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.

Reviewed by Editorial Board: August 2015
Accepted: December 2016
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
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 (Hoelzl 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...
A 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.

### 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) |

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, geoidically 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 and 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...
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 (e.g., 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 (e.g., 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 (e.g., 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 glacialized 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
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;...
(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 Antonio 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 Antonio 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
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 (Akshirak 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 long-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).
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
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 (e.g., 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.

**ACKNOWLEDGMENTS**

The Swiss Agency for Development and Cooperation (SDC) is supporting WGMS capacity building and twinning activities and SMD-related knowledge management at the Universities of Zurich and Fribourg through the Sustainable Mountain Development for Global Change (SMD4GC) program. Special thanks are extended to collaborators of the PACC, Glaciares, and CATCOS projects (supported by SDC/MeteoSwiss) as well as to the local institutions in the study regions for their collaboration. We are grateful to Erin Gleeson of SciencEdit.CH for carefully checking and correcting the English. The comments and suggestions from the editors and 2 anonymous reviewers significantly improved the manuscript and are greatly appreciated.
REFERENCES

Ariza C, Maselli D, Kohler T. 2013. Mountains: Our Life, Our Future. Progress and Perspectives on Sustainable Mountain Development From 1992 to 2012 and Beyond. Bern, Switzerland: Swiss Agency for Development and Cooperation, Centre for Development and Environment.

Bamber J. 2006. Remote sensing in glaciology. In: Knight PG, editor. Glacier Science and Environmental Change. Oxford, United Kingdom: Blackwell, pp 370–382.

Baraer M, Mark BG, KicKenzie MJ, Condon T, Bury J, Huh KI, Portocarrero C, Gomez J. 2012. Glacier recession and water resources in Peru’s Cordillera Blanca. Journal of Glaciology 58:134–150.

Barandun M, Huss M, Sold L, Farinotti D, Asl, E, Salzmann N, Usasilaver B, Merkushin A, Hoelzle MJ. 2015. Re-analysis of seasonal mass balance at Abramov glacier 1968–2014. Journal of Glaciology 61:1103–1117.

Barnett TP, Adam JC, Lettenmaier DP. 2005. Potential impacts of a warming climate on water availability in snow-dominated regions. Nature 438:303–307.

Basantases-Serrano R, Rabatel A, Francisco B, Vincent C, Mateinsch C, Carese B, Galarraga R, Alvarez D. 2016. Small mass loss revealed by reanalyzing glacier mass-balance observations on Glaciar Antisana 15x (inner tropics) during the 1995–2012 period. Journal of Glaciology 62:124–136.

Bolinski S, Verstraete M, Peterson TC, Richter C, Simmons A, Zemp M. 2014. The concept of Essential Climate Variables in support of climate research, applications, and policy. Bulletin of the American Meteorological Society 95:1-34, 5.

Carey M, Baraer M, Mark BG, French A, Bury J, Young KR, McKenzie JM. 2014. Toward hydro-social modeling: Merging human variables and the social processes, applications, and policy. Bulletin of the American Meteorological Society 95:1-34, 5.

Cogley JG, Hoek R, Rasmussen LA, Arendt AA, Bauder A, Braithwaite R, Cogley JG. 2015. Glacier Mass Balance and Related Terms, IHP-VII Technical Documents in Hydrology No. 86, International Association of Cryospheric Sciences Contribution No. 2, Paris, France: United Nations Educational, Scientific and Cultural Organization-International Hydrological Programme.

Collins DN. 2008. Climatic warming, glacier recession and runoff from Alpine basins after the Little Ice Age maximum. Annals of Glaciology 48:119–124.

Drenkhan F, Girlanda A, Boeglin B, Delmotte F, J unt C. 2010. Contribution potential of glaciers and ice caps in the Canadian Arctic Archipelago. Nature 473:357–360.

Haefeli W, Chiar J, Barry RG. 2000. Glacier monitoring within the Global Climate Observing System. Annals of Glaciology 31:241–246.

Haefeli W, Whitman C, Shroder JF, editors. 2015. Snow and Ice-Related Hazard, Risks, and Disasters. Amsterdam, Netherlands: Elsevier.

Hijoka Y, Lin E, Pereira JI, Corlett RT, C19 e, Risueño K, Rosario A, Huggel C, Frey H, Garcia J, Cochachin A, Portocarrero C, Mesa L. 2016. Managing glacier related risks in the Cordillera Vilcanota, Bolivia. Journal of Arid Environments 110:084017, doi:10.1088/1474-9326/10/8/084017.

Huss M, Souther LM, editors. 2016. Sensitivity of very small glaciers in the Swiss Alps to future climate change. Frontiers in Earth Science 4:32, doi:10.3389/feart.2016.00034.

Huss M, Jouvet G, Farinotti D, Bauer A. 2010. Future high-mountain hydrology: A new parameterization of glacier retreat. Hydrology and Earth System Sciences 14:815–829.

Immerzew WW, Kraajenbrink PDA, Shea JM, Shrestha AB, Pelliccioni F, Bierkens MFM, de Jong JM. 2014. High-resolution modeling of Himalayan glacier dynamics using unmanned aerial vehicles. Remote Sensing of Environment 150:93–103.

IGOS [Integrated Global Observing Strategy]. 2007. For the Monitoring of Our Environment From Space and From Earth, Tropical Glaciers: Application. WMO/TD-No. 405, Geneva, Switzerland: World Meteorological Organization.

IPCC [Intergovernmental Panel on Climate Change]. 2013: The Physical Science Basis. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Bosung NJ, Nauels A, Xia Y, Bex V, Midgley PM, editors. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press.

Jacob T, Wahr J, Pfeffer WT, Swenson S. 2012. Recent contributions of glaciers and ice caps to sea level rise. Nature 482:514–518.

Kaser G, Leonard GJ, Bishop MP, Käsb E, Raup BH, editors. 2014. Global Land Ice Measurements from Space. Berlin, Germany: Springer.

Kaser G, Fountain A, Jansson P. 2003. A Manual for Monitoring the Mass Balance of Mountain Glaciers, IHP-VI Technical Documents in Hydrology No 59. Paris, France: United Nations Educational, Scientific and Cultural Organisation.

Kaser G, Grosshauser M, Marxvitz B. 2010. Contribution potential of glaciers to water availability in different climate regimes. Proceedings of the National Academy of Sciences 107:20223–20227.

Kaser G, Osmaston H. 2002. Tropical Glaciers. New York, NY: Cambridge University Press.

Kronenberg M, Barandun M, Hoelzle MJ, Huss M, Farinotti D, Asl, E, Usasilaver B, Gafurov A, Petrovok D, Käsb A. 2016. Mass-balance reconstruction for Glacier No. 354, Tien Shan, from 2003 to 2014. Annals of Glaciology 57:92–102.

Lobiumiteva E, Henebrey GM. 2009. Climate and environmental change in arid Central Asia: Impacts, vulnerability, and adaptations. Journal of Arid Environments 73:963–977.

Magrin GO, Marengn JA, Boulander JP, Buckeridge MS, Castellanos E, Poveda G, Scarano FR, Vicuña S. 2015. 21st century and South America. In: Barros VR, Field CB, Dokken DJ, Mastrandrea MD, Mach KJ, Bilir TE, Chatterjee M, Ebi KI, Otsuki Estrada Y, Genova RC, Girma B, Kissel ES, Levy AN, MacCracken S, Mastrandrea MT, White LL, editors. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: Cambridge University Press, pp 1499–1566.

Mark BG, McKenzie JM, Gomez J. 2005. Hydrochemical evaluation of changing glacier meltwater contribution to stream discharge: Callejón de Huaylas, Peru. Hydrological Sciences Journal 50:975–987.

Mira-Salama D, Rohe M, Salzmann N, Silvestre E, Víceu L, Zappa M, Bierkens MFP, de Jong SM. 2015. Sensitivity of very small glaciers in the Swiss Alps to future climate change. Frontiers in Earth Science 4:32, doi:10.3389/feart.2016.00034.

Muir M, Gonzalez C, Price K, Rosario A, Huggel C, Frey H, Garcia J, Cochachin A, Portocarrero C, Mesa L. 2016. Managing glacier related risks in the Cordillera Vilcanota, Bolivia. Journal of Arid Environments 473:357–360.

Mountain Agenda

Mountain Research and Development 151

http://dx.doi.org/10.1659/MRD-JOURNAL-D-15-00038.1
Paul F, Escher-Vetter H, Machguth H. 2009. Comparison of mass balances for Vernagtferner, Oetztal Alps, as obtained from direct measurements and distributed modeling. Annals of Glaciology 50:169–177.

Paul F, Kääb A, Rott H, Shephard A, Strozzi T, Volden E. 2009. GlobGlacier: a new ESA project to map the world’s glaciers and ice caps from space. EARSeL eProceedings 8:11–25.

Price MF, Kohler T. 2013. Sustainable mountain development. In: Price MF, Byers AC, Friend DA, Kohler T, Price LW, editors. Mountain Geography: Physical and Human Dimensions. Berkeley, CA: University of California Press, pp 333–365.

Rabatel A, Francou B, Soruco A, Gomez J, Cáceres B, Ceballos JL, Basantes R, Vuille M, Sicart J-E, Huggel C, Scheel M, Lejeune Y, Arnaud Y, Collet M, Condom T, et al. 2013. Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. The Cryosphere 7:81–102.

Rau F, Mauz F, Vogt S, Khalsa SJS, Raup B. 2005. Illustrated GLIMS Glacier Classification Manual: Glacier Classification Guidance for the GLIMS Inventory. Version 1.0. GLIMS Regional Center “Antarctic Peninsula.” Freiburg im Breisgau, Germany: Institut für Physische Geographie, Albert-Ludwigs-Universität.

Raup B, Khalsa SJS. 2010. GLIMS Analysis Tutorial. Boulder, CO: National Snow and Ice Data Center.

Rees WG. 2006. Remote Sensing of Snow and Ice. Boca Raton, FL: Taylor & Francis.

Rivera A, Bown F, Nepoeleni F, Muñoz C, Vuille M. 2016. Balance de masa glaciar. Valdivia, Chile: Ediciones CECs.

Salzmann N, Huggel C, Rohrer M, Stoffel M. 2014. Data and knowledge gaps in glacier, snow and related runoff research: A climate change adaptation perspective. Journal of Hydrology 518, Part B:225–234.

Seiz G, Foppa N. 2007. National Climate Observing System (GCOS Switzerland). Zurich, Switzerland: MeteoSwiss & ProClim.

Strachan S, Kelsey EP, Brown RF, Dascalu S, Harris F, Kent G, Lyles B, McCurdy G, Slater D, Smith K. 2016. Filling the data gaps in mountain glaciers and ice caps through advanced technologies, refined instrument siting, and a focus on gradients. Mountain Research and Development 36:518–527.

Tedesco M. 2015. Remote Sensing of the Cryosphere. Chichester, United Kingdom: John Wiley & Sons.

UN [United Nations]. 2015. Transforming Our World: The 2030 Agenda for Sustainable Development. New York, NY: United Nations.

Vergara W, Deeb AM, Valencia AM, Bradley RS, Francou B, Zarzar A, Grünwald A, Haussling SM. 2007. Economic impacts of rapid glacier retreat in the Andes. EOS 88:261–264.

Vivroll D, Weingartner R, Messerli B. 2003. Assessing the hydrological significance of the world’s mountains. Mountain Research and Development 23:32–40.

Vuille M, Francou B, Wagnon P, Juen I, Kaser G, Mark BG, Bradley RS. 2008. Climate change and tropical Andean glaciers: Past, present and future. Earth-Science Reviews 89:79–96.

WGMS [World Glacier Monitoring Service]. 2015. Global Glacier Change Bulletin No. 1 (2012–2013). Zemp M, Gärtner-Roer I, Nussbaumer SU, Hüslar F, Machguth H, Mögl N, Paul F, Hoelzle M, editors. Zurich, Switzerland: World Glacier Monitoring Service.

Williams RS Jr, Hall DK. 1998. Use of remote-sensing techniques. In: Haebeli W, Hoelzle M, Suter S, editors. Into the Second Century of Worldwide Glacier Monitoring: Prospects and Strategies. Studies and Reports in Hydrology, 56. Paris, France: United Nations Educational, Scientific and Cultural Organisation, pp 97–111.

Zemp M, Thibert E, Huss M, Stumm D, Rolstad Denby C, Nuth C, Nussbaumer SU, Moholdt G, Mercer A, Mayer C, Joerg PC, Jansson P, Hynek B, Fischer A, Escher-Vetter H, et al. 2013. Reanalyzing glacier mass balance measurement series. The Cryosphere 7:1227–1245.