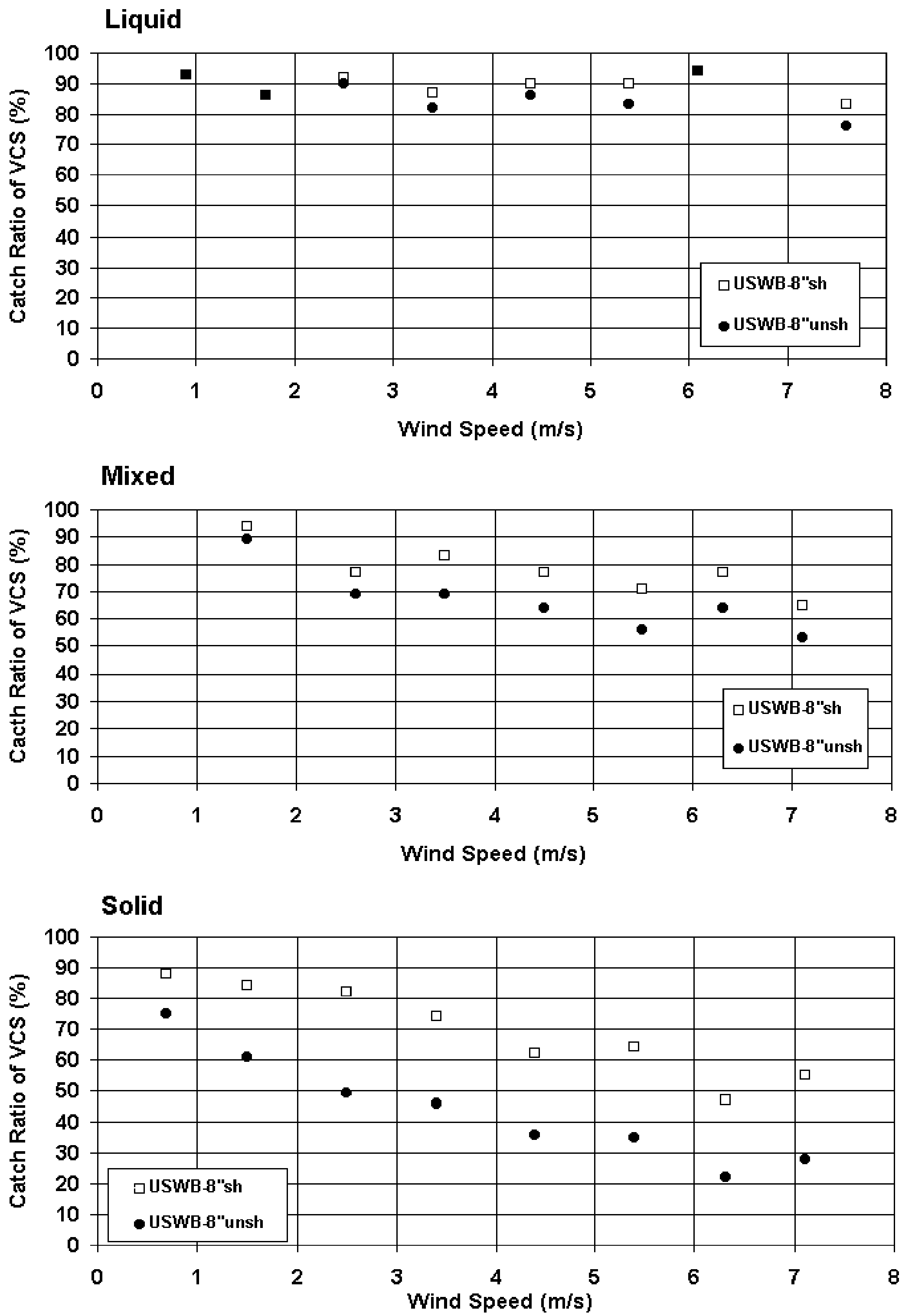


Figure 5.H.19 Precipitation amount (% of VCS) of different types caught by the US Weather Bureau precipitation gauges at different wind speeds.

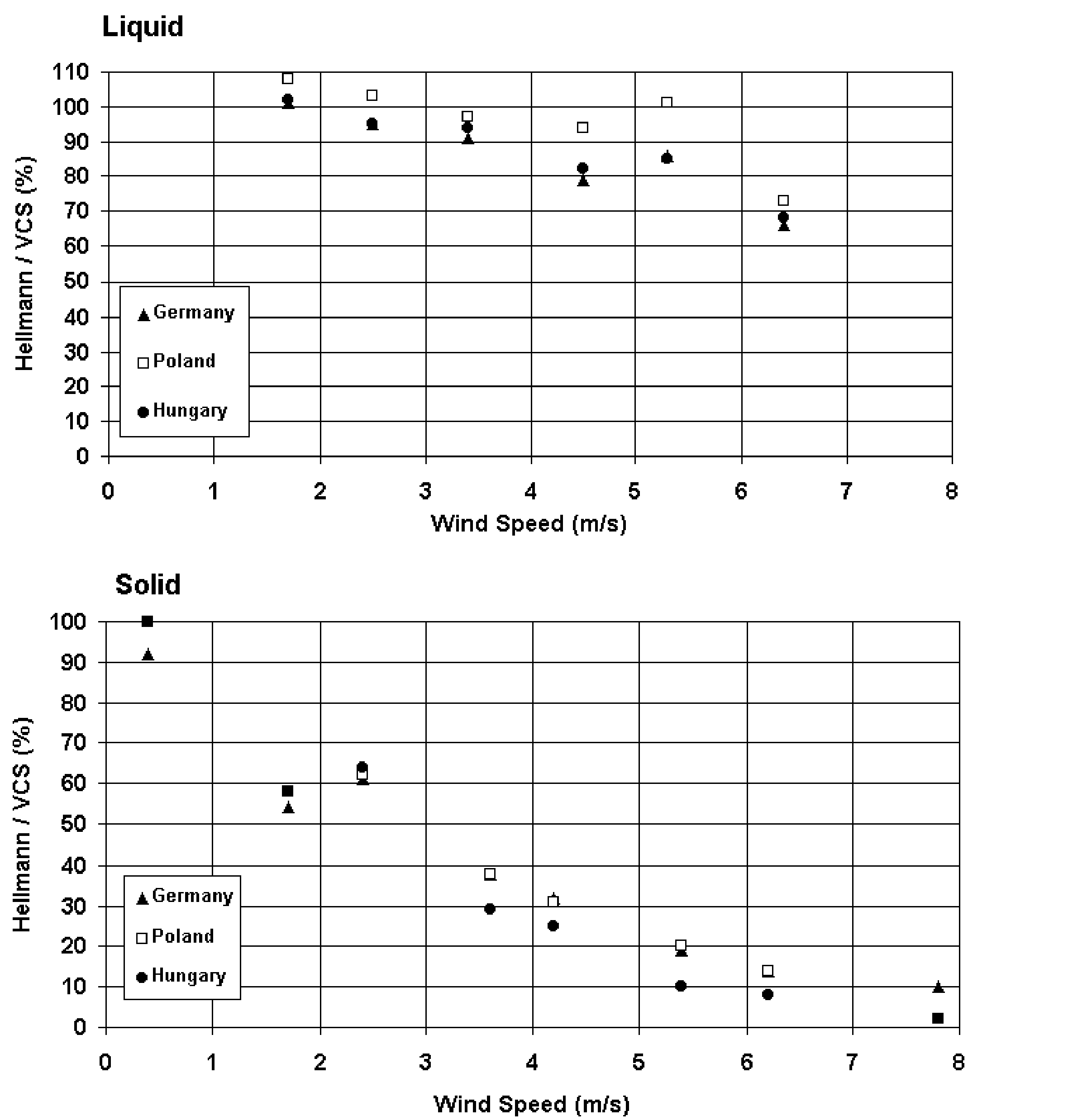


Figure 5.H.20 Amount of different type precipitation (% of VCS) at different wind speeds caught by Hellmann precipitation gauges.

4. CORRECTION OF PRECIPITATION MEASUREMENT RESULTS

4.1 Correction Methods

Methods for correction of precipitation data published in the scientific literature may be conventionally divided into three groups.

The first group, which is quite numerous, embraces models in which for a specific type of the precipitation gauge the empirical relations between individual components of the systematic error (wind field deformation, wetting, evaporation, etc.) and meteorological parameters are used. These methods are widely practiced as they may be applied both to the current observation results and to the data stored during the previous years.

The second group of methods covers models of correction based on empirical relations between the actual precipitation amount and the ratio of readings of two precipitation gauges which greatly differ in aerodynamic features. The methods of this group are not widely applied because no regular network observations by two different precipitation gauges at one site are made. However, these methods are worthy of notice and application to the observation results at the stations which contribute to the intercomparison of solid precipitation measurements.

Methods of correction based on physio-mathematical models may be considered as the third group of methods; these methods are based on the results of precipitation gauge testing in wind tunnel, and they take into account the actual weather conditions and spectral characteristics of atmospheric precipitation according to the size and velocity of falling. From the theoretical viewpoint, this group of methods is most validated. The practical application of these methods is limited in view of the fact that many parameters are not directly observed.

The first and the second groups of methods have two principal drawbacks. One of the drawback is that every author accepted his own reference for comparison. There was no generally acknowledged reference method for precipitation measurements. Intercomparison and the assessment of the accuracy characteristics of control measuring instruments used by different authors was never made. The other drawback is that characteristics of the atmospheric precipitation structure were taken into account by indirect factors. A parameter of precipitation intensity was introduced for liquid precipitation and air temperature was introduced for solid and mixed precipitation. Such solutions, valid for long-term averaged data, may result in great errors for short time intervals during particular years.

In this connection it is reasonable to emphasize an importance of the update intercomparison of the national methods for solid precipitation measurements carried out under the auspices of the WMO. During this intercomparison for the first time we have an opportunity to estimate, firstly, the quality of initial results of measurements and, secondly, the quality of the results corrected by different methods, and on the basis of these estimates we can see quantitatively advantages and disadvantages of various correction methods.

The model which is the basis of the methods for correction of regular precipitation measurements may be presented in form of the equations below:

$$P = KP', \qquad (5)$$

where P is an actual (close to true) amount of precipitation fallen from clouds onto the land surface at observation point; P' is the amount of precipitation caught by precipitation gauge; K is an aerodynamic coefficient (correction coefficient).

The amount of precipitation caught by precipitation gauge consists of the measured precipitation (P'') and a correction (ΔP) compensating precipitation losses when precipitation is in the gauge and when measurements are being performed:

$$P' = P'' + \Delta P. \qquad (6)$$

The precipitation gauge may contain not only water fallen from the clouds (P''_c) but water of ice particles of deflation (blizzard) origin (P''_f) and moisture on the inner walls of the gauge resulted from condensation (P_{cond}):

$$P'' = P''_c + P''_f + P_{cond}, \qquad (7)$$

Then the amount of precipitation from clouds caught by the precipitation gauge would be equal to:

$$P''_c = P'' - P''_f - P_{cond}. \qquad (8)$$

In equation (8) we know only the total amount of the measured precipitation (P''), and the items of this sum taken separately are not known and may be only calculated.

A detailed equation of correction may be presented as follows:

$$P = K(P'' - P''_f - P_{cond} + \Delta P). \qquad (9)$$

The terms in the brackets can be supplied by additional items which take into account water which splashes into the collector when rain drops fall onto the ring around the gauge or onto some other objects around. This water may result from snow flakes, which are blown into the collector from the surface of the wind shield and from other objects near the precipitation gauge.

However, these factors are avoided if possible when regular precipitation measurements are arranged. It is more difficult to solve the problem associated with the estimation of condensed water in the gauge. When there was no precipitation from the clouds, the availability and amount of this water is fixed by the observer as precipitation resulted from dew or hoar-frost. It is hardly possible to answer the question if there was any condensed moisture (and how much) in the gauge or not during the days when precipitation from the clouds occurred. Therefore the condensation of atmospheric moisture on the walls of the gauge (P_{cond}) is either not taken into account during correction or it is taken into account together with the precipitation lost from the vessel for evaporation (P_E) and wetting (P_w) as the only correction (ΔP):

$$\Delta P = P_w + P_E - P_{cond} , \qquad (10)$$

By the present time a great experience has been gained to solve practically equations (9) in the reduced and detailed forms. One of the solution of this equation has been carried out by V.S. Golubev [20]. The empirical parameters of his correction model were determined on the basis of precipitation measurements by the VCS. This model is briefly described below.

4.2 Correction Method of Half-daily and Monthly Precipitation Totals

4.2.1 Model Structure

The model structure of correction of half-daily and monthly precipitation totals developed by Golubev [20, 43] in principle does not differ from the structure of equation (9). There are some differences in the technique of determining the aerodynamic correction coefficient (K) and correction (ΔP) as well as in the techniques of estimating the amount of false precipitation caught by the precipitation gauge during the general and land blizzards. The method and the values of empirical parameters were published in 1973 and in 1975. Later this method was improved but its basic parameters were not changed.

The correction of half-daily and monthly precipitation is carried out according to the following equation:

$$P = K(P" - P"_{f_i} + \Delta P) , \qquad (11)$$

where: K is the aerodynamic correction coefficient; $P"$ is the measured precipitation amount; $P"_{f_i}$ is the amount of false precipitation caught by the precipitation gauge during the general (i =1) and the land (i =2) blizzards; ΔP is a correction to the measured precipitation which takes account of the total systematic errors caused by evaporation, condensation and wetting.

The techniques of computation of the items of equation (9) and the values of empirical parameters for different time intervals differ and are given below.

4.2.2 Aerodynamic Coefficient

The aerodynamic correction coefficient shows in how many times it is necessary to increase the amount of precipitation caught by the precipitation gauge to obtain the actual amount, i.e. precipitation quantity fallen from clouds onto the ground surface at a point of observations. The values of the correction coefficient are connected with the aerodynamic features of the precipitation gauge design, with the fall velocity of precipitation particles (equilibrium fall velocity in air) and dynamic characteristics of air flow during precipitation fall.

(a) aerodynamic coefficient for half-daily precipitation amounts

The formula for computation of the correction coefficient for 12-hour time interval is as follows:

$$K = 1 + A_0 \mu^2 U_h^{\ 2} , \qquad (12)$$

where wind speed at height of the precipitation gauge (U_h) and relative air density (parameter μ) are used to estimate the energy of dynamic effect of turbulent air flow on the precipitation gauge during the precipitation fall, and the empirical parameter A_0 is used to estimate the measure of this energy effect change under the conditions of standard atmosphere expressed by means of the correction coefficient depending on the type of precipitation gauge (aerodynamic features) and the type of precipitation (fall velocity). The standard atmosphere is the air density at temperature (t_a) equaled to 0 ^0C , air humidity (e_a)

equaled to 0 hPa and atmospheric pressure (p_a) of 1000 hPa. If all these meteorological parameters are observed, the parameter μ is computed from the following equation:

$$\mu = \frac{p_a}{1000} \times \frac{273}{273 + t_a} \times \frac{p_a}{p_a + 0.4e_a} . \qquad (13)$$

If the data on the atmospheric pressure and air humidity are not available, the relative air density may be computed from the following equation:

$$\mu = 1.013 \times (1 - \frac{6.5H}{288})^{5.255} \times \frac{273}{273 + t_a} , \qquad (14)$$

where H is a site elevation above mean sea level, in km.

Parameter A_0 has been derived from the data of special precipitation measurements by the following equation:

$$A_0 = \frac{P - (P'' + \Delta P)}{(P'' + \Delta P)\mu^2 U_h^2} , \qquad (15)$$

where: P is the actual precipitation fallen from the clouds onto ground surface (in the studies of V.S. Golubev the value of P is accepted from the results of measurements by the VCS); P'' is the amount of precipitation caught by the tested precipitation gauge. The averaged A_0 values for the different precipitation types for 12-hour time interval are given in Table 5.H.11.

When the correction coefficient is computed to assess of the actual precipitation for 12-hour or 24-hour periods it has been recommended to use equation (11) with the meteorological components averaged over 12-hour or 24-hour periods.

Table 5.H.11 The Values of A_0 Parameter for the Different WMO References

Intercomparison reference	**A_0 parameter value for precipitation types**			
	solid	**mixed**	**liquid**	
			at $t_a \le 2^0 C$	**at $t_a > 2^0 C$**
DFIR	0.005	0.005	0.005	0.003
WNRG	0.0.33	0.017	0.008	0.004
IRPG	0.050	0.027	0.009	0.004

(b) Aerodynamic coefficient for monthly precipitation

It has been recommended to calculate the correction coefficient for monthly precipitation totals using the following equation:

$$K = 1 + A\mu^2(\omega U_h)^2 , \qquad (16)$$

where: $A = A_i(\alpha - thx)$,
$x = \gamma(t_a - \beta)$,
$\omega = 1.485 - \ln n$.

Here n is the number of days with precipitation during a month; A_i is a measure of aerodynamic effect of air flow on the precipitation gauge readings under standard conditions; th is a function of hyperbolic tangent; ω is a coefficient of transition from mean monthly wind speed to its effective value for days with precipitation; α, β, γ are the empirical coefficients. The values of A_i, α, β, γ coefficients are accepted depending on the type of precipitation gauge (Table 5.H.12).

Table 5.H.12 The Values of A_i, α , β , γ Parameters for Monthly Precipitation Amounts

Precipitation type	Parameter values			
	A_i	α	β	γ
DFIR	0.0050	1.0	0	0.01
WNRG	0.0165	1.1	1	0.10
IRPG	0.0350	1.1	-1	0.20

The mean monthly values of air temperature, wind speed and other meteorological parameters are used for the calculation by equation (15).

4.2.3 Correction for Wetting, Evaporation and Condensation

The systematic errors related to precipitation losses from the precipitation gauge and during the measuring precipitation are studied quite well and in principle these errors are not high. However, a reliable estimation of these errors during a correction of observation results is a complicated methodological problem. This is related to absence of the information on the fact whether the bucket for precipitation collection was wet or dry when the observer exposed it, how many times this bucket was wetted by rain, and how many times it was dry during the exposure, whether the inner walls of the bucket were wetted completely or partially during a particular measurement. Besides, it is practically unknown if there was any condensation of water vapour on the inner walls and how much it was if any.

The measurements of evaporation out of different precipitation gauges show (Figure 5.H.21) that if air humidity is close to saturation, a condensation is possible on the inner walls of the precipitation gauge.

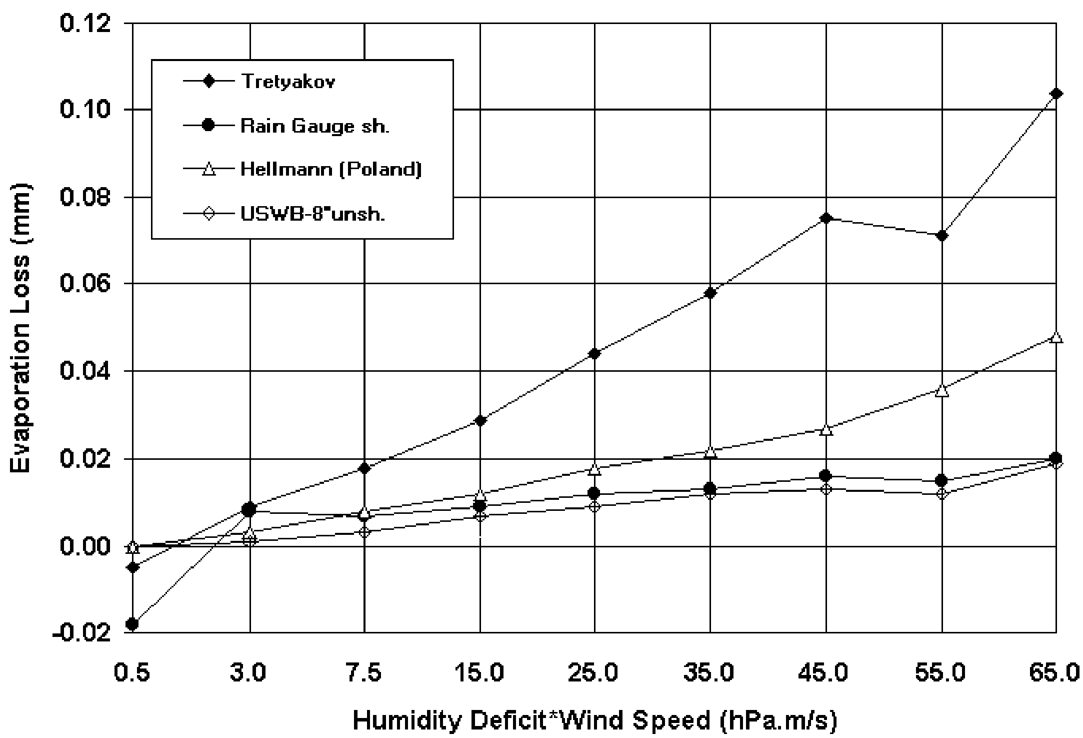


Figure 5.H.21 Dependence of evaporation rate of precipitation out of the precipitation gauge (E, mm/h) on a value of product of air humidity deficit (d, hPa) by wind speed (U, m/s).
1 - Tretyakov precipitation gauge; 2 - rain gauge with Nipher shield; 3 - Hellmann gauge (Poland);
4 - precipitation gauge USWB-8"unsh

The analysis of precipitation measurement results by two sets of gauges of the same type (in one of them standard volumetric measurements are performed; in the other one the weighing measurement technique with an addition of mineral oil as evaporation depressor are used) shows (Table 5.H.13) that the total monthly losses (if precipitation is in the bucket) reach 15% in Valdai. In winter when the spare bucket is kept in a warm building and it is highly possible that it would be exposed dry for measurements, the total precipitation losses in its relative expression is higher as compared with those in summer when the spare bucket is kept under usual conditions and it often cannot be dry during 12 hours.

Table 5.H.13 Mean Long-Term Relative Monthly Total Precipitation by Different Precipitation Gauges

Gauge	Monthly precipitation totals and its differences in % of VCS											
	1	2	3	4	5	6	7	8	9	10	11	12
Tretyakov gauge bucket:												
weighing technique	33	39	53	79	84	92	89	91	86	72	61	41
volumetric technique	31	33	45	68	82	91	89	88	85	77	56	36
difference of readings	2	6	8	11	2	1	0	3	1	-5	5	6
Tretyakov gauge:												
weighing technique	62	67	75	89	88	94	92	94	89	88	77	66
volumetric technique	57	64	79	81	90	96	93	94	91	89	75	63
difference of readings	5	3	-4	8	-2	-2	-1	0	-2	-1	2	3
Rain gauge bucket:												
weighing technique	38	42	55	82	87	93	91	93	91	81	64	43
volumetric technique	23	26	42	70	86	94	92	93	91	81	56	31
difference of readings	15	16	13	12	1	-1	-1	0	0	0	12	12
Rain gauge with Nipher shield:												
weighing technique	51	56	66	85	91	95	93	95	91	86	71	57
volumetric technique	46	51	61	81	91	97	94	96	96	89	70	54
difference of readings	5	5	5	4	0	-2	-1	-1	-5	-3	1	3

The experience of taking account of precipitation losses for wetting and evaporation from precipitation gauge convinces that it is a complicated methodological problem, which is better solved for a monthly time interval than for a particular period of measurements.

The generalized values of corrections (ΔP) are accepted in the model by Golubev where evaporation, wetting and condensation are taken into account totally.

(a) Correction to half-daily precipitation amounts

The correction to half-daily measured precipitation amounts is introduced with the sign plus (+) taking account of precipitation type, its amount and type of the precipitation gauge (Table 5.H.14a).

Table 5.H.14a Corrections ΔP for half-daily Precipitation amounts

Precipitation type	Measured precipitation amount (P", mm)					
	P" = 0.0			P" $\geq$ 0.1		
	solid	mixed	liquid	solid	mixed	liquid
DFIR	0.0	0.1	0.1	0.1	0.2	0.2
WNRG	0.0	0.1	0.1	0.1	0.2	0.2
IRPG	0.0	0.05	0.0	0.05	0.05	0.0

(b) Correction to monthly total precipitation

The correction to monthly total of the measured precipitation is computed by the following equation:

$$\Delta P = qn\,, \tag{17}$$

where q is a mean correction for 24 hours with precipitation; n is the number of days with precipitation during a month.

Mean daily corrections are in Table 5.H.14b, with the account of mean monthly air temperature and the type of precipitation gauge.

Table 5.H.14b   Mean Daily Corrections to Monthly Total Precipitation

Precipitation type	**Mean daily correction at mean monthly air temperature**		
	$t_a \leq$ **-2**	**-2 <** t_a **< 2**	$t_a \geq$ **2**
DFIR	0.15	0.2	0.3
WNRG	0.15	0.2	0.3
IRPG	0.05	0.05	0.0

4.2.4 Account of False Precipitation

The amount of false precipitation caught by the precipitation gauge ($P_f^{,,}$) is computed proceeding from the information on the blizzard nature (general or land), its duration and total blizzard discharge.

On the basis of the physical analysis of the process of falling the blizzard particles into the precipitation gauge and basing on the research results of A.K. Dyunin [77], L.R. Struser [76] in 1971 proposed a theoretical approach to a quantitative assessment of false precipitation caught by the precipitation gauge during general and land blizzards. At this, Struser accepted the following assumptions:

- velocity of equilibrium fall of blizzard particles in air equals 0.3 m/s on average at any air temperature;
- vertical wind profile in blizzard flow is the same as in air flow without suspended solid particles, i.e. it is close to logarithmic;
- solid blizzard discharge varies over height according to the hyperbolic law;
- aerodynamic coefficient of precipitation gauge for deflation particles at any air temperature when blizzards occurred is equal to the correction coefficient for snowfalls at the air temperature of -20 ^0C.

The amount of false precipitation in the precipitation gauge is proportional to intensity of drifting and duration of blizzard. The intensity of the drifting the false precipitation into the bucket, in turn, depends on the total blizzard discharge, the aerodynamic features of the precipitation gauge and the orifice height above the ground. The total blizzard discharge depends on the wind speed, features of snow cover surface and length of blizzard run.

To estimate false precipitation caught by the Tretyakov precipitation gauge during a blizzard, Struser [44, 76] proposed two calculation formulas based on the assessments of the total discharge of saturated blizzard using the equation by V.M. Kotlyakov [78]. The gauge height in these equations was accepted to be constant and equal to 2 m.

To make the formulas by Struser universal, these formulas were supplemented by two correcting multipliers. The first multiplier (B_h) takes account of a transition from the height of 2 m to the actual height of the gauge (h). The second multiplier (L_f) takes account of the air flow saturation by deflation particles depending on the length of run and nature of blizzard at the appropriate wind direction.

Thus taking into account these multipliers the equation for a computation of the false precipitation amount caught by the gauge during the general blizzard is as follows:

$$P_{f_1}^{,,} = 0.033(U_2{}^{2,2} - 4.2^{2.2})\frac{1}{KU_2} B_h L_f \tau_{f_1}, \quad (\text{ at } U_2 \leq 4.2\ ,\ P_{f_1} = 0). \qquad (18)$$

The amount of false precipitation caught by the gauge during the land blizzard is calculated by the following equation:

$$P_{f_2}'' = 8.9 \cdot 10^{-6} (U_2^{5.1} - 8.5^{5.1}) \frac{1}{KU_2} B_h L_f \tau_{f_2}, \text{ (at } U_2 \leq 8.5 \text{ , } P_{f_2} = 0\text{)}. \qquad (19)$$

Here τ_{f_1} and τ_{f_2} are the durations of general and land blizzards, respectively; U_2 a is a wind speed at height of 2 m; K is a correction coefficient of the precipitation gauge.

$$B_h = \frac{2}{h} \times \ln\frac{2}{z_0} \times (\ln\frac{h}{z_0})^{-1} , \qquad (20)$$

where z_0 is a height of layer of the snow cover dynamic roughness.

$$L_f = th \frac{\varepsilon l}{l_0} , \qquad (21)$$

where ε is the coefficient equal to 1 in case of land blizzard and equal to 3 in case of general blizzard; l is a length of blizzard run along the definite wind direction (azimuth or compass point); l_0 is a length of the saturated blizzard run.

As evident from the analysis of the equations (19) and (20), false precipitation may be caught by the precipitation gauge during snowfalls at the wind speeds higher than 4.2 m/s. During land blizzard the deflation particles may be blown into the gauge bucket at the wind speeds of 8.5 m/s and higher. At the processing of solid precipitation measurement results these facts should be taken into account at each point of intercomparison.

4.3 Results of Correction of the Precipitation Values Measured by Different Gauges

4.3.1 Intercomparison Reference(DFIR)

The correction of half-daily and monthly precipitation by the Double Fence Intercomparison Reference (DFIR) has been carried out using the method developed by Golubev [20, 61]. A detailed description of computation procedure is given in [56, 62]. Here the major emphasis is focussed on the characteristics of accuracy and efficiency of correction according this method. It should be also noted that the conclusions and assessments are preliminary because they are based on the selected observation series and on the correction model which does not contain a block for an account of false precipitation. The obtained estimates of systematic and random errors of the measured and corrected precipitation values by the Intercomparison reference (DFIR) are given in Table 5.H.15.

Table 5.H.15 Estimates of Systematic (ΔP) and Random ($\pm\delta P$) Errors of the DFIR measured and corrected data

Period of summing	**Measured precipitation**			**Corrected precipitation**		
	ΔP, %	$\pm\delta P$, %	$\left\lvert\frac{\Delta P}{\delta P}\right\rvert$	ΔP, %	$\pm\delta P$, %	$\left\lvert\frac{\Delta P}{\delta P}\right\rvert$
12 hours (solid precipitation)	-9	16	0.6	2	18	0.1
Month (cold period of year)	-9	10	0.95	-2	6	0.3
Month (annual cycle)	-7	7	1	-1	5	0.2

For half-daily solid precipitation amounts the correction may be not effective because the random error of the initial (basic) data is about twice higher than the systematic error. To make this correction effective it is necessary to reduce the random component of the error. The modulus of random error would be close to systematic error if the number of the same type reference gauges with the same accuracy is increased up to three. Then the random error of mean measurement result would be about 10%, and the correction would be necessary but it would be related to the result of observations averaged over three instruments.

After the correction of the half-daily solid precipitation values by the DFIR the systematic error was reduced in about 4 times (up to 2%), while the random error was increased by 2% higher and was equal to 18%. The modulus of the ratio of systematic error to random one was reduced from 0.6 to 0.1 and this bears evidence to the fact that the repeated correction to the 12-hour precipitation amounts are not required, and meanwhile the random error of the corrected data remained high.

The monthly total precipitation during a cold period of year contains the systematic error which is almost equal to the random one. In this case the data correction is essential. The corrected results have the remains of systematic error equal to -2%. The random error is equal to 6%. The modulus of the ratio of systematic error to random one equals 0.3. In case of such ratio of errors the correction is quite effective, and the quality of data corrected by the applied method may be characterized only by the value of random error.

The monthly total precipitation for the annual cycle contain the systematic, and random errors and their ratios are close to similar characteristics for the cold period of year. Therefore the conclusions for the cold period are completely applied to the annual cycle.

Further, the modulus values of the ratio of the random error of the basic data obtained by the different precipitation gauges to the appropriate random error of the corrected data obtained by the DFIR (Tables 5.H.16 to 5.H.19) were estimated.

Table 5.H.16 Tretyakov Precipitation Gauge (WNRG)

Period of summing	Measured precipitation			
	ΔP, %	$\pm\delta P$, %	$\left\lvert\frac{\Delta P}{\delta P}\right\rvert$	$\left\lvert\frac{\delta P}{\delta P_{DFIR}}\right\rvert$
12 hours (solid precipitation)	-43	45	0.95	2.5
Month (cold period of year)	-34	22	1.5	3.7
Month (annual cycle)	-18	15	1.2	3.0

Table 5.H.17 Intermediate Reference Precipitation Gauge of WMO (IRPG)

Period of summing	Measured precipitation			
	ΔP, %	$\pm\delta P$, %	$\left\lvert\frac{\Delta P}{\delta P}\right\rvert$	$\left\lvert\frac{\delta P}{\delta P_{DFIR}}\right\rvert$
12 hours (solid precipitation)	-51	48	1.1	2.7
Month (cold period of year)	-44	26	1.7	4.3
Month (annual cycle)	-23	20	1.2	4.0

Table 5.H.18 Rain gauge with Nipher Shield

Period of summing	Measured precipitation			
	ΔP, %	$\pm\delta P$, %	$\left\lvert\frac{\Delta P}{\delta P}\right\rvert$	$\left\lvert\frac{\delta P}{\delta P_{DFIR}}\right\rvert$
12 hours (solid precipitation)	-58	56	1.0	3.1
Month (cold period of year)	-43	26	1.7	4.3
Month (annual cycle)	-19	19	1.0	3.8

Table 5.H.19 Hellmann Precipitation Gauge (Germany)

Period of summing	Measured precipitation			
	ΔP, %	$\pm\delta P$, %	$\left\lvert\frac{\Delta P}{\delta P}\right\rvert$	$\left\lvert\frac{\delta P}{\delta P_{DFIR}}\right\rvert$
12 hours (solid precipitation)	-67	57	1.2	3.2
Month (cold period of year)	-56	32	1.8	5.3
Month (annual cycle)	-27	24	1.1	4.8

In the cases under the consideration these ratios vary from 2.5 to 5.3 that, according to the meteorological requirements, indicates that the corrected precipitation values obtained by the DFIR may be used as the reference data for the results of measurements by the WNRG and IRPG references of the WMO as well as by the national precipitation gauges both without wind shields and with wind shields.

4.3.2 Working and Intermediate Reference Precipitation Gauges of the WMO (WNRG, IRPG)

The data of observations obtained by the WNRG and IRPG have been corrected by the same method. The remains of systematic error for the corrected precipitation values do not exceed a half of the random error (Table 5.H.20).

Table 5.H.20 Estimates of Systematic (ΔP) and Random ($\pm\delta P$) Errors of the Corrected Data Obtained by the Working (WNRG) and Intermediate (IRPG) References of the WMO

Period of summing	WNRG			IRPG		
	ΔP, %	$\pm\delta P$, %	$\left\lvert\frac{\Delta P}{\delta P}\right\rvert$	ΔP, %	$\pm\delta P$, %	$\left\lvert\frac{\Delta P}{\delta P}\right\rvert$
12 hours (solid precipitation)	0.4	32	0.0	3.8	39	0.1
Month (cold period of year)	1.5	11	0.1	6	16	0.4
Month (annual cycle)	7	14	0.5	-0.2	13	0.1

Further, on the basis of the estimates of the random error of the corrected values (δP_{WNRG} and δP_{IRPG}) and estimates of random errors of uncorrected total precipitation obtained by the rain gauge with Nipher shield (see Table 5.H.18) and Hellmann precipitation gauge (see Table 5.H.19), the modulus values of the ratios of these random errors (Table 5.H.21) were considered.

Table 5.H.21 Moduli of Random Errors Ratios

Period of summing	Rain gauge with Nipher shield		Hellmann gauge	
	$\left\lvert\frac{\delta P}{\delta P_{WNRG}}\right\rvert$	$\left\lvert\frac{\delta P}{\delta P_{IRPG}}\right\rvert$	$\left\lvert\frac{\delta P}{\delta P_{WNRG}}\right\rvert$	$\left\lvert\frac{\delta P}{\delta P_{IRPG}}\right\rvert$
12 hours (solid precipitation)	1.75	1.44	1.78	1.46
Month (cold period of year)	2.36	1.63	2.91	2.00
Month (annual cycle)	1.36	1.46	1.71	1.85

Proceeding from the analysis of the obtained results it is possible to conclude that the corrected values obtained by the Working and Intermediate references of the WMO cannot be applied for calibration of observation results obtained by the national precipitation gauges, the random errors of which are close to the accuracy characteristics of the rain gauge with the Nipher shield or the Hellmann precipitation gauge. For calibration purposes at least three reference precipitation gauges should be installed at each point of intercomparison.

5. CONCLUSIONS

The experience gained during the intercomparison of solid precipitation measurements at the experimental polygon in Valdai (Valdai Branch of the State Hydrological Institute) makes it possible to draw the following conclusions:

1) The results of measurements by the Double Fence Intercomparison Reference (DFIR) should be corrected to eliminate systematic error;

2) The corrected results of measurements by the Double Fence Intercomparison Reference are suitable for calibration of the results of measurements by the standard national gauges;

3) It would be desirable that the National Services for hydrometeorology and the WMO take appropriate measures on the conservation of the experimental bases organized during the third period of the third WMO intercomparison for the nearest 10-year period to study new methods for precipitation measurements, to test methods of correction as well as to estimate the quality of the corrected precipitation data using independent material;

4) In addition during that 10-year period it should be given a special attention to the studies and account of precipitation of deflation origin.

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ANNEX 5.I SLOVAKIA

SOLID PRECIPITATION MEASUREMENTS INTERCOMPARISON IN SLOVAKIA

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1. INTRODUCTION

Precipitation measurements intercomparison by various gauges was made at the Bratislava-Koliba observatory since 1975, the results were published in several papers and reports (Lapin and Priadka, 1987, Lapin and Šamaj, 1991, Lapin, 1993). Limited intercomparisons were also conducted at 2 other Slovak meteorological stations (Lapin, 1993). Method of correcting the systematic errors in precipitation measurement was developed and accepted in former Czecho-Slovakia in 1985. Correcting method for errors due to wetting and evaporation losses was simplified and considered as a final version. Method of correcting wind induced errors was considered as a preliminary one.

In this report the results of the WMO Solid Precipitation Measurement Intercomparison Project (Goodison, et al., 1988) for the period of 1987-1993 are presented. The importance of wind induced error in solid precipitation measurement was emphasized.

2. SITE AND DATA

The Bratislava-Koliba observatory is situated at the flat top of a hill in the Little Carpathians (286 m a.s.l., 150 m above the surrounding lowland). Mean air temperature and total precipitation are -2.0 °C and 43 mm in January and 19.3 °C and 74 mm in July, the annual total precipitation is 669 mm. Mean number of days of snow cover are 49.8 (34.3 days ≥ 5 cm, 14.3 days ≥ 5 cm in January) and the mean number of days with solid or mixed precipitation are 39. The site is relatively windy, with annual mean wind speed at 22.5m being 4.6 m/s (5.1 m/s in winter). Wind regime in winter is summarized as follows: calm 2.4 %, 1-2 m/s 27.3 %, 3-5 m/s 38.5%, > 5 m/s 27.9 %.

The pluviometric polygon at the Bratislava-Koliba observatory was established in 1975 and measurements are provided by standard Metra gauge (orifice at 1m height, unshielded, different version for snow and rain observations), standard Russian Trtyakov gauge (2 m height, shielded), standard Hellmann gauge (1 m height, unshielded, Hungarian version), shielded Metra gauge (Tretyakov wind shield and Nipher wind shield), sunken Metra and Hellmann gauges (with orifice at the ground level) and some other gauges with different wind shields and paintings (Lapin and Pridka, 1987, Lapin and Šamaj, 1991, Lapin, 1993).

Precipitation measurements were made daily at 7 a.m. (mean local time). The daily intercomparison measurements by the standard Metra and Tretyakov gauges were analyzed in this report.

3. RESULTS

Daily precipitation measured by the Metra gauge were corrected for wetting and evaporation losses according to the method presented by Lapin and Priadka (1987). Daily data observed by the Tretyakov gauge were corrected for wetting loss only, correction of evaporation loss was not conducted..

Intercomparison measurements of the Metre and Tretyakov gauges for the winter seasons of 1987/88 to 1992/93 were summarized in Table 5.I.1. Total precipitation and averaged catch ratios of the Metra gauge (shielded and unshielded) to the Tretyakov gauge were presented for various precipitation types. The Tretyakov gauge was designated as the working reference when the DFIR was not installed for the intercomparison (WMO, 1985); thus, it is used as a reference in this analysis.

The average catch ratios of the unshielded Metra gauge range from 89.7% for rain to 81.5% for snow. The difference of the catch ratios between snow and rain are relatively small, because of the low wind speed at the site. The catch ratios of shielded Metra gauge vary from 92.3% for rain to 107.8% for snow. It catches more snow than the Tretyakov gauge due to the larger wind shield attached on the gauge (Lapin, 1993). Compared with the unshielded Metra gauge, shielded Tretyakov gauge.

Relationship between the daily catch ratio and environmental factors was investigated. Statistical analysis shows that daily catch ratio of snow for the unshielded Metra gauge does not change significantly with daily air temperature and daily mean wind speed is the only factor affecting the gauge catch (Figure 5.I.1). For mixed precipitation and rain, there is no statistically significant correlation between daily gauge catch and wind speed.

Table 5.I.1 Summary (total and %) of daily observed precipitation for the Tretyakov and Metra gauges at Bratislava-Koliba WMO Intercomparison site, 1987/88-1992/93 winter seasons.

Type of precip.	Number of days	Temperature (°C) max.	min.	mean	Wind speed at 2m (m/s)	Tretyakov shielded	Metra shielded	Metra unshielded	
snow	115	0.9	-4.0	-1.5	1.5	273.6	295.1	222.9	(mm)
						100	107.9	81.5	(%)
mixed	119	4.5	-0.7	1.9	1.7	588.3	566.7	525.3	(mm)
						100	96.3	89.3	(%)
rain	276	10.8	3.8	7.3	1.6	812.7	753.5	728.7	(mm)
						100	92.7	89.7	(%)

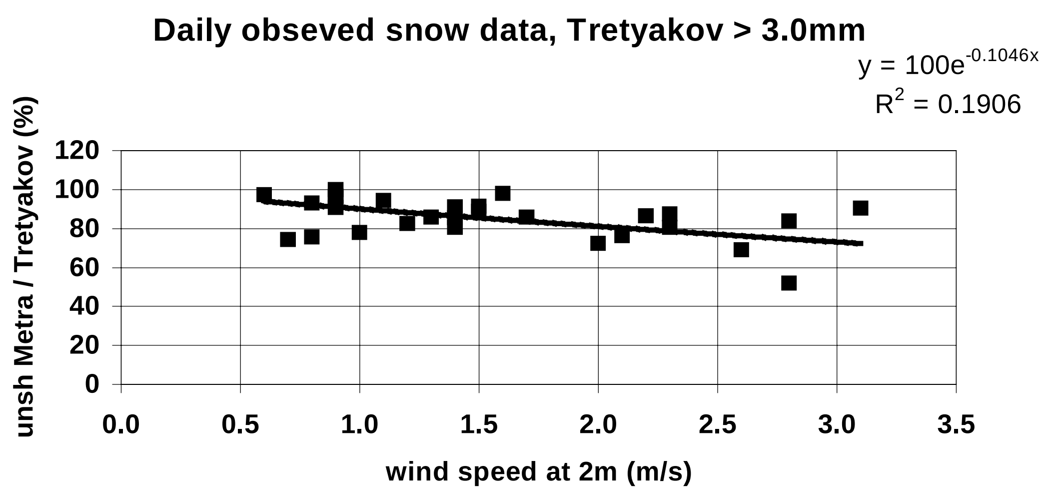

Figure 5.I.1 Catch ratio of the unshielded Metra gauge to the Tretyakov gauge as a function of daily wind speed at the gauge height.

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ANNEX 5.J SWITZERLAND

USE OF A DOUBLE FENCE INTERCOMPARISON REFERENCE ON THE TOP OF GAMSERRUGG

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ABSTRACT

In autumn 1991 the Geography Department of the Swiss Federal Institute of Technology installed a DFIR (Double Fence Intercomparison Reference) on the top of Gamserrugg (47°12'N/9°21'E) in the Eastern Swiss Alps, to correct precipitation measurements. Intercomparison measurements between a Belfort gauge protected by a DFIR and an unprotected Belfort gauge showed a measurement increase of about 48% on average. The measurement differences between the two gauges increase with decreasing temperatures and increasing wind velocities. For wind velocities higher than 8 m/s, measurement differences decrease because in such cases the DFIR itself acts as an obstacle.

1. INTRODUCTION

In autumn 1991 the Hydrology section of the Swiss Federal Institute of Technology installed a DFIR on the top of Gamserrugg (47°12'N/9°21'E; 2074 m a.s.l.). A Belfort gauge was installed in the center of the DFIR so, that these results could be compared with those from an unprotected Belfort gauge at a distance of only about 50 m, used in the project "Precipitation Conditions in the Alps" (Blumer & Lang, 1993, 1994). The Swiss DFIR was an octagonal vertical double fence, inscribed into circles 4 m and 12 m in diameter. The inner fence was 2.2 m high and the outer one 3.0 m. The fences were made of wooden picket boards 1.5 m high and 0.05 m wide, with a gap between the vertical bars of 0.05 m. The distance between the ground and the bottom of the picket boards was 0.7 m for the inner fence and 1.5 m for the outer fence.

2. RESULTS

During the winter season 1991/92 and 1992/93, 56 precipitation events were compared with a total precipitation amount of 523 mm for the unshielded gauge (100%) and 776 mm for the DFIR protected Belfort gauge (148%), so indeed the precipitation amount was increasing by 48,4% using a DFIR. Maurer (1993) shows that measurement differences between the two gauges increase with decreasing temperature. For precipitation events with wind velocities of less than 8 m/s there can also be found a general increase of measurement differences with increasing wind velocity. For events with higher wind velocities the DFIR acts as an obstacle and measurement differences between the two gauges get lower (Table 5.J.1). In Table 5.J.2 increasing differences can be found for decreasing precipitation intensities.

Table 5.J.1 Measurement values of a DFIR protected Belfort gauge compared to an unprotected Belfort gauge (100%) dependent on temperature and wind velocity at the top of Gamserrugg.

	Wind velocity	**0 < u < 3.5 (m/s)**	**3.5 < u < 8.0 (m/s)**	**8.0 < u (m/s)**	**Total (m/s)**
snow	Temp. < -1°C	153.4%	167.2%	156.3%	159.5%
snow/rain mixed	Temp. > -1°C	123.3%	155.8%	129.7%	135.3%
		138.5%	162.6%	143.9%	148.4%

Table 5.J.2 Measurement values of a DFIR protected Belfort gauge compared to an unprotected Belfort gauge (100%) dependent on temperature and precipitation intensity at the top of Gamserrugg.

	Precipitation intensity	**0 < I < 0.4 (mm/h)**	**0.4 < I < 0.9 (mm/h)**	**0.9 < I (mm/h)**	**Total (mm/h)**
snow	Temp. < -1°C	165.6%	190.8%	140.4%	159.5%
snow/rain mixed	Temp. > -1°C	160.0%	139.7%	125.6%	135.3%
		164.5%	157.7%	133.7%	148.4%

Only 6 of these 56 events show a higher value for the unshielded gauge (Table 5.J.3). However, these are generally small events, where other measurement errors of the two gauges are greater than the influence of the DFIR (Blumer, Maurer and Steinegger, 1994). Compared to other intercomparison measurements (i.e., Goodison, 1978: Elomaa, 1988), the differences between the two gauges are low because of the relatively high temperatures and the generally intense precipitation events.

During the summer season measurement differences between the two gauges are normally less than 5% (Blumer, 1994). Using the average of the DFIR of 48% for the winter season and a value of 10%, according to Sevruk (1986), for the summer season, the annual precipitation amount of the top of Gamserrrugg increases from 1332 mm to 1627 mm (122.1%) in 1990 and from 1270 mm to 1548 mm (121.9%) in 1991. - As a result it is obvious that using conventional precipitation measurements the annual precipitation amount on the top of the Gamserrugg is underestimated by about 18%.

Table 5.J.3 Differences between the protected an the unprotected Belfort gauge and corresponding weather conditions on the top of Gamserrugg for all 56 precipitation events.

Month	Duration of the event (h)	Intensity (mm/h)	Temp (°C)	Wind velocity (m/s)	Unshielded Belfort gauge (mm)	DFIR (mm)	DFIR/ Belfort gauge (%)
oct. 91	15	0.593	2.4	3.0	8.9	8.0	89.9
oct. 91	18	0.400	5.2	2.3	7.2	8.6	119.4
oct. 91	27	0.481	-0.7	8.8	13.0	17.3	133.1
oct. 91	51	0.304	-7.2	3.4	15.5	21.8	140.6
oct. 91	3	0.100	-1.6	2.3	0.3	0.3	100.0
nov. 91	5	0.320	1.4	4.8	1.6	1.6	100.0
nov. 91	3	0.133	4.4	3.1	0.4	0.5	125.0
nov. 91	27	0.222	-3.2	9.5	6.0	11.0	183.3
nov. 91	2	0.300	2.3	6.7	0.6	0.9	150.0
nov. 91	22	0.273	-7.0	9.7	6.0	10.7	178.3
nov. 91	18	0.278	-2.8	10.6	5.0	12.2	244.0
nov. 91	33	0.364	-7.2	3.6	12.0	23.7	197.5
nov. 91	11	0.245	-2.4	0.7	2.7	4.0	148.1
nov. 91	18	0.050	-5.1	5.8	0.9	1.5	166.7
dec. 91	4	0.175	-9.0	0.3	0.7	0.4	57.1
jan. 92	4	0.175	-2.8	8.0	0.7	1.7	242.9
jan. 92	4	0.350	1.3	5.9	1.4	1.6	114.3
jan. 92	16	0.113	-3.7	2.1	1.8	1.9	105.6
jan. 92	12	0.108	-7.1	6.3	1.3	7.6	584.6
feb. 92	68	0.949	-4.7	12.3	64.5	100.2	155.3
feb. 92	2	0.500	-4.5	0.5	1.0	3.3	330.0
feb. 92	7	0.229	-3.7	11.8	1.6	4.4	275.0
mar. 92	5	0.880	-5.2	8.6	4.4	7.4	168.2
mar. 92	5	0.160	0.1	5.8	0.8	2.0	250.0
mar. 92	12	0.950	-5.9	7.1	11.4	14.1	123.7
mar. 92	18	0.444	-2.0	6.0	8.0	16.3	203.8
oct. 92	8	0.900	2.4	0.2	7.2	6.6	91.7
oct. 92	7	0.514	2.9	0.1	3.6	5.9	163.9
oct. 92	6	0.983	2.4	0.0	5.9	10.8	183.1
oct. 92	5	0.400	2.7	0.7	2.0	3.0	150.0
oct. 92	5	0.320	4.4	4.1	1.6	2.0	125.0
oct. 92	30	0.270	-4.8	1.7	8.1	16.3	201.2
oct. 92	11	0.509	2.0	7.3	5.6	10.0	178.6
oct. 92	21	0.548	-1.8	8.1	11.5	12.0	104.3
nov. 92	26	0.673	0.1	8.2	17.5	23.5	134.3
nov. 92	16	0.425	2.5	6.4	6.8	8.9	130.9
nov. 92	4	1.000	-1.7	6.8	4.0	7.6	190.0
nov. 92	51	0.975	-4.9	9.9	49.7	60.1	120.9
nov. 92	16	0.681	1.3	6.7	10.9	24.3	222.9
nov. 92	37	1.138	1.3	11.6	42.1	54.0	128.3
nov. 92	15	1.993	0.6	10.9	29.9	29.8	99.7
nov. 92	38	0.895	0.6	10.3	34.0	45.7	134.4
dec. 92	22	0.427	-2.5	8.5	9.4	29.0	308.5
dec. 92	27	0.519	-5.2	6.7	14.0	30.7	219.3
jan. 93	42	0.400	-1.2	4.4	16.8	19.9	118.5
jan. 93	5	0.240	-1.5	7.3	1.2	2.5	208.3
jan. 93	5	0.540	-1.2	7.8	2.7	2.3	85.2
jan. 93	8	1.563	0.0	7.0	12.5	15.7	125.6
jan. 93	13	1.338	0.0	6.4	17.4	25.2	144.8
jan. 93	32	0.219	-0.6	11.3	7.0	15.9	227.1
feb. 93	12	0.058	-6.7	3.2	0.7	0.8	114.3
feb. 93	9	0.622	-6.1	6.4	5.6	8.8	157.1
feb. 93	4	0.275	-18.3	2.4	1.1	0.5	45.5
mar. 93	40	0.105	-9.9	2.3	4.2	6.1	145.2
mar. 93	42	0.236	-0.7	4.9	9.9	12.6	127.3
mar. 93	3	0.667	-2.5	4.4	2.0	2.1	105.0
average:	17.3	0.808	-2.1	8.1	522.6	775.6	148.4

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ANNEX 5.K UNITED STATES OF AMERICA

1. RABBIT EARS PASS, COLORADO, USA, *G. Leavesley, USGS, Denver, Colorador, USA*

The Rabbit Ears Pass study site is located in the headwaters of the Walton Creek drainage basin, near Rabbit Ears Pass, about 18 km southeast of Steamboat Springs, Colorado. It is located in a large sub alpine meadow at an elevation of 2925 m.

Two precipitation gauges were used in this study. One was the Russian Tretyakov gauge which was selected by WMO as the index gauge to be used by all sites participating in this intercomparison study. The second gauge was the Universal Belfort precipitation gauge which uses a weighing bucket mechanism to measure gauge catch and a drum-chart to record the time trace of this measurement. Each gauge type was installed in three different types of wind shields and with no shield. The three types of wind shields were a Double Fenced Intercomparison Reference (DFIR), a Wyoming, and an alter shield. A Canadian Nipher wind shield was also installed on a Universal Belfort gauge. The Nipher shielded gauge, however, was not installed in the study until January of 1991. In addition, the adjacent research watershed used an alter-shielded Universal Belfort gauge located in a small forested opening to measure precipitation. This forested opening is located about 200 m from the study site and provided an additional measure for comparison.

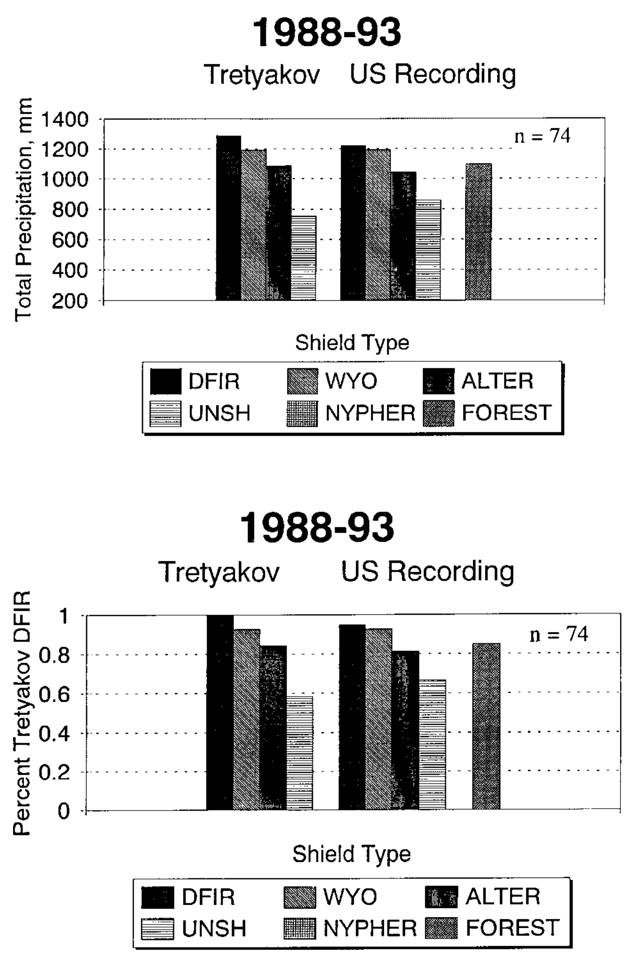
A total of 194 storm periods were measured between April 9, 1988, and April 24, 1993. A storm period is counted when at least one of the gauges in the study records precipitation. Storm periods ranged from 1 to 5 days depending on the duration of storms and the ability of the observer to reach the site to make a measurement. Some storm periods contain more than one individual storm event.

Malfunctions in selected gauges at various times resulted in only 74 of the 194 storm periods having all gauges functioning at the same time. Because the Nipher shield was not installed until 1991, this number is reduced to 51 storm periods for comparison of the Nipher shielded gauge with the other gauges. Figures 5.K.1a,b show the total precipitation measured in the various gauges and the ratio of the precipitation measured in each gauge to that measured in the Tretyakov DFIR gauge for the period 1988-1993. Figures 5.K.2a,b show the same values for the period 1991-1993 which includes the Nipher gauge.

The Tretyakov DFIR gauge caught the most precipitation during the 74 storm periods of 1988-1993. The ranking of the performance of the wind shields for both gauge types as compared to the Tretyakov DFIR was the same. The DFIR caught the most precipitation, followed by the Wyoming, alter, and unshielded gauges. Ratios for the individual wind shields were very similar for both gauge types. The largest difference between gauges types occurred for the unshielded gauges with the Tretyakov unshielded gauge being about 8 percent lower than the unshielded Belfort gauge. The forest opening was 4 percent higher than its alter-shielded counterpart at the study site.

For the 1991-1993 period the rankings of wind shield performance were similar to those observed for the 1988-1993 period. However, the Nipher gauge ranked very close to the Tretyakov DFIR catching 98 percent of the Tretyakov DFIR. Small differences between result primarily from the 1991-1993 period being a smaller sub sample of 1988-1993.

Figures 5.K.1 show the total precipitation measured in the various gauges and the ratio of the precipitation measured in each gauge to that measured in the Tretyakov DFIR gauge for the period 1988-1993



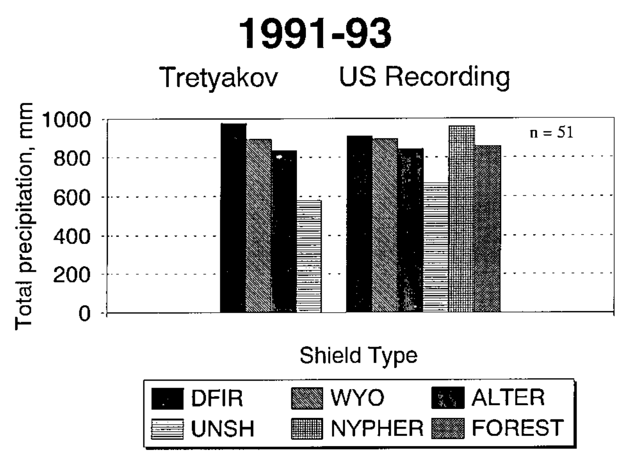
While the number of storm periods during which all gauges were operational was limited to 74 and 51, comparisons between the Tretyakov DFIR gauge and each individual gauge provided a much larger sample from the 194 total storm periods. Results of these individual gauge comparisons are shown in Figure 5.K.3. The number of storm periods used to compute the ratios shown are noted inside each bar in the graph. Bars showing a similar or equal sample size may not be using the same subset of storms. However the sample sizes are significantly increased over those used in Figures 5.K.1 and 5.K.2 and each includes storms whose magnitudes are representative of the full range of those observed.

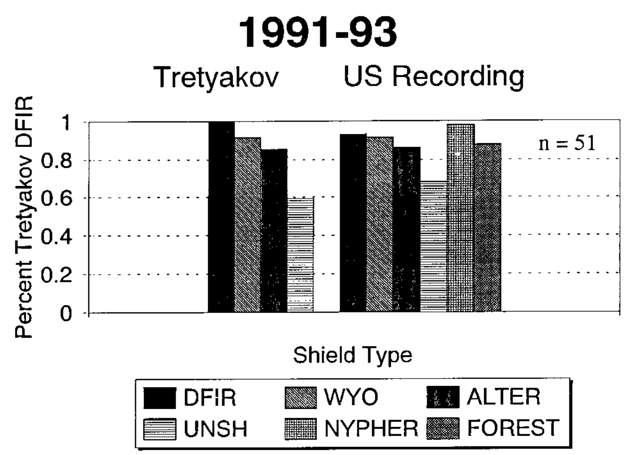
The rankings and magnitudes of the ratios shown in Figure 5.K.3 are very comparable to those shown in the smaller samples of Figures 5.K.1 and 5.K.2. A small exception to this is the small decrease in the ratio of the alter-shielded Belfort gauge whose ratio for 113 storm periods dropped to 0.80.

1.1 Storm Period Precipitation

The comparisons between the Tretyakov DFIR gauge and the individual gauges and wind shields were examined by regression analysis. The equations for the linear regression line of best fit and selected measures of the fit are also given for each gauge comparison. In general, more scatter about the regression line is noted for the Belfort gauges as compared to the comparably shielded Tretyakov gauges. Scatter about the line also increased with increasing magnitude of storm period precipitation. The resulting regression equations are given in Table 5.K.1.

Figures 5.K.2 show the total precipitation measured in the various gauges and the ratio of the precipitation measured in each gauge to that measured in the Tretyakov DFIR gauge for the period 1991-1993 which includes the Nipher Gauge





Figures 5.K.2 show the total precipitation measured in the various gauges and the ratio of the precipitation measured in each gauge to that measured in the Tretyakov DFIR gauge for the period 1991-1993 which includes the Nipher Gauge

Table 5.K.1 Regression analysis of Gauge-shield combinations vs Tretyakov DFIR gauge

Gauge	Shield	Regression Gauge-shield(y) vs Tret DFIR (x)	n	r^2	se
Tretykov	unshielded	y = 0.602x - 0.30	135	0.94	2.04
	Alter	y = 0.831x - 0.37	152	0.96	2.21
	Wyoming	y = 0.975x - 0.44	133	0.99	1.25
Universal Belfort	unshielded	y = 0.689x - 0.93	135	0.91	2.82
	Alter	y = 0.846x - 0.85	113	0.95	3.80
	Wyoming	y = 0.887x + 0.70	126	0.89	4.24
	Nipher	y = 0.930x + 0.70	83	0.93	3.48
	DFIR	y = 0.957x - 0.12	138	0.93	3.58
	Forest	y = 0.875x - 0.02	113	0.87	4.09

Two large storms were removed from the Tretyakov DFIR data set before the regression analysis. These periods were February 18-21, 1989, and March 5-6, 1991. A total of 62.2 m and 52.6 mm of precipitation were recorded in the Belfort DFIR during these periods while the Tretyakov DFIR measured 42.6 mm and 22.1 mm for the same storms. A review of the drum chart showed that the majority of the precipitation in both storms was received in less than a 24 hr period. It appears that the capacity of the Tretyakov was not sufficient to handle these two short duration, high-intensity storms. Gauge capacity may have been a factor in catch differences measured for other storm periods but the absence of an on-site observer made a full assessment of this effect not possible.

One additional adjustment was required for the alter shielded Belfort gauge. Selected periods in 1990, 1991, and 1992 had a problem with registering storm period timing accurately. Where sequences of successive storm periods occurred, it was necessary to lump multiple storm periods together to more accurately compare the data with the Tretyakov gauge. In most cases this involved lumping 3 to 4 storm periods together over a 7 to 10 day time frame. One exception was the lumping of six storms over the period November 17, 1991 to December 3, 1991. Regression analysis was conducted with these summed periods included (Figure 5.K.4a) and the four longest periods excluded (Figure 5.K.4b). As is shown in these figures, there is little difference in the regression results for both cases and the six storm sum with a Tretyakov DFIR sum of 124.9 mm plots well in relation to the smaller storm totals.

1.2 Wind Effects

To examine the effect of wind on catch efficiency, the ratio of precipitation measured in each gauge to that measured in the Tretyakov DFIR was plotted against wind speed. A linear regression analysis was conducted to evaluate the relation between this ratio and wind speed. The resulting regression equations and selected measures of the fit are also given in Table 5.K.2.

A test of the null hypothesis that the slope of the regression line for each gauge is equal to zero can only be rejected for the alter and unshielded Tretyakov and Belfort gauges. Rejection for the Tretyakov gauges is at the 0.01 level of significance while the rejection for the Belfort gauges is only at the 0.05 level of significance.

Figure 5.K.3 Results of individual gauge comparisons with the Tretyakov DFIR gauge

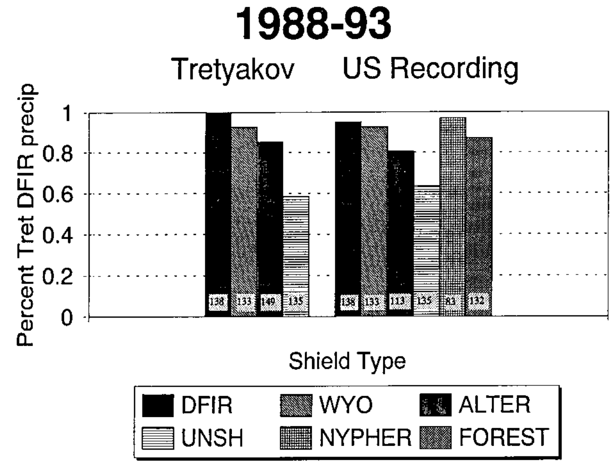


Figure 5.K.4 Regression of Universal Belfort Gauge with Alter Shield vs Tretykov DFIR Gauge (a) with lumped multiple storms, and (b) with four of the longest lumped periods removed

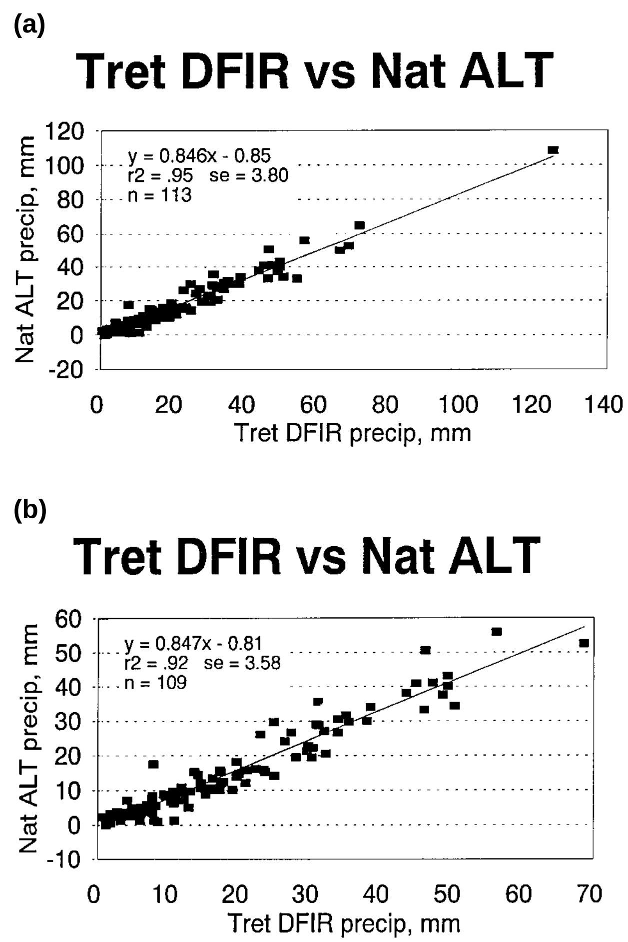


Table 5.K.2 Regression analysis of (Gauge-shield combination/Tretyakov DFIR) Ratio vs Wind speed at 2 metres (m/sec)

Gauge	Shield	Regression Ratio(y) vs 2 metre wind speed (x)	r^2	se
Tretykov	unshielded	y = -0.029x + 0.66	0.08	0.13
	Alter	y = -0.038x + 0.99	0.09	0.17
	Wyoming	y = 0.0036x + 0.91	0.002	0.10
Universal Belfort	unshielded	y = -0.039x + 0.76	0.036	0.26
	Alter	y = -0.064x + 1.02	0.04	0.37
	Wyoming	y = -0.022x + 1.03	0.005	0.38
	Nipher	y = -0.034x + 1.15	0.01	0.39
	DFIR	y = 0.0028x + 0.96	0.001	0.31
	Forest	y = -0.044x + 1.08	0.01	0.48

2. REYNOLDS CREEK EXPERIMENTAL WATERSHED, IDAHO, USA, *C. Hanson and A. Rango, US Dept. of Agriculture, ARS, Idaho, USA*

The information in Table 5.K.3 provides a summary of the total catch by gauge for events of 3mm and greater for the study period, 1987-1994 at the Reynolds Creek Experimental Watershed. Daily totals were not included in Table 5.K.3 because at this site, event and daily amounts were about the same and the catch ratios between the DFIR gauge and the other gauges were essentially the same as those for events. The nomenclature for the gauges are given in Table 5.K.4.

As shown in Table 5.K.3, snow catch by the CAN, WYO and the NATSHLD gauges was within 3% of the DFIR gauge catch. The TRET, NATUNSHLD and BELSHLD gauges caught between 5 and 9% of the DFIR snow catch. The BELUNSHLD gauge only caught 79% of the DFIR snow catch. Gauge catch of mixed precipitation was about the same relative to the DFIR gauge as that recorded for snow except the BELUNSHLD gauge caught a higher percent.

For precipitation that fell as rain, all of the gauges caught within 6% of the DFIR catch. Four of the gauges (CAN, NATUNSHLD, NATSHLD, NWO) caught essentially as much or up to 5% (WYO) more than the DFIR gauge. The NATSHLD, CAN and WYO gauges caught within 2% of the total precipitation measured by the DFIR gauge.

The linear relationship between (gauge catch/DFIR catch) and wind speed is shown in Table 5.K.5 for the Reynolds, Idaho site. These equations indicate that there was no consistent relationship between any of the gauges and the DFIR catch as affected by wind speed. These results may be due to the small number of events, the fact that most events were not large and/or because wind speeds were generally low during the precipitation events.

TABLE 5.K.3 Total gauge catch (mm) for events of 3 mm and greater, Reynolds Creek Experimental Watershed, Idaho, USA

	GAUGE							
SNOW	**DFIR**	**TRET**	**NATSHLD**	**NATUNSHLD**	**CAN**	**WYO**	**BELUNSHLD**	**BELSHLD**
	182.1	172.2	175.8	166.8	183.6	180.6	143.7	167.5
Ratio[1]		0.95	0.97	0.91	1.01	0.99	0.79	0.92
MIXED	97.8	94.2	98.0	91.3	96.2	99.5	83.2	91.4
Ratio		0.96	1.00	0.93	0.98	1.02	0.85	0.93
RAIN	119.8	116.6	123.7	120.0	118.1	126.4	113.1	115.4
Ratio		0.97	1.03	1.00	0.99	1.05	0.94	0.96
TOTAL	399.7	383.0	397.5	378.1	397.9	406.5	340.0	374.3
Ratio		0.96	0.99	0.95	0.99	1.02	0.85	0.94

[1]Gauge values/DFIR

Table 5.K.4 Gauge Nomenclature

GAUGE	**NOMENCLATURE**
DFIR	WMO Reference Standard Gauge
TRET	Tretyakov
NATSHLD	Belfort Universal Recording Gauge with Alter Shield
NATUNSHLD	8" National Weather Service without Shield
CAN	Canadian Nipher Shield Gauge
WYO	Belfort Universal Recording Gauge with Wyoming Shield
BELUNSHLD	Belfort Universal Recording Gauge, orifice at 3.05 m, without Shield
BELSHLD	Belfort Universal Recording Gauge, orifice at 3.05m, with Alter-type Shield

TABLE 5.K.5 Relationship between the ratio of the DFIR and the other gauges (gauge catch/DFIR catch) and wind speed (m/sec) at 3 m for precipitation amounts of 3mm and greater, Reynolds Creek Experimental Watershed, Idaho, USA.

Gauge		Snow	R	N		Mixed Precip	R	N
TRET	Events	Y=0.960-0.016X	-0.227	27		Y=0.913+0.013X	0.645	15
	Daily	Y=0.952-0.007X	-0.098	29		Y=0.913+0.011X	0.534	12
NATSHLD	Events	Y=0.965-0.008X	-0.130	27		Y=0.905+0.027X	0.621	15
	Daily	Y=0.942-0.013X	-0.297	29		Y=0.912+0.026X	0.595	12
NATUNSHLD	Events	Y=0.972-0.045X	-0.515	27		Y=0.935-0.001X	- 0.020	15
	Daily	Y=0.922-0.012X	0.137	29		Y=0.955-0.003X	- 0.094	12
CAN	Events	Y=0.996-0.020X	-0.261	27		Y=0.983+0.000X	0.013	15
	Daily	Y=1.007-0.011X	-0.139	29		Y=0.971+0.000X	0.000	12
WYO	Events	Y=1.004-0.011X	-0.176	27		Y=0.980+0.124X	0.367	15
	Daily	Y=0.984+0.007X	+0.152	29		Y=1.031+0.003X	0.608	12
BELUNSHLD	Events	Y=0.857-0.061X	-0.493	27		Y=0.798+0.013X	0.354	15
	Daily	Y=0.800-0.016X	-0.115	29		Y=0.758+0.025X	0.568	12
BELSHLD	Events	Y=0.948-0.034X	-0.382	27		Y=0.927+0.003X	0.088	15
	Daily	Y=0.911-0.002X	-0.035	29		Y=O.862+0.020X	0.582	12

Gauge		Rain	R	N
TRET	Events	Y=0.976-0.004X	-0.173	20
	Daily	Y=0.974-0.004X	-0.186	24
NATSHLD	Events	Y=0.869+0.048X	0.588	20
	Daily	Y=0.901+0.042X	0.628	24
NATUNSHLD	Events	Y=0.902+0.028X	0.570	20
	Daily	Y=0.954+0.009X	0.177	24
CAN	Events	Y=1.031-0.015X	-0.288	20
	Daily	Y=0.962+0.007X	+0.148	24
WYO	Events	Y=0.913+0.043X	0.554	20
	Daily	Y=0.919+0.040X	0.694	24
BELUNSHLD	Events	Y=0.955+0.002X	0.036	20
	Daily	Y=0.909+0.014X	0.307	24
BELSHLD	Events	Y=0.935+0.012X	0.243	20
	Daily	Y=0.915+0.017X	0.450	24

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