The Response of Glaciers to Climate Change: Observations and Impacts[☆]

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Glossary (cf. Cogley et al., 2011)

Calving (of glaciers) Breaking off of ice from the front of glaciers into water; the term "dry calving" is sometimes used for the same process but without water (sometimes generating ice avalanches).

Calving instability Rapid retreat and disintegration of glacier tongues ending in deep waters of the sea (tidal glaciers) or of lakes, once their (calving) front loses contact with subaquatic moraines or rock thresholds forming in shallow water.

Cryosphere The domain of snow and ice on Earth; including seasonal snow, sea ice, continental ice sheets, ice shelves, glaciers and ice caps, lake and river ice, daily, seasonally, and perennially frozen ground (permafrost).

Debuttresing Stress redistribution in steep valley walls as a consequence of unloading related to glacier vanishing, which can lead to long-term rock deformation and slope instability.

Essential Climate Variable (ECV) Atmospheric, terrestrial, and oceanic phenomena selected to provide key policy-relevant information from systematic monitoring as part of the Global Climate Observing System (GCOS) in support of the United Nations Framework Convention on Climate Change (UNFCCC).

Glacier mass balance Relation between gain (accumulation) and loss (ablation) of glacier mass; accumulation is predominantly through snowfall whereas ablation mainly takes place through melting of snow and ice but can also involve other processes such as sublimation (loss of ice directly to vapor), calving of ice into lakes or the sea, snow erosion by wind or avalanching of ice from steep glacier parts. The latter two can result in mass gain for neighboring glaciers. Long-term observation of glacier mass balance should combine *in situ* measurements (snow pits, ablation stakes) for high temporal resolution and process understanding with independent geodetic/photogrammetric mapping for overall volume/mass change and calibration. Values are reported as average rates of change in glacier thickness corrected for snow/ice density (unit: meter water equivalent per year).

Global Terrestrial Network-Glaciers (GTN-G) The long-term observational network responsible for the worldwide monitoring of glacier changes within GCOS. It is run in cooperation by the World Glacier Monitoring Service (WGMS; mainly *in-situ* measurements), the Global Land Ice Measurement from Space initiative (GLIMS; remote sensing) and the National Snow and Ice Data Centre (NSIDC; data management).

Polythermal glaciers Glaciers containing ("temperate") ice at phase-equilibrium ("melting/freezing") temperature as well as ("cold") ice at lower temperatures.

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1 Introduction

Large areas of snow and ice are close to melting conditions and, therefore, react strongly to climate change. Historically, this fundamental principle has helped to identify the Quaternary ice ages and the related dramatic changes in climate and environmental conditions during the younger parts of the Earth history. Modern programs of systematic worldwide climate observation include glaciers as key indicators in nature and as unique demonstration objects with respect to ongoing atmospheric warming trends and possible future climatic and environmental conditions on the Earth. Within about three centuries, the perception of glaciers in the mountain landscape thereby changed fundamentally. This started from an early view of icy mountains as holy seats of gods or a threat to humans (*montes horribiles*). Especially in the densely populated Alps, romantic admiration of green, garden-like landscapes with clean, white and seemingly eternal firn and ice in a blue sky (Fig. 1; cf. Rasmo et al., 1981) became a striking and often-used symbol of an intact human–environment relation (Haeberli, 2007). The first comprehensive scientific field studies on the ice of glaciers (Fig. 2; Agassiz et al., 1847; cf. Rasmo et al., 1981) later led to the initiation of systematic monitoring toward the end of the nineteenth century (Forel, 1895). Today, satellite-born virtual perspectives using digital terrain information provide a new, very different view of the Alps and clearly reveal past glacier extents with their exposed moraine deposits (Fig. 3). Glaciers and their striking changes have become evident worldwide and thereby today indeed one of the most often-invoked icons of rapid and worldwide climate change (WGMS, 2008; Zemp et al., 2015).

Melting of snow and ice under the influence of above-zero temperatures is a common experience for a great number of people. Glacier changes as a response to climatic changes—the focus of this article—can not only be physically recognized but can also be qualitatively understood without an academic or scientific background. The task of the related field of science is to understand, quantify, and assess what is happening with regard to mountain ice and climate in nature. The following text emphasizes the internationally coordinated efforts to fulfill this task in view of difficult policy-relevant questions about climatic and living conditions for future generations. It starts with a short overview of cryosphere components in the climate system in order to characterize the specific function of glaciers. Based on this, it then describes the development of coordinated worldwide glacier monitoring for more than a century, summarizes the observed changes, discusses perspectives and challenges for the coming decades, and tries to outline some of the consequences of resulting environmental impacts in view of possible adaptation options. Thereby, the anticipation, understanding and modeling of process interactions and of corresponding geomorphic systems in rapidly developing new cold-mountain landscapes constitutes a major challenge for, and rapidly emerging field of, geomorphological research (Haeberli, 2017).

Fig. 1 The romantic view of glaciers, snow, and ice: Mont Blanc, French Alps, from Sallenches in 1802. Painting by Pierre-Louis de la Rive. Adapted from Rasmo N, Röthlisberger M, Ruhmer E, Weber B, and Wied A (1981) *Die Alpen in der Malerei*. Rosenheim: Rosenheimer, with permission from Rosenheimer.

Fig. 2 Early glaciologists at Unteraar Glacier: The Agassiz team in the Hôtel des Neuchâtelois (the large boulder serving as shelter) on the medial moraine of Unteraar Glacier. Lithograph after a drawing by Joseph Bettanier published by Agassiz (1840–41). Adapted from Rasmo N, Röthlisberger M, Ruhmer E, Weber B, and Wied A (1981) *Die Alpen in der Malerei*. Rosenheim: Rosenheimer, with permission from Rosenheimer.

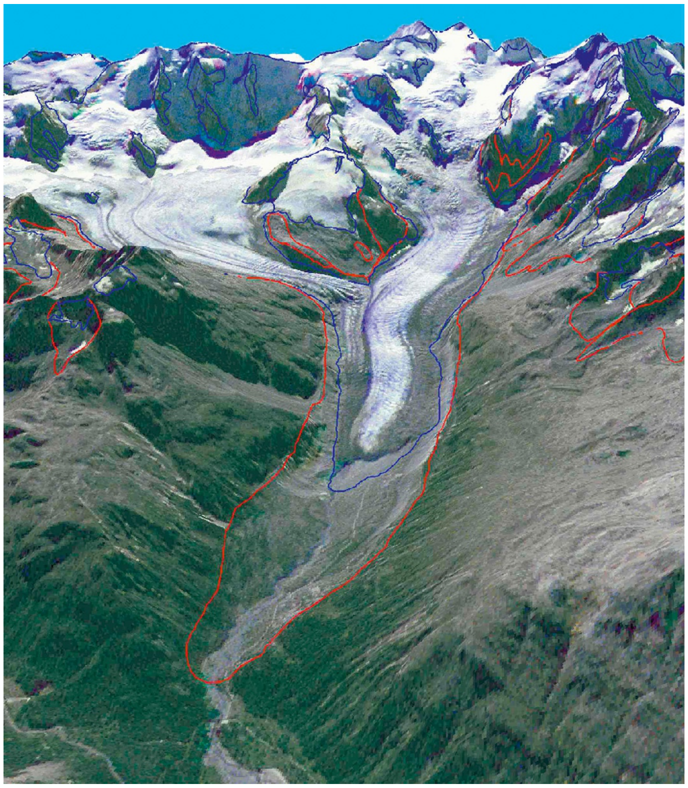

Fig. 3 Oblique view of Morteratsch Glacier, Swiss Alps. IRS-1C satellite image of September 20, 1997 (10 m resolution, black and white) fused with a Landsat image of August 31, 1998 (25 m resolution, color) and draped over a digital terrain model. Marked glacier extents are 1850 (red) and 1973 (blue).

2 Glaciers and the cryosphere components in the climate system

In order to better understand the specific role of glaciers in the climate system and their response to climate change, it is useful to first consider them as part of the entire cryosphere (Table 1). Ongoing climate-related changes in snow and ice can be spectacular (IPCC SROCC, 2019). Together with easily accessible information from deep ice core drilling on the variability of the greenhouse effect in recent Earth history, the widespread recognition and knowledge of Arctic sea ice reduction, deep permafrost warming and worldwide glacier shrinking indeed constitute a fundamentally important source and background of the now-existing awareness with respect to questions of ongoing climate change.

Research on climate and the cryosphere is a vast scientific field. A number of comprehensive overviews have become available; among others are: Bamber and Payne (2004), Knight (2006), IGOS (2007), UNEP (2007, 2009), Singh et al. (2011), and IPCC SROCC (2019). The Fifth Assessment Reports of the IPCC (2013, 2014) contain specific cryosphere chapters and deal with cryosphere aspects in various other sections such as regional chapters or chapters about sea level and paleoclimate. Snow cover, sea ice, glaciers, permafrost and the two ice sheets in Greenland and Antarctica are essential climate variables (ECVs) in the Global Climate Observing System (GCOS, 2003, 2009) that has been established in support of the United Nations Framework Convention on Climate Change (UNFCCC). Cryosphere components are interconnected in various ways. Specific aspects of change detection, attribution to causes and impacts are summarized below.

With its large area covered, small volume and correspondingly high spatio-temporal variability, snow is an *unstable interface* between the atmo-, litho-, cryo-, hydro-, and biosphere. Its albedo effect on the global radiation balance and its role in the water cycle relate snow cover to the climate system via important feedbacks and interactions (Barry et al., 2007). Observed trends (decreasing spring snow extent in the Northern Hemisphere) point to some effects from warming but they remain vague as changes in precipitation also cause changes in snow cover. Attribution to impacts concerns many parts of the climate system—especially cryospheric components and the water cycle. For glaciers (including ice masses with predominant radial flow called ice caps), snow is fundamentally important in that it essentially influences the mass exchange as well as the energy fluxes via snow cover and albedo effects.

Due to its high albedo and its influence on the formation of oceanic deep water, sea ice relates to the climate system with important *interactions and feedbacks* (Gerland et al., 2007). The continued decrease in Arctic sea-ice extent, age, and thickness (Stroeve and Notz, 2018), and especially the shrinking to new record low extents in 2007 and 2012–13, is probably the most dramatic recent change in the Earth's cryosphere, taking place at a rate that clearly exceeds the range of previous model simulations (Dorn et al., 2008; UNEP, 2009). Sea ice around Antarctica, however, shows little change—a fact that is still not fully understood. Continued sea-ice monitoring is a key element of detection strategies for global climate change. Attribution to causes is complex as the development is influenced by higher air and ocean temperatures and by particular ocean circulation patterns or wind stress. The development of the Arctic sea ice is of great concern, because attribution with respect to impacts involves aspects of highest global importance such as albedo and ocean circulation as well as navigation through the northwest and northeast passages. High-arctic glaciers can have direct contact with sea ice (Fig. 4) and become exposed to stronger humidity advection with decreasing sea-ice extent in summer.

The two continental ice sheets are important *drivers* in the climate system. Slow changes in their mass balance and flow are complex and relate to centennial and millennial timescales, making attribution to causes of shorter trends difficult. Modern altimetry and gravimetry technologies are now strongly improving detection possibilities at shorter (decadal) timescales (Bentley et al., 2007; Tedesco, 2015). This is especially important in view of possible ice-sheet instabilities from recent flow acceleration of outlet glaciers with beds far below sea level (Rignot et al., 2002; Vaughan and Arthern, 2007; Steiger et al., 2018; Vieli, 2020) and corresponding surface drawdown of large catchment areas (Fig. 5). Attribution to causes of impacts primarily relates to long-term sea-level rise and changes in the global atmosphere/ocean circulation (Allison et al., 2020). Probably, the clearest and most significant cryospheric information on past climate change is from ice core analysis in Antarctica and Greenland (e.g., EPICA Community Members, 2004; Masson-Delmotte et al., 2010; Bereiter et al., 2015). Especially high-resolution greenhouse gas and isotopic ice core records reaching 10^5–10^6 years back in time are fundamental for detection and documentation of past climatic

Table 1 Components of the cryosphere.

Component	*Area (10^6 km^2)*	*Volume (10^6 km^3)*	*Potential sea-level rise (cm)*
Snow on land (Northern Hemisphere)	1.9–45.2	<0.01	0.1–1
Sea ice (Arctic and Antarctic)	19–27	0.019–0.025	0
Ice sheets			
Greenland	1.7	2.9	730
Antarctica	12.3	24.7	5660
Glaciers and ice caps	0.51–0.54	0.05–0.13	15–37
Permafrost	22.8	4.5	7
River and lake ice	<1.0	–	–

The exact numbers are subject to continuous change as reported in the IPCC reports (for instance, IPCC SROCC, 2019).
Source: Reproduced from UNEP (2007) *Global Outlook for Ice & Snow.* Norway: UNEP/GRID-Arendal.

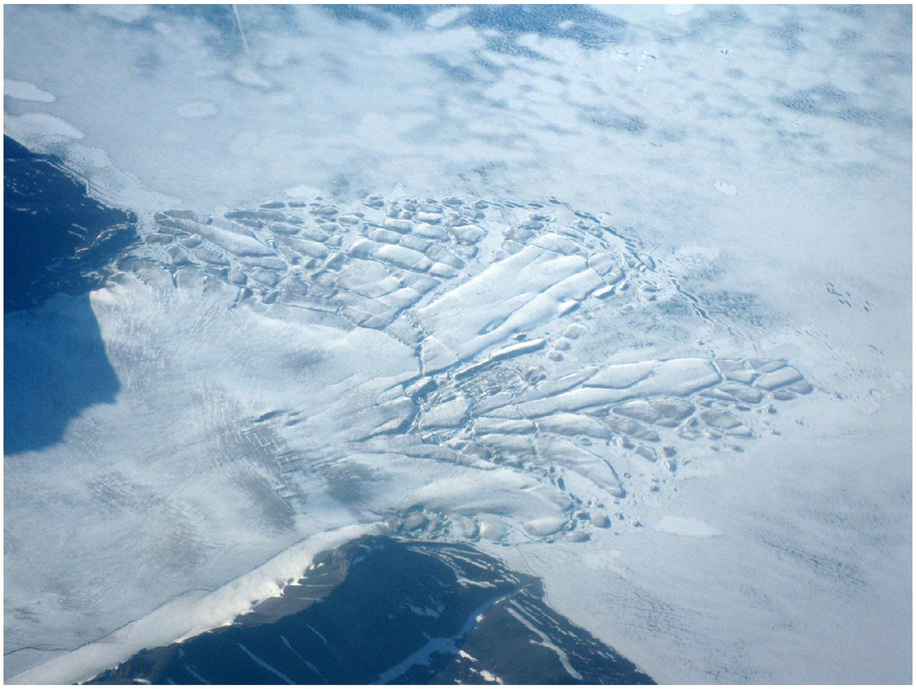

Fig. 4 Glacier on Ellesmere Island in contact with sea ice. Photograph by W. Haeberli, 2008.

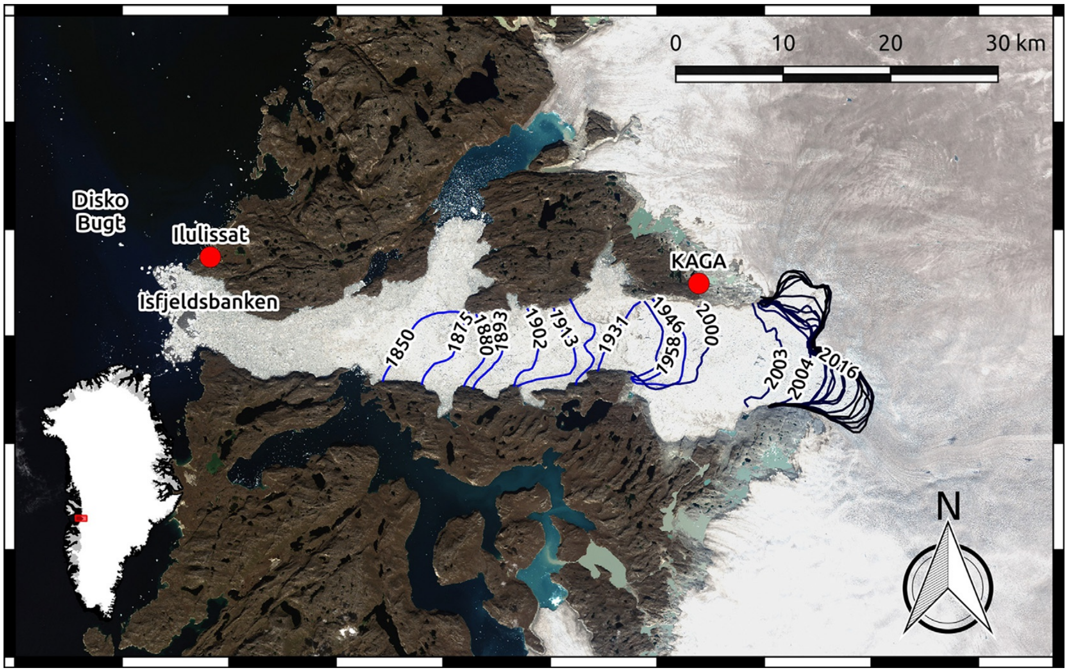

Fig. 5 Retreat of Jakobshavn Isbre, Greenland west coast since 1850. The total backward displacement of the calving front during the twentieth century is comparable to the distance of retreat between 2001 and 2006, corresponding to an acceleration of the retreat rate by about a factor of 20. As the flow velocity roughly doubled around the turn of the millennium, the rate of ice discharge during this time interval increased by about a factor of 40 as compared to the average historical rate. The fjord west of the present glacial margin is filled with icebergs from calving events. Background map is a Landsat-8 image from August 16, 2016 (from the U.S. Geological Survey). From Steiger N, Nisancioglu KH, Åkesson H, de Fleurian B, and Nick FM (2018) Simulated retreat of Jakobshavn Isbræ since the Little Ice Age controlled by geometry. *The Cryosphere* 12: 2249–2266. doi: 10.5194/tc-12-2249-2018, with permission.

changes and for attribution of corresponding causes. These records clearly show increases to the extraordinary level of modern greenhouse gas concentrations and contain quantitative evidence from the past about natural variability and ranges as well as about the magnitude of possible anthropogenic effects. Borehole temperature profiles in cold firn and ice provide independent checks on records of isotopic temperature proxies and reflect changes in atmospheric (annual) temperatures. If more systematically monitored (change of temperature at depth with time) and analyzed (numerical modeling of heat diffusion and flow effects), the temperature profiles would be important for detecting and attributing atmospheric warming as compared to conditions over very long time periods in the past (de Robin, 1983).

Transitional characteristics to glaciers exist with respect to outlet glaciers and ice shelves. The rapid disintegration and collapse of ice shelves in the Antarctic Peninsula (Scambos et al., 2000; Wellner et al., 2019) and the almost complete disappearance of the Canadian ice shelves on Ellesmere Island (Copland et al., 2007) are well-documented changes. The anticipated progression of ice-shelf collapse toward colder parts of Antarctica forms a key element of cryospheric detection strategies. Complex air/ocean/ice interactions make attribution to exact causes difficult, but warming as a general cause appears to be evident. Attribution to impacts concerns high-latitude marine ecosystems, the stability of outlet glaciers and ice streams in Antarctica, and, with this indirectly long-term sea level.

Perennially frozen ground or permafrost at high latitudes is a significant *feedback element* in the climate system (e.g., CH_4). Important information on rising ground temperatures in permafrost at high latitudes and high altitudes (mountain permafrost) as compared to historical conditions can be derived from changing subsurface temperatures and from heat flow anomalies in deep boreholes (Harris et al., 2009; Romanovsky et al., 2010; Biskaborn et al., 2019). Observed changes in active layer thickness and measurements of subsidence from thaw settlement in ice-rich materials so far still show rather weak trends. In both cases, attribution to climatic causes is complicated by multiple interactions of frozen ground with vegetation, snow, and surface water. Attribution to impacts involves large terrestrial ecosystems and living conditions (water resources and infrastructure) at high latitudes and slope stability and soil humidity at high altitudes (Romanovsky et al., 2007). Permafrost is intimately related to polythermal and cold glaciers in regions with dry continental-type climatic conditions (Fig. 6), whereas temperate glaciers penetrating down to non-frozen areas predominate in humid-maritime regions.

The duration of river and lake ice is an *indicator* of winter and lowland conditions, complementing summer/altitude evidence from glaciers in mountains. Shortening of the season with lake and river ice in extensive northern regions can be generally attributed to winter-warming effects. Highly complex influences from short-term weather patterns (wind and precipitation/snow fall) and aquatic conditions (water circulation, groundwater influx, lake turnover, etc.) make attribution to exact causes and modeling difficult. Trafficability and ecosystem evolution are primary aspects of attribution to impacts (Prowse et al., 2007).

The shrinking of glaciers is among the clearest and most easily understood evidence in nature for rapid climate change at a global scale and, hence, constitutes a key element of *early detection* strategies for global climate change. As explained in further detail below, mass-balance monitoring shows a striking acceleration of loss rates since the 1980s (Kaser et al., 2006; Zemp et al., 2009, 2015). Glacier extent (length and area) may have reached warm minimum limits of pre-industrial (Holocene) variability ranges (Solomina et al., 2008) and is far out of equilibrium conditions at many mid- and low-latitude sites. Attribution to atmospheric (summer) temperature rise as a primary cause is relatively safe as air temperature not only relates to all energy-balance factors but also to rain/snowfall and hence accumulation. Complications are due to variable englacial temperature conditions (cold, polythermal, and

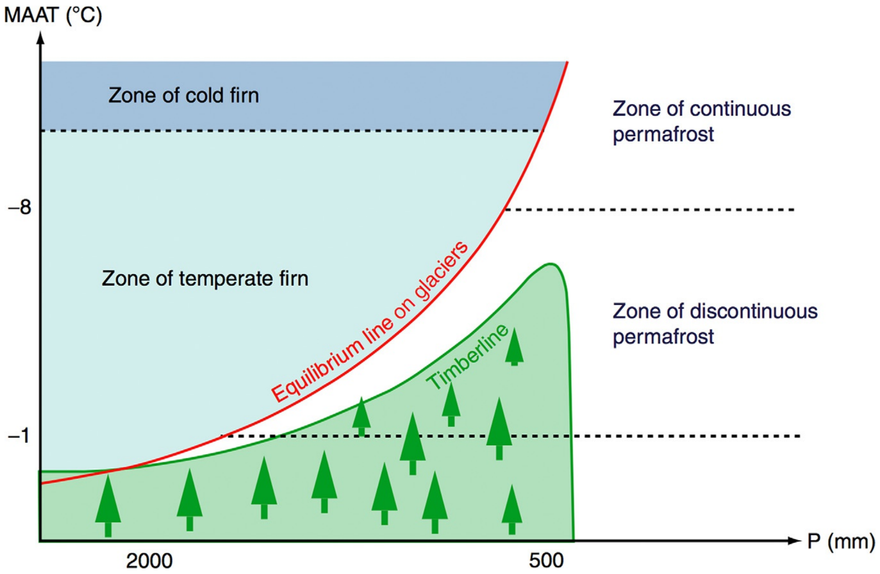

Fig. 6 Scheme of glacier and permafrost occurrence as a function of mean annual air temperature and annual precipitation. Reproduced from UNEP (2007) *Global Outlook for Ice & Snow*. Norway: UNEP/GRID-Arendal.

temperate firn/ice) and strong feedbacks (positive: albedo and elevation/mass balance; negative: adjustment of geometry and debris cover). As discussed below in more detail, attribution to impacts involves landscape changes, runoff seasonality, hazards (lake outburst floods and slope instability), and erosion/sedimentation cascades (debris flows, river load, lake filling, etc.).

Rather surprisingly, important climatic information has been generated from tiny cold/old ice patches/miniature ice caps not usually described in cryosphere overviews (Fig. 7; Farnell et al., 2004; Haeberli et al., 2004; Reckin, 2013). Dating of organic matter from disappearing ice patches with low-flow to even non-flow conditions reveals that ice (and summer air temperature?) conditions without precedence during many past millennia have now been reached in subarctic and alpine regions (Miller et al., 2013).

3 Long-term worldwide glacier observation

Fluctuations of glaciers have been systematically observed for more than a century in various parts of the world (Haeberli et al., 1998; WGMS, 2008). The early establishment of a coordinated worldwide program of data collection and dissemination greatly facilitated documentation of observed glacier changes. The evolution of this program was not without intermittent crises but nevertheless remarkably progressed over time, integrating simple observations and sophisticated scientific approaches.

3.1 Historical background

The internationally coordinated collection of information about ongoing glacier changes was initiated in 1894 with the foundation of the International Glacier Commission at the 6th International Geological Congress in Zurich, Switzerland. It was hoped at that time that the long-term observation of glaciers would provide answers to questions about global uniformity and terrestrial or extraterrestrial forcing of past, ongoing, and potential future climate and glacier changes (Forel, 1895). The monitoring strategy consisted of regular surveys at selected glacier tongues (terminus position, length change, and advance or retreat of glaciers) and also included indigenous knowledge about earlier glacier stages collected by scientists through communication with the mountain people.

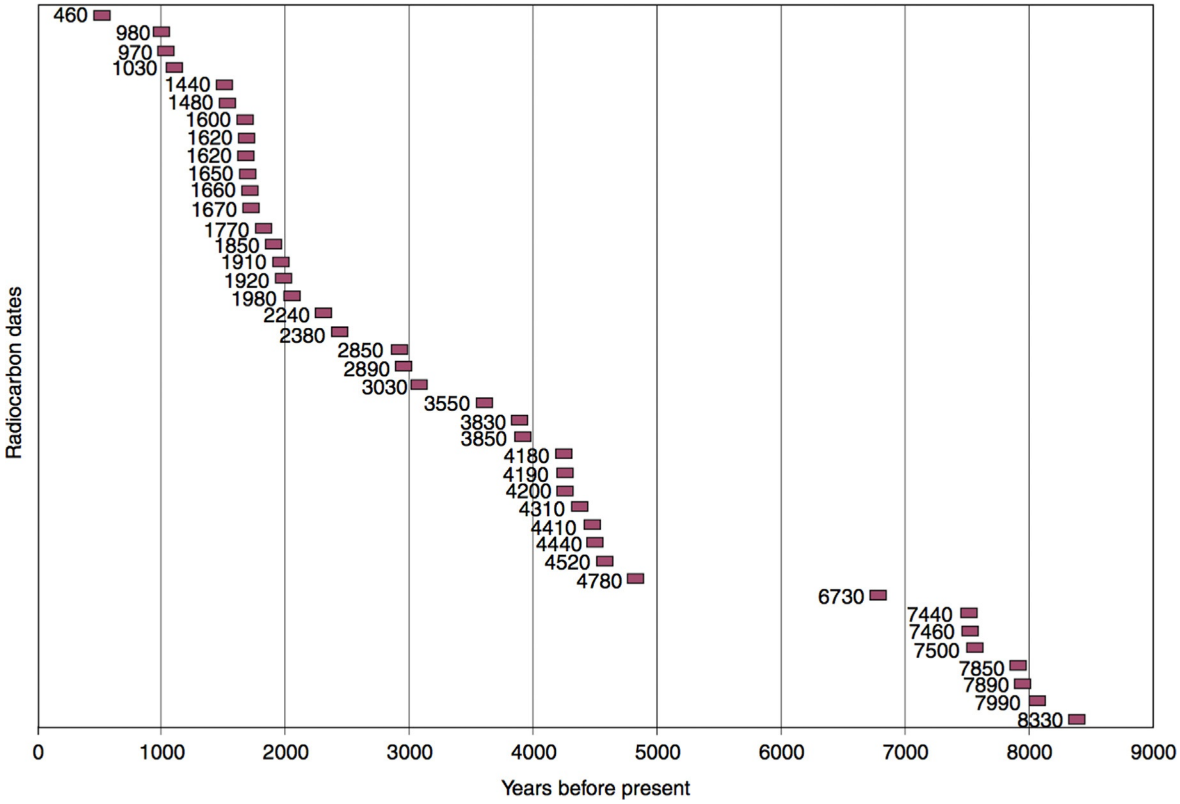

Fig. 7 Radiocarbon dates ordered according to age from organic remains in still existing remains of now rapidly shrinking if not vanishing perennial snowbanks (ice patches and miniature ice caps) in Southwestern Yukon, Canada. The oldest ages indicate that such ice patches have existed during the past about 8000 years. Reproduced from Farnell R, Hare GP, Blake E, Bowyer V, Schweger C, Greer S, and Gotthardt R (2004) Multidisciplinary investigations of alpine ice patches in Southwest Yukon, Canada: Paleo-environmental and paleobiological investigations. *Arctic* 57 (3): 247–259, with permission from Canada Artic Journal.

During the twentieth century, the evolution of the international glacier monitoring was marked by five distinct phases. The *first phase* of international glacier observation, around the turn of the century, was characterized by the search for regular oscillations in the climate/glacier-system, as is illustrated by the titles of the corresponding reports ("Les variations périodiques des glaciers"; Forel, 1895). The *second phase* spans the two world wars and the period of economic crisis between them, when glacier observations were reduced to a minimum. As a consequence, a major glacier advance phase in the 1920s along with the following strong shrinkage in the 1930s and 1940s passed virtually unnoticed in the scientific literature. The *third phase* saw the reorganization of the international network under the umbrella of the UNESCO. In 1967, the Permanent Service on the Fluctuations of Glaciers (PSFG) was established. This resulted in a series of reports in 5-year intervals, the Fluctuations of Glaciers. Mass-balance data from various countries, including the Soviet Union, the United States, and Canada, were included in these reports for the first time, forming the essential link between climate fluctuations and glacier length changes. Length variation data from the United States, the Soviet Union, and other countries completed the corresponding records from the Alps, Scandinavia, and Iceland. *The fourth phase* of international glacier monitoring started around the 1970s. A World Glacier Inventory (WGI) was initiated to become a snapshot of ice conditions on the Earth during the second half of the twentieth century and a temporary technical secretariat (TTS/WGI) began operations in 1976. Detailed and preliminary regional inventories were compiled all over the world to update earlier compilations (Field, 1975; Mercer, 1967) and to form a modern statistical basis of global glacier distribution. The *fifth phase* finally saw the start of the World Glacier Monitoring Service (WGMS), combining and integrating PSFG and TTS/WGI, and developing modern comprehensive observational strategies including results from remote sensing.

3.2 Current glacier monitoring strategy

Today, glacier monitoring is organized in a tiered strategy to optimally combine detailed field-based studies on individual glaciers for process understanding (e.g., energy balance and run-off) with measurements of index variables at several glaciers (glaciological mass balance and length changes) and remote sensing information to obtain complete spatial coverage at decadal time steps (e.g., glacier inventories, geodetic mass balance). The four relevant Tiers are, in detail (cf. Haeberli et al., 2000, 2007):

- Extensive glacier mass and energy balance studies within major climatic zones for improved process understanding and for calibrating numerical models.
- Regional glacier mass changes within major mountain systems, observed with a limited number of strategically selected stakes/pits combined with geodetic mapping at about decadal intervals for calibration (e.g., Zemp et al., 2013; Huss et al., 2015).
- Long-term observations of glacier length changes and, especially, remotely sensed volume changes for large glacier samples within major mountain ranges to assess the representativeness of glaciological mass-balance series (Zemp et al., 2020).
- Glacier inventories repeated at time intervals of a few decades using satellite remote sensing in combination with digital elevation models (DEMs) to enable global coverage (Paul et al., 2009) and detailed regional assessments.

Detailed process-oriented long-term mass/energy-balance and ice flow studies, for example at Storglaciären in northern Sweden, Vernagtferner in the eastern Alps, or Tuyuksu Glacier in the Kazakh Tien Shan have formed the basis for a multitude of model studies (cf. early overviews by Oerlemans (2001, 2008)). Annual measurements on more than 100 glaciers worldwide reflect regional patterns of mass change. A sub-sample of 41 reference glaciers provides continuous information on mass change rates (Fig. 8). Attempts are made to fill gaps in spatial coverage such as in the Himalayas (Bolch et al., 2012; Azam et al., 2018) or to re-establish long observational series, which were discontinued in the 1990s (e.g., Barandun et al., 2018). Front variations of about 500 glaciers are currently measured each year in several regions of the world, serving as a key to reconstruct past climatic fluctuations using dynamic fitting of glacier flow models (e.g., Leclercq and Oerlemans, 2012) or simpler concepts of mass conservation (Hoelzle et al., 2003). The collected data is compiled and published by WGMS in the Global Glacier Change Bulletin and also reported annually in electronic form (WGMS, 2019, and earlier versions). Updating glacier inventories requires continuous upgrading and analyses of existing and newly available data and is now organized as a large community effort (Fig. 9). About 215,000 glaciers have been catalogued in the latest version (v6) of the so-called Randolph Glacier Inventory (RGI) described by Pfeffer et al. (2014) and documented by the RGI Consortium (2017). Recently, Gärtner-Roer et al. (2019) assessed the status of national implementations of the international monitoring strategy. They developed a standardized procedure to evaluate existing glacier data from international data repositories (as of 2015) for all glacierized countries and regions. This is the first time baseline data on glacier distribution and change have been systematically compiled and evaluated. By this process, observational gaps and uncertainties are revealed to demonstrate their influence on related decisions at the national, regional, and sectorial (e.g., agricultural economy, energy management) levels, as well as to strengthen and develop future efforts in glacier monitoring.

The observing strategy is implemented in the Global Terrestrial Network for Glaciers (GTN-G) that has been established as part of the Global Terrestrial/Climate Observing Systems (GTOS/GCOS). It is especially designed to provide quantitative, understandable, and policy-relevant information related to questions about process understanding, change detection, model validation, and environmental impacts in a trans-disciplinary knowledge transfer to the scientific community as well as to policy makers, the media, and the public. The network is jointly operated by three operational bodies in glacier monitoring, which are the WGMS (mainly *in situ* observations), the National Snow and Ice Data Center (NSIDC: mainly data management), and the

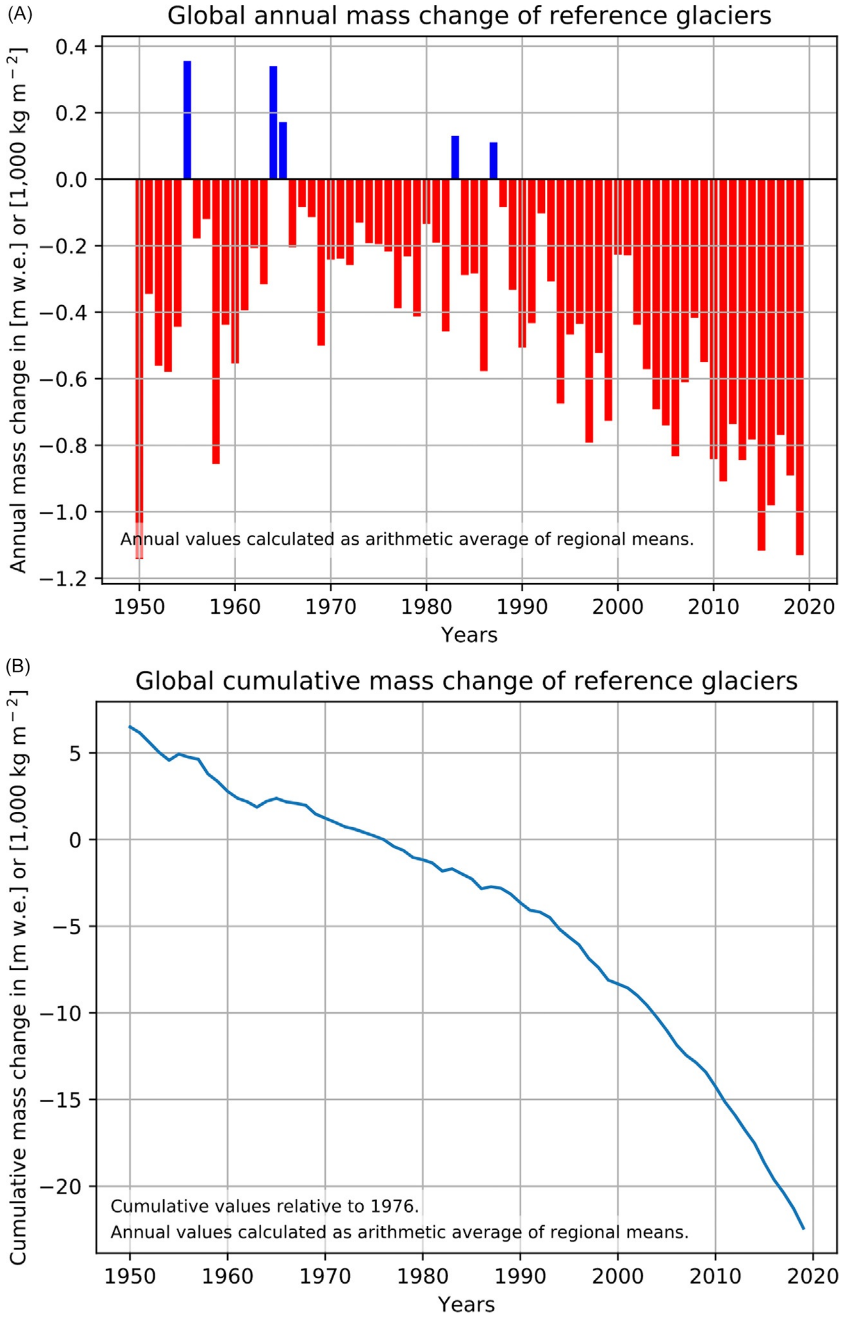

Fig. 8 Average annual (A) and cumulative (B) glacier mass balances from 30 reference glaciers in nine mountain ranges. The blue line in (B) is the mean value calculated for all reported mass balances irrespective of the length of the time series. Reproduced from WGMS website 2020 (http://www.wgms.ch/), free download.

Global Land Ice Measurements from Space initiative (GLIMS: mainly satellite observations) in coordination with the International Association of Cryospheric Sciences (IACS), an association of the International Union of Geodesy and Geophysics (IUGG).

The online service of GTN-G (gtn-g.org) provides fast access to regularly updated information on glacier inventory data. The RGI version 6.0 (RGI Consortium, 2017) provides a global, almost complete inventory relating to around the year 2000, while the GLIMS database additionally hosts multi-temporal glacier outlines for many regions. The Fluctuations of Glaciers (FoG) database of the WGMS (2020) currently stores >46,000 front variations from 2500 glaciers, >7000 glaciological mass balances from 460 glaciers, and >90,000 geodetic mass changes from >27,000 glaciers. In addition, NSIDC hosts a collection of >24,000 glacier photographs (NSIDC 2002, 2019). Overview reports were published in 2008 in cooperation with UNEP (WGMS, 2008) and in 2015 (Zemp et al., 2015) and are periodically updated in the Global Glacier Change Bulletin series of the WGMS (WGMS, 2020, and earlier issues).

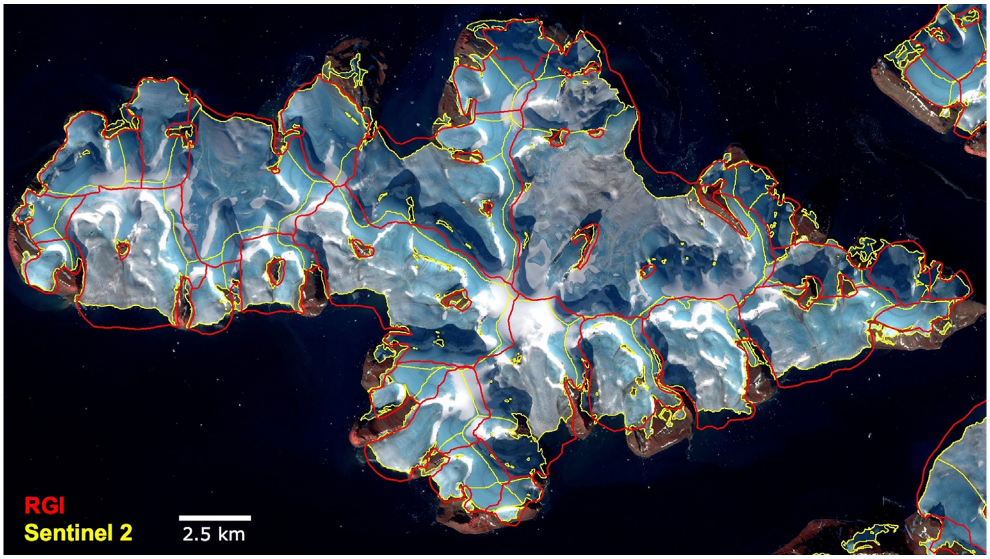

Fig. 9 Sentinel-2 image (false color infrared) of Luigi Island in the Franz-Josef-Land Archipelago of the Russian Arctic acquired on September 12, 2016. Nearly all snow (white) melted in that year, the surrounding ocean (black) is ice-free, and the bare ice (blueish) is subject to massive surface melt. Red outlines show glacier extents and ice divides from the RGI, yellow lines refer to the 2016 Sentinel-2 scene and the new ArcticDEM (shifting the ice divides to the correct place). Image: Copernicus Sentinel data 2016.

3.3 Data interpretation

Regional glacier mass changes within major mountain systems measured by reduced stake networks provide information on accumulation, ablation, mass balance, and mass turnover at seasonal to annual time resolution. In the same way as detailed mass-balance measurements with extended stake/pit networks, they need careful calibration by repeated precision mapping, which allows for exact determination of volume/mass changes integrated over the entire glacier (Andreassen, 1999; Thibert and Vincent, 2009; Zemp et al., 2010, 2013).

Statistical analysis indicates that spatial correlations of short-term mass-balance measurements typically have a critical range of about 500 km (Cogley and Adams, 1998; Rabus and Echelmeyer, 1998) but tend to increase markedly with increased length of time period under consideration as it applies to meteorological variables in general (e.g., Vincent et al., 2017). Decadal to secular trends are comparable beyond the scale of individual mountain ranges with continentality of the climate being the main classifying factor (Letréguilly and Reynaud, 1990) besides individual hypsometric effects (Furbish and Andrews, 1984; Tangborn et al., 1990).

Carefully calibrated modeling backwards into the final phase of the Little Ice Age confirms large variability even within short distances (Huss et al., 2008, 2010) which is still not well understood from weakly correlated individual topographic influences (Fig. 10). Over such extended timescales (about 150 years), decreasing glacier area accompanying long time series of mass loss appears to have compensated about 50% of the mass loss, which would have taken place with constant unchanged area (Nemec et al., 2009; Paul, 2010; Huss et al., 2012).

Extrapolation of available mass-balance measurements has been used in various studies for estimating annual rates of sea-level rise due to glacier melt (e.g., Kaser et al., 2006; Bahr et al., 2009), increasingly combined with glacier volume changes derived from DEM-differencing over large individual glacierized regions (e.g., Berthier et al., 2010; Gardelle et al., 2013; Brun et al., 2017; Braun et al., 2019; Shean et al., 2020) and also globally (Zemp et al., 2019). The growing difference from equilibrium conditions must thereby be considered. The assumption that the mass balance of a glacier is fairly well decoupled from the dynamic response of the glacier and primarily constitutes a direct signal of climatic conditions at the site is reasonable only for relatively steep glaciers with a short response time and that remain relatively close to steady state or for slow climate forcing. With accelerating climate change, various feedbacks come into play. *Size effects* (small/large glaciers), *thermal aspects* (cold/temperate firn areas), *positive feedbacks* (albedo and surface elevation), and *process changes* (rock outcrops/collapse/lake formation) are especially critical.

Size effects concern the different response characteristics of small and often more steeply inclined glaciers with short response times and large, mostly flat glaciers with long response times. As the latter cannot retreat quickly enough and lose exposed areas through time, rapid forcing leads to *positive feedbacks* related to changes in surface elevation (mass-balance/altitude feedback), which are cumulative and—after some time—tend to completely dominate thickness change (Raymond et al., 2005) and to induce runaway effects (down-wasting and collapse). The related massive surface elevation changes are easily visible from DEM differencing (e.g., Larsen et al., 2007; Paul and Haeberli, 2008; Melkonian et al., 2016; Falaschi et al., 2017). As a consequence, even under comparable climatic conditions, results from mass-balance measurements on small glaciers (Cogley and Adams, 1998; Dyurgerov

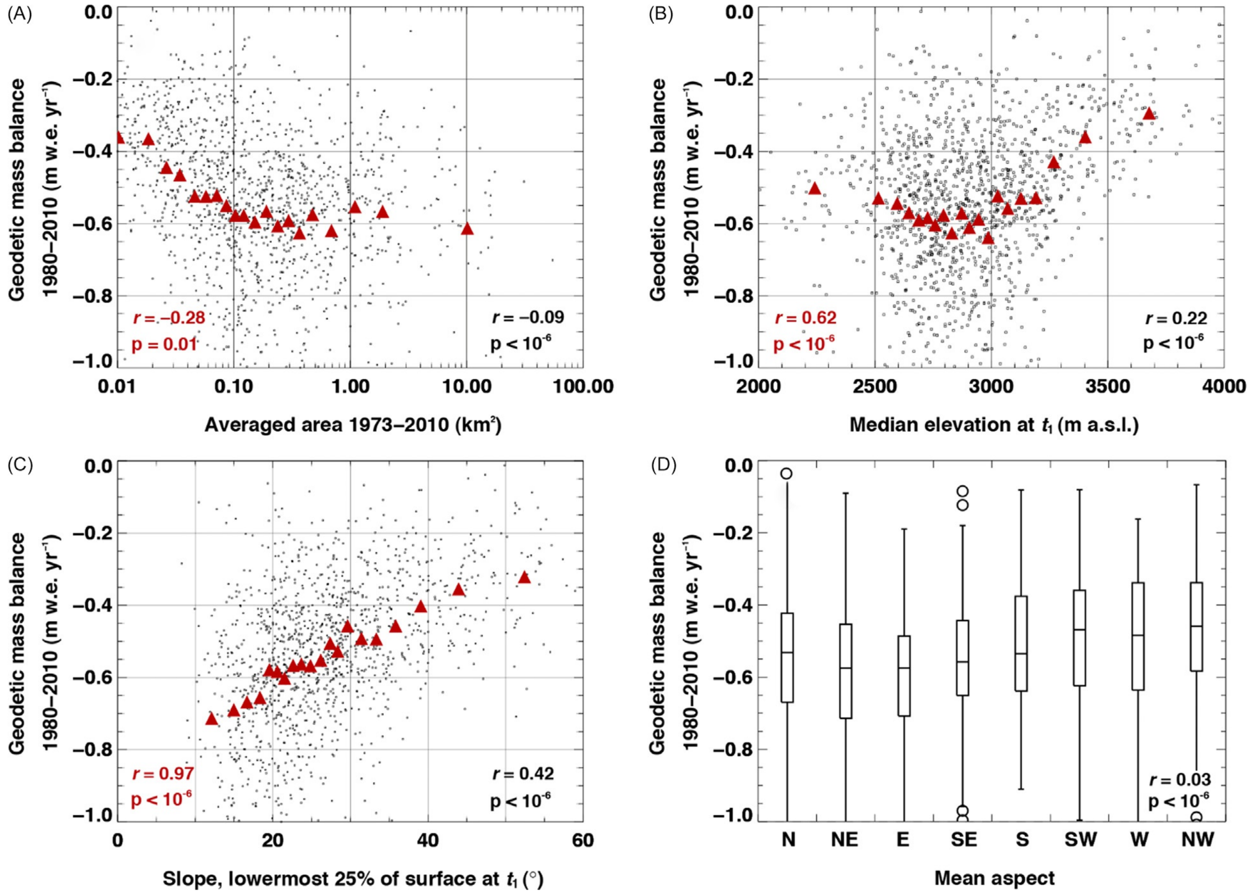

Fig. 10 Correlation of temporally homogenized geodetic mass balance 1980–2010 and several geometrical indices for the glaciers in the Swiss Alps. (A) Average area 1973–2010, (B) median elevation at the beginning of the considered time interval, (C) surface slope averaged over the lowermost 25% of the glacier and (D) mean aspect; red triangles show mean values for 5% quantiles of the data. From Fischer M, Huss M and Hoelzle M (2015b) Surface elevation and mass changes of all Swiss glaciers 1980–2010. *The Cryosphere* 9: 525–540.

and Meier, 1997; Kaser et al., 2006) may not be extrapolated in a simple straightforward way to large glaciers. This is especially important with respect to estimates of sea-level rise caused by the melting of the largest glaciers on Earth.

Extrapolation in time is also made difficult because of *process changes*. For instance, cold firn areas in regions with a dry-continental climate (cf. Zemp et al., 2007) or at high altitudes (Suter et al., 2001; Vincent et al., 2007) may warm, become temperate, start losing mass from large parts of their accumulation area and, hence, strongly increase their mass-balance sensitivity with respect to atmospheric warming. Moreover, many heavily glacierized regions in the Arctic can be classified as ice caps or ice fields with a limited altitudinal range. The latter implies that they could quickly melt once a critical threshold in the climate is passed (Nesje et al., 2008; Fisher et al., 2012). As an additional effect, some large glaciers terminate in deep ocean water or in local lakes, causing calving instability or even (partial) flotation and dynamic thinning (Fig. 11; Meier et al., 2007), but do not contribute to global sea-level rise with their parts below the water level (Haeberli and Linsbauer, 2013; Loriaux and Casassa, 2013).

Fluctuations in glacier length are easily determined but involve the full complexity of dynamic glacier response to climate change. The cumulative advance/retreat of glacier margins indeed represents a delayed, filtered, and enhanced signal of climate forcing. Considered over time periods corresponding to the dynamic response time for full adjustment to changed climatic conditions, cumulative length changes can be quantitatively related to the mean mass balance (Haeberli and Hoelzle, 1995; Hoelzle et al., 2003). They are the key to quantitative comparison with past glacier changes. For a long time these changes constituted the only possibility for assessing how representative are the more direct signals from the few measured mass balances.

Special conditions, which limit possibilities of climatic interpretation, are related to features of downwasting, collapse (as treated later), extraordinary flow conditions (calving instability and surges; Truffer et al., 2020, Vieli, 2020), heavy debris cover (enhancing the delay in response), avalanching, or accelerated retreat induced by lake formation (Yde and Paasche, 2010). Taku glacier, for instance, is one of the relatively few glaciers on Earth, which continued to grow and advance for decades (Fig. 12). This is due to the fact that the glacier is in the advance stage of its calving-instability cycle after a drastic retreat phase (Truffer et al., 2009). A thick debris cover on glacier tongues can greatly reduce ablation near the terminus and thereby multiply the dynamic response time, which is inversely proportional to the balance at the terminus. Heavily debris-covered glaciers can, therefore, remain in extended

Fig. 11 Sawyer Glacier, Stikine Ice Field, Southern Alaska. The glacier is in the rapid retreat phase of its calving instability cycle. It has shortened by about 35 km since its maximum extent reached during the Little Ice Age. Photograph by Haeberli W (2007) Changing views of changing glaciers. In: Orlove B, Wiegandt E, Luckman BH (eds.) Darkening Peaks – Glacial Retreat, Science and Society, pp. 23–32. Berkeley, CA: University of California Press.

Fig. 12 Taku Glacier, Juneau Ice Field, Southern Alaska. The glacier is in the advance stage of its calving instability cycle, advancing with its front on a delta-moraine pushed through the fjord. Photograph by Haeberli W (2007) Changing views of changing glaciers. In: Orlove B, Wiegandt E, Luckman BH (eds.) Darkening Peaks – Glacial Retreat, Science and Society, pp. 23–32. Berkeley, CA: University of California Press.

positions for many decades if not centuries, thereby constricting the flow of up-glacier ice (Fig. 13; Schmidt and Nüsser, 2009; Scherler et al., 2011).

Quantitative information from detailed glacier inventories compiled during the second half of the twentieth century mainly concerns four parameters: highest and lowest elevations, area, and length. From these four basic parameters and some additional topographic and climatic data, important characteristics of numerous glaciers in entire mountain ranges can be derived. Based on a corresponding parametrization scheme, Haeberli and Hoelzle (1995) analyzed the entire sample of glaciers $>0.2\ \mathrm{km}^2$ of the European Alps around 1975 with respect to several factors. The factors included the frequency distribution of surface area (maximum occurrence: 0–5 km^2), mean altitude or mid-range elevation (2800–3000 m a.s.l.) and overall slope (20–25 degrees), mean basal shear stress (40–80 kPa), slope- and stress-dependent mean ice thickness (a few tens of meters), mean flow velocity

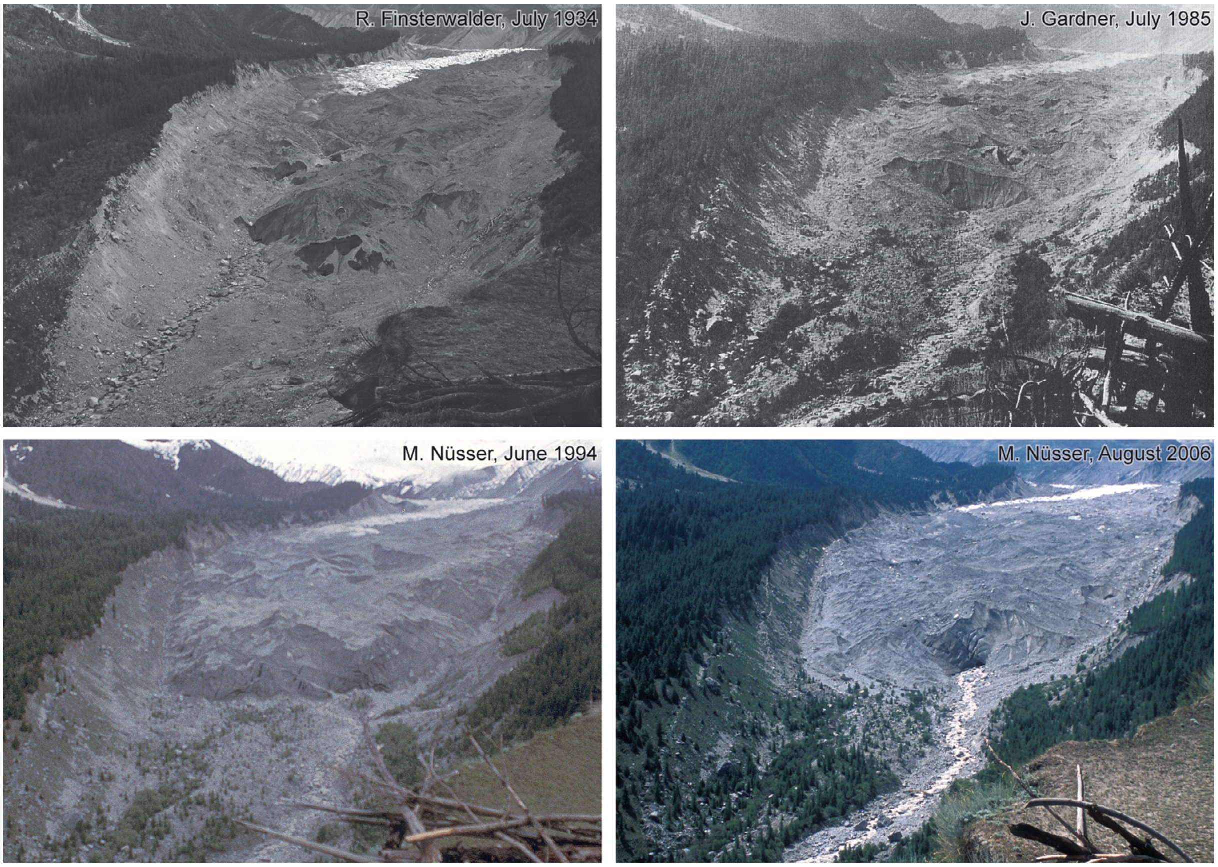

Fig. 13 Repeat terrestrial photography of the Raikot Glacier terminus, Nanga Parbat, northern Pakistan, between July 1934 and August 2006. Reproduced from Schmidt S and Nüsser M (2009) Fluctuations of Raikot Glacier during the past 70 years: A case study from the Nanga Parbat massif, Northern Pakistan. *Journal of Glaciology* 55(194): 949–959.

(0–30 m year^{-1}), characteristic reaction time as the delay of tongue length-change onset with respect to marked changes in mass balance (10–20 years), typical slope-dependent dynamic response time for full adjustment to changed mass-balance conditions (20–40 years; cf. Zekollari et al., 2020), and relaxation time as the difference between response and reaction time (often 10–20 years), as well as probable occurrence of temperate, polythermal, and cold ice as well as corresponding altitudinal relations with periglacial permafrost. Such numbers immediately make it clear that the great majority of glaciers in mountain ranges comparable with the European Alps are small, steep, thin, close to (or at) melting temperature and, hence, highly vulnerable to even small increases in atmospheric energy content (Hoelzle et al., 2007; Raper and Braithwaite, 2009). Together with simple approaches based on mass conservation and step changes between equilibrium conditions (i.e., no transient effects) inventory data were also used to approximate future glacier development (e.g., Haeberli and Hoelzle, 1995; Paul et al., 2007a; Zemp et al., 2007). The resulting information remains realistic over longer time periods (dynamic response time) and with smaller glaciers.

3.4 Modern technologies

Remote sensing at various scales (satellite imagery, aerophotogrammetry) and GIS technologies can now be combined with digital terrain information (Kääb et al., 2002; Paul et al., 2002; Kargel et al., 2005; Andreassen et al., 2008; Kääb, 2008; Paul and Andreassen, 2009; Bolch et al., 2010). Furthermore, new technologies such as airborne laser altimetry in combination with kinematic GPS (Abdalati et al., 2004; Arendt et al., 2002, 2006; Meier et al., 2007), laser scanning (Geist et al., 2003; Fischer et al., 2015a,b), and space-borne DEMs from sensors such as SRTM, ASTER, ALOS, TanDEM-X, and SPOT or very high resolution sensors such as Quickbird and WorldView (ArcticDEM, High Mountain Asia DEM) lead to new dimensions for glacier monitoring (Fig. 14). Spectacular results have already been obtained from DEM differencing (after careful co-registration of both DEMs), reflecting changes in surface elevation at pixel resolution for large regions (e.g., Berthier et al., 2004, 2010; Gardelle et al., 2013; Larsen et al., 2007; Bolch et al., 2008; Rignot et al., 2003). In fact, differencing the SRTM DEM (Rabus et al., 2003) with regionally available DEMs from earlier aerial photography introduced quantitative information on volume/mass changes during the past decades for hundreds and thousands of large and small glaciers as well as on their individual parts. With these new techniques, it is now possible for the first time to directly investigate how representative the thickness changes of the glaciers in the mass-balance

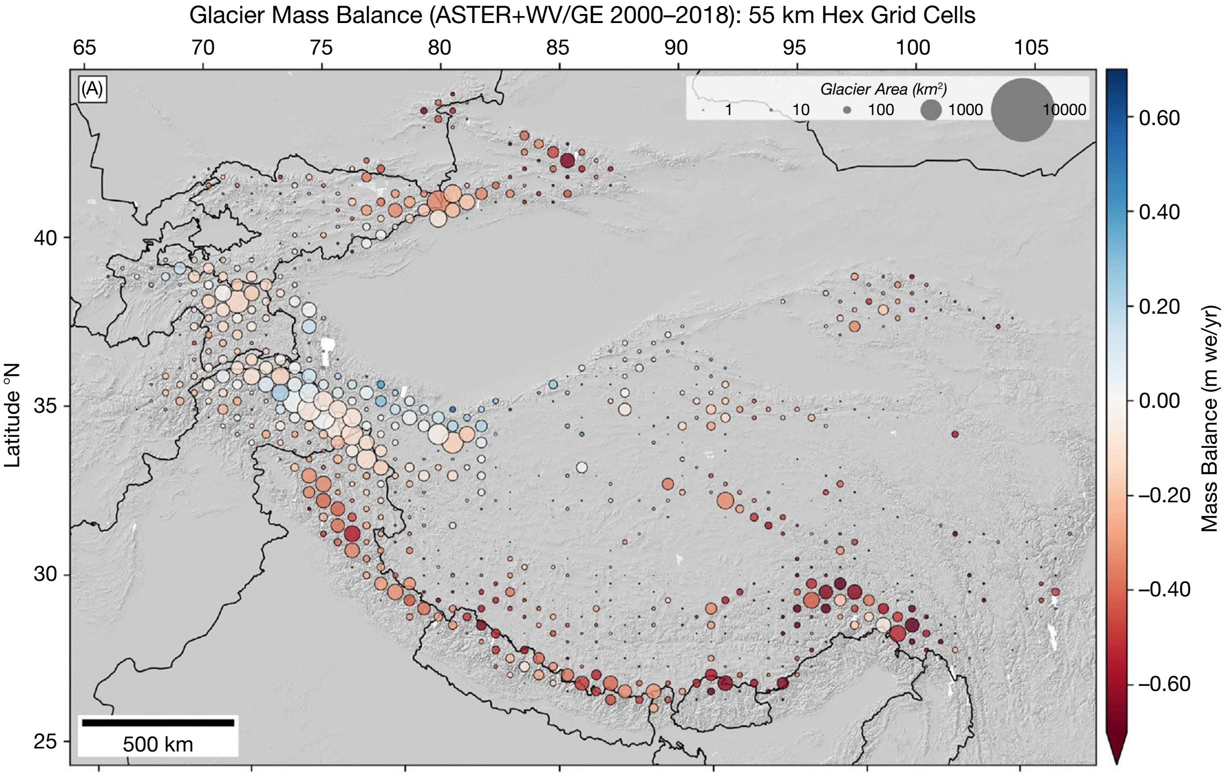

Fig. 14 Specific glacier mass balance (m w.e. a^{-1}) in High Mountain Asia (centered over western China) over the period 2000–2018, aggregated over 55 km grid cells. The size of the circles is proportional to the total glacierized area. Approximate international borders from Natural Earth 1:10 M products are plotted for reference. Taken from Shean DE, Bhushan S, Montesano P, Rounce DR, Arendt A, and Osmanoglu B (2020) A systematic, regional assessment of high mountain asia glacier mass balance. *Frontiers in Earth Science* 7: 363. doi: 10.3389/feart.2019.00363, with permission.

network compare with all glaciers of entire mountain chains (Paul and Haeberli, 2008), what is the variability in space and how variability depends on factors such as size, slope, exposure, altitudinal extent or (micro-) climatic conditions of individual glaciers. Relative differences between long-term volume or mass changes of individual glaciers can be transformed into correction factors for fitting mass-balance time series with transitions from replaced to replacing glaciers.

At the beginning of space-borne geodetic mass balance calculation, several studies used the SRTM DEM acquired in February 2000 (Rabus et al., 2003) and subtracted regionally available national DEMs from earlier aerial photography and other elevation sources (e.g., Rignot et al., 2003; Surazakov and Aizen, 2006; Larsen et al., 2007; Schiefer et al., 2007; Paul and Haeberli, 2008). Later on, the SRTM DEM was subtracted from more recent DEMs derived from satellite data such as SPOT (Gardelle et al., 2013) or TanDEM-X (e.g., Vijay and Braun, 2016; Li et al., 2017; Braun et al., 2019; Jaber et al., 2019). Outside the coverage of SRTM, SPOT and ASTER DEMs have also been subtracted from historic national DEMs to obtain elevation changes over longer time periods (e.g., Berthier et al., 2010). Recently, DEM generation from optical satellite stereo imagery was automatized (Shean et al., 2016) and applied to time series of ASTER stereo imagery to obtain glacier elevation changes as a robust trend from all DEMs available rather than only two (e.g., Brun et al., 2017; Dussaillant et al., 2019). As a temporal extension back in time historic satellite images from the Keyhole Mission (Corona and Hexagon) were also used to follow the long-term development of glacier elevation and mass changes, in particular in High Mountain Asia (e.g., Bolch et al., 2008, 2017; Holzer et al., 2015; Maurer et al., 2016, 2019; Goerlich et al., 2017; Zhou et al., 2017, 2018).

The SRTM DEM was also used in combination with space-borne laser altimetry data from the ICESat GLAS sensor (Zwally et al., 2002) to obtain glacier elevation changes from regional (e.g., Kääb et al., 2012) to global (e.g., Gardner et al., 2013) scales. Additional data was also generated by a combination with mass change information derived from the GRACE gravimetry sensor (Wahr et al., 2004), or from GRACE alone (Jacob et al., 2012; Wouters et al., 2019). On a more regional scale, ICESat data alone have been used to determine glacier elevation changes (e.g., Moholdt et al., 2010, 2012; Bolch et al., 2013; Neckel et al., 2014). A comprehensive overview of LIDAR studies that include smaller scales and the two ice sheets is provided by Bhardwaj et al. (2016). The major issue when using ICESat data is the "correct" spatial extrapolation of the partly sparse point data to all altitudes with glacier coverage and consideration of the possibly different changes with altitude for glacier surfaces that are not covered or complex, for instance due to debris cover or surge behavior (Ke et al., 2015). For large and flat ice caps Cryosat-2 data also have been used to derive surface-elevation changes that cover the time period after ICESat and that provide a much higher data density (Gray et al., 2015; Foresta et al., 2016; Ciraci et al., 2018). However, as for the SRTM and TanDEM-X DEMs, the penetration of radar sensors into dry snow and firn can be very large and has to be corrected to the extent possible (e.g., von Albedyll et al., 2018).

Towards IPCC SROCC (2019), there have been further considerable improvements with respect to available datasets. Geodetic volume change assessments for entire mountain ranges have become possible thanks to recently available and comparably accurate DEMs from very high-resolution sensors (Shean et al., 2020). At the same time, new space-borne altimetry (ICESat-2) and gravimetry (GRACE-FO) missions are in orbit and about to release data products to the science community. This will open new opportunities for regional evaluations of results from different methods (e.g., Moholdt et al., 2012; Brun et al., 2017; Braun et al., 2019; Huber et al., 2020) as well as for truly global assessments of glacier mass changes and related contributions to sea-level rise (Wouters et al., 2019; Zemp et al., 2019). Together with *in situ* measurements of glacier mass balance, satellite-derived quantitative information about glaciers in entire mountain ranges is becoming the core of future-oriented worldwide glacier monitoring. However, the glacier research and monitoring community is facing new challenges related to data size, formats, and availability as well as by new questions with regard to best practices for data processing chains and for related uncertainty assessments.

New programs of collaboration with advanced observational technologies (remote sensing and geoinformatics) became more and more involved in glacier monitoring at the beginning of the 21st century (e.g., Paul et al., 2002; Bishop et al., 2004; Kargel et al., 2005) and new detailed glacier inventories were compiled in regions previously not covered in detail (Fig. 9) or, for comparison and change assessment, as a repetition of earlier inventories (e.g., Paul et al., 2004). This task was greatly facilitated by the launch of the Terra Satellite with its sensor ASTER and the GLIMS initiative (Kieffer et al., 2000). Later on, free access to the entire archive of (already orthorectified) Landsat imagery (Wulder et al., 2012) and the Shuttle Radar Topography Mission (SRTM) paved the way for compiling glacier inventories (including topographic information for each glacier) in various parts of the world (Kargel et al., 2014 and Chapters therein), for determination of glacier changes globally, and for numerous applications using GIS technologies and largely automated data processing (Paul et al., 2009; Racoviteanu et al., 2009; Kienholz et al., 2015). Today, the Sentinel satellites from the Copernicus programme have revolutionized space-borne glacier monitoring by providing multispectral images at 10 m resolution from nearly all parts of the world at 5-day intervals. This gives a higher chance for cloud-free image acquisition and allows rapid processes such as glacier surges in the Arctic to be followed with unprecedented detail (Willis et al., 2018, Fig. 15). Owing to the free data access policy of the GLIMS glacier database and a special effort of the glacier mapping community in support of IPCC AR5, an initial version of a globally complete dataset of vector outlines from more than 200,000 glaciers (named the Randolph Glacier Inventory, RGI) was published (Pfeffer et al., 2014) and has been improved several times (RGI Consortium, 2017).

The new dataset, in combination with DEMs, allowed for numerous global-scale applications that would have been unthinkable just a few years before. This includes automated calculation of glacier drainage divides (e.g., Kienholz et al., 2013) and center lines for all glaciers worldwide (Machguth and Huss, 2014), as well as glacier-specific elevation and mass changes as described above and detailed below. In addition, slope- and stress-dependent modeling of ice thickness distribution became possible at pixel resolution (e.g., Huss and Farinotti, 2012; Linsbauer et al., 2012; Farinotti et al., 2019a), providing digital terrain models without glaciers and enabling detailed modeling of future glacier evolution and related contributions to sea-level rise (e.g., Marzeion et al., 2012; Huss and Hock, 2015; Hock et al., 2019) amongst other hydrological applications from regional to global scales (Bliss et al., 2014; Linsbauer et al., 2016; Huss and Hock, 2018; Farinotti et al., 2019b).

The development of distributed energy and mass balance models has seen dramatic progress over the past two decades as well. The comprehensive long-term investigations of the energy and mass balance at a small sample of mountain glaciers together with dedicated field campaigns (e.g., Oerlemans, 2010) enabled the development of realistic numerical models considering the

Fig. 15 Sentinel-2 image of the surging Vavilov Ice Cap on Severnaya Zemlya in the Russian Arctic acquired on September 12, 2017. At its 10 m resolution individual crevasses are resolved and the dynamic evolution of the surge can be followed in unprecedented detail. Image: Copernicus Sentinel data 2017.

dominant physical processes. Simple statistical relations between meteorological parameters and measured mass balances (Reynaud and Dobrowolski, 1998) had already pointed to the strong dominance of (summer) air temperature with its influence on all energy- and mass-balance parameters (cf. Ohmura, 2001; Braithwaite et al., 2003; Arendt et al., 2009), including accumulation via the solid/liquid threshold temperature. The related simplified degree-day models (e.g., Braithwaite, 1995; Hock, 2005) then increasingly led to the treatment of the full energy and mass balance (e.g., Oerlemans, 1991, 2001; Klok and Oerlemans, 2002; Arnold et al., 2006; Anslow et al., 2008), albeit for individual glaciers only. Such models at various degrees of sophistication and complexity—even though almost exclusively for assumed temperate firn and ice—are now widely used but still need strong tuning due to highly uncertain assumptions about complex spatial patterns of snowfall and snow redistribution by wind and avalanches (e.g., Machguth et al., 2006a; Dadic et al., 2010; Sold et al., 2013; McGrath et al., 2015), among others (Machguth et al., 2008). Application of mass balance models at the regional (e.g., Machguth et al., 2006b, 2009; Paul et al., 2008) or global scale is thus subject to simplifications and parametrizations (e.g., using a degree-day approach instead of the energy balance) and requires careful calibration/validation with available time series of measured glacier mass balances (e.g., Giesen and Oerlemans, 2013; Marzeion et al., 2012; Radić and Hock, 2014).

Combined mass-balance and flow models have become important instruments to study past and possible future glacier evolution (e.g., Zuo and Oerlemans, 1997; Oerlemans et al., 1998; Sugiyama et al., 2007; Jouvet et al., 2009; Zekollari et al., 2014) or to help with interpreting past glacier changes with respect to global warming and sea-level rise (Oerlemans, 2005; Oerlemans et al., 2007; Fig. 16). Like the driving mass-balance models, their parameters also need heavy tuning (e.g., for ice deformation and basal sliding, or bed geometry). Despite remaining difficulties, such models reflect an advanced quantitative understanding of past and present glacier evolution and enable realistic sensitivity studies to be undertaken with respect to potential impacts on glaciers from continued energy increase in the climate system.

Recently, the Global Glacier Evolution Model GloGEM by Huss and Hock (2015) has been extended with a simplified flow model (GloGEMflow) to overcome the earlier simplified ice thickness change parameterization (Huss et al., 2010) for determination of future glacier volume change. This model was applied to a large sample of glaciers in the Alps (Zekollari et al., 2019). The Open Global Glacier Model (OGGM) by Maussion et al. (2019) provides a range of modular capabilities (mass and energy balance, ice flow, volume and geometric evolution) to compute future glacier evolution for both individual and groups of glaciers. Coded in Python, the source code is open to the community for further improvement (e.g., new functionalities) and offers the possibility to further improve calculations based on input from numerous experts.

4 Observed glacier changes and future evolution

4.1 Observed changes

The spectacular retreat of most glaciers during the past 100–150 years has been recognized by the public as well as by policy-related organizations far beyond scientific circles. It is among the clearest—if not the clearest—indication in nature that climatic conditions have been changing rapidly and at a worldwide scale (IPCC, 2013; IPCC SROCC, 2019). One of the most remarkable phenomena in this context is the interannual and spatial homogeneity of the signal as observed especially since the latest part of the twentieth century (Zemp et al., 2015; Fig. 17). Intermittent glacier re-advances were reported from various parts of the world, especially from

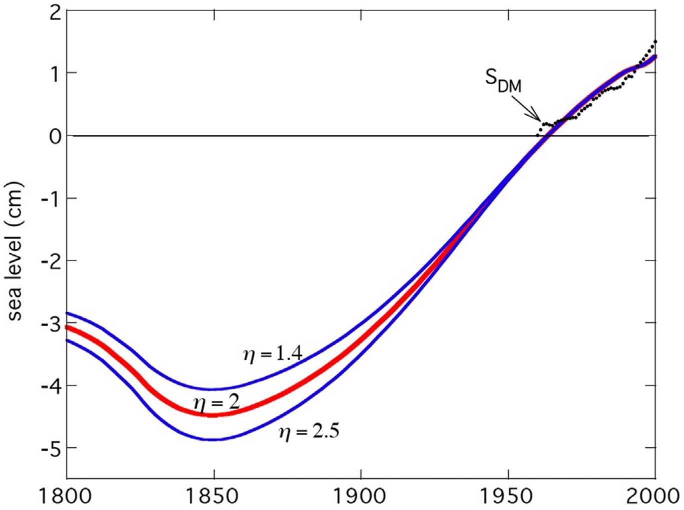

Fig. 16 Reconstruction of the glacier contribution to sea-level change based on data about cumulative glacier length change. Values for η denote different length/volume scaling and the dots (S_{DM}) show the cumulative effect of global annual mass balance as calculated by Dyurgerov and Meier (2005) from observations. Reproduced from Oerlemans J, Dyurgerov M, and van de Wal RSW (2007) Reconstructing the glacier contribution to sea-level rise back to 1850. *Cryosphere* 1: 59–65, with permission from J. Oerlemans.

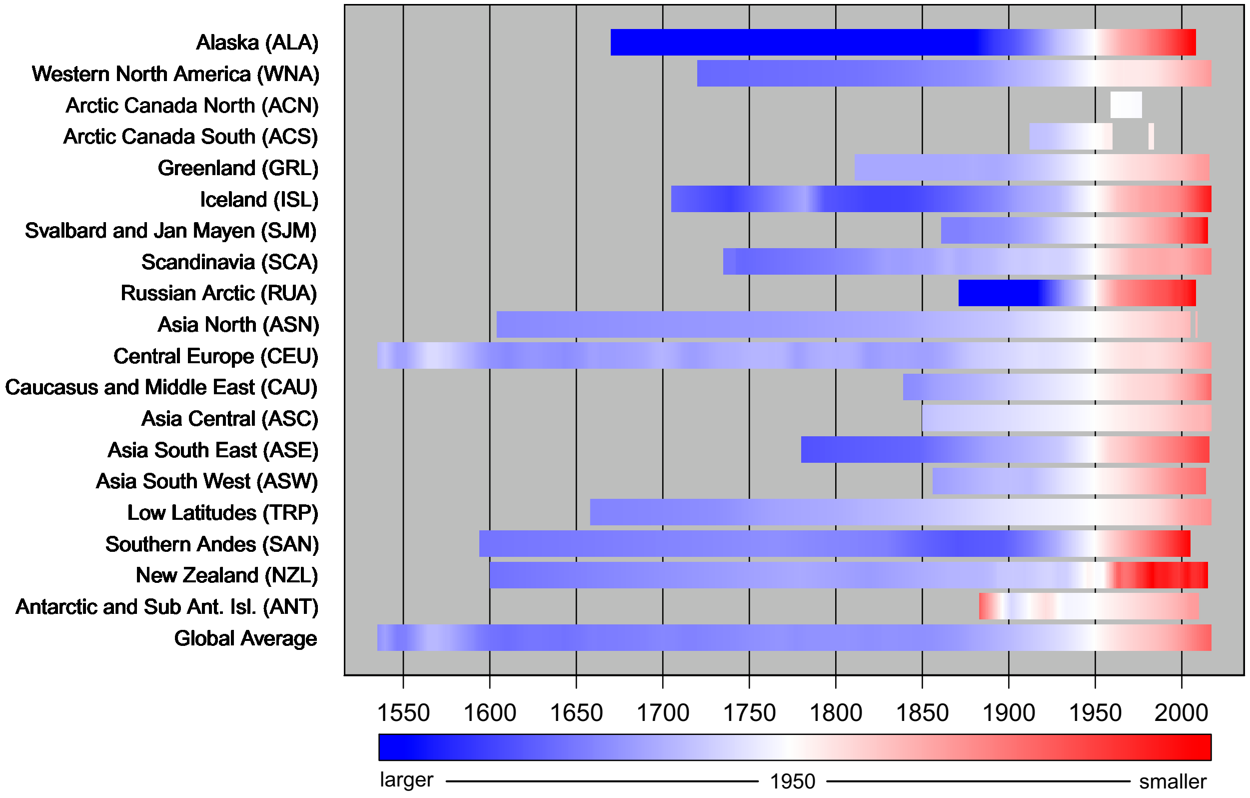

Fig. 17 Global glacier front variation observations from 1535 to 2017. Qualitative summary of cumulative mean annual front variations. The colors range from dark blue for maximum extents (+2.5 km) to dark red for minimum extents (–1.6 km) relative to the extent in 1950 as a common reference (i.e., 0 km in white). The figure is based on all available front variation observations and reconstructions, excluding absolute annual front variations larger than 210 m a^{-1} in order to reduce the effects of calving and surging glaciers. From WGMS (2020) Global glacier change bulletin no. 3 (2016–2017). In: M. Zemp et al. (eds.), ISC *(WDS)/IUGG(IACS)/UNEP/UNESCO/WMO*. Zurich, Switzerland: World Glacier Monitoring Service. Publication based on database version. doi: 10.5904/wgms-fog-2019-12, free download.

the Alps, where mass balances were predominantly positive during the late 1960s and 1970s. Similarly, the advance period of glaciers in Scandinavia during the 1990s can be related to a surplus of mass due to higher winter precipitation in the years before (e.g., Nesje, 2005). Steep outlet glaciers from major ice caps with short response times showed the strongest advances (Winkler and Nesje, 2009). For the first time, empirical information about glacier responses to well-documented and strong signals in mass-balance history started to become available. Other glacier advance periods such as in the 1890s and 1920s are less constrained by a specific meteorological forcing. Grove (2004) and Paul and Bolch (2019) provide overviews concerning the abundant literature related to this evolution. It has to be noted that in regions with many surge-type glaciers (cf. Sevestre and Benn, 2015) possible "advance periods" can actually also be related to several glaciers being in the active phase of their surge cycles. As surges generally occur independent of a specific climatic forcing (e.g., Jiskoot, 2011), a careful check of the sample is required.

Comparison with past glacier front variations can be made on the basis of moraines deposited during earlier maximum extents and of trees overridden by the ice after earlier minimum extents and now becoming exposed at retreating glacier margins. Interpretation of such deposits require careful reflections about the mechanisms of dynamic glacier response, the corresponding delay with respect to mass balance and climate forcing, as well as various other effects (e.g., building up of elevated morainic glacier beds as often observed for heavily debris-covered glaciers). Solomina et al. (2008) explain such glaciological frameworks and provide an overview, indicating that by the first years of the twenty-first century glacier lengths and volumes have shrunk beyond variability ranges during the late Holocene (about the past 5000 years) in many mountain ranges. Moreover, they found that in many cases upper (warm and energy-rich) limits of variability ranges of glacier extent and volume during even the entire Holocene may have been reached and could soon be exceeded (cf. Reichert et al., 2002). This is especially remarkable as present-day incoming radiation on the Northern Hemisphere is considerably reduced in comparison with conditions during the early Holocene. General overviews on glacier fluctuations over the past 2000 years and the Holocene are provided by Solomina et al. (2015, 2016).

In principle, unchanged climatic conditions would cause mass balances to approach zero values after some time. Constantly non-zero mass balances therefore reflect continued climatic forcing and the observed trend of increasingly negative mass balances is consistent with an accelerated trend in global warming and correspondingly enhanced energy flux toward the earth surface. Reconstructed mass balance time series for the Northern Hemisphere (Letréguilly and Reynaud, 1990) clearly revealed the widespread, long-term, and rather simultaneous trend of glacier mass loss during the twentieth century. Based on overview studies by Dyurgerov and Meier (2005), Kaser et al. (2006), Meier et al. (2007), Cogley (2009), and Zemp et al. (2009), the time between 1980 and 2020 shows a clear accelerating trend of mass loss (Fig. 8). Based on a combination of mass balance and inventory data, glaciers in the European Alps are now estimated to have lost about half their total volume (roughly −0.5% per year) between the end of the Little Ice Age (1850) and 1975. In their recent model inter-comparison, Farinotti et al. (2019a,b) estimate the glacier volume in Central Europe at 130 ± 30 km^3 for the year 2003. Based on the compilation of annual volume losses by Zemp et al. (2019) and a rough guess of about 4-km^3 volume loss in the most recent years of 2017 and 2018, a total volume loss of some 40–50 km^3 (slightly more than −1 km^3 per year) can be estimated for the time period since 1980 (Haeberli et al., 2019; Zekollari et al., 2019). Roughly 30 km^3 (−2 km^3 per year) were lost during the past 15 especially hot years (Haeberli et al., 2019; Zekollari et al., 2019). On a global scale, glaciers have lost about 9600 Gt of water from 1961 to 2016 according to Zemp et al. (2019), which gives a total glacier area of 705,740 km^2 and over a 55-year period a mean specific loss of −0.25 m w.e. per year. From 2006 to 2016 this rate doubled to −0.48 m w.e. or −335 Gt a^{-1} giving a roughly 0.9 mm contribution to sea-level rise each year (about 1/3 of all contributions) and a loss of 0.23% per year of the total remaining glacier volume (i.e., 161,543 km^3).

The new global assessment of glacier mass loss since 1961 by Zemp et al. (2019) has become possible by combining the annual mass balance measurements performed in the field with geodetic mass balances from nearly 20,000 glaciers derived from satellite data (DEM differencing) and statistical modeling. Somewhat lower values for global glacier mass loss over this recent period have been derived from a range of other methods (see 3.4), for example satellite altimetry and gravimetry (Bamber et al., 2018) or numerical modeling (Marzeion et al., 2018). However, this could also be due to slightly different samples. Independent of the techniques applied, all more-regional scale studies on glacier mass changes from DEM differencing revealed a high spatial heterogeneity of glacier-specific as well as regionally averaged values, dominant mass loss in nearly all regions of the world over the past two decades, and approximately stable conditions only in the Pamir-Karakoram-Kunlun Shan Region (e.g., Shean et al., 2020; Fig. 14). The reasons for this diverting behavior are not fully understood (field measurements are largely absent) and the special climatic and topographic conditions in this region are thus a key subject of current research (e.g., Farinotti et al., 2020). Analysis of historic DEMs reveal that balanced mass budgets persist in the Karakoram since the 1970s (Bolch et al., 2017; Zhou et al., 2017) and regular glacier surges occurred over at least the last 200 years (Paul, 2020).

Numerous studies have used time-series of satellite data to create glacier outlines from different points in time to perform change assessment. In most cases these studies are temporally restricted by the scenes available from Landsat Thematic Mapper (TM), i.e., back to about 1985, but often older images (back to 1972) from the Landsat Multispectral Scanner (MSS) are also considered. Some examples are Nuth et al. (2013) for Svalbard, Winsvold et al. (2014) for Norway, Paul et al. (2020) for the Alps, Khromova et al. (2019) for E-Russia, Veettil et al. (2017) for the tropical Andes, and Tielidze and Wheate (2018) for the Caucasus. An overview on earlier studies can be found in Vaughan et al. (2013). In all these regions the partly strong shrinkage (up to about −2% a^{-1}) of glaciers can be followed. The historic extents are particularly useful to constrain the regions where glacier volume changes are extracted. Some studies have used digitizing of trimlines and other techniques to also create maximum glacier extents from near the end of the Little Ice Age. Some examples are Baumann et al. (2009) for a part of Norway, Fischer et al. (2015a,b) for Austria, Meier et al. (2018) for Patagonia, Loibl et al. (2014) for SE-Tibet, or Lucchesi et al. (2014) for NW-Italy. The further application of these datasets (e.g., to initialize glacier evolution models) is still ahead.

4.2 Outlook for glaciers

Since the time of F.A. Forel, the first president of the International Glacier Commission, various aspects involved in monitoring have changed in a most remarkable way. There is hardly a question anymore of the originally envisaged periodical variations of glaciers. Under the growing influence of human impacts on the climate system (enhanced greenhouse effect), dramatic scenarios of future developments—including complete deglaciation of entire mountain ranges—must be considered (Marzeion et al., 2018; Hock et al., 2019; IPCC SROCC, 2019). For example, global and regional ice-mass decline rates have been generated for three scenarios of climate change based on representative concentration pathways (RCP) of greenhouse gas concentrations (Fig. 18). Such future scenarios may lead far beyond the range of historical/Holocene variability and most likely will introduce processes (extent and rate of glacier vanishing and difference from equilibrium conditions) without corresponding precedence. An example for such new conditions is depicted in the Sentinel-2 image from Franz-Josef-Land depicted in Fig. 9. Maybe for the first time, most of the ice caps in the region lost the largest part of their snow cover during the preceding summer and were subject to massive surface melt. For flat ice caps such as these, conditions like this could be the beginning of their end.

The increasingly rapid (vertical) thickness loss combined with the delayed (horizontal) retreat now in many cases has begun to cause a reduction in slope- and thickness-dependent driving stress. This effect, in turn, reduces ice flux toward the glacier margins and leads to a change from an active retreat mode of glacier shrinkage to more and more widespread stagnation, down-wasting, collapse, or disintegration modes of glacier vanishing (Paul et al., 2007a). A spectacular phenomenon accompanying such developments is the formation of large caves at the glacier bed (Fig. 19) and resulting collapse phenomena. Increased melt-water runoff at the glacier bed melts out large vaults in the ice above, which the reduced glacier thickness (decreasing normal stress) cannot efficiently compress anymore during wintertime. Rising warm (summer) air from the glacier forefield can then better penetrate into these large caves and enhance melting of the ice roof. Few quantitative effects from increased sub-glacial melting have been reported but may represent an additional positive feedback mechanism of glacier shrinking. There is also self-acceleration of glacier down-wasting due to the higher temperatures at lower elevations. In particular, for large and flat glacier tongues this process is becoming increasingly important. Locally, an increasing amount of debris cover might slow down this process (Jouvet et al., 2011). In contrast,

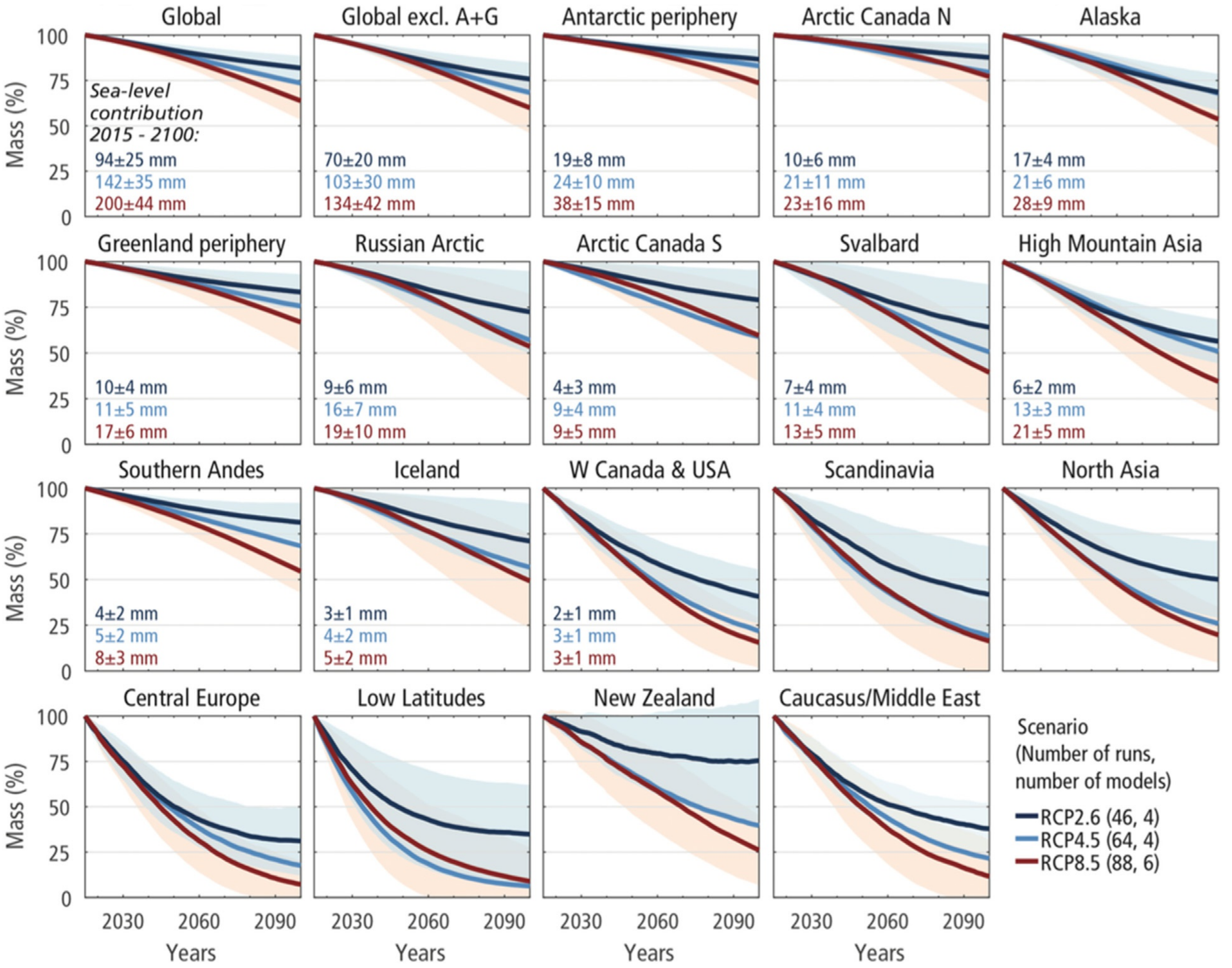

Fig. 18 Projected evolution of glacier mass for 2015–2100 relative to conditions in 2015 (100%) based on three RCP emission scenarios. Thick lines show the averages of 46–88 model projections based on four to six glacier models for the same RCP, and the shading marks ±1 standard deviation (not shown for RCP4.5 for better readability). From IPCC SROCC (2019) *Special Report on the Ocean and Cryosphere. WMO and UNEP*. New York: Cambridge University Press; based on Hock R, Bliss A, Marzeion B, Giesen RH, Hirabayashi Y, Huss M, Radić V, and Slangen ABA (2019) GlacierMIP—A model intercomparison of global-scale glacier mass-balance models and projections. *Journal of Glaciology* 65 (251): 453–456. doi: 10.1017/jog.2019.22

albedo lowering due to very small particles (e.g., transported to the glacier surface from increasingly ice-free lateral moraines) will enhance surface melt (Oerlemans et al., 2009; cf. Fig. 4). The increasing number of pro-glacial lakes (Paul et al., 2007a; Emmer et al., 2015) will enhance glacier melt for a couple of years but can increase the hazard potential for a much longer time (see Section 5).

A rapidly approaching problem in the field of glacier monitoring is the imminent disappearance of glaciers with long mass-balance records. Extensive mass-balance observations, as well as less sophisticated determinations of mass changes as regional climate signals, are based on studies of a limited number of small- to medium-size glaciers (Braithwaite, 2002) with surface areas typically a few km^2, and average thicknesses of tens rather than hundreds of meters (Table 2). With yearly thickness losses increasing from characteristic 20th-century values of a few tens of centimeters to nearly a meter, many of these glaciers are likely to disintegrate and completely vanish within the coming decades (Paul et al., 2007a; Zemp et al., 2006; Carturan et al., 2013). Such processes can already be observed throughout the Alps (Paul et al., 2007b): From the nine glaciers with long-term mass-balance series, some might disappear soon or have already started to disintegrate (Fig. 20; Carturan et al., 2013) as the example of the Caréser Glacier in the Italian Alps impressively shows.

Mass-balance measurements could lose value as a climate indicator due to disintegration of the observed glacier, years before the final ice remnant has melted (Carturan et al., 2020). In order to save the mass-balance network through the near future and to guarantee continuity of the measured data, new and larger glaciers which reach to higher elevations must be envisaged as replacements. Corresponding activities must start now or at least very soon, because an overlapping time period with parallel measurements on the previous as well as on the new glaciers must be foreseen (Carturan, 2016). A strategy for assessing suitable new glaciers should be based on field experience and local knowledge but should also consider observed changes (Pelto, 2010) and

Fig. 19 Subglacial cave at Morteratsch Glacier, Swiss Alps. The thin ice of the tongue (reduced normal stress) cannot close—in wintertime—the large channels melted out in the basal ice in summer. Ablation underneath the glacier starts to increase due to enhanced inflow of warm air. The glacier margin has melted back far beyond this site since this photo was taken. Photograph by J. Alean, 2009.

Table 2 Characteristics and changes of glaciers with long-term mass balance observations in the Alps.

Name	*Year*	A_{70} *(km²)*	A_{00} *(km²)*	ΔA *(%)*	$V^{6}_{7010}\,{}^{3}_{m}$	*h (m)*	$\sum b_{80-06(m\ w.e.)}$	ΔV *(%)*	$\Delta A/\Delta V$	*Decay time*
Sonnblick (AU)	1959	1.77	1.39	20	45	20–30	–15	55	0.36	2010–30
Vernagt (AU)	1965	9.56	8.36	20	435	40–50	–15	30	0.66	2050–?
Kesselwand (AU)	1953	4.24	3.85	10	255	55–65	–6	10	1	2020–?
Hintereis (AU)	1953	9.47	7.40	20	840	80–90	–21	20	1	2100–?
Careser (IT)	1967	4.68	2.83	40	175	30–40	–35	75	0.53	2010–30
Silvretta (CH)	1960	3.25	2.89	10	165	45–55	–15	28	0.36	2030–?
Gries (CH)	1962	6.60	5.26	20	540	75–85	–24	25	0.80	2040–?
St. Sorlin (FR)	1957	3.54	3.00	15	155	40–50	–24	50	0.30	2030–70
Sarennes (FR)	1949	0.90	0.50	44	25	20–30	–32	90	0.49	2010–40
Findelen	2005	19.9	15.3	23	1610	80–90	–19	21	1.1	2050–?

Year, beginning of regular mass balance determinations; A_{70}, surface area around 1970; A_{00}, surface area around 2000; ΔA, area change; V_{70}, estimated volume in 1970; h, estimated mean glacier thickness around 1970; $\sum b_{80-06}$, cumulative mass balance 1980–2006; ΔV, volume change from around 1970/80 to 2006; Decay time, estimated time of possible glacier disappearance; disintegration or complete loss of accumulation area (? = undefined). Values are rounded and rough estimates based on WGMS data and the parameterization scheme of Haeberli and Hoelzle (1995).

simplified rules. Apart from glacier size and elevation range, also their topographic (e.g., hypsometry) and morphological characteristics (e.g., breaks in slope) should be considered (Carturan et al., 2020).

5 Impacts and adaptation

With plausible/realistic scenarios of climate evolution the Earth's glacier cover will be dramatically reduced within the coming decades (Marzeion et al., 2018; Hock et al., 2019). Consequences of glacier disappearance are likely to be strongly felt in connection with landscape evolution, geomorphological systems processes, options for new developments and natural hazards/risks in cold mountains, as well as with the water cycle at local to global scales. The following is an attempt to outline prominent aspects concerning the full complexity of the involved changes, consequences and challenges.

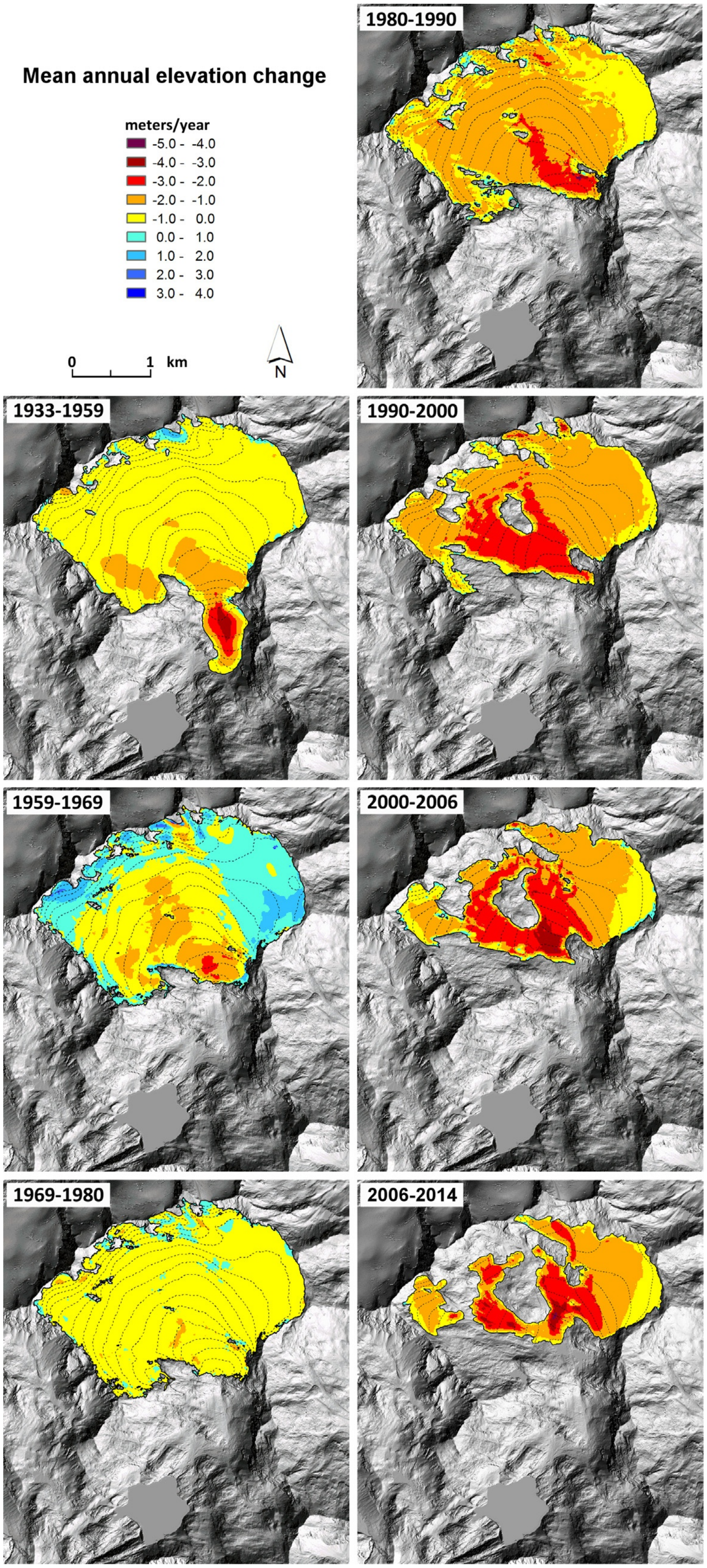

Fig. 20 Disintegration between 1933 and 2014 of Careser glacier (Italian Alps)—a long-observed important but now rapidly vanishing glacier in the worldwide glacier mass-balance network. Updated by L. Carturan based on Carturan L, Filippi R, Seppi R, Gabrielli P, Notarnicola C, Bertoldi L, Paul F, Rastner P, Cazorzi F,

Dinale R, and Dalla Fontana G (2013) Area and volume loss of the glaciers in the Ortles-Cevedale group (Eastern Italian Alps): Controls and imbalance of the remaining glaciers. *The Cryosphere* 7: 1339–1359.

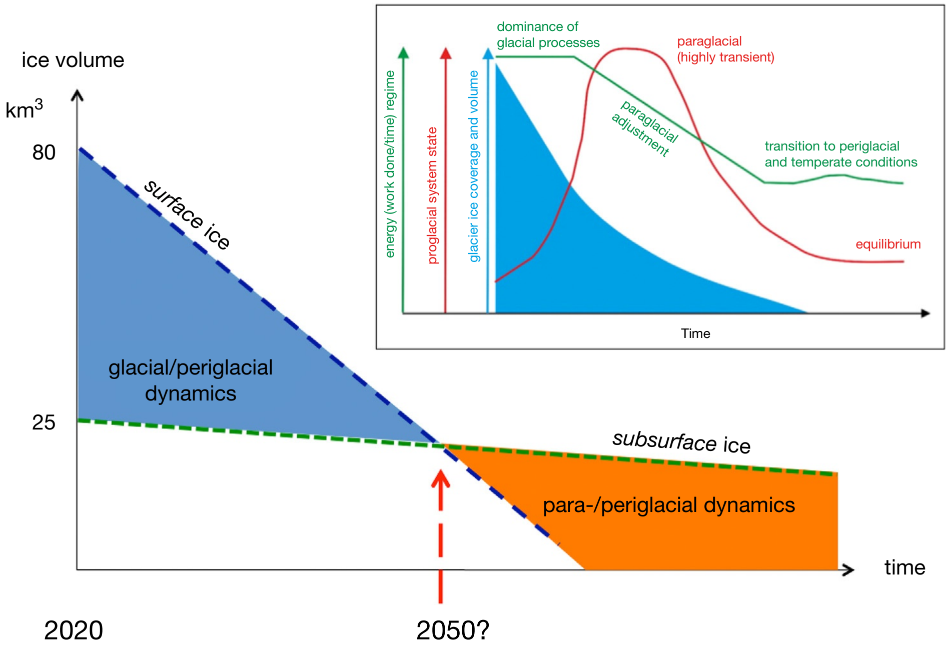

Fig. 21 Landscape transformation in the Alps and comparable mountain ranges. Periglacial processes relate to intense frost while paraglacial processes include system reorganization after de-glaciation. Because of slow heat diffusion at depth, subsurface ice in deeply thermally disturbed permafrost will continue to exist after surface ice in glaciers has long disappeared. From Haeberli W, Oerlemans J, and Zemp M (2019) The future of alpine glaciers and beyond. *Oxford Research Encyclopedia, Climate Science* 36 p. doi:10.1093/acrefore/9780190228620.013.769.

5.1 New landscapes and geomorphic systems

The progressive retreat and disappearance of glaciers causes new landscapes to form with geo- and ecosystems of rocks, debris, sparse vegetation, new lakes and slowly thawing permafrost (Haeberli et al., 2017). Glacial environments thereby primarily change into periglacial and fluvial systems (Fig. 21; Haeberli et al., 2017; Carrivick and Heckmann, 2017). As highly different response characteristics with time scales of decades to many millennia are involved (Ballantyne, 2002), conditions of strong and long-lasting dis-equilibrium of geomorphic and biological processes must be expected. Anticipating, understanding and modeling such new landscapes in view of potential opportunities and risks is a new, emerging research field. Pioneering investigations so far primarily created qualitative to semi-quantitative knowledge. Strong needs exist for comprehensive, quantitative modeling of highly interconnected systems as a basis for sustainable adaptation in view of possible human activities and infrastructure developments within the new landscapes as well as of large-scale process chains reaching far beyond them into already inhabited areas (Haeberli, 2017).

The basic step for quantitatively studying future landscapes in de-glaciating regions was the introduction by the World Glacier Monitoring Service (WGMS) of 3D/slope-related approaches for estimating glacier thicknesses in analyses of glacier inventory information (Haeberli and Hoelzle, 1995; cf. Haeberli, 2016). These approaches later combined with digital terrain information to construct distributed glacier-bed topographies (Linsbauer et al., 2009, 2012; Carrivick et al., 2016) provide realistic approximations of future surface topographies after ice-retreat. The resulting information enables glacier-bed overdeepenings to be determined as sites of possible future lake formation in various regions such as the Himalaya-Karakoram (Fig. 22; Linsbauer et al., 2016), the cordilleras of Peru (Colonia et al., 2017), Central Asia (Kapitsa et al., 2017) or the French Alps (Magnin et al., 2020). The reliability of the obtained information must be considered with respect to the accuracy of calculated glacier-bed topographies and to local factors influencing lake formation processes. Extensive testing with field data and inter-comparison of numerical models for ice-thickness calculations (Farinotti et al., 2017) document that absolute values of glacier thickness remain uncertain within about 10–20% of the estimated values for larger samples and even beyond that for individual cases. This is primarily due to the difficulty of appropriately parameterizing mass fluxes related to the surface mass balance and flow of unmeasured glaciers. In contrast to such considerable uncertainties about absolute elevations of glacier-bed topographies and potential future surfaces, corresponding spatial patterns and topological characteristics more directly depend on surface slope and are therefore more reliable. The best procedure for mapping presently still glacier-covered overdeepenings is to combine numerical modeling with morphological criteria (Frey et al., 2010; cf. Colonia et al., 2017; Magnin et al., 2020) for defining confidence levels of the obtained results. Beyond such technical aspects, the possible existence of still unpredictable, local deep and narrow incisions at potential lake outlets

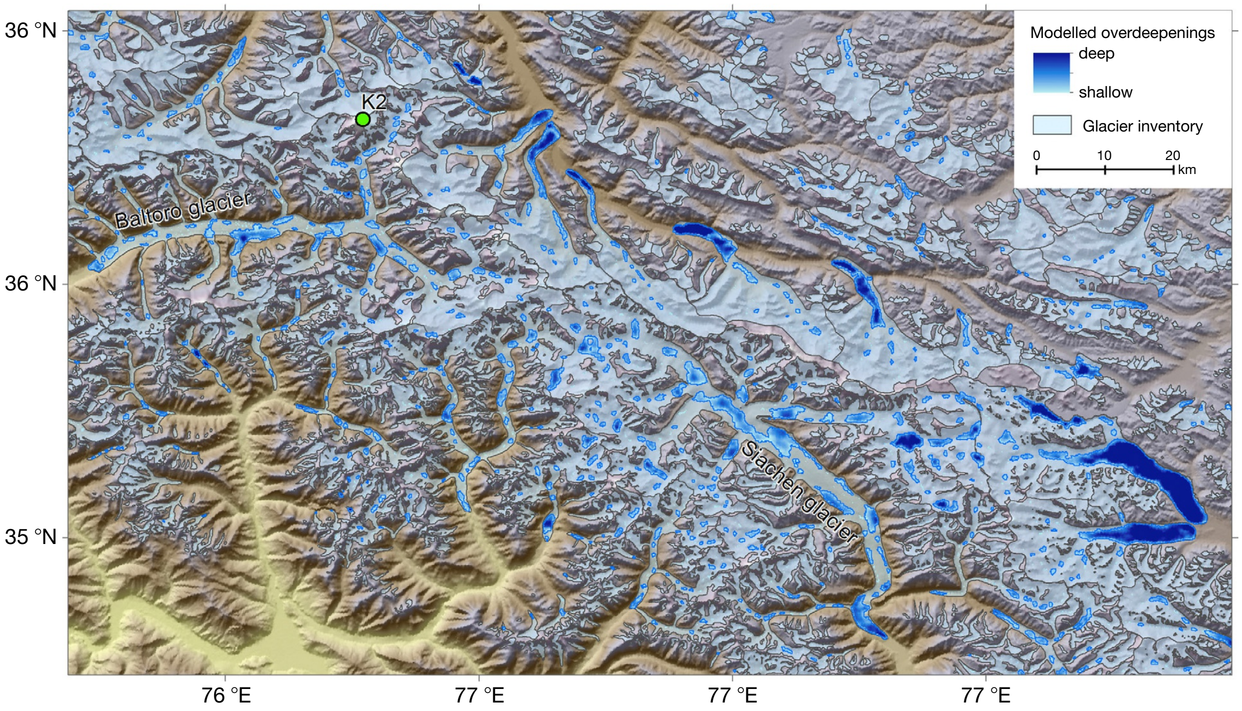

Fig. 22 Modeled glacier-bed overdeepenings as sites of potential future lake formation in the Himalaya-Karakoram region (cf. Linsbauer et al., 2016).

can limit lake formation. Moreover, sediment infill defines potential future lake-lifetimes and must be considered in connection with lake geometries and sediment cascades in the lake catchment.

Important aspects that characterize geomorphic systems and surface processes in newly developing, de-glaciating mountain landscapes relate to slope instability and activated sediment cascades. This is because the slow stabilization of freshly exposed debris by vegetation and soil development takes place over time periods of decades to centuries and millennia (Egli et al., 2006; Eichel et al., 2015; Cuesta et al., 2019), and to processes of glacial de-buttressing and permafrost degradation (Ballantyne, 2002; Noetzli and Gruber, 2009; Kos et al., 2016; Deline et al., 2020). Many ice-related rock avalanches were recently documented around the world (Huggel, 2009; Deline et al., 2020; Evans et al., 2020). Examples are the Brenva and Triolet rock avalanches in the Mont Blanc massif in the eighteenth and twentieth centuries (Deline, 2009), the Kolka-Karmadon ice/rock-avalanche in the Caucasus (Huggel et al., 2005; Evans et al., 2009), a significant number of rock avalanches in the Karakorum (Hewitt, 1988), and in British Columbia, Canada (Geertsema et al., 2006; Coe et al., 2018), just to name a few. Continued atmospheric temperature rise could cause enhanced meltwater percolation into cold firn with a widespread transformation of cold to polythermal or temperate ice on steep slopes and thus alter the potential source zones for ice avalanches (Huggel et al., 2010), because cold ice masses are more stable at steeper slopes than temperate ice (Huggel et al., 2004).

The number of large rock-ice avalanches from warming and degrading permafrost is apparently increasing (e.g., Coe et al., 2018; cf. Krautblatter et al., 2013; Patton et al., 2019). This is especially dangerous where large high-energy events (De Blasio et al., 2018) can affect major lakes and produce impact flood waves with far-reaching consequences (Haeberli et al., 2017), or where subsequent process chains including debris flows reach inhabited areas (Carey et al., 2012a; Walter et al., 2019). Sediment cascades in new landscapes can be intensified as the disappearance of ice in most cases implies increased sediment availability. Since the end of the Little Ice Age, new proglacial areas with marked moraines and large amounts of poorly consolidated sediments have been uncovered and are now prone to erosion, slope failure and debris flows. In the Alps, some of the largest debris flows that have occurred in recent years originated from such formerly glacierized areas (Zimmermann and Haeberli, 1992; Chiarle et al., 2007; Huggel et al., 2010). Erosion rates in recently-exposed moraine-covered terrain or steep rock slopes can drastically increase (Hinderer, 2001; Fischer et al., 2012). The resulting additional input of loose material can affect river systems over extended distances and time scales (Lane et al., 2017). The enhanced sediment availability and erosion will likely have serious implications for the management of alpine reservoir lakes connected to hydropower facilities (Boillat et al., 2003). More rapid filling of lakes by sediment and enhanced input of sediment into turbines will lead to extremely costly maintenance, which additionally affects the operation schedule of these facilities. Sediment cascades can, however, also be locally interrupted by the formation of new lakes in de-glaciating areas, which function as efficient sediment traps, holding back larger components and high percentages of suspended load. Repeated bathymetric surveys of new lakes provide important information about sediment supply and related future life times of new lakes. Characteristic supply rates into new lakes from de-glaciating catchments have been derived from Pasterze, Austrian Alps, to amount to about 10^2 to 10^4 tons per km^2 per year (Geilhausen et al., 2012). Catchment size and erosion rates define the ratio between lake

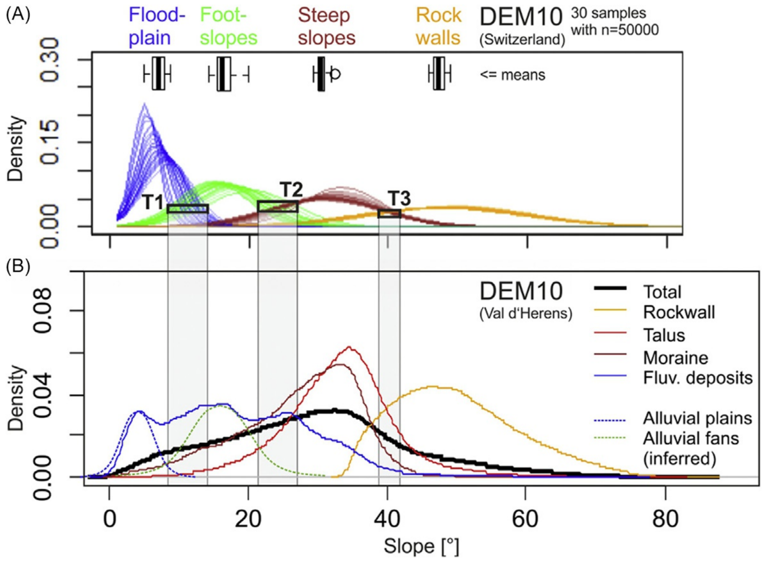

Fig. 23 Normal distributions of slope for four proglacial landform types (A); the ranges where probability density functions intersect are denoted T1 (floodplain ⊠ footslopes), T2 (footslopes ⊠ steep slopes) and T3 (steep slopes ⊠ rock walls). Boxplots show the distribution of corresponding means. Intersections of empirical slope distributions of four landform types from a geomorphological map of Val d'Hérens (B). From Carrivick JL, Heckmann T, Turner A, and Fischer M (2018) An assessment of landform composition and functioning with the first proglacial systems dataset of the central European Alps. *Geomorphology* 321: 117–128. doi:10.1016/j.geomorph.2018.08.030

volumes and the input rate of sediments: Shallow depressions may rapidly transform into floodplains but a good number of modeled new lakes (if formed) can easily attain lifetimes of 10^2–10^3 years even with high debris inputs (Linsbauer et al., 2016). A promising way forward towards more detailed quantification and improved projections of related emerging geomorphic systems in new landscapes after ice retreat is to combine information from estimates of bedrock or sediment characteristics of glacier beds to be exposed (Zemp et al., 2005) with quantitative landform analyses of already exposed glacier fore-fields. Carrivick et al. (2018), for instance, attribute major geomorphological landform types (Fig. 23) and process domains (fluvial, fans, moraine/scree, bedrock) in mountain catchments to characteristic ranges of slope angle. Information about the latter exists in now-available "DEMs without glaciers" (Linsbauer et al., 2009).

5.2 Glacier vanishing and water

Mountains with snow and ice are important "water towers" serving vast surrounding lowlands (Immerzeel et al., 2019). These water supplies are, however, also highly sensitive to impacts from global warming. Corresponding consequences affect the water cycle and related aspects of human livelihood at local to regional, continental and global scales (Haeberli, 2019).

At global scales, sea-level rise will constitute a major challenge for human civilization (IPCC SROCC, 2019; Allison et al., 2020). The total possible contribution of glaciers and ice caps other than the continental ice sheets of Antarctica and Greenland is estimated at a few tens of centimeters (Oerlemans et al., 2007; cf. Huss and Hock, 2015). Glacier melt-water influx to the ocean has been increasing during the past few decades (Fig. 24) and most likely continues far into our century to constitute a primary source of sea-level rise (Meier et al., 2007). An estimated 10–15% of the ice remaining in tidal glaciers is already below sea level (Haeberli and Linsbauer, 2013; cf. Huss and Hock, 2015; Farinotti et al., 2019a). Some glacier melt-water might not reach the ocean but evaporate along systematically lengthening paths to the ocean or be kept back in over-deepened parts of glacier beds, which may become lakes or groundwater-bearing floodplains when exposed by glacier retreat (Marzeion et al., 2016). The latter effect is pronounced in the Himalaya-Karakoram region where a large number of new lakes and floodplains may come into existence (Fig. 22; Linsbauer et al., 2016). Especially in Asia, considerable amounts of glacial melt-water do not reach the ocean but end in endorheic basins (Huss et al., 2017). Due to the strongly-delayed response of larger glaciers (tens of years to more than a century, Haeberli and Hoelzle, 1995) important commitments exist: Future large additional glacier mass losses must be considered inevitable, making the identification and execution of appropriate adaptation measures mandatory (Marzeion et al., 2018).

At continental to regional scales, impacts from global warming increasingly affect the seasonality of river discharge as liquid precipitation is more quickly released than when stored in snow and glacial systems. An important seasonal shift of water resources from summer to spring takes place, unfavorably affecting agriculture and irrigation in the lowlands (Hagg et al., 2013). In fact, seasonal changes in available water resources due to enhanced early melting of snow and ice are among the most important socio-economic implications of climate change effects on glaciers, especially in semi-arid regions (Bradley et al., 2006; Sorg et al., 2012). A robust projection is the general shift of mid-latitude peak runoff from summer toward spring. Continued atmospheric warming

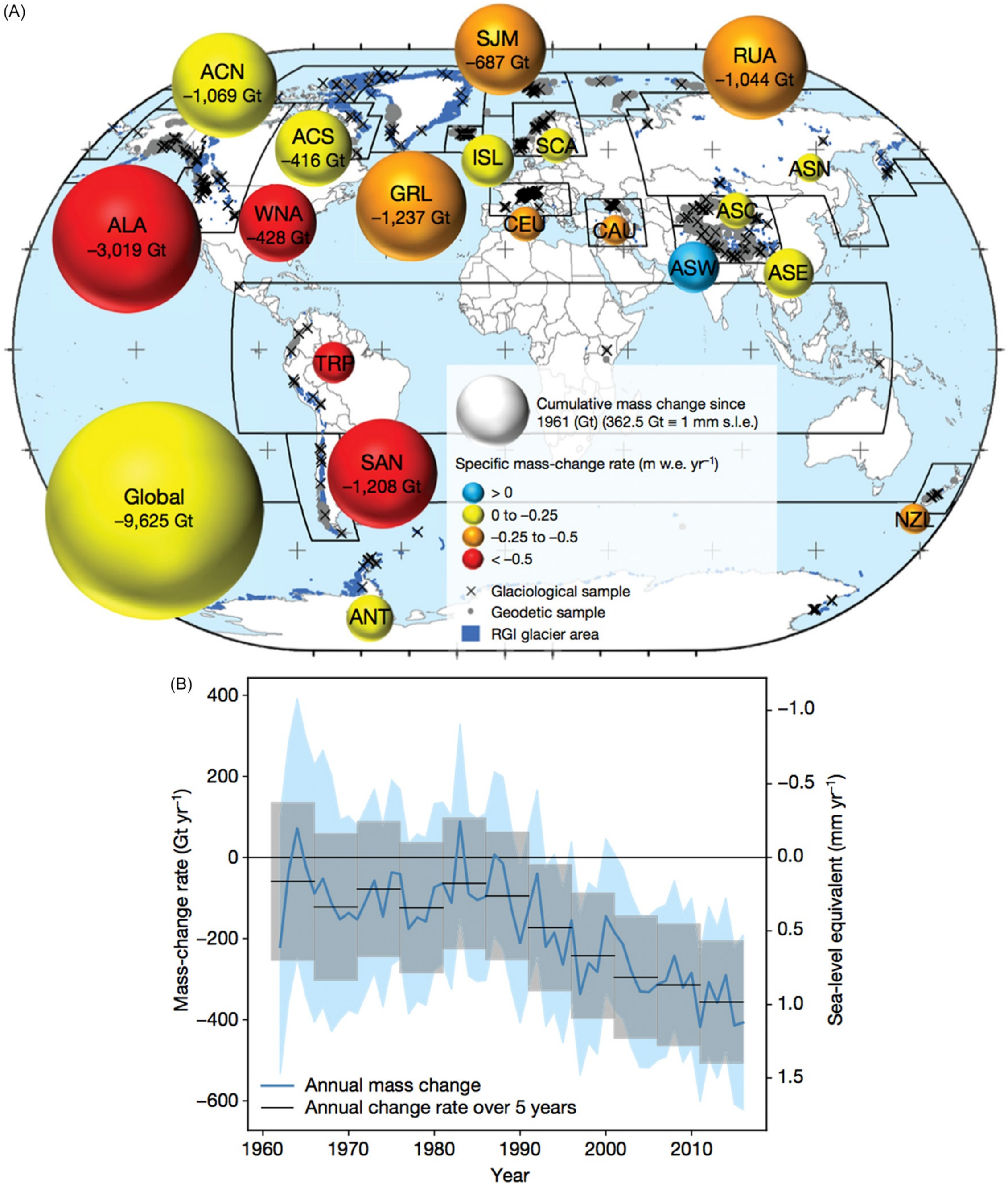

Fig. 24 Overall regional glacier contribution from 1961 to 2016 (A) and overall development in time of global glacier melt-water contribution to sea level rise (B). From Zemp M, Huss M, Thibert E, Eckert N, McNabb R, Huber J, Barandun M, et al. (2019) Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. *Nature* 568 (7752): 382–86. doi: 10.1038/s41586-019-1071-0.

first causes additional water supplies at the expense of the reduction of long-term water storage as ice in glaciers. Such melt-water surplus goes through a maximum called "peak water" in areas where glaciers still exist but then diminishes with further decreasing glacier areas. The timing of peak water is primarily a function of glacier size and climate scenarios. For most mountain ranges on Earth, peak water already has occurred during the past decades or will take place until around mid-century (Huss and Hock, 2018). Only those catchments with the largest glaciers in the Himalaya-Karakoram range or in the Chugach Mountains of Alaska will experience peak flow as late as the second half of the century. In regions with dry/warm seasons such as the upper Tarim River in central Asia (Duethmann et al., 2015), stream-flow tended to increase due to glacier mass losses during the past decades in some headwater catchments but it is likely to soon start declining if not compensated by increasing precipitation (Hoelzle et al., 2019). As compared to a 1961–90 reference period, Juen et al. (2007) already modeled a ~10–20% runoff decrease in the dry season for a

Fig. 25 Proglacial lakes in exposed sedimentary glacier beds at Hooker (upper left) and Mueller (from lower left to center) Glaciers, New Zealand. Photograph by T. Chinn.

34% glacierized catchment in the Cordillera Blanca, Peru, depending on time horizons (2050, 2080) and emission scenarios, and a ~10–25% runoff increase during the humid season (cf. Baraer et al., 2012). An ongoing shift towards earlier snowmelt tends to increase the pressure on freshwater availability during the early vegetation period (Dietz et al., 2014). Some limited amounts of water from slowly-thawing subsurface ice in widespread permafrost areas is likely to continue flowing during extended future time periods (centuries; cf. Jones et al., 2018). This phenomenon needs intensified scientific research.

At local to regional scales, glacier thinning and retreat has led to the formation of numerous new lakes in high-mountain regions (Fig. 25) and more lakes are likely to form in the near future as a result of continued glacier shrinkage. The formation of new lakes in de-glaciating areas involves opportunities but also enhanced risks (Haeberli et al., 2016a). Opportunities primarily relate to hydropower production and freshwater supply while risks concern sudden and far-reaching floods. Disastrous outbursts floods from glacier lakes have repeatedly been reported (Evans and Clague, 1994: cf. Emmer, 2017; Clague and O'Connor, 2020). Glacier lakes can be classified into several types according to their position relative to the glacier, their morphogenetic setting and the dam characteristics (Richardson and Reynolds, 2000; Clague and Evans, 2000; Cook and Quincey, 2015). Outburst susceptibility is closely related to such criteria (Emmer and Vilímek, 2014). Lake geometries are extremely variable. Detailed bathymetries and model calculations show that no simple geometric rules exist. Predictions of water depths or volumes for unmeasured lakes from empirical-statistical rules have high uncertainty ranges (Haeberli et al., 2016b; Muñoz et al., 2020) and must be considered to be order-of-magnitude estimates only.

5.3 Dealing with options and risks

As a consequence of continued glacier retreat, areas are becoming increasingly accessible for various new human activities. These areas are, however, in transient conditions with intensified surface processes related to complex interconnected geo- and ecosystems which are far out of equilibrium and will need long time periods to stabilize. Moreover, various interests are coming into play and need harmonization. Options and risks related to these newly-accessible regions and their surroundings must therefore be carefully considered. Constructive and critical reflection, especially concerning possible uses, has hardly begun yet but is of highest importance in view of sustainable adaptation strategies. Options for infrastructure development primarily relate to hydropower development, to freshwater supply and to tourism, but these options must respect hazard/risk potentials, environmental concerns and landscape protection (Haeberli et al., 2016a). Regional-to-global worldwide future potential capacities concerning freshwater supply and hydropower production from possible artificial reservoirs in remaining glacier-covered regions have been roughly assessed (Farinotti et al., 2016, 2019b) and a number of specific projects in the European Alps are already quite far advanced (Terrier et al., 2011; Haeberli et al., 2016a).

Concepts of hazard reduction and risk management commonly relate to future time periods of decades. In connection with continued global warming and ice disappearance, anticipation of hazards over such future time periods faces difficult challenges: Ice conditions and related natural systems will not only be different from the past but also from the present. Scenario-based assessments must therefore be applied. A technical guidance document has been produced by GAPHAZ (2017), the Scientific Standing Group for Glacier and Permafrost Hazards in Mountain Regions of the International Association of Cryospheric Sciences

(IACS) and the International Permafrost Association (IPA). The treatment of process chains with potential impacts far beyond historically-affected reaches (Huggel et al., 2005; Carey et al., 2012a; Walter et al., 2019) represents a specific challenge, especially in relation to already-existing but also possible future new lakes and in connection with decreasing stability of surrounding de-buttressed slopes and icy peaks as the result of degrading permafrost (Magnin et al., 2020). Remarkable progress has been achieved with the modeling of such process chains using corresponding model chains (Schneider et al., 2014; Westoby et al., 2014; Somos-Valenzuela et al., 2015, 2016; Frey et al., 2018; Mergili et al., 2020). Critical questions thereby relate to assumptions about break-off volumes in initial high-energy mass movements (Schaub et al., 2016; cf. De Blasio et al., 2018) and to the quantification of erosional effects and corresponding transitions between floods, hyperconcentrated flows and debris flows (Schneider et al., 2014). The frequency of outburst floods from moraine-dammed lakes seems to remain rather stable in time despite growing lake areas (Harrison et al., 2018; Veh et al., 2018, 2019). There are several possible reasons for this, among others being that breaching of moraine dams can eliminate dangerous lakes, mostly making such events non-repetitive, or that continuous glacier retreat leads to lake formation at increasing distances from terminal moraines built up during repeated Holocene glacier advances under colder conditions. The latter effect, on the other hand, enables lake formation closer and closer to slowly destabilizing rugged icy peaks, thereby increasing the probability of floods from impact waves in connection with ice-rock avalanches.

Hazard assessments in view of dangerous natural processes (Haemmig et al., 2014; Schneider et al., 2014; Muñoz et al., 2016; Frey et al., 2018) form an essential basis for developing risk reduction strategies. In view of lakes and long-term adaptation strategies, however, and especially in connection with possible needs for large infrastructure and investment, the first steps have been undertaken to include societal perspectives such as risks from droughts or competitive and growing demands (Drenkhan et al., 2019; cf. Brunner et al., 2019). Concerning new lakes, multi-purpose projects combining flood retention, hydropower production, freshwater supply and possibly even tourism may enable politically acceptable options with realistic funding possibilities (Kellner, 2019). Such integrative solutions require participatory planning (Haeberli et al., 2016a) and polycentric governance (Kellner et al., 2019). Difficult questions concerning loss and damage may thereby have to be analyzed (Huggel et al., 2019) in order to avoid unintended conflicts (Carey et al., 2012b) and to fully meet the challenge of sustainably adapting to impacts from climate change in presently still glaciated mountain systems (McDowell et al., 2019).

6 Conclusion and outlook

Systematic and internationally coordinated observation with free data access of glacier response to climatic changes already started in the late 19th century. Its results today represent a unique information source concerning the long-term evolution of climate-sensitive cold-mountain environments. Focused field investigations combined with products from modern remote sensing technologies today provide rich, worldwide and detailed quantitative data, which document a clear overall trend of rapid if not accelerating glacier shrinking. This phenomenon is perceivable and understandable to a wide public as a key indication of ongoing energy increase in the global climate system. Results of corresponding numerical model calculations as related to past developments as well as to realistic future scenarios have remained robust for decades.

As glacier retreat is a delayed response to climate change, most glaciers are now far out of equilibrium. Moreover, future climate scenarios only start to markedly deviate from each other after about mid-century. As a consequence of these two factors, further rather dramatic glacier mass losses appear to be inevitable and many low-latitude mountain chains may essentially loose their glaciers within the coming decades. It is therefore now high time to start thinking beyond glaciers and to plan for adaptation strategies related to cold-mountain environments in transition from glacial to periglacial environments and under conditions of strong and long-lasting imbalances. Realistic and comprehensive anticipation, modeling and managing is needed of new landscapes with their surface processes as well as options and risks for human activities. In this rapidly emerging research field, modern quantitative, integrative and future-oriented geomorphology must play a key role.

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