

Worldwide Assessment of National Glacier Monitoring and Future Perspectives

Authors: Gärtner-Roer, Isabelle, Nussbaumer, Samuel U., Hüsler, Fabia, and Zemp, Michael

Source: Mountain Research and Development, 39(2)

Published By: International Mountain Society

URL: <https://doi.org/10.1659/MRD-JOURNAL-D-19-00021.1>

BioOne Complete (complete.BioOne.org) is a full-text database of 200 subscribed and open-access titles in the biological, ecological, and environmental sciences published by nonprofit societies, associations, museums, institutions, and presses.

Your use of this PDF, the BioOne Complete website, and all posted and associated content indicates your acceptance of BioOne's Terms of Use, available at www.bioone.org/terms-of-use.

Usage of BioOne Complete content is strictly limited to personal, educational, and non-commercial use. Commercial inquiries or rights and permissions requests should be directed to the individual publisher as copyright holder.

BioOne sees sustainable scholarly publishing as an inherently collaborative enterprise connecting authors, nonprofit publishers, academic institutions, research libraries, and research funders in the common goal of maximizing access to critical research.

Worldwide Assessment of National Glacier Monitoring and Future Perspectives

Isabelle Gärtner-Roer^{1*}, Samuel U. Nussbaumer¹, Fabia Hüsler², and Michael Zemp¹

* Corresponding author: isabelle.roer@geo.uzh.ch

¹ World Glacier Monitoring Service, University of Zurich, Winterthurerstrasse 190, 8057 Zurich, Switzerland

² Federal Office for the Environment (FOEN), Papiermühlestrasse 172, 3063 Ittigen, Switzerland

© 2019 Gärtner-Roer et al. This open access article is licensed under a Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>). Please credit the authors and the full source.

It is widely accepted that glaciers are retreating throughout the world and that their decline causes serious impacts on many societies. Knowledge of glacier distribution and quantification of glacier changes is crucial to assessing the impact of glacier shrinkage on the transboundary hydrological cycle and related issues, such as irrigation, energy production, and natural hazard prevention. Therefore, glacier monitoring is vital to the development of sustainable adaptation strategies in regions with glaciated mountains. Baseline documentation is needed to assess the current status of glacier monitoring. The aim of this study is to assess the status of national implementations of the international monitoring strategy developed by the Global Terrestrial Network for Glaciers (GTN-G) to make the data easily accessible to a broader audience, to identify gaps in the monitoring setup, and to guide countries in improving their monitoring schemes. We developed a standardized procedure to evaluate existing glacier data from international data

repositories; these freely accessible data on glacier distribution and changes (as of 2015) for all glacierized countries and regions form the basis of this study. The resulting country profiles are analyzed in relation to the existing GTN-G monitoring strategy. Gaps between the current implementation of glacier monitoring and implementation targets are compiled in a solid gap analysis, which allows countries to be categorized as having poorly developed monitoring, needing improvement, or having well-developed monitoring. Three pilot cases (Kyrgyzstan, Bolivia, and Switzerland) are presented in detailed country profiles.

Keywords: Glaciers; monitoring strategy; mountain regions; country profiles.

Peer-reviewed: June 2019 **Accepted:** June 2019

Introduction

Changes in glaciers throughout the world provide some of the clearest evidence of global climate change (IPCC 2013). Glacier decline will have serious impacts on many societies that are dependent on glacier meltwater, as life on earth is intimately connected to availability of water (Kaser et al 2010; Kraaijenbrink et al 2017; Mark et al 2017). In many mountain environments, as well as in adjacent lowlands, glaciers play a crucial role in freshwater provision and regulation (Buytaert et al 2017; Huss and Hock 2018). It has been estimated that 140 million people live in river basins where at least 25% of the annual runoff comes from glacier melt (Schaner et al 2012; Egan and Price 2017). While these impacts relate more to local and regional scales, glacier retreat also acts on a global scale, significantly contributing to sea-level rise (Zemp et al 2019). Therefore, glacier observation data from major mountain ranges are key to improving our understanding of glacier changes: they provide fundamental information on climatological and hydrological processes (Bojinski et al 2014) and related hazard assessments (Nussbaumer et al 2017).

Insights from glacier monitoring can help to raise people's awareness of their dependence on water resources from glacierized mountains and of their exposure to hazards related to glacier changes. This can motivate them to take adaptive measures to deal with the changes. It has therefore been suggested that glacier monitoring—which provides long-term information on system changes based on sound data—should be included in the development of sustainable adaptation strategies in regions where glaciers occur (Bjørnsen Gurung et al 2012; Nussbaumer et al 2017). This requires exchange of data between providers and users (at both the science and policy levels) across disciplines and sectors (ICSU 2010; McBean 2011). Such exchange has already been initiated for global assessments (IPCC 2013; Zemp et al 2019), but on the regional and local levels the full potential of existing data has not been tapped, or the baseline data are inadequate for thorough assessments and related decision-making processes.

Based on a long history of glacier monitoring and century-long observations (Zemp et al 2015), the Global Terrestrial Network for Glaciers (GTN-G) has developed an integrated, multilevel strategy for global glacier observations. The strategy is based on a system of tiers of

the Global Hierarchical Observing Strategy (Haeberli et al 2000) and serves as a reference within the United Nations Framework Convention on Climate Change (UNFCCC) and its Global Climate Observing System (GCOS). It combines process-oriented in situ studies on single glaciers (eg annual mass balance measurements) with satellite-based coverage of large glacier ensembles in entire mountain systems (ie glacier inventories, combined with digital elevation models). The need for a worldwide inventory of existing perennial ice and snow masses was first noted during the United Nations Educational, Scientific and Cultural Organization's (UNESCO) International Hydrological Decade, 1965 to 1974 (UNESCO 1970; Hoelzle and Trindler 1988); however, more than half a century later, implementation of international monitoring has little improved.

In this study, we use the GTN-G strategy to compile a systematic and comprehensive assessment of the current glacier-monitoring status in all glacierized countries. This is the first time baseline data on glacier distribution and change have been systematically compiled and evaluated. By this process, observational gaps and uncertainties are revealed to demonstrate their influence on related decisions on the national, regional, and sectoral (eg agricultural economy, energy management) levels, as well as to strengthen and develop future efforts in glacier monitoring.

The evaluation of the current performance of glacier monitoring focuses on the following questions:

- What political and scientific structures and networks support and secure the long-term monitoring of glaciers?
- How much of the national glacier area is currently under observation, and how much is subject to standardized long-term monitoring?
- What is the quality of the existing data series (length of series, number of gaps, etc)?
- Which countries have particular challenges, what are they, and how can they be addressed?

Methods

We developed a standardized procedure to assess glacier monitoring at national and regional levels. The full assessment comprises 2 main parts. The first compiles information on glacier distribution and changes. To achieve this, we analyzed inventories from the “World Glacier Inventory” (WGI; WGMS and NSIDC 1989, updated 2012), the “Global Land Ice Measurement from Space” initiative (GLIMS; GLIMS and NSIDC 2005, updated 2012), and all available data on glacier changes from the “Fluctuations of Glaciers” (FoG) database (WGMS 2015). Glacier changes are described by glacier front variations, mass balances based on the glaciological method, and thickness/volume changes deduced from in situ, airborne,

or spaceborne geodetic surveys. For the present assessment, we considered only glacier data available from the aforementioned international repositories (downloaded from www.gtn-g.org) as of 2015. This approach allowed a standardized comparison between countries and regions and hence provides an immediate baseline for assessing progress in glacier monitoring at the various tiers of the GTN-G monitoring strategy (Box 1).

The compilation of glacier observations is presented as national profiles, hereafter called “country profiles.” Each profile (Figures 1–3 give different examples) is presented in a standardized layout beginning with a short introduction on the country-specific characteristics of glaciers and key statistics. For all countries and regions, key statistics are presented, compiled from available data, such as glaciated area (in km²) based on the Randolph Glacier Inventory version 5.0 (RGI Consortium 2015), area covered by glacier inventories (WGI and GLIMS), and series data on front variation, mass balance, and thickness change (FoG database). This is followed by a graphical illustration of all data series accompanied by a written summary of the series. On the right, the status description for 5 tiers (see Box 1) is given. Finally, a map of the country shows the location of mass balance, front variation, and thickness changes series.

In the second part of the assessment, the compiled country profiles are evaluated. A gap analysis was used to compare the actual observational network, as given by entries in the GTN-G databases, to the target, as described in the international monitoring strategy. To translate the qualitative levels (Tiers 1–5) into a quantitative system, a defined key is applied (1 pt = fully implemented, 0.5 = partly implemented, 0 = not implemented at all):

- Tier 1 concerns the structural and organizational level of national glacier monitoring and was evaluated by the existence of a National Correspondent (0.5 pt) and functioning national coordination (0.5 pt).
- Tier 2 refers to the existence of detailed long-term series on glacier mass balances (0.5 pt) and “reference” glaciers with more than 30 years of ongoing measurements (0.5 pt).
- Tier 3 addresses the number of available series on mass balances (more than 3 = 0.5 pt) and the related average number of observations (more than 10 years of observations = 0.5 pt).
- Tier 4 includes the numbers of front variations series and the average number of observations (>10 series with more than 30 years = 0.5 pt) and the number of thickness change series and the average number of observations (>10 series with more than 30 years = 0.5 pt).
- Tier 5 concerns the available coverage in the glacier inventories with respect to the total glacier area, as available from RGI 5.0 (complete coverage in one or the other repository = 1 pt, part coverage in one or the other repository = 0.5 pt).

BOX 1: GTN-G strategy: integrative multilevel approach

The GTN-G monitoring strategy provides quantitative and comprehensive information on global glacier changes. This information is directly connected to questions about ongoing processes, change detection, model validation, and environmental impacts facilitating interdisciplinary knowledge transfer to the scientific community, policy-makers, the media, and the public. In order to link scientific process studies with global coverage by satellite imagery and digital terrain information, GTN-G provides observations at the following levels:

- Tier 1:** Multicomponent system observations across environmental gradients;
- Tier 2:** Extensive glacier mass balance and flow studies within major climatic zones for improved process understanding and calibration of numerical models;
- Tier 3:** Determination of glacier mass balance using cost-saving methodologies within major mountain systems in order to assess the regional variability;
- Tier 4:** Long-term observations of glacier length change data and remotely sensed volume changes for large glacier samples within major mountain ranges to assess the representativeness of mass balance measurements;
- Tier 5:** Glacier inventories repeated at time intervals of a few decades using remotely sensed data.

This multilevel monitoring system provides the basic data sets required for integrative studies and assessments of the distribution and changes of glaciers by combining in situ, remote-sensing, and numerical modeling components. While this study focuses on observations on different scales, related progress in process understanding and modeling approaches is supported by the wider scientific community.

More information on the GTN-G strategy can be found in Haeberli et al (2000) and Haeberli (2004), with updates on the present state from Haeberli and Barry (2006), Zemp et al (2008), and Zemp et al (2009).

Following this procedure, most of the information (Tiers 2–5) is derived from the key statistics compiled in each country profile. Information on WGMS National Correspondents and national coordination, as well as on reference glaciers (= glaciers with more than 30 years of

ongoing glaciological mass balance measurements), is taken from WGMS (2015). With this quantification scheme, a country can achieve a maximum of 5 points, showing a full implementation of the strategy and a well-developed monitoring scheme (4.5–5 pts). A sum of 3.5–4 points indicates that the strategy is partly implemented and needs improvement, and a sum of 0–3 points indicates that the strategy is poorly implemented and needs urgent support. The results are summarized in a matrix (Figure 4) and categorized in a “signal-light matrix” evaluation (Figure 5) based on this gap analysis. The standardized and quantitative procedure enables repeated or regular assessments in the future to evaluate developments in the implementation of the international monitoring strategy.

Country profiles have been compiled for 34 countries and 4 regions that are independent of national boundaries (“Africa” representing the few countries with a very small number of glaciers [Kenya, Tanzania, and Uganda], “Greenland” and “Antarctica” representing the peripheral glaciers around the 2 ice sheets, and “Svalbard and Jan Mayen” for the archipelagos).

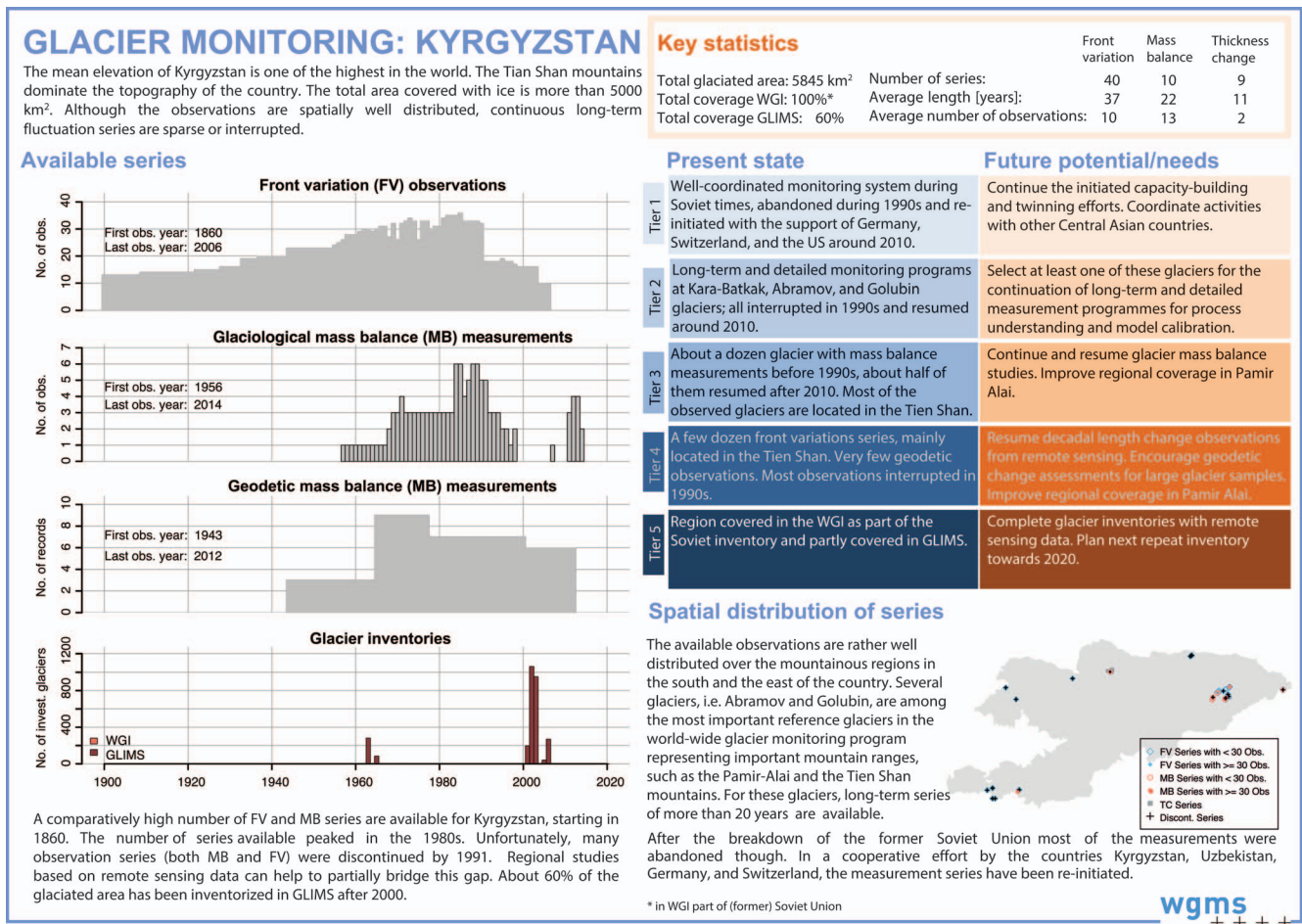
Evaluation and discussion of country profiles

The status of glacier monitoring at national and continental levels along with 3 exemplary country profiles showing different maturities in glacier monitoring are presented here. All 38 country profiles can be accessed through the WGMS website: <https://wgms.ch/national-glacier-state>. These country profiles allow data users, decision-makers, and others with an interest to gain an overview of the glaciated area, available glacier data, and their quality. In addition, we summarize compiled data for different continents to provide a regional overview of glacier-monitoring status and related challenges.

National/regional assessments

Kyrgyzstan in Central Asia shows a varied history of glacier monitoring (Figure 1). This is not only driven by scientific paradigms and technical developments, but also strongly influenced by political changes and the related stability and changes in prioritization. A well-established monitoring system existed during Soviet times but was almost completely abandoned in the 1990s. Almost 2 decades later, some monitoring programs were resumed, with the support of countries such as Germany, Switzerland, and the United States (Hoelzle et al 2017). Monitoring series need to be secured for the future. In addition, length change observations should be resumed, and geodetic observations are encouraged. The application of remote-sensing data will allow improvements in regional coverage, such as in Pamir Alai. Ongoing capacity-building efforts should be maintained.

FIGURE 1 Country profile of Kyrgyzstan and status of implementation of the 5 tiers of the GTN-G monitoring strategy. FV: front variation; MB: mass balance; TC: thickness change.



Another interesting example is **Bolivia** (Figure 2), where glacier-monitoring activities started in the 1990s. However, Bolivia lost one of its benchmark glaciers (Chacaltaya) around 2009 (Rabatel et al 2012), and only one long-term monitoring series is left, on Zongo Glacier (Soruco et al 2009). There are more mass balance series, but several are based on endangered glaciers. New mass balance programs on other glaciers that are less at risk need to be established. There is an urgent need to safeguard monitoring at Zongo Glacier, which reaches elevations above 6100 masl. Remote-sensing techniques will allow a complete glacier inventory to be compiled and enable more assessments of glacier changes in length, area, and volume. Additional efforts are needed to include existing data in international glacier data repositories.

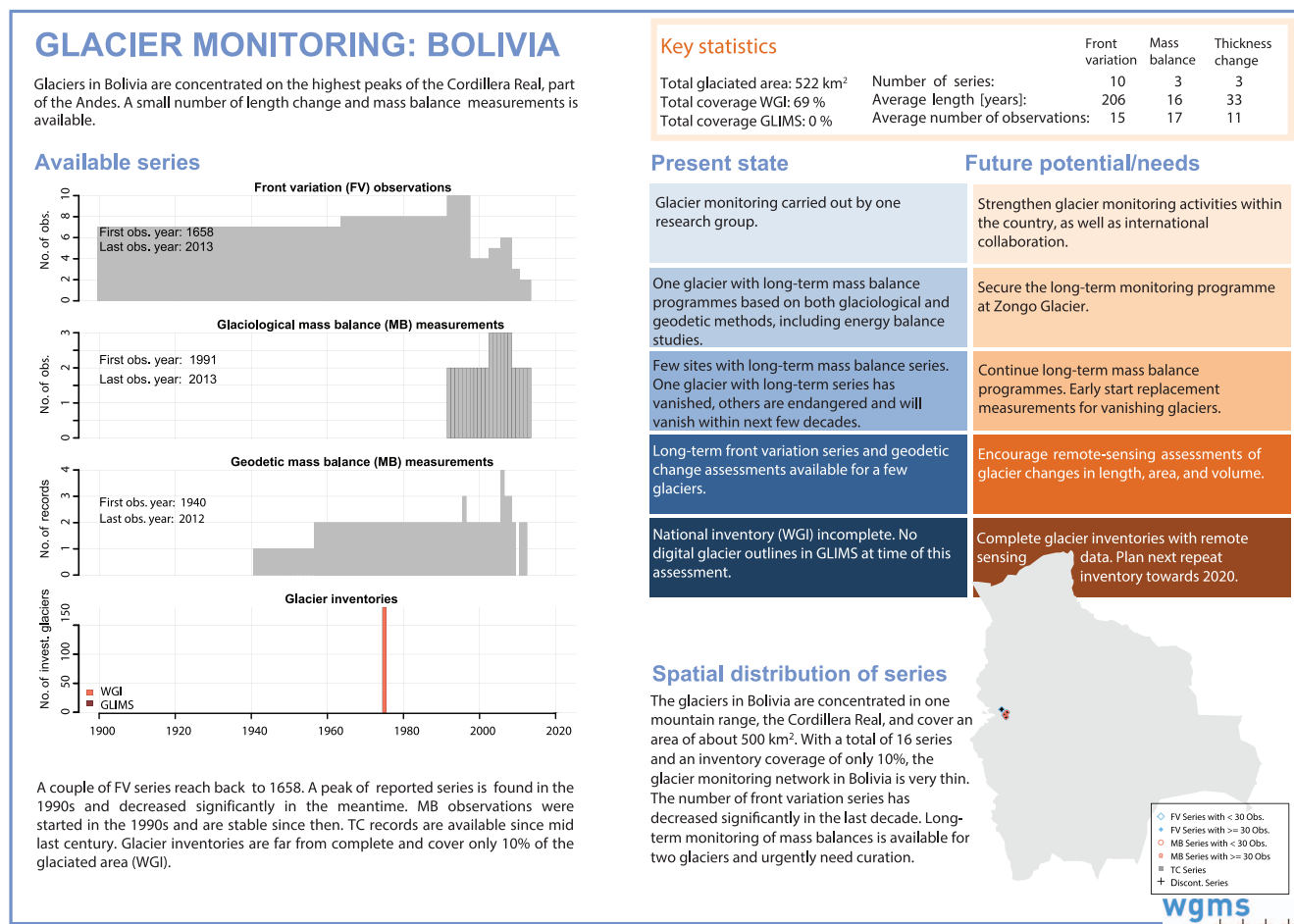
In contrast, **Switzerland** (Figure 3) represents well-coordinated glacier-monitoring activities with regular national reporting (GLAMOS 2018 and earlier reports), a long-term strategy, and secure funding. Several long-term series for mass balance and front variations exist, with a good spatial coverage (Huss et al 2009). In the future, replacement measurements for vanishing glaciers will

need to be established. The geodetic assessment of all Swiss glaciers by Fischer et al (2015) became available only after 2015 and, hence, was not considered for the assessment. However, the profile is still a model example for the national implementation of Tier 4.

To compare the current implementation of the international monitoring strategy across different countries, the present state (blue tables in the country profiles) is translated into a point system summarized in Figure 4 (tiers fully implemented [1], partly implemented [0.5], not implemented at all [0]; the sum of the points for the individual tiers represents the national status in glacier monitoring as of 2015). In contrast to this national view, the single columns can also be considered. For example, when evaluating the implementation of remote-sensing data in glacier monitoring, column “Tier 5” gives an overview of the compiled glacier inventories from remotely sensed data.

The points per country are added, and the sum is used to categorize their general evaluation levels, into so-called “signal lights”: countries with urgent need for action (0–3 points, orange); countries where the baseline is initiated

FIGURE 2 Country profile of Bolivia and status of implementation of the 5 tiers of the GTN-G monitoring strategy. FV: front variation; MB: mass balance; TC: thickness change.



but an improvement is needed (3.5–4 points, yellow); and countries with successful implementation (4.5–5 points, green). This compilation allows comparison of national situations irrespective of the individual history of glacier monitoring. The aim of this comparison is to raise awareness of current challenges and problems and to highlight future needs, as presented in Figure 5. Generally, countries in Europe and North America, as well as Chile, China, Kyrgyzstan, and Russia, have implemented the international strategy and can guarantee long-term monitoring, while many other Asian and South American countries are in urgent need of support.

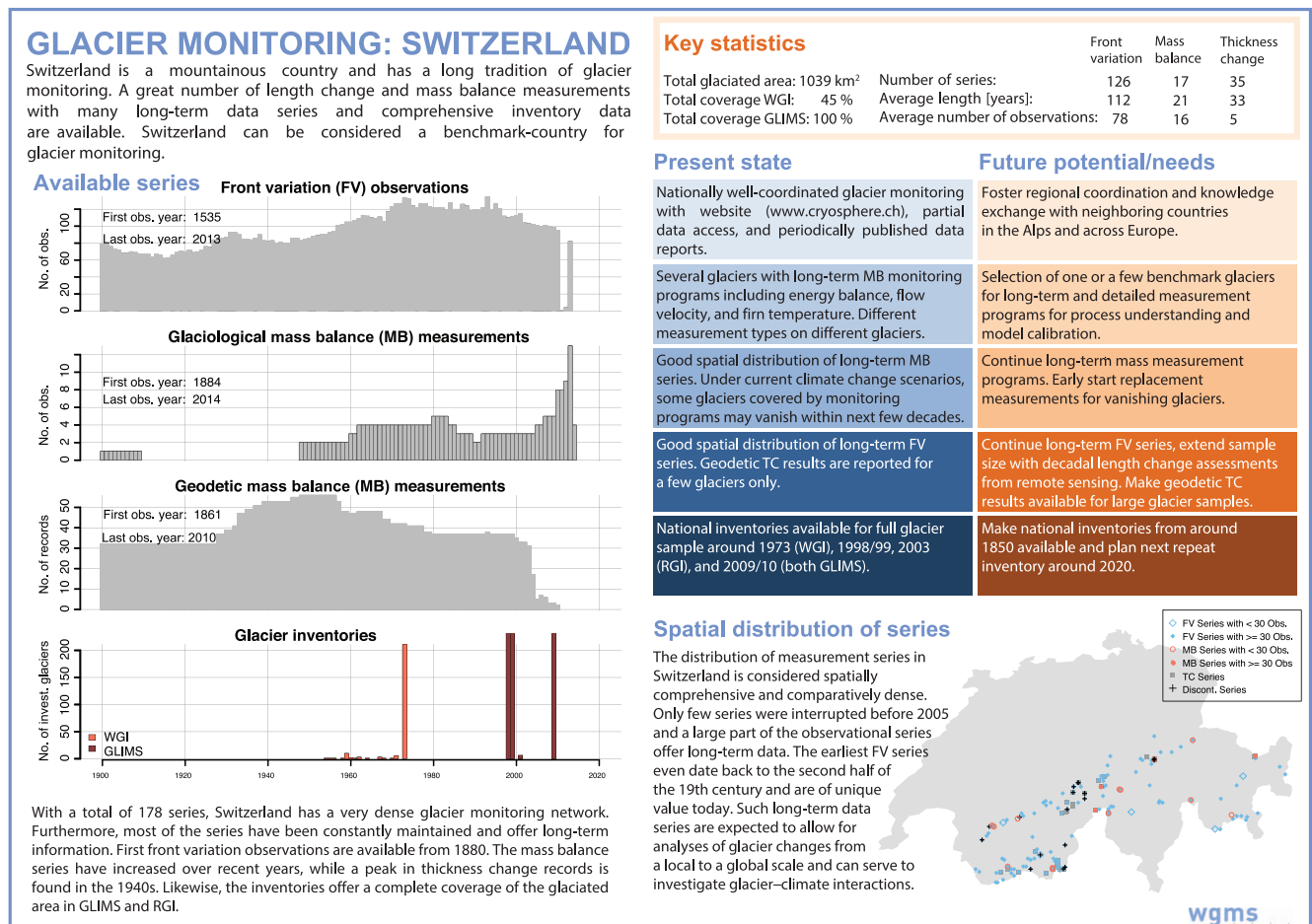
Continental assessments

In **North America**, glaciers occur in the mountains along the Pacific Coast and in the high Arctic, as well as on volcano tops in Mexico. In total, glaciers cover an area of about 222,000 km² (RGI 2015). Because of the very different climates, glaciers show very different characteristics (WGMS 2008). Both Canada and the United States have a long history of glacier observation

with front variation series reaching back to the 17th and 18th centuries. In the United States, glacier inventories are almost complete, a stable number of front variation series exists, and, for several glaciers, long-term mass balance series are available (Cox and March 2004; Josberger et al 2007). Few long-term mass balance series are available from western Canada and the Canadian Arctic (Thomson et al 2016). In addition, the glacier inventories cover only half of the glaciated area. With this, future needs are clearly defined: the inventories need to be completed and integrated into the GLIMS database, and long-term mass balance programs need to be continued and extended. Beyond that, the long-term series in the Canadian High Arctic, where access and logistics are very difficult, need to be secured. Coordination between North American countries could be fostered to address future challenges, such as the strong recession and disintegration of mass balance glaciers in western North America.

Glaciers in **South America** reach from tropical glaciers on volcano tops, such as in Colombia, to the large icefields in Patagonia (Chile and Argentina) and cover an area of

FIGURE 3 Country profile of Switzerland and status of implementation of the 5 tiers of the GTN-G monitoring strategy. FV: front variation; MB: mass balance; TC: thickness change.



about 31,000 km² (RGI 2015). In most regions of the continent, glaciers play an important role in freshwater supply (Mark et al 2017). Therefore, information on local and regional glacier occurrence and development, as well as related water availability, is of high significance. Glaciers are retreating in every Andean country. The most rapid retreat is in lower-altitude glaciers in the tropical Andes (Schoolmeester et al 2018). In all South American countries, the number of mass balance series is very small (Rabatel et al 2012), and there is only one reference glacier (with a continuous measurement series of more than 30 years): Echaurren Norte in Chile. Unfortunately, this glacier is about to disintegrate. In Chile and Argentina, the countries with the largest glaciated areas, national glacier-monitoring networks are well established. In both countries, front variation observations are extensive, and the inventories cover about 80% of the glaciated area. In Peru, only about a third of the glaciers are inventoried. Some mass balance series are available, but long-term and detailed monitoring series are lacking. In Bolivia, Colombia, and Ecuador, only a few glacier data series exist, and the inventories are incomplete. However,

each of the countries has one longer mass balance series (Zongo, Bolivia; Conejeras, Colombia; Antizana 15 Alpha, Ecuador); these need to be secured. National glacier-monitoring programs are developed in most of the countries, but long-term funding is often lacking and coordination could be improved. In view of the importance of glaciers as water resources in many South American countries, complete glacier inventories are urgently needed. The collaboration of national monitoring networks throughout the continent could be strengthened with the aim of finding continuous funding sources and discussing regional issues, such as the establishment of glacier laws, as recently happened in Argentina (Tollefson and Rodriguez Mega 2017).

In Europe, glaciers are widespread in the high mountain chains (eg Alps), as well as in the Subarctic and Arctic regions (eg Iceland, Greenland) and cover about 163,000 km² (RGI 2015). Most of the national monitoring programs are well established and reflect the long tradition of glacier monitoring. For most, there is an active network of observers, providing data for several glaciers with long-term mass balance programs (Zemp et

FIGURE 4 Current implementation of the international monitoring strategy for each country (based on the 2015 database versions). Tiers are fully implemented (1.0), partly implemented (0.5), or not implemented at all (0.0) (see Methods). The sum of the points for the individual tiers represents national status in glacier monitoring as of 2015 (see Figure 5).

Continent	Country/region	Tier 1	Tier 2	Tier 3	Tier 4	Tier 5	Sum of all tiers
North America	Canada	1.0	1.0	1.0	0.5	0.5	4.0
	Mexico*	0.5	0.0	0.0	0.0	1.0	1.5
	United States of America	1.0	1.0	1.0	0.5	1.0	4.5
South America	Argentina	1.0	0.5	0.5	0.5	0.5	3.0
	Bolivia	1.0	0.5	1.0	0.5	0.5	3.5
	Chile	1.0	0.5	1.0	0.5	0.5	3.5
	Colombia	1.0	0.5	0.0	0.5	0.0	2.0
	Ecuador	1.0	0.5	0.5	0.5	0.0	2.5
	Peru	1.0	0.0	1.0	0.0	0.5	2.5
Europe	Austria	1.0	1.0	1.0	1.0	0.5	4.5
	France	1.0	1.0	1.0	0.5	1.0	4.5
	Germany*	1.0	0.0	0.0	0.0	0.0	1.0
	Greenland	0.5	0.5	0.5	0.0	1.0	2.5
	Iceland	1.0	0.5	1.0	0.5	1.0	4.0
	Italy	1.0	1.0	1.0	0.5	0.5	4.0
	Norway	1.0	1.0	1.0	0.5	1.0	4.5
	Spain	1.0	0.5	0.5	0.5	0.0	2.5
	Svalbard/Jan Mayen	0.5	1.0	1.0	0.5	0.5	3.5
	Sweden	1.0	1.0	1.0	0.5	1.0	4.5
Switzerland	1.0	1.0	1.0	1.0	1.0	5.0	
Africa	Kenya, Tanzania, Uganda	0.5	0.5	0.5	0.5	0.5	2.5
Asia	Afghanistan	0.5	0.0	0.0	0.0	1.0	1.5
	China	1.0	0.5	1.0	0.0	1.0	3.5
	Georgia	0.5	0.0	0.5	0.5	0.5	2.0
	India	0.5	0.0	0.5	0.0	1.0	2.0
	Iran	0.5	0.0	0.0	0.0	0.0	0.5
	Japan*	0.5	0.0	0.0	0.0	0.0	0.5
	Kyrgyzstan	1.0	0.5	1.0	0.5	1.0	4.0
	Kazakhstan	0.5	0.5	1.0	0.0	0.5	2.5
	Mongolia	0.5	0.0	0.0	0.0	1.0	1.5
	Nepal	0.5	0.0	0.5	0.0	1.0	2.0
	Pakistan	0.5	0.0	0.0	0.5	0.5	1.5
	Russia	0.5	1.0	1.0	0.5	1.0	4.0
	Tajikistan	0.0	0.0	0.0	0.0	0.0	0.0
Uzbekistan	0.5	0.0	0.0	0.0	0.0	0.5	
Other	New Zealand	1.0	0.5	0.5	0.0	1.0	3.0
	Antarctica	0.0	0.5	0.5	0.0	0.5	1.5

* Countries with very little ice cover

National glacier monitoring status

- Urgent need for action (0–3 points)
- Need for improvement (3.5–4 points)
- Well developed (4.5–5 points)

al 2013 and references therein), data on front variation, information on geodetic changes, and glacier inventories. Other programs, such as the Greenland glacier-monitoring program coordinated by Denmark, have a shorter history with fewer and shorter series available and are still working on the completion of glacier inventories. In addition, there are some countries with marginal glaciation, such as Spain with only one glaciological mass balance series in the Pyrenees and Germany with a long history in glacier research but only some glacier remnants around the Zugspitze (northern Alps). In general, glaciers in Europe are very well monitored, and the availability of glacier data for local and regional assessments is comparatively good. Of course, the long-term

commitment of the individual national networks is needed because all the series must be continued and safeguarded. In addition, monitoring activities in some regions should be extended or intensified (eg Greenland) or additional assessments made using remote-sensing data. A recent challenge in most regions of Europe is the disintegration and disappearance of glaciers that had long-term mass balance programs. With glacier retreat and recession in steeper positions, where in situ measurements are no longer possible (eg Weissbrunnferner, Italy), long-term monitoring series should be abandoned and new monitoring sites established, wherever possible.

FIGURE 5 Signal lights indicating status of country's/regions' current implementation of the international monitoring strategy.

<p>Baseline poorly developed/urgent action required</p> <ul style="list-style-type: none"> - most of the glaciers not investigated - short/interrupted data series - no monitoring network
<p>Baseline initiated/improvement needed</p> <ul style="list-style-type: none"> - some glaciers investigated - some long-term series exist - monitoring network is set up
<p>Baseline well developed/upgradeable</p> <ul style="list-style-type: none"> - large number of glaciers investigated - several long-term series exist - successful monitoring network exists

The few **African** glaciers are found on mountain tops in Kenya, Tanzania, and Uganda, covering an area of about 4 km² (see corresponding country profile on <https://wgms.ch/national-glacier-state>). Studies of these glaciers go back to the late 19th century and document the glaciers' recession (eg Hastenrath 2005). Most of the front variation series had stopped by 2005. Lewis Glacier on Mount Kenya is the only glacier with a mass balance series (Prinz et al 2011 and references therein). The aim of monitoring now is to properly document the complete disappearance of African glaciers.

In **Asia**, glaciers cover an area of about 163,000 km² (RGI 2015). In northern Asia, glaciers are located on the East Arctic Islands, in the mountain ranges from Ural to Altay, and in East Siberia and Kamchatka. Here the available series are sparse, and most of the measurements were discontinued by the end of the 20th century. The longest series come from the Russian Altay (eg Levyi and Maliy Aktru). In Central Asia, glaciers cover more than 100,000 km², which is about one sixth of the global glacier area. The main mountain chain in Central Asia is the Himalaya and its adjacent mountain ranges such as Karakoram, Tien Shan, Kunlun Shan, and Pamir. Their glaciers are essential contributors to several large rivers. About 1.9 billion people directly depend on the Hindu Kush–Himalaya for water, food, and energy (Wester et al 2019). Therefore, data on glacier change are of high significance. Available front variation series are well distributed over the region, but most of the observation series were discontinued before the 1990s. Only 2 long-term mass balance series exist: on Tsentralniy Tuyuksuyskiy (Kazakh Tien Shan) and on Urumqi Glacier No. 1 (Chinese Tien Shan). While glacier monitoring has been (re)established in some of the countries (eg China,

Kyrgyzstan, and Russia), it is just starting in other countries (eg Afghanistan, Pakistan).

The glaciers in **New Zealand** and around **Antarctica** cover areas of 1160 km² and 132,867 km², respectively (see corresponding country profiles at <https://wgms.ch/national-glacier-state>). In New Zealand, most glaciers are situated in the Southern Alps. Here, some of the glaciers show periods of advance (ie in the 1980s) related to regional climate conditions (Mackintosh et al 2017). The country has a long tradition of observing and monitoring glaciers; however, the focus was on front variation measurements. Long-term glaciological mass balance measurements are available for only 1 glacier, and thickness change measurements are not available at all. In Antarctica, glaciers (excluding the ice sheet) are mainly concentrated on the Antarctic Peninsula, as well as on the subantarctic islands and in the dry valleys. Glacier front observations are available for many glaciers (measured between 1960 and 1990); however, mass balance information is available for only 3.

Conclusions and perspectives

This study provides the first standardized assessment of national implementation of the international glacier-monitoring strategy by GTN-G. The country profiles compiled are available to national and sectoral policy-makers to get an overview of the status of glacier monitoring and existing data before using the data for further analysis and informed decision-making. In addition, the signal-light matrix highlights challenges to guaranteeing long-term sustainable glacier monitoring.

The assessment provides a baseline for targeted measures to improve the status of glacier monitoring in each country (rows in Figure 4). Unfortunately, those countries or regions with the highest glacier coverage are not the ones with the highest number of observation series. The sectoral analysis of the assessment (columns in Figure 4) clearly indicate where national monitoring activities are indispensable (Tiers 1, 2, and 3), while other issues (Tiers 4 and 5) can also be organized on an international level, such as by space agencies. Improvements at Tier 1 require action with respect to organizational structure and resources. Depending on the national structures, this may have implications for universities, federal agencies, or private companies observing glacier changes. Improvements at Tiers 2 and 3 (mass balance measurements) and 4 (front variations) require a capacity-building and twinning agenda for international agencies in collaboration with national stakeholders from the WGMS network. Improvements at Tiers 4 (geodetic surveys) and 5 (inventory) can be largely addressed by remote-sensing applications. Hence, the strengthening of national structures for glacier monitoring, as well as the compilation of in situ measurements, is a prerequisite for all glacierized nations or regions. In addition, all countries should

support the submission of glacier data to the international repositories organized within the GTN-G to guarantee availability and open access to the community. Persisting data gaps may result in ill-informed decisions and have severe consequences for the agriculture, water, and energy sectors and hence for human beings. The evidence from national glacier-monitoring activities will further strengthen the countries as actors in climate change negotiations.

The gap analysis of the implemented tiers also has its limitations. For example, for countries with small glaciated areas, such as Germany, Japan, or Mexico, there is often no national coordinated glacier monitoring (Tier 1), and the number of measurement series and observations is small (Tier 3, Tier 4). On the other hand, it is easy to provide an area-wide inventory of all glaciers (Tier 5). Still, the available data from these countries are of interest and can be analyzed in a more regional (eg Germany in relation to the Alpine countries) or continental (eg Mexico in relation to other tropical glaciers) context.

Although this assessment of national and regional glacier monitoring may be challenging in some cases, it provides accessible and reliable glacier data for scientists, as well as for decision-makers, by summarizing and extracting key information on inventories and long-term monitoring series, evaluating their relevance, and emphasizing needs for action. In this sense, it can be used to assess the national status in glacier monitoring. But it is only a starting point, which will hopefully trigger processes to improve glacier monitoring and enable more detailed process studies or model approaches to provide a better basis for decision-making processes.

As shown by our analysis, the GTN-G strategy can be used to assess glacier changes on various scales, from single countries to mountain ranges or entire continents. Since decision-making mainly happens at the national level, the situation needs to be analyzed for each country, and shortcomings, as mentioned for the countries with very small glaciated areas, need to be addressed. In summary, this profiling method summarizes the richness of glacier data for a country or region, presenting it as a single sheet, and making it understandable and valuable for scientists, policy-makers, and lay people. It can therefore help in (1) gaining better insight into ongoing

glacier changes and related processes, (2) fostering the establishment of better structures for glacier monitoring (eg funding, long-term commitment), (3) setting up provisions for the assimilation of additional data on glacier distribution and changes, and (4) ensuring the realistic treatment of data gaps and their effects on political decisions. All these aspects are relevant to assess glaciers as essential climate variables. In addition, an enhanced process understanding allows for well-adapted measures for sustainable mountain development, given that the data are included in decision-making processes. In the latter context, the assessment will identify opportunities for sectoral policies and policy instruments, such as disaster risk reduction (DRR) and integrated water resource management, key elements of Agenda 2030 and the Sendai Framework for DRR.

The profiles are intended to provide common ground for discussion and negotiation among data providers and users, focusing on challenges and needs regarding systematic long-term glacier monitoring. To achieve this, it is essential that action is taken, and we therefore invite:

- WGMS National Correspondents to foster the national coordination of glacier monitoring;
- National development agencies to support countries in their organizational structure for the implementation of in situ programs; and
- Space agencies to support the worldwide assessment of glacier distribution and changes with remote-sensing techniques.

Measures and procedures may be different in specific countries and regions, based on the delineated gaps. In this context, it must be kept in mind that glacier changes, as well as related land-use changes, occur on the local scale but have impacts at regional and global scales. Therefore, mitigation and adaptation solutions need to be addressed at local to global scales, if possible. The assessment can easily be repeated at regular intervals with the aim of reporting (positive and negative) developments in glacier monitoring at global, regional, and national levels. Thus, the present study provides a sound baseline for subsequent status reports assessing the progress made in national glacier monitoring and its contribution to the GCOS.

ACKNOWLEDGMENTS

We thank all the WGMS National Correspondents and Principal Investigators and their sponsoring agencies (as listed in WGMS 2017 and earlier issues) for their long-term collaboration and willingness to share glacier observations. This assessment is a contribution to the Sustainable Mountain Development for Global Change (SMD4GC) program supported by the Swiss Agency for

Development and Cooperation (SDC). The WGMS receives financial support from the Swiss Global Climate Observing System Office at the Federal Office of Meteorology and Climatology MeteoSwiss. We greatly appreciate the valuable comments of the anonymous reviewers and the editors.

REFERENCES

Björnsen Gurung AB, Wymann von Dach S, Price MF, Aspinnall R, Balsiger J, Baron JS, Sharma E, Greenwood G, Kohler T. 2012. Global change and the

world's mountains: Research needs and emerging themes for sustainable development. *Mountain Research and Development* 32(S1):S47–S54. <https://doi.org/10.1659/MRD-JOURNAL-D-11-00084.S1>.

- Bojinski 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(9):1431–1443. <http://dx.doi.org/10.1175/BAMS-D-13-00047.1>.
- Buytaert W, Moulds S, Acosta L, De Bièvre B, Olmos C, Villacis M, Tovar C, Verbist KMJ.** 2017. Glacier melt content of water use in the tropical Andes. *Environmental Research Letters* 12:114014. <https://doi.org/10.1088/1748-9326/aa926c>.
- Cox LH, March RS.** 2004. Comparison of geodetic and glaciological mass-balance techniques, Gulkana Glacier, Alaska, USA. *Journal of Glaciology* 50(170):363–370.
- Egan PA, Price MF, editors.** 2017. *Mountain Ecosystem Services and Climate Change: A Global Overview of Potential Threats and Strategies for Adaptation*. Paris, France: UNESCO.
- Fischer M, Huss M, Hoelzle M.** 2015. Surface elevation and mass changes of all Swiss glaciers 1980–2010. *Cryosphere* 9:525–540. <https://doi.org/10.5194/tc-9-525-2015>.
- GLAMOS** 2018 (and earlier reports), The Swiss Glaciers 2015/16–2016/17, Glaciological Reports No 137/138, Yearbooks of the Cryospheric Commission of the Swiss Academy of Sciences (SCNAT), published since 1964 by VAW/ETH Zurich. Glacier Monitoring Switzerland. Available at: www.glamos.ch; accessed on 18 July 2019.
- GLIMS [Global Land Ice Measurement from Space] and NSIDC [National Snow and Ice Data Center].** 2005, updated 2012. *GLIMS Glacier Database*. Boulder, CO: National Snow and Ice Data Center.
- Haeblerli W.** 2004. Glaciers and ice caps: Historical background and strategies of world-wide monitoring. In: Bamber JL, Payne AJ, editors. *Mass Balance of the Cryosphere*. Cambridge, United Kingdom: Cambridge University Press, pp 559–578.
- Haeblerli W, Barry R.** 2006. Global Terrestrial Network for Glaciers (GTN-G). In: GTOS, editor. *GTOS Biennial Report 2004–2005*. GTOS Document 40. Rome, Italy: Global Terrestrial Observing System, pp 30–31.
- Haeblerli W, Cihlar J, Barry RG.** 2000. Glacier monitoring within the Global Climate Observing System. *Annals of Glaciology* 31:241–246.
- Hastenrath S.** 2005. The glaciers of Mount Kenya 1899–2004 (Veränderungen der Gletscher am Mount Kenya 1899–2004). *Erdkunde* 59(2):120–125.
- Hoelzle M, Azisov E, Barandun M, Huss M, Farinotti D, Gafurov A, Hagg W, Kenzhebaev R, Kronenberg M, Machguth H, Merkushev A, Moldobekov B, Petrov M, Saks T, Salzmann N, et al.** 2017. Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia. *Geoscientific Instrumentation Method and Data Systems* 6:397–418.
- Hoelzle M, Trindler M.** 1998. Data management and application. In: Haeblerli W, Hoelzle M, Suter S, editors. *Into the Second Century of World Wide Glacier Monitoring: Prospects and Strategies*. Contribution to the International Hydrological Programme (IHP) and the Global Environment Monitoring System (GEMS), UNESCO Studies and Reports in Hydrology 56. Paris, France: United Nations Educational, Scientific and Cultural Organization (UNESCO).
- Huss M, Bauder A, Funk M.** 2009. Homogenization of long-term mass-balance time series. *Annals of Glaciology* 50(50):198–206.
- Huss M, Hock R.** 2018. Global-scale hydrological response to future glacier mass loss. *Nature Climate Change* 8:135–140.
- ICSU [International Commission of the Scientific Union].** 2010. *Earth System Science for Global Sustainability: The Grand Challenges*. Paris, France: International Council for Science (ICSU).
- IPCC [International Panel on Climate Change].** 2013. *Climate Change 2013: The Physical Science Basis*. Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, 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.
- Josberger EG, Bidlake WR, March RS, Kennedy BW.** 2007. Glacier mass-balance fluctuations in the Pacific Northwest and Alaska, USA. *Annals of Glaciology* 46:291–296.
- Kaser G, Grosshauser M, Marzeion B.** 2010. Contribution potential of glaciers to water availability in different climate regimes. *PNAS* 107(47):20223–20227.
- Kraaijenbrink PDA, Bierkens MFP, Lutz AF, Immerzeel WW.** 2017. Impact of a global temperature rise of 1.5 degrees Celsius on Asia's glaciers. *Nature* 549:257–260.
- Mackintosh AN, Anderson BM, Lorrey AM, Renwick JA, Frei P, Dean SM.** 2017. Regional cooling caused recent New Zealand glacier advances in a period of global warming. *Nature Communications* 8:14202.
- Mark BG, French A, Baraer M, Carey M, Bury J, Young KR, Polk MH, Wigmore O, Lagos P, Crumley R, McKenzie JM, Lutz L.** 2017. Glacier loss and hydro-social risks in the Peruvian Andes. *Global and Planetary Change* 159:61–67.
- McBean GA.** 2011. Coping with global environmental change: Need for an interdisciplinary and integrated approach. In: Brauch HG, Spring UO, Mesjasz C, Grin J, Kameri-Mbote P, Chourou B, Dunay P, Birkmann J, editors. *Global Environmental Change, Disasters and Security*. Hexagon Series on Human and Environmental Security and Peace 5. Berlin, Germany: Springer, pp 1193–1204. https://doi.org/10.1007/978-3-642-17776-7_73.
- Nussbaumer SU, Hoelzle M, Hüsler F, Huggel C, Salzmann N, Zemp M.** 2017. Glacier monitoring and capacity building: Important ingredients for sustainable mountain development. *Mountain Research and Development* 37(1):141–152.
- Prinz R, Fischer A, Nicholson L, Kaser G.** 2011. Seventy-six years of mean mass balance rates derived from recent and re-evaluated ice volume measurements on tropical Lewis Glacier, Mount Kenya. *Geophysical Research Letters* 38(20):1–6.
- 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.** 2012. Current state of glaciers in the tropical Andes: A multi-century perspective on glacier evolution and climate change. *Cryosphere* 7(1):81–102.
- RGI [Randolph Glacier Inventory] Consortium.** 2015. *Randolph Glacier Inventory: A Dataset of Global Glacier Outlines: Version 5.0*. Technical Report, Global Land Ice Measurements from Space (GLIMS). Boulder, CO: Digital Media. <https://doi.org/10.7265/N5-RGI-50>.
- Schaner N, Voisin N, Nijssen B, Lettenmaier DP.** 2012. The contribution of glacier melt to streamflow. *Environmental Research Letters* 7:1–8. <https://doi.org/10.1088/1748-9326/7/3/034029>.
- Schoolmeester T, Johansen KS, Alifhan B, Baker E, Hesping M, Verbist K.** 2018. *The Andean Glacier and Water Atlas: The Impact of Glacier Retreat on Water Resources*. Paris, France, and Arendal, Norway: UNESCO and GRID-Arendal.
- Soruco A, Vincent C, Francou B, Ribstein P, Berger T, Sicart JE, Wagnon P, Arnaud Y, Favier V, Lejeune Y.** 2009. Mass balance of Glaciar Zongo, Bolivia, between 1956 and 2006, using glaciological, hydrological and geodetic methods. *Annals of Glaciology* 50:1–8. <https://doi.org/10.3189/172756409787769799>.
- Thomson LI, Zemp M, Copland L, Cogley JG, Ecclestone MA.** 2016. Comparison of geodetic and glaciological mass budgets for White Glacier, Axel Heiberg Island, Canada. *Journal of Glaciology* 63(237):55–66. <https://doi.org/10.1017/jog.2016.112>.
- Tollefson J, Rodriguez Mega E.** 2017. Geoscientist faces criminal charges over glacier survey. *Nature* 552:159–160.
- UNESCO [United Nations Educational, Scientific and Cultural Organization].** 1970. *Perennial Ice and Snow Masses. A Guide for Compilation and Assemblage of Data for a World Glacier Inventory*. UNESCO/IAHS Technical Papers in Hydrology. Zurich, Switzerland, and Paris, France: UNESCO.
- Wester P, Mishra A, Mukherji A, Shrestha AB, editors.** 2019. *The Hindu Kush Himalaya Assessment—Mountains, Climate Change, Sustainability and People*. Cham, Switzerland: Springer.
- WGMS [World Glacier Monitoring Service] and NSIDC [National Snow and Ice Data Center].** 1989, updated 2012. *World Glacier Inventory*. Zurich, Switzerland: World Glacier Monitoring Service, and Boulder, CO: National Snow and Ice Data Center. <https://doi.org/10.7265/N5/NSIDC-WGI-2012-02>.
- WGMS [World Glacier Monitoring Service].** 2008. *Global Glacier Changes: Facts and Figures*. Zemp M, Roer I, Kääb A, Hoelzle M, Paul F, Haeblerli W, editors. Zurich, Switzerland: UNEP, World Glacier Monitoring Service.
- WGMS [World Glacier Monitoring Service].** 2015. *Global Glacier Change Bulletin No. 1 (2012–2013)*. Zemp M, Gärtner-Roer I, Nussbaumer SU, Hüsler F, Machguth H, Mölg N, Paul F, Hoelzle M, editors. Zurich, Switzerland: ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service. Publication based on database version: <https://doi.org/10.5904/wgms-fog-2015-11>.
- WGMS [World Glacier Monitoring Service].** 2017. *Global Glacier Change Bulletin No. 2 (2014–2015)*. Zemp M, Nussbaumer SU, Gärtner-Roer I, Huber J, Machguth H, Paul F, Hoelzle M, editors. Zurich, Switzerland: ICSU(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO, World Glacier Monitoring Service. Publication based on database version: <https://doi.org/10.5904/wgms-fog-2017-10>.
- Zemp M, Frey H, Gärtner-Roer I, Nussbaumer SU, Hoelzle M, Paul F, Haeblerli W, Denzinger F, Ahlstrom AP, Anderson B, Bajracharya S, Baroni C, Braun LN, Cáceres BE, Casassa G, et al.** 2015. Historically unprecedented global glacier decline in the early 21st century. *Journal of Glaciology* 61(228):745–762. <https://doi.org/10.3189/2015Jog15J017>.
- Zemp M, Gärtner-Roer I, Haeblerli W, Hoelzle M, Paul F, Armstrong R, Barry R, Cihlar J, Kääb A, Kargel J, Khalsa SJ, Monteduro M, Raup B, Seiz G, Sessa R.** 2009. *ECV T6—Glaciers and Ice Caps. Assessment of the Status of the*

Development of the Standards for the Terrestrial Essential Climate Variables. Rome, Italy: GTOS Secretariat.

Zemp M, Haeberli W, Hoelzle M, Paul F. 2008. Glaciers and ice caps. In: GTOS, editor. *GTOS Biennial Report 2006–2007*. GTOS Document 50. Rome, Italy: Global Terrestrial Observing System, pp 2–3.

Zemp M, Huss M, Thibert E, Eckert N, McNabb R, Huber J, Barandun M, Machguth H, Nussbaumer SU, Gärtner-Roer I, Thomson L, Paul F, Maussion F,

Kutuzov S, Cogley G. 2019. Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* 568(7752):382–386. <https://doi.org/10.1038/s41586-019-1071-0>.

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. Reanalysing glacier mass balance measurement series. *Cryosphere* 7:1227–1245. <https://doi.org/10.5194/tc-7-1227-2013>.