The Future of Alpine Glaciers and Beyond

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Summary and Keywords

Like many comparable mountain ranges at lower latitudes, the European Alps are increasingly losing their glaciers. Following roughly 10,000 years of limited climate and glacier variability, with a slight trend of increasing glacier sizes to Holocene maximum extents of the Little Ice Age, glaciers in the Alps started to generally retreat after 1850. Long-term observations with a monitoring network of unique density document this development. Strong acceleration of mass losses started to take place after 1980 as related to accelerating atmospheric temperature rise. Model calculations, using simple to high-complexity approaches and relating to individual glaciers as well as to large samples of glaciers, provide robust results concerning scenarios for the future: under the influence of greenhouse-gas forced global warming, glaciers in the Alps will largely disappear within the 21st century. Anticipating and modeling new landscapes and land-forming processes in de-glaciating areas is an emerging research field based on modeled glacier-bed topographies that are likely to become future surface topographies. Such analyses provide a knowledge basis to early planning of sustainable adaptation strategies, for example, concerning opportunities and risks related to the formation of glacial lakes in overdeepened parts of presently still ice-covered glacier beds.

Keywords: Alps, glaciers, global warming, monitoring, numerical models, landscapes, lakes, hazards, adaptation to climate change

Introduction

There is not much left of a future for glaciers in the Alps (Figures 1 and 2). As in many other icy mountain ranges on Earth, glaciers in the Alps are shrinking rapidly and beyond historical precedence (Zemp et al., 2015). As a consequence of continued if not accelerated global warming, they are likely to largely disappear within the coming decades (Huss, 2012; Zekollari, Huss, & Farinotti, 2018; Zemp, Haeberli, Hoelzle, & Paul, 2006).

Figure 1. Aletsch glacier as the key element of the UNESCO World Natural Heritage Swiss Alps Jungfrau-Aletsch. Simple as well as complex model calculations show that even with moderate scenarios of continued atmospheric warming most of this largest glacier in the European Alps will probably disappear during the coming decades. Rapid transformation is taking place from a glacial into a peri-/paraglacial landscape under conditions of strong disequilibria in geo-/ecosystems and with a sequence of new lakes.

Photograph Frank Paul, August 1992.

For historical reasons, glacier changes in the densely populated Alps are among the best documented in the world. Systematic observations had already started during the 19th century (Forel, 1895). The resulting quantitative information formed the basis for investigating the relation between climate change and glacier fluctuations (Oerlemans, 2001). Especially since the late 20th century, these models not only provide a basic process understanding but also enable realistic future scenarios to be considered concerning effects from human-induced climate change. As a latest development during the past about 10 years, quantitative anticipation and modeling of future landscapes in de-glaciating regions constitute an emerging field of scientific research in sustainable adaptation strategies with respect to impacts from climate change (Haeberli, 2017).

This article compiles some brief notes on historical perspectives about glaciers and climate change in the Alps, describes and analyzes available observational documentation and model results, and provides an outlook concerning future landscapes, that is, a view to likely developments and conditions after the termination of the future for most glaciers in the Alps.

Historical Perspectives

Because of the close neighborhood and interaction between humans and icy peaks in the European Alps, *glacier science has a long and rich history in this region*. In fact, the early roots of international glacier research are found here, and from here important impulses had already stimulated international research since the 19th century. The interdisciplinary work of Agassiz and colleagues at Unteraar Glacier (Agassiz, Guyot, & Desor, 1847), for instance, marks the beginning of modern experimental studies on mountain glaciers, and in 1894, internationally coordinated long-term glacier monitoring was established following the example of systematic glacier observations in the Austrian and Swiss Alps (Fischer et al., 2018; Forel, 1895; World Glacier Monitoring Service [WGMS], 1998). Here, some historical milestones concerning research about past changes and the likely future of glaciers in the Alps are sketched.

From the very beginning, *long-term observations of glaciers in the Alps* constituted a central part and mirror of internationally coordinated glacier monitoring (Haeberli, 2007). Until the Second World War, glacier length changes measured in the field constituted the primary database. The two world wars and the economic crises in between them thereby not only limited the possibilities of observations but also the perception of the collected information in the scientific community and the public: while the intermittent re-advances of Alpine glaciers around 1890 and 1920 had reinforced ideas about *"les variations périodiques"* of glaciers and climate in connection with solar cycles (World Glacier Monitoring Service [WGMS], 1998), the strong general glacier shrinkage during the 1930s and 40s was hardly noted. Following the example of work on glaciers in Scandinavia (Storglaciären/Storbreen) in the late 1940s, a network of glacier mass balance programs was established in the Alps (Zemp, Hoelzle, & Haeberli, 2009). This "missing link" in the process chain "climate–mass balance–ice thickness–ice flow–length change" in cases completed by energy balance measurements successfully improved the process understanding concerning climate–glacier relations (Oerlemans, 2001). Around 1970, systematic glacier inventories, mainly based on aerial photography and early satellite imagery (Landsat), were compiled in the Alps and worldwide in order to assess patterns of glacier distribution, characteristics, and changes representative at the scale of countries and entire mountain ranges like the Alps (Haeberli & Hoelzle, 1995; WGMS, 1989). Since about the turn of the century, high-resolution satellite imagery, together with digital terrain information, shifted the interest toward systematic large-scale observations, especially in view of water resources (sea level, water supply at regional to continental scales; Huss & Hock, 2018; Marzeion et al., 2016). Local mass balance programs can increasingly be supported by modern geodetic surveying technologies (LIDAR, drone photogrammetry). Glacier length changes can in principle now be determined automatically using algorithms for flow-line construction but become increasingly problematic in their interpretation because of long response times and processes of collapse, disintegration, and downwasting that now often predominate over active retreat (Paul, Kääb, & Haeberli, 2007).

First attempts to *model glaciers* mathematically had already been made around the year 1900 (Finsterwalder, 1907; De Marchi, 1895; cf. Clarke, 1987). With the International Conference on Glacier Fluctuations and Climatic Change in Amsterdam 1987, modelers and observers started to closely work together. Numerous and systematic efforts were undertaken to model climate–glacier relations. They built on quantitative information from measurements about mass–energy balance and flow on individual glaciers and from glacier inventories for larger glacier ensembles. The simplest approaches compared quasi-steady state conditions over time intervals roughly corresponding to the response time of the glaciers. Already such basic calculations showed that by the second half of the 21st century, continued atmospheric warming could reduce the surface area and volume of the Alpine glaciers to a few percent of the values reconstructed or estimated for the “Little Ice Age” maximum (Haeberli & Hoelzle, 1995). Systematic transient model calculations for individual glaciers, using the concept of dynamic fitting to observed long-term length changes (Oerlemans et al., 1998), confirmed such rough estimates and introduced more detailed process understanding. An increasing number of numerical model simulations followed, based on approaches at various degrees of complexity for individual glaciers (e.g., Jouvet, Huss, Funk, & Blatter, 2011; Zekollari, Fürst, & Huybrechts, 2014) or nationwide ensembles of glaciers (Salzmann, Machguth, & Linsbauer, 2012), increasingly considering large samples of glaciers over entire mountain ranges (Huss, 2012; Linsbauer, Paul, Machguth, & Haeberli, 2013, Zekollari et al., 2019) and even at global scale (Huss & Hock, 2015; Huss et al. 2017). A prerequisite for such modeling of large glacier samples had been the combination of slope-related ice-thickness estimates and digital terrain information for calculating glacier-bed topographies (Linsbauer et al., 2009; Linsbauer, Paul, & Haeberli, 2012), which also form the basis for looking beyond disappearing glaciers.

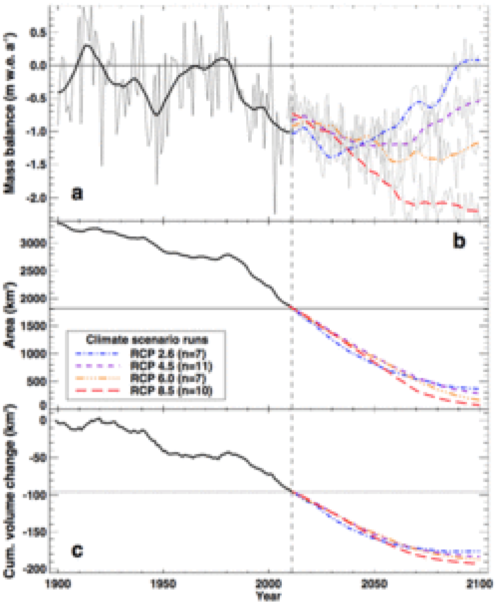

Figure 2. Mass balance, area and ice volume change series extrapolated to all glaciers in the European Alps for 1900–2100. The vertical dashed line indicates the onset of future modeling results (2011). (a) Area-weighted average of mean specific annual mass balance. For 2011–2100 the ensemble mean mass balance of n GCMs according to the four RCPs is shown. Annual series (gray) are 11-year low-pass filtered (bold). (b) Total glacierized area in the European Alps. (c) Cumulative ice volume changes assuming an ice density of 900 kg m^{-3}.

Source: Huss (2012)

Anticipating and modeling *new landscapes* in de-glaciating mountain ranges such as the Alps is the youngest among the scientific domains treated here. Three main factors opened this emerging research field around the turn of the millennium: (a) the robust model results pointing to strong future glacier vanishing, even with relatively modest climate scenarios (Figure 2; Huss, 2012); (b) the availability of glacier inventories as combined with high-resolution digital terrain information (Pfeffer et al., 2014); and (c) the development of slope-related distributed ice-thickness estimates (Haeberli, 2016; Haeberli & Hoelzle, 1995). The calculation of glacier-bed topographies enabled the construction of digital elevation models (DEMs) "without glaciers" (Linsbauer et al., 2009), providing a realistic impression of future surface topographies in areas becoming exposed by glacier retreat. With this, a basis was established for anticipating future conditions, processes, and interactions in cold mountain regions where original glacial landscapes rapidly turn into para- and periglacial landscapes and where geo- and ecosystems will be characterized by strong disequilibria for generations to come. Among the first results are large-scale assessments of glacier-bed overdeepenings where future lakes may form, involving risks as well as options for use (Haeberli, Buetler, et al., 2016).

Observed Glacier Changes

National and international *coordination of systematic glacier observations* since the late 19th century have resulted in the compilation of unprecedented datasets concerning glacier distribution in space and changes over time (Figure 3). A first complete picture of glacier distribution in the Alps was compiled based on national inventories from aerial surveys and topographic maps as a contribution to the World Glacier Inventory (WGMS, 1989). This inventory identified 5,162 glaciers covering an area of 2,903 square kilometers around 1970. Such information made first calculations of the total glacier volume possible: 130 (100–140) cubic kilometers for the 1970s (Haeberli & Hoelzle, 1995; Haeberli, Hoelzle, Paul, & Zemp, 2007). Two more Alpine-wide glacier inventories were computed for the year 2003, based on Landsat images (Paul, Frey, & Le Bris, 2011) and for the year 2015, based on Sentinel data (Paul et al., 2018). Additional inventories are available at national levels (Table 1). Zemp et al. (2007) estimated the total glacier area around 1850 to some 4,500 (4,474) square kilometers by scaling national glacier changes to the full inventory from the 1970s. Since the Little Ice Age (LIA) maximum, Alpine glaciers have lost more than 60% of their area (Table 2). A total ice volume of 114 cubic kilometers, corresponding to an average glacier thickness of around 55 meters, was calculated for the European Alps for the year 2003 (Huss, 2012; cf. 117 cubic kilometers given for Central Europe by Huss & Farinotti, 2012), based on numerical modeling making use of glacier inventories, digital elevation models, and local glacier thickness observations (Farinotti, Huss, Bauder, & Funk, 2009). The uncertainty range of glacier thickness estimates for large ensembles of unmeasured glaciers is about ±20% (Farinotti et al., 2016) or even larger (Gärtner-Roer et al., 2014). In their recent model inter-comparison, Farinotti et al. (2019) estimate the glacier volume in Central Europe at 130 ±30 cubic kilometers for the year 2003. Based on the compilation of annual volume losses by Zemp et al. (2019) and a rough guess of about 4-cubic-kilometer volume loss in the most recent years of 2017 and 2018, a total volume loss of some 40–50 cubic kilometers (slightly more than –1 km^3 per year) can be estimated for the time period since 1980. Roughly 30 cubic kilometers (–2 km^3 per year) were lost during the past 15 especially hot years. Such numbers make it possible to update earlier estimates of Alpine glacier volumes to values remaining in 2018 and to directly compare them: 85 (50–100) cubic kilometers from Haeberli and Hoelzle (1995), 84 cubic kilometers from Huss (2012) and, slightly less than 100 (70–130) cubic kilometers from Farinotti et al. (2019) and Zekollari et al. (2019). The “best estimates” (84, 85, and nearly 100 km^3) are within or at the upper limit of the overlapping part (70–100 km^3) of the uncertainty ranges assumed by Haeberli and Hoelzle (1995) and Farinotti et al. (2019).

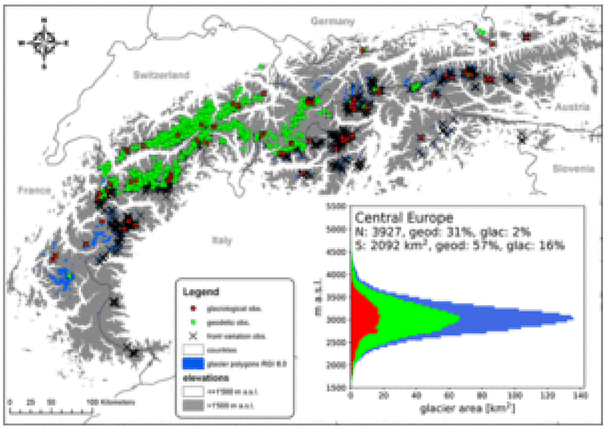

Figure 3. Glacier distribution and available observations in the European Alps. Glacier locations with available fluctuation series (WGMS, 2017) are plotted over glacier outlines of 2003 (Paul et al., 2011; RGI Consortium, 2017). The background map shows country borders (ESRI, 2019) and elevations above 1,500 meters above sea level (EU DEM v1.1, N.D.). The inset plot shows glacier hypsometry overlaid by the observational coverage of glaciers with glaciological and geodetic observations together with corresponding statistics for the total glacier number (N) and area (S) for Central Europe (including glaciers in the Pyrenees and in the Apennine).

Glacier front variation measurements have been carried out at a few hundred glaciers since the late 19th century (Fischer et al., 2018; SCNAT, 2017). These direct observations are extended by reconstruction of glacier front variations based on geomorphological evidences, tree rings, pictorial sources, and historical documents through the LIA (Nussbaumer, Zumbühl, & Steiner, 2007; Pelfini & Smiraglia, 1988; Zumbühl & Holzhauser, 1988) and into the Holocene (Holzhauser, Magny, & Zumbühl, 2005; Joerin, Stocker, & Schlüchter, 2006; Nicolussi & Patzelt, 2000). These datasets prominently document the glacier maxima of the LIA and provide evidences of longer periods with reduced glacier extents during the early Holocene (Figure 4). After the last LIA maximum around 1850, glaciers started their extensive retreat all over the Alps, with intermittent periods of minor re-advance in the 1890s, 1920s, and 1970s–1980s (Figure 5). Today, glaciers continue their dwindling beyond Holocene variations as evidenced by archaeological findings (Grosjean, Suter, Trachsel, & Wanner, 2007; Kutschera & Rom, 2000).

The glaciological method, based primarily on stake and pit measurements, provides observations of *seasonal or annual mass balance* (Cogley et al., 2011). Pioneer point observations extend back to the late 19th century (Chen & Funk, 1990; Huss, Bauder, & Funk, 2009; Mercanton, 1916) and have been expanded to glacier-wide observation networks in all Alpine countries since the 1950s (Escher-Vetter, Kuhn, & Vetter, 2009; Fischer, 2010; Huss, Dhulst, & Bauder, 2015; Vincent, 2002). The use of the geodetic method (Cogley et al., 2011) for mapping glaciers started with terrestrial surveys in the 19th century, resulting in high-quality topographic glacier maps (Finsterwalder, 1897: Mercanton, 1916). Air- and space-borne repeat mapping opened new opportunities for glacier change assessments. Validation and—if necessary—calibration of glaciological time series with multi-year geodetic surveys (Zemp et al., 2013) have become best practice over the past decade (Fischer, 2011; Huss et al., 2009A; Klug et al., 2018; Thibert & Vincent, 2009). Moreover, the assessment of glacier volume changes at catchment and even country scale became possible (Fischer, Huss, & Hoelzle, 2015; Knoll & Kerschner, 2009; Paul & Haeberli, 2008; Rabatel, Dedieu, & Vincent, 2016). The geodetic method provides mass-balance results at a relatively low temporal resolution (i.e., decadal), but for large glacier samples. Long-term glaciological time series are available from a much smaller sample but come with seasonal resolution and hence provide much more insight into the processes related to atmospheric conditions and driving overall glacier changes.

Table 1. Overview on National Glacier Inventories in the European Alps

Country	**Time Period**	**Source**
Austria	1850s	(Gross, 1987)
	1969	(Patzelt, 1980)
	1998	(Lambrecht & Kuhn, 2007)
	2004–2012	(Fischer et al., 2015A)
France	1895	(Mougin, 1925)
	1960s	(Vivian, 1975)
	2000s	(Gardent et al., 2014)
Germany	1950–2007	(Hagg, Mayer, & Steglich, 2008)
Italy	1959–1962	Comitato Glaciologico Italiano (various reports)
	2005–2011	(Smiraglia et al., 2015)
Slovenia	1893–2011	(Cekada, Zorn, & Colucci, 2014)
Switzer-land	1850s	(Maisch et al., 2000)
	1973	(Maisch et al., 2000; Müller, Caflisch, & Müller, 1976)
	1998/1999	(Kääb et al., 2002; Paul et al., 2002)
	2008–2011	(Fischer, Huss, Barboux, & Hoelzle, 2014)

Table 2. Glacier Extents Around 1850, 1970s, in 2003, and in 2015 as Derived From Alpine-Wide Inventories

Year	**1850**	**1970s**	**2003**	**2015**
Area	4,474 km^2	2,903 km^2	2,050 km^2	1,785 km^2
Relative to 1850	100%	65%	46%	40%
Source	Zemp et al. (2007)	WGMS (1989)	Paul et al. (2011)	Paul et al. (2018)

Long-measured mass-balance time series from both glaciological and geodetic methods show a clear centennial trend of glacier mass loss in the Alps. At decadal scale, intermittent time periods of mass (re-)gain are found from 1910–1920 and from 1965–1985. Like most glaciers worldwide, glaciers of the Alps had already experienced extensive mass loss in the 1940s and again since 1985. Annual mass loss since the year 2000 has increased to threefold of the average over the 20th century (Figure 6). Glaciological observations indicate that glacier changes were mainly driven by summer balance (Zemp et al., 2015).

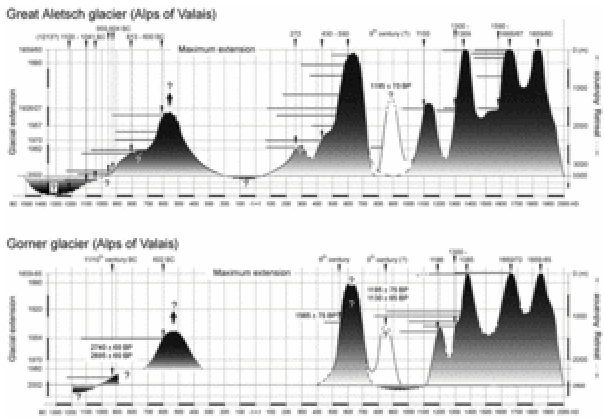

Figure 4. Fluctuations of the Great Aletsch and Gorner glaciers over the last 3,500 years. Horizontal black lines indicate the lifetime of fossil trees.

Source: Holzhauser et al. (2005).

The sustained unfavorable conditions since the mid-1980s have resulted not only in extensive mass loss but also have driven glaciers into an *unbalanced state*, that is, the glaciers reacted with vertical downwasting rather than by dynamic horizontal retreat. An estimate of the committed ice loss is provided by the ratio between the decadal average accumulation area ratio (AAR) and the balanced-budget AAR_0 as derived from glaciological observations (Mernild et al., 2013). For Central Europe, the committed loss in glacier area is estimated at about 50% under sustained climatic conditions, as in the period 2001–2010 (Zemp et al., 2015).

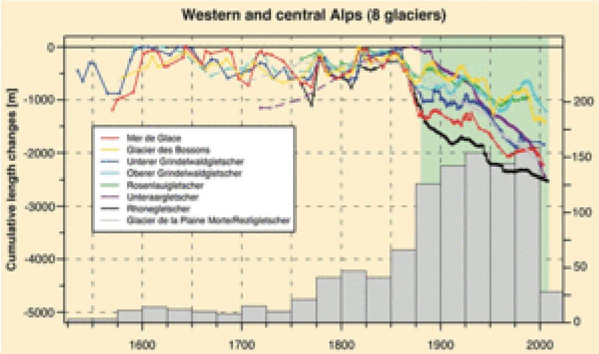

Figure 5. Reconstructed and measured cumulative glacier front variations in the Alps since the Little Ice Age (LIA). The zero value on the left y-axis corresponds to the most extensive front position of glaciers during the LIA. Gray vertical bars show the total number of available dated front positions for the selected glaciers (right y-axis). The period with direct front measurements is indicated by light green background.

Source: Zemp et al. (2011)

Glacier monitoring in the European Alps has developed from pioneer observations and a main focus on glacier front variations in the late 19th century to an integrated monitoring strategy combining in situ measurements with remote sensing and process understanding at individual glaciers, with mountain-wide assessments of glacier distribution and changes (Haeberli et al., 2007). Glacier front variations have an important role in the communication of climate change impacts to a wider public and are the key to understanding present versus pre-industrial variations. Glacier mass-balance measurements from glaciological and geodetic methods provide in-depth process understanding and allow quantification of glacier changes from glacier to catchment scale. Multi-temporal glacier inventories keep stock of the total glacier distribution for a given point in time. Numerical modeling is used to extrapolate the observations from individual glaciers to the entire glacierization of the Alps and to provide estimates of future glacier evolutions under consideration of climate change scenarios (Figure 2). A new challenge to glacier monitoring is the downwasting, disintegration, and complete vanishing of glaciers. It requires a critical reflection of the established observational networks, including estimates of survival years—in a number of cases, years to a few decades only (Haeberli, Huggel, Paul, & Zemp, 2013)—of glaciers with long-term measurement programs and the timely set-up of replacement measurements at larger and higher-ranging glaciers, where possible.

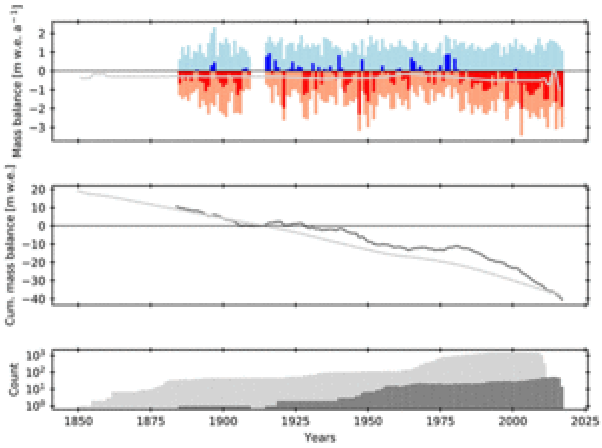

Figure 6. Annual and cumulative mass balances measured/reconstructed on Alpine glaciers from around 1850 to 2017 based on combined results from field observations and geodetic/photogrammetric monitoring. (top) Annual glaciological balances are shown with positive and negative values indicated in blue and red, respectively. Winter and summer balances are shown in light blue and salmon, respectively. Annual mass-change rates from (multi-annual) geodetic surveys are shown in light gray and were calculated assuming a glacier-wide average density of 900 kg m^{-3}. (center) Cumulative geodetic (light gray) and glaciological (dark gray) balances relative to 1914. (bottom) The number of available observations from geodetic (light gray) and glaciological (dark gray) data are indicated in log scale. Note the observational gap in the glaciological sample from 1910–1914. The strong variability of the geodetic mean after 2010 results from a drop in sample size to a few glaciers.

Data source: WGMS (2017) and earlier reports.

Glacier-Climate Modeling

Early quantitative studies of the relation between glacier fluctuations and climate were of a statistical nature (e.g., Hoinkes, 1968). For instance, annual percentages of retreating/advancing glaciers were compared with a series of summer temperature and winter precipitation. Such studies give a broad indication of how glaciers react to climate change, but suppress the primary aspect of cumulative developments and do no justice to the fact that individual glaciers have vastly different *response times* and *climate sensitivities*. The concepts of response time and climate sensitivity are essential in understanding the dynamics of glaciers. The response time determines how fast a glacier can adapt its geometry to changed climatic conditions. With a glacier model, the response time can be determined by suddenly changing the climatic forcing to a glacier that is in steady state and seeing how long it takes until a new steady state is approached. The climate sensitivity, on the other hand, describes how large the difference in steady-state glacier geometry (i.e., length) is for two different climatic forcings. So when a particular glacier retreats faster than its neighbor, this can be due to either a shorter response time *or* a larger climate sensitivity. The simplest way to describe the climatic conditions felt by a glacier is to use the concept of the equilibrium line. The equilibrium line separates the accumulation area (where more snow accumulates in winter than melts away in summer) from the ablation area (where all winter snow melts). The mass gain in the accumulation zone and the mass loss in the ablation zone imply that for a glacier to be in a steady state, ice has to flow downward from the accumulation to the ablation zone (Figure 7). In the Alps the equilibrium line altitude (ELA) varies within a range of a few hundred meters, depending on local conditions. The most important factors are precipitation (more precipitation implies a lower ELA), temperature (higher temperature causes a higher ELA), and orientation (on southerly slopes the ELA is higher because solar radiation is more intense). Before the strong and rather abrupt warming in the Alps, which started around 1980, long-term ELA values ranged from 2600 meters in the wettest regions to about 3100 meters in the dry interior (Kuhn, 1993). Apart from spatial variations the ELA also fluctuates from year to year. Hot summers, like those in 2003 or 2018, can push the equilibrium line upward by hundreds of meters, often beyond the highest point of smaller glaciers.

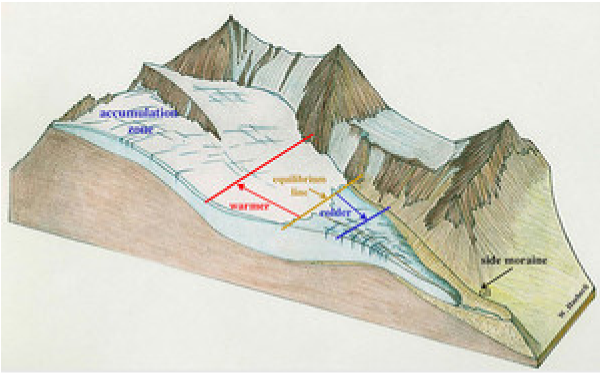

Figure 7. Scheme of a characteristic mountain glacier illustrating shifts in equilibrium-line altitude with changing climatic conditions.

In case of *atmospheric warming* by 1°C the equilibrium line shifts upward, depending on the local conditions by 100 to 150 meters. Such a shift implies that the accumulation zone becomes smaller, and the ablation zone larger. This results in a negative mass budget, and the glacier will shrink. As a purely geometric effect, the increase in the ablation area will be larger when the surface slope along the glacier is smaller. By means of a simple analytical model (Oerlemans, 2001), it can be shown that in a first-order estimate the climate sensitivity varies as $-2/s$, where s is the mean glacier slope. The longest glacier in the Alps, the Great Aletsch glacier (Figure 1), has a mean slope of about 0.08. A +100-meter change in the ELA would imply that, in case of equilibrium, the glacier would be 2,500 meters shorter. Climate sensitivities for glaciers over the world vary by typically one order of magnitude (Figure 8). The values shown in Figure 8 are estimates. Many glaciers have complex topography-related geometries, which will affect the sensitivity (ice falls, strongly varying width). Numerical models are then needed to get a more precise estimate of the climate sensitivity.

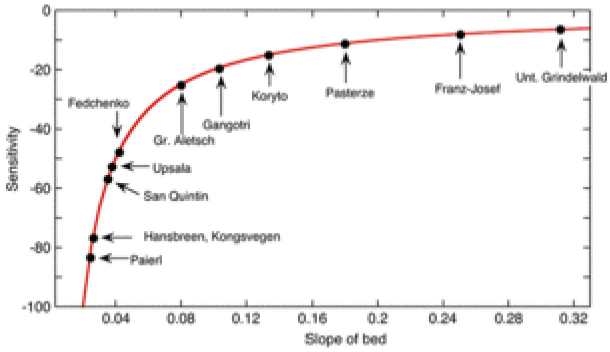

Figure 8. Relation between bed slope and mass balance sensitivity of mountain glaciers. Sensitivity is defined as change in equilibrium glacier length (m) per change in ELA (m).

The response time also depends on the *glacier geometry and the climatic conditions* (Jóhannesson, Raymond, & Waddington, 1989). Glaciers with small slopes have larger response times (Haeberli & Hoelzle, 1995). Model calculations have shown that glaciers in dry climates with lower mass balance gradients and related mass turnover (e.g., some parts of central Asia, Canadian Arctic, and the Transantarctic Mountains) react more slowly to climate change than glaciers in wet climates with higher mass-balance gradients and related mass turnover (Oerlemans, 2001). Precipitation rates in the Alps vary considerably (the inner central parts being the driest), but altogether the climatic conditions are maritime to transitional, with typical high-altitude annual amounts of precipitation between 1.5 and 3 meters. Glacier models show that the response time of glaciers in the Alps is between 10 (small steep glaciers) and 70 years (long glaciers) (Haeberli & Hoelzle, 1995; Oerlemans, 2001). The larger glaciers have the longest response times mainly because they also have smaller slopes.

To predict the *future evolution of a glacier*, a numerical model is needed that takes into account the broad geometric characteristics. Because input data are always scarce and often uncertain (e.g., concerning the bed profile), calibration with information on glacier changes in the past greatly improves the reliability of a projection. Simulating the past changes of a glacier, that is, a length record over the past 100 years, is an essential step. This often involves the reconstruction of the climate forcing by an iterative procedure, in which the difference between observed and simulated glacier length is minimized ("dynamic calibration," Oerlemans, 1997; Oerlemans et al., 1998). As an example, Figure 9 shows the result of such a procedure for the Vadret da Morteratsch.

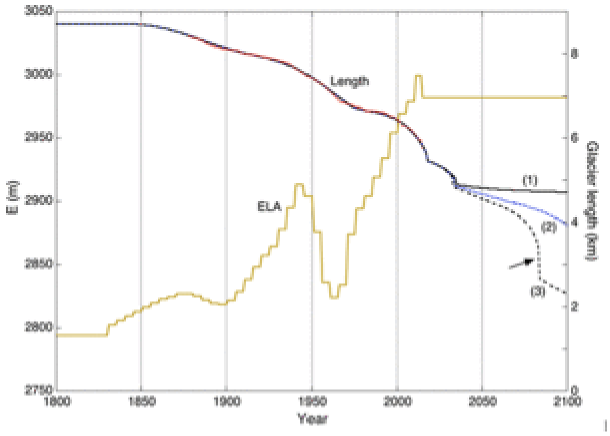

Figure 9. Model calculation concerning equilibrium-line altitude and length change for Morteratsch glacier, Swiss Alps. See text for detailed explanation.

The Vadret da Morteratsch is a ~6-kilometer-long valley glacier in South-East Switzerland (close to St. Moritz). Its behavior over the past 150 years is typical for long valley glaciers in the Alps. The glacier front has retreated over a distance of 2.5 kilometers (observations: red dots). The ELA history that gives the best fit between simulated and observed glacier length is shown by the brown curve. It was obtained by running a glacier flow-line model, with measured bed topography, in an iterative procedure, in which the ELA was allowed to change every 5 years (Oerlemans et al., 2017). The model was initialized by finding the ELA value that produces the Little Ice Age maximum stand as a steady state. The model calculation shows that a ~200 meter increase in the ELA since 1900 is needed to explain the observed glacier retreat. There is a striking interruption of the rise in the equilibrium line in the period 1950–1980, related to the marked slowing down of the glacier retreat during the period 1970–1990. In fact, during this period many smaller glaciers in the Alps stopped retreating or even started to re-advance (cf. Figure 5).

Once the model has been calibrated, it can be used to study the future *response to climate change*. The first question to consider is: What would happen if the climatic conditions did not change? Curve (1) shows the evolution of the glacier length for the case that the ELA stays at the mean value for the period 2001–2015. The glacier would shrink for a while, until around the year 2035, when it would approach a new steady state (length ~4.7 km). However, this is an unlikely scenario. If the Paris agreement became reality, an additional rise of the ELA of 2 meters a^{-1} has to be taken into account, which then leads to curve (2). For a business-as-usual scenario, the rise in the ELA is more likely to be of the order of 4 meters a^{-1}, and this produces a really dramatic retreat of the glacier. In the year 2100, only a steep glacier 2 kilometers long, with little volume, would be present on the highest part of the mountain (altitude range 3,900–2,800 meters). The corresponding ice volume would be less than 10% of the current volume. The very rapid decrease in glacier length from 4 to 2.5 kilometers (arrow in Figure 9) is associated with an overdeepening in the bed profile, possibly leading to the formation of a future lake (Linsbauer et al., 2012, Zekollari et al., 2014) and accelerated retreat of the glacier front.

Such models of intermediate complexity are suitable to be used in iterative procedures where hundreds of runs have to be carried out. However, more *sophisticated models* exist. In recent years, three-dimensional higher-order models have been employed, for instance, for the Rhone glacier (Jouvet et al., 2009), and for the Morteratsch glacier (Zekollari et al., 2014). These models contain a full three-dimensional representation of the stress and velocity fields, providing unprecedented details about the glacier mechanics. However, there are some practical issues in using these models for climate studies. Large amounts of geometric input data are required, and the issue of boundary conditions in steep terrain has not yet been resolved in a satisfactory way (dynamic simulation of steep, ice-free slopes and mass conservation).

A number of *issues remain that add uncertainty* to the projections for individual glaciers, irrespective of the degree of complexity of the ice-flow model. It has been observed that the snout of retreating glaciers darkens, mainly because of deposition of dust from the surrounding moraines walls. Because of the associated increase in absorption of solar radiation, the ablation rate increases significantly (Oerlemans, Giesen, & van den Broeke, 2009), leading to a faster retreat of the snout. In more general terms, the accumulation of debris on alpine glaciers complicates the link between mass balance and atmospheric processes and also has an effect on the dynamics of a glacier. In many cases, a debris layer on the glacier surface reduces the ablation rate, but the formation of ice cliffs and associated high melt rates may sometimes compensate for this (e.g., Brun et al., 2018). The formation of lakes also has an effect on the retreat of a glacier snout (e.g., Funk & Röthlisberger, 1989; Tsutaki, Nishimura, Yoshizawa, & Sugiyama, 2011), but is difficult to model when direct measurements about calving rates are not available.

Along a different line, models have been constructed to treat the *entire glacier population over mountain chains* (Huss, 2012; Zekollari et al., 2019) and even on the globe (e.g., Huss & Hock, 2015; Radic et al., 2014). At a global scale, these models focus on estimating global glacier mass changes as a response to global warming and its effect on sea-level rise. Processes like accumulation, melting, calving, and dynamic adjustments of glacier geometries are treated in a schematic way. The models have a large number of empirical parameters and are tuned by comparison with observed mass-balance data over the past decades. Clearly, when questions of a global nature have to be dealt with, global models are needed in which not every single glacier can be treated in detail. Nevertheless, it seems that in studies of this kind, historical data on glacier fluctuations over the past centuries can still be more fully exploited.

And Beyond: New Landscapes in De-Glaciating Regions

As scenarios with or without climate mitigation only show marked differences after about mid-century (Huss, 2012; Marzeion, Kaser, Maussion, & Champollion, 2018), the near-complete disappearance of glaciers in the Alps can hardly be avoided. Commitments already now exist to changes, which must be considered to be irreversible at human time scales: even with optimistic climate scenarios, only about one third of the glacier volume existing in 2018 is likely to remain at the end of the 21st century (Zekollari et al., 2019). Within a very short time, but for many generations to come, *high-mountain glacier landscapes* rapidly transform into new and completely different periglacial landscapes (Figure 10).

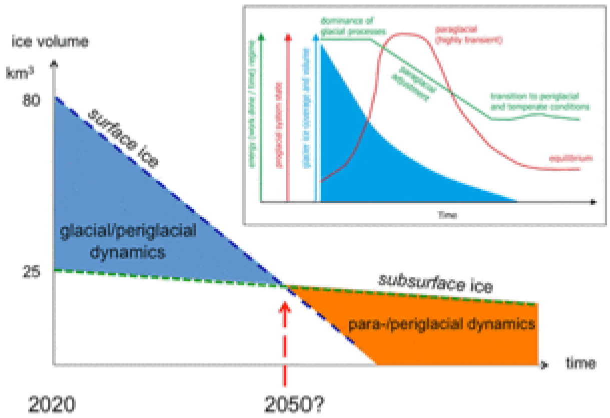

Figure 10. On-going landscape changes in the Alps. Periglacial processes relate to intense frost effects while paraglacial processes include system reorganizations after de-glaciation, often via strong disequilibria in complex geo- and ecosystems. Due to rapid glacier vanishing and much slower permafrost thaw, the amount of surface ice in glaciers may decrease below the amount of subsurface ice in permafrost already around mid-century.

Combined from Haeberli et al. (2017) and Carrivick and Heckmann (2017).

The new landscapes forming in de-glaciating high-mountain regions will be characterized by rocks, debris, sparse vegetation, numerous lakes, and slowly degrading permafrost (Carlson et al., 2018, Haeberli et al., 2016, 2017), but also by paraglacial processes (Ballantyne, 2002) affecting *geo- and ecosystems under conditions of strong and long-lasting disequilibria*. Realistic assessments of corresponding options and risks must be based on a qualitative understanding and quantitative modeling of related processes and process interactions—an emerging research field and essential knowledge basis for the planning of sustainable adaptation strategies. Initial steps in this direction are briefly described here, and some general ideas about further needs are outlined.

The application of spatially distributed ice-thickness estimates for the construction of “DEMs without glaciers” constitutes the basis for working with possible future surface topographies and related processes. Corresponding achievements but also uncertainties must be discussed first. A discussion of risks and options related to new lakes possibly forming in exposed glacier-bed overdeepenings then leads to an outlook concerning future needs and possibilities of modeling complex geo- and ecosystems in new high-mountain landscapes.

Based on distributed glacier thickness modeling, glacier-bed topography can be calculated as a realistic approximation of potential *future surface topography*. The first "DEM without glaciers" for an entire still glacierized mountain region was produced by Linsbauer et al. (2009) for the Swiss Alps. Farinotti et al. (2016) outline the background of scientific approaches for estimating distributed ice thicknesses and present results of an inter-comparison between various model approaches in order to assess their performance. Their study documents that large differences exist between individual solutions. Only a few models are able to operate at a regional to global scale. The simplest of these approaches applicable at large scales (GlabTop; Linsbauer et al., 2009, 2012) rapidly calculates ice depths from surface slope and basal shear stress (Nye, 1952). Basal shear stress is assumed to be constant along the central flow line of individual glaciers but to depend on mass turnover and hence elevation-range for each glacier (Haeberli & Hoelzle, 1995). In view of practical applications, such simple models, primarily using glacier outlines and DEMs without any tuning needed, perform equally well, in particular for real-world cases, as compared with heavily tuned, more complex approaches based on assumptions about mass fluxes at the surface and within/at the base of the ice, and requiring correspondingly rich and mostly unavailable data input. The strength of more complex approaches relates to improved process understanding rather than to simple estimates of ice thickness. The flux-driven model calculations for the Taku glacier in Alaska (Huss & Farinotti, 2012), for instance, demonstrates that the assumption of a constant basal shear stress of about 150 kilopascals for large glaciers used in the GlabTop model is quite realistic but may cause glacier-internal deviations of up to ±30% from the estimated mean value, a result which corresponds to comparisons of estimated ice thicknesses with local radio-echo soundings (Linsbauer et al., 2012).

Absolute values of estimated ice depths and of resulting glacier-bed elevations are related to considerable uncertainty. The large scatter in the empirical database on glacier geometry from drillings, geophysical soundings (Gärtner-Roer et al., 2014), or observations in glacier forefields (Haeberli, 2016) represents a strongly limiting factor. Exact parameterization of mass fluxes for complex flux-driven approaches faces problems of regionally inadequate climate data (especially about spatial patterns of solid precipitation and accumulation) or of not exactly known flow parameters (especially basal sliding, velocity ratio). Information on relative topographic differences within individual glacier beds, that is, the *glacier-bed topology with its neighborhood-relations*, is much safer than absolute values of glacier-bed elevation because it much more directly relates to spatial patterns of surface slope. The primary remaining uncertainty is given by the way glacier surface slope must be determined in order to realistically account for longitudinal stress coupling in glacier flow. Corresponding smoothing functions are critical (Adhikari & Marshall, 2013), but general patterns of bed topographies nevertheless appear to be rather robust (Figure 11; cf. Figure 6 in Frey et al., 2014).

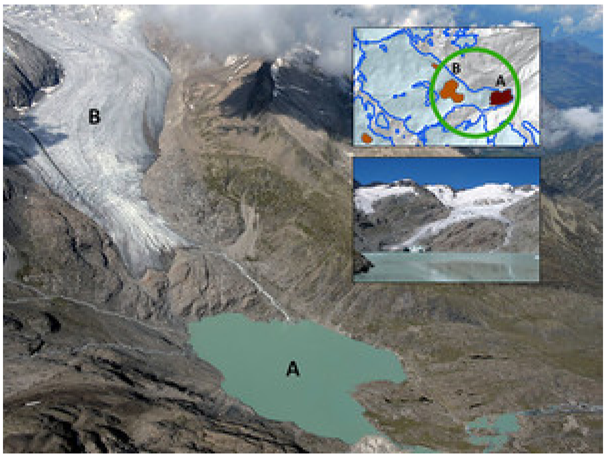

Figure 11. New proglacial lake (A) at Gauli glacier in 2018 (Photo: Christine Levy), Swiss Alps, formed since around the turn of the century. The upper inset shows modeled glacier-bed overdeepenings as potential sites (A, B) of lake formation with continued glacier retreat based on the GlabTop approach and on a digital elevation model representing the 1970s, that is, long before lake formation. The lower inset documents the glacier position in 2012 (Photo: Michael Bütler) with the ice margin still being in contact with the lake. Another lake (B) may start forming most probably before mid-century in the crevasse-free flat zone of compressing flow up-glacier of the bedrock riegel characterized by lateral narrowing of the glacier and the transition to extending flow with transverse crevasses on an increasingly steep bed.

Modified and updated after Haeberli and Linsbauer (2013).

The first application of distributed glacier-bed topographies in view of future landscape characteristics related to *glacier-bed overdeepenings and sites of possible future lake formation* is in the Swiss Alps (Frey et al., 2010; Linsbauer et al., 2012). Among the most striking features of glacier-bed topographies and glacially sculpted landscapes are marked overdeepenings with adverse slopes at their down valley end (Cook & Swift, 2012). When exposed by retreating ice, such overdeepenings can turn into lakes, which represent striking landmarks and can be related to important geo-system mechanisms, risks, and options (Haeberli, Buetler, et al., 2016). Model calculations can thereby be compared with visual/qualitative inspection of primary morphological surface characteristics related to glaciers flowing through overdeepened parts of their beds and across adverse slopes (Frey et al., 2010). In the meantime, large-scale overviews (e.g., Linsbauer et al., 2016, for the Himalaya-Karakoram region) and systematic planning-applied national inventories (e.g., Colonia et al., 2017, for Las Cordilleras Glaciares in Peru) have been produced.

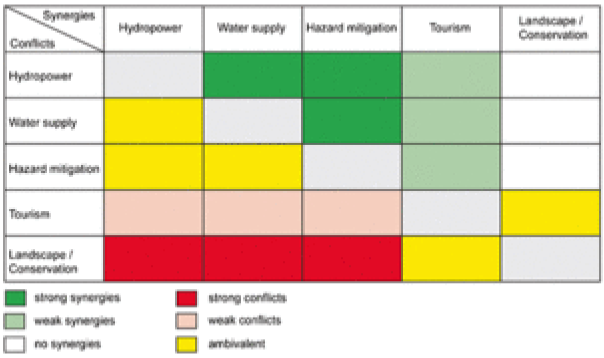

Figure 12. Schematic matrix recommended for systematic consideration in participative planning about possible future lakes in de-glaciating mountain regions. Color attribution here reflects often-encountered situations in the Alps. From Haeberli et al. (2016).

The *morphometry of glacier-bed overdeepenings* and related existing or potential future lakes is characterized by extreme variability: there is no simple or straightforward statistical relation between factors like area, length, width or elongation, and depth (Haeberli, Linsbauer, et al., 2016). The safest information concerns the general location and approximate size of possible features (Figure 11). Modeled shapes (areas, depths, volumes) are at best order-of-magnitude estimates. Artifacts from various sources (DEM smoothing, problematic glacier outlines, etc.) must be eliminated, and the plausibility of modeled features should be examined by visual inspection using Google Earth or the like and applying the morphological criteria introduced by Frey et al. (2010); cf. Colonia et al., 2017). Even if a glacier-bed overdeepening is realistically simulated, this is no guarantee for the formation of a lake. A deep-narrow erosional gorge through the rock threshold may drain (part of the) water and cannot be captured by any model, or a shallow depression may quickly become filled with sediments from upslope erosion. Avoiding lake formation by artificially slowing down glacier retreat using snow production (Oerlemans, Haag, & Keller, 2017; cf. Zekollari et al., 2014) may be a rather expensive and difficult option for local applications. An important learning process is possible through analysis of landforms, which evolve or have already evolved, with ongoing ice retreat. Using digital terrain information from the 1970s, for instance, new lakes at Rhone and Gauli (Figure 11) or Trift glaciers in the Swiss Alps document successful predictions. The fact that the corresponding medium-size glaciers had been relatively close to equilibrium conditions at the time of this older DEM may thereby have helped. With later DEMs documenting downwasting, collapsing, or disintegrating glaciers, many basic model assumptions are becoming more and more questionable. A comprehensive consideration of potential future lakes for the still glacier-covered parts of the entire Alps remains to be accomplished. It is nevertheless quite safe to assume that significant new lakes will especially form where glaciers are large and flat (Mer de Glace, Glacier d’Argentière, Gorner glacier, Aletsch glacier, Rhone glacier, Pasterze, etc.).

With respect to human activities and infrastructure, the emerging landscapes in de-glaciating mountain regions involve *options and risks*. New water bodies in de-glaciating mountains, for instance, can be attractive for tourism, interesting for hydropower production (Terrier et al., 2011), and useful for water supply (Farinotti, Pistocchi, & Huss, 2016) but can also constitute serious new hazard sources (Haeberli, Schaub, & Huggel, 2017). Corresponding synergies and conflict potentials must be addressed in a comprehensive way and with participative planning in order to reach sustainable solutions with long-term acceptance (Figure 12).

Comprehensive approaches are especially relevant in view of the *strong and long lasting disequilibria*, which are developing in complex and interconnected geo- and ecosystems after de-glaciation (Ballantyne, 2002; Carrivick & Heckmann, 2017). Such disequilibria evolve far beyond previous conditions and hence far beyond human historical-empirical knowledge. They are a consequence of the highly variable response characteristics related to individual system components and their interactions. Involved time components range from days, seasons, and years (snow; Marty, Schlögl, Bavay, & Lehning, 2016) to years and decades (glaciers, melt water; Huss, 2012; Huss et al., 2017), to decades and centuries (lakes, sediment cascades, permafrost, vegetation, soils; Cannone, Diolaiuti, Guglielmin, & Smiraglia, 2008; Carrivick & Heckmann, 2017; Carrivick & Tweed, 2013; Egli et al., 2006; Messenzehl et al., 2017; Noetzli & Gruber, 2009) or even millennia (slope stability; Krautblatter, Funk, & Günzel, 2013). As an example, slowly degrading permafrost will continue to exist for centuries in many steep icy peaks of the Alps and other cold mountain chains on Earth, when glaciers at their foot will long have disappeared already. Corresponding long-term slope instability in permafrost-affected rock faces and glacially de-buttressed slopes must be considered (Haeberli et al., 2017; Huggel, Clague, & Korup, 2012; Krautblatter et al., 2013; Krautblatter & Leith, 2015; McColl & Draebing, 2019), especially in connection with new lakes where impact waves can produce far-reaching floods and debris flows or complex process chains, thereby extending potential hazards zones down-valley into previously safe zones (Haeberli et al., 2017; Somos-Valenzuela et al., 2016; Worni et al., 2014).

Among the most striking examples of such possible developments is the region of *Aletsch glacier* (Figure *1*), *the largest glacier in the Alps* and the primary focus of the UNESCO World Natural Heritage site at Jungfrau-Aletsch. Especially those possible new lakes that are expected to form after about mid-century will be surrounded by steep de–buttressed lateral slopes and high bedrock faces with degrading permafrost and correspondingly decreasing stability (Figure 13). A multipurpose project combining long-term hydropower production, water supply during droughts, and flood retention could be realized at the existing reservoir Gibidum above the town of Brig (Haeberli, 2017). This could help avoid heavy impacts from construction sites and infrastructure for protection work in the upper catchment with its remarkable landscape under rapid change. The near-complete loss of the Aletsch glacier, which is expected to occur during the course of the 21st century (Jouvet et al., 2011), may be perceived as a striking case of rapidly transforming new high-mountain landscapes of the Anthropocene with complex and delicate new processes and process combinations (Brown et al., 2017; Carrivick, Heckmann, Turner, & Fischer, 2018;

Haeberli, Schaub, & Huggel, 2017; Kos et al., 2016; Saulnier-Talbot & Lavoie, 2018). Visualization of potential future development scenarios, such as the one shown in Figure 14, may help with planning and decision-making in view of sustainable adaptation strategies.

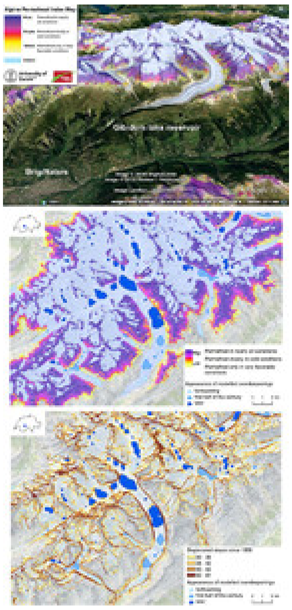

Figure 13. Region of Aletsch glacier in the UNESCO World Nature Heritage Centre Jungfrau-Aletsch, Swiss Alps. Top: oblique view (Google Earth) with permafrost occurrence after Boeckli, Brenning, Gruber, and Noetzli (2012). Center: Map of glacier bed with permafrost distribution outside the present-day glaciers and possible future lakes (from Haeberli et al., 2017). Bottom: Map with possible future lakes and over-steepened/de-buttressed lateral slopes (brown) in the bed of the presently existing glaciers (model and graph: Yvonne Schaub).

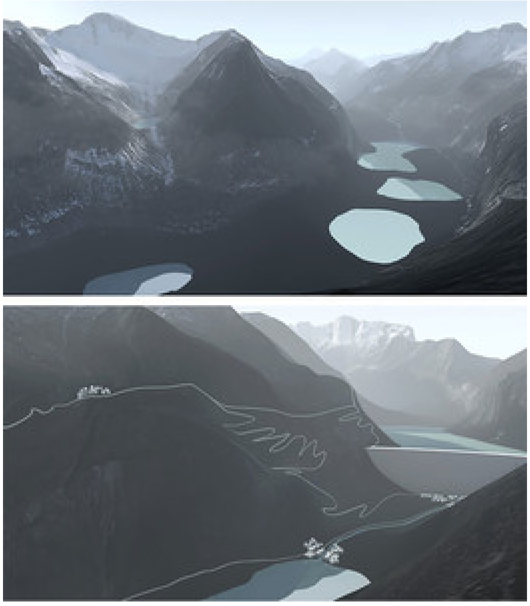

Figure 14. Visualization of possible future landscapes in the Aletsch-Jungfrau region with/without potential human activities.

Source: Noemi Chow. Video *Nach dem ewigen Eis* (in German).

Conclusions and Perspectives

Long-term glacier monitoring since the late 19th century, with an especially dense observational network, together with advanced and well-calibrated numerical modeling, provides a clear picture about the past evolution and future destiny of glaciers in the European Alps:

- Glacier length change, as a unique natural indication concerning public awareness of ongoing climate change, is a key element for comparison with past variability ranges. After a slight long-term trend toward glacier growth during the Holocene, Alpine glaciers started to rapidly retreat following the Little Ice Age and are now dwindling beyond Holocene variability ranges. This process has accelerated in such a way that effects of glacier downwasting, disintegration, and collapse have in many cases become predominant over terminus retreat.
- Since the 1950s, glacier-wide mass-balance observations have formed the basis for developing a quantitative process understanding concerning the climate–glacier relation and for applying corresponding numerical models. Such model calculations document the strong relation between rising atmospheric temperature, and changing radiation and glacier mass changes, including feedback effects like changes in solid/liquid precipitation, firn/ice surface albedo, glacier surface altitude, or debris cover. The delayed response of larger glaciers will cause further losses of the order of about 50% to occur, even in the unlikely case of stable atmospheric temperatures from now on. Projections into the future also reflect the fact that climate scenarios with or without mitigation efforts will start to markedly differ only after about the mid-century. The reduc-

tion of the total Alpine glacier area and volume to small percentages of their original (Little Ice Age) value appears to be inevitable.

- Since about the turn of the century, repeat glacier inventory work providing quantitative information on area, thickness, and volume changes of all glaciers has become a primary source of information about ongoing glacier changes. Modern geodetic technologies, such as high-resolution satellite images, laser altimetry, or drone photogrammetry, offer possibilities to document rapid changes over large regions in great detail and over short time intervals. Management of the corresponding data flood and related quality control is becoming a primary challenge. Detailed repeat glacier inventories will not only document processes of shrinking or even vanishing of glaciers in the Alps but will also provide important information about the terrains which are becoming ice-free.

The foreseeable shrinking to near-complete disappearance of the Alpine glaciers within coming decades makes it necessary to anticipate and model the new ice-free landscapes of rocks, debris, sparse vegetation, and numerous lakes. First steps in this direction are based on modeled glacier-bed topographies as potential future surface topographies. The developing complex and interconnected geo- and ecosystems will be characterized by strong, long-lasting disequilibria. Consideration of corresponding opportunities and risks for human activity and infrastructure constitutes a knowledge basis for adaptation planning. This needs an expansion of research toward integrated, comprehensive, and inter/trans-disciplinary landscape-ecological approaches.

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Author Contributions

Wilfried Haeberli planned the concept of the contribution and drafted the sections on historical and future aspects; Michael Zemp contributed the section on observations; and Johannes Oerlemans, the section on modeling. All three authors cooperated with the completion and final editing of the entire contribution.

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