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GLOBAL CRYOSPHERE WATCH

FINAL REPORT
Tropical Regions Cryosphere Workshop

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Chair, Publications Board
World Meteorological Organization (WMO)
7 bis, avenue de la Paix
P.O. Box 2300
CH-1211 Geneva 2, Switzerland

Tel.: +41 (0) 22 730 8403
Fax: +41 (0) 22 730 8040
E-mail: Publications@wmo.int

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GROUP PHOTO

Figure 1: Mount Kilimanjaro

EXECUTIVE SUMMARY

The first session of the Global Cryosphere Watch (GCW) Tropical Regions Cryosphere Workshop opened at 09:00 hours on Tuesday, 04 July 2017. It was hosted by the Tanzanian Meteorological Agency, in Arusha, United Republic of Tanzania. The opening ceremony was hosted by Dr Agnes Kijazi, the Permanent Representative (PR) of Tanzania with the World Meteorological Organization (WMO). The meeting was formally opened by the the Guest of Honour, Mr. Mrisho Gambo, the Regional Commissioner of Arusha Region.

The meeting was chaired by Dr Árni Snorrason, the Chair of the GCW Steering Group, and the PR of Iceland with WMO.

The Chair summarized the goals of the workshop, to (1) recommend candidate stations for the GCW surface observing network (existing or required), (2) identify opportunities for data rescue, improved data exchange, policy harmonization; (3) provide recommendations for additional activities and services related to cryosphere in these regions, and (4) identify strategies for capacity building. Á Snorrason provided an overview of the links between GCW goals and the UN Sustainable Development Goals. He also outlined linkages between cryosphere and hydrological services.

Dr Jeff Key provided an overview of GCW, its structure, regional activities, and goals. He outlined the close links of GCW with the Polar Satellite Task Group (PSTG) of WMO, and the challenges in obtaining accurate information for mountainous regions.

Dr Kijazi invited the GCW experts to actively examine the lessons learned from previous WMO cross-cutting project, and identify how to plan its engagements in the tropical regions and the programme overall, more effectively, by building on the past experience

All participants were invited to present the country specific cryosphere related programs, challenges, their expectations from this workshop, and their potential contribution towards a common work plan, highlighting the areas of particular interest and collaboration within the framework of GCW.

The participants agreed on two GCW overarching priorities, which need to be sustained. One is on promoting observations and monitoring of weather, climate and cryosphere over high mountains in tropical areas, and the second, on promoting the preparation and implementation of research strategies for enhancing the understanding about the dynamics and potential impacts of climate change on cryosphere and on the ecosystem in tropical high mountains.

The discussions covered the glacier related activities in Peru, Ecuador, Bolivia, Colombia, and Indonesia; the snow monitoring programs in Morocco, the permafrost monitoring in Peru, and the challenges related to observations of glaciers and snow in Tanzania, Kenya, and Democratic Republic of Congo. For all cases, the impacts on available products and services was assessed, and recommendations for further work and engagements, were made.

Dr Rainer Prinz provided a thorough overview of the cryosphere research projects in tropical regions organized by Universities from Europe or United States. This gave a good perspective of new opportunities for collaboration between national organizations and international research projects.

A Kijazi stressed out the fact that in addition to glaciers, there is snowfall in Africa, e.g. July-August in Tanzania, also South Africa, Lesotho. She encouraged GCW to consider promoting snowfall observations on the highlands of Africa, in addition to the north African areas, recognizing the scale and importance of questions to be addressed.

Rodney Martinez Güingla, the Director of the Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN) provide, remotely, an overview of the work of CIIFEN, focusing on the potential for collaboration between CIIFEN and GCW. Andre Kamga Foamoufoue, Director of the African Regional Climate Centre (ACMAD), in Niger, provided an overview of the ACMAD mission, functions, and the potential links with cryosphere. It was agreed that GCW will develop linkages with CIIFEN and ACMAD, similar to those with the Arctic PRCC and the planned Asia High Mountain-RCC. It was also agreed that cryosphere data needs to be made available via the GCW Data Portal for use for applications, by CIIFEN and ACMAD.

The participants agreed on several key actions relevant to cryosphere related research and services in tropical regions. Among those the most relevant are (1) GCW to take a lead role in addressing cryosphere related observations and development of services for tropical regions, taking into account the specificity of each region, (2) the development and publication of best practices for the configuration, operation, maintenance of sustainable observations, and data availability for stations at high elevation, in very remote locations, operating in harsh environments, (3) promoting the exchange of snow water equivalent, (4) further expansion of the CryoNet and contributing stations network of GCW, (5) improvements in communication from GCW to contributors and the national representatives, emphasizing the value of contributions to GCW, (6) data rescue, data sharing, and data exchange, including from past and on-going research projects, (7) contribution to capacity building on topics specific to tropical regions, (8) engagements with other WMO Programmes , UNESCO.

An area of particular interest was the sustainability of observations over the long term, and GCW agreed to assume a lead role in linking with funding agencies to enable this goal.

At the end of the meeting, all participants appreciated the quality of discussions, the soundness of the work plan, and they committed to contribute to its implementation.

The list of actions and recommendations resulting from this workshop is summarised in Annex 5.

The meeting adjourned on 6 July 2017, at 12:00.

Contents

MEETING REPORT

1. ORGANIZATION OF THE MEETING

1.1 Opening of the meeting

The first session of the Global Cryosphere Watch (GCW) Tropical Regions Cryosphere Workshop opened at 09:00 hours on Tuesday, 04 July 2017. It was hosted by the Tanzanian Meteorological Agency, in Arusha, United Republic of Tanzania.

The opening ceremony was hosted by Dr Agnes Kijazi, the Permanent Representative (PR) of Tanzania with the World Meteorological Organization (WMO). The meeting was formally opened by the the Guest of Honour, Mr. Mrisho Gambo, the Regional Commissioner of Arusha Region. In their opening remarks, Mr Gambo and Dr Kijazi thanked the WMO for organizing the workshop in Tanzania, the home of the highest mountain peak in Africa, Mount Kilimanjaro, which has a significant role in all the socio-economic aspects of the region, including water, energy, agriculture, tourism, forestry.

In their respective addresses, Mr Gambo and Dr Kijazi noted that the environments in high mountain areas in most of the tropical countries are not adequately monitored in spite of their important contribution to the socio-economic sustainability. They expressed confidence that the workshop will lead to concrete steps in addressing the challenges facing these regions, and for enhancing their climate resilience. Both noted the National Climate Change Strategy (NCSS, 2012) developed by the Government of Tanzania, as a framework for an increased focus on high mountain issues in Tanzania. Additional details from the opening remarks of the hosts are available in Annex 3.

Dr Árni Snorrason, the Chair of the Steering Group of GCW and the PR of Iceland with WMO, thanked the hosts and the participants for their engagement. In his remarks, Á Snorrason recalled the seven WMO strategic priorities from for the 2016-2019 financial period, and in particular those relevant to this workshop, (i) Polar and High Mountain regions, (ii) WMO Integrated Global Observing System (WIGOS), (iii) Global Framework for Climate Services (GFCS), (iv) Disaster Risk Reduction, and (v) Capacity Development. He noted that the Polar and High Mountain activities focus on improving the meteorological and hydrological monitoring, prediction, and services in these regions.

Á Snorrason noted that the goals of the workshop are to (1) recommend candidate stations for the GCW surface observing network (existing or required), (2) identify opportunities for data rescue, improved data exchange, policy harmonization; (3) provide recommendations for additional activities and services related to cryosphere in these regions, and (4) identify strategies for capacity building, at national and regional level.

On behalf of the Secretary General of WMO, Prof Petteri Taalas, Ms Rodica Nitu, thanked Mr Gambo, Dr Kijazi, and TMA for their kind invitation to hold the workshop in Arusha, and for their strong support of the WMO Programmes. She noted that the workshop is an action from the Decision 51, of the 68th session of the WMO Executive Council (EC-68), Polar and High Mountain activities, which *endorsed the organization of regional workshops on high-mountain areas, including tropical regions, with a view to identifying high-mountain sites and assess them for potential inclusion into CryoNet.*

All speakers noted the broad geographical diversity of participants, representing from countries from 5 continents, as an indication of the importance of this initiative.

1.2 Introduction of participants

The Chair invited the participants to introduce themselves. The list of participants is available in Annex 2.

1.3 Adoption of the Agenda

The Provisional Agenda as provided in Annex 1 was adopted by the participants.

1.4 Working Arrangements

The meeting was conducted as a committee of the whole. The workshop was chaired by Á Snorrason. The session and documentation were in English only. The meeting documentation plan was available at http://www.wmo.int/pages/prog/www/OSY/Meetings/GCW_Meetings/GSGDocumentPlan.html.

2. WMO Global Cryosphere Watch (GCW) framework

2.1 GCW Overview

Dr Jeff Key, Co-chair of the GCW Information and Services Working Group, presented an overview of GCW as a developing programme of WMO. He spoke about the observing component of GCW and its core network, CryoNet, the products available and planned, the GCW Data Portal and the data exchange plans, outreach plans, and an overview of the previous GCW regional engagements in Asia and South America. He noted the current gaps in the GCW Observing Network, including in Africa. He highlighted that GCW is reaching out to the research and academia communities, facilitating the collaboration with the operational communities on emerging global issues related to changes in the cryosphere, and their impact on climate, weather, hydrology, and ecosystem sustainability. J Key noted that the GCW programme bears the marks of operational programs facilitated by WMO, and this sets it apart from research oriented programs such as the Climate and Cryosphere (CliC) project of the World Climate Research Program (WCRP), or the Scientific Committee for Antarctic Research (SCAR). WMO is about operational observations, over the long term, and sustainability.

He outlined the close links of GCW with the Polar Satellite Task Group (PSTG) of WMO, and the challenges faced by the space agencies in obtaining accurate information for mountainous regions. He noted that currently, PSTG does not have a focus on the tropical cryosphere, and invited the participants to consider making recommendations for the PSTG strategic plan regarding the observations of cryosphere in tropical regions.

On the products being developed as part of GCW, J Key noted that the Southern Hemisphere snow cover assessments, glaciers, ice sheets continue to remain a gap, and invited the participants to recommend actions which could address it. This is one of the products intended for the WMO yearly climate reports.

2.2 GCW goals and mission and its links to the UN Sustainable Development Goals

In his presentation, Á Snorrason outlined the WMO focus on high mountain regions where cryosphere is present. He highlighted that the 69th session of the WMO Executive Council (EC-69) approved a revised definition of the scope of WMO's high mountain activities, as "mountain regions where permanent or seasonal cryosphere is present and has an impact on the water scarcity and disaster risk reduction". He noted the linkages of the WMO goals in high mountains to the UN Sustainable Development Goals (http://www.un.org/sustainabledevelopment/sustainable-development-goals/) and the Sendai Framework on disaster risk reduction 2015-2030 (http://www.unisdr.org/we/coordinate/sendai-framework). Á Snorrason stressed the need to include the hydrological component as an integral part of the GCW strategy, and reflect the cryosphere-related water management goals and flood forecasting needs.

The participants agreed that the advanced studies for accurate climate change attributions, e.g. International Panel co Climate Change, IPCC (http://www.ipcc.ch/) reports, require access to additional cryosphere data from, currently, data sparse areas. The regions represented at this workshop are confronted with major observational gaps, and leadership from GCW is needed to address them.

A Kijazi noted that WMO has initiated many initiatives and invited the GCW experts to actively examine the lessons learned, and identify how to make the planned engagements in the tropical regions and the program overall, more effective, by building on the past experience (action). Aspects for consideration are the implementation of cross cutting programmes with a large number of components, with different organizations and communities, maintaining the focus on sustainability, securing funding to translate workshop plans into practice, maintaining the enthusiasm and momentum.

2.2 Overview of the connection between Cryosphere and Hydrosphere

Á Snorrason provided an overview of WMO hydrological program activities relevant to the connection between cryosphere and hydrosphere. The HYCOS initiative has been running for a number of years as an instrument for focused projects linking hydrological observations and services, e.g. Arctic HYCOS and the Hindu Kush Himalaya HYCOS (HKH).

More recently, the WMO Commission for Hydrology (CHy) jointly with the WMO Commission for Basic Systems (CBS), and in collaboration with the US National Weather Service, Hydrologic Research Center (HRC), and USAID/OFDA have developed the concept of the Flash Flood Guidance System (FFGS) with global coverage.

Relevant examples of regional Flash Flood Guidance (FFGS) projects, implemented or under implementation, where cryosphere plays a role, are:

- Southern Africa Region FFG (SARFFG): (Operational) Botswana, Lesotho, Malawi, Mozambique, Namibia, South Africa (RC), Swaziland, Zambia, and Zimbabwe;
- South Asia FFG (SAsiaFFG) (under implementation): Afghanistan, Bangladesh, Bhutan, India (RC), Nepal, Pakistan (RC), and Sri Lanka;
- Central Asia Region FFG (CARFFG) (under implementation): Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, and Uzbekistan;
- South America Pilot FFG (under implementation): Zarumilla River Basin (Peru and Ecuador);

FFGSs are being implemented to enhance NMHSs capacities to issue timely and accurate flash flood warnings to mitigate the adverse impacts of hydro-meteorological hazards, by generating flash flood early warning products using state-of-the-art hydro-meteorological forecasting models; by providing training to the hydro-meteorological forecasters; and by improving collaboration between NMHSs (between meteorology and hydrology) and Disaster Management Agencies (DMA). There are several snow products relevant for these projects: Gauge Mean Areal Temperature (GMAT), the average soil moisture (ASM), the snow water equivalent (SWE), snow coverage area (SCA), melt of snow, persistence flash flood threat. These highlight the relevance of the melting of snow and ice for hydrology and high-resolution models.

The group discussed the need to consider similar projects in Africa and South America. The participants agreed that the meteorological, hydrological, and glaciological/research communities in each country need to be better linked, and take a whole value chain view, from observations to models.

3. Country reports

All participants were invited to present the country specific cryosphere related programs, challenges, and their expectations from this workshop and their potential contribution towards a common work plan.

3.1 Tanzania:

Dr Ladislaus Chang'a summarised the cryosphere related challenges in Tanzania.

Overview

Mount Kilimanjaro is the highest in Africa, of 5,895 m a.s.l. TMA has weather stations in the surrounding area e.g. Moshi, Kilimanjaro International Airport, and Lyamungo Agrometeorological Station, but not on the mountain.

There are no known hydrological stations on and around Mount Kilimanjaro, for potential use as input for the climate modelling effort to close the water balance.

In the 20th century, Mount Kilimanjaro ice fields extent decreased by about 80%. (IPCC 2007). Climate variability and change have affected the glacier, the mountain ecosystems and, consequently, the social economic sectors (increasing frequency and magnitude of droughts, higher temperatures);

The TMA have been aware of international research projects and the installation of Automatic Weather Stations (AWS) on top of Mount Kilimanjaro, but have not been consistently engaged. e.g. University of Massachusetts projects, https://www.geo.umass.edu/climate/kibo.html.

To address the challenges of Climate Change, the Government of the United Republic of Tanzania has developed the National Climate Change Strategy (NCSS, 2012). It documents the national commitment to address climate change adaptation and mitigation, and it calls for enhanced awareness and additional research pertaining to climate change.

A Kijazi emphasized the fact that assessments of direct impacts on communities are difficult because there are no data to support them. Thus, the increased availability of data from observations is the critical first step to understand impacts and causes and develop adaptation strategies.

L Chang'a noted the following gaps related to cryosphere, in Tanzania:

- On observations and monitoring:
    - inadequate observing stations and data availability around and on Mount Kilimanjaro;
    - lack of snow observations on the highlands;
    - lack of coordination with internationally funded projects;
- Inadequate capacities in accessing and utilizing satellite data.
- On research, modelling and prediction:

- lack of research capabilities for adequately understanding the mesoscale climate patterns,
- lack of computing facilities and capacity to support adequate research;
- challenges in developing and retaining technical and scientific expertise, including the lack or insufficient expertise on modelling.

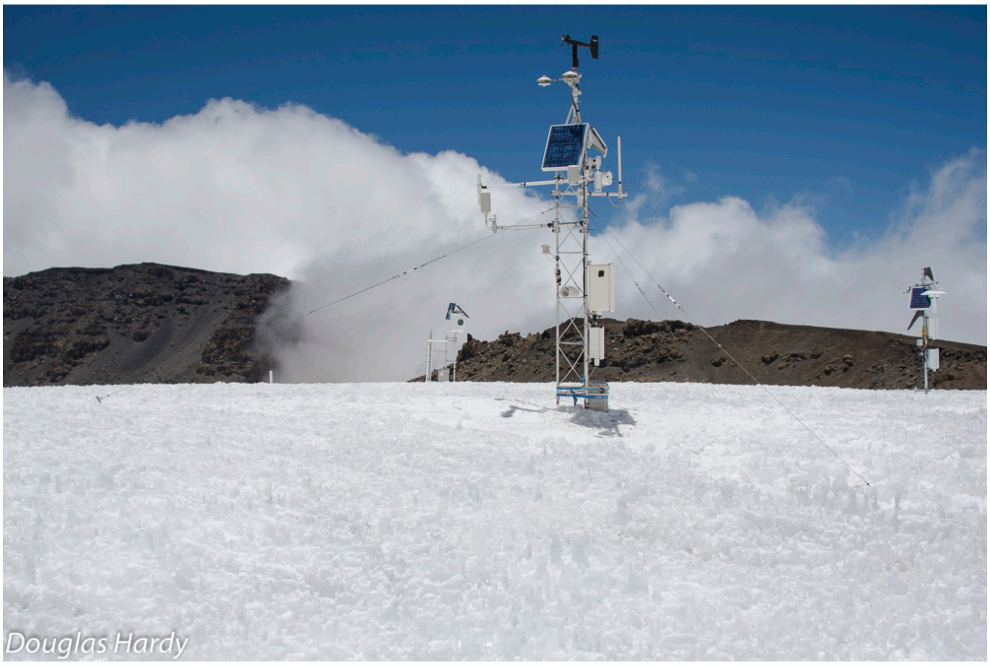


Figure 2: Mount Kilimanjaro, Northern Icefield instrumentation site at ~noon, looking toward Uhiru Peak on left skyline (2 km distance), from http://kiboice.blogspot.ch/2017/10/at-summit-days-92-96-in-crater.html

On behalf of TMA, L Chang'a recommended the following actions:

- Establish at least two CryoNet stations in East Africa/Mountain Kilimanjaro and some stations on the highlands, where seasonal snow is present;
- Install additional AWSs around Kilimanjaro and on the highlands to capture Meso-scale weather patterns.

He asked that GCW to play an active role in facilitating:

- TMA's engagement with international projects on climate and cryosphere, and contribute to knowledge transfer and capacity building[1];
- the development of national capacity for research and modeling, e.g. the Numerical Weather Prediction (NWP) with a focus on high mountains;
- developing outreach material to be disseminated for raising the awareness on the importance of High Mountain, and the potential impacts of climate change on cryosphere and ecosystem in High Mountain (Mountain Kilimanjaro); including the promotion of cryosphere related topics, including in schools.
- preparation of funding proposals for studies on the impact of climate change on Mountain Kilimanjaro ecosystem;
- the exchange of expertise on CryoNet observations between tropical and extra-tropical, and polar regions.

[1] *Following the workshop, Dr Chang'a successfully accompanied D Hardy to Kilimanjaro summit in Oct 2017 – http://kiboice.blogspot.co.at/2017/10/at-summit-days-92-96-in-crater.html (correspondence with R Prinz)*

L Chang'a encouraged the workshop participants to prepare a statement from this workshop to support:

1. Enhanced efforts for monitoring of weather, climate and cryosphere over high mountains in tropical areas
2. Preparation and implementation of research strategies for enhancing the understanding about the dynamics and potential impacts of climate change on cryosphere and on the ecosystem in tropical high mountains.

3.2 Democratic Republic of Congo

Jean Louis Ebengo B Mpotokele from the Agence Nationale de Meteorologie et de Teledetection par Satellite (ANMTS), of the Democratic Republic of Congo noted that the country has four high mountains of which The Rwenzori massif consists of three glacierized peaks, these do not have, currently observing stations providing data to the National Meteorological Service. Of these, Uganda and DR Congo share Stanley and Speke peaks, while Baker peak is on Ugandan territory only.

The existing stations are measuring meteorological parameters, but not snow, including in areas where seasonal snow is present. On behalf of (ANMTS) he expressed interest in participating in GCW, contributing to increasing awareness of the role of cryosphere in the climate in Congo.

3.3 Morocco

Dr Meriem Alaouri presented an overview of the cryosphere aspects in Morocco.

Overview:

Mountains cover more than two thirds of the country, with several summits over 4000 m, where regular heavy snowfall, is present. Morocco is located in a semi-arid Mediterranean region, with a strong spatio-temporal variability of precipitation, leading to periods of high water deficit in summer, a critical issue for Morocco.

For all seven Moroccan watersheds, the mountain snowpack is the most important source of surface water for all sectors, and irrigation is the most important user. The continuing changes in climate are expected to lead to a decrease in winter precipitation and an increase in drought periods by 2050, which will greatly emphasize the role as water towers played by snow in the Moroccan Atlas; this will require the development of policies for the rational use of water, and for better seasonal prediction.
Accurate snow monitoring and better understanding of the factors governing its variability, are critical to Morocco. Increased understanding of processes and variables that control the hydrological cycle are needed to accurately assess of water inputs to dams throughout the snowmelt season. Winter tourism is marginal in Morocco, with only two ski resorts in Oukaimden and Michlifen.

M Alaouri noted several scientific research projects:

The IRD and the Caddy Ayad University of Marrakech on assessing and forecasting water resources at watershed level. This includes observations of snow cover, accumulation, and snow melt, the estimation of snow melting contribution to river flows; satellite mapping of snow-covered areas of the entire mountain ranges; analyses of spatial and temporal variations in snow cover across the High Atlas; the generation of snow resource indicators.

The evaluation of the MODIS snow product MOD10A1 in the Moroccan Atlas and snow cover variability analysis; results support the understanding of the spatial and temporal dynamics of the snowpack, and characterizing snow cover in semi-arid mountains by watershed, to produce a mapping of snow surfaces in the Atlas Mountains.

The National Meteorological Department of Morocco (DMN) has recently implemented a network of 156 automatic weather stations, of which, 19 have sensors for measuring snow depth, and data are available since 2013 in the DMN climatological database (Figure 2). Additionally, five automatic naval stations were acquired under the SudMed project for understanding semi-arid region eco-systems, and IMPETUS project (Integrated Approach to Effective Water Resource Management in West Africa). These stations are implemented in the watersheds of Tensift and Draa, and managed by the Center for Space Studies of the Biosphere – CESBIO and the Cadi Ayyad University in Marrakesh.

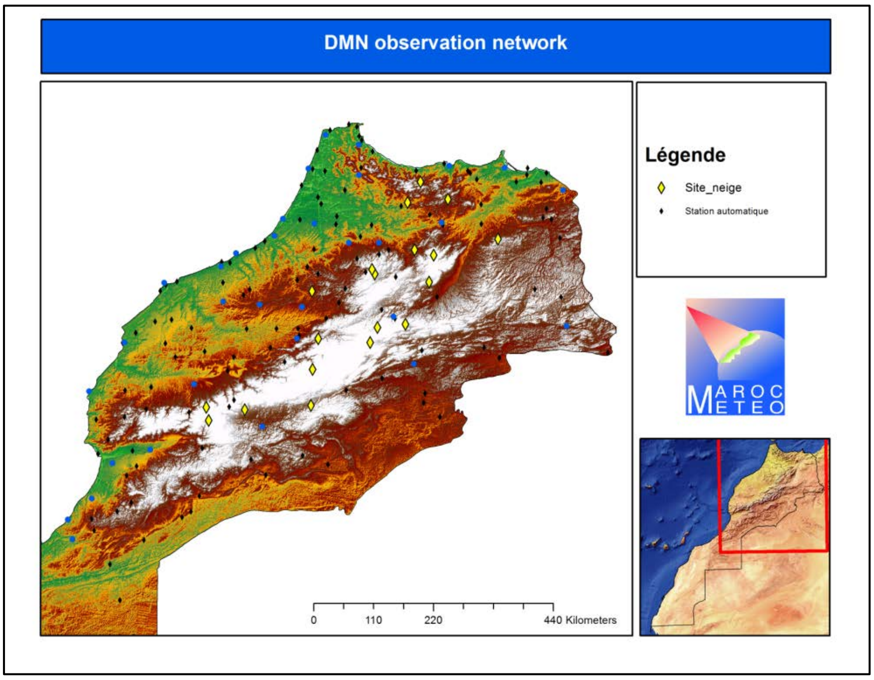


Figure 3: DMN observing network

The satellite snow cover data are an important source of information, increasingly, being used, operationally.

M Alaouri noted that in 2017, DNM established an agreement with the national hydrology agency, regarding flood risk management and water resource management, and they using hydrological models at watershed level (using their own model and ALADIN).

Ms Alaouri summarised the planned activities in Morocco, on supporting cryosphere and hydrological services:

- Strengthening of naval stations network with transmission data in near-real time,
- Better monitoring and modeling of the spatio-temporal dynamics of snowpack;
- Estimating the water equivalent of the snowpack;
- Risk management and water resources planning through hydrological models;

Ms. Alaouri noted that Morocco is interested in collaborating internationally for assessing climate change impacts, evaluate impacts on socio-economic sectors, and support policy decisions.

The discussions on snowpack assessment to agreement of all participants that accurate SWE data, available broadly, preferably in (near) real time, is an important contribution which GCW should make, as SWE is a critical parameter for hydrological applications (water resource management, flood forecasting). It was recognized that the remote sensing of SWE has improved, recently; estimations of SWE with passive microwave instruments is possible, but difficult in the mountains, and new instruments are needed. GlobSnow SWE product from FMI is better, as it blends satellite with in-situ observations.

As a result of the group discussions, it was decided that:

- *GCW leads the development of mechanisms for reporting and exchange SWE data within the WMO framework, from manual and automatic stations, operationally.*
- *GCW needs to work with PSTG to promote improvements to satellite based observations of SWE in mountainous regions.*

3.4. Indonesia

Dr Donaldi Permana presented an overview of the requirements, challenges and impacts related to the cryosphere changes in Indonesia.

Overview:

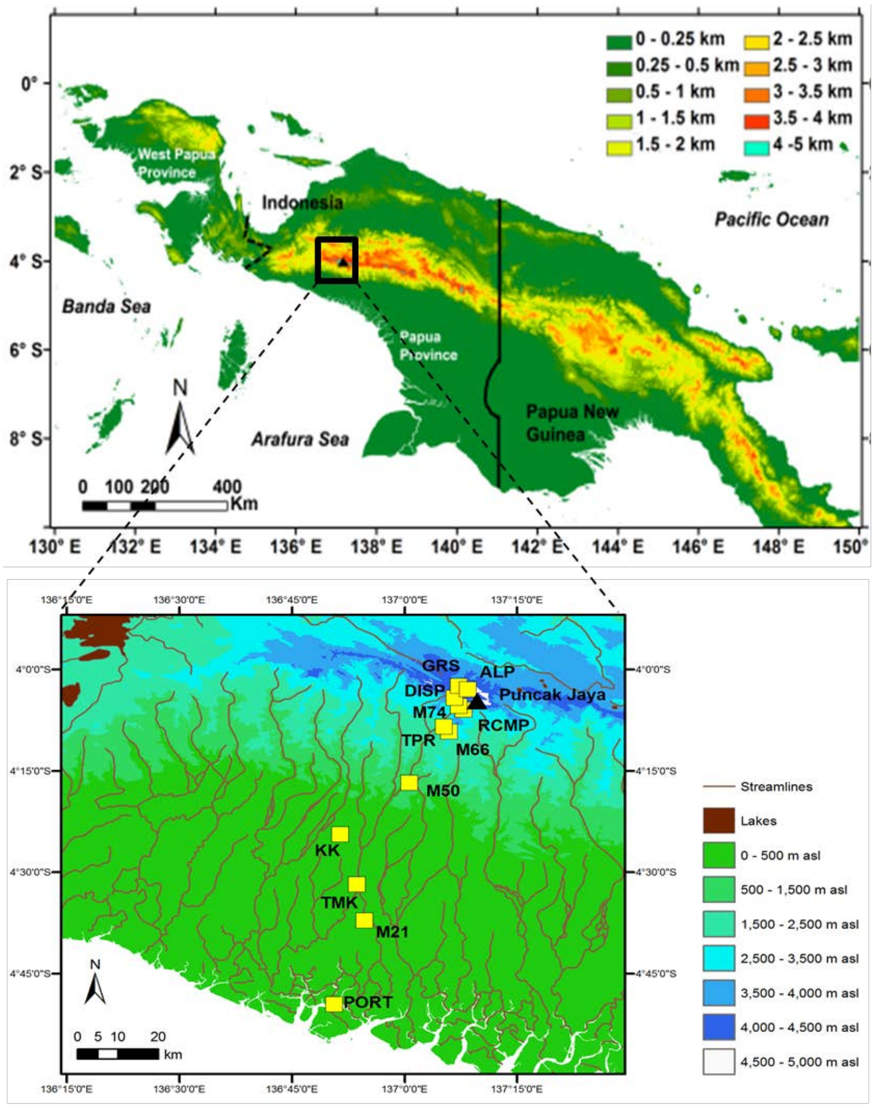
In Indonesia cryosphere is present as ice fields near Puncak Jaya, the highest peak in the Maoke Mountains, which stretch across the island of New Guinea, at 4,884 meters a.s.l. Seasonal snow is also present at high elevation, but not monitored, regularly (Figure 3).

Dr Permana gave a short overview of the network of meteorological observations of the Meteorological, Climatological, and Geophysical Agency of Indonesia (BMKG). Currently, there are no BMKG observations (snow, ice, accumulation and glacier) on Papua glaciers. The available meteorological observations (the AWS network of 11 stations, with 3 stations at high elevation), at about 5-6 km to the east of the ice fields areas, are maintained by the large mining company PT Freeport Indonesia (PTFI), and the instruments are calibrated by BMKG every year .

The only glacier thickness observations from the ice fields of Puncak Jaya are from the accumulation stakes installed in mid-2010 during the ice core drilling project, led by of the Ohio State University.
Dr Permana noted that oxygen isotope record from ice cores have shown that the disappearance of the ice fields on Pukak Jaya are linked to the warming of the atmosphere, and is a concern from multiple perspectives; e.g. socio-culturally, glaciers are considered sacred sites by the local tribes.

The loss of glaciers would impact the tourism business, with direct impact to the local economy (porter activities), but has minimum impact on water resources as high precipitation occurs every month in the region, which are the main water resource, including for agriculture.

There is an impact on public health in a broader context, as malaria, one of the most important infectious diseases throughout the tropical regions, is easily transmitted in warmer and high humidity climates, including on Papua. The vulnerability of Papua highland with malaria diseases has increased recently due to a combination of climate system and socio-infrastructure systemic transformations.



Location of PTFI AWS network in Papua, Indonesia

Figure 4: Topography of Papua Province and its borders; the black triangle marks the highest peak of Puncak Jaya, where ice fields are still present. The yellow squares represent the stations operated by PTFI.

Indonesia's expectations from this workshop, and from the engagement with GCW, include:

- Promoting infrastructure development to observe and measure cryosphere parameter (snow, ice, glacier, permafrost) on Papua glaciers areas. The M50 station (Figure 3) is probably the site with the highest average annual rainfall in the world (~ 12,000 mm/year).
- GCW to help in developing highly skilled resources to analyze the cryosphere changes and its links to atmosphere and
- GCW to develop and make available best practices and training to support the development of skills to maintain observing equipment in high mountain areas, and enable good quality observations.

Dr Permana also noted that:

- BMKG is interested in an active engagement with GCW by conducting glaciers monitoring, and on broader collaboration on research related to high mountain cryosphere in tropical regions within the framework of the WMO Polar and High Mountain activities;

- The collaboration with the mining company PTFI is a positive example of engagement with private sector companies, which are increasingly active in high mountain regions;
- D Permana invited GCW to consider how to build on and support engaging private entities in high mountain areas. Specific research has been possible using data from the PTFI, e.g. elevation dependent warming, altitudinal transect AWS network **(action)**;
- Currently, there is no existing or recommended station which could be included in the GCW surface observing network. Ideally, station(s) could be developed to observe the cryosphere on the Papua glaciers.

3.5 Bolivia

Dr Alvaro Soruco, from Universidad Mayor de San Andres (UMSA), La Paz, presented cryosphere related aspects, in Bolivia.

Overview

The most important impact of glaciers in South America is providing access to water resources, as well as being key indicators of climate change. Annually, on average, glaciers contributed with 15% to the water resources for La Paz, the capital of Bolivia, increasing to 27% in the dry season. La Paz is located at elevations between 4000 and 3300ma.s.l.

Glaciers in the tropics respond rapidly to climate fluctuations due to their relatively small size, the strong atmosphere–surface-energy exchanges at low latitudes, and specific tropical climate conditions that maintain the lower reaches of glaciers in almost permanent ablation conditions, all year round. As a result, small changes in temperature and precipitation (albedo) have large impacts on the glacier mass balance.

Overall, he noted that all tropical glaciers have been retreating since late 1970 at a speed not seen before, i.e. since the Little Ice Age (17^{th} century). Studies have shown that tropical glaciers at altitudes below 5400 m (-0.6 m.w.eq), are diminishing at a rate double that of glaciers over 5400 m (-1.2 m.w.eq). The sea surface temperature (SST) of the Pacific Ocean is one of the main factors controlling the variability of mass balance of Andean glaciers.

A Soruco also showed results indicating that in 1975 80% of glaciers had surfaces of less than 0.5 Km^{2}. From 1963 to 2006, a significant loss of 50% in the glacier surfaces was evidenced in Bolivia.

A. Soruco noted that glacier research activities in Bolivia are coordinated with organizations from neighbouring countries and international organizations, such as l'Institut de recherche pour development (IRD), France. Several programs have run successively since 1991, with most recent being GREATICE (Glaciers at Resource en Eau dans les Andes Tropicales, Indicateurs Climatiques et Environmentaux), which started in 2011 and will continue until, at least, 2020.

GREATICE has three main themes, (1) glacier evolution from the Little Ice Age, (2) the glacier energy surface balance and climate parameters, and (3) the impact of glacier decline on water resources.

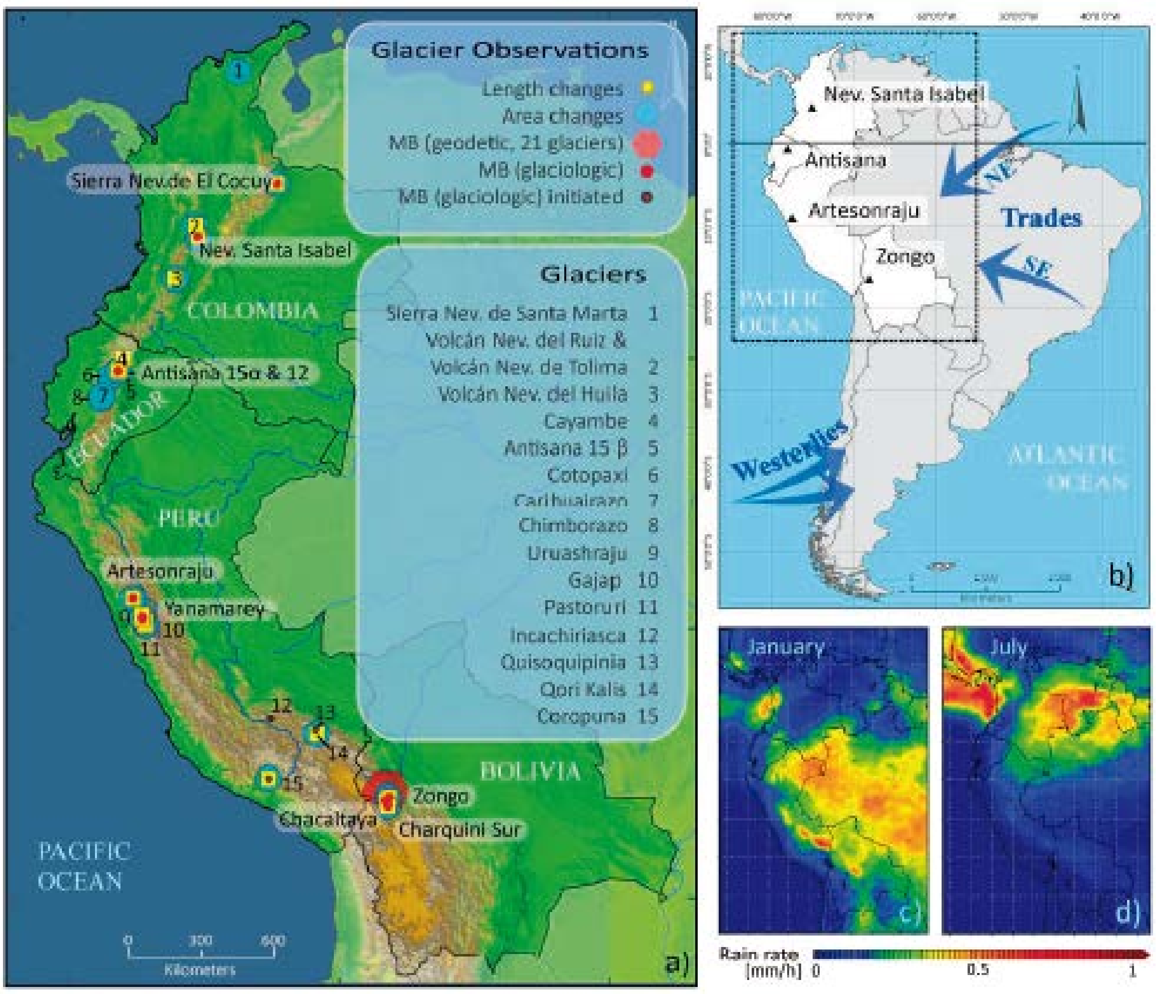


Figure 5: Glaciers monitored in the tropical Andes (A Rabatel et al.; Current state of glaciers in the tropical Andes, The Cryosphere, 7, 81-102, 2013)

A Soruco mentioned that the observing station on the Zongo glacier is a CryoNet station. Zongo Glacier has the longest and most accurate mass-balance series in the Andean region, data showing a rapid and continuous decrease of the mass of the glacier since 1975. He expressed concerns that the disappearance of the Zongo glacier opens the door to mining explorations, and the increasing activities are further impacting the fragile ecological balance.

It was noted that additional observations are needed at high elevation, together with the improved glacier models for energy balance and glacier dynamics, to enable glacier simulations for new climate scenarios.

A Soruco expressed concerns about the fragmentation of glacier observations, services and research between different, often, rival organizations, including in the same country, and the strong dependence on international funding. He noted that as university researchers in Bolivia, they are not engaged, at all, with the Servicio National de Meteorologia e Hydrologia of Bolivia, in spite of having tried repeatedly.

A Soruco asked GCW to support the national programs, on the following:

- GCW to help link cryosphere researchers in Bolivia with the operational organizations, and the Office of the PR of Bolivia **(action);**
- A Soruco asked WMO to promote stronger environmental regulations in developing countries, in areas affected by climate change, where new economic

opportunities become available as a result of those changes, e.g. melting and disappearance of glaciers, including by promoting the protection of sensitive areas, and finding the right balance with economic development. **(action)**

- GCW to lead the development of funding proposals, to ensure the sustainability of observations in high mountain areas of Bolivia and the entire region **(action).**

3.6 Ecuador

Mr Bolivar Caceres Correa, from the Instituto National de Meteorologia e Hydrologia (INAHMI) of Ecuador, presented a summary of glacier studies in Ecuador. He is the head of Ecuadorian Glacier Program at INAMHI since 2002, coordinating all activities related to cryosphere studies for Ecuador.

He noted that Ecuador contributes to the GCW surface observing network with:

- the CryoNet Antisana 15 Alpha station, operational since ~2007, and includes glaciology research and meteorological observations.
- the GCW Contributing station Traub on the Quito Glacier on Greenwich Island of the Antarctic Peninsula. Studies, here, are conducted as cooperation between Instituto Antartico Ecuadoriano (INAE), the Navy of Ecuador, and INAMHI.

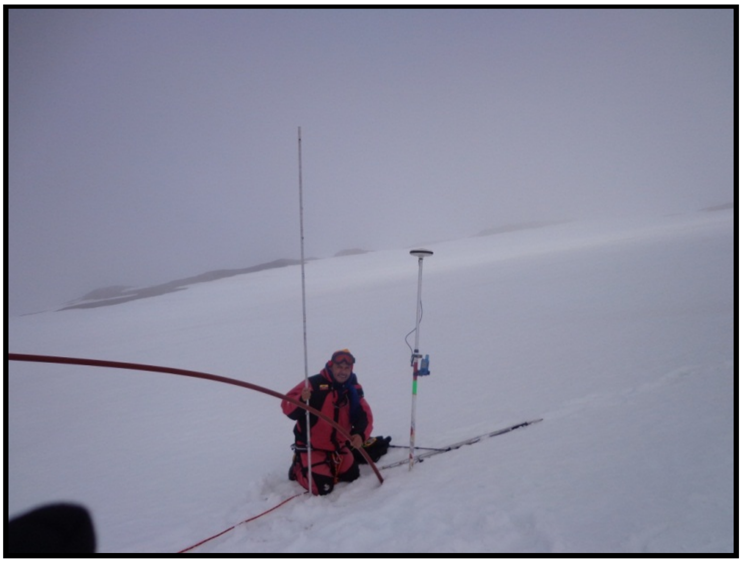


Figure 6: GCW Contributing station Traub, Quito Glacier, Greenwich Island, Antarctic Peninsula

Additionally, meteorological and glaciological observations are available from the stations on Cotopaxi (Glaciology), Chimborazo, and Carihuayrazo glaciers. The latter could disappear in the next few years.

Overview

Several glacier research and monitoring projects have taken place recently in Ecuador, in the context of advancing the understanding of climate change impacts, disaster risk, and availability of water resources for power generation, agriculture, drinking water:

The “Programa Glaciares Ecuador“ of INAMHI, is under way with glaciological measurements and research on the Antisana, Cotopaxi, Chimborazo, Carihuayrazo, Altar, and the Cayambe glaciers.

The Programa Glaciológico Antártico Ecuatoriano of INAMHI in collaboration with the Instituto Antártico Ecuatoriano (INAE) , conducted glaciological observations and climate change research from 2010 to 2017, at the Pedro Vicente Maldonado Base on Shetland Island, Antarctic Peninsula Greenwich Island.

The MONITOREO DE GLACIARES TROPICALES ANDINOS EN UN CONTEXTO DE CAMBIO CLIMÁTICO Project, organized at regional level (Colombia, Ecuador, Perú, Bolivia), sponsored by the Cooperation Interamerican Development Bank (IDB), and INAMHI and focusing on the Chimborazo and Carihuayrazo glaciers.

The "Glacioclim" project on the Antisana glacier, organized by the Institute pour Research and Development (IRD), France and INAMHI, with measurements at the 15 Alpha and Los Crespos stations.

The project "CATCOS (phase 2) –Capacity building and Twinning for climate observing system", a cooperation between MeteoSwiss and INAMHI, was recently completed. It supported field work in Antisana 15 Alpha for four years. It focused on studies of climate change in mountainous regions. It led to the publication in 2015 of the Snow and ice-related hazards, risk, and disasters book.

Figure 7: SAMAE-2 (INAMHI)-Glacier 12 meteorological station

The data from the Antisana, Cotopaxi, and Chimborazo glaciers are critical for developing policy decisions on climate change; however costs, difficulties with data transmission, difficulties in ensuring continuous support of observations, make it difficult to ensure their full availability. Plans are being made for real-time transmission of data from the Antisana station via GOES or an alternate method, provided that appropriate financing is available.

The scarcity of financial resources has been a major challenge and it continues to jeopardize the sustainability of observations, including for the Antisana 15 CryoNet station and the support for establishing a permanent climatological station on Quito glacier, on the Antarctica Peninsula.

B Caceres asked GCW to support cryosphere activities in Ecuador, as follows:

- WMO to promote the importance of understanding the linkages between climate changes in the high mountain regions and climate change in low altitudes, similar to how impacts in the Polar Regions are promoted (higher vs lower latitude teleconnections).
- Currently, cryosphere research activities in Ecuador are not funded from regular budgets. WMO is urged to reach out to the relevant national organizations to increase the awareness of the linkages between changes in the cryosphere and socio-economic stresses and risks, and to provide tools for policy makers to manage adaptation. B Caceres noted that UNESCO initiated projects have had the political and financial support, and have made notable progress. Could GCW do the same, perhaps in conjunction with UNESCO-IHP?

- Facilitating the engagement of international funding organizations (World Bank, the Inter-American Development Bank, others) for priority cryosphere related activities, and in conjunction with national organizations.
- Promote the understanding of the importance of integrated research to understand natural hazards, e.g. studies of cryosphere/glaciers and the connections with the risks of volcano eruptions.

B Caceres noted that contribution with additional CryoNet stations depends on the ability to sustain these stations.

3.7 Peru

Mr Marti Bonshoms presented an overview of the current activities and challenges related to cryosphere in Peru, where the Servicio National de Meteorologia e Hydrologia del Peru (SENAMHI), of the Ministry of the Environment, is actively engaged.

SENAMHI operates the station Quelccaya, which is already a CryoNet station. The site is operated by the Quelccaya Institute, Dr Baker Perry. SENAMHI has agreement with the University to contribute to the maintenance of the station. He noted the difficulties in maintaining the station at its current location because of the remote location and very harsh conditions.

It was noted that Wilson Suarez represented Peru at the 2014 GCW workshop in South America.

Overview:

M Bonshoms noted that, as reported in 2014, Peru has over 1300 km^2 of glaciers, over 70% of the world tropical glaciers, which would make it a good candidate for the "4th pole", after the Hindu Kush Himalayan region being recognized as the 3rd pole. According to the Tyndall Center, Peru is the third in the world in terms of vulnerability to climate change.

In Peru, the responsibility of glacier related activities is shared between several organizations:
- SENAMHI focuses on the monitoring of atmospheric parameters on glaciers, and does not performs any glacier mass balance assessment
- The recently established El Insituto National de Investigation en Glaciares y Ecosistemas de Montana – the National Research Institute for Mountain Glaciers and Ecosystems (INAIGEM) aims to promote and expand scientific and technological research in the field of glaciers and mountain ecosystems, promoting their sustainable management for the benefit of populations living in or benefit from such ecosystems.
- Autoridad National del Agua – National Hydrological Authority (ANA)
- Consorcio para el Deserrollo Sostenible de la Eccoregion Andina (CONDESAN)

M Bonshoms provided a short overview of the CRYOPERU 2.0 project, a multidisciplinary and multi-institutional efforts to monitoring and study glaciers in Perú. Within it, a research project is under way, «Analysis of recent and past ELA to evaluate the impact of climate change and the glacier evolution in the Pacific basin of the Peruvian Andes along next decades», assessing the glaciers' impact on water resources.

He presented details regarding the meteorological observations available on several other glaciers in Peru, Cordillera Huaytapallana (at 4684 m), in Cordiliera Central at 5005 m and at 5080 m on Chuecon Glacier), Cordillera Blanca (stations at 4797 and 5000m), Artesonraju (of Univ Innsbruck and ANA), Cordilliera Vilcanota (complete weather stations at 5180 m and 5650 m), Quisoquipina (5000 m), Cordilierra Ampato (Corupuna complete weather station at 5780 m). Many of these meteorological stations are close to hydrological stations operated by ANA, as well as glacier mass balance measurements, but the data is not shared with SENHAMI.

Figure 8: Quelccaya CryoNet Station

There are three other stations in Peru, proposed for CryoNet, Yanamarey, Gueshgue, and Artesonraju. These are all operated by ANA. *M Bonshoms will provide to the GCW PO an update on the person responsible of these stations, following the departure from ANA of the original submitter.* ***(action)***

Most stations on glaciers are often destroyed be moving, receding glaciers. The ruggedness of instruments and the installation techniques in remote, high elevation locations are major challenges for SENAMHI. They are requesting GCW to enable the access to information on improvements to current weather stations (transmission systems, upgrade sensors) and on standardized, reliable, protocols for installation, collection of data and maintenance of stations at high elevation **(action).**

Figure 9: Illustration of challenges in organizing the installation of stations in remote, rugged regions.

M Bonshoms informed about the network of permafrost observations established by SENAMHI in 2004, as an important potential contribution to GCW. This network uses HOBO thermometers installed underground with 9 or 10 points of measurement, providing 30-min temperature data. Data is available from SENAMHI, freely and he will explore how to make it available to GCW **(action).**

M Bonshoms noted that SENAMHI is seeking GCW's support for:

- Accessing best practices for rugged stations at high elevation, in remote locations, on glaciers and off glaciers.
- Support for analysis of the direct relation between the discharge of glacier origin with the rivers in the high, middle and low parts of the basins.
- Evaluation of the retreat of the glaciers and their impact within different scenarios of climate change.

3.8 Kenya:

Mr. Constance Okuku from the Kenyan Meteorological Department (KMD) presented the cryosphere related issues in Kenya.

Overview:

He noted that Mount Kenya is the highest mountain in Kenya and the second highest in Africa, and the Lewis glacier is situated at about 5,000 m. The IPCC report noted the dramatic changes on the Lewis glacier. The mountain is important as the water tower, for tourism, and the rivers from this mountain feed two major rivers in Kenya, Tana and Ewaso Ng'iro.

KMD has been operating a GAW station on Mount Kenya, since 1999, reporting on ozone, CO_2, meteorological parameters.

Currently, KMD does not observe any cryosphere variables. Limited studies have been organized in Kenya related to cryosphere/glaciers, but are scattered among various government departments. Currently, the glacier is small and fragmented, and impossible to monitor, according to the WGMS. M Okuku noted that records of the changing of glaciers over time, are critical, including as a qualitative measurement, e.g. monitor the change with pictures.

R Prinz noted that the meteorological data is already there and the precipitation measured by Kenya wildlife service shows that 20% of mass is sublimating, not only melting. One open question is on whether it is possible to measure the run off.

KMD recognizes the need to enhance its observing program and add cryosphere variables, and to share its climate data.

M Bonshoms was asked to provide to GCW for sharing with all participants, an estimate of the cost to install and maintain a station in the mountains of PERU, on the life span of a station, and the major challenge encountered in operations. ***(action)***

Figure 10: Mount Kenya, AWS on Glacier (courtesy R Prinz)

C Okuku summarized the challenges experienced in KMD, where GCW could make a difference:

- Availability of funding, the remoteness of operations at high elevations, scarcity of power for operating stations with complex observing systems, availability of appropriate computing infrastructure to process datasets;
- Training human resources necessary to operate and maintain such stations to produce high quality datasets that meet international standards;
- Acquisition of relevant computing infrastructure, soft and hardware necessary to process such datasets is necessary.

KMD planned contribution to GCW, and for which KMD would seek the support of GCW:

- Establish at least one cryosphere monitoring station in the country;
- Fast track archiving of fragmented cryosphere data with various government agencies for research and policy development;
- Enhance coordination in establishment of cryosphere stations with interested parties/international agencies on cryosphere science and research;
- Initiate capacity building (Both human and infrastructure) to anchor sustainable cryosphere measurements.

3.9 Colombia:

Jorge Luis Ceballos from the National Institute of Meteorology, Hydrology, and Environmental Studies of Colombia (IDEAM), who was unable to attend the meeting in person, sent a very informative pre-taped presentation on the cryosphere related activities in Colombia. J Ceballos, as the only glaciologist in Colombia, is responsible for studying the 6 small glaciers in Colombia.

Overview:

The Colombian glaciers are located very close to the equator and are very important for the study of climate change in the region. In 2016, they occupied a total area estimated at 37 Km^2, and are situated at elevations above 4800 m. At the current rate, in 30-40 years, the glaciers of Colombia will have disappeared.

In Colombia, the alpine tundra ecosystems (paramos) situated at altitudes between 3200 m and 4700 m, just below the glaciers, are the main water regulator systems in the country, and provide 85% of the water resources. In Colombia the glaciers do not have relevance as water resource, but are sacred places for the indigenous communities, with high landscape value. They are located in national parks, and are veritable climate change laboratories.

The Colombian glaciers are: (1) Sierra Nevada de Santa Marta, no longer a continuous mass. The retreat of this glaciers raises the concerns of the indigenous people; (2) Sierra Nevada Cocuy; (3) Ruiz, Tolima, Santa Isabelle. The Conejeras glacier of the Santa Isabel range has been monitored and reported to WGMS since 2009.

Figure 11: Installation of ablation stakes on Santa Isabel glacier (2006), from J Ceballos; E Tobón, Glaciares Colombianos: Evolución reciente y estados actual, published in Boletín de Geología, Vol 29, No 2, julio-diciembre de 2007.

J L Ceballos indicated that the monitoring network at high elevation, in Colombia, includes:

- Since 2006, two glacier stations, on Conejeras and Cocuy, have been reporting the glacier mass balance. Data show an accentuated retreat of Conejeras, but are not so conclusive for Cocuy;
- 20 hydro-meteorological stations are operational at altitudes between 2700 m and 5000 m;
- People are also engaged: a participative monitoring network has been established in the areas surrounding the glaciers, and the local people report temperature and precipitation.

J L Ceballos outlined his expectations from the Cryosphere Workshop, and the GCW:

- A decision on the evaluation of the submission to GCW of the Conejeras station, as a CryoNet station **(action, GCW);**
- Access to best practices for glacier monitoring in the tropical regions, to improve current approaches to glacier observations **(action);**
- Access to information on the experience and practices from other countries;

- Encourages GCW to promote the establishing a “World Glacier Day” **(action).**

4. Research perspectives on tropical cryosphere

Dr Rainer Prinz, University of Graz, provided an overview of the research projects and results on cryosphere in tropical regions. More detailed information is available in Annex 4 : Cryosphere research activities in Tropical Regions.

He noted that the East African glaciers are climate proxies for mid troposphere, used to validate and optimize the climate models. Glaciers translate weather into climate, as one can decode a climate signal from glaciers.

He mentioned that, currently, there are no active observations on Mt Kenya, due to the lack of funding. R Prinz noted that there is a good process understanding of processes and historical data are available.

For Kilimanjaro, there are more than 15 years of meteorological and cryospheric observations, with a good process understanding; also, there are ongoing observation and modelling studies (see Annex 4). R Prinz recommended that the observing station on Mount Kilimanjaro is proposed as a CryoNet station, and he will facilitate the engagement for the submission.

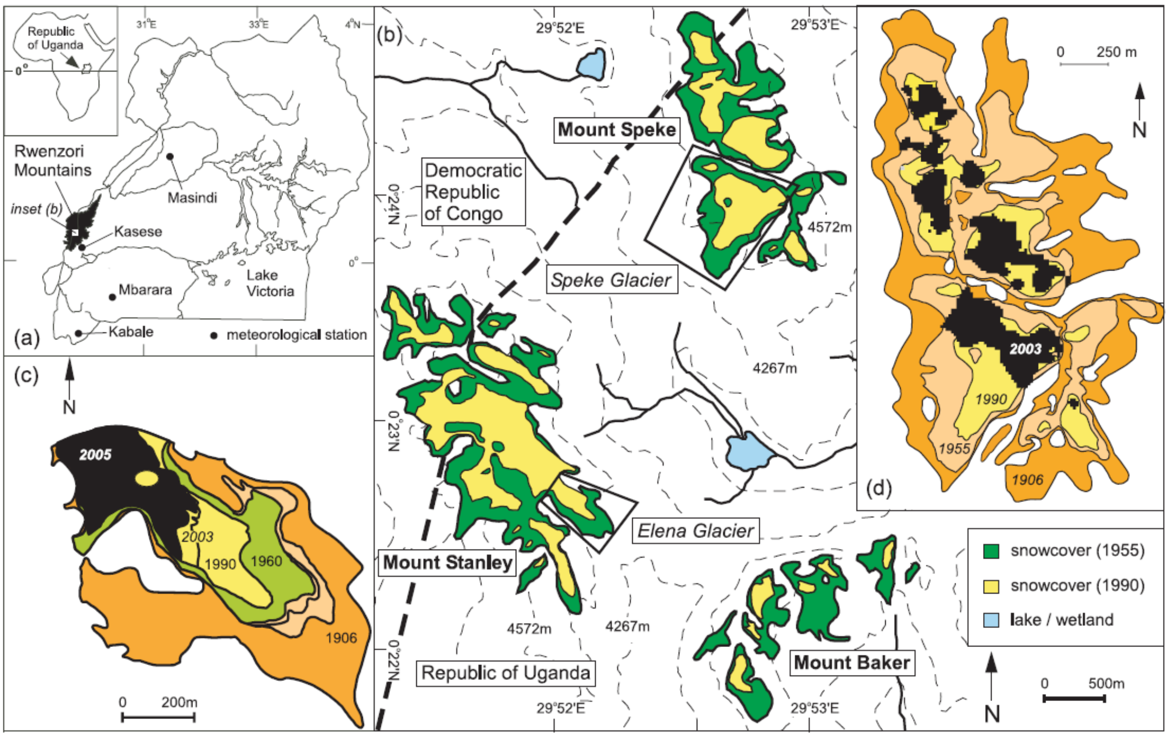


Figure 12: Mount Rwenzori, from Taylor et al, 2006

The observations on Mount Kilimanjaro include:

- AWS 1) Northern Ice Field, continuously operating since about 2000 (http://kiboice.blogspot.com/ contact: Douglas Hardy, University of Massachusetts dhardy@geo.umass.edu). D Hardy supports any idea of data sharing; GCW could work with D Hardy on making data available.
- AWS 2) Southern Ice Field, continuously operating since 2005; the point of contact is Thomas Mölg, University of Erlangen-Nuremberg, Germany. Data access

is restricted for self-publication – after that it will be free for use, while 2005-2010 data should be available.

The participants, in particular those representing Tanzania and Kenya, appreciated the information provided by R Prinz, noting that they were not aware of all projects presented.

The participants asked GCW to explore **(actions)**:

1. Means to access research data available;
2. How to bring together national services and internationally funded projects.

A Kijazi mentioned knowing about an AWS installed in 2000, and there were discussions about sharing of the data, but this was never done. She appreciates the potential about the sharing of data in the future. She encouraged GCW and the international research community to engage more with the Tanzania University, to advance the research. R Prinz indicated the Tanzanian representatives that the researchers are interested to collaborate, and he could facilitate the engagement.

R Prinz noted the difficulties faced by international researchers in accessing research areas and establishing new projects. This is due to difficulties in fully understanding the national and local approval processes. He strongly recommended that GCW plays the role of liaison between research and NMHSs, regarding new cryosphere related projects.

Action: *GCW was asked to play an active role in facilitating engagements (data sharing, collaboration for future projects, including the engagement of NMHSs in securing approvals for projects, e.g. by developing a framework for engagement).*

Action: *GCW to work with R Prinz to identify how to engage Tanzania University, and the operational community to facilitate the sharing of data and the engagement of the local research and operational communities.*

L Chang'a reiterated the need to clarify the role of climate change in in the retreat of glaciers. The issue of teleconnections between SST on Indian Ocean and the melting of glacier on Kilimanjaro needs to be addressed.

The group agreed that research initiatives are funded by soft money, with limited timelines and fenced objectives. For long term monitoring, sustainability of initiatives is needed, and GCW is seen as a mechanism to enhance the collaboration efforts, for long term, sustainable monitoring in the tropical high mountain regions.

It was recognized that a holistic view is needed, of which the cryosphere is only a part. The group invited GCW to facilitate the development of strategies for looking at the integrated system, atmosphere, hydrosphere, and cryosphere, and include the modeling capabilities to answer this question.

A Snorrason recommended that the experts consider whether there is value in configuring AWS on and off the glaciers, to better characterize the changes. He noted that consideration should be given whether some changes are linked to volcanic activity.

5. GCW linkages with Operational Services

5.1 Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN)

Rodney Martinez Güingla, the Director of the Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN) provides, remotely, an overview of the work of CIIFEN, focusing on the potential for collaboration between CIIFEN and GCW.

CIIFEN is an international non-profit organization established in 2003, as the result of several resolutions adopted by the United Nations. It is located in Guayaquil, Ecuador.
Its International Board is composed by the Governments of Ecuador and Spain, the United Nations Office for Disaster Risk Reduction (UNISDR) and the World Meteorological Organization (WMO) as observer.
The CIIFEN mission is to implement actions to consolidate the science-policy interaction and improve the climate services in order to contribute to risk management and adaptation.
CIIFEN is designated by WMO, as a Regional Climate Centre (RCC) for West of South America, RCC-WSA, strengthening the operational capabilities of the National Meteorological and Hydrological Services of Western South America (IDEAM, IMAMHI, SENAMHI, INAMEH), to contribute to the continuous improvement of their climate services.

R Martinez noted the main challenges facing CIIFEN:

- Availability of funding for further developing regional activities;
- Asymmetries in the development of technical capabilities of members;
- Limited communications and coordination between NMHSs;
- Access to data from Global Production Centers (GPCs) is still limited;
- Communication gap between information generators and users of information;
- The area of communication with users is not, yet, a priority for some NMHSs.

R Martinez noted that there is a need to change the views of authorities, private companies, and international organizations, into considering the NMHS more than a provider of information, but as a strategic partner for policy development and management.

R Martinez emphasized that glacier data would be very useful for the RCC-West and South America (WSA), as they are very relevant for the Andean hydrological modeling, ecosystem management, risk and disaster management, drought management, water supply prediction. He asked GCW to become engaged in facilitating the access to these data, either directly from the national organizations, but preferably via the GCW Data Portal.

5.2 African Regional Climate Centre (ACMAD/RCC) and links with cryosphere

Andre Kamga Foamoufoue, Director of the Centre Africain pour les Applications de la Météorologie au Développement (ACMAD), in Niger, provided an overview of the ACMAD mission, functions, and the potential links with cryosphere.

ACMAD has been accredited by WMO, as a RCC for Africa. Its primary users are the NMHSs. Its functions include data services, training, monitoring, long range forecasting, climate prediction and projection, research and development, coordination.
A Kamga noted that hazard scenarios over Africa show that drier December/January with a reduction in accumulation of snow over the Atlas Mountain and lower amounts of water in the spring over parts of Morocco and Algeria. With drier than average winter seasons over highlands, less snow is available to supply water in spring or summer in parts of Eastern/Southern Africa. Also, in dry years, e.g. recent Southern Africa drought (2015/16). Water from ice melting over the highlands is very much needed to reduce deficits due to drought, and drier winter, less snow over highlands in East Africa, are expected.
Overall, more observations in the Atlas and East African highlands are proposed to improve climate forecast services. In 2017, major drought declared in Kenya and Somalia.

A Kamga identified several key recommendations for GCW:

Warming levels and rates over Africa, observed and projected, increase the frequency and intensity of droughts, also increasing summer ice melting, and reducing winter snow accumulation in African highlands, all with multiple socio-economic consequences.

- Cryosphere observations and monitoring tools and products are required to support adaptation planning and practices in the affected areas, and should be made available, including to ACMAD.
- Priority areas for cryospheric observations, monitoring, and service provision include the Atlas region in Morocco and Algeria, Kilimanjaro, Ruwenzori, Kenya mountains.

He also recommended improvement in communication regarding cryosphere observations in South Africa, as well as improved observations and data sharing among partners.

6. Plenary discussions and planning forward

6.1 Discussion on the use of satellite data

J Key led a group discussion on the access and use of satellite data in the analysis of snow cover and glaciers. Workshop participants were asked about their current and planned use of satellite data to study the tropical cryosphere.

Meriem Alaouri noted the use in Morocco of the NASA's Moderate Resolution Imaging Spectroradiometer (MODIS) snow cover product for the analysis of snow cover in the watershed areas of the Atlas Mountains. The MODIS product provides snow cover at 500 m resolution every day. They can compare it 8 m data from but Formosat-2, but it is commercial. Snow depth and snow water equivalent (SWE) products are being tested.

Alvaro Soruco uses high-resolution data such as SPOT for digital elevation models (DEMs). The Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) instrument can also be used, but it is lower resolution. He creates the DEMs himself about every 5 years. He stated that it is not useful when there is snow on the glacier. He wondered if it is possible to use multiple MODIS bands to increase the spatial resolution.

Rainer Prinz stated that Frank Paul, University of Zurich, might have useful information on the use of satellite data.

Donaldi Permana does not use satellite data in his glacier work.

Martí Bonshoms noted that SENAMHI uses MODIS for snow cover in Peru, and some imagery for calculating glacier area. Peru had France developed a panchromatic "PeruSat" with a 70 cm resolution.

Rainer Prinz explained that glaciers in the tropics, particularly Africa, are small so high-resolution data are needed. A problem with optical data is cloud cover. He and his colleagues have used Landsat (30 m) over Mt. Kenya but it is generally not good enough. They've also used ASTER and data from the Tropical Rainfall Measuring Mission (TRMM). He wrote a proposal to get TandemX digital elevation models for East African mountains but was unsuccessful because it is sensitive data for all tiles containing the territory of the Democratic Republic of Congo. Surface temperature from space would be useful, but it needs to be high resolution.

Regarding altimeters, which can be used to monitor glacier elevation and therefore changes in mass, none of the participants have used them.

6.2 Proposed future activities

The participants agreed on activities and priorities, where GCW is expected to lead.

A Kijazi stressed out the fact that in addition to glaciers, there is snowfall in Africa, e.g. July-August in Tanzania, also South Africa, and Lesotho. She encouraged GCW to consider promoting snowfall observations on the highlands of Africa, in addition to the North African areas, recognizing the scale and importance questions to be addressed.

The participants agreed on two key priorities for GCW:

- Promote enhanced efforts on the monitoring of weather, climate and cryosphere over high mountains in tropical areas;
- Promote the preparation and implementation of research strategies for enhancing the understanding about the dynamics and potential impacts of climate change on cryosphere and on the ecosystem in tropical high mountains.

The participants agreed on the following actions and recommendations:

- Develop and disseminate best practices guidelines for the configuration, operation and maintenance of instruments and stations for all relevant cryosphere components. Address the need for rugged instruments and installations in remote areas, and under difficult conditions;
- Promote the measurement, reporting, and exchange of SWE;
- Finalise assessment of candidate stations for the GCW Observing Network (e.g. ANA stations in Peru and Conejeras, Colombia);
- Lead activities for accessing funding to support sustained observations at stations in the GCW observing network; target projects for supporting existing (Antisana, Quito glacier) and new stations (Tanzania, Congo, Kenya, South Africa);
- Promote improved observations and data sharing and improved communication on cryosphere observations in Southern Africa (South Africa, Lesotho, ...);
- Encourage contributions to developing yearly assessments for Northern and Southern Hemisphere: data needed to be developed with the implementation of stations measuring /reporting snow depth/cover;
- Collaborate with UNESCO and assess the continuation of current glacier monitoring projects in South America. It was agreed that B Caceres will represent GCW at the Mendoza UNESCO meeting, scheduled for August 2017;
- Fast track archiving of fragmented cryosphere data with various government agencies for research and policy development;
- GCW was asked to take a lead role in defining an approach for brokering the access to existing and available research data (e.g. develop agreements, using PANGAEA, https://www.pangaea.de/);
- Secretariat to thank the PR offices represented at the workshop for support and encourage the continuation of engagement (valuable for building linkages between communities, e.g. Bolivia);
- WMO to send formal letters to indicate the acceptance of a site and the requirements for its sustainability, explain the global significance;
- Facilitate the development of capacity at national level, by making available outreach materials, reports, organize targeted training (observations), engage

other parts of WMO, involvement of Universities in countries with stations contributing to the network;

- Facilitating the collaboration at national and regional level, and the engagement of other organizations, in particular hydrological services, and the access to Flood forecasting guidance systems: instruments to build on at regional scale;
- Engage the national organizations to facilitate the speed up in obtaining national research permit policies, which increasingly become too expensive and too slow, especially for immediate actions required to safe monitoring equipment over unstable ground (snow/ice surfaces).
- Facilitate the documentation of impacts of cryosphere changes, including the socio-cultural implications (link to services, disaster risk management);
- Communicate with other relevant WMO activities on needs for improvements in the computing infrastructure, communications (RT, near RT);
- Communicate with other relevant WMO activities on needs for improvements in the computing infrastructure, communications (RT, near RT);
- Continue to develop linkages with CIIFEN and ACMAD, similar to those with the Arctic PRCC and the planned TP-RCC. As CIIFEN, ACMAD are interested in integrating the cryosphere data, the GCW Data Portal will be a reasonable gateway for this.

The participants recommended several research themes, which GCW will promote with its research partners, including WMO research programs **(action)**:

- o Research and adequate understanding on mesoscale climate patterns;
- o Communicate the need for capacity development in Numerical Weather Prediction (NWP) with a focus on high mountain areas;
- o Analyze the direct relation between the discharge of glacier and the rivers in the high, middle and low parts of the basins;
- o Evaluate the retreat of the glaciers and their impact within different scenarios of climate change, using REMO and PISM model simulations;
- o Further develop knowledge and monitoring of the spatio-temporal dynamics of the snowpack and the estimate of the water equivalent of the snowpack
- o Risk management and water resources planning through hydrological models.

Monitoring of permafrost was not discussed much during this workshop, but its importance in these regions, was noted. Only Peru mentioned the availability of permafrost operational data. The WMO Secretariat to follow up with the participants to find out additional information **(action).**

6.3 Country specific perspectives

A Snorrason invited all participants to summarise their takeaway from this workshop and the priorities, which should guide the work of GCW for the coming period.

6.3.1 Ms Alaouri noted that for Morocco, the priorities are:

- Implementing near RT data transmission, broadly;
- Access to SWE data, operationally;
- Increase the use of hydrological models for limited area modelling in the mountains;

- GCW to provide specific recommendations on practices for the measurement and reporting of snow cover and SWE, manually and with automatic instruments, and to support national and international collaboration on the use of cryosphere data from in-situ and remote systems.
- Clearly define and communicate the linkages of GCW with other programs using cryosphere data, e.g. CHy, and GFCS (water and disaster risk sectors).
- Contributions to the GCW observing network need to be discussed internally, first; M Alaouri will follow up with WMO Secretariat **(action).**

6.3.2 Dr Permana noted that for Indonesia, GCW could further contribute by:

- Providing a letter of recommendation to the PR to highlight the importance of continued cryosphere observations, and encourage the setup of a CryoNet station on Puncak Jaya, Papua.
- Making available best practices for observations on glaciers;
- Contributing to capacity building, infrastructure and skilled resources, to support research and operations on cryosphere in the tropics.

6.3.3 M Bonshoms summarised the expectations from GCW, for Peru:

- GCW to clarify the characteristics of contributing stations versus CryoNet stations;
- GCW is urged to publish and promote best practices for measurements on glaciers, as well as for snow cover practices, recognizing that these observations are configured in very remote regions with difficult access and adverse operating conditions (instrument damage is a frequent occurrence). GCW PO to share the current draft of Best Practices on snow, with M Bonshoms;
- GCW is encouraged to actively contribute to capacity building, promoting training on instrumentation and data management.

6.3.4 B Caceres summarised the priorities, as a result of this workshop, on behalf of Ecuador:

- GCW to send a letter to the PR recognizing the contribution of Ecuador to GCW, the importance of continuous support for these stations, and the need for funding;
- GCW to make available well documented best practices guidelines to help the development of skills on cryosphere measurements;
- Would like to upgrade the status of the station on the Quito glacier into a CryoNet station, but it depends on the availability of funding;
- On the linkages with CIIFEN, it is important to have the data accessible via the GCW Data Portal, and use GCW as a source of info for centres like CIIFEN. The GCW PO to link B Caceres and R Martinez.

6.3.5 A Soruco summarised the following priorities for Bolivia:

- In Bolivia, the glacier measurements will continue with financial support from France (GlacioClim project);
- For Zongo glacier CryoNet station, the configuration of the metadata for GCW is quite complex. He requested GCW to find ways to harvest the metadata directly from the questionnaire. Their group has very little support and would not be

able to enter the metadata, once again. For WGMS, they prepare an excel spreadsheet with data and maps and WGMS prepares the reports;

- Strongly recommended that GCW develops a standard for showing data from stations (CryoNet, contributing) on the portal, and be very clear about how GCW is different from WGMS, to avoid duplication and show the value added;
- In glaciology, glacier and permafrost are separated. He encouraged GCW to clearly identify and support each area of measurement, i.e. glacier, permafrost, and snow;
- Around Zongo glacier, there are mining operations and, there are pollution issues, raising concerns about the sustainability and the quality of observations on the glacier. A Soruco asked whether WMO can do anything to influence the mining operation. It is recommended that WMO provides a letter to support for the operation of this station over the long term, in collaboration with WG*MS, which is interested to support communication on securing the glacier measurement, which is the longest in the tropics.*

6.3.6 On behalf of Democratic Republic of Congo, Jean Louis Ebengo B Mpotokele noted:

- The experience and information made available at the workshop are valuable for the country, given the variability of climate;
- Could benefit from the recommendations from this workshop to advance the situation of monitoring in the country;
- *Requested that the GCW documentation is made available in French, to be shared with the national meteorological service* ***(action).***

6.3.7 L Chang'a, on behalf of the Tanzanian delegation, noted that as a result of the workshop, TMA is committed to:

- enhance the observations and monitoring over high mountains;
- identify existing hydrometric observations in the areas where potential cryosphere stations are proposed;
- Work towards digitizing the available data, still in paper format.

Overall, L Chang'a noted that GCW is asked to play a lead role in:

- Enhancing the available of cryosphere data and products in the region;
- Enhancing the access to information and the collaboration with international organizations and projects, to answer critical questions regarding mountain climates;
- Active efforts to ensure sustainability of new observations.
- Use the data and information for the WMO statement of status of climate as an incentive for collaboration, and use the information for teaching and for increasing the awareness.
- Publish a newsletter to document the initiative in tropical areas: on-going and future and activities.

6.3.8 On behalf of Kenya, C Okuku thanked WMO for organizing this workshop, and reiterated the commitment of KMD to collaborate with GCW in:

- Establishing a CryoNet station on Mount Kenya; Suggested to conduct feasibility studies at Mount Kenya and Mount Kilimanjaro, to assess the situation before making the submission;

- He encouraged GCW to consider the development of capacity building activities similar to those of GAW, e.g. training station operators and managers.

7. Closing remarks

The participants expressed satisfaction with the engagement and the outcomes of this workshop.

J Key noted that he was impressed by the quality of discussions, the engagement of experts, their preparation for the meeting, the ideas discussed, and the plan of action.

R Prinz expressed satisfaction with the workshop discussions, and for hearing the interest and enthusiasm on cryosphere observations, at national level. He expects that the momentum will continue, given the engagement of local authorities. If these actions are implemented, he recommended that GCW facilitate the organization of a training course on snow measurement. The take-home message for him is the importance of capacity building, and will give to it a higher priority, in the future.

L Chang'a noted that this was a historical workshop, as never before has the cryosphere been discussed in a workshop in Africa. He expressed optimism for the results of the cooperation established at this workshop.

A Kijazi thanked WMO for organizing the workshop in Arusha, thanked the participants for very engaged conversations, and for the quality of information presented, and invited them to return to Arusha. She noted that the workshop objectives have been met. As a member of the Executive Council of WMO, Dr Kijazi invited the participants, the GCW experts, and the WMO Secretariat to carry out to completion the actions agreed here, and achieve all objectives of GCW. She expressed confidence that countries will play their role in establishing those stations and contributing to GCW.

A Snorrason thanked Dr Kijazi, TMA staff who effectively supported the meeting, and Mr Wilbert Timiza Muruke, in particular, and the Government of the Republic of Tanzania for the warm welcome and the excellent meeting venue. He thanked the participants for their contribution to a very successful workshop.

The list of actions and recommendations resulting from this workshop is summarised in Annex 5.

The session was closed at 12:00 local time, on 06 July 2017.

8. Annex 1: Workshop Agenda

1. ORGANIZATION OF THE MEETING
    - Opening of the meeting and adoption of the Agenda
    - Working Arrangements
    - Introductions of participants

2. WMO GLOBAL CRYOSPHERE WATCH (GCW) FRAMEWORK
    - GCW overview, GCW surface observing network, data exchange goals
    - GCW goals and mission and its links to the UN Sustainable Development Goals
    - Outcomes from previous regional workshops

3. OVERVIEW OF COUNTRY SPECIFIC REQUIREMENTS, CHALLENGES AND IMPACTS RELATED TO CHANGES IN CRYOSPHERE.
    - Presentations made by the invited representatives of Members, by country.
    - Overview of Regional Services

4. OPERATIONAL AND RESEARCH ACTIVITIES RELATED TO CRYOSPHERE IN TROPICAL REGIONS
    - Overview of research, operational activities conducted by national or international organizations.
    - Evaluation of opportunities for collaboration (group discussions)

5. EVALUATION OF OPPORTUNITIES TO ADDRESS GAPS AND CHALLENGES (group discussions)
    - Identify potential candidate stations for the GCW surface observing network.
    - How GCW can contribute to addressing local and regional challenges?

6. THE WAY FORWARD
    - Further collaboration and engagements between national and international organizations
    - Identify feasible future activities to address goals: plan next steps
    - GCW contribution to capacity building at national and regional level

7. Field Trip: visit a Tanzanian Meteorological Agency station

9. Annex 2: List of Participants

No.	Name	Institution/Affiliation	e-mail
1	Árni Snorrason Chair, GCW Steering Group	Icelandic Meteorological Office, Reykjavik, Iceland	arni.snorrason@vedur.is
2	Jeff Key	Cooperative Institute for Meteorological Satellite Studies, University of Wisconsin-Madison, Madison WI, USA	jkey@ssec.wisc.edu
3	Rainer Prinz	University of Graz, Austria	rainer.prinz@uni-graz.at
4	Alvaro Soruco	Universidad Mayor de San Andrés (UMSA), Instituto de Investigaciones Geológicas y del Medio Ambiente (IGEMA) La Paz Bolivia	alvaro.soruco@gmail.com
5.	Jean-Louis Ebengo Bakele Mpot'okle	Agence Nationale de Météorologie et de Télédétection par Satellite (METTELSAT) Dem Rep of Congo	jlebmpotokole@gmail.com
6.	Bolivar Caceres	Servicio Meteorológico e Hidrológico Nacional del Ecuador (INAMHI), Ecuador	bcaceres@inamhi.gob.ec
7.	Donaldi Permana	Meteorological Climatological and Geophysical Agency (BMKG), Indonesia	donaldi.permana@bmkg.go.id donaldi.sp@gmail.com
8.	Constance Okuku	Kenya Meteorological Department, Kenya	colnex2004@yahoo.co.uk
9.	Meriem Alaouri	Centre National du Climat Direction de la Météorologie Nationale Morocco	meriemalaouri@gmail.com
10.	Marti Bonshoms Calvelo	Servicio Nacional De Meteorología e Hidrología Del Perú (SENAMHI) , Perú	mbonshoms@senamhi.gob.pe
11.	Agnes Kijazi	Tanzanian Meteorological Agency Tanzania	agnes.kijazi@meteo.go.tz
12	Wilbert Muruke	Tanzanian Meteorological Agency Tanzania	wilbert.muruke@meteo.go.tz
13	Ladislaus C'hanga	Tanzanian Meteorological Agency Tanzania	ladislaus.changa@meteo.go.tz
14	Rodney Martinez (Remote participation)	Centro Internacional para la Investigación del Fenómeno de El Niño (CIIFEN)	r.martinez@ciifen.org
15	Andre Kamga (Remote participation)	Climate and Environment Department African Centre for Meteorological Applications for Development (ACMAD)	akamgaf@yahoo.com
16	Rodica Nitu	WMO Secretariat, Geneva, Switzerland	rnitu@wmo.int

10. Annex 3: Address, Governor of Province of Arusha

Ladies and Gentlemen,

On behalf of the Government of the United Republic of Tanzania express my appreciation and sincere thanks to the World Meteorological Organization (WMO) for organizing and supporting this important workshop and choosing my Region Arusha as a venue.

Tanzania is blessed with several natural attractions including National Parks with huge number of animals such as Serengeti, Manyara, Mikumi just to mention a few. Other natural attractions include Ngorongoro Crater, Mount Kilimanjaro, the snow caped mountain and the highest peak in Africa; Mount Meru and the spice islands of Zanzibar

I have been informed that, the objective of this workshop is to develop practical aspects of the implementation of Cryosphere observation network (CryoNet), research and services in high mountain areas. I congratulate you for such important vision and actually great initiative. It is evident that high Mountains areas in most of the tropical countries are still not adequately observed in spite of their important contribution in weather and climate, and in ecological and socio-economic development. This workshop therefore provides a great and unique opportunity and it is an important step in addressing the observation and monitoring challenges facing high mountains areas particularly in tropical region. Addressing these challenges will significantly contribute to informed and effective decision making in socio-economic development and will enhance the climate change resilience of the large communities that depend on high mountains together with its ecosystem for their livelihoods.

I am pleased to learn that this workshop is held in my country, Tanzania, where the snow caped and highest mountain in Africa, Mount Kilimanjaro, is found. Mount Kilimanjaro contributes significantly in various socio-economic sectors including water, energy, agriculture, tourism and forestry.

As we are all aware, Tanzania like many other countries is experiencing the impacts of climate change which, among others has caused retreat of glaciers on mount Kilimanjaro leading to shortage of water supply for humans, agriculture and livestock, just to mention a few. However, inadequate or lack of observations and monitoring of weather and climate, and cryosphere dynamics limits our understanding of possible future impacts of cryospheric changes on water resources and risk of natural disasters. It is therefore my hope that this workshop will come up with strategies and recommendations for enhancing observations, monitoring and research to enable better understanding of the climate regimes and potential impacts of climate change to the tropical mountains and their ecosystems.

Tanzania is among the vulnerable countries to the impacts of increased climate variability and climate change. Over the last few years devastating droughts and floods causing loss of life, death of livestock, and significant impacts in livelihoods, infrastructure and socio-economic development have impacted some parts of Tanzania including areas surrounding the slopes of mount Kilimanjaro. To address these challenges, the Government has undertaken several efforts including the preparation of the National Climate Change Strategy (NCSS, 2012). The Strategy highlights the steps and commitment to address climate change in both adaptation and mitigation. The Strategy also calls for enhanced awareness and research pertaining to climate change. In this regards this workshop and the initiatives you are taking are in line with our National Climate Change Strategy and also contributes to the achievement of other National and Global agenda including the National Five Year Development Plan 2016/17-2020/21, the Tanzania Development Vision 2025 and the Sustainable Development Goals (SDG’s).

It's my hope that, activities planned in this workshop will help to identify the challenges facing participating countries in observations, monitoring, and assessing the impacts of changes in the cryosphere such as snow and glaciers on various socio-economic sectors including weather, climate and water; then develop an appropriate strategy for improving the community understanding of those changes.

11. Annex 4 : Cryosphere research activities in Tropical Regions

Prepared by: Dr Rainer Prinz, University of Graz, Austria

This document compiles cryospheric research activities in the Tropics.

Table 1 summarizes activities and data sets available for different sites. A thematic focus is on glaciers as observations on snow and permafrost are few and further information will hopefully be shared during the workshop by other participants. A regional focus is on East Africa, because of personal experience, workshop location and because the key sites for glaciological research in South America are CryoNet Stations already and thus well documented. In contrast to East Africa, in tropical South America, the local authorities and stakeholders are much more involved in research management, facilities and in-situ observations, due to a higher socio-economical relevance of glaciers.

It is important to note that (meta)data is often well documented at the homepages of respective project coordinators e.g. at the University of Innsbruck, University of Massachusetts, University of Grenoble (Glacioclim), Byrd Polar and Climate Research Center, University of Zurich, WGMS, etc.

Table 1: Overview of different observations on glaciers in the tropics: current (**+**), historic (**o**) and no or unknown activities/observations (**–**). Further information is given in the text below.

	Mountain	Country	Current activites	AWS	Mass balance	Ice core	Comment
Asia	Puncak Jaya	IDN	–	–	–	o	
Africa	Rwenzori	UGA/COD	+	+	+	–	
	Mt Kenya	KEN	–	+	o	o	
	Kilimanjaro	TZA	+	+	+	o	
South America	Quelccaya Ice Cap	PER	+	+	+	–	CryoNet Station
	Cordillera Vilcanota	PER	+	+	+	–	
	Cordillera Blanca	PER	+	+	+	–	
	Cordillera Huaytapallana	PER	+	+	o	–	
	Cordillera Central	PER	+	+	–	–	
	Cordillera Quisoquipina	PER	+	+	+	–	
	Cordillera Ampato	PER	+	+	+	–	
	Sajama	BOL	–	o	–	o	
	Illimani	BOL	–	o	–	–	
	Zongo	BOL	+	+	+	–	CryoNet Station
	Antizana	ECU	+	+	+	–	CryoNet Station
	...	COL, VEN, MEX					

1. Asia

Papua (Irian Jaya)

No current activities could have been identified. (*A/N*[2] *Updates were provided at the workshop by Dr D Permana*).

In 2010 an ice core was taken under the lead of the Byrd Polar and Climate Research Center, Ohio State University. A detailed analysis of the ice core has not yet been published, although as a precondition a study on rainfall isotopic ratios is available.

Further reading on basic or most recent literature:

Allison, I., and P. D. Kruss (1977), Estimation of recent climate change in Irian Jaya by numerical modeling of its tropical glaciers, *Arctic and Alpine Research*, *9*(1), 49–60.

Klein, A. G., and J. L. Kincaid (2006), Retreat of glaciers on Puncak Jaya, Irian Jaya, determined from 2000 and 2002 IKONOS satellite images, *Journal of Glaciology*, *52*(176), 65–79, doi:10.3189/172756506781828818.

Klein, A. G., and J. L. Kincaid (2008), On the disappearence of the Puncak Mandala ice cap, Papua, *Journal of Glaciology*, *54*(184), 195–198.

Permana, D. S., L. G. Thompson, and G. Setyadi (2016), Tropical West Pacific moisture dynamics and climate controls on rainfall isotopic ratios in southern Papua, Indonesia, *Journal of Geophysical Research: Atmospheres*, *121*, 2222–2245, doi:10.1002/2015JD023893.

2. Africa

In 2013 UNEP published a report on the African glaciers, but unfortunately its key messages were incorrect and missing the relevant literature. A response to this report summarizes the key facts:

- Glaciers in East Africa are too small to act as relevant water reservoirs for the population in the lowland.
- Glaciers in East Africa are shrinking dramatically, but not at an unprecedented pace.
- Glaciers in East Africa are controlled by precipitation and moisture, which modulate mass input and the energy balance. The sensitivity to air temperature is low. Thus, the glacier retreat in Africa is not a warming signal but a drying signal. However, this drying signal may be strongly related to an increase of sea surface temperatures due to Global Warming. Sublimation plays an important role in the mass balance. But it is the size of the glaciers that minimizes melt water availability not the fact that sublimation reduces at the expense of melt.

Mölg, T., N. J. Cullen, D. R. Hardy, G. Kaser, L. Nicholson, R. Prinz, and M. Winkler (2013), East African glacier loss and climate change: Corrections to the UNEP article “Africa without ice and snow,” *Environmental Development*, *6*, 1–6, doi:10.1016/j.envdev.2013.02.001.

2.1 Rwenzori

Last glacier mapping dates back to 2003, but the interpretation of results are controversial and contradict the physical understanding of tropical climate-glacier interactions. An automatic weather station was installed in 2006 by the Italian Ev-K2-CNR association (contact: Elisa Vuillermoz), just below Elena Glacier terminus. The AWS is very likely still active (status June 2017), but lacks automated data transfer. Funding restrictions prohibit data retrieval and maintenance work.

There is an AWS (Davis Instruments Vantage Pro2 Weather Station) installed and functioning on Speke Glacier since Feb 2016 (contact: Denis Samyn), and now available

[2] Author’s Note

for scientific purpose. The rain gauge is unfortunately not working properly, owing to frequent hail/water refreezing in the bucket.

There is mass balance monitoring currently going on since 2013 on Stanley Glacier. A time-lapse camera was also installed in Feb 2016 and is running fine.

Currently, attempts were made to access a TanDEM-X digital elevation model to update glacier extent and volume change, but there is a problem with restricted data availability as the territory of the Democratic Republic of Congo is flagged as *Sensitive Area*. Dartmouth College (contact Meredith Kelly) investigates the Last Glacial Maximum paleoclimatology in the Rwenzori Range.

Further reading on basic or most recent literature:

Kaser, G., and H. Osmaston (2002), *Tropical Glaciers*, Cambridge University Press, Cambridge.

Lentini, G., P. Cristofanelli, R. Duchi, A. Marinoni, G. Verza, E. Vuillermoz, R. Toffolon, and P. Bonasoni (2011), Mount Rwenzori (4750 m a.s.l., Uganda): Meteorological characterization and air-mass transport analysis, *Geografia Fisica e Dinamica Quaternaria*, *34*, 183–193, doi:10.4461/GFDQ.2011.34.17.

Mölg, T., H. Rott, G. Kaser, A. Fischer, and N. J. Cullen (2006), Comment on “Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature” by Richard G. Taylor, Lucinda Mileham, Callist Tindimugaya, Abushen Majugu, Andrew Muwanga, and Bob Nakileza, *Geophysical Research Letters*, *33*(20), 33–36, doi:10.1029/2006GL027254.

Nicholson, L. I., R. Prinz, T. Mölg, and G. Kaser (2013), Micrometeorological conditions and surface mass and energy fluxes on Lewis Glacier, Mt Kenya, in relation to other tropical glaciers, *The Cryosphere*, *7*(4), 1205–1225, doi:10.5194/tc-7-1205-2013.

Taylor, R. G., L. Mileham, C. Tindimugaya, A. Majugu, A. Muwanga, and B. Nakileza (2006), Recent glacial recession in the Rwenzori Mountains of East Africa due to rising air temperature, *Geophysical Research Letters*, *33*(10), L10402, doi:10.1029/2006GL025962.

2.2 Mt Kenya

After decades of glaciological research Stefan Hastenrath retired from mass balance (1996) and aerial surveys (2004). University of Innsbruck, Austria, re-initiated glacio-meteorological observations in 2009 and stopped in 2014, as funding was depleted and the largest glacier (Lewis) split in two tiny parts, making mass balance observations somewhat pointless.

Results from modelling clarify that the mass balance sensitivity is higher to precipitation and moisture than to air temperature, despite the glacier's location close to the mean 0°C altitude. Little Ice Age maximum glacier extents cannot be explained by colder air temperature, but higher precipitation in amount and frequency. A ~80 years mass balance time series exists from glaciological and geodetic observations, ~8 years of AWS record and plenty of other studies e.g. on glacial biology are available.

Currently, University of Innsbruck (contact Armin Heller) and Austrian Alpine Club are performing a remote sensing study (based on Pléiades scenes) to update the Mt Kenya trekking map. Satellite images may be available for glaciological use as well. An AWS is operating at ~4800 m with satellite data transfer, but sensor maintenance may be needed and as well there is a lack of funding. AWS data (~2,5 years on-glacier and ~5 years off-glacier) is open for use (contact Rainer Prinz). TanDEM-X DEM was recently acquired (contact Rainer Prinz).

Further reading on basic or most recent literature:

Hastenrath, S. (1984), *The Glaciers of Equatorial East Africa*, D. Reidel Publishing Company, Dordrecht / Boston / Lancaster.

Prinz, R., A. Fischer, L. Nicholson, and G. Kaser (2011), Seventy-six years of mean mass balance rates derived from recent and re-evaluated ice volume measurements on tropical Lewis Glacier, Mount Kenya, *Geophysical Research Letters*, *38*(20), L20502, doi:10.1029/2011GL049208.

Prinz, R., L. Nicholson, and G. Kaser (2012), Variations of the Lewis Glacier, Mount Kenya, 2004-2012, *Erdkunde*, *66*(3), 255–262, doi:10.3112/erdkunde.2012.03.05.

Prinz, R., L. Nicholson, T. Mölg, W. Gurgiser, and G. Kaser (2016), Climatic controls and climate proxy potential of Lewis Glacier, Mt. Kenya, *The Cryosphere*, *10*(1), 133–148, doi:10.5194/tc-10-133-2016.

Uetake, J., S. Tanaka, K. Hara, Y. Tanabe, D. Samyn, H. Motoyama, S. Imura, and S. Kohshima (2014), Novel biogenic aggregation of Moss Gemmae on a disappearing African glacier, *PLoS ONE*, *9*(11), e112510, doi:10.1371/journal.pone.0112510.

2.3 Kilimanjaro

Glacier mappings on Kilimanjaro have a similar abundant history as on Mt Kenya (e.g. Hastenrath) and the most recent was published in 2013. Glacio-meteorological studies were initiated in 2000 by the University of Massachusetts (contact Doug Hardy) and complemented in 2005 by the University of Innsbruck (contact Georg Kaser and Thomas Mölg – University of Erlangen-Nürnberg now). Since then at least 4 AWS have been continuously operating at the summit, providing a base line for glaciological and atmospheric modelling.

Results decipher the tropical climate-cryosphere interactions, locally and regionally, through analyses on climatic teleconnections and underline the precipitation sensitivity (snowfall as mass input and albedo control) of Kilimanjaro glaciers controlled by sea surface temperatures on the Indian Ocean. A clear distinction must be made between the slope glaciers and the tabular glaciers in the summit crater with their iconic vertical cliff features. In general, energy fluxes are controlled by moisture (and cloudiness and precipitation as a consequence), resulting in a dominant role of sublimation in the mass balance. Locally, (especially on the ice cliffs) solar geometry plays an important role. The age of the Kilimanjaro ice is under debate as the interpretation of the ice core stratigraphy contradicts atmospheric controls on the glaciers. Deforestation of Kilimanjaro slopes has been identified as a minor impact on the summit glaciers, but has significant influence on the mountain precipitation regime.

Current research projects (University of Erlangen-Nürnberg, Germany) continue the AWS records and focus the ENSO footprint on Kilimanjaro. The University of Massachusetts and the Paul Scherrer Institute, Switzerland, (contact Margit Schwikowski) investigate the age-depth relation in the Kilimajaro ice. AWS data will be open after publication or maybe earlier within a tight collaboration agreement.

Further reading on basic or most recent literature:

http://www.thomasmoelg.info/factsheet_kili.pdf

Bohleber, P. et al. (2017), Ground-penetrating radar reveals ice thickness and undisturbed englacial layers at Kilimanjaro's Northern Ice Field, *Cryosphere*, *11*(1), 469–482, doi:10.5194/tc-11-469-2017.

Cullen, N. J., P. Sirguey, T. Mölg, G. Kaser, M. Winkler, and S. J. Fitzsimons (2013), A century of ice retreat on Kilimanjaro: the mapping reloaded, *The Cryosphere*, *7*(2), 419–431, doi:10.5194/tc-7-419-2013.

Kaser, G., T. Mölg, N. J. Cullen, D. R. Hardy, and M. Winkler (2010), Is the decline of ice on Kilimanjaro unprecedented in the Holocene?, *The Holocene*, *20*(7), 1079–1091, doi:10.1177/0959683610369498.

Mölg, T., and G. Kaser (2011), A new approach to resolving climate-cryosphere relations: Downscaling climate dynamics to glacier-scale mass and energy balance without statistical scale linking, *Journal of Geophysical Research*, *116*(D16), 1–13, doi:10.1029/2011JD015669.

Mölg, T., N. J. Cullen, D. R. Hardy, M. Winkler, and G. Kaser (2009a), Quantifying climate change in the tropical midtroposphere over East Africa from glacier shrinkage on Kilimanjaro, *Journal of Climate*, *22*(15), 4162–4181, doi:10.1175/2009JCLI2954.1.

Mölg, T., J. C. H. Chiang, and N. J. Cullen (2009b), Temporal precipitation variability versus altitude on a tropical high mountain: Observations and mesoscale atmospheric modelling, *Quarterly Journal of the Royal Meteorological Society*, *135*, 1439–1455, doi:10.1002/qj.461.

Mölg, T., G. Kaser, and N. J. Cullen (2010), Glacier loss on Kilimanjaro is an exceptional case., *Proceedings of the National Academy of Sciences of the United States of America*, *107*(17), E68, doi:10.1073/pnas.0913780107.

Mölg, T., M. Großhauser, A. Hemp, M. Hofer, and B. Marzeion (2012), Limited forcing of glacier loss through land-cover change on Kilimanjaro, *Nature Climate Change*, *2*(4), 254–258, doi:10.1038/nclimate1390.

Thompson, L. G. et al. (2002), Kilimanjaro ice core records: evidence of holocene climate change in tropical Africa, *Science*, *298*(5593), 589–593, doi:10.1126/science.1073198.

Winkler, M., G. Kaser, N. J. Cullen, T. Mölg, D. R. Hardy, and W. T. Pfeffer (2010), Land-based marginal ice cliffs: Focus on Kilimanjaro, *Erdkunde*, *64*(2), 179–193, doi:10.3112/erdkunde.2010.02.05.

3. South America

As stated above, there is plenty of information for the CryoNet Stations Quelccaya, Antizana and Zongo, thus no further elaboration about these sites.

For cryospheric activities in Mexico, Colombia and Venezuela the workshop will hopefully provide more information.

Studies on Sajama and Ilimani were initiated in the late 1990ies and ceased a few years after. Results can be found at Doug Hardy's homepage.

Studies on Shallap and Artesonraju glacier investigate the climate-glacier interaction in the Cordillera Blanca and teleconnections to ENSO (University of Innsbruck) and were initiated in the 1990ies with more or less continuous observational time series. Close to both glaciers AWS are installed, but their status is unclear as funding ceased in 2014. Operational climate and mass balance observations are regularly performed at different mountain ranges by Peruvian authorities (SENAMHI, INAIGEM, CONDESAM, ANA). A current project on downscaling climate model data into the glacier boundary layer (University of Innsbruck: Marlis Hofer) for a large scale model attempt of the climate-glacier interactions selected the Cordillera Blanca as a test site.

Complementary to that are studies on climate change adaption focusing runoff, glacial hazards and water availability (University of Zurich: Christian Huggel; University of Hamburg: Martina Neuburger; University of Innsbruck: Wolfgang Gurgiser; Byrd Polar and Climate Research Center: Bryan Mark).

12. Annex 5 List of Workshop Actions and Recommendations

No.	Ref	Actions and Recommendations	Responsible	Due
1	3.1; 6.2	*Promote enhanced efforts in observation and monitoring of weather, climate and cryosphere over high mountains in tropical areas (overarching);*	GSG	On-going
2	3.1; 6.2	*Promote the preparation and implementation of research strategies for enhancing the understanding about the dynamics and potential impacts of climate change on cryosphere and on the ecosystem in tropical high mountains (overarching).*	GSG	On-going
3	2.1	GCW experts to actively examine the lessons learned from previous WMO cross-cutting project, and identify how to plan its engagements in the tropical regions and the programme overall, more effectively, by building on the past experience Aspects for consideration are the implementation of cross cutting programmes with a large number of components, with different organizations and communities, maintaining the focus on sustainability, securing funding to translate workshop plans into practice, maintaining the enthusiasm and momentum.	GSG	On-going
4	3.2 4.0 6.1	GCW to work with PSTG to promote improvements to satellite based observations of SWE and other cryosphere variables in mountain regions, including in tropical regions, where the glaciers are small, particularly Africa, are small so high-resolution data are needed	CryoNet Team / J Key	PSTG-7, Dec 2017
5	3.7; 3.9; 6.2	Complete the evaluation of stations candidate for the GCW Observing Network, (e.g. ANA stations in Peru and Conejeras, Colombia); M Bonshoms will provide to the GCW PO an update on the person responsible of these stations, following the departure from ANA of the original submitter.	CryoNet Team	Jan 2017
6	6.2 6.3.1 6.3.2 6.3.3 6.3.4 3.4 3.7 3.8 3.9	Publish and promote best practices for measurements on glaciers, of snow, and permafrost: - addressing configuration, operation, and maintenance, for high mountain regions, including in tropical regions, - recognizing that these observations are configured in very remote regions, with extremely difficult access, requiring rugged and efficient instruments and reliable power sources; - providing standardized, reliable, protocols for installation, - including recommendations for data collection and transmission. - manually and with automatic instruments; - use of data and products from in-situ and remote sensing;	C Fierz/ T Thorsteinsson	2018

7	3.1 6.2	GCW to promote additional/improved observations of snow in countries in Southern Africa (South Africa, Lesotho, …), where seasonal snow is present. (A/N. To be discussed at GSG-5 for further guidance)	GSG	Jan 2017
8	6.2	GCW will send formal letters to indicate the acceptance of a station as part of GCW observing network, and the requirements for its sustainability, explaining the global significance of the contribution; the letter to be addressed to proponents and the respective PRs	GCW PM	On going
9	4.0	GCW to play an active role in facilitating engagements (data sharing, collaboration for future projects, including the engagement of NMHSs in securing approvals for projects, e.g. by developing a framework for engagement). e.g. GCW to work with R Prinz to identify how to engage Tanzania University, and the operational community to facilitate the sharing of data and the engagement of the local research and operational communities. To be discussed at GSG-5	GSG-5; R Prinz	Jan 2018
10	2.1 3.1 3.5 3.6 3.8 6.2 6.3.4	GCW to assume a lead role for accessing funding to support sustained observations for stations approved for the GCW observing network; Target projects for supporting existing (Antisana, Quito glacier) and new stations (Tanzania, Congo, Kenya, South Africa); (A/N. To be discussed at GSG-5 for further guidance)	GSG	Jan 2017
11	6.3.1	Promote the further develop knowledge and monitoring of the spatio-temporal dynamics of the snowpack and the estimate of the water equivalent of the snowpack	Snow Watch Team	2018
12	6.3.3	Clarify for all potential candidates the characteristics of contributing stations versus CryoNet stations.	CryoNet Team	Jan 2018
12	6.3	Submission of new CryoNet stations: Kenya: (3.1;6.3.8) GCW to work with KMD to establish a CryoNet station in Kenya, and access existing research data - Tanzania: (3.1; 4.0; 6.3.7) establish one CryoNet station on Mountain Kilimanjaro and some stations on the highlands, where seasonal snow is present; - Indonesia: 3.4: Currently, there is no existing or recommended station which could be included in the GCW surface observing network in Indonesia. Ideally, station(s) could be developed to observe the cryosphere on the Papua glaciers; - Ecuador: 3.5 additional CryoNet stations from Ecuador depend on the ability to sustain these stations. (6.3.4) Would like to upgrade the status of the station on the Quito glacier into a CryoNet station, but it depends on the availability of funding - Morocco: 6.3.1 submissions from Morocco are possible; M Alaouri will follow up with the WMO Secretariat, after internal discussions.	CryoNet Team R Prinz (to link with the researchers operating the station on Kilimanjaro)	Jan 2018

14	6.3.3	GCW and SENAMHI to collaborate on making available the permafrost data already collected in Peru	GCW PM	2018
15	6.2	Follow up on the monitoring of permafrost in the countries represented at the workshop	GCW PM/ Observations WG	2018
16	3.8	*M Bonshoms was asked to provide to GCW for sharing with all participants, an estimate of the cost to install and maintain a station in the mountains of PERU, on the life span of a station, and the major challenge encountered in operations.*	M Bonshoms	Dec 2017
17	3.4 6.2	*GCW to lead the development of WMO mechanisms for reporting and exchange of SWE data, from manual and automatic stations, operationally.*	Snow Watch Team	June 2018
18	6.2 6.3.7 6.3.8	Data rescue: - GCW to collaborate with representatives of meeting participants (Tanzania, Kenya) towards digitizing the available data, still in paper format, and from sources other than the NMHS. - Fast track archiving of fragmented cryosphere data with various government agencies for research and policy development; - Promote the access of existing hydrometric observations in the areas where potential cryosphere stations are proposed (Tanzania);	Snow Watch Team	2018
19	6.2	Encourage contributions to developing yearly assessments for northern and southern hemisphere: identify sources of data and promote new observations (see actions above on observations)	GSG	On-going
20	4.0 6.2 3.1; 3.8	GCW to take a lead role in defining an approach for brokering the access to existing and available research data, that is reproducible (e.g. agreements, using PANGAEA); (A/N. To be discussed at GSG-5 for further guidance)	GSG	Jan 2017
21	6.3.1	GCW to support national and international collaboration on the use of cryosphere data from in-situ and remote systems.	Integrated Products WG	
22	6.3.5	GCW to find ways to harvest the metadata from stations directly from questionnaires. Smaller contributors to GCW have very little support and would not be able to enter the metadata, once again. E.g. for Zongo glacier, for the contribution to WGMS, an excel spreadsheet with data and maps was provided and WGMS prepares the reports.	Observations WG and Data Portal Team	2018
23	6.3.5	GCW develops a standard for showing data on the portal, and be very clear about how GCW is different from WGMS, to avoid duplication, and show the value added. (A/N. To be discussed at GSG-5 for further guidance)	Data Portal Team; GSG	Jan 2018
24	6.2	GCW to engage the national organizations to facilitate the speed up in obtaining national research permit policies, which increasingly become too expensive and too slow, especially for immediate actions required to safe monitoring equipment over unstable ground (snow/ice surfaces);	GSG	On-going

		A/N: to be further discussed at GSG-5 for further guidance		
25	5.1; 5.2 6.2 6.3.4	GCW to develop linkages with CIIFEN and ACMAD, similar to those with the Arctic PRCC and the planned Asia High Mountain-RCC. As CIIFEN, ACMAD are interested in integrating the cryosphere data, the GCW Data Portal will be the gateway for this.	Information and Services and Integrated Products WGs	2018
26	3.6 6.2	Collaborate with UNESCO on the continuation of current glacier monitoring projects in South America. B Caceres to represent GCW at the Mendoza UNESCO meeting, August 2017;	GCW PM GSG	2017
27	3.5 3.6 6.2 6.3.2	Secretariat to prepare letters to the PRs of countries represented at the workshop, to: • Thank for support and encourage the continuation of engagement (valuable for building linkages between communities, e.g. Bolivia); • Providing a letter to the PR of Indonesia, highlighting the importance of continued cryosphere observations, and encourage the setup of a CryoNet station on Puncak Jaya, Papua. • Provide a letter to support for the operation of the Zongo glacier station over the long term, in collaboration with WG*MS, which is interested to support communication on securing the glacier measurement, which is the longest in the tropics;* • GCW to send a letter to the PR recognizing the contribution of Ecuador to GCW, the importance of continuous support for these stations, and the need to sustain these, with funding	GCW PM	GSG-5
28	6.2 6.3.3 6.3.5 6.3.8	GCW to facilitate the development of capacity at national level where CryNet and contributing stations are operated: - on observations, data exchange, advanced products), - by making available outreach materials, reports, organize targeted training (observations), engage other parts of WMO, involvement of Universities in countries with stations contributing to the network (all GCW WG) - GCW to consider the development of capacity building activities similar to GAW, e.g. training station operators and managers;	All GCW WG	On-going
29	3.5	GCW to help link cryosphere researchers in Bolivia with the operational organizations, and the Office of the PR of Bolivia;	GCW PM	GSG-5
30	3.1 3.9	GCW to facilitate the exchange of expertise on CryoNet observations between tropical and extra-tropical, and polar regions		
31	6.3.6	GCW to prepare outreach material in French, to be shared with the national meteorological service of francophone countries, e.g. Dem Rep of Congo	GCW PM	2018

32	6.2	GCW to facilitate the collaboration at national and regional level, and the engagement of hydrological services, and the access to flood forecasting guidance systems: instruments to build on at regional scale;	GSG	2018
33	3.1 3.8 6.2	Communicate with other relevant WMO activities on needs for improvements in the computing infrastructure, communications (RT, near RT) and the need for capacity development in Numerical Weather Prediction (NWP) with a focus on high mountain areas; (A/N. To be discussed at GSG-5 for further guidance)	GSG	Jan 2017
34	6.3.1	Provide more clarity to all partners about the linkages of GCW with other programs using cryosphere data, e.g. CHy, and GFCS (water and disaster risk sectors). (A/N: To be discussed at GSG-5 for further guidance)	Information and Services WG	Jan 2017
35	6.3.7	Recommended that a newsletter is published to document the initiative in tropical areas: on-going and future and activities	GCW PM; Information and Services WG	GSG-5
36	3.4	GCW to consider how to build on and engage private entities already active in high mountain regions	GSG	2018
37	3.5	A Soruco asked WMO to promote stronger environmental regulations in developing countries, in areas affected by climate change, where new economic opportunities become available as a result of those changes, e.g. melting and disappearance of glaciers, including by promoting the protection of sensitive areas, and finding the right balance with economic development.	GSG	EC-70
39	6.2	Communicate research areas of interest to WMO Research programmes, as outlined in section 6.2 of the report	GCW PM	GSG-5
40	3.6 3.7	GCW to contribute the documentation of impacts of cryosphere changes, including the socio-cultural implications (link to services, disaster risk management); Support for analysis of the direct relation between the discharge of glacier origin with the rivers in the high, middle and low parts of the basins. WMO to promote the importance of understanding the linkages between climate changes in the high mountain regions and climate change in low altitudes, similar to how impacts in the Polar regions are promoted (higher vs lower latitude teleconnections). Promote the understanding of the importance of integrated research to understand natural hazards, e.g. studies of cryosphere/glaciers and the connections with the risks of volcano eruptions. (A/N. To be discussed at GSG-5 for further guidance)	GSG	GSG-5
38	3.9	GCW to promote establishing a “World Glacier Day”	GSG	2018

13. ANNEX 6: Acronyms

ACMAD	Centre Africain pour les Applications de la Météorologie au Développement
ANA	Autoridad National del Agua (Peru)
ANMTS	Agence Nationale de Meteorologie et de Teledetection par Satellite (of Dem Republic of Congo)
BMKG	Meteorological, Climatological, and Geophysical Agency of Indonesia
CIIFEN	Centro Internacional para la Investigación del Fenómeno de El Niño
DMN	National Meteorological Department of Morocco
EC	Executive Council (of WMO)
GCW	Global Cryosphere Watch
GFCS	Global Framework for Climate Services
IDEAM	National Institute of Meteorology, Hydrology, and Environmental Studies of Colombia
INAHMI	Instituto National de Meteorologia e Hydrologia of Ecuador
IPCC	International Panel co Climate Change
KMD	Kenyan Meteorological Department
NCCS	National Climate Change Strategy (of Tanzania)
NMHS	National Meteorological and Hydrological Services
NWP	Numerical Weather Prediction
PR	Permanent Representative
PSTG	Polar Satellite Task Group
SENAMHI	Servicio National de Meteorologia e Hydrologia del Peru
TMA	Tanzanian Meteorological Agency
UMSA	Universidad Mayor de San Andres
WMO	World Meteorological Organization
WIGOS	WMO Integrated Global Observing System