125 years of internationally coordinated glacier monitoring: achievements and future challenges

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Summary report on the IUGG General Assembly and the WGMS General Assembly of National Correspondents 2019

9–16 July 2019: IUGG General Assembly, Montreal, Canada

14–17 August 2019: WGMS General Assembly Europe and North America, Zurich, Switzerland

10–14 September 2019: WGMS General Assembly Asia, Almaty, Kazakhstan

22–26 October 2019: WGMS General Assembly Latin America, El Calafate, Argentina

wgms World Glacier Monitoring Service

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Summary report on the IUGG General Assembly and the WGMS General Assembly of National Correspondents 2019

Worldwide collection of information about ongoing glacier changes was initiated in August 1894 with the foundation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland (Forel, 1895; Allison et al. 2019). Today, grown to a worldwide collaboration network in more than 40 countries, glacier monitoring is coordinated within the framework of the Global Terrestrial Network for Glaciers (GTN-G), under the coordination and support of the GTN-G Advisory Board, which is chaired by the International Association of Cryospheric Sciences (IACS).

In 2019, the WGMS celebrated the 125-year jubilee of internationally coordinated glacier monitoring jointly with IACS during the 27th General Assembly of the International Union of Geodesy and Geophysics (IUGG) and later with its National Correspondents during the WGMS General Assembly. To connect the different meetings, video messages have been recorded that address the attendees of the respective meetings. These messages are available from the WGMS website: https://wgms.ch/jubilee_2019/

27th IUGG General Assembly

The IUGG General Assembly was held in **Montreal**, Canada, in **July 2019** and brought together more than 3500 registrants from more than 100 countries, including many IACS members. GTN-G was present at the conference with a symposium on glacier monitoring from *in situ* and remotely sensed observations. It included three sessions, of which one session was dedicated to aspects of the history of cryospheric sciences on the occasion of the anniversary of the International Glacier Commission. The GTN-G symposium on glacier monitoring was one among 15 IACS symposia, in addition to 15 joint symposia of IACS with other IUGG associations.

During the conference, IACS held its open plenary administrative meeting where the WGMS handed over an original 1895 report by F.A. Forel on behalf of the International Glacier Commission ("Les variations périodiques des glaciers") as a gift to IACS. The legacy of the "Commission Internationale des Glaciers" (CIG) was also highlighted by I. Allison in his solicited talk on the history of IACS. Although IACS is the most recent association of IUGG, its forbearers stretch back even further than IUGG, starting with the formation of the CIG in 1894. As an important and more direct legacy of the CIG, the coordination of international glacier monitoring has been continued until the present, with the WGMS in charge of the collection and publication of standardized information on distribution and ongoing changes in glaciers. Today, the WGMS is a service of IACS within the World Data System (WDS) of the International Science Council (for more details, see Allison et al. (2019) in the anniversary special issue on "The International Union of Geodesy and Geophysics: from different spheres to a common globe", published in *History of Geo- and Space Sciences*).

Scientific and administrative components were finally completed by IACS' traditional Fiesta Cryospherica, which was held in the old town of Montreal.

WGMS General Assembly of National Correspondents

The WGMS General Assembly was split into three regional meetings, which allowed the WGMS to focus on regional challenges and networks and to substantially reduce the related carbon footprint.

In **August 2019**, the National Correspondents from Europe, North America, and Africa met at the University of **Zurich, Switzerland**. The meeting stood in the light of the jubilee of internationally coordinated glacier monitoring – 125 years ago, worldwide glacier monitoring was initiated at the same place. 125 years later, the focus changed and many receding and even vanishing glaciers challenge monitoring efforts all over the world.

In **September 2019**, the meeting in **Almaty, Kazakhstan** was jointly organized with colleagues from the Institute of Geography of the Republic of Kazakhstan. Here, the main focus was on the national status of glacier monitoring programmes (cf. Gärtner-Roer et al. (2019) in *Mountain Research and Development*) and on the progress needed to better support water resource management and disaster risk reduction. As an outcome, the participants aim for the establishment of a Central Asian Working Group on Snow and Ice to improve cooperation and capacity building within the region.

The General Assembly was completed with the meeting in **El Calafate, Argentina** in **October 2019**, with a focus on regional challenges and strengthening of the regional network as well as dedicated public outreach in view of the upcoming UN Climate Change Conference (COP25).

The WGMS General Assembly resulted in a joint Letter of Concern, addressed to the United Nations Framework Convention on Climate Change and the parties of COP25 held in Madrid in December 2019. In addition, the letter was published – in a shortened version – as Correspondence in *Nature* (Zemp et al. 2019).

In the following, a summary of the three regional meetings and the country reports by the Nationals Correspondents are given; they are supplemented with the meetings' outcome (Letter of Concern, media reports) and background information on the air miles monitoring, which was done on the occasion of the WGMS General Assembly:

Acknowledgements

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Programme GA Zurich

14.08.2019: Ice breaker @ WGMS office (University Campus Irchel, Winterthurerstrasse 190, 8057 Zürich → Building 25, Floor H, rooms 82/84)

17–20	Registration, ice breaker, informal gathering

15.08.2019: History & current status of glacier monitoring @ UZH (main building)

from 8.30	Registration *(bring your material and get your badge)*
9–9.15	Welcome & "courier message" (M. Zemp)
9.15–10	Glacier monitoring: historical background, achievements & challenges (M. Zemp)
10–10.30	Coffee break
10.30–11	International monitoring strategy & country profiles (baseline 2015) (input I. Gärtner & discussion)
11–12.30	I. Country reports & discussion (AT, CH, DE, FR, ES) *(S. Nussbaumer)*
12.30–13.30	lunch
13.30–15	II. Country reports & discussion (IT, IS, NO, SE, PO) *(J. Bannwart)*
15–15.30	coffee break
15.30–17	III. Country reports & discussion (Africa, CA, UK, USA, GL, Australia) *(I. Gärtner-Roer)*
17–17.30	Discussion on challenges, national implementations
17.30–18	Welcome by WGMS director Michael Zemp Welcome by UZH rector Michael Hengartner Welcome by MeteoSwiss director Peter Binder
18	Group picture *(F. Paul)*
…	Apero & conference dinner (UniTurm)

16.08.2019: GTN-G Mid-term Evaluation @ UZH (main building)

9–10	I. *In situ* measurements in times of vanishing glaciers (input M. Huss & discussion) *(M. Zemp)*
10–10.30	coffee break
10.30–12	II. Regional glacier change assessments from remote sensing (input A. M. Trofaier, J. Muñoz, F. Paul & discussion) *(P. Rastner)*
12–13	lunch
13–14	III. Database management & infrastructure (input M. Zemp & discussion) *(I. Gärtner-Roer)*
14–15	IV. Last evaluation report and related progress (input L. Andreassen (IACS), M. Zemp & discussion) * *(S. Nussbaumer)*
15–15.30	Coffee break
15.30–17	Summary, concluding discussion & mile stones for the next decade
18	BBQ at the lake

* = videoconference (GTN-G Advisory Board & Boulder)

17.08.2019: Excursion to Rosenlaui glacier and Kunsthaus Interlaken (8 am – 7 pm)

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Impressions from the WGMS General Assembly at the University of Zurich and at Rosenlaui glacier, Bernese Oberland (photos: Rebecca Hawkins).

Current state, progress, and challenges of glacier monitoring in Austria

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Current state (2015)

In the latest glacier inventory, 921 glaciers covered an area of about 415.11 ± 11.18 km^2 (Fischer et al. 2015; representing the years 2004 to 2012). This is only 44% of the glacier area during LIA maximum. Glacier inventories so far are available for the LIA maximum, 1969, 1998 and 2004-2012 (depending on region). About 10% of the glaciers are subject to monitoring of fluctuations carried out by the glacier survey of the Austrian Alpine Club (Fischer et al. 2018), initiated in 1891. Some of the series date back much longer, as for example for Paterzenkees or glaciers in Rofental (Ötztal Alps).

Glacier mass balance is measured on Hintereisferner, Kesselwandferner (from 1952/53 onwards, Strasser et al. 2018) and Vernagtferner (Braun and Escher-Vetter 2012) in Ötztal Alps, on Stubacher Sonnblickkees (series dating back to 1948), Pasterzenkees, Kleinfleisskees, Goldbergkees, Wurtenkees, Venedigerkees (a former tributary of Obersulzbachkees), and Mullwitzkees in Hohe Tauern (Fischer et al. 2014), Jamtalferner in Silvretta (Fischer and Markl 2009) and Hallstätter Gletscher in the Dachstein region (Stocker Waldhuber et al. 2015). Ablation stakes are installed for several years at Ödenwinkelkees, Gepatschferner, Taschachferner, Weissseeferner and Schlatenkees. Past measurements took place on Rotmoosferner, Schladminger Gletscher, Schaufelferner, Daunkogelferner, Fernauferner, Mittelbergferner, Rettenbachferner and Tiefenbachferner (single stakes), Übergossene Alm, Ochsentaler and Vermuntgletscher (full mass balance). Runoff gauges are mounted at the glacier rivers of Vernagtferner (Braun and Escher-Vetter 2012), Stubacher Sonnblickkees and Obersulzbachkees (Fischer et al. 2016). Time series of ice velocities seems to be sensitive indicators of glacier state and are recorded at Pasterzenkees, Hintereisferner, Kesselwandferner, Gepatschferner and Taschachferner (Stocker Waldhuber et al. 2019). The total Austrian ice volume was 15.9 km³ in 2006 (Helfricht et al. 2019), distributed volume data based on data measured on about 70 glaciers is available for all glaciers. The glacier monitoring activities are carried out in a close cooperation with the Hydrographical Surveys of the Federal States and the Austrian Ministry for Sustainability and Tourism.

Progress after 2015

In the years 2015, 2017, and 2018 Austrian glaciers retreated extremely, with even more negative specific mass-balance rates then in 2003 – although a major portion of the past ablation area with extreme melt rates is ice free today, and total runoff decreases even when specific mass balance is more negative than in 2003. As a case study with newest LiDAR data in Stubai valley shows that the annual area loss increased from 0.12 km²/year (1969–1998) to 0.24 km²/year (1998-2006) to 0.36 km²/year (2006–2017). The extreme retreat rates come along with disintegration of glaciers and the respective geomorphological processes (Stocker-Waldhuber et al. 2017) which can be considered as indicators for this stage of glacier decay. Glacial lakes (Buckel et al. 2018) have gained increased attention as potential sources of natural disasters. The paraglacial area in general is subject to several research projects, as the sediment transport in areas which became ice free recently is affecting infrastructure downstreams. Constraining the age of Eastern Alpine glaciers (Bohleber et al. 2018) and the development of new methods for revealing LIA mass balances (Feng et al. 2019) might enable us to prolongate time series and thus increase our knowledge on glacier-climate interaction at regional and local level. Additional runoff gauges have been installed at the glacier rivers of Jamtalferner and in Rofental valley.

Challenges

Classical glacier monitoring as direct mass-balance monitoring and length change measurements has become challenging as both techniques and theory is not applicable to disintegrating glaciers with increasing debris cover as observed in recent years. For example, ELA has been above summits on the majority of mass-balance glaciers during the last decade. The rapid loss of ablation area has high impact on specific mass balance. Different methods have been applied to separate geometry signal from climatic signals (Charalampidis et al. 2018; Vincent et al. 2017). We cope with the challenges by increasing our effort in repeat inventories, including the evolution of debris cover, dynamics and disintegration as so far not quantified important feedback mechanisms.

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Glacier monitoring: Canada

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Canada hosts the largest area of ice outside the Greenland and Antarctic ice sheets, comprising 25,554 individual glaciers within the Randolph Glacier Inventory and amounting to 159,708 km^2 of ice (Pfeffer et al. 2014). These glaciers are primarily located within the mountain ranges of western Canada (e.g. Coast, Rockies, St. Elias) and within the Canadian Arctic Archipelago. Canada hosts seven of the World Glacier Monitoring Service's official reference glaciers, being those glaciers with >30 year of glaciological mass-balance observations. Long-term, field-based measurements of glacier mass balance have primarily been led by researchers from the Geological Survey of Canada, and enhanced by university-based research programmes that contribute additional mass-balance data and observations of glacier length, area, and volume change. This summary focuses on the glaciological mass-balance observations for Canada.

In western Canada, which hosts 13,851 km^2 of ice (13,669 glaciers), glaciers play an important role as a freshwater resource for communities and agriculture, for hydro-electric power generation, and as a stabilizing mechanism for summer stream and river temperatures that directly impact ecosystems and commercial fisheries in the region. There are three official reference glaciers in western Canada that are managed by the Geological Survey of Canada (Ednie and Demuth 2019). In the southern Coastal Mountains, Place Glacier (3.09 km^2) and Helm Glacier (0.74 km^2) have been monitored continuously since 1965 and 1977, respectively. These glaciers have been dominated by negative mass-balance conditions over the period of record, with average glacier-wide mass balances of –86 cm w.e. a^{-1} for Place Glacier (1965-2016) and –125 cm w.e. a^{-1} for Helm Glacier (1977–2016). In concert with persistent negative mass-balance conditions, notable area losses have resulted for both glaciers. In the Rocky Mountains, the Peyto Glacier basin (9.4 km^2) within the Wapta Icefield has been monitored since 1966. Peyto Glacier has also been dominated with negative mass-balance conditions over the period of record, with an average glacier-wide mass balance of –63 cm w.e. a^{-1} from 1966–2016, resulting in notable area and volume losses to the iconic terminus of this glacier (Kehrl et al. 2014). The projected demise of western Canada's glaciers (Clarke et al. 2015) emphasizes the need for ongoing monitoring in this region to support adaptation strategies for the future.

The glaciers of Arctic Canada can be divided into the regions of Arctic Canada North (Queen Elizabeth Islands) and Arctic Canada South (Baffin & Bylot islands and northern Labrador). Arctic Canada North hosts 4538 glaciers covering 104,873 km^2 (Pfeffer et al. 2014), which includes four official reference glaciers to the World Glacier Monitoring Service. The Melville, Meighen, and Devon ice cap monitoring programmes are managed by researchers at the Geological Survey of Canada (Burgess 2017), while the White Glacier monitoring programme has been managed by university researchers (Müller 1962; Cogley et al. 1996; Thomson et al. 2017). The glacier monitoring programmes in this region began in the early 1960s, with surface mass-balance measurements being conducted once per year in late spring (April/May). Over the period of record there is notable agreement between the glacier mass-balance records which indicated slightly negative mass-balance conditions through the 1960s, net-zero or slightly positive mass balances from 1970–1990, and an acceleration of negative mass-balance conditions over the past 30 years. These losses are attributed to enhanced melt conditions under amplified Arctic warming (Serreze and Barry 2011), which has led to a fivefold increase in glacier mass losses since 2005 (Sharp et al. 2011). Arctic Canada South hosts 7,347 glaciers covering 40,894 km^2. Currently, not long-term glaciological mass-balance programmes are being maintained in Arctic Canada South, however efforts are being made to ensure this region is sampled in the future. Together, the Canadian Arctic (north and south) hosts a large number of ocean-terminating glaciers and, until recently, the dynamic component of ice loss by calving was unknown. Remote sensing studies have revealed that this contribution is small, accounting for <5% of total mass losses in the Canadian Arctic (Van Wychen et al. 2014, 2015). The combined effect of significant ice cover and enhanced Arctic warming has led to the Canadian Arctic becoming one of the largest contemporary contributors to sea-level rise (Zemp et al. 2019), making this a globally important region to monitor in the years ahead.

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Progress report, Glacier Monitoring in Switzerland

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The monitoring of glaciers looks back onto a long tradition in Switzerland. In 1884, the first mass-balance measurements worldwide were performed at a stake network on Rhône Glacier, and at the same time length change records at several dozens of glaciers were started that are continued until today. Since 2016, glaciological measurements are performed in the frame of the multi-institution programme GLAMOS (Glacier Monitoring Switzerland) that is fully funded by several federal institutions and GCOS, thus replacing the previous, only partly coordinated activities. GLAMOS is responsible for collecting data on direct seasonal mass balance at about 20 glaciers in all regions of Switzerland, frontal variation at about 100 glaciers, geodetic ice volume change for about 30 glaciers, as well as performing regular updates of the Swiss glacier inventory, measurements of surface velocity at selected glaciers, and observations of englacial temperature at one site (see Fig. 1 for examples). Switzerland hosts four reference mass-balance series of the World Glacier Monitoring Service, all starting at around 1960. The longest observational time series of mass balance and length span over more than a century without interruption, hence, representing a valuable basis for enhancing our understanding of the glacier-climate linkage and for further developing and calibrating/validating glacier models.

The most important progress of the last years clearly is the kick-off of GLAMOS that has allowed us to tackle many of the previous challenges due to the benefits of a coordinated and funded monitoring programme. A new website / data portal (www.glamos.ch) now allows direct access to GLAMOS data for a wider public. The website is connected to a database hosting all GLAMOS data centrally. We have made major progress in the collaboration with the Federal Office of Topography regarding the use of regularly repeated high-resolution terrain elevation models (geodetic mass balance), as well as 6-yearly updates of glacier outlines (including debris-cover maps) based on 0.25 m orthophotographs providing an up-to-date glacier inventory, and length change assessments of inaccessible and/or decaying glaciers. Furthermore, in relation with various research projects, monitoring activities at several sites have been intensified with two large glaciers (Rhone, Findelen) approaching the definition of Tier 2 benchmark glaciers.

We identify several important challenges and goals for Swiss glacier monitoring over the coming years. Our overarching goal is to maintain and consolidate the successful monitoring programme at a high quality. We intend to amplify efforts in documenting data acquisition as well as evaluation procedures, both for future measurements, as well as by revisiting past field data records. Experience has indicated that a fast and more specific response to requests for data and information (both for scientific and public use) is required, and we intend to further improve public data access and availability. Over the next years, we also plan to intensify the use of operational remote sensing data, and other new monitoring techniques to more regularly update our data products, thus supporting, extending and also partly replacing laborious field measurements. A crucial challenge is climate change threatening several of the long-term glaciological series. Our recently developed concepts to start monitoring activities on larger, more resilient glaciers, or shift to observational techniques adapted to the changed situations, need to be implemented during the next years.

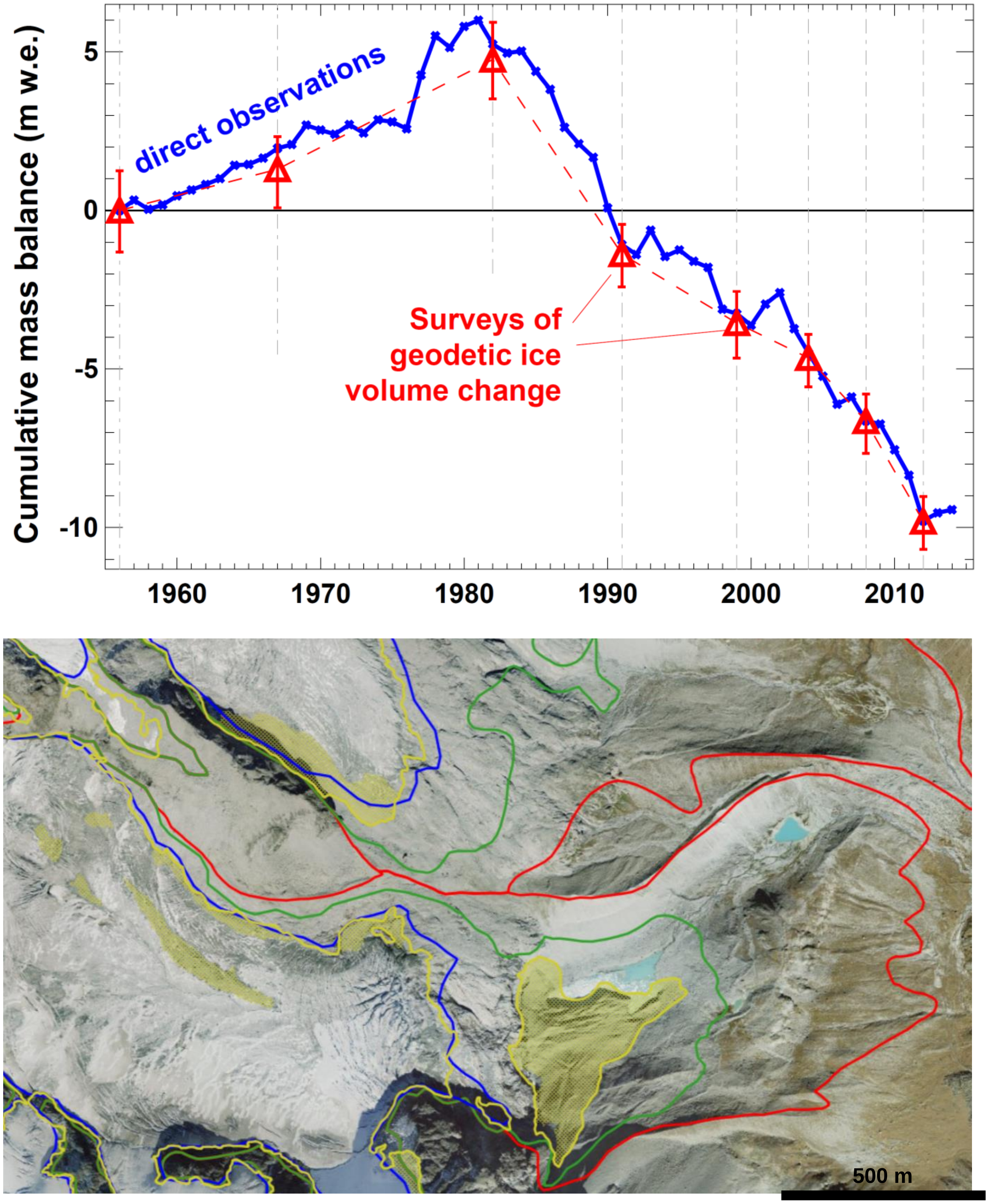

Fig. 1: Top: Long-term series of observed glacier-wide mass balance at Allalingletscher, validated using independent ice volume changes derived from aerial photogrammetry (red triangles). Bottom: Example of the Swiss glacier inventories of 1850 (red), 1973 (green) and 2010 (blue) for a site in the Southern Valais (Gabelhorngletscher). The yellow outlines refer to the most recent, yet unpublished, inventory (outlines referring to 2016) that is based on high-resolution imagery, thus partially detecting glacier ice that was missed in earlier inventories. Debris-covered ice is indicated (yellow hatched areas).

The current state of the Icelandic glaciers

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Glaciers in Iceland have retreated rapidly for a quarter of a century, and glacier downwasting is one of the most obvious consequences of the warming climate in the country. However, the warming in Iceland has slowed down since 2010 compared with the preceding three decades. At the same time, the glaciers have retreated substantially, which has reduced their ablation area and therefore the annual mass loss. This development is reflected in the country-wide average glacier mass balance, which was ca. –1 m w.e. a^{-1} in the period 1995–2010 but ca. –0.3 m w.e. a^{-1} in the period 2011–2018. Since 2000, the area of Iceland's glaciers has decreased by more than 750 km^2, and by ca. 2100 km^2 since the end of the 19th century when the glaciers reached their maximum extent since the country's settlement in the 9th century CE. The glacier area has on average decreased by ca. 40 km^2 annually in recent years.

In situ surface mass-balance records from Vatnajökull ice cap (~7700 km^2), Langjökull ice cap (~840 km^2) and Hofsjökull ice cap (~810 km^2) are available since the glaciological years 1991–92, 1996–97 and 1987–88, respectively. Shorter records of accumulation and ablation are available from Mýrdalsjökull and Drangajökull ice caps and geodetic mass balance has been calculated for Hofsjökull, Drangajökull, Eyjafjallajökull and ~20 smaller glaciers. The surface mass balance of the largest Icelandic glaciers has been negative since 1995, with the exception of the year 2015. The mass balance in 2016 was again negative by a magnitude similar to that in recent years. The mass balance of Langjökull and Hofsjökull was also negative in 2017, whereas Vatnajökull was almost in balance. All three ice caps were near balance in 2018. The glaciers have lost ca. 250 km^3 of ice since 1995, which corresponds to ca. 7% of their total volume.

Geodetic mass-balance records further back in time have been deduced from reconstructed glacier surface maps based on glacial geomorphological evidence, maps, historical aerial photographs, declassified spy satellite images, modern satellite stereo imagery and airborne lidar. These data show a consistent story of slow retreat from 1890 to 1920, high rates of mass loss 1930 to 1950, a period of close to equilibrium or slight mass increase in 1960–1990, a similar rate of mass loss from 1995 and through the first decade of the 21st century as in the 1930s and 1940s, and finally a somewhat slower mass loss since 2010. A detailed examination of shorter periods for a number of the smaller glaciers shows that they are subject to somewhat different climate forcing and that higher decadal mass-balance variability is found on glaciers located at the south and west coast, in contrast to glaciers located inland, and in north and northwest Iceland.

The proglacial landscape has undergone rapid changes in recent years. Many ice-marginal lakes have formed in front of glacier termini in Iceland in recent decades due to warming climate, particularly at the southern margin of Vatnajökull, making frontal measurements more difficult in a few locations. At the same time, most lateral glacier-dammed lakes have decreased in size or disappeared because of the thinning of the glaciers, and jökulhlaups released from them have become smaller. The lakes are associated with hazard to settlements and travellers in the adjacent area, as landslides into the lakes or on the glaciers that propagate into the lakes can create tsunami waves with a high run-up and sudden, very dangerous flash floods in the glacier forelands.

A recent study on the non-surface mass balance of glaciers in Iceland, shows that neglecting that component leads to one-sided bias in traditional surface mass-balance measurements in case they are interpreted as records of total mass balance. Several Icelandic glaciers are located in the neo-volcanic zone where geothermal heat flux is much larger than the global average, leading to geothermal basal melting. Energy dissipation in the flow of water and ice is also rather large for the high-precipitation, temperate glaciers of Iceland resulting in internal and basal melting of 20–140 mm w.e. a^{-1}. Also, calving is a significant mass-balance component for the Breiðamerkurjökull outlet glacier on the south side of Vatnajökull and is becoming non-negligible for several other glacier tongues terminating in recently formed proglacial lakes. In total, non-surface melting of glaciers in Iceland excluding melting due to volcanic eruptions, is 45–460 mm w.e. a^{-1} in average for the main ice caps, largest for Mýrdalsjökull, the south side of Vatnajökull and for Eyjafjallajökull. This amounts to ∼15–50% of the magnitude of the (negative) mass balance of glaciers in Iceland since 1995 which has on average been near −1 m w.e. a^{-1}.

The Icelandic Meteorological Office (IMO) and several collaborators are preparing an inventory for all glaciers in Iceland, collecting glacier outlines at several points in time since the end of the 19th century. The outlines of Icelandic glaciers at different times have been digitized by several research groups in recent decades from maps, aerial and satellite images. Glacial geomorphological features have been used to delineate the maximum Little Ice Age extent of the glaciers. These data have hitherto not been gathered systematically; they have been published in numerous scientific papers and are stored at different institutions, and not easily available.

The glacier termini monitoring website (http://spordakost.jorfi.is/) presents the results of the frontal measurements of the volunteers of the Iceland Glaciological Society graphically through a map interface as well as providing access to the raw data for users interested in further analysis. Historical photographs of some of the termini at several different points in time are provided in a few cases. Graphs showing the variations of many different termini on the same plot are also provided, as well as the annual reports about the measurements from the journal *Jökull*, scientific papers about glacier variations in Iceland and links to international data centres and scientific organisations that work with glacier variations.

An effort to obtain accurate geodetic mass balance for all the Icelandic glaciers is in preparation by the IMO and the National Land Survey of Iceland in collaboration with the Polar Geospatial Center in the US. A similar effort for Arctic glaciers will be promoted within the Arctic Council during the presidency of Iceland in 2019–2021. Other remote sensing efforts of the Icelandic glaciers are also planned with international collaborators, including an extensive monitoring of ice-flow velocities of the glaciers.

A few challenges related to glacier monitoring in Iceland are worth mentioning. Dead ice at retreating termini complicates the definition of the location of the glacier boundary and makes access to the glacier more difficult. Melting of buried dead ice outside of the glacier boundary is not considered in the monitoring but contributes to river runoff and sea-level rise. Snow radar measurements show that wind drifting of snow in the windy Icelandic climate has more effect on the spatial distribution of winter balance than previously realised. Calving into proglacial lakes is becoming a non-negligible mass-balance component but is rarely measured. Other non-surface mass-balance components also need to be considered. Finally, volcanic eruptions lead to short-lived disturbances in the mass balance that are hard to measure.

In recent years, increased effort has been made to communicate scientific findings, and the Ministry for the Environment and Natural Resources launched in 2016 the project *Icelandic glaciers, a natural laboratory to study climate change*, in short *Melting glaciers*, in co-operation with the IMO, the Vatnajökull National Park, the Institute of Earth Sciences, University of Iceland, and the South East Iceland Nature Research Center. This work has included the publication of an educational brochure about glaciers and climate change (in Icelandic and English), an educational website about glaciers (https://www.vatnajokulsthjodgardur.is/en/areas/melting-glaciers) and the creation of educational hiking paths in the area south of the Vatnajökull ice cap.

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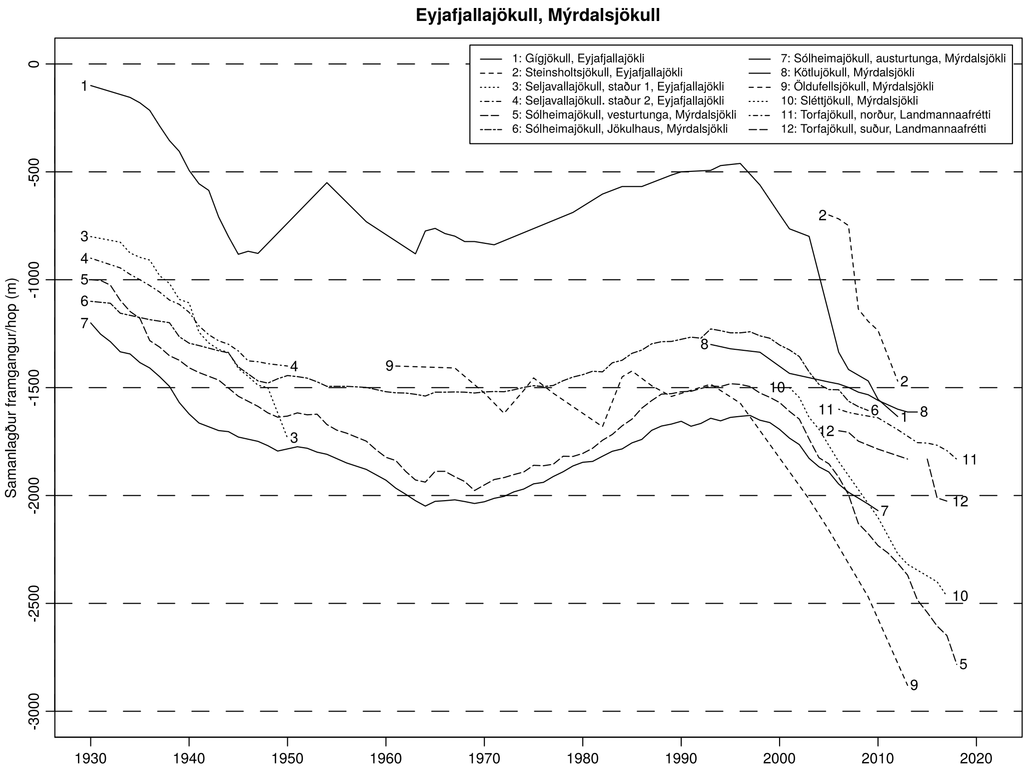

Fig. 2: The monitored outlet glaciers of Eyjafjallajökull and Mýrdalsjökull ice cap, image: spordakost.jorfi.is

Current state of glacier monitoring in Italy and challenges overcoming: toward a new dynamic glaciers inventory and updatable dataset

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CGI – Comitato Glaciologico Italiano (Italian Glaciological Committee)

The "Comitato Glaciologico Italiano" (CGI) promotes and coordinates glaciological research and monitoring of Italian glaciers since 1895. CGI recognized the importance of measuring frontal variations, which were regularly conducted since end of the 19th century, with the only exception of the war periods, and now they supply one of the longest observations series of glacier snout fluctuations in the world (in some cases extendable to the end of the 18th century; https://www.glaciologia.it/en/i-ghiacciai-italiani/le-campagne-glaciologiche/).

Annual glaciological surveys provide a large amount of data and a precious photographic documentation regularly published in the CGI Bulletin since 1914 (later published as *Geografia Fisica e Dinamica Quaternaria* from 1977 to present, http://gfdq.glaciologia.it/issues/).

About 130 snout variations are presently measured (2018), although many other glaciers are visited every year by a large number of surveyors (linked to CGI and to other regional volunteer associations). All the data of frontal variation CGI surveyed during the last 100 years were recently revised and validated in the framework of the CNR project of strategic interest NEXTDATA. Measurements of snout variation refer to 408 Italian Glaciers, 137 of which have no validated measurements nor real data consistency (less than 10 measurements). 238 of the monitored Italian glaciers supply 10 or more measurements of front variation, while only 116 glaciers have more than 30 measures. The Lys-Garstelet Glacier (Mt. Rosa Group) furnishes the highest number of validated observations (105) with measurement coverage of 115 years (1902-2017). The Ventina Gl. (Bernina Group), the Forni Gl. (Ortles-Cevedale Group) provide the longest TD curves spanning from 1896 (1898) to 2018 (TD curves of these and other Italian glaciers are further extendable to the beginning of the 19th century on the basis of historical maps and other documents). The Forni Gl. registered the most vigorous frontal retreat (> 2050 m from 1898 to 2017).

Reconstructed time-distance curves underline a strong retreat of glacial bodies: since the end of Little Ice Age the Italian glaciers have experienced a generalized phase of retreat, interrupted by periods of stasis or by short re-advance phases, the most vigorous of which occurred during the late '70s and early '80s of the 20th century, as recorded by many alpine glaciers. Since the '90s, almost all the Italian glaciers resumed their retreat showing a progressive dramatic acceleration during the last 30 years.

Mass-balance surveys started in 1966/67 and 18 Italian glaciers are monitored at present: 4 in the Western Alps, 13 in the Eastern Alps (including the Lombardy Sector) and 1 in the Apennines. Most of the monitored glaciers furnish more than a decade of measurements. Careser Gl. (Ortles-Cevedale Group provides the largest and richest observation record among the Italian glaciers having lost 56 m w.e. on average from 1967 to 2017. The glacier is currently out of balance, being its ELA located above the maximum altitude of the glacier since many years. It will most probably disappear within few decades. Mass-balance surveys were conducted since 2003 on La Mare Glacier to replace the long-term monitored and rapidly vanishing Careser Glacier. Annual reports of Italian glaciers monitoring are transmitted to WGMS database (https://wgms.ch/data_databaseversions/).

A new database outlining the state of Italian glaciers during different hydrological periods (1957–1958, 1988–1989, 2006–2007, 2014–2015) was recently realized in the framework of the Nextdata Project. The aim was to improve the knowledge of the Italian glacial resource through the creation of a dynamic and updateable quantitative inventory. Glaciers outlines were detected by the interpretation of a new set of orthorectified aerial photos at high geometric resolution available through the Web Map Service (WMS) provided by national and local Geoportals. Glacial bodies outlines were manually digitized in GIS environment, for mapping glaciers as polygons in a vector domain. Alphanumeric attribute table associated with the glacier outline retains the main morphometric glaciological parameters (area, maximum length, width, slope, max and min elevation, aspect, latitude and longitude of the glacier centroid, etc.) according to the WGMS guidelines for the compilation of glacier inventory data from digital sources.

The construction of a new dynamic glaciers inventory and of an updatable dataset on the current state of Italian glaciers is essential to monitor and characterize the on-going unprecedented glacier decline. Furthermore, the new dynamic glaciers inventory and the related dataset will furnish a key tool for improving our understanding of observed variability, timescale of responses, trends, and climate feedbacks. In fact, the data derived from the multitemporal analysis allow quantification of the progressive and dramatic mass loss experienced by Italian glaciers since the last three decades. The glaciers decline is underlined by diffused extinction of smaller bodies, by the fragmentation of wider glaciers and by remarkable reduction of their thickness also in the accumulation area. As a consequence of the on-going rising temperature, almost 100% of the Italian glaciers are retreating; numerous alpine glaciers have repeatedly found entirely below the snowline, experienced relevant frontal retreat, contraction of the accumulation basins, thinning of glacial bodies and tongues. The strong imbalance that characterizes alpine glaciers, compared to current climatic conditions, underlines that if this situation will endure, further dramatic areal and volume reductions must be expected.

Acknowledgements

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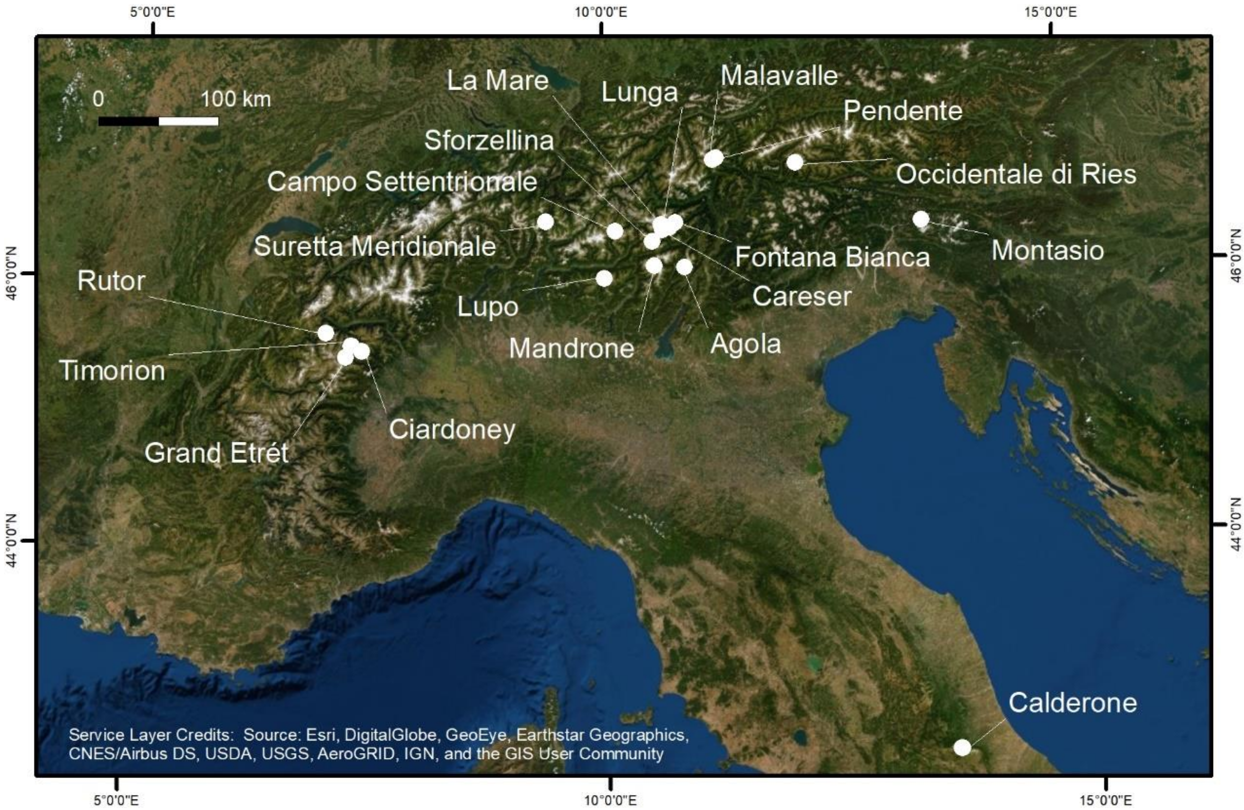

Fig. 3: Geographic location of the Italian glaciers monitored for mass-balance measurements.

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State of glacier monitoring and recent developments in East Africa

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The recession of tropical glaciers is stronger than the global mean (Zemp et al. 2019). This result is especially true for East Africa where, e.g. Lewis Glacier, the largest ice body on Mount Kenya, lost 85% of its area and 95% of its volume since the early 20th century (Fig. 4). Consequently, and if the current climate conditions prevail, Mount Kenya is endangered to be deglaciated in the early 2030s, and could be the first mountain range losing its glaciers because of anthropogenic climate change.

Currently, there is no continuous *in situ* monitoring of the glaciers in East Africa. This is partly because glacier monitoring experiences low political and institutional priority in this part of the world and because of an imbalance of high effort and low funding opportunities. Therefore, and due to the strong glacier disintegration (Fig. 4), the longest time series of mass-balance observations in Africa, Lewis Glacier on Mount Kenya, was halted in 2014.

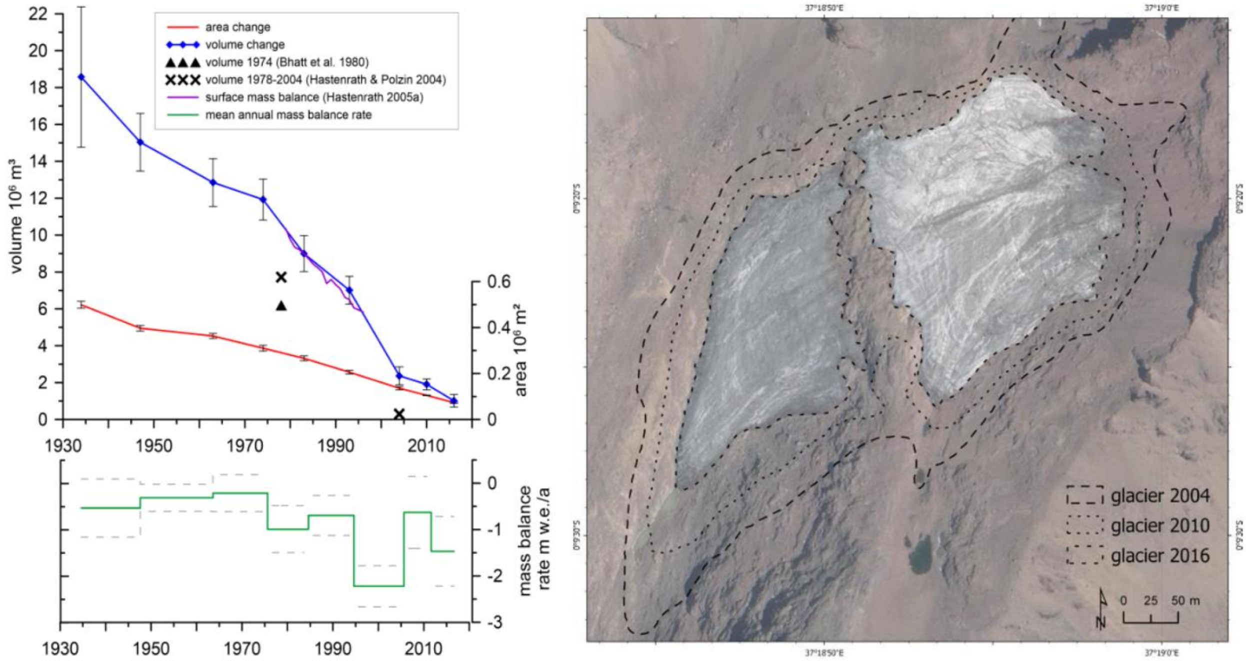

Fig. 4: Recession of Lewis Glacier, Mount Kenya. Left: The time series of area (red) and volume (blue) changes on Lewis Glacier and the derived mass-balance rates (green). Right: Disintegration of Lewis Glacier between 2004 and 2016 (Prinz et al. 2018).

However, at all three glacierized mountains in East Africa (Mount Kenya, Kilimanjaro, Rwenzori) scientists try to keep glacier monitoring ongoing by progressively using remotely sensed data. As the small glaciers in East Africa are difficult to identify in Landsat or Sentinel scenes, the Pléideas Glacier Observatory is a highly appreciated initiative for updating glacier inventories requiring very high spatial resolution (Prinz et al. 2018). The glacier inventory of Mount Kenya was refreshed in 2016 and a new inventory for Rwenzori, backed up with *in* *situ* data, is expected to be published soon. On Kilimanjaro data acquisition is scheduled within the next months. Pléiades images and even sparse field information offer an estimate of the geodetic mass balances, which serve as a basis for extended research interests e.g. on glacial biology (Rwenzori) and on climate change (Mount Kenya, Kilimanjaro). Additionally, automated weather stations operate at all three mountains at elevations above 4500 m a.s.l. providing a unique data set understanding local environmental changes (glaciers, permafrost, ecology, …) in a climatological context. Kilimanjaro was listed as a CryoNet Station within the World Meteorological Organization's Global Cryosphere Watch. Yet, expected synergies and local capacity building for glacier monitoring are pending.

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Glacier monitoring in Norway

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Norway has a long history of glacier monitoring, both in mainland Norway and in Svalbard. In mainland Norway the Norwegian Water Resources and Energy directorate (NVE) takes well care of the monitoring programme. Data is available and reported regularly, see: https://www.nve.no/hydrology/glaciers/.

In mainland Norway the total glacier area is about 2,700 km^2. The glacier length change information back to the century of 1600 is related to the advance of glaciers during the little ice age that in general culminated around 1750. From that time some historical observations of length changes, advance and retreat, is documented. This is mainly because glaciers advanced and destroyed farmland. Systematic annual front position measurements started around 1900, and about 70 glaciers have been measured since then. However, there are several glaciers with only a few years of observations. Many glaciers retreated from the 1930s to the 1980s. Several, but not all glaciers then advanced from the end of the 1980s to about 2000. All glaciers have retreated since 2000. Front position measurements in 2018 showed that 29 of 32 measured glaciers had retreated, many retreated several tens of metres. The largest annual retreat in 2018 were measured at Engabreen inn northern Norway with 140 m.

Mass-balance measurements have been carried out at 45 Norwegian glaciers during the period 1949–2018, but some for only a few years. Systematic measurements started at Storbreen in Jotunheimen in 1949. This is still running and among the longest continuous series in the world. In early 1960s several other series were started, mainly related to the need from the hydropower companies. The development of the mass balance in southern Norway is well illustrated in Fig. 5 below. This shows a clear difference between the western, maritime glaciers with less negative mass balance than the easterly, high elevation glaciers. From 1989 to 1995 mass balance was positive at most of the measured glaciers in Norway, caused by high winter precipitation, but has generally been negative since 1995. Geodetic mass-balance data are available from the 1940s on and cover several glaciers. The last full coverage glacier inventory was published in 2012.

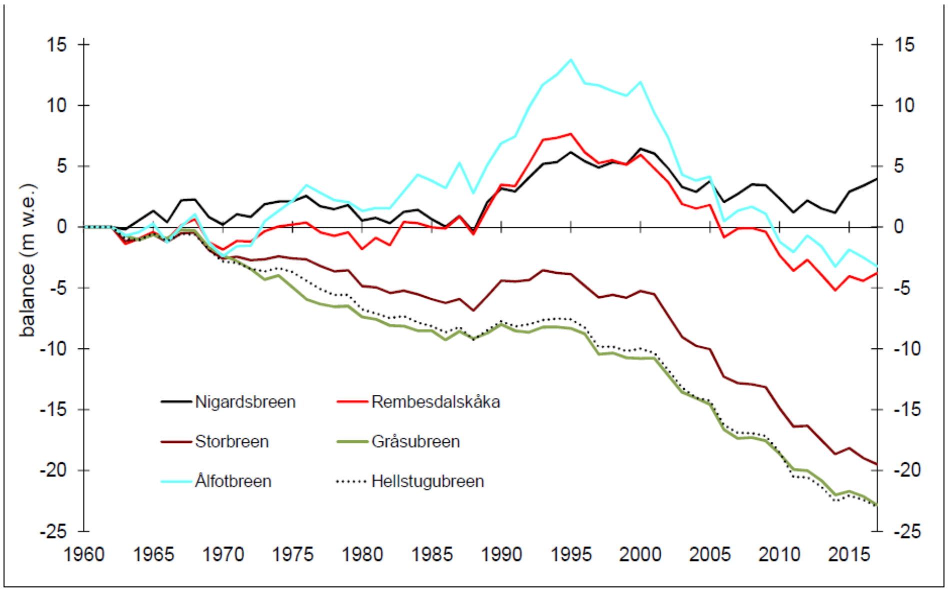

Fig. 5: Cumulative mass balance for reference glaciers in southern Norway 1963–2017.

In Svalbard the total glacier area is about 34,000 km^2. The history of direct mass-balance measurements in Svalbard was started on Finsterwalderbreen (11 km^2) in 1950. Every second year between 1950 and 1966 the glacier and the net mass balance was calculated for biannual intervals. Only two of the periods show positive mass balance and the mean for the period 1950–1968 was –0.25 m w.e. During the summer 1966 the measurements were started on Austre Brøggerbreen in Kongsfjorden in north-west Spitsbergen. The year after, in 1967, the measurements were started also on Midre Lovénbreen. Since then annual measurements of winter and summer balance have been done as part of the Norwegian Polar Institute monitoring programme and is thus one of the longest continuous time series of mass balance in the Arctic. To obtain data covering a more representative hypsometry series were started on Kongsvegen in 1987. Kongsvegen has an area of ca. 102 km^2 and covers an altitude range from sea-level to 800 m a.s.l. The two small glaciers, both with size of ca. 5 km^2 cover an altitude range of 50 to 600 m a.s.l. and show a strong negative mass balance of –0.49 and –0.39 m w.e., respectively, over the last 50 years while Kongsvegen over the last 30 years shows much fewer negative values with a mean of –0.08 m w.e. Since 2004 mass balance has been measured also on Etonbreen (883 km^2), and outlet glacier of the Austfonna Ice Cap (7800 km^2) in eastern Svalbard.

In addition to the Norwegian series Polish researchers have carried out annual mass-balance measurements on Hansbreen (57 km^2) in south-Spitsbergen since 1988. Russian scientists have studied five glaciers in west and central Spitsbergen over periods from 5 to 14 years in the 1970ies and 1980ies. The results show significant variability but correlates well with the long time-series in Kongsfjorden.

Glacier front changes are not measured regularly in Svalbard. A recent and digital glacier inventory of Svalbard glaciers is available with a complete coverage available for the 2001–2010. Geodetic mass balance has been calculate based on satellite data and old maps.

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Sweden

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The systematic survey of Swedish glaciers was initiated in 1895 as a direct consequence on the formation of the International Glacier Commission in Zürich the previous year. The Swedish delegate Fredrik Svenonius encouraged and supported young researchers and students to perform glacier investigations. In 1908 the programme involved 18 glaciers. In 1910 an inventory of the status of Swedish glaciers and ongoing glaciological research was compiled in an atlas published by the Swedish Geological Survey (SGU). The volume came timely for the 11th International Geological Congress (the present IUGS) in Stockholm 1910.

The next major research advancement was the launch of the Tarfala research activities in 1945/46 with the mass-balance series of Storglaciären and observations of glacier length changes. When Permanent Service of Fluctuations of Glaciers was formed in the 1960s, the Swedish monitoring programme was reorganized concentrating on the northern mountain areas and with an increase of the number of glaciers observed.

Between 1980 and 2000 the *mass-balance programme* was extended and covered at most 8 glaciers, a number which in 2019 is reduced to four. In addition to these four glaciers, where glaciological field work is performed, six glaciers are analyzed with geodetic methods a number which is planned to increase within coming years.

Inventories of Swedish glaciers, besides the 1910 description exists from 1959–62, 1973 and the GLIMS inventory in 2000. In addition to this an inventory was also published in 2012, but the data on size is unfortunately not fixed in date in this compilation.

In Sweden we experienced a mass surplus on glaciers between 1987 and 1995 mainly due to increased winter precipitation. However, during the last two decades a dramatic loss in mass and glacier length have been observed. The thinning of Storglaciären since then is of the same order magnitude as the rate of change prior to 1945 when the field mass-balance programme was initiated.

In 2013 the Swedish Infrastructure for Ecosystem Science (SITES) was established including monitoring at 8 Swedish field research stations, among them Tarfala. The monitoring at Tarfala overlap to some extent the data sent to the WGMS. Thus, the mass balance of Storglaciären, weather data from the station and hydrology data have now a financially long-term solution. Other mass-balance series and front monitoring is financed by support from Stockholm University and on soft money.

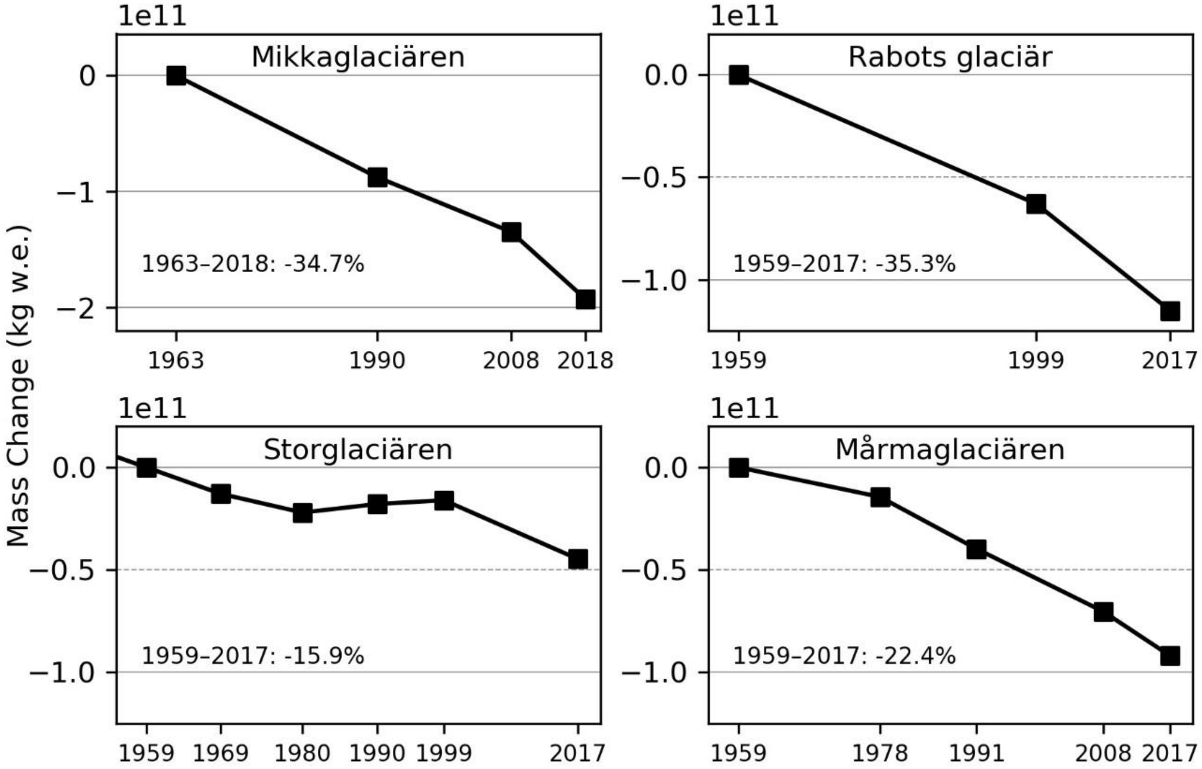

Fig. 6: Geodetic mass-balance surveys of four different Swedish glaciers in an ongoing project on the thermal influence on glacier responses to climate change.

United Kingdom, British Antarctic Territory (BAT) and South Georgia and the South Sandwich Islands (SGSSI) – Current state, progress and challenges

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Although no glaciers currently exist in the British Isles, there is a long history of UK based researchers investigating and monitoring glaciers across the globe. Alongside other researchers internationally, part of this work has involved monitoring efforts on the South Georgia and South Sandwich Islands Group (SGSSI) and within British Antarctic Territory (BAT; Fig. 7). These regions possess a wide range of glaciated environments, including significant numbers of land and marine terminating glaciers, discharging from valley glaciers, the Antarctic Peninsula and West Antarctic Ice Sheet. These are entirely situated well away from major population centres and travel routes, meaning that their remote and inaccessible nature pose significant logistical challenges for regular *in situ* measurements and monitoring. However, remote sensing systems do offer significant opportunities for glacier monitoring in these regions. The sheer number of glaciers in these regions means that consistent and complete updates of glacier frontal variation and mass balance are often impossible, frequently relying on individual studies that may have varying spatial and temporal scales. Below provides a *brief* update on monitoring related activities undertaken by UK and non-UK based glaciologists since 2015 in these regions.

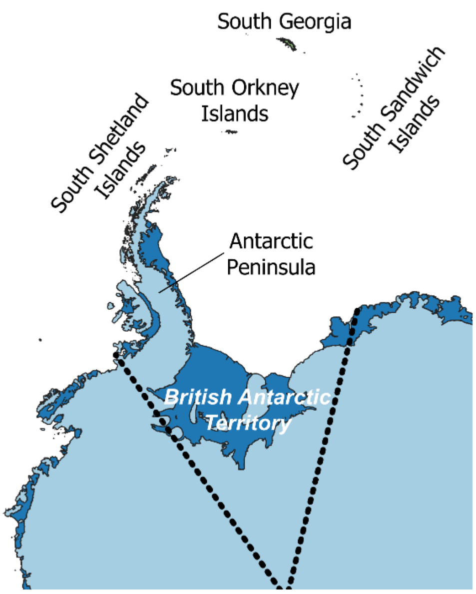

Fig. 7: Map showing locations of British Antarctic Territory and South Georgia and South Sandwich Islands Group.

Current state and progress

Antarctic Peninsula and South Shetland Islands

The WGMS *Fluctuations of Glaciers* (FoG) database currently contains front variation observations for 278 marine terminating glaciers located on the Antarctic Peninsula and its immediate surrounding islands. These are almost entirely collated from the work of Cook et al. (2005), showing glacier change between the mid-20th century and early 21st though this is due to be supplemented by a complete glacier inventory collated for the region by Huber et al. (2017). Subsequent work to this has focussed primarily on seeking to explain the drivers of these changes through a combination of altimetry, stereophotogrammetry, velocity, gravity and oceanographic observations (e.g. Wouters et al. 2015; Cook et al. 2016; Fieber et al. 2018; Seehaus et al. 2018), finding that glacier dynamics have been driven primarily by a combination of oceanographic forcing and (where retreat has occurred) dynamic thinning causing further retreat. Progress has also been made on modelling both ice thickness and volume of the glaciers in this region, notably through an intercomparison of different thickness reconstruction approaches as part of a global study by Farinotti et al. (2019), and a perfect plasticity modelling approach applied specifically to the Antarctic Peninsula region by Carrivick et al. (2019). The latter study notes excellent agreement between their modelled thicknesses and available radar flightline observations. However, as with many reduced physics approaches to ice thickness reconstruction, mismatches to observations are frequently greatest in areas of fast flowing ice close to the grounding lines of marine terminating margins.

South Georgia

Ice front and mass-balance data for the extensively glaciated island of South Georgia within the FoG database are sparse, with observations for four glaciers (collated from Gordon et al. 2008), and two glaciers respectively. However, more extensive data do exist, with Cook et al. (2010) evaluating frontal change for 103 land terminating glaciers between the 1950s and early 21st century, subsequently been updated by the British Antarctic Survey to include annual positions up to 2017 (accessible via https://www.sggis.gov.gs/). Observations for the 39 marine terminating glaciers on the island will soon be supplemented by detailed observations of frontal change between 1999 and 2019 utilising every available Landsat and Sentinel 2 satellite image, comprising 2764 observations (White et al. in prep). Opportunities for evaluating glacier change within the context of daily weather observations have also been dramatically improved through the publication of data spanning the majority of the 20th century up to the present from the former whaling station of Grytviken on the north coast of the island (Thomas et al. 2018).

South Sandwich Islands and South Orkney Islands

Glaciers on these island groups are typically small compared to those of South Georgia, while the South Sandwich Islands are also notable for being volcanically active. Extensive cloud cover often makes observations using optical remote sensing satellites challenging, though increased availability of synthetic aperture radar (e.g. Sentinel 1) provides opportunities for more detailed study. No data currently exist within the FoG database for these island groups, and they remain largely unstudied beyond a single set of manually digitised outlines (Bliss et al. 2013).

Challenges and outlook

Mass balance

The aforementioned challenges of accessibility to the remote locations of BAT and SGSSI exert severe limitations on the ability of glaciologists to conduct *in situ* studies, such as evaluating mass balance. However, the launch of Icesat-2 provides excellent potential to monitor changes in elevation through satellite altimetry despite the along track posting of initial height retrieval data being 40 m. As more data are collected on the coming years this will potentially allow significantly improved monitoring of these regions.

Frontal variations
The time intensive nature of manual digitisation of glacier fronts/outlines and requirement to individually download and process imagery has placed substantial limitations on the analysis of ice front variations. However, the development of new, cloud computing based tools for the rapid visualisation and manual digitisation of ice fronts from satellite imagery (*Google Earth Engine Digitisation Tool*; Lea 2018) has allowed dramatic improvements in time efficiency. For example, within White et al. (*in prep.*) a single operator was able to digitise nearly 3000 ice fronts for South Georgia in <1 month. Coupled with rapid frontal change analysis tools (*Margin change Quantification Tool*; Lea 2018), these allow substantial improvements in the rapid evaluation of the magnitude and variability of glacier frontal change.

Extensive cloud cover over many regions of BAT and SGSSI also place limitations on our ability to monitor glacier front change and surface characteristics using optical satellite imagery. The increased availability of imagery from cloud-penetrating SAR systems offer significant potential in this regard, though the accuracy offered by existing digital elevation models for topographic correction means that the accuracy of these data should be treated with extreme caution.

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Programme GA Almaty

10.09.2019:	**Ice breaker @ Hotel Almaty**
18–20	Registration, ice breaker, informal gathering

11.09.2019:	**History & current status of glacier monitoring**
from 8.30	Registration *(bring your material and get your badge)*
9–9.15	Welcome messages by local organizers as well as by representatives from Switzerland and Kazakhstan
9.15–10	Glacier monitoring: historical background & international monitoring strategy (M. Zemp)
10–10.30	Coffee break
10.30–11	Country profiles (baseline 2015) & discussion (I. Gärtner)
11–12.30	I. Country reports & discussion (KZ, KG, UZ, TJ, AF)
12.30–13.30	Lunch
13.30–15	II. Country reports & discussion (RU, GE, IR, CN, NZ)
15–15.30	coffee break
15.30–17	III. Country reports & discussion (BT, IN, NP, MO, JP)
17–17.30	Discussion on achievements and challenges at national and regional levels (all)
17.30–18	Summary by UNESCO (K. Tovmasyan)
18	Group picture
19	Dinner

12.09.2019:	**Thematic workshops**
9–10	I. Reanalyzing glacier mass-balance series (input M. Zemp & discussion)
10–10.30	coffee break
10.30–12	II. National and global glacier inventories (input T. Bolch & discussion)
12–13	Lunch
13–14	III. Data submission to WGMS and GLIMS (input M. Zemp & T. Bolch & discussion)
14–15	IV. Glacier monitoring for water resource management and disaster risk reduction (input T. Saks & discussion)
15–15.30	Coffee break
15.30–16.30	V. Strengthening the regional monitoring network (input A. Wehrli & discussion)
16.30–17	Summary & outlook (M. Zemp)
18	Dinner

13.09.2019:	**Excursion to Big Almaty Lake Research Station**
7.30	Departure by off roader from Hotel Almaty
19	Return by off roader to Hotel Almaty

14.09.2019: **Individual departure**

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Impressions from the WGMS General Assembly in Almaty (Hotel Almaty) and Big Almaty Lake (photos: Isabelle Gärtner-Roer and Levan Tielidze).

Glacier mass-balance measurements in Afghanistan

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The sphere is even now suffering its impacts on biodiversity, freshwater resources and local livelihoods. By means of current climate change trends, by 2100, the average global temperature may rise by 1.4–5.8 °C according to the Third Assessment Report from the Intergovernmental Panel on Climate Change (IPCC 2001). This is certain disaster for fragile ecosystems like glaciers.

The Hindu Kush is one of the great watersheds of Central Asia, forming part of the vast Alpine zone that stretches across Eurasia from east to west. It runs northeast to southwest and divides the valley of the Amu Darya (the ancient Oxus River) to the north from the Indus River valley to the south. To the east the Hindu Kush buttresses the Pamir range near the point where the borders of China, Pakistani and Afghanistan meet, after which it runs southwest through Pakistan and into Afghanistan, finally merging into minor ranges in western Afghanistan. The highest peak is Mount Tirich Mir, which rises near the Pakistan-Afghanistan border to 7,690 metres.

Overall glaciers are receding across the globe the same condition is applicable to Afghanistan glacier which are located mostly in the high plateau of Pamir and Hindu Kush mountain in north-east part of Afghanistan the high plateau of the Hindu Kush plays the rule of mother of water in the country. Remote sensing studies in 2016 discovered more than 18% reduction in area of Afghanistan's glaciers (ICIMOD/WRD Glacier Mapping Team, Ministry of Water and Energy of Afghanistan) but there is no long term data of a practical work or mass-balance measurement available, in the last two years field observations data by Geoscience faculty of Kabul University confirms the scenario of the degradation , as for as the Afghanistan is in the arid category with most of rainfall in winter and early spring, the streams are fed by snow mostly glaciers in the rest seasons.

To understand the hydrological potentials of Afghanistan and its consequent associated advantage and disasters the regular and long-term glaciers monitoring and mass-balance measurements are required.

The Geoscience Faculty of Kabul university started observation of the upper Kabul river basin's glaciers to perform long term mass-balance measurement to provide accurate/reliable data to relevant authorities such Ministry of Water and Energy, Ministry of Agricultural and livestock, National Environmental Protection Agency and Afghanistan National Disaster Management Authority to make plan and Take appropriate mitigation and adaptation measures in future.

Sixty years of glacier monitoring in China

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Glaciers in China are concentrated in the western part of the country on the Tibetan Plateau and the surrounding mountain ranges including Altai, Tianshan, Karakorum, Kunlun, Qilian, Hengduan, and Himalaya Mountains. Glaciers are an important water source for both China and its neighbouring countries and thus have an influence on geopolitical stability. The monitoring of modern glaciers in China was initiated when Lanzhou Institute of Glaciology and Geocryology (LIGG), Chinese Academy of Sciences (CAS) was established in 1958, which now combined into Northwest Institute of Eco-Environment and Resources, CAS. Over the past 60 years, more than sixty glaciers have been investigated through field expeditions and *in situ* observation. About ten glaciers among them are monitored nowadays in a regular base (Fig. 8). Tianshan Glaciological Station, set up in 1959 for long-term monitoring of Urumqi Glacier No. 1, has been a focal point of Chinese glaciological research since its beginning. With continuous mass-balance record over six decades, research findings from Urumqi Glacier No. 1 and its environment have contributed in a sustained way to the fields of glacier physics, meteorology, hydrology and geomorphology, and to our knowledge of the ecosystems and glacial history of the Tianshan. Today, in addition to Tianshan Glaciological Station, glacier monitoring in China has also been carried out by the Institute of Tibetan Plateau Research, CAS and a few other research groups. A selection of the data including Urumqi Glacier No. 1 and of Parlung Glacier No. 94 series and glacier inventories are reported to WGMS and GLIMS. Most of data from other glaciers have not been reported in WGMS.

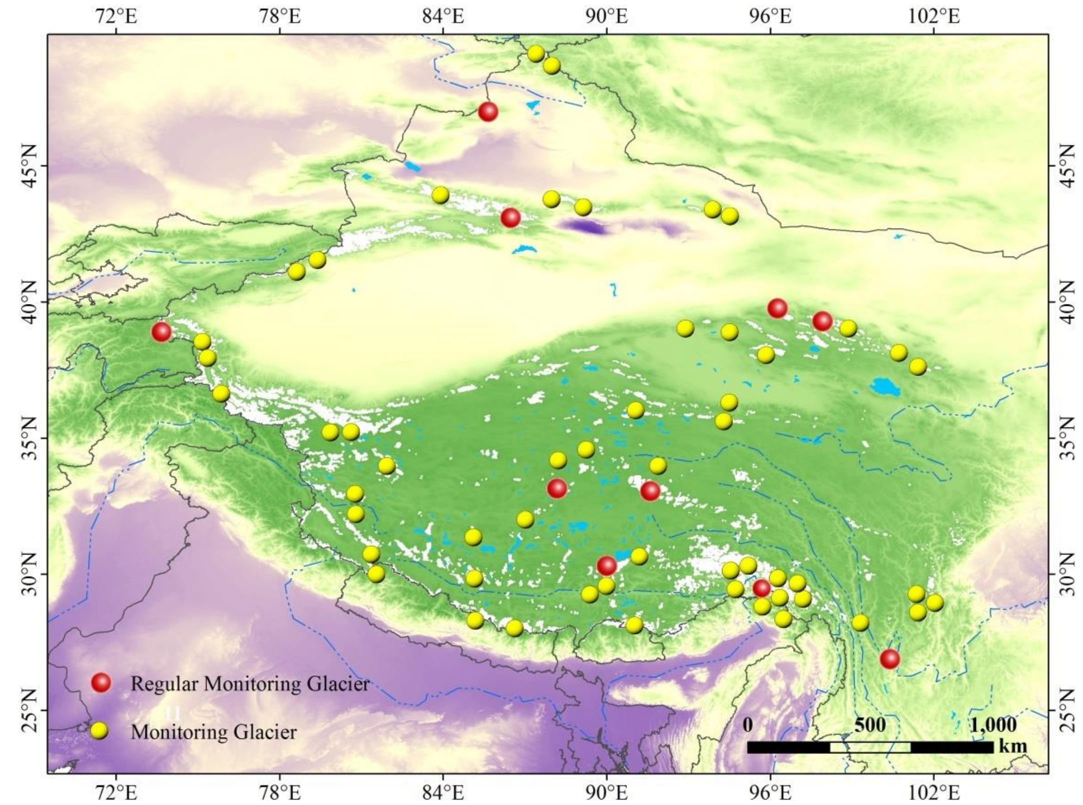

Fig. 8: Spatial distribution of monitored glaciers in China since 1958.

Glacier inventories

There are two national inventories available in GLIMS. The First Chinese Glacier Inventory (CGI) was carried out by Chinese glaciologists from 1978 to 2002. Each glacier was measured from aerial photographs and topographical maps made as early as in the mid-late 1950s. CGI showed that China has 46377 glaciers with 59,425.18 km^2 of area. The Second Chinese Glacier Inventory (SCGI) has been compiled based on multi-source remote sensing images. The SCGI shows that there are 48,571 glaciers with a total area of 5.18×10^4 km^2 during 2006~2009 in China. By comparing the digital results of two Chinese Glacier Inventories, it is found that glaciers in China have shrunk by about 18% in area since mid-late 1950s.

Length fluctuations

Front variation observation in China was started in 1900 and had its peak in the 1970s with about 30 series. Today about 15 glaciers are measured regularly or irregularly. Annual or sub-annual, on-the-ground, measurements are made at Urumqi Glacier No. 1 in Tianshan from 1959, at Muz Taw glacier in Altai Mountains from 2015, and a few other glaciers on Tibetan Plateau as well.

Mass balance

On approximate 10 glaciers in Tibetan Plateau and the surrounding mountain ranges mass balance is regularly measured by using glaciological method. There are few glaciers with mass-balance series made available. Only one long-term mass-balance programme at Urumqi Glacier No. 1 based on both glaciological and geodetic methods. Relevant research including energy balance, surface velocity, ice flow model, and glacier hydrology is carried out on the glacier. The establishment of Altai Cryospheric Sciences Research Station in Chinese Altai Mountain region in 2014 by CAS provides a unique opportunity to extent the long-term and detailed measurement programme at Muz Taw glacier as second bench mark glacier for process understanding and model calibration. Except for Urumqi Glacier No. 1, geodetic mass-balance measurement in China is almost inexistent.

Other observations

Over the past 60 years, the glacier thickness was measured by using Ground Penetrating Radar (GPR) on more than 20 glaciers distributed mostly in Tianshan and Qilian Mountains. Surface velocity measurement was made on around 15 glaciers basically by Total Station or GPS-RTK technique. Borehole temperature of a glacier is an important parameter for its classification in China because most of glaciers there are cold glaciers. Measurement of borehole temperature (>10 m) was made on about 20 glaciers in different climate zone so far.

Glacier monitoring activities in Georgia

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Glacier importance for Georgia

Glaciers are an important source of fresh water in Georgia, and runoff in large glacially-fed rivers supplies several hydroelectric power stations. Glacial meltwaters are one of the main factors in river runoff formation in the mountainous areas of Georgia.

Also, glacier outburst floods and related debris flows are a significant hazard in Georgia. Unfortunately, such hazards are relatively common in this region and have led to major loss of life. In May 17 of 2014, Devdoraki Glacier (Georgia) catastrophic rock-ice avalanche and glacial mudflow killed nine people. Future trends in glaciers variations are thus a topic of considerable interest to the region.

Background

The study of glaciers in the Caucasus began in the first quarter of the 18th century, in the works of Georgian scientist Vakhushti Bagrationi, followed by foreign scientists a century later.

First statistical data on the glaciers of Georgia are found in the catalog of the Caucasus glaciers compiled by Podozerskiy (1911). Subsequently, in the 1960s large-scale (1:50,000) topographic maps were published and compiled from aerial photographs taken 1955–1960. Based on these maps, Gobejishvili (1989) documented further statistical information about the glaciers of Georgia. The glacier inventory of the former USSR was published in 1975, where data on the glaciers of Georgia were obtained from (1955–1957) aerial images.

All these studies mainly focused on glacier mapping or reconstructing past glacier positions by geomorphological methods. A full programme of glaciological mass-balance monitoring was obtained during 1968-1980 when the climatic conditions of the glacial zone, accumulation and ablation of the glaciers, glacier runoff, glacier ice formation zones, and snow and firn stratigraphy were investigated.

Due to the Soviet Union collapse, the mass-balance monitoring was stopped in the 1990s.

Current status

Nowadays study of glaciers in Georgia progress both *in situ* and remote sensing techniques. According to recent inventory, there are 725 glaciers with a total area of about 370 km^2. Glaciers of Georgia decreased by about 35% over the last half-century.

Inventory

1. The percentage and quantitative changes in the number and area of glaciers for all Georgian Caucasus in the years 1911–1960–2014, by individual river basins have been created: https://www.the-cryosphere.net/10/713/2016/

2. An updated and expanded glacier inventory at three time periods (1960, 1986, 2014) covering the entire Greater Caucasus have been created: https://www.the-cryosphere.net/12/81/2018/

Observation network

The observation data (front variation, area, elevation etc.) for the 43 glaciers from Georgian Caucasus have been added in WGMS database: https://wgms.ch/fogbrowser/

Projects

1. 2014–2016 – Glaciological Catalog of Georgia (Funding – Shota Rustaveli National Science Foundation of Georgia).
2. 2016–2017 – The Greater Caucasus Glacier Inventory (Funding – Shota Rustaveli National Science Foundation of Georgia).
3. 2017–2019 – Caucasus Glacier Monitoring Network (Funding – Shota Rustaveli National Science Foundation of Georgia).

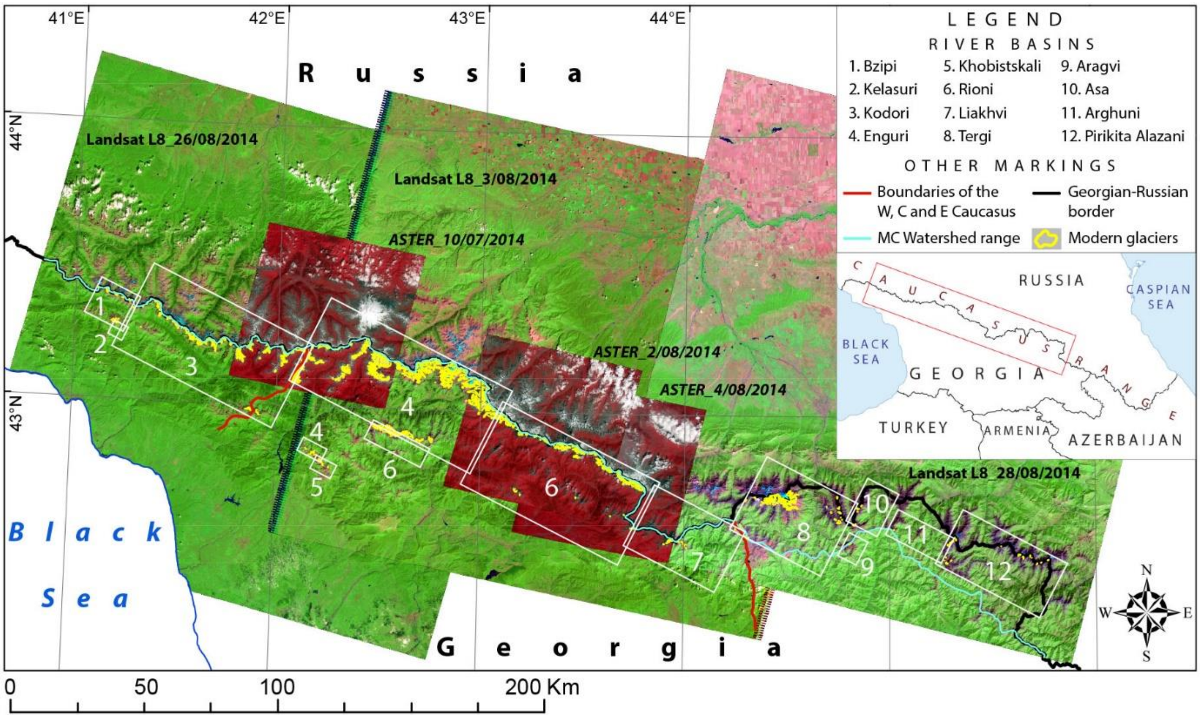

Fig. 9: Georgian Caucasus glacier inventory/outlines (in yellow) derived from Landsat and ASTER imagery according to the different river basins (Tielidze 2016).

Other activities

1. Digitized glacier outlines (1960, 1986, 2914) for the entire Greater Caucasus mountains, have been submitted in the GLIMS database: https://www.glims.org/maps/glims
2. Large glacier photographs have been added in a world glacier photograph collection database: http://nsidc.org/data/glacier_photo/search/?collection=repeat

Future challenges

Renewing the mass-balance monitoring programme remaining one of the scientific challenges in Georgia today. We hope to restore this programme with support of international organizations and foreign colleagues.

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Observation on glaciers mass-balance trends in Indian Himalayan Region (IHR)

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Glaciers are dynamic, self-regulating and highly sensitive to the climate. Changes in glacier mass is a key parameter for assessing the glacier's health, water resources, climate change, sea-level rise and environmental appraisal. With around 9,575 glaciers, within the jurisdiction of the Indian Himalayan Region (IHR), an estimated ice cover area about 36,000 km^2 and an overall ice volume ~2,000 km^3 is significant (Rain and Srivastava 2008). The area is characterised by its huge areal extent with varied climatic conditions that make inconsistency in mass changes process and comparatively differ all over the Himalayan regions. These glaciers are perennial source of water that feed three major rivers system, supporting livelihood for about millions of people in the area and downvalleys, but unfortunately, data on glacier mass changes are sparse and poorly observed, thus, the rate at which these glaciers are changing remains constrained. The mass-balance measurement of Indian Himalayan Region started in seventies by Geological Survey of India. The first series of measurements was on the Gar glacier (1974–1982), north-west Himalaya. Similarly, during the period 1975 to 1990, six glaciers located in different glacierized basins were taken up for mass-balance measurements, however these measurements were restricted for short periods. A good set of mass-balance data has been collected and interpreted. After nineties, more glaciers for mass-balance measurement were conducted across the Himalayan ranges. The studies reveal that most of the studied glaciers have negative mass balance. The present studies mainly emphasise on annual mass balance of studied glaciers in the IHR.

Mass-balance trends

The field base mass change measurements of the Indian Himalayan glaciers are available for 17 glaciers in the western Himalaya, 5 glaciers in the central Himalaya and one in the eastern Himalaya. The studies reveal that most of the studied glaciers are continuously losing mass with variable rate. It is observed that during 1975 to 1980, these glaciers show mean annual specific mass balance of –0.31 m w.e. a^{-1} (5 glaciers average), similarly –0.41 m w.e. a^{-1} (11 glaciers average) during 1981–90 and –0.906 m w.e. a^{-1} (4 glaciers average) during 2001–2010. However, during 1993–2000 (one glacier with gap years 1996 and 1997) shows average net loss of –0.39 m w.e. a^{-1}. The decadal analysis indicates that the first decade of the 21st century (2001–2012) has enhanced the rate of mass loss compared to second half of the last century. Cumulative mass loss observed over different regions of the Indian Himalayan glaciers shows negative mass-balance trend since the first in-suit measurement conducted in 1974. Mass balance of six glaciers in the Chandra basin (Indus) north-west Himalaya was estimated during the years 2013 to 2018 (NCPOR, personal communication). The result shows that all the glaciers have negative balance ranging between –0.28 ± 0.04 and –1.56 ± 0.30 m w.e. a^{-1}. Overall mean mass balance for all the 23 observed glaciers is –0.59 m w.e. a^{-1} between 1975 and 2018.

In addition, on a regional level, the geodetic studies suggest that on the whole western, the central and the eastern Himalaya experienced vast thinning during the last decade (2000s). Recent geodetic mass-balance study of 23 glaciers of different size (0.47 to 75.47 km^2) from Sikkim, eastern Himalaya has been carried out for the period between 2000 and 2017. Results reveal a region-wide average mass budget of −0.65 ± 0.07 m w.e. a^{-1} during the study period. At the same time, total area of glaciers significantly reduced from 227.91 km^2 in 2000 to 219.05 km^2 in 2017 (Garg et al. 2019). In general, Himalayan glaciers are under thinning (mass loss) and reduction of length and area in the present climate conditions. However, the recession rate and the amount of mass loss of Himalayan glaciers vary with one to other. Average altitude of snowline at the end of ablation season is 5400 m a.s.l. for southern and 5297 m a.s.l. for northern facing glaciers.

Recently, the monitoring coverage of Himalayan glaciers is improving, but there are still constraints, such as variable retreat rates, less glacier mass-balance data and a lack of long-term *in situ* measurement. Therefore, there is a need to understand the widespread distribution of glaciers in different climate regime.

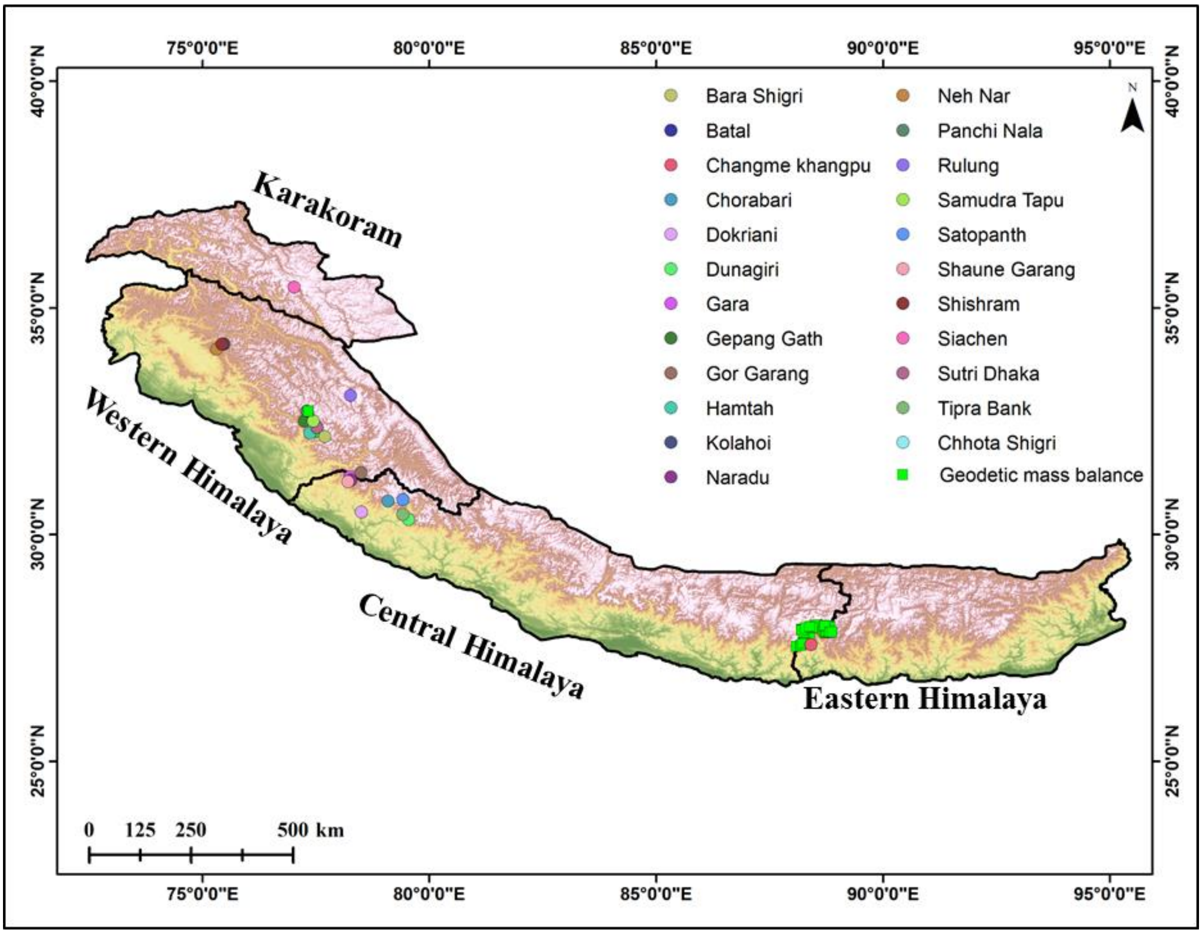

Fig. 10: Location map of glaciers studied for mass-balance estimation in Indian Himalaya.

Kyrgyzstan

Ryskul Usubaliev
Central Asian Institute of Applied Geosciences, Bishkek

Currently, there are 9,959 glaciers in the Kyrgyz Republic with a total area of 6,683.9 km^2, including: 6,227 glaciers with size of more than 0.1 km^2, with a total area of 6,494.0 km^2 and 3,732 glaciers with size of less than 0.1 km^2, with a total area of 189.9 km^2 according to the updated Catalog of Kyrgyzstan's glaciers, made from Landsat-8 satellite images of 2013-2016. The area of glaciation in Kyrgyzstan, compared with the catalog of glaciers of the USSR (40–70s of the twentieth century) reduced by 16%. The total number of glaciers increased by 22%. This is due to the general degradation of glaciation and an increase in the number of small glaciers (with sizes less than 0.1 km^2).

So far, the regime of Kyrgyzstan's glaciers has been studied quite well, quantitative dependence of the glaciers melting, their movement from the main climatic elements have been revealed, but due to changes in the volume and size of glaciers, the patterns revealed do not always correspond to the ongoing glacio-hydrological processes.

Therefore, the most objective indicator of the state of glaciers and their evolution is, of course, long-term data on the mass balance of glaciers. In the Soviet and early post-Soviet times, continuous annual measurements of the mass balance of glaciers were carried out on 3 glaciers of Kyrgyzstan. They are Kara-Batkak glacier (the northern slope of the Teskey Ala-Too Ridge) characterizes the mass balance of the glaciers in the inner parts of the Tien Shan, in particular the Issyk-Kul Basin. The Golubina Glacier (northern slope of the Kyrgyz Ala-Too Ridge) characterizes the mass balance of the glaciers of the Northern Tien Shan. The Abramov Glacier characterizes the mass balance of the Gissaro-Alai glaciers. Observation materials on the mass balance of the Golubina, Kara-Batkak and Abramov glaciers were regularly presented in the publication "Glacier Mass Balance Bulletin", published by UNESCO.

Funding, especially of expeditionary work, drastically decreased, and stationary observations have almost stopped when Kyrgyzstan gained its independence. The newest phase in the revitalization of the researches on the glacial systems of Kyrgyzstan started in the late 20th and early 21st centuries. They are associated with international and foreign financial support. International projects such as: "Central Asian Water" (CAWa), "Capacity Building and Climate Observing Service" (CATCOS), "Cryospheric climate services for improved adaptation" (CICADA) aimed at long-term monitoring of the mass balance of glaciers are being implemented by research teams from Kyrgyzstan, Germany, Switzerland and Russia. Since 2015, according to the research programme of the Central Asian Institute of Applied Geosciences (CAIAG) on a budgetary basis, and also since 2017, with the financial and technical assistance of the Republic of Finland, similar observations are being carried out together with Kyrgyz Hydromet. And from then on, glaciological measurements have been carried out continuously. Thus, mass-balance glaciological observations and studies were restored on previously monitored glaciers, and on some glaciers were newly organized.

Currently, the glacial systems of the Northern, Inner Tien Shan and the Issyk-Kul basin, as well as the glacial systems of the Gissar-Alai are being monitored. Several glaciers in different regions of Kyrgyzstan were selected as objects of research. These glaciers are: No. 354, Sary-Tor and Bordu, they are located in the northwestern slope of the Ak-Shyyrak mountain massif; Western Suek, located on the northern slope of the Jetim-Bel ridge (Inner Tien Shan); Golubina (basin of the Ala-Archa River, the northern slope of the Kyrgyz Ala-Too Ridge); Abramov, located on the southern slope of the Alai Ridge; No. 599, Kara-Batkak and Turgen-Aku-Suu, respectively, are located, the first on the southern slope of the Küngei Ala-Too ridge, and the second and third on the northern slope of the Terskey Ala-Too ridge of the Issyk-Kul basin. Certain types of glaciological works are also carried out on stationary glaciers South Enilchek (Central Tyan-Shan) and Adygene (basin of the Ala-Archa river, northern slope of the Kyrgyz Ala-Too ridge) and glacier No. 182 (northern slope of the At-Bashy ridge) (Fig. 11).

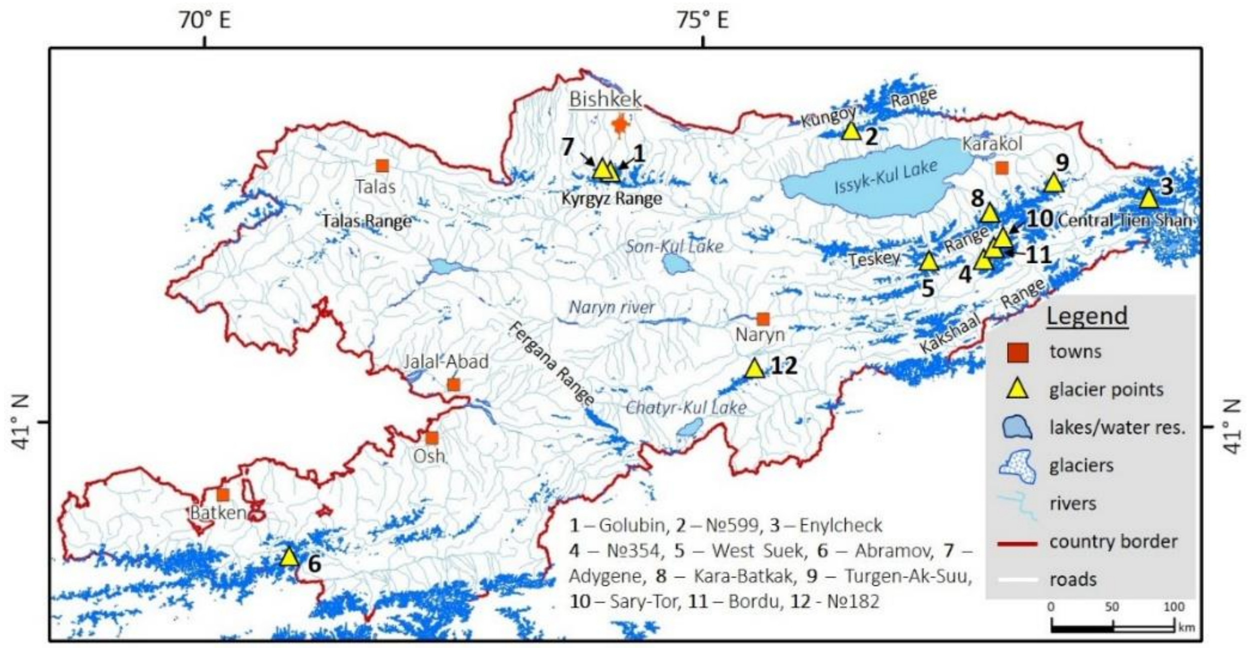

Fig. 11: Location scheme of representative glaciers of Kyrgyzstan.

The mass balance of glaciers is constantly negative, with the exception of some years, due to increased moisture in these years. Thus, due to the frequent excess of the output balance than the input, processes both of thinning of the surface and retreat of the glacier front have been observed - they are actively degrading.

In Kyrgyzstan, the World Glacier Monitoring Service (WGMS) under the projects “Capacity Building and Definitions for a Climate Observing System” (CATCOS) and “Cryosphere Climate Data for Improving Adaptation” (CICADA) with the support of the Swiss Agency for Development and Cooperation (SDC) and MeteoSwiss together with the UNESCO Cluster Office (Almaty) twice organized a summer school on measuring the mass balance of glaciers and their analysis for Central Asian countries.

Glacier monitoring in the Nepalese Himalaya

Sharad P. Joshi
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Glaciers are an essential climate variable (ECV), and mass-balance monitoring is a key method to improve our understanding of climate-glacier interactions. The ice repository in the Hindu Kush Himalaya is the largest outside the polar region, and contributes to 10 major rivers of Asia. The Himalaya acts as barrier for the monsoon, and Nepal lies in the centre of the Himalayan range. The climate is dominated by the Indian summer monsoon, which is followed by a dry autumn and winter, and a slightly wetter pre-monsoon season.

There are more than 3800 glaciers in Nepal with an area of about 3900 km^2 (Bajracharya et al. 2014). From 1980 to 2010, the glacier area decreased by 24%, and the number of glaciers increased by 11%. The glaciers of Nepal range from an altitude of 3880 m to 7880 m a.s.l.

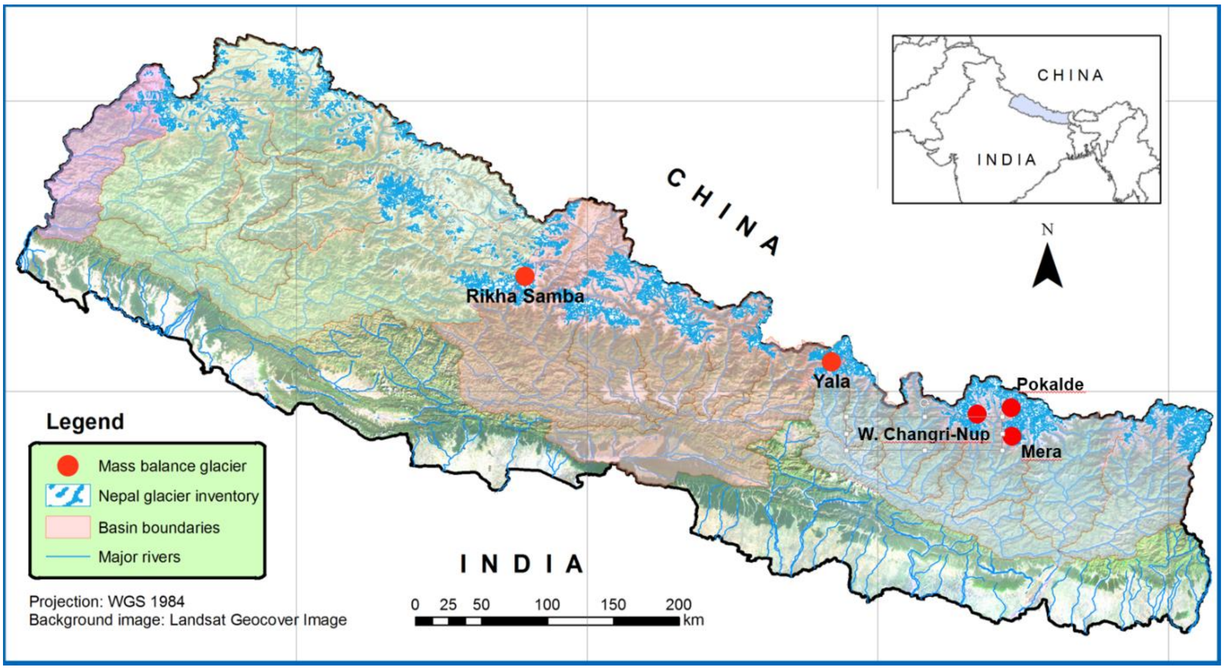

Fig. 12: Glaciers with mass-balance monitoring programmes shown as red dots.

In Nepal, glacier monitoring is carried out by various actors, including national and international research institutes, ICIMOD and the government. The benchmark glaciers with ongoing mass-balance measurements are Mera, Pokalde, West Changri-Nup, Rikha Samba and Yala glacier (Fig. 12, which started continuous monitoring between 2007 and 2011. The programmes on Mera and Yala glacier have detailed measurements with good coverage of measurement sites including hydro-meteorological monitoring, and the other programmes cover additional regions or type of glaciers. However, the far western and eastern parts of Nepal are not yet covered by any kind of mass-balance monitoring.

The glacier frontal variation measurements are limited to a couple of mass-balance benchmark glaciers, with mainly *in situ* and remote sensing analysis. For the future, it would be good to have a systematic monitoring of glacier frontal variations with remote sensing along designated transects in Nepal. There are several records of geodetic mass balances covering larger regions, which were mainly analysed by foreign researchers. ICIMOD published a glacier inventory in 2014 with data from 2010, which has been injected in GLIMS.

Challenges of glacier monitoring in Nepal are manifold, including the field measurements, limited financial and human resources. Nepal's glaciers have their main accumulation season during pre-monsoon and monsoon, and the main ablation season overlapping during monsoon. This makes *in situ* measurements harder in particular to measure accumulation because the last year's measurement surface is difficult to mark. Also, the glacier snowline is an unreliable proxy for the ELA because of the obscuring monsoon snow. Nepal is characterised by an extreme topography with high elevations, which causes several challenges. The access is challenging because the glaciers are at remote high locations, which usually require a couple of days on mountain roads and several days of hike. The steep and high topography can be challenging not only to acclimatise, or evacuate in case of emergency, but also for remote sensing measurements because it casts shadows on the images. Additionally, snow and cloud coverage during monsoon can obscure images. The human resources to take mass-balance measurements and analyse the data is concentrated on few people, which makes it necessary to continuously train new people. However, often trained young people leave for further education, and governmental professionals rotate within the governmental system. The funding of glacier monitoring programmes is not yet sustainable, also because of the resource intensive fieldwork (time, human resource, and logistics). However, glacier monitoring is a priority for the glacier monitoring executing organisations.

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Current state of glacier monitoring in Russia 2019

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Moscow State University, Geographical Faculty

I remember that nine years ago, at our previous meeting of National Correspondents held in Zermatt, the tonality of my speech on glacier monitoring in Russia has been rather pessimistic. And today my sincere hopes for the improvement of the situation still cannot change this tonality, unfortunately. No progress…

On one hand, we do have a long and glorious history of tracing glacier fluctuations since the Soviet times, and the present state of glacier monitoring in Russia mainly inherits glaciological backgrounds created by Soviet glaciologists. All glaciers of the USSR were thoroughly catalogued, and a vast set of key objects for a detailed glacier monitoring has been established all over this huge territory. I would say that a quite harmonic unity of terrestrial exploration, remote sensing and periodical remapping has constructed the ideal model of glacier monitoring for those times – one of the best on a world scale.

But on the other hand, successes of Russian glaciology should be recognized as much more modest. It can be partly explained that after the decay of the Soviet Union most of the formerly observed alpine glaciers found themselves outside Russia – in new independent states. Of course, the glaciated area of Russia is still large enough. However, it is mostly represented either by ice sheets of the Arctic islands (where monitoring principles are not completely devised yet), or by numerous mountain ridges with sporadic glaciations in Siberia (which are almost non-explored due to severe accessibility problems). Only three mountain systems with the developed alpine glaciations exist over the vast territory of Russia: namely, Caucasus, Altai and Kamchatka. Only three… This circumstance, alas, vigorously influenced actions and decisions of policy-making governmental institutions, which do not definitely promote glacier monitoring in Russia today. Observation series on a number of Russian glaciers in the Arctic, Urals and Kamchatka have been irretrievably broken off. Therefore, after the pleasant picture in the USSR, our observation network of the last decade looks much more miserable.

This so-called network is represented by three glaciers: Djankuat and Garabashi in the Caucasus and Aktru in the Altai. Each one has its one peculiarity concerning the research history and methods, but all of them have rather long mass-balance time series and a long-term sequence of geometric values. One can notice a general evolutionary tendency for all 3 investigated objects on this diagram: a strong negative trend after the end of the 20th century or, to be strict, over the last 15 years.

Let me start with the Djankuat Glacier – not because I am personally responsible for its research, but due to the fact that nowadays it is the most extensively studied glacier in Russia. It has the longest uninterrupted mass-balance series in our country – since 1967, so that the current year is the 52nd in the sequence. Besides standard glaciological procedures, a set of automatic weather stations, water level recorders, sonic rangers and different data loggers is a major requisite for reconstructions and forecasts. Accuracy and combination of independent approaches, applied there in the course of direct 4-month-long fieldwork annually, held by Moscow University, are unprecedented not only over Russia but even in wider scope. Abundance of data allowed us to improve mass-balance calculation scheme by introducing some methodic innovations. They made it possible to solve a number of important tasks such as estimation of snow avalanche nourishment, melting rate in crevasses, runoff from under the debris cover, tracing continuous migration of implicit ice divide between Djankuat and Lexyr Glacier in Georgia on the divergent crestal firn plateau. You can see this plateau on the satellite image. Our monitoring reveals the gradual shift of ice divide towards Georgia during last decades, meaning that Djankuat catchment area increases in time and that Russian glacier Djankuat continuously steals more and more ice from Georgia (Levan, I am sorry for that). Recently we introduced several modern technical devices in order to simplify laborious mass-balance fieldwork. Since Djankuat lies in a maritime climate, snow accumulation here sometimes exceeds 10–12 m in the firn area and we must dig impressive snow pits, so now we started to apply snow depth profiling by means of ground penetrating radars. Nevertheless, even such amount of snow melts in summer, so that ablation stakes that we install in springtime using ski-tour equipment, turn out to be absolutely inaccessible by the end of ablation season, being separated by huge crevasses which are numerous in some parts of the glacier. In order not to lose valuable information, last years we launch drones towards inaccessible stakes for committing remote readings.

All this permits us to insert many special amendments for obtaining very precise mass-balance estimates, and creation of the local GIS made it possible to draw very detailed spatial fields of mass balance and morphometrical parameters. However, this sophisticated algorithm has a very serious shortcoming that upsets me greatly, because this is my responsibility. Satisfying all the methodical requests for the sake of super preciseness and super detailness requires a lot of time for processing raw data, and while I have a lot of assistants in the fieldwork, I have almost no employed assistants in Moscow University for calculation, mapping, drawing and so on. That’s why last years all values that we submit to Zurich for the global database of World Glacier Monitoring Service are not more than preliminary ones. Of course, we proceed processing raw data for the previous years to obtain final and exact values for inserting corrections into the database, and we shall continue doing this, because annually we have indeed a plenty of good data, but the time lag, separating us from the last season with already calculated exact values, grows with every year. This is my greatest concern. It’s a pity, because Djankuat experiences very dynamic changes just during last years. We have unprecedented long period of negative balances, and the previous year became the first exception over the last 15 years. Terminal retreat accelerated greatly, up to several dozens of metres some years. Its retreat over the recent 12 years exceeded that of the previous 40 years more than twice. Progressive deglaciation on the rocks above the accumulation area led to separation of some branches and to tremendous increase of debris on the snout due to frequent rockfalls from the currently ice-free slopes. Thus, I would do my best to finalize calculations for deriving the exact balance values characterizing such an anomalous stage of Djankuat evolution. But in fact, I strongly need a permanent employed assistant for this.

Anyway, all the rest problems with Djankuat are of minor importance. Several years ago we managed to restore our field station which has been destroyed by a tremendous and unusual snow avalanche. Instead of old huts today we have 5 buildings with gas, electricity, warm water, satellite TV antenna, cellular phones and internet (though very slow). Some people in this hall have visited Djankuat research station already. And to those who have not yet, I can say only “welcome”. At present Djankuat remains a definite leader among all the monitored glaciers in Russia. Moreover, it is an excellent training polygon for glaciological education, and almost all young generations of Russian glaciologists passed through Djankuat during their studenthood.

Another glacier under investigation in the Caucasus, Garabashi, is situated nearby, only 15 km afar from Djankuat. Being a section of star-shaped glacier complex of the Mt. Elbrus extinct volcano, it is much less representative for the whole mountain system, but covers the extreme altitudinal span that is very important even despite its shorter time series, migrating ice divides and rather simplified monitoring scheme established here by Institute of Geography, Russian Academy of Science, though the observational network was expanded here this year. Garabashi has the advantage of transportation, since it is accessible by cable roads, ski-doos and snowmobiles. We usually use this object for testing or applying heavy equipment, like radar sounding, as we did together with Philippe Huybrechts and his Belgian team from Brussels University.

Due to its accessibility, Garabashi has a lot of evidence on its frontal fluctuations - for more than 60 years. Like on Djankuat, one can see an obvious recent acceleration of its degradation. Similarity with Djankuat can be also traced for its mass-balance series. A favourable 15-year-long period until 1997, when balance was also slightly positive, was followed by a strong mass loss – mainly at the expense of summer warming. Garabashi lost about 14% of its volume and 11% of its area during the 36-year-long monitoring period (since 1982 to 2017). Vast formerly subglacial lava streams emerged onto the day surface throughout the last decade.

The third monitored glacier, Aktru in Altai, has very peculiar history. Its research has been started yet in the first half of the 20th century by Tomsk University, which has erected a research and education field station there. Later Aktru was selected as a representative glacier for International Hydrological Decade. However, all this period it was continuously splitting into pieces, so now the glacier basin consists of five separate glaciers. Mass-balance measurements were organized on three of them, but they had different measurement periods. All three mass-balance series show that Aktru glaciers spent four final decades of the 20th century in quasi-stationary position, but approximately after 1998 (very similar to the Caucasus!) an abrupt change of their evolutionary trend took place, and the stage of intensive glacier decay began. The longest time series belong to Maliy Aktru Glacier – since 1962, though it contained a certain amount of indirect estimates, especially at the initial stage. This glacier was selected as a key object in the Aktru basin. After mid-1990s, however, mass-balance components were calculated directly not every year. Since 2012 glacier monitoring here was ceased at all due to the death of local principal investigator, Dr. Narozhniy.

This year glacier monitoring in Aktru basin was restored by joint efforts of Tomsk University and Institute of Geography. However, the reconnaissance showed that preserving Maliy Aktru as a main reference glacier in not safe because of new icefall formation and frequent rockfalls, dangerous for the entire surface of the narrow snout. Therefore, the status of reference glacier was passed to Leviy Aktru. The first measurement year is not yet finished, but it started with establishing network of stakes and snow pits and with carrying out the snow depth survey over a good part of the glacier. Besides, a radar sounding survey for measuring glacier thickness was undertaken in the lower reaches of the glacier. I think there are good hopes for restoring the monitoring complex here, but for the serious conclusions they should restore indirectly the continuity of mass-balance series too.

Programme GA El Calafate

22.10.2019:	**Ice breaker @ GLACIARIUM glacier museum**
18	Meeting point at Hotel Sierra Nevada, registration
	Transfer to GLACIARIUM
	Welcome, ice breaker, informal gathering
22	Transfer to Hotel Sierra Nevada

23.10.2019:	**History and current status of glacier monitoring @ Hotel Los Alamos**
9-9.15	Welcome speeches
9.15–9.45	Glacier monitoring: historical background & international monitoring strategy (M. Zemp)
9.45–10	Country profiles (baseline 2015) & discussion (S. Nussbaumer)
10–10.30	Coffee break
10.30–12.30	I. Country reports & discussion (AR, BO, CL, CO)
12.30–13:30	Individual lunch
13.30–15	II. Country reports & discussion (EC, MX, PE)
15–15.30	Coffee break
15.30–16.30	Workshop on (i) national and global glacier inventories (input B. Raup & discussion)
16.30–17.30	Discussion on achievements and challenges at national and regional levels (all)
17:30–17:45	Wrap-up
18	Group picture
19–22	Dinner

24.10.2019:	**Thematic workshops @ Hotel Los Alamos**
9–10	(ii) Reanalysing glacier mass-balance series (input M. Zemp & discussion)
10–10.30	Coffee break
10.30–11.30	(iii) Global and regional geodetic glacier change assessments (input M. Zemp & discussion)
11.30–12.30	(iv) Data submission to WGMS, GLIMS, and RGI (input S. Nussbaumer/ WGMS & B. Raup/GLIMS & discussion)
12.30–13.30	Individual lunch
13.30–14.30	(v) Strengthening the regional (monitoring) network (input M. Doria/UNESCO & A. Rabatel/ GLACIOCLIM & discussion)
14:30–15	(vi) UNFCCC Letter of Concern (discussion; all)
15–15.30	Coffee break
15.30–16.45	(vii) Public outreach at COP25, other outreach (input M. Doria/UNESCO & discussion)
16.45–17	Wrap-up & outlook (M. Zemp)
17.15	Transfer to GLACIARIUM
18–19	Public lecture at GLACIARIUM (Auditorium)
	Transfer to restaurant
20–23	Dinner

25.10.2019:	**Excursion to Los Glaciares National Park (P. Skvarca)**
8	Departure from Hotel Sierra Nevada
20	Return to Hotel Sierra Nevada

26.10.2019:	**Individual departure**

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Impressions from the WGMS General Assembly at GLACIARIUM, El Calafate (previous page) and Los Glaciares National Park (this page) (photos: GLACIARIUM).

Bolivian glaciers

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Bolivian glaciers are mainly located in the eastern mountain range (eastern and western mountains ranges are part of the “Cordillera de los Andes”). The eastern mountain range in Bolivia has an approximate extension of 180 km with a NW-SE direction, delimiting the wet Amazonas basin in the East and the dry Altiplano basin in the West. Glaciers are situated predominantly from 4900 m a.s.l. to more than 6000 m a.s.l. on the south, southeast and southwest aspect.

Approximately 20% of the all Tropical Glaciers (1826 glaciers covering a surface area of 591.6 km²), according to the only official and first glaciological inventory (on the basis of 1975 aerial photographs), are concentrated in Bolivia (Jordan 1991). Wherein 80% are considered small to very small glaciers with a surface area less than 0.5 km².

Afterwards, in Bolivia started a long-term glaciological programme carried out since September 1991, by the French IRD Institute (Institut de Recherche pour le Développement (Francou et al. 1995; Ribstein et al. 1995), local Institutes from “Universidad Mayor de San Andres” (IGEMA and IHH) and the National Institute of Hydrology and Meteorology (SENAMHI). Today, the Bolivian Glaciological programme is part of the framework of the French glacier monitoring programme called “GLACIOCLIM (les GLACIers, un Observatoire du CLIMat)” (http://www-lgge.obs.ujf-grenoble.fr/ServiceObs/index.htm).

The programme was intended to monitor one “big” glacier and one “small” glacier, in order to represent the glacier diversity of Bolivian glaciers. Zongo (1.96 km²) and Chacaltaya (0.007 km²) glaciers were initially selected and monitored by traditional approaches (glaciological mass-balance method and the setup of meteorological and hydrological stations). Given the imminent disappearance of Chacaltaya glacier (Ramirez et al. 2001), another glacier monitoring programme was started on Charquini Sur glacier (0.35 km²) (Rabatel 2005; Rabatel et al. 2006) in 2002. Furthermore, these glaciers were selected mainly because of the influence of ice melting on water resources for human consumption and hydropower generation for the city of La Paz.

The climate is characterized by one dry and one wet season, the latter occurring during the austral summer. Melting takes place mainly during the summer, reaching a peak in November, before the peak of precipitation, which take place between January to March.

Charquini Sur glacier is monitored using the traditional glaciological method, has two rain gauges, one flow measurement station and one temperature/humidity station on the hydrological basin. Zongo glacier is monitored using the traditional glaciological method, has four rain gauges (two automatic and two manually stations), one flow measurement station, and three automatic weather stations (one on the glacier, and two around the glacier). In both glaciers, geodetic mass-balances measurements were carried out in different time periods.

As all glaciers in the region, Chacaltaya (completely disappeared in 2008), Charquini Sur and Zongo glaciers shows a more often negative mass balances, accentuated during the perturbation of the Sea Surface Temperature at the Pacific´s (El Niño Southern Oscillation).

In average, Zongo glacier lost around –0.6 m w.e. a^{-1} and Charquini Sur glacier lost around –1.2 m w.e. a^{-1}. During an ENSO event, glaciers lost two to three times more.

Today, Zongo glacier has the longest continuous and precise mass-balance series on the Intertropical region.

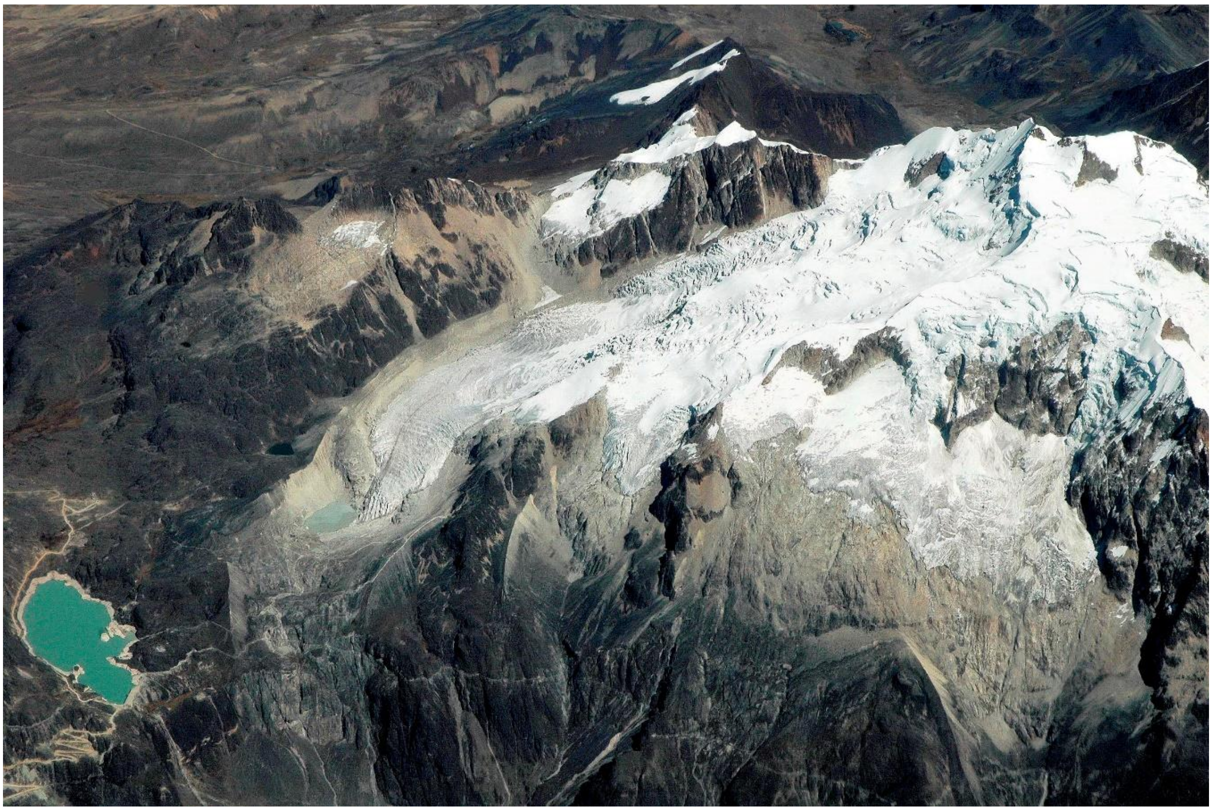

Fig. 13: Zongo Glacier, from the aerial photogrammetric flight of 2006.

Glacier research in Chile

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In Chile there are roughly 24,000 glaciers covering an area of 23,708 km². 95% of the glacier surface is located South of 36º S, which marks the transition from the Wet Andes in the South to the Dry Andes in the North of Chile. In the Dry Andes there exist 4,681, which include an important number of debris covered glaciers and rock glaciers. In the Dry Andes, where the capital Santiago de Chile is located, the glaciers can make an important contribution to river runoff during summer and autumn, especially during dry years. This contribution is not guaranteed for the future considering the retreat and thinning of glaciers, however detailed projections for glacier development during the 21st century are lacking.

Global studies found that glaciers in the Southern Andes Region, which, as defined in the Randolph Glacier Inventory, comprise all Chilean Glaciers have the most negative specific mass change rate of all glacier Regions. This seems to contradict the moderate relative volume change projections for the 21st century as predicted by the Glacier MIP project. One of the reasons for this contradicting result might be the fact that most of the models participating in the Glacier MIP project do not include the process of calving which is estimated to account for 35% of the total ablation of the Patagonian Icefields.

According to the recently updated national glacier inventory based on satellite images of the year 2018, 8% of the overall glacier surface was lost in comparison to the previous inventory which was based on images of 2002. A high variability of area changes was observed: in the Arid Andes clean ice glaciers showed much higher area changes, where debris covered glaciers and rock glaciers show less changes. In the Wet Andes area change and retreat rates are especially variable due to the existence of many calving glaciers who's retreat rates do not only depend on climate signals but also on the geometry of the water body in which they are calving. Extremely high annual average retreat rates of more than 200 m/year were observed for Glaciers Jorge Montt and HPS12 in the last two decades. A study which analyzed glacier area changes since the middle of the last century in the Central Andes found average area change of –30% until 2013/2014 and also found high variability of these changes between the glaciers. At Mocho Glacier in the Wet Andes an area reduction of 45% was inferred since 1976.

Several studies have analyzed volume and mass changes of Chilean Glaciers using remote sensing techniques like altimetry and gravimetry. Most of these studies focus on the Patagonian Icefields (including Argentinian Glaciers), where the absolute mass changes are highest. The obtained mass changes rates of the Patagonian Icefields during the 21st century of the different studies shows important variability and range from 15.4 Gt/year obtained from radar altimetry to 24.3 Gt/year obtained from data of the Gravity Recovery and Climate Experiment (GRACE).
Studies which analyzed mass changes over all the Andes Range agree in their conclusions that highest specific mass changes are observed in Patagonia and more specifically on the large calving glaciers of the Patagonian Icefields.

Direct Surface Mass-Balance observations on Chilean Glaciers are scarce and intermittent. The only long-term glaciological surface mass-balance observational series is from the

WGMS Reference Glacier Echaurren Norte (Fig. 14), which is located in the Maipo Catchment in the Dry Andes at 50 km from the Santiago. The cumulative surface mass balance has a clearly negative trend since the 1980s and this trend is even more negative since 2009. The glacier area of 0.4 km² in 1955 is also strongly decreasing since the beginning of the nineties and the glacier will most probably disappear before the middle of this century (Fig. 14).

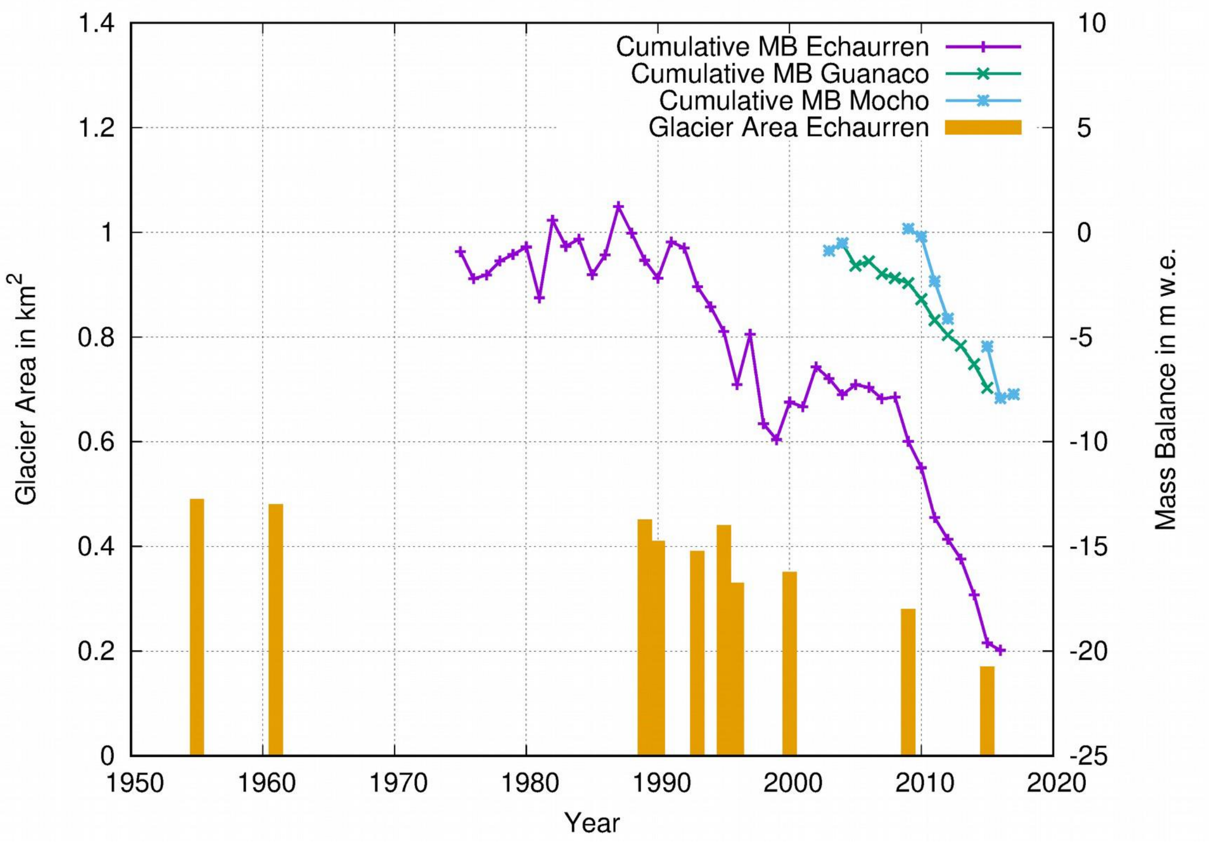


Fig. 14: Cumulative surface mass balance for Glaciers Echaurren Norte, Guanaco and Mocho and area change for Echaurren Norte Glacier.

Since the early 2000s several glaciers are monitored in the Pascua Lama Region in the north of Chile and Mocho Glacier is monitored in the Lakes Region forming part of the Wet Andes. All the monitored glaciers show negative trends for the cumulative surface mass balance (Fig. 14).

Among the import challenges for future glaciological investigations in Chile, the most urgent one is probably to start a continuous surface mass-balance programme on a glacier next to Echaurren Glacier, to be able to continue this time series once the glacier disappears. There is also an urgent need for reliable projection of future glacier extend and freshwater discharge in the highly stressed catchments of the Dry Andes, especially the Rio Maipo Catchment, where more than half of the Chileans are living.

To understand the complex dynamics of calving glaciers in the Patagonian Andes seems to be one of the important conditions to be able to project future contribution of Chilean glaciers to sea-level rise.

Glaciares ecuatoriales en Colombia

Jorge Luis Ceballos
Profesional Instituto de Hidrología, Meteorología y Estudios Ambientales IDEAM

Estado actual

La posición geográfica de los glaciares colombianos, aproximadamente entre los 3° y 11° de latitud norte, los clasifica como glaciares ecuatoriales; lo que implica una alta sensibilidad al desplazamiento intranual de la Zona de Confluencia Intertropical y a fenómenos extremos de variabilidad climática interanuales como El Niño-Oscilación del Sur (ENOS).

La criósfera colombiana actual está conformada por seis glaciares de montaña:

- *Sierras Nevada Santa Marta (10º 50' N; 73º 41' W; 5775 m)*
- *Sierras Nevada El Cocuy o Güicán (6º 30' N; 72º 15' W; 5380 m)*
- *Volcán Nevado Ruiz (4º 53' N; 75º 19' W; 5330 m)*
- *Volcán Nevado Santa Isabel (4º 48' N; 75º 22' W; 4968 m)*
- *Volcán Nevado Tolima (4º 39' N; 75º 19' W; 5280 m)*
- *Volcán Nevado Huila (2º 55' N; 76º 01' W; 5364 m)*

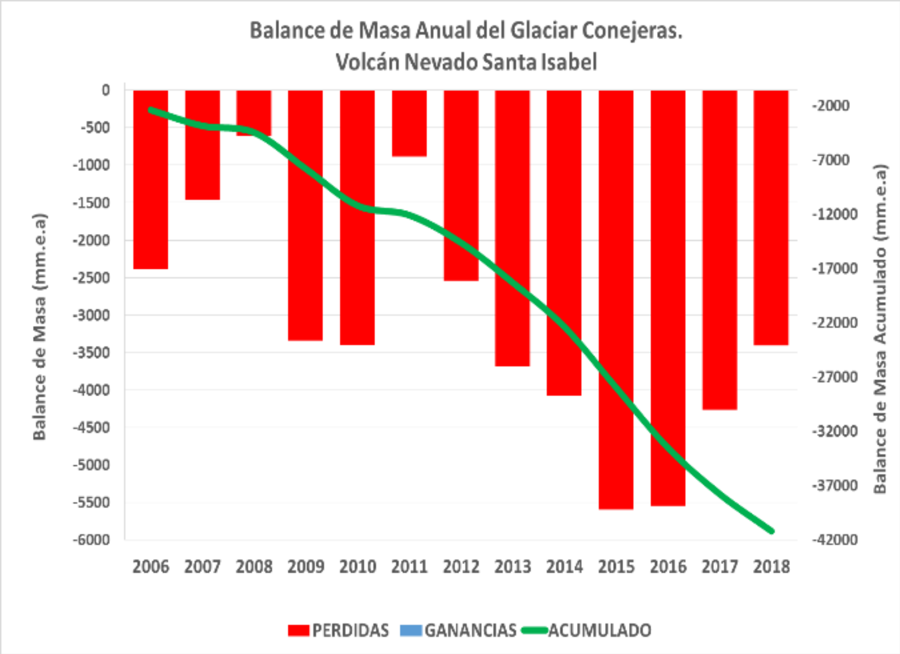
En el trascurso de los últimos 30 años, se extinguieron en Colombia 47.1 km^2 de masa glaciar (que representan el 56% de los 87 km^2 estimados para la década de 1980) y en lo que va corrido de la última década, el área glaciar colombiana se ha reducido un 22% (10.6 km^2). Para el año 2017, las masas glaciares cubrían un área total aproximada de 37 km^2. La causa principal se atribuye al desequilibrio con las actuales condiciones climáticas del planeta; no obstante, cada glaciar colombiano tiene una dinámica y evolución propia que responde a las condiciones atmosféricas de escala global, regional y local, además de sus características topográficas, geológicas y geomorfológicas.

Adicionalmente, se ha evidenciado una estrecha relación entre el fenómeno extremo de variabilidad climática "El Niño" con la disminución de área glaciar. De hecho, el ENOS 2015–2016 impactó de manera drástica los nevados colombianos. Solamente entre enero de 2014 y abril de 2016, el glaciar Santa Isabel, perdió aproximadamente el 33% de su área y el espesor de hielo disminuyó 14 metros. Existe una especial preocupación nacional por la muy probable extinción de este glaciar en la próxima década.

Avances

En Colombia, el Instituto de Hidrología, Meteorología y Estudios Ambientales (IDEAM), desde el año 2006–2008, dos glaciares son objeto de estudio detallado *in situ*: el volcán Nevado Santa Isabel y la Sierra Nevada El Cocuy o Güicán, con una frecuencia de visitas mensual y bimestral respectivamente, para calcular balances de masas por el método directo. Se complementa el monitoreo con estaciones hidroclimatológicas alrededor de estos glaciares.

Respecto al balance de masa glaciológico, el nevado Santa Isabel (sector Conejeras) registra ininterrumpidamente desde 2006 un balance de masa negativo. En contraste, la Sierra Nevada El Cocuy o Güicán, sector Ritacuba Blanco, presenta un comportamiento más estable, incluso con ganancia de masa desde 2017.



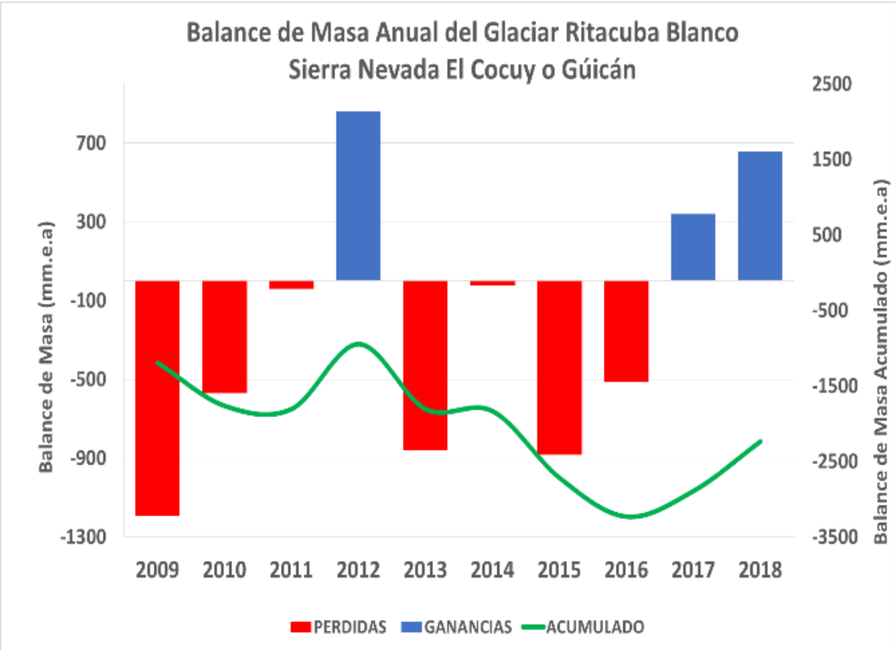


Fig. 15: Balance de masa de los glaciares Conejeras y Ritacuba Blanco.

Información adicional sobre resultados que evidencian la dinámica pasada y actual de los glaciares colombianos es posible encontrarla en:
http://www.ideam.gov.co/web/ecosistemas/glaciares

Retos

1. Asegurar periódicamente el monitoreo en los dos glaciares donde se calcula el balance de masa.
2. Calcular cada dos o tres años el área glaciar en Colombia mediante el uso de imágenes satelitales de alta resolución espacial o fotografías aéreas.
3. Mantener operando y actualizar la red de estaciones hidroclimatológicas.
4. Conformar tres grupos locales de monitoreo glaciar participativo y comunitario (ciencia ciudadana) como una forma de apropiación del conocimiento y del territorio.

Monitoreo glaciar en Ecuador

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Balance de masa

Mediciones continuas del balance de masa son realizadas sobre la zona de ablación y acumulación en el Glaciar 15 del Antisana ubicado en los Andes del Ecuador (Cordillera Oriental) empezando en enero de 1995 y se las lleva adelante hasta el presente de manera continua.

Se ha identificado una fuerte dependencia relacionada con la ocurrencia del fenómeno de El Niño (Oscilación del Sur – ENOS). Sobre los veinte y cuatro años (24) investigados los balances de masa son negativos en los años del evento El Niño, durante el evento frío de La Niña se pueden observar balances próximos al equilibrio y en algunos casos valores positivos (1999–2000), esto fue evidenciado usando el Multi Variable ENSO Index (MEI).

Los efectos de la variabilidad en la ocurrencia del fenómeno ENSO se considera que son importantes sobre el área de acumulación la cual representa del 80–85% de la cobertura del glaciar durante la fase de La Niña y 45–68% durante la fase de El Niño, es decir las tasas de acumulación varían descendiendo o aumentando según la ocurrencia de estos eventos cálidos o fríos, el balance neto específico y la dinámica de todo el glaciar se encuentra fuertemente afectada por la ocurrencia de este fenómeno global.

La dependencia estacional de la ocurrencia del ENSO y los mecanismos físicos ligados con las variaciones del balance de masa sobre los Andes del Ecuador son diferentes a las observadas en los otros glaciares de los Andes Tropicales (Colombia, Perú, Bolivia).

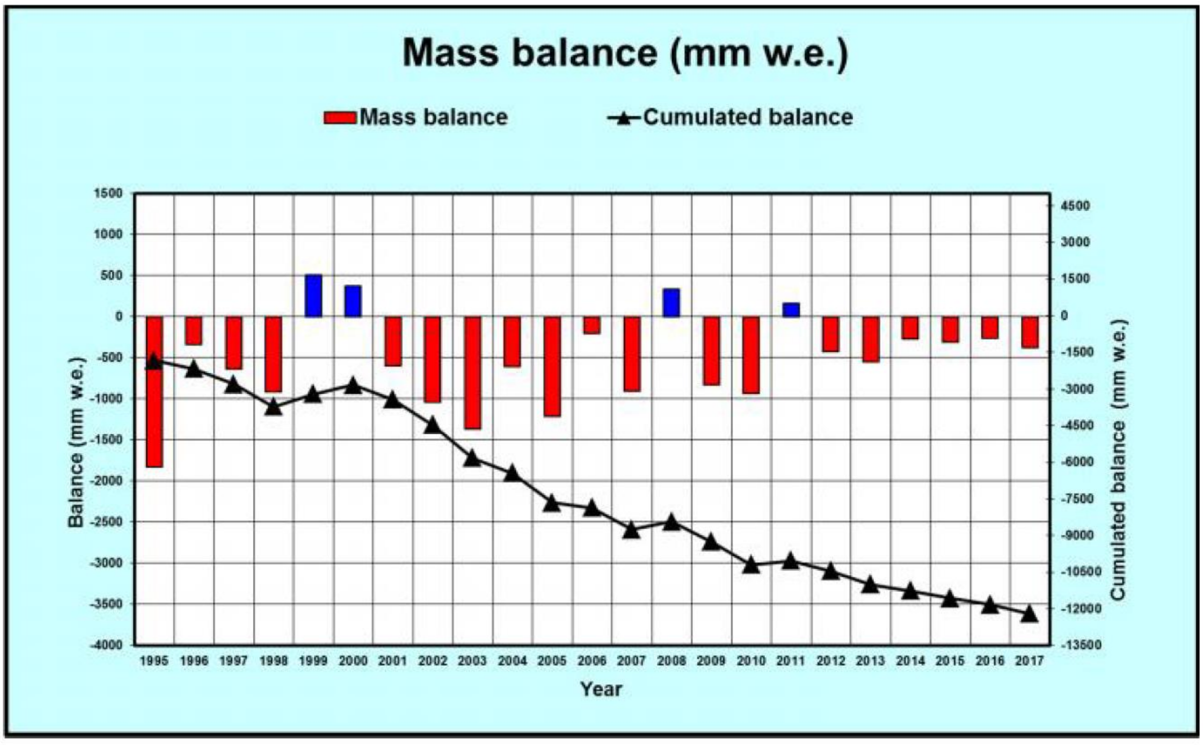

Fig. 16: Balance de masa del Glaciar 15 del Antisana.

Sobre el Glaciar 15 del Antisana para el período (1995–2017) se ha medido un valor de balance de masa promedio de –526 mm de agua equivalente y la línea de equilibrio en promedio se ubica a los 5126 m s.n.m.

Se ha realizado el balance geodésico en el período 1956–1997.

Inventario Nacional de Glaciares

Para la realización de esta actividad se han utilizado fotografías aéreas tomadas por el Instituto Geográfico Militar (IGM) en el período comprendido entre 1956–2016 las cuales han sido procesadas usando métodos digitales para obtener las orto fotografías, posteriormente analizar las mismas, y con el complemento de trabajo de campo ha permitido evaluar las siete coberturas glaciares del Ecuador y actualizar el inventario nacional.

El primer inventario sistemático de los glaciares en el Ecuador fue realizado a inicios de los años noventa (Hastenrath-Jordan) encontrando una cobertura de 92 km^2. Posteriormente se realizaron dos inventarios (2010 / 2016–2017) en el INAMHI (Cáceres B.) evidenciando la pérdida acelerada sobre las siete coberturas glaciares del país. Para 2016 la cobertura glaciar en el Ecuador tuvo un valor de 43.5 km^2 con una pérdida del 55% tomando como punto de partida el año 1960.

Year of inventory (aerial photos)	*Area (km^2)*	*Author, year*
1960	97.2	Hastenrath-Jordan 1999
1997	60.7	Cáceres 2010
2015–2016	43.5	Cáceres 2016–2017

Se ha realizado evaluaciones sobre la afectación de los casquetes Glaciares del Cotopaxi y Chimborazo en relación con la actividad volcánica (Cotopaxi-Tungurahua) que afecto el proceso normal de ablación por las caídas de ceniza para el período 2010–2016.

Algunos datos importantes relacionados con este inventario:

- Área glaciar (2016): 43.5 km^2
- Coberturas glaciares: 7
- Lenguas evaluadas: 88
- Porcentaje de reducción del área glaciar promedio desde 1960: 55.2%
- Línea de equilibrio (ELA) promedio: 5120 m s.n.m.

WGMS Letter of Concern to COP25

Glacier-mass changes are a reliable indicator of climate change. The worldwide network of glacier observers urges parties to the United Nations Framework Convention on Climate Change (UNFCCC) to boost international cooperation in monitoring these changes, and to include the results in the Paris Agreement's global stocktake.

Full version of the Letter of Concern to the UN Climate Change Conference (COP25):

Long-term, sustainable systematic observation of the Earth's climate is the foundation for our understanding of climate change and its associated impacts. The systematic monitoring of glaciers, distinct from the Greenland and Antarctic ice sheets, has been internationally coordinated for 125 years (Forel 1895).

Glacier mass changes are well recognized as a high-confidence indicator of climate change (Bojinski et al. 2014). It is now clear that humans are both the primary cause and will bear the greatest negative impact of glacier melt (Marzeion et al. 2014). Since 1960, glaciers have lost more than 9,000 gigatonnes (1 Gt = 1,000,000,000,000 kg) of ice worldwide, which corresponds to a layer of ice covering all of Chile to a depth of 14 metres. The melting of this ice alone has raised global sea level by nearly 3 centimetres (Zemp et al. 2019).

Long-term observations provide evidence that current mass-loss rates are historically unprecedented on a global scale (Zemp et al. 2015), and they indicate that several mountain ranges such as the European Alps, the Caucasus, western Canada, and the Tropics could lose the vast majority of their glaciers within this century (Zemp et al. 2019).

According to conservative business-as-usual climate change scenarios (RCP8.5), we face the possibility of near-complete loss of all glaciers on planet Earth by the year 2300 (Marzeion et al. 2012). Present and future glacier shrinkage severely impacts the local risk of geohazards (Haeberli and Whiteman 2015), regional fresh-water availability (Huss and Hock 2018), and global sea-level rise (Marzeion et al. 2012), and will result in the loss of life, livelihood, cultural heritage sites, and the forced displacement of millions of people in coastal regions (Marzeion and Levermann 2014).

On behalf of the worldwide network of glacier observers, we urge the parties of the UNFCCC:

- *(i) to further engage promotion and cooperation in systematic observation of glaciers (and other essential climate variables),*
- *(ii) (ii) to take related scientific results seriously into consideration for the global stocktake (cf. Paris Agreement, Article 14), and*
- *(iii) to take immediate and tangible actions to halt further human-caused climate change.*

As scientists, we will continue glacier monitor and, hence, document for current and future generations our society's progress in limiting climate change and related impacts.

This Letter of Cconcern was co-signed by the Director and 37 National Correspondents of the WGMS and sent to the Executive Secretary UNFCCC in the run-up to the COP25.

In addition, a shortened version was published as Correspondence in *Nature*:

Zemp, M., Sajood, A.A., Pitte, P., van Ommen, T., Fischer, A., Soruco, A., Thomson, L., Schaefer, M., Li, Z., Ceballos Lievano, J.L., Cáceres Correa, B.E., Vincent, C., Tielidze, L., Braun, L.N., Ahlstrøm, A.P., Hannesdóttir, H., Dobhal, D.P., Karimi, N., Baroni, C., Fujita, K., Severskiy, I., Prinz, R., Usubaliev, R., Delgado-Granados, H., Demberel, O., Joshi, S.P., Anderson, B., Hagen, J.O., Dávila Roller, L.R., Gadek, B., Popovnin, V.V., Cobos, G., Holmlund, P., Huss, M., Kayumov, A., Lea, J.M., Pelto, M., and Yakovlev, A. (2019): Glacier monitoring tracks progress in limiting climate change. *Nature*, 576, p. 39 (https://www.nature.com/articles/d41586-019-03700-3)

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Selection of media reports

The 125-year jubilee of internationally coordinated glacier monitoring attracted considerable media attention:

«Michael Zemp zu Gast im Morgengespräch»
Rai Südtirol, 16. August 2019

«Wie sich die Arbeit von Gletscherforschern verändert»
Deutschlandfunk Nova, 20. August 2019

«CO2-Fussabdruck der Wissenschaft»
Nano, 3sat, 28 November 2019

«Unsere Gletscher – Wunderschön und so fragil»
Nano, 3sat, 13 Dezember 2019

Reports from the regional meeting for Latin America at GLACIARIUM, El Calafate:

«Las dramáticas cifras del derretimiento de glaciares»
Ahora Calafate, 24 October 2019

«El Calafate fue escenario de una cumbre de expertos en glaciares»
El Patagónico, 26 October 2019

«El Calafate: Simposio de glaciólogos manifestó preocupación por el aceleramiento del retroceso de glaciares»
WInfo, Santa Cruz, 26 October 2019

«Los glaciares de la Patagonia, entre los que más hielo perdieron en el mundo»
La Nación, Argentina, 5 November 2019

Radio interview in El Calafate: Pedro Skvarca, glaciologist and intellectual father of GLACIARIUM, Pierre Pitte, WGMS National Correspondent of Argentina, Samuel Nussbaumer and Michael Zemp, WGMS in the radio studio.

Air miles monitoring

In 2019, the WGMS organized three regional meetings for the General Assembly (GA) of National Correspondents (NCs) instead of one global meeting. The first meeting took place in Switzerland (Zurich) for the NCs from Europe and North America, the second one in Kazakhstan (Almaty) for the NCs from Asia (and New Zealand), and the third one in Argentina (El Calafate) for the NCs from Latin America. The goal of this change in the organization of the General Assembly was to reduce the air travel emissions (by about half) with no additional costs (Zemp et al. 2018).

Figure 17 shows the different air travels done by the NCs to take part in the different meetings. The number of participants, their means of transport, the distance travelled, and the emission of CO_2 are summarized in Table 1. Calculations of distances travelled by air and corresponding CO_2 emissions have been carried out using the online tool provided by www.atmosfair.de.[1] At the meeting in Switzerland, 48% of the participants were already in Zurich and 26% of the participants could take the train. Only 26% of the participants had to travel by air to attend the event. At the meeting in Kazakhstan, 67% of the participants travelled by air and 6% by car. 28% of the participants were already in Almaty. At the meeting in Argentina, 54% of the participants travelled by air, and 42% travelled by car. 4% of the participants were already in El Calafate. In total, 69 participants attended these three meetings. The total distance travelled (by air) was **343'497 km** and the total CO_2 emissions amount to **79'686 kg**. The CO_2 emissions per capita amount to **1'155 kg**.

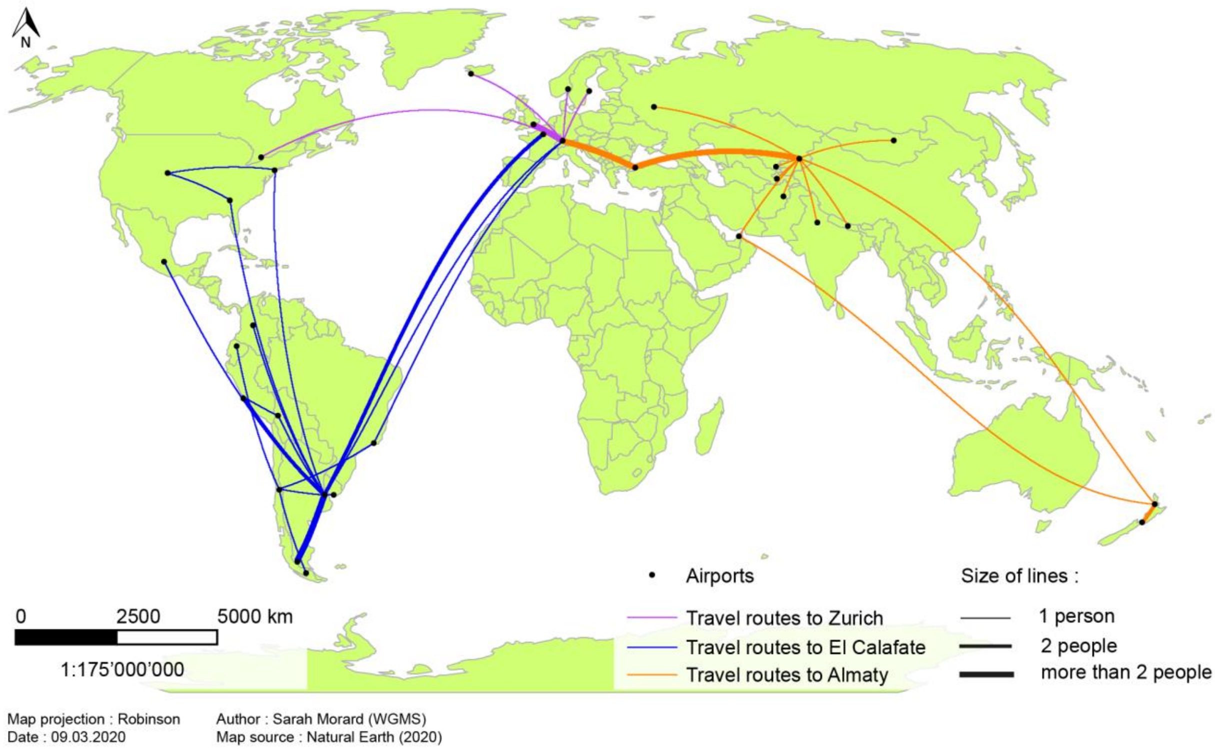

Fig. 17: Air travel routes from the departure airports of the NCs and other participants to the three GA meetings (Zurich, Almaty, and El Calafate) in 2019.

[1] Parameters: Flight class = Economy; Flight type = Optional; Aircraft type = Optional (last access 09.03.2020)

Table 1: Summary of the number of participants per meeting and their air travel distances and CO_2 emissions.

GA of NCs	Zurich	Almaty	El Calafate
Date	14.–17.09.2019	10.–14.09.2019	22.–26.10.2019
Number of participants	27	18	24
Air travels	7	12	13
Journeys by train / by car	7	1	10
Number of participants already there	13	5	1
Total distance in km (air travels)	29’434	122’016	192’047
Total CO_2 emission in kg (air travels)	6’308	30’134	43’244
Average distance in km per participant	1’090	6‘779	8‘002
Average CO_2 emission in kg per participant	234	1‘674	1‘802

In 2010, the WGMS General Assembly of National Correspondents took place in Zermatt, Switzerland.[2] In 2018, the WGMS developed different scenarios for the organization of the forthcoming General Assembly (Graf 2018). In that study, it was assumed (“traditional” scenario) that 41 participants would attend the General Assembly to be held in Zermatt in 2019. Out of 41 participants, 12 would travel by train. The total air travel distance would have been 419’644 km and the total CO_2 emission would have amounted to 111’893 kg (emissions per capita: 2’729 kg CO_2). The comparison of this scenario with a scenario with three regional meetings showed that the CO_2 emissions and the air distance travelled by the participants were substantially lower (about half) if the General Assembly is splitted into three regional meetings.

Note that in 2019, 28 more people attended the GA meetings compared to the estimation from the scenarios mentioned above. Hence, the effective total CO_2 emissions amount to 71% of the projected total emissions that would have resulted from one central meeting in Switzerland. On the other hand, the emissions per participant were reduced by more than half compared to that scenario and amount to 42%. Nevertheless, effective total CO_2 emissions from the three GA meetings in 2019 were higher compared to the GA held in 2010, but per capita emissions were reduced by 32%.

References

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[2] 41 people attended the the GA in Zermatt in 2010, whereof 20 travelled by air; the corresponding total CO_2 emissions amounted to 69’522 kg, the CO_2 emissions per capita amounted to 1’696 kg (Zemp et al. 2018).