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Glacier Monitoring and Capacity Building: Important Ingredients for Sustainable Mountain Development

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Glacier observation data from major mountain regions of the world are key to improving our understanding of glacier changes: they deliver fundamental baseline information for climatological, hydrological, and hazard assessments. In many mountain ecosystems, as well as in the adjacent lowlands, glaciers play a crucial role in freshwater provision and regulation. This article first presents the state of the art on glacier monitoring and related strategies within the framework of the Global Terrestrial Network for Glaciers (GTN-G). Both in situ measurements of changes in glacier mass, volume, and length as well as remotely sensed data on glacier extents and changes over entire mountain ranges provide clear indications of climate change. Based on experiences from capacity-building activities undertaken in the Tropical Andes and Central Asia over the past years, we also review the state of the art on institutional capacity in these regions and make further recommendations for sustainable mountain development. The examples from Peru, Ecuador, Colombia, and Kyrgyzstan demonstrate that a sound understanding of measurement techniques and of the purpose of measurements is necessary for successful glacier monitoring. In addition, establishing durable institutions, capacity-building programs, and related funding is necessary to ensure that glacier monitoring is sustainable and maintained in the long term. Therefore, strengthening regional cooperation, collaborating with local scientists and institutions, and enhancing knowledge sharing and dialogue are envisaged within the GTN-G. Finally, glacier monitoring enhances the resilience of the populations that depend on water resources from glacierized mountains or that are affected by hazards related to glacier changes. We therefore suggest that glacier monitoring be included in the development of sustainable adaptation strategies in regions with glaciated mountains.

Keywords: *Glacier monitoring; sustainable mountain development; capacity building; in situ measurements; remote sensing; Tropical Andes; Central Asia.*

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Introduction

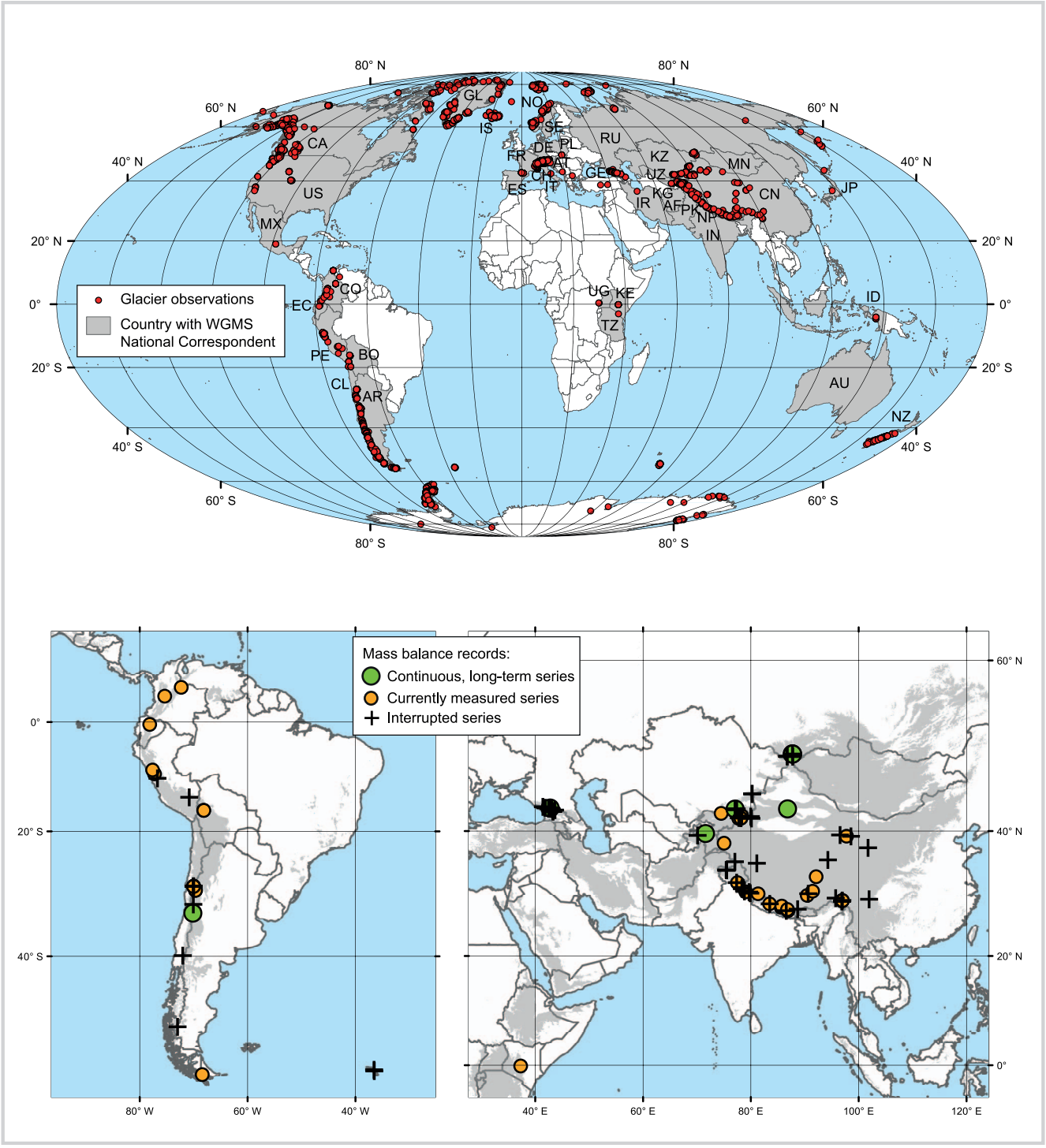
The cryosphere forms an integral part of many mountain ecosystems around the world. Snow and glaciers, and to some extent permafrost, are important resources that buffer and balance seasonal water deficits thanks to their high water-storage capacity (Viviroli et al 2003; Barnett et al 2005; Vuille et al 2008). The observed and projected atmospheric warming and the corresponding melt of glaciers leads to serious changes on global, regional, and local scales (IPCC 2013). Depending on the degree of glacier cover and its location within a catchment, runoff from glacierized catchments is expected to increase (or be maintained at the current level) in the near future due to glacier melting; a significant reduction is expected over the long term (Huss et al 2010). For some catchments, such as in the Cordillera Blanca (Peru) or the Alps, so-called "peak water" has already passed (Collins 2008; Baraer et al 2012; Huss and Fischer 2016).

Because of their high sensitivity, mountains in general and glaciers in particular play an important role with regard to water management, hydropower planning, and natural hazards, including glacial lake outburst floods. Glaciers are an indicator of climate change and a contributor to current sea-level rise. Systematic and long-term monitoring of cryospheric changes makes it possible to account for the strong variations among mountain regions and river catchments that go along with the diversity of climate change impacts. The broad range of climatic and topographic environments and complex geophysical settings pose extra challenges for mountain research and monitoring, and many knowledge gaps remain (Salzmann et al 2014; Strachan et al 2016).

The Tropical Andes and Central Asia are considered to be particularly vulnerable to impacts of climate and cryospheric changes, and they are among the mountain regions that are most important for providing water for human needs (Kaser et al 2010; Magrin et al 2014;

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FIGURE 1 Top: The World Glacier Monitoring Service (WGMS)'s worldwide network for scientific collaboration, showing countries with WGMS National Correspondent in gray and available glacier change observations (mass, length, and volume) in red. Bottom: Glaciological mass balance data in the study regions as reported to the WGMS. Long-term series with more than 30 consecutive years of measurements ("reference" glaciers) are indicated in green, glaciers currently measured (since 2010) are indicated in yellow, and interrupted measurement series are shown as black crosses. Elevations above 1000 m asl are given in gray (glacier data up to 2015: WGMS 2015, updated).



Drenkhan et al 2015). Glaciers contribute significantly to water supplies for power production, consumption, and irrigation, particularly during the dry season. Moreover, people and infrastructure are especially vulnerable to glacier-related hazards such as glacial lake outburst floods (Carey et al 2014; Hijioka et al 2014). Despite this, they are among the regions with less dense glacier observations (Figure 1), and both regions are currently the focus of

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Box 1: Data access through the GTN-G

Several online databases containing a wealth of diverse data types with different levels of detail and global coverage provide fast access to continuously updated information on glacier fluctuation and inventory data. All glacier datasets are made freely available through the respective operational bodies within GTN-G (http://www.gtn-g.org). Glacier inventory data are digitally available from the website of the National Snow and Ice Data Center (http://nsidc.org), which hosts the World Glacier Inventory, the Global Land Ice Measurement from Space initiative database (http://www.glims.org) and the Randolph Glacier Inventory, as well as the Glacier Photograph Collection. The glacier fluctuation datasets are made digitally available through the World Glacier Monitoring Service (WGMS; www.wgms.ch), an international scientific collaboration network with national correspondents in 38 countries and thousands of contributing observers around the world.

Terminology standards and best observational practices for in situ glacier measurements have been developed by Cogley et al (2011). For further information, we refer to the classic guidebook by Østrem and Brugman (1991) and the manuals by Kaser et al (2003) and Rivera et al (2016). The manual by Francou et al (2004) focuses on the Tropical Andes in particular.

For detailed overviews on remote sensing of glaciers, we refer to Tedesco (2015), Williams and Hall (1998), Rees (2006), and the Integrated Global Observing Strategy Cryosphere Theme Report (IGOS 2007). A variety of robust and well-defined algorithms to retrieve glacier parameters are available (Rau et al 2005; Paul, Kääb et al 2009; Raup and Khalsa 2010; Kargel et al 2014).

international capacity-building activities and collaborations.

Local knowledge and understanding of climate change impacts on water resources are crucial for further developing and implementing adaptation and risk-management strategies (Muñoz et al 2016). Building on and tapping such knowledge includes the strengthening of local stakeholders (institutions, universities). This process is particularly important to enhance monitoring, modeling, developing case studies, and predicting local hydrological responses to climate change impacts in mountain regions (Huggel et al 2015). As such, it can support the protection and conservation of mountains and their ecosystems, which are key to 3 of the Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development (Agenda 2030) (UN 2015).

Sustainable mountain development (SMD) includes both mountain regions and the populations that depend on them. With respect to glacierized mountain ecosystems, glacier monitoring addresses both components: the objective of this article is to show the need for observing glaciers and to understand how the local to regional context links to international glacier monitoring efforts. We first review concepts and applications of internationally coordinated glacier monitoring. Then, we evaluate a number of pertinent experiences from the Tropical Andes and Central Asia, specifically from the perspective of how glacier monitoring can contribute to SMD. Based on these results, we identify the needs and gaps for local in situ glacier monitoring as a component of SMD.

Glacier monitoring: international strategies and methods

Monitoring strategy of the Global Terrestrial Network for Glaciers

Glacier mass loss over the past decades can largely be attributed to anthropogenic forcing; in fact, globally retreating glaciers have become an icon of human-induced climate change (Marzeion et al 2014). An important component of glacier monitoring is mass balance, which is the direct response of a glacier to annual atmospheric conditions. When monitored over the long term, mass balance is a clear indicator of climate dynamics. In contrast, length change measurements—the main data collected during the initial phases of international glacier monitoring—constitute an indirect and delayed response to the climate signal (Hoelzle et al 2003). These in situ measurements provide evidence of rapid glacier decline over entire observation periods (WGMS 2015).

Coordinated worldwide collection of data on glacier distribution and fluctuations was initiated in 1894 (Forel 1895). Today, after more than a century of scientific research and monitoring, glaciers are officially recognized as indicators of climate change and are classified among the Essential Climate Variables and are part of political considerations at national to international levels (Bojinski et al 2014). In 1997, these efforts resulted in the creation of the Global Terrestrial Network for Glaciers (GTN-G) as a framework for the internationally coordinated monitoring of glaciers and ice caps in support of the United Nations Framework Convention on Climate Change and authorized under the Global Climate Observing System (GCOS) (see Box 1).

The Global Hierarchical Observing Strategy is a multilevel, integrative strategy that was developed to facilitate the collection of reliable, representative, and long-term data about the world's land and freshwater ecosystems (Haeberli et al 2000). GTN-G follows this

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TABLE 1 System of tiers of the Global Hierarchical Observing Strategy (Haeberli et al 2000) and how it is implemented by the Global Terrestrial Network for Glaciers (GTN-G).

Monitoring levels	Description	Role	Implementation of monitoring strategy within GTN-G
Tier 1	Large-area experiments, for example large catchment study	Observation of spatial processes	*Multicomponent observation system across environmental gradients* *→for example, transect along the American Cordilleras*
Tier 2	Research centers	Process-level understanding	Process understanding and model calibration →extensive energy/mass balance, flow
Tier 3	Stations responsible for a set of observations at tier-4 sites	- Observation of processes with an annual cycle - Calibration and validation of tier-5 products	Regional indicators →mass change (index stakes, photogrammetry, light detection and ranging [LIDAR])
Tier 4	Observation sites visited periodically	Statistically representative in situ sample	Regional representativeness →cumulative length change; digital elevation model (DEM) differencing
Tier 5	Repeated complete coverage by satellite remote sensing	Spatial and temporal interpolation	Global coverage →inventories (remote sensing/geoinformatics)

tiered monitoring system (Table 1) and integrates in situ measurements with remote sensing data to bridge the gap between detailed (process oriented) local studies of glaciers and globally relevant datasets.

Glacier monitoring from in situ measurements

The determination of the *glaciological mass balance* requires intensive fieldwork but provides reference information on seasonal and annual components of the surface mass balance; it leads to improved process understanding and additional information about long-term interannual variabilities.

In situ measurements are also time consuming and must often be performed under harsh outdoor conditions. They can be expensive, especially when maintained over the long term. Currently, numerous sites exist that reflect regional patterns of glacier mass change, but they are not optimally distributed because the measured glaciers are typically chosen for their accessibility and other practical reasons.

Observational concepts with a combination of a limited number of strategically selected, local index stakes (annual resolution; tier 3, see Table 1) are adequate for application in remote areas. They can be complemented with topographic precision mapping at about decadal intervals (volume change of entire glaciers) for smaller ice bodies or with laser altimetry/kinematic Global Positioning System for large glaciers. Following the monitoring strategy of the GTN-G, it is recommended to periodically validate and calibrate annual glaciological mass balance series with decadal, geodetically derived mass balances in order to detect and remove potential measurement or calculation errors (see Zemp et al 2013).

In addition, *glacier front variation series* (ie length changes) are key to assessing the representativeness of the existing mass balance measurement programs (tier 4). These series provide insight into climate–glacier processes and glacier dynamics, often further back in time than mass balance series.

Monitoring sites have usually been chosen for practical reasons, such as accessibility; in future, site selection should be based on statistical considerations concerning climate characteristics, size effects, and dynamics (eg normal ice flow versus debris cover, surging, and calving effects), and glaciers in remote areas should be included.

Glacier monitoring from remote sensing

Spaceborne remote sensing has become an attractive and useful source of information for glacier mapping (including estimating changes in glacier volume and the related availability of water resources) in recent years. Moreover, it has helped to overcome spatial, political, economic, and security-related limitations, especially in remote mountain regions (Kargel et al 2014). Such techniques enable globally standardized glacier monitoring, which implies the potential for mountain-wide and global inventories, as recommended by GTN-G (tiers 4 and 5; eg the Global Land Ice Measurement from Space initiative and Randolph Glacier Inventory, see Box 1). Remote sensing also enables automated image analyses, thereby reducing the cost and time required to calculate changes in glacier length. This technique further allows determination of geodetic glacier mass changes for both individual glaciers and entire mountain ranges, which provides fundamental information for spatial analysis and modeling (tiers 2 und 3). New datasets, such as gravimetric mass balance estimates from the GRACE mission (see Gardner et al 2011; Jacob et al 2012), provide change estimates representative of whole glacierized regions or

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even entire mountain ranges, but they are typically difficult to break down to individual glaciers.

A variety of satellite instruments have been successfully used in the field of glacier mapping, from declassified Corona panchromatic images (in operation from 1960 to 1972) to the suite of Landsat platforms (1972–today), Advanced Spaceborne Thermal Emission and Reflection Radiometer (2000–today) and Satellite pour l'Observatoire de la Terre (1986–today). More recently, high-resolution satellites such as QuickBird, WorldView, and ESA Sentinel (Kargel et al 2014, and references therein) are also providing important information. In parallel, active (see Tedesco 2015) and passive (see Bamber 2006) microwave techniques have been employed to retrieve various glacier parameters (eg glacier flow speed). Relatively new techniques include unmanned aerial vehicles, which have been used for professional mapping and surveying in areas that are difficult to access (eg Immerzeel et al 2014).

Following the GTN-G strategy, remote sensing data are complementary to in situ measurements. Recent developments in remote sensing techniques promise automatic retrieval of glacier lengths in the near future, which will enlarge the available dataset substantially. Although satellite imagery allows for glacier outline mapping, terminus-position identification, and area and elevation determination and monitoring (also in remote areas), other observations can only be obtained in situ. Because ice can be hidden beneath the surface, proper mapping of debris-covered glaciers often requires control by fieldwork. Locally measured data are indispensable for understanding the physical processes that link glaciers and climate—information that is necessary for constructing better forecasting models. Finally, direct measurements are still (and will remain) indispensable for validating remotely sensed (and other) data; as such, they constitute the basis for evaluating new methods.

Sustainable mountain development and glacier monitoring

The SDGs of Agenda 2030 highlight mountain environments as fragile ecosystems that are essential for sustainable development (UN 2015; see SDGs 6 and 15). SMD implies preserving mountain ecosystems for future generations in accordance with the 3 fundamental dimensions of sustainable development (social, economic, and environmental) as well as strengthening efforts related to peace, justice, and effective institutions.

Ariza et al (2013) specify water resource management, climate change adaptation, and disaster risk reduction, among others, as key policy actions to promote SMD. Knowledge and awareness of glacier shrinkage and its impact is critical to all of these actions. Water is a critical good for mountain ecosystems and downstream areas; as such, assessment of water availability and changes thereof is a key pillar of SMD. Coping with mountain hazards is often related to water and, in high mountain areas, to the cryosphere in particular (Haeberli et al 2015). In situ measurement techniques are therefore often transferable within cryospheric research and beyond (eg water research and hazard assessment).

Other ingredients of SMD are the education and training of local investigators in conservation and development, including strengthening regional cooperation (Price and Kohler 2013). In situ glacier monitoring involves applied and participatory research and the dissemination of research results. Knowledge-based water management calls for reliable, long-term baseline data. In glacierized areas, these data can only be retrieved through sustained, long-term glacier monitoring.

In the next section, we highlight the need to maintain glacier mass balance observation programs at the local level. Figure 2 provides a conceptual framework for glacier monitoring in relation to glacier change impacts that are also reflected in the SDGs.

Glacier monitoring experience in the Tropical Andes and Central Asia

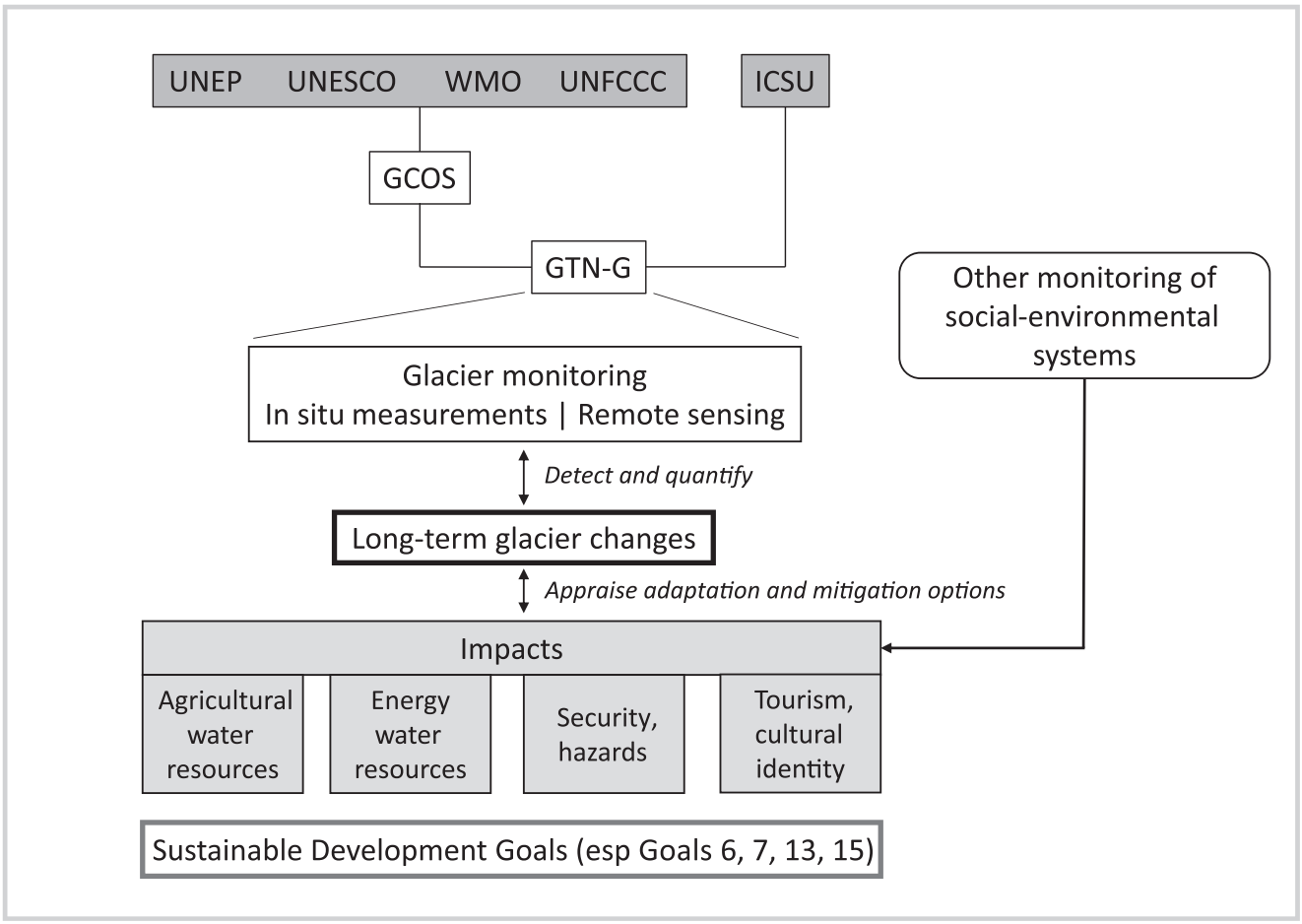
Tropical Andes: importance of baseline data, institutional establishment, and reliance on regional partners

In the Tropical Andes, a pronounced decline in glacier area and volume has been observed in recent decades (Francou et al 2005; Salzmann et al 2013). Increasing air temperatures and minimal change in precipitation could greatly reduce glacial coverage and eliminate small glaciers whose upper reaches are located close to the current equilibrium line altitude (Rabatel et al 2013). In future, in addition to warming, a considerable reduction of precipitation is also projected for the Central Andes (Neukom et al 2015). In the western Peruvian Andes, for example, this is a serious concern because large populations live in these arid regions and depend on glacier water for agriculture, domestic consumption, and hydropower (Vergara et al 2007; Drenkhan et al 2015). Efforts to understand secondary climate change impacts and identify mitigation and adaptation measures are hampered by a lack of long-term, high-quality meteorological and glacier observation series, as well as by a lack of coordination amongst ongoing efforts.

Peru: Peru has a comparatively long historical record of glacier monitoring. Some of the first available observations were made by Richard Finsterwalder and his team back in the 1930s in the Cordillera Blanca. The Peruvian government became involved in the 1940s and 1950s, mainly in relation to glacier lakes and outburst floods. Glacier monitoring was thus initially driven by an interest in hazard prevention. The operational monitoring activities have passed through a remarkable number of different institutions since the 1940s, from the

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FIGURE 2 Conceptual framework for glacier monitoring within The Global Terrestrial Network for Glaciers (GTN-G) and in relation to impacts of glacier changes in relation to the SDGs. The GTN-G operates under the auspices of the International Council for Science (ICSU) and international organizations (UNEP, UNESCO, WMO) in support of the United Nations Framework Convention on Climate Change (UNFCCC).



Geology Institute of Peru and its successors (1941–1950; 1977–1981) to the Commission of Lakes (1951–1969), the Santa Corporation (1969–1973), Electro Peru (1973–1977; 1981–1999), the Instituto Nacional de Recursos Naturales (1999–2010), and eventually, the Autoridad Nacional del Agua (ANA, 2010 to present). Although glacier and glacier lake monitoring has had a dedicated office within these institutions, institutional instability has been a continuous threat to the continuity of the monitoring program. Until recently, as in many other countries, there was no university program in glaciology in Peru. Peruvian experts were educated abroad or trained on the job but often lacked a more basic glaciological education, implying some limitations with respect to the quality of the monitoring activities. In 2015, the Instituto Nacional de Investigación en Glaciares y Ecosistemas de Montaña (INAIGEM) was created. Although the roles of the different national institutions have yet to be further clarified, particularly with regard to glacier monitoring, INAIGEM has the potential to significantly strengthen Peru's glacier monitoring and research capacity.

ANA's Unidad de Glaciología y Recursos Hídricos, the Servicio Nacional de Meteorología e Hidrología del Perú, INAIGEM, and a number of universities have made numerous important efforts in recent years to improve the capacities and expertise of Peruvian professionals. The French Institut de Recherche pour le Développement (IRD) has run master's and PhD programs that have notably improved glacier-related expertise in Peru. Furthermore, scientists from Austria (Institute of Geography, University of Innsbruck) and the United States (including Ohio State University and others) have maintained long-term research collaborations with Peruvian colleagues, mostly in the Cordillera Blanca (eg Kaser and Osmaston 2002; Mark et al 2005). Within the Global Programme on Climate Change of the Swiss Agency for Development and Cooperation, 2 projects, the Climate Change Adaptation Program (PACC) and Glaciares, have (1) focused on capacity building in the context of climate change and disaster risk reduction by targeting professionals from ANA, other government agencies and universities; (2) developed joint glaciology research projects with ANA, INAIGEM, and universities;

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(3) supported the institutionalization of glacier monitoring; and (4) improved information support for local and national climate adaptation activities.

The assessment of the potential flood risks posed by rapidly changing glaciers and lakes in the Cordillera Blanca greatly benefited from the glaciological knowledge generated by these projects. For example, as a consequence of the rock-ice avalanche from Mount Hualcán into Lake 513 on 11 April 2010, which triggered an impact wave and a devastating debris flow down-valley toward the city of Carhuaz, a hazard monitoring program was established by local authorities and organizations (Figure 3A; Muñoz et al 2016). Here, glaciological and meteorological data are a prerequisite for evaluating the immediate hazard potential. Lake 513 is only 1 of 14 glacier lakes identified as potentially dangerous in the Cordillera Blanca. Others include Lake Parón below Artesonraju (where glacier mass balance measurements are available since 2005) and Lake Palcacocha above the city of Huaraz.

Another site of recent activity is the Cordillera Vilcanota in southern Peru. It is the second largest glacierized mountain range in Peru and provides water to the relatively densely populated Cusco region. Despite its size and importance, no systematic mass balance monitoring effort was attempted in this region until recently (Salzmann et al 2013). In 2010, a new glacier monitoring program was started on 2 glaciers in the Cordillera Vilcanota, Suyuparina, and Quisoquipina, under the aforementioned Climate Change Adaptation Program project (Salzmann et al 2009). Currently, the monitoring of the Suyuparina glacier is continued under a research program at the Universidad Nacional de San Antonia Abad del Cusco with the support of the Glaciares project, in collaboration with ANA, the Servicio Nacional de Meteorología e Hidrología del Perú, and IRD (Molina et al 2015). The initiation of this glacier monitoring in 2010 was accompanied by the introduction of postgraduate glaciology courses at the Universidad Nacional de San Antonia Abad del Cusco and Universidad Nacional Santiago Antúnez de Mayolo (the national universities in Cusco and Huaraz, respectively), in collaboration with other Peruvian institutions (Unidad de Glaciología y Recursos Hídricos, Huaraz). Furthermore, several short-term stays of Peruvian professionals in Switzerland were organized to deepen their field measurement and data analysis skills.

These examples reveal the importance of baseline data and local institutional structures and capacity to ensure long-term glacier monitoring as a basis for climate change adaptation and risk reduction strategies. Capacities have been strengthened, resulting in a number of new or improved activities and products, but the efforts need to be sustained. Institutional (in-)stability therefore continues to be a major hurdle in Peru. There is a large potential for developing and further strengthening research in glaciology and high mountains at local universities. First experiences of joint projects show positive results but also a great need for improving local research capacities and overcoming administrative and bureaucratic barriers affecting research development and implementation.

Ecuador and Colombia: Glaciological mass balance measurements have been carried out for outlet glaciers of the Antizana ice cap in Ecuador and for the Santa Isabel ice cap in Colombia since 1995 and 2005, respectively (Ceballos et al 2012; Rabatel et al 2013). These observation series are conducted monthly by glaciologists from the national meteorological services in Ecuador (Instituto Nacional de Meteorología e Hidrología) and Colombia (Instituto de Hidrología, Meteorología y Estudios Ambientales). The WGMS/University of Zurich and the IRD/Laboratoire de Glaciologie et Géophysique de l'Environnement have jointly supported the continuation of these monitoring programs within the framework of the Capacity Building and Twinning for Climate Observing Systems (CATCOS) project. Led by local and regional partners, in situ mass balance measurements have been carried out and homogenized. The in situ measurement series is completed with geodetic surveys in order to assess the remaining extent and volume of ice and their changes over the past decades. In Ecuador, aerial photographs of the entire Antizana ice cap from 2011 were provided by the Ministerio de Agricultura, Ganadería, Acuacultura y Pesca and are processed with the support of the international partners (Basantes-Serrano et al 2016). In Colombia, an aerial survey was not feasible within the available budget and timeframe. Instead, a terrestrial laser scanning survey was successfully carried out in 2014.

Additional capacity-building activities included training courses on glacier mass balance measurements and analysis and scientific exchanges, which showed the value of and need for technical skills and knowledge as an important component for producing quality in situ glacier data. These efforts align with the goal to strengthen local capacities and institutions to ensure the sustainability of monitoring activities. The aim is further to provide the evidence for climate change in the mid-troposphere of the Tropical Andes and to understand the relation to glacier changes, runoff, and related consequences on freshwater, ecosystems, and socioeconomic impacts and related adaptation.

Central Asia: the long-term perspective (eg in Kyrgyzstan)

Glacier mass balance measurements in Kyrgyzstan are among the longest records worldwide, dating back to the times of the former Soviet Union. Unfortunately, the records end with the breakdown of the Soviet Union (Dyurgerov 2002); related monitoring capacities and institutional settings also declined over the subsequent

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FIGURE 3 (A) Monitoring stations in the Cordillera Blanca of Peru, where potential ice and rock-ice avalanches into Lake 513 constitute a serious danger for downstream communities, including the city of Carhuaz. The rapidly changing glaciers can also exacerbate the hazard situation (Photos provided by N. Salzmann, 18.9./7.10.2013); (B) In situ mass balance measurements: determination of the accumulation (left) and ablation (right) at Golubin glacier in the Tien Shan, Kyrgyzstan. (Photos provided by M. Hoelzle, 13./14.8.2012).

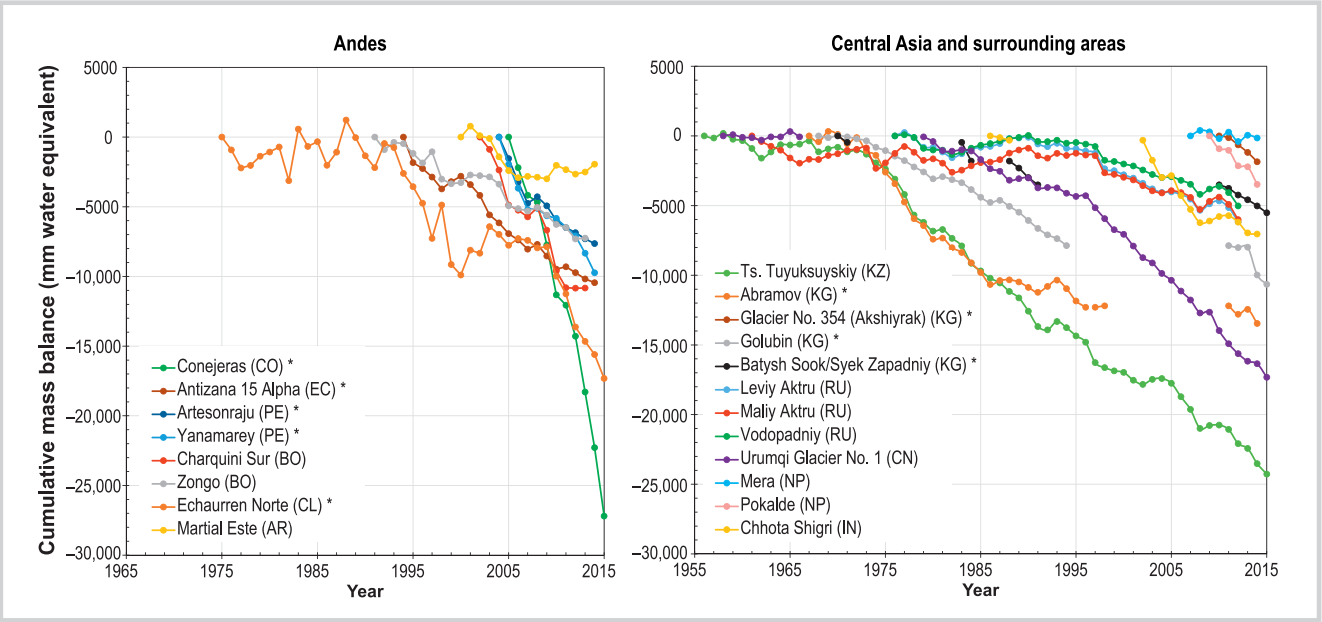


decades. Today, a growing number of programs seek to rebuild the scientific, technical, and institutional capacity in the region, and some of the most important mass balance measurements have been reestablished in recent years. Interest and awareness have substantially risen due to critical water issues in the region during the past years. Moreover, the glacierized mountain ranges in Central Asia are crucial from a global perspective because they fill important gaps in the observation network. Therefore, joint Kyrgyz–Swiss measurement campaigns were initiated in 2010 on several glaciers, such as Abramov and Glacier No. 354 (Akshiyrak range) within the framework of the aforementioned CATCOS project (Figures 3B, 4; Barandun et al 2015; Kronenberg et al 2016). These activities were accompanied by capacity-building programs, including joint field visits, educational programs, summer schools, and research exchange stays in both directions.

Enabling former Soviet Union countries in Central Asia and their institutions and experts to regain their high level of capacity is a major challenge, one that is common to many other regions and fields of research. One of the most significant current challenges is the lack of longer-term career prospects for young glaciologists. To ensure long-term perspectives for both glacier monitoring and scientific careers, a critical mass of experts, especially younger experts, is required. Capacity-building efforts need to be sustained on multiple levels and address institutional stability and resources as well as training in research and monitoring. These actions are especially important in view of the role of glaciers in supplying freshwater to the region and the anticipated challenges related to changing and declining runoff, which will have consequences for the economic development and political stability of the region (Lioubimtseva and Henebry 2009).

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FIGURE 4 Direct glaciological measurements in the study regions. Series supported by the projects presented here are marked with an asterisk. (Data: WGMS 2015, updated).



Discussion and conclusions

SMD concerns both mountain regions and the populations that depend on them. Water flowing from mountain areas is recognized as perhaps the most important element of SMD at the global scale (Price and Kohler 2013). Data from glacier monitoring efforts are essential to informed water management, which can help buffer the high and increasing variability of water availability over time. These data are the baseline for the development of adaptation strategies, particularly in data-scarce regions, such as parts of the Andes and Central Asia. Based on these data, assessments of glacier change impacts on freshwater availability and local hazards and risks should be promoted. Glacier monitoring efforts and their associated lessons (Figure 5) apply also to other aspects of SMD, particularly with respect to capacity building and institutional settings, and are therefore very important to overall SMD efforts.

Documentation of glacier changes helps to raise awareness about the ongoing consequences of global change. Because in situ measurements require extensive logistics that depend on the participation of local investigators, glacier monitoring efforts offer many opportunities for international cooperation and capacity-building exercises. They also help foster a broader appreciation of glaciers as sensitive climate indicators and of their role in freshwater provision and hazard regulation, thereby enhancing the resilience of the populations dependent on these mountain ecosystems (Drenkhan et al 2015). In addition, traditional measurements are important for bringing people in contact with the observed object—the glacier—which ensures that measurements are also understood and valued by the local population. The monitoring eventually strengthens regional stakeholders and their knowledge capacities, which in turn are key pillars to promote SMD (Price and Kohler 2013).

Strengthened regional cooperation, collaboration with local investigators and institutions, and enhanced knowledge sharing and dialogue are therefore envisaged in worldwide glacier monitoring. An important component of glacier monitoring is based on remote sensing, which facilitates an understanding of changes over large areas (mountain ranges) and time periods. This approach is consistent with the level of tier 1 according to the GTN-G monitoring strategy that extends the focus beyond country-specific activities. However, this approach often implies a potentially limited involvement of local experts and institutions. To ensure the long-term sustainability of quality glacier monitoring efforts, future projects should take advantage of both remotely sensed data and in situ measurements obtained by local project partners as well as local expertise—the combination of which has been shown to yield improved overall results (eg Paul, Escher-Vetter et al 2009). However, the knowledge and expertise needed for such engagement is lacking in many regions.

As with meteorological/climatological observations, glacier monitoring needs a strong local institutional framework, local expertise, and financial support if it is to be sustained over the long term (see Figure 5). This includes promotion of young people and well-educated staff, including through academic curricula and dedicated courses in the respective countries. The support of long-term measurements is a major task of WGMS and its

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FIGURE 5 Identified needs and gaps for local in situ measurements as a component of sustainable mountain development (SMD).

Region (project)	Peru ("Glaciares", "PACC")	Ecuador/Colombia ("CATCOS")	Central Asia ("CATCOS")
Gaps	- Strong glacier retreat → potential flood waves from large rock/ice avalanches on destabilized mountain flanks, and other glacier hazards - Missing local capacity to assess glacier risks - Data-scarce regions → missing reliable, regional baseline data (for hazard assessments and adaptation programs)	- Strong glacier retreat → loss of cultural identity - Glacier–volcano risk assessment - Knowledge of glacier–climate interactions in the mid-troposphere - Understanding of local processes cannot be captured by remote sensing techniques	- Interrupted (long-term) time series - Critical water issues in the region → conflict potential - Strong glacier retreat → potential disasters related to floods, debris flowing from ice-dammed lakes and breaching moraine dams, impacting people down-valley - Remote areas with difficult access, but high impact for lowland areas
Key elements:	- Glacial hazard prevention - Freshwater availability and ecosystem services	- Understanding of climate change in the mid-troposphere - Freshwater availability and ecosystem services	- Importance of long-term monitoring - Increased awareness of critical water issues
Challenges:	- Institutional instabilities - Local capacities	- Long-term continuation of monitoring - Critical mass of investigators and young people needed	- Sustainability of knowledge transfer - Remoteness, access is difficult
Outcome and lessons learnt:	- Strengthening of research in glaciology and high-mountains ecosystems - Improvement of local research capacities (process understanding) - Long-term initiatives are needed → call for institutional frame and financial support	- Strengthening of network in glaciology and beyond - Investigators/institutions become actors regarding climate change impacts in the respective regions - Confidence in more intense collaboration and exchange within the regions	- Re-establishment of time series - GTN-G network serves as starting point for further collaboration and partnerships - Accurate figures for runoff incl. high-quality data for model projections

In situ measurements imply:
- Long-term engagement
- Difficult logistics
- Involvement of well-trained people with basic glaciological education

→ **Recognition and appropriate resources are required to sustain long-term continuation of measurements.**

global network, where GTN-G and its monitoring strategy can provide a framework for capacity building and twinning activities. In many regions, its historically developed observation network can be used as a starting point. If structures are missing or weak, it can help to foster new cooperation efforts. At this point GCOS can come into play, as has been demonstrated by the example from GCOS Switzerland, which tries to support all relevant long-term measurement series (mainly all Essential Climate Variables). The basis for such an evaluation is an inventory per country to see which variables get support and where there is room for improvement (see Swiss inventory; Seiz and Foppa 2007).

It is also important to recognize that in remote mountain regions, such as the Tropical Andes or Central Asia, glaciers are often difficult to access and elevations are high. In the case of the Tropical Andes, the optimal measurement frequency is typically higher than it is for other mountain areas (eg Alps, Scandinavia) due to the seasonality of precipitation and the absence of seasonal temperature variations. Consequently, institutional and financial support must be sufficient to ensure long-term commitment. Long-term support for glacier monitoring activities brings with it opportunities for new generations of scientists. Finally, sustained glacier monitoring activities imply strong networks of both local and international experts as well as the concomitant opportunities for knowledge exchange and capacity building. These networks and increased knowledge exchange and capacities are important ingredients for sustainable development.

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