http://www.scar.ac.cn
Sciences in Cold and Arid Regions
2012, 4(1): 0001–0012
DOI: 10.3724/SP.J.1226.2012.00001

High Asia cryospheric observation: a proposed network under Global Cryosphere Watch (GCW)

CunDe Xiao [1,2*], ZhongQin Li [1], Lin Zhao [1], ShiChang Kang [1,3], YuanQing He [1], Xiang Qin [1], XiaoBo He [1]

1. State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences, Lanzhou, Gansu 730000, China
2. Institute of Climate System, Chinese Academy of Meteorological Science, China Meteorology Administration, Beijing 100081, China
3. Institute of Tibetan Plateau Research, Chinese Academy of Sciences, Beijing 100871, China

*Correspondence to: Dr. CunDe Xiao (vice-president of International Association of Cryospheric Sciences, IACS), State Key Laboratory of Cryospheric Sciences, Cold and Arid Regions Environmental and Engineering Research Institute, Chinese Academy of Sciences. No. 320, West Donggang Road, Lanzhou, Gansu 730000, China. Email: cdxiao@lzb.ac.cn

Received: May 22, 2011   Accepted: July 30, 2011

ABSTRACT

In coordination with Global Cryosphere Watch (GCW) initiated by World Meteorology Administration (WMO), a regional observation network is proposed based on existing stations/sites over High Asia and cryospheric elements required by GCW. Thus, High Asian Cryosphere (HAC) network is preliminary designed, composing of seven "supersites", each containing several reference sites. The network covers major mountain ranges in High Asia, such as East Tianshan, Qilian, Tanggula, Nyainqentanglha, Himalayas as well as the central and eastern Qinghai-Xizang (Tibet) Plateau. Although multiple cryospheric elements were observed at the existing HAC network, many others, which are required by Integrated Global Observation System-Cryosphere Theme (IGOS-Cryosphere), are not yet included. More comprehensive observations are necessary to be included into "supersites" of HAC, so that the basic requirements for validation of satellite data, assimilation and coupled regional models can be met.
Keywords: cryosphere; reference site; supersite; standardization; High Asia

1. Introduction

The cryosphere collectively describes components of the climate system consisting of all snow, ice and frozen ground (including permafrost) on and beneath the surface of the earth and ocean (Lemke *et al*., 2007). This includes solid precipitation, snow cover, ice sheets/shelves, permafrost, seasonally frozen ground, glaciers, ice caps, sea ice, and lake and river ice. The cryosphere is distributed at all latitudes with large areas in the Arctic, Antarctic, and mountain regions. Frozen water and its variability and change in the atmosphere, on land, and on the ocean surface have direct feedbacks within the climate system, affecting energy, moisture, gas and particle fluxes, clouds, precipitation, hydrological conditions, and atmospheric and oceanic circulation. The cryosphere provides some of the most useful indicators of climate change, yet is one of the most under-sampled domains of the Earth system. Improved cryospheric monitoring is essential to fully assess, predict, and adapt to the variability/change of climate and water availability.

Considering the importance of cryosphere, most global observation plans and initiatives highlight the necessity of cryospheric monitoring. These programs/initiatives include Global Earth Observation System of System (GEOSS), Global Atmospheric Observation System (GCOS), Global Terrestrial Observation System (GTOS), Integrated Global Observing Strategy (IGOS), Polar Observation, Research and Service (PORS), and many others. Among these programs and initiatives, PORS for the first time initiated an overall monitoring of global cryosphere, called Global Cryosphere Watch (GCW), which was approved by the 16th World Meteorology Administration (WMO) Congress in

2011. GCW will be an international mechanism for supporting all key cryospheric in-situ and remote sensing observations, from research and operations, and for implementing the recommendations of the Integrated Global Observing Strategy Partnership (IGOS-P)—Cryosphere Theme (Key *et al*., 2007).

The major part of High Asia, including the Tibetan Plateau, Pamir Plateau and Tianshan Mountains, is one of the most cryosphere-developed areas in the mid-latitudes. There are more than 50,000 glaciers in this region with total area of about 127,000 km^2 and ice volume of 15,000 km^3 (Wang and Su, 2003). The total discharge from meltwater amounts to 150 km^3, with about half outflows towards oceans and another half supplies the interior dry basins. The overall area of permafrost is larger than 1.5×10^6 km^2. Snow covers an area of up to 2.5×10^6 km^2 of High Asia in extreme winter/spring climate.

High Asian cryosphere (HAC) is highly relevant to regional weather/climate and is a critical source for water availability, thus it is extremely important in sustainable development in this most populated region of the world (Barnett *et al*., 2005; Ding and Qin, 2009; Immerzee *et al*., 2010).

Approximately eight large rivers originate from HAC, among them, the Yangtze and Yellow rivers flow into the Pacific; the Ganges, Indus, Yarlung Zangbo/Brahmaputra and Lantsang/Meikong rivers flow into the Indian Ocean; while the Ob and Yenisei rivers flow into the Arctic. Interior rivers originating from high altitudes feed large oasis in the lower deserted areas of the hinterland of Asian continent. The largest basin, Tarim River Basin, has a large population (about 20 million people), along with the Hexi Corridor (5 million people). Life would not exist in these dry basins without snow/ice in the high mountains. Cryospheric changes in High Asia directly impacts sustainable development in local and adjacent regions, along with potential socio-economic impacts on downstream regions.

GCW is about to initiate IGOS-P—Cryosphere's recommendation on establishment of a network of reference sites or "supersites". The first step is to identify and evaluate the appropriateness of the location, the type of measurements, existing measurement standards, and availability of data. GCW would implement a standardized network of cryospheric observatories in cold climate regions, where many cryospheric elements would be monitored long-term in a standard manner. These sites would be suitable for validation of satellite and model outputs of cryospheric elements.

In the last approximately 50 years, long-term observation stations and sporadic observation sites have been set up in High Asia. To meet the requirements of validation of satellite observation and model inputs, these stations/sites are needed to be redesigned as "supersites"/reference sites under GCW.

2. Current observation network of HAC

Since the late 1950s, cryospheric observations have been operating in the High Asia area (Figure 1). The longest glacier observation is for Glacier No. 1 at the headwater of Urumqi River, Tianshan Mountains. In the recent two decades, there are about 20 glaciers under regular measurements, covering the major glacial areas in HAC. Frozen ground was monitored mainly along the Qinghai-Xizang (Tibet) Highway/Railway in the past, but has been expanded to a wider area over HAC in recent years. Snow cover is observed at year-around meteorological stations located in HAC. Approximately 12 hydrological stations are located in the cryospheric area, but less than 10 stations are operated by the National Hydrological Bureau (Figure 1). These in-situ observations have laid a solid foundation for a more comprehensive observation network in this region (Xiao *et al*., 2007, 2008), and the foundation for calibration and validation of remote sensing data.

Currently, most available networks are within China territorial, we here list seven planned "supersites", each contains several reference sites. But in long term, HAC will certainly be extended to outside of the Tibetan Plateau and Tianshan Mountains, and we are looking forward to a comprehensive observation system in High Asia.

Cryospheric observation data on HAC have been achieved in the World Data Center D (WDC-D, http://wdcdgg.westgis.ac.cn). WDC for Glaciology and Geocryology, Lanzhou, is the main part of the World Data Center. It is also one of the professional databases of Chinese Scientific Database, which aims at the collection, saving, management and analysis on Chinese Cryosphere Database that includes the Polar regions and High Asia regions. This data center can also promote the sharing of the cryosphere data in the Earth sciences. It would contribute to the research of the global change, the protection of the cold and arid regions, the exploitation of the natural resource, the construction of the projects and the work to forefend and reduce the disaster.

3. Planned "supersites" and reference sites for HAC

HAC covers an area of approximately 27°N–50°N in latitudes and 70°E–105°E in longitudes. Different parts of HAC locate in different geographic units and climatic zones, thus develop different types of glaciers, frozen ground and different annual durations of snow cover. Cryosphere in different areas has different hydrological regime, *i.e*., exterior rivers and interior rivers. Therefore, when studying the role of HAC, we should divide it into several sub-regions according to these natural units and exist observing network, thus seven "supersites" are proposed as follows (Figure 2):

(1) ETCON: East Tianshan Cryosphere Observing Network. The "supersite", Tianshan Glacier Station, is a state key observatory of China. The network monitors cryospheric changes of major interior rivers in the dry hinterland of Asian continent, such as rivers in the Tarim River Basin.

(2) CRS: Cryospheric Research Station. This station is a state key observatory of China. It observes large permafrost areas of the north part of HAC.

(3) NAMOR: Nam Co Station for Multisphere Observation and Research, CAS. The "supersite" locates at the 2nd

largest lake area (Nam Co) on the Plateau. It is an ideal site for long-term monitoring of atmosphere-cryosphere-hydrosphere-biosphere-land surface interactions.

(4) QLCON: Qilian Mountain Cryosphere Observing Network. This is another key region that interior rivers originated from. The rivers originate from Qilian Mountains are "life cradles" of Hexi Corridor, feeding more than 5 million people.

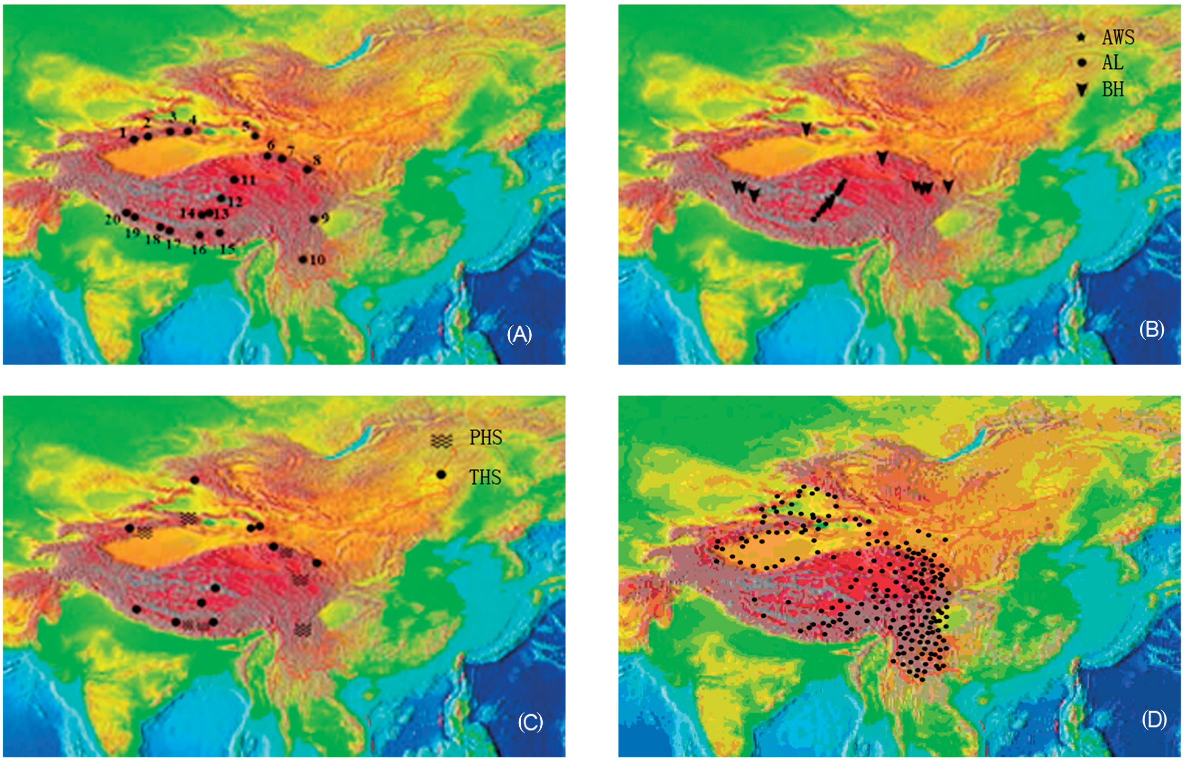

Figure 1 Current stations/sites over High Asia where cryospheric components are being observed. (A) Glaciers; (B) Frozen ground, with AWS for automatic weather station, AL for active layer and BH for borehole; (C) Hydrology, with PHS for permanent hydrology station and THS for temporal hydrology station; (D) Snow cover.

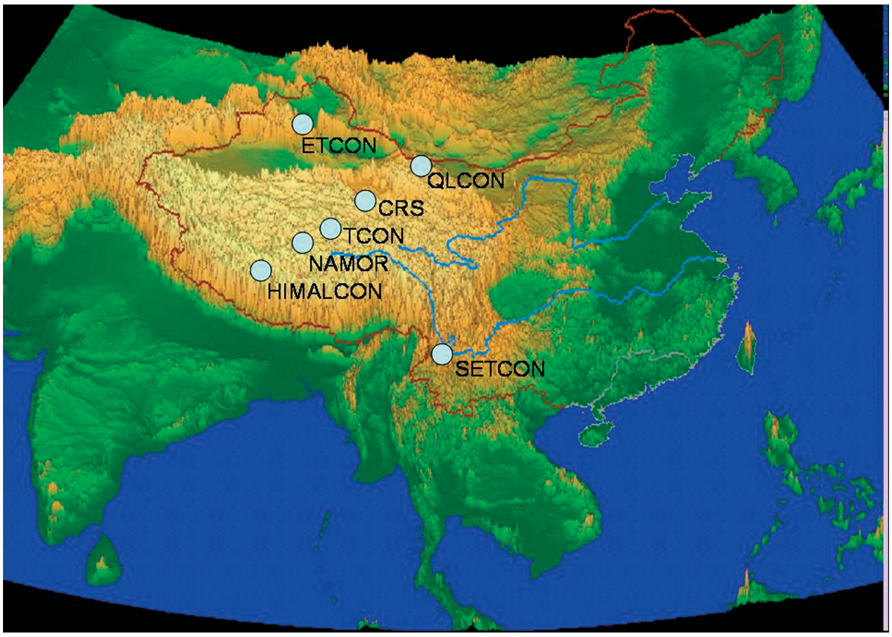

Figure 2 Location of seven "supersites" planned for HAC

(5) SETCON: The Southeastern Tibetan Plateau Cryosphere Observing Network Glaciers in this area are maritime type, which are very sensitive to climate changes.

(6) TCON: Tanggula Cryosphere Observing Network. This network locates in the center part of HAC, which may reveal the less sensitive changes of cryosphere of the region.

(7) HIMALCON: Himalayas Cryosphere Observing Network. Himalayas is so-called "Earth's roof". The network locates in the southern margin of the HAC, mainly reflects the influences of Indian Monsoon, and the cryosphere of Himalayas impacts water resources of Indus, Ganges and Yarlung Zangbo/ Brahmaputra basins.

Here we list cryospheric and related parameters currently observed at the seven "supersites" and their reference sites (Table 1). These parameters include cryospheric and related atmospheric and biospheric essential variables.

Table 1 Cryospheric parameters and other related elements observed in HAC network

Observation items			Method	Frequency	Accuracy	Supersites
Cryopsheric components	Glacier	mass balance	manual	annually	cm	all but CRS
		area	satellite	annually	5 m	all but CRS
		thickness	radar	1/2yr	1 m	all but CRS
		terminal position	GPS	annually	cm	all but CRS
		surface velocity	GPS	1/2yr	cm/yr	all but CRS
		ice temperature	platinum thermometer	aperiodic	0.1 °C	all but CRS
		ELA	calculated	annually	m	all but CRS
		others (debris, serac, glacial lakes)	manual	aperiodic		HIMALCON
	Snow cover	coverage (%)	manual and satellite	daily	10%	all but CRS, QLCON
		precipitation	gauge	daily	mm	all but CRS
		depth	manual	daily	cm	all
		water content	manual	daily	mm w.e.	all but TCON
		density	manual	daily	0.1 g/cm^3	all but CRS, QLCON
		temperature	manual	daily	0.1 °C	all but CRS, QLCON, SETCON
		grain size	manual	daily	0.1 mm	ETCON,NAMOR,QLCON
		albedo	AVHRR, MODIS	daily	7%	all
		SWE	manual	daily	mm w.e.	NAMOR, ETCON, QLCON, TCON
		start date	visual, satellite	annually	day	all
		end date	visual, satellite	annually	day	all
		melt date	visual, satellite	annually	day	all
	Frozen ground	active layer depth	interpolate	daily	5 cm	CRS,TCON
		soil temperature	auto	0.5 hr	0.1 °C	CRS,TCON
		soil water content	auto	0.5 hr	0.5%	all but HIMALCON
		heat flux	auto	0.5 hr	3%	all but HIMALCON
		borehole temperature	auto	0.5 hr	0.1 °C	CRS, ETCON, QLCON
		ground deformation	manual	1/bi-month	3 mm	CRS
		SFG depth	interpolate	daily	5 cm	all
	Solid precipitation	snowfall	T200B	daily	mm	all but CRS
		types	optical	daily	mm	all but CRS
		gain size	manual	daily	0.1 mm	ETCON, NAMOR
		capture rate	T200B	daily	5%	all but CRS
		snow/rain ratio	manual	daily	0.1	NAMOR
	River/lake ice	first-ice date	visual, satellite	daily	day	NAMOR
		freeze-up date	visual, satellite	daily	day	NAMOR
		ice coverage (%)	visual, satellite	daily	5%	NAMOR
		water free date	visual, satellite	daily	day	NAMOR
		break-up date	visual, satellite	daily	day	NAMOR
		ice free date	visual, satellite	daily	day	NAMOR

(to be continued)

(continuation)

Table 1 Cryospheric parameters and other related elements observed in HAC network

		ice cover duration	calculated	annual	day	NAMOR
		snow depth on ice	manual	weekly	cm	NAMOR
		ice thickness	manual	weekly	cm	NAMOR
	Hydrology	water level	HOBO	1 hr/seasonally	0.3 cm	all
		discharge	calculation	As above	0.2 m^3	all
		temperature	HOBO	As above	0.3 °C	all
		pH value	Acidity meter	seasonally	0.1	ETCON, NAMOR
		conductivity	Conductivity meter	seasonally	0.1 ms/cm	ETCON, NAMOR
Other components related to climate system	Atmosphere	air temperature	AWS	30 min	0.1 °C	all
		air pressure	AWS	30 min	5 mbar	all
		wind (speed, direction)	AWS	30 min	0.3 m/s, 3 deg.	all
		humidity	AWS	30 min	3%	all
		solar radiation	AWS	30 min	10% daily sum	all
		precipitation	AWS	30 min	0.1 mm	all
		evaporation	manual	12 hr	0.1 mm	all
		cloud	manual	12 hr	1/10	all
		sunshine duration	AWS	daily	5 min	all
	Biosphere	vegetation (coverage, biomass, diversity)	manual	seasonally	5%, 1 g, 1%	CRS, QLCON, NAMOR

3.1. HAC-ETCON

ETCON consists of a "supersite" and seven reference sites. The "supersite" is on the Urumqi River Basin where the well-known Urumqi Glacier No. 1 is located. Six reference sites are distributed along the Tianshan Montains, and each site contains at least one long-term monitored glacier (Li *et al*., 2003). These glaciers are Miao’ergou icecap, Bogeda Feng, Kuitun No. 51, Keqikaer, and Shenqi Feng (Figure 3). We also include one reference site located in Altay into ETCON. The long-term observation of cryospheric components, such as glaciers, snow cover and frozen ground, in the "supersite" was initiated in 1959 with the foundation of Tianshan Glaciological Station (TGS) at the headwater of the Urumqi River. The relevant observations in the seven reference sites have operated regularly since 1998.

Today, ETCON is basically maintained by TGS and generates various observational data on changes in cryospheric components with time, as well as statistical data on the spatial distribution of glacier inventories in East Tianshan. Such parameters are key variables in climate system monitoring; they form a basis for hydrological modeling with respect to possible effects of atmospheric warming on arid and semi-arid lands in central Asia. The current tasks of ETCON include: (1) in-situ observations with remote sensing data; (2) traditional measurements with new technologies by using an integrated and multi-level strategy; (3) to collect and publish standardized data relating to cryospheric components in regular intervals; (4) to periodically assess ongoing changes; (5) to stimulate satellite observations of cryospheric components in order to reach global coverage; (6) to improve physical process understanding and calibration of numerical models.

3.2. HAC-CRS

The Chinese Academy of Sciences (CAS) established this station in 1987, headquartered at Golmud. It was selected as one of the State Field Observation and Research Stations in 2005, whose main role is environmental monitoring and research of permafrost (Zhao *et al*., 2004).

The observational network of CRS consists of one "supersite" and four reference sites (Figure 4). The "supersite" is the observational transect along the Qinghai-Xizang Highway/Railway, and the observational sites are distributed between Xidatan and Naqu with a range of more than 700 km (31°59′N–35°59′N, 91°58′E–94°13′E) with three auto weather stations (AWS), four eddy covariance systems, 13 active layer monitoring sites (ALMS) and more than 20 permafrost temperature monitoring boreholes (PTMB). The four reference sites are at Maxian Mountain near Lanzhou (35°43′N, 103°59′E) (1 AWS, 1 ALMS and 2 PTMB), Tianshui Lake region in the West Kunlun Mountains (35°35′N, 79°53′E) (1 AWS, 1 ALMS and 10 PTMB), Daxigou Valley in the source area of the Urumqi River (43°06′N–43°13′N, 86°49′E–87°07′E) in Xinjiang Province (1 AWS, 2 ALMS and 2 PTMB), and Wenquan region in Qinghai Province (35°12′N–35°42′N, 99°6′E–99°42′E) (1 AWS, 1 ALMS and 10 PTMB).

The main objective of CRS is to quantify cryospheric changes, especially permafrost under both natural and human-affected conditions on the Plateau. It is expected to understand the processes and mechanism of cryospheric change, and to quantify the interaction between plateau cryosphere and climate, environment, and human activity. All CRS studies are oriented to provide a data platform for research on plateau cryosphere, climate change, ecological environment, engineering and hydrology in cold regions, and to provide scientific support for regional socio-economic development.

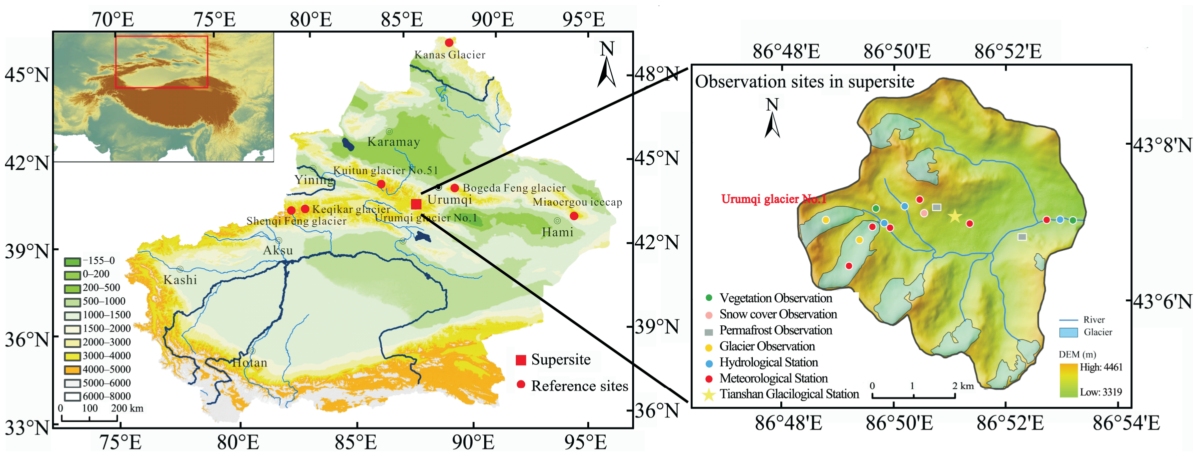

Figure 3 Map of East Tianshan Cryosphere Observing Network (ETCON). Right: supersite at the headwater of the Urumqi River Basin

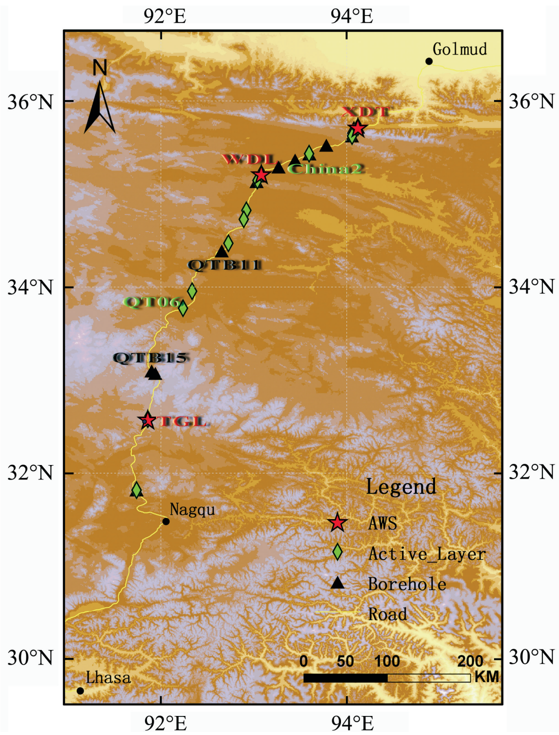

Figure 4 Monitoring sites along the Qinghai-Xizang (Tibet) Highway by CRS

The field monitoring systems of CRS are composed primarily of an automated monitoring system and a manual monitoring system. The former includes external sensors such as air temperature, humidity, wind speed and direction, soil temperatures and moisture, connected to a data collecting system. The latter includes ground-penetrating radar (GPR) and geophysical data processor (GDP) for regular detection of permafrost, and investigating the characteristics of vegetation at most of the observation sites. Current monitoring systems cover the research fields of cryospheric changes in the Qinghai-Xizang Plateau, land surface processes in the permafrost regions, ecological and hydrological processes, and snow and ice disasters in cold regions. Certain monitoring sites have been selected as long-term monitoring sites of the Global Terrestrial Network Permafrost (GTN-P), Circumpolar Active Layer Monitoring (CALM), and the National Snow and Ice Data Center.

3.3. HAC-NAMOR

NAMOR (30°46.44′N, 90°59.31′E, 4,730 m a.s.l.) is located along the southeastern shore of Nam Co Lake, northern slope of the Nyainqentanglha Mountains, 220 km from Lhasa. The Institute of Tibetan Plateau Research, Chinese Academy of Sciences established this station in June 2005. Nam Co Lake is the second largest lake in the inland Tibetan Plateau with an area of 2,000 km^2 and the whole basin area of 10,070 km^2 (Figure 5). The Nam Co Basin possesses glaciers, frozen ground and alpine permafrost, lake and lake ice, river ice, wetlands, and alpine meadows. Due to its environmental diversity, the basin is a key region (or an ideal natural laboratory) for studying the multi-spheric interactions over the Qinghai-Xizang (Tibet) Plateau, especially interactions of the cryosphere with atmosphere, hydrosphere, and biosphere (Kang *et al.*, 2011). Global warming causes quick changes in the cryosphere, which accelerates the heat and water cycle for the basin to regional, even hemispheric scale. However, there is limited in-situ observation data in the high elevation cryosphere due to a harsh and remote environment, which limits our understanding on how the cryosphere responds to global change and further affects climate and environments. Establishment of NAMOR can provide integrated, high quality data from long-term and systematic observation for studies of cryospheric changes and its influence on the high elevation basin.

Through monitoring and observations on glaciology, meteorology, hydrology, lake and river ice, snow and permafrost, atmospheric components, and vegetation, NAMOR aims at understanding the interactions among glaciers, permafrost, lakes, atmosphere, and vegetation in Earth system and their response to global change. The primary tasks of NAMOR include: (1) in-situ observations with remote sensing data; (2) traditional measurements with new technologies by using an integrated and multi-level strategy; (3) to collect standardized data related to the cryosphere and related environmental components in regular time intervals; (4) to periodically assess ongoing changes of land surface; (5) to validate satellite observations of environmental data; (6) to improve process understanding and calibration of numerical models.

Current research projects are as follows: (1) Meteorological and hydrological observation. Using AWSs and hydrological measurements in the south and north of Nyainqentanglha Mountain and around the Nam Co Basin, collecting basic environmental and climatic data in order to understand the climate and hydrology in the Nam Co region. (2) Cryospheric monitoring. Observing the Zhadang Glacier (mass balance and terminal position), snow, lake/ice, seasonal frozen ground and alpine permafrost in the basin to explore cryospheric response to climate change. (3) Atmospheric boundary observation. Using a 52-m atmospheric boundary tower and eddy covariance (CO_2/H_2O flux) to collect meteorological data at different layers, we can study regional land/atmosphere processes, moisture transport and water cycle, and add the parameter database of effective land surface process to the Tibetan Plateau. (4) Present processes of lake and environmental change. Monitoring physical and chemical features of lake water, sedimentary rate, chemistry and biology of sediments, and coring lake sediments in Nam Co. This will broaden our knowledge of environmental significances and features of lake sediments, and further to reconstruct palaeo-environmental change. (5) Atmospheric environment observation. Monitoring precipitation and aerosol chemistry as well as greenhouse gases, to investigate the source, transport, and deposition flux of chemical species in the atmosphere and their seasonal variations. (6) Ecosystem observation. Observing vegetation diversity and biomass, combining them with soil and meteorological data, in order to understand the response of alpine meadows to climate change.

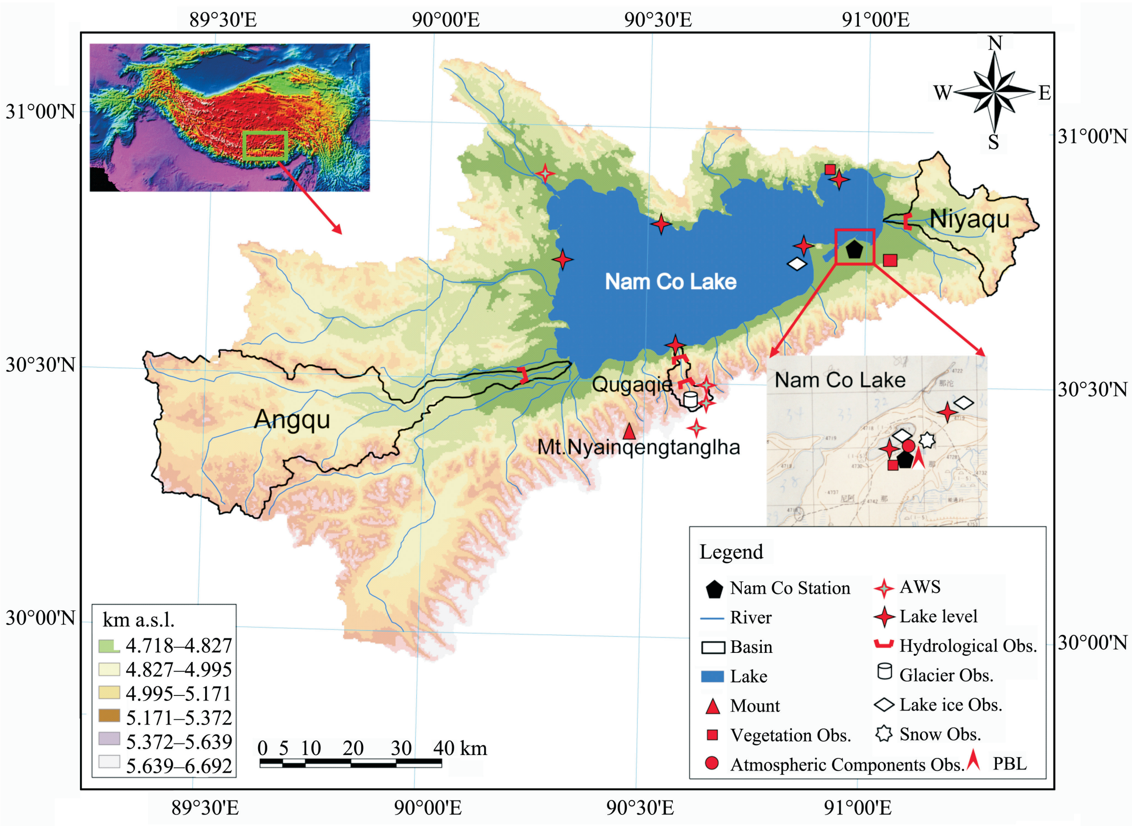

Figure 5 Distribution of observation sites at NAMOR

3.4. HAC-QLCON

QLCON consists of a "supersite" and three reference sites. The "supersite" is at the headwater of Shule River in the western part of the Qilianshan Mountains. The three reference sites are distributed along the Qilianshan Mountains, each site contains at least one long-term monitored glacier. These glaciers are Qiyi, Shiyi, and Ningchanhe No. 3 (Figure 6).

The Qilianshan Station of Glaciology and Ecologic Environment (QSSGEE), Cold and Arid Regions Environmental and Engineering Research Institute, CAS, currently maintains QLCON. The QSSGEE consists of the Basic Station in Yumen City and Laohugou Station, which is located in the western part of the Qilianshan Mountains. The observations are mostly on cryospheric components, such as glacier, snow cover and frozen ground. Observations at the "supersite" was initiated in 1958, and ceased in 1962. Afterwards, some short-term scientific expeditions to the glacier were taken in the mid-1970s and 1980s. In 2005, an integrated cryospheric component monitoring network was resumed at the headwater of Shule River (Du *et al.*, 2008). The relevant observations at the three reference sites have been operated routinely since 2006.

Based on in-situ observations such as glaciers, frozen ground, snow cover, meteorology, hydrology, ecology, and remote sensing data, at the headwater of Shule River Basin, we devote our efforts on: (1) Cryospheric processes. Carrying out routine monitoring of various parameters of the cryosphere, establishing the glacier dynamics model, glacier/snow/frozen ground mass-energy model, and estimating future changes in glacier/frozen ground. (2) Hydrological processes and water resources. Building up the basin hydrological model, which includes glacier changes, snowmelt and permafrost thawing. Combining climate change scenarios and driven hydrological model, provides future projections on the impact of glaciers, snow cover, and permafrost changes on water resources within the Shule River Basin. (3) Ecological community and its environmental changes. Monitoring various types of vegetation changes, ecological communities at different altitudes, and revealing their relationships with environmental change due to natural succession and human activity.

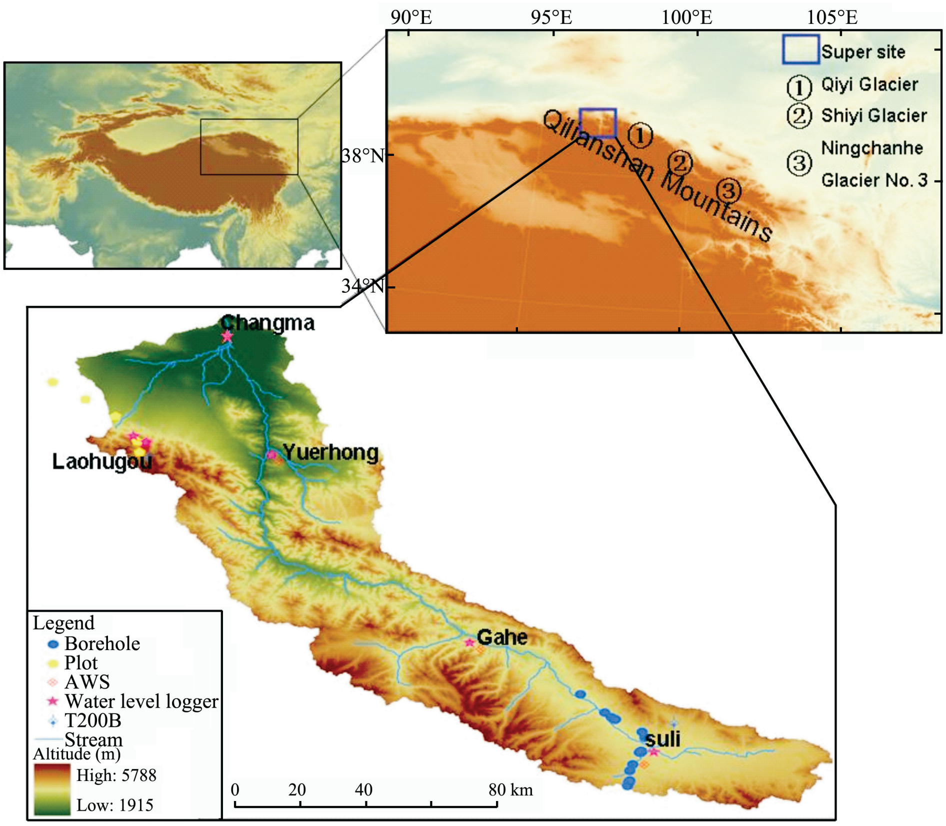

Figure 6 Qilian Mountains Cryosphere Observing Network (QLCON)

3.5. HAC-SETCON

SETCON consists of a "supersite" and six reference sites. The "supersite" is located at Yulong Snow Mountain (27°10′N, 100°13′E) in Lijiang, Yunnan Province, with Baishui Glacier No. 1 selected (there are a total of 15 glaciers on the mountain) as a long-term monitored site (He *et al.*, 2010; Pang *et al.*, 2010). The six reference sites are distributed in different parts of the southeastern Tibetan Plateau, and each site contains at least one long-term monitored glacier, including Mingyong Glacier (28.43°N, 98.68°E) on Meili Mountain, Hailuogou Glacier on Gongga Mountain, Palongzangbu Glacier No. 4 (29.22°N, 96.92°E), No. 10 (29.28°N, 96.93°E), No. 94 (29.38°N, 96.98°E) and No. 390 (29.37°N, 97.73°E) in the eastern Nyainqêntanghla Mountains (Figure 7).

The long-term observation of cryospheric components, such as glacier, melt water runoff, snow cover and frozen ground in the "supersite" was initiated in 2006 with the foundation of Yulong Mountain Glacial and Environmental Observation Station (YGS). Relevant information at the six reference sites has been collected regularly since 2007.

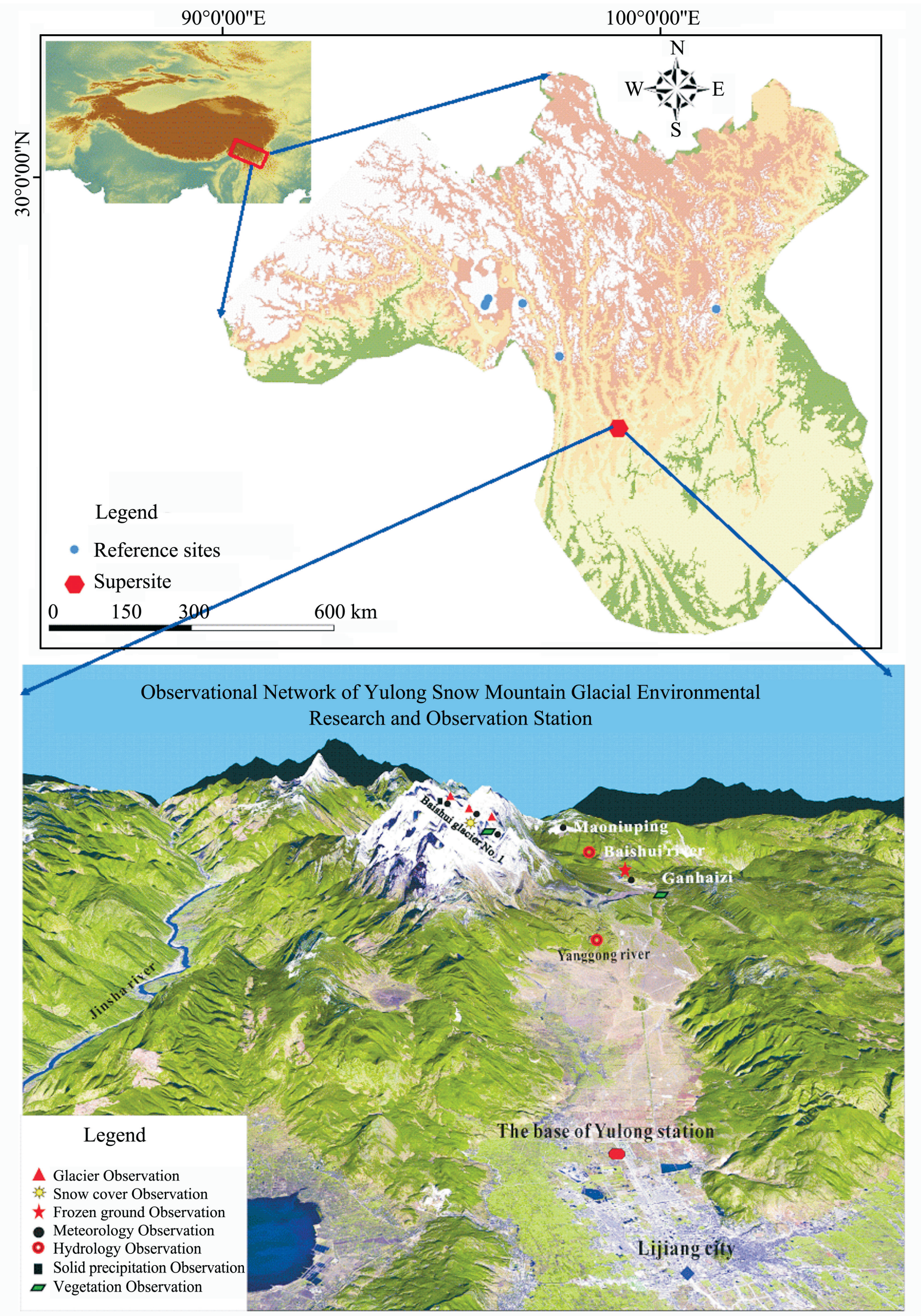

Figure 7 The southeastern Tibetan Plateau Cryosphere Observing Network (SETCON)

Today, SETCON is basically maintained by YGS and generates various observational data on changes in cryospheric components with time. Such parameters are essential variables in climate system monitoring; they form a basis for hydrological modeling and ice-snow variations with respect to possible effects of atmospheric warming on the southeastern part of the Tibetan Plateau. The main tasks of SETCON are: (1) to monitor cryospheric changes indicated by different components when using traditional measurements and in-situ observations integrated with new technologies, such as remote sensing data; (2) to collect standardized data in relation to cryospheric components in regular time intervals; (3) to establish the foundation for an overall understanding on the effect of cryosphere system to climatic process; (4) to validate satellite observations of cryospheric components in the southeastern Tibetan Plateau; (5) to enhance understanding of physical processes and calibration of numerical models.

3.6. HAC-TCON

TCON consists of a "supersite" and four reference sites. The "supersite" is located at the headwater of the Yangtze River, near Tanggula Mountain Pass, hinterland of the Qinghai-Tibet Plateau. The reference sites are hydrological and meteorological stations distributed along the Qinghai-Tibet Highway (Figure 8).

The long-term observation of cryospheric components, such as glacier, snow cover and frozen ground in the "supersite" was initiated in 1989 with the foundation of Tanggula Cryosphere Station (TCS) at the headwater of Yangtze River (Yao *et al*., 2011). The observation framework was developed from glaciological and hydro-climatologically observations at the beginning, to current comprehensive cryospheric observations including permafrost and the ecosystem. These observations have benefited glaciological and hydrologic research and anticipate contributing to cryospheric research in the Tibetan Plateau. The reference sites are respectively two national meteorological stations and two hydrological stations, with long-term records at the headwater region of the Yangtze River. The two meteorological stations, Tuotuohe and Amdo have recorded data from 1956 and 1965, respectively. The two hydrological stations, Yanshiping and Tuotuohe are located in the upper Yangtze River with drainage area of about 2,580 km^2 and 15,920 km^2, respectively. Data recorded at both stations are from 1961 to the present.

The cryospheric observations of TCON includes: (1) Glacier monitoring: mass balance, equilibrium line altitude (ELA), surface velocity, terminal position and glacier area. (2) Permafrost: active layer observation (depth, soil temperature and water content), borehole temperature, groundwater table and heat flux. (3) Hydrological observation: water level and discharge, water temperature and pH value. (4) Meteorological observation: temperature, humidity, wind, pressure, precipitation, radiation, snow depth, sunshine duration, and flux from eddy covariance. (5) Vegetation: plant communities, species composition and biodiversity, biomass and vegetation coverage.

3.7. HAC-HIMALCON

The Himalayas are considered the "roof" of the Earth. Among the 14 mountain peaks higher than 8,000 m a.s.l. worldwide, 11 are located along the Himalayas. There are more than 15,000 glaciers in the Himalayas, with estimated glacier area of 19,500 km^2, and ice volume larger than 1,700 km^3 (Qin, 1999). Glaciers distributed over Qomolangma Mountain (Everest) and adjacent mountainous regions are origins of several Asian rivers, such as the Arun, Indus, Sutlej, Ganges, and Brahmaputra/Tsangpo. These rivers support a large, diverse ecosystem and a population of more than one billion people. This area contains several in-situ observational sites such as Rongbuk Glacier at Qomolangma Mountain and several reference sites located at Naimona Nyi Mountain, Gyemayangzong (which is the original source of Yarlung Zangbu/Brahmaputra), Xixiabangma Mountain, Zengcuo, Qudang, and Nanjiabawa mountains. HIMALCON contains all these sites that are currently located only in the northern slope of the Himalayas. It consists of a "supersite" (Everest Mt. site) located in the Pengqu River Basin, upstream of the Arun Basin, and about eight reference sites along the strike (Figure 9).

These sites focus mainly on the observation of cryospheric variables such as glacier variation, mountainous meteorology, cryospheric hydrology, glacio-chemistry and relative aspects since the mid-1950s and have obtained volumes of first-hand data.

Specifically, the observations of Pengqu/Arun Drainage and Qomolangma Mountain region include: (1) Glacial observation and measurement: mass balance, glacial flow velocity and movement features of East Rongbuk Glacier. (2) Meteorological observation: the meteorological parameters at 6,500 m a.s.l. and various lower altitudes, such as solar and ground radiation, ice reflection, wind speed and direction, ground, ice and air temperatures, air pressure, total precipitation and precipitation characteristics on the basis of automatic weather stations (AWSs) and solid precipitation gauges. (3) Hydrological measurement: sites at the glacier terminus, upstream of Arun, and along the Pengqu River, has obtained meteorological information, such as water level, discharge and water temperature. (4) Atmospheric physical observation: in-situ station—Qomolangma Mountain Station and several reference sites such as Qudang, and Chentang have observed atmospheric boundary process and relative meteorological elements. (5) The reference site —Gyemayangzong Glacier, located in the western Himalayas, which is the headwater of Tsangpo, has observed elements such as glacial changes, ice-melt hydrology and high mountain meteorology. A reference site further west—Naimona Nyi, with around 10 years of data, has measured mass balance, terminal changes, meteorology and hydrology. In the central and eastern sections of the Himalayas are Zengcuo and Nanjiabawa Mountain glacier observation sites that are studying glacial changes, meteorological and hydrological elements of high altitudes.

With the aforementioned network, it is expected that observations could be extended in order to fulfill the following scientific tasks: First, combine in-situ observations with remote sensing data so as to quantitatively assess glacial changes along the Himalayan ranges. Second, obtain key parameters of glaciers at reference sites, develop dynamic glacial models and predict future changes of glaciers under certain climate scenarios. Third, assess how much extent snow/ice meltwater contributes to overall river discharge in current and future climate regimes. Finally, develop a multi-sphere coupling model to quantify the role of the Himalayan cryosphere in regional weather/climate/water.

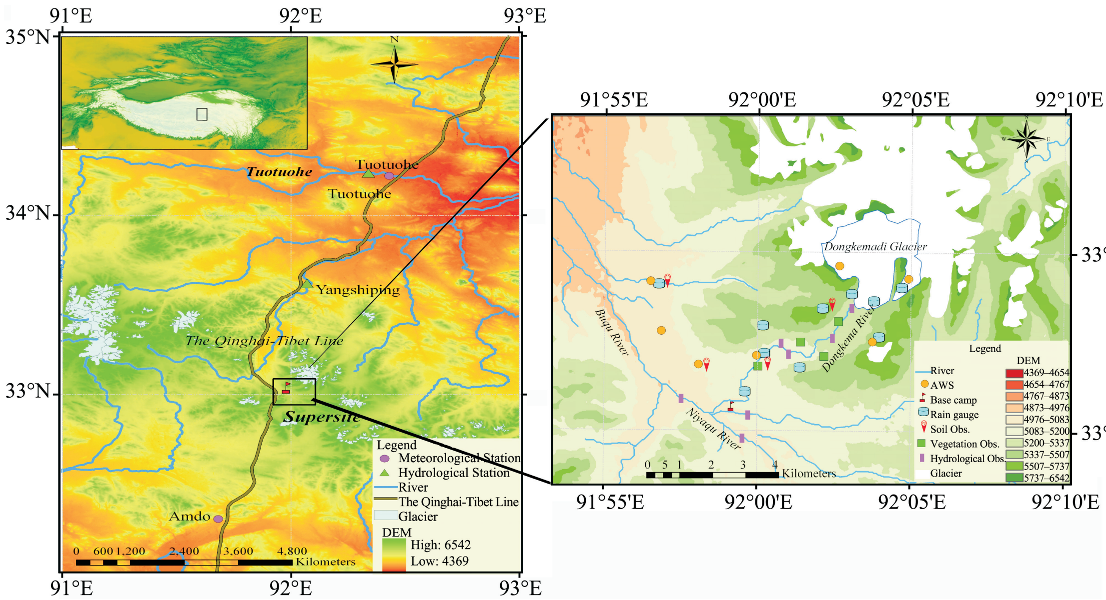

Figure 8 Distribution of Tanggula Cryospheric Observing Network (TCON)

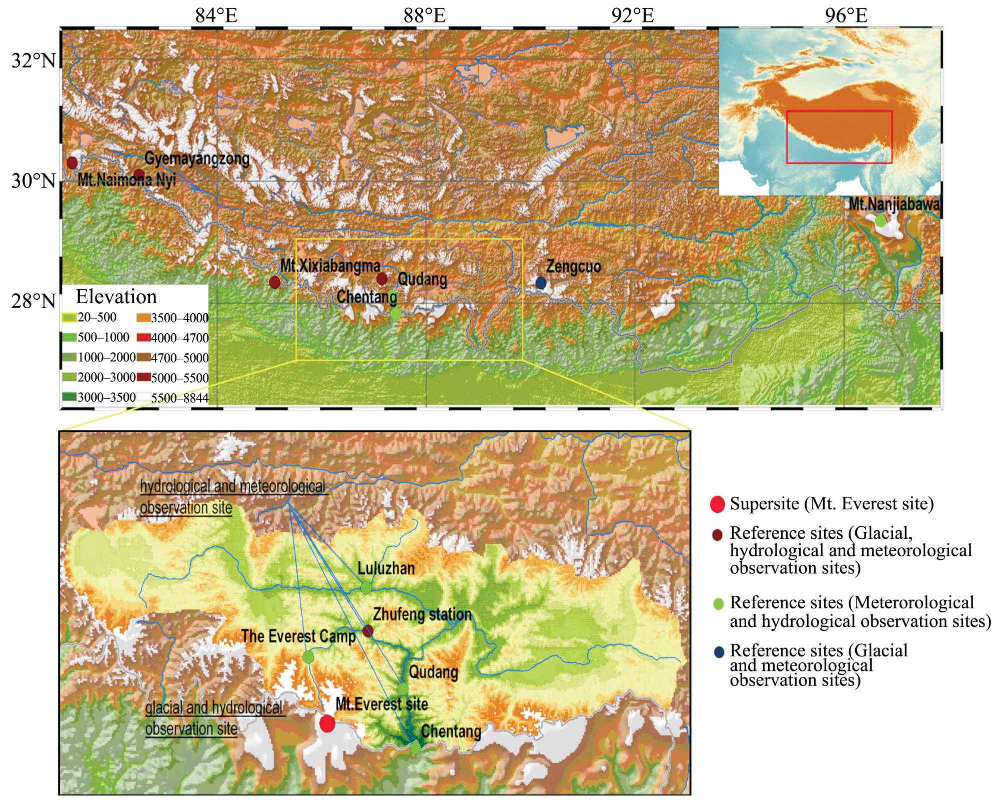

Figure 9 Distribution of Himalayas Cryospheric Observation Network (HIMALCON)

4. Gaps and improvements

"Supersite" observation, as we understand, is a site for data assimilation from in-situ observations or at least merging into satellite data, thus eventually satisfying numerical models. Although the aforementioned HAC sites have been observing various cryospheric elements, many of them still have gaps in terms of fulfilling the requirements by IGOS-Crysphere Theme (Key *et al.*, 2007). The immediate gaps that need to be addressed include:

(1) Glaciers. Major gaps exits on ground truth for remote sensing, parameters for dynamic models. They are: yearly

observations of terminal positions by GPS, ice thickness, ice flow velocity, and mass balance. Most important, key parameters from boreholes such as ice temperature, stress rate, water content, and bottom deformation are urgently needed due to present day warming glaciers. There should be at least one glacier that operates full observations for the aforementioned seven "supersites".

(2) Snow cover and solid precipitation. Most meteorological stations over High Asia observe only snow cover and precipitation (rain gauge). Yet these observations have poor coverage of high mountains, where fresh water originates for dry basins. Many parameters are not on a routine observation list that remote sensing data requires for validation/calibration, such as depth of snow cover, water equivalent, snow density, impurity content (including light absorbing contents such as black carbon), solid precipitation by WMO standard (Goodison *et al*., 1998), precipitation types, and snow crystals (Fierz *et al*., 2009).

(3) Frozen ground. Most comprehensive observations operate along the Qinghai-Xizang (Tibet) Highway. Further development may include: adding observation sites over the northwestern Plateau, deeper borehole observations, vehicle-loaded observation system, and methodology on remote sensing.

(4) Cold regions hydrology: HAC is the origin of Asian rivers, monitoring the contributions of meltwater separating from glaciers, frozen ground and snow cover are essential in distributed hydrology models in cold regions. More stations/sites for hydrology should be established over HAC network in the future, so that the separate roles of cryosphere and climate to river runoff can be assessed precisely (Ren *et al*., 2011).

(5) Other cryosphere-related components. To understand the cryospheric role in global/regional climate, hydrology and ecology, and other related observations that are combined with cryospheric measurements. Meteorological observations (such as temperature, wind, humidity, radiation, albedo, and air pressure) at ground surface and boundary layers are always necessary for physical processes and models. Ecological observations have been operating at several sites at the headwater areas of Yangtze, Yellow and Meikong rivers. Deterioration/desertification of tundra and wetlands are closely related to the thawing of frozen ground in these regions (Wang *et al*., 2004). Long-term ecologic observations during the growing season at the aforementioned seven "supersites" should be carried out in studying atmosphere/hydrosphere/cryosphere/biosphere interactions.

Acknowledgments:
The authors are grateful to WMO/EC-PORS for supporting CunDe Xiao's attendance at the GCW discussions in Ottawa/Canada and Hobart/Australia. DaHe Qin, YongJian Ding, JiaWen Ren and NingLian Wang coordinated the discussion of HAC network. This study is supported by Chinese 973 Project (2007CB411503), Chinese COPES (GYHY200706005) and Hundred Talent Project of Chinese Academy of Sciences.

REFERENCES

Barnett TP, Adam JC, Lettenmaier DP, 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature, 438: 303–309.

Ding YJ, Qin DH, 2009. Cryosphere change and global warming: impact and challenges in China. China Basic Science, 3: 4–10.

Du WT, Qin X, Liu YS, Wang XF, 2008. Variation of the Laohugou Glacier No. 12 in the Qilian Mountains. Journal of Glaciology and Geocryology, 30(3): 373–379.

Fierz C, Armstrong RL, Durand Y, Etchevers P, Greene E, McClung DM, Nishimura K, Satyawali PK, Okratov SA, 2009. The International Classification for Seasonal Snow on the Ground. IHP-VII Technical Documents in Hydrology No. 83, IACS Contribution No. 1, UNESCO-IHP, Paris.

Goodison B, Louie PT, Yang DQ, 1998. WMO Solid Precipitation Measurement Intercomparison (Final Report), WMO. Instruments and Observing Methods Report, 67: 1–211.

He YQ, Pu T, Li ZX, Zhu GF, Wang SJ, Zhang NN, Wang SX, Xin HJ, Theakstone WH, Du JK, 2010. Climate change and its effect on annual runoff in Lijiang basin—Mt. Yulong region, China. Journal of Earth Science, 21(2): 137–147.

Immerzee WW, van Beek LPH, Bierkens MFP, 2010. Climate change will affect the Asian water towers. Science, 328: 1382–1385.

Kang SC, Yang YP, Zhu LP, Ma YM, 2011. Modern Environmental Processes and Changes in the Nam Co Basin, Tibetan Plateau. China Meteorological Press, Beijing, pp. 1–418.

Key J, Drinkwater M, Ukita J, Ryabinin V, kaczmarska M, Goodison B, Lytle V, Summerhayes C, Hinsman D, 2007. Integrated Global Observing Strategy (IGOS): Cryosphere Theme Report—for the Monitoring of our Environment from Space and from Earth, Geneva. World Meteorological Organization: WMO/TD, 1405: 100.

Lemke P, Ren J, Alley RB, Allison I, Carrasco J, Flato G, Fujii Y, Kaser G, Mote P, Thomas RH, Zhang T, 2007. Observations: Changes in Snow, Ice and Frozen Ground. In: Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds.). Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Li ZQ, Han TD, Yang HA, Jin ZF, Jiao KQ, 2003. A summary of observed facts on 40-year climate variation and glacier No.1 at headwater of Urumqi River, Tianshan. Journal of Glaciology and Geocryology, 25(2): 117–123.

Pang HX, He YQ, Zhang NN, Li ZX, Theakstone WH, 2010. Observed glaciohydrological changes in China's typical monsoonal temperate glacier region since 1980s. Journal of Earth Science, 21(2): 179–188.

Qin DH, 1999. Map of Glacier Resources in the Himalayas. Science Press, Beijing.

Ren JW, Ye BS, Ding YJ, Zhao L, 2011. Initial estimate of the contribution of cryospheric change in China to sea level rise. Chinese Science Bull, 56: 1661−1664. DOI: 10.1007/s11434-011-4474-3.

Wang GX, Ding YJ, Wang J, Liu SY, 2004. Land ecological changes and evolution patterns in the source regions of the Yangtze and Yellow rivers in recent 15 years. Acta Geographyca Sinica, 59(2): 163–173.

Wang ZT, Su HC, 2003. Glaciers in the world and China: distribution and their significance as water resources. Journal of Glaciology and Geocryology, 25(5): 498–503.

Xiao CD, Liu SY, Zhao L, Wu QB, Li PJ, Liu CZ, Zhang QW, Ding YJ, Yao TD, Li ZQ, Pu JC, 2007. Observed changes of cryosphere in China over the second half of the 20th century. Annals of Glaciology, 46: 382–390.

Xiao CD, Qin DH, Yao TD, Ding YJ, Liu SY, Zhao L, Liu YJ, 2008. Progress on observation of cryospheric components and climate-related studies in China. Advances in Atmospheric Sciences, 25(2): 164–180. DOI: 10.1007/s00376-008-0164-8.

Yao TD, Zhang YS, Pu JC, Tian LD, Ageta Y, Ohata T, 2011. Hydrological and climatological glaciers observation 20 years on Tanggula Pass of Tibetan Plateau: its significance and contribution. Sciences in Cold and Arid Regions, 3(3): 187–196.

Zhao L, Ping CL, Yang DQ, Cheng GD, Ding YJ, Liu SY, 2004. Changes of climate and seasonally frozen ground over the past 30 years in Qinghai-Xizang (Tibet) Plateau, China. Global and Planetary Change, 43(1–2): 19–31.