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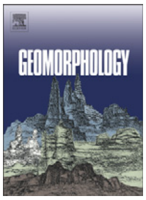

Integrated research on mountain glaciers: Current status, priorities and future prospects

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ABSTRACT

Mountain glaciers are sensitive probes of the local climate, and, thus, they present an opportunity and a challenge to interpret climates of the past and to predict future changes. Furthermore, glaciers can constitute hazards, including: glacier outburst floods; changes in the magnitude and timing of runoff in the mountains and adjacent regions; and, through worldwide loss of glacier ice, a global rise in sea level. To understand and ultimately to predict the dynamics and nature of climate and associated glacial and hydrological changes requires an integrated approach with communication and collaboration among glaciologists, glacial geologists, atmospheric scientists, geomorphologists, geochronologists, and tectonists. Current strategies of research are evolving towards integrating research on mountain glaciers to address key scientific, socio-economic and political issues. Given the rapid birth and growth of new technologies and tools with which to study glaciers and glacial landscapes, this community stands poised to address many of these challenges in the near future. The key challenges that must be met soon include: 1) determining the spatial–temporal pattern of fluctuations of mountain glaciers from the last glacial cycle through the present; 2) relating historical and past fluctuations in glaciers to variability in the primary features of ocean-atmospheric circulation; 3) identifying important but poorly understood processes controlling the motion and erosion of glaciers; 4) developing and expanding the application of numerical models of glaciers; 5) modeling the evolution of mountain landscapes in the face of repeated glaciation; 6) examining the climate and the balance of energy and mass at the surface of glaciers; 7) characterizing the role of intrinsic climate variability on glacier variations; and 8) predicting the distribution, sizes, and nature of glaciers in the future. While these ambitious goals are achievable and the research tools exist, success will require significant bridging between the existing research communities involved and ambitious integration of research on mountain glaciers.

1. Introduction

One of the greatest challenges facing humankind in the next century will be predicting and coping with the consequences of rapid climate change (Gore, 2006). The evidence of rapid change has been mounting over the last few decades and the broader public is now becoming genuinely concerned about the prospects of a very different world (Watson et al., 1997, 1998; Dyurgerov and Meier, 2000; Houghton et al., 2001; IPCC, 2007a,b). Many of these concerns pivot about the ongoing rapid changes in the cryosphere (Corell et al., 2004; IPCC, 2007a,b). The most global of these effects is the rise of sea level from melting glaciers (Arendt et al., 2002; Meier et al., in review). For good reason, glaciers have emerged as the poster-children of climate change (Gore, 2006). Accompanying the growing concern about climate change is awareness that the hydrologic system of the globe could be radically altered. This in turn has consequences for the availability of water as a resource, and the types and frequencies of natural hazards associated with its delivery to and transport across the surface of Earth. Climate change will inevitably alter how we manage water resources (a sizable fraction of which lies in glacier ice) and will significantly alter the hazards posed by mountainous regions. The study of mountain glaciers, therefore, lies at the core of several societal and intellectual challenges of our time.

Mountain glaciers are sensitive probes of the local climate, and, thus, they present an opportunity and a challenge to interpret climates of the past and to predict future changes (e.g., Oerlemans

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et al., 1998; Barry, 2006). Furthermore, glaciers are the filter through which the climate signal passes into sedimentary archives (Benn and Evans, 1998). They not only ornament the tips of mountain ranges with distinctly glacial landforms, but through efficient erosion of the landscape, can drive strong geophysical feedbacks in upland areas and strong reactions of the landscapes downstream, into which water and eroded sediment debouch. As humans live and recreate in glacial landscapes, they must acknowledge the hazards posed by glaciers. Foremost among glacial hazards are outburst floods (Walder and Costa, 1996; Pickering and Owen, 1997; Montgomery et al., 2004; O'Connor and Costa, 2004). Moreover, a large part of the population lives in regions whose hydrology is strongly influenced by glaciers. The challenges of understanding the glacial system in its full breadth will foster communication and collaboration among glaciologists, glacial geologists, atmospheric scientists, geomorphologists, geochronologists, and tectonicists. Given the rapid initiation and growth of new technologies and tools with which to study glaciers and glacial landscapes, this community stands poised to address many of these challenges in the near future.

Within the Earth Science community, one of the most exciting and integrative challenges in the last two decades has been the quantitative understanding of the evolution of landscapes. This endeavor requires understanding the links between atmospheric, lithospheric and surface processes. In the mountains the heat engine of Earth and the heat engine of the sun compete for supremacy. The evolution of mountainous landscapes has received the most attention. This new focus on landscape evolution has created a new generation of Earth scientists who live between the classical subdisciplines of the sciences. The mountains are the training ground for this new generation, who come armed with a suite of new analytic tools. Mountain glaciers serve as a focus to link many of the disciplines of modern Earth science. Current research strategies are evolving towards integrating research on mountain glaciers to address key scientific, socio-economic and political issues (Fig. 1).

Understanding the role of mountain glaciers in the system of Earth is motivated by several recent realizations. These realizations themselves lead to defined long-term challenges. In this paper, we identify the challenges and scientific priorities that need to be addressed in the coming years. We highlight and suggest focus areas of research that will aid in addressing key questions and issues pertaining to the nature and dynamics of mountain glaciation and associated environmental change. We argue that a better understanding of mountain glaciers and how they respond to climate will enable humankind to project more robustly the likely contribution to sea level change, the alteration of the hydrologic cycle and the evolution of alpine natural hazards. In addition, we emphasize how this knowledge can add to a quantitative understanding of the long-term evolution of alpine landscapes in which humans live and recreate. Furthermore, to understand in detail how the anthropogenic perturbations to the radiation balance of Earth are manifest in the response of glaciers, we identify a set of integrative tasks that the research community on mountain glaciers is poised to tackle within the coming years, with tools that now exist.

2. Mountain glaciers as climate probes

The predicted spatial pattern of global change in response to greenhouse forcing is quite complex. The highest changes in amplitude are expected to occur in the Arctic, and significant variation of response is expected across the oceans and adjacent land masses because of anticipated changes in the strength of oceanic and atmospheric circulation. These predicted responses are based on the use of sophisticated computer modeling, which can only be tested by comparing the results of models with geologic data from specific times in the past when climate was significantly different. Landforms and sediments produced by mountain glaciers provide geologic proxies for environmental change throughout many mountain ranges, at all latitudes and for a large range of timescales. Glacial geologic evidence produced by mountain glaciers is particularly useful because mountain glaciers can only exist under a specific range of climatic conditions and are extremely sensitive to environmental change, notably changes in temperature and precipitation. Thus, they have the potential to record subtle and large magnitude environmental changes. Research on mountain glaciers, however, generally has suffered from a lack of disciplinary integration, critical to elucidating the linkages between climate, glacier processes, and geologic records.

In recent years, work on ice cores has shown the complex, high magnitude and rapid nature of climate change in the past. These long, high-resolution records of climate have been extracted from ice cores in polar settings (Greenland and Antarctica largely) and in a few of the highest mountain ranges (Thompson et al., 1989, 1997; Thompson, 2000; Thompson et al., 2005, 2006). These archives of climate change, however, have little to say about the spatial pattern of glacial fluctuations and associated responses to climate shifts, whereas geologic evidence from mountain glaciers provides spatial and temporal data on paleoenvironmental change worldwide. Benn et al. (2005) emphasized that the usefulness of the glacial geologic record as a 'climate probe', however, depends to a large extent on whether researchers rigorously reconstruct glacier dimensions and ELAs. Very often, dates are obtained on moraines, but no attempt is made to calculate ELAs. Without the calculations of ELAs and glacier dimensions, dated limits for glaciers are of limited use to climate modelers or others interested in past climates.

Research on mountain glaciers can, therefore, be utilized to determine the spatial distribution, extent, and nature of past glaciers as robust probes of the spatial distribution of climatic conditions at specific times in the past. We must, therefore, develop the capabilities of modeling the extent of past change in glaciers as a means of testing our knowledge and modeling the meteorological forcing and the predicted glacial and associated responses. Given the wide global distribution of glaciers, these capabilities will allow us to reconstruct the spatial distribution of climate at specific times in the past, which in turn will serve to define evolving models of global climate used to understand past climates and predict future ones.

3. Resources and hazards of glacial landscapes

Humans are increasingly exploiting and exploring mountains for recreation and living space. It is no coincidence that many landscapes set aside for protection as national or state parks or other protected areas are either presently draped with glaciers or have been sculpted by glaciers in the past. Water derived from melting of glacier ice provides much of the water for the population in temperate and sub-tropical latitudes. This water continues to be released from glacierized landscapes after the entire seasonal snowpack has been melted from the landscape, providing water to the rivers in the mid-to-late summer, dramatically altering the shape of the seasonal hydrograph and buffering streamflow during dry years. The ice involved includes comes from traditional glaciers, rock glaciers (rock-mantled ice masses), and ground ice that extend into lower latitudes and altitudes. The extent to which glaciers modulate patterns of runoff depends very much on the seasonal patterns of precipitation and temperature. In areas with an arid summer (e.g. Afghanistan and Pakistan), runoff from glacier comprises a very important component of river discharges. In contrast, in sub-tropical monsoonal areas, such as Nepal, glacier accumulation occurs mainly during the summer monsoon, and the accumulation and ablation seasons are largely coincident. This means that river discharges are not modulated by glacier storage to such a large degree.

Although glaciers move slowly, significant hazards are associated with glacial occupation of the headwaters. Water ponded for months to decades behind glacier dams, in lakes occupying tributary valleys or

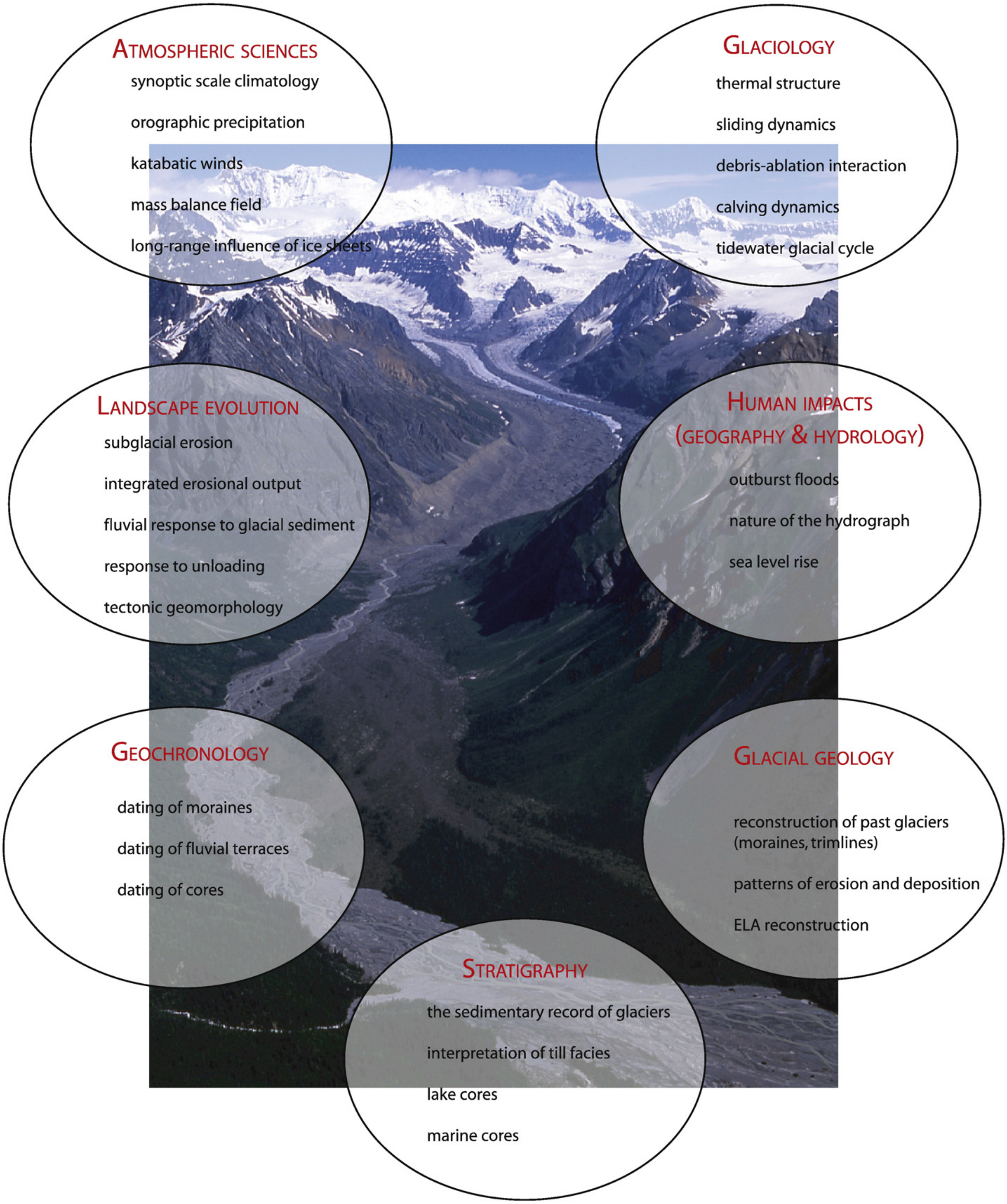

Fig. 1. Key disciplines and elements of integrated research on mountain glaciers that are required to advance our knowledge on the role of glaciers in the past, present and future systems of Earth.

behind moraine dams, can cause large outburst floods. These glacial lake outburst floods (GLOFs) may have peak discharges that are orders of magnitude greater than those associated with weather-related floods, and, thus, present unique hazards. More than 70 glacially-ponded lakes presently exist in Alaska alone. Many more such glacially-ponded lakes occur in the Himalaya and the Andes. In Nepal, for example, a catastrophic GLOF has occurred approximately once every four years during the last few decades. The role of GLOFs in glaciated landscapes is important, but the importance of seasonal high flow floods should not be neglected. The relative magnitude of GLOFs and seasonal high flow floods (SHFFs) change dramatically downstream, because GLOF hydrographs attenuate with distance downstream, whereas SHFFs increase downstream as catchment area increases. Cenderelli and Wohl (2001) showed that, in the Khumbu region of Nepal, recent GLOF peak flows are ~60 times the size of SHFFs close to source, but only ~6 times as large as SHFFs at a distance of 27 km. The implication of this relationship is that at greater distances downstream, GLOFs will fall within the range of normal SHFFs. Because villages are not located on valley floors in the high Khumbu, they are unlikely to be seriously affected by GLOFs. In the foothills, villages do tend to be located closer to rivers, but will only be adversely affected if GLOFs are larger than 'normal' annual peak flows.

The interaction of glaciers with volcanoes can lead to a suite of processes that serve to extend greatly the potential impact of volcanic eruptions in the landscape. The retreat and eventual demise of glaciers also presents a hazard, particularly where meltwater is used for irrigation, resulting in the abandonment of farmland and even entire villages (e.g., in northern Pakistan; Pickering and Owen, 1997). Ice retreat frequently leaves over-steepened slopes prone to rapid slope failures that can present significant hazards to local populations. Finally, the large volumes of sediment fed to the fluvial system can reduce the longevity of reservoirs, and cause rapid changes in river channels that can alter river navigability.

On the larger scale, global sea level is rising (Fig. 2), in part because alpine ice is being lost from the inventory. Although loss from ice sheets is increasing as well, mountain glaciers will continue to contribute several tens of percent of the rate of sea level rises because of an increase in ocean volume (Arendt et al., 2002; Dyurgerov, 2002; Meier and Dyurgerov, 2002; Rignot et al., 2003; Meier et al., in review). At least one-half of the 3.1 mm/yr of present rate of sea level rise is attributable to the loss of land-based ice (the other half caused by expansion of the water column upon warming). Of this, 60% is derived from sources other than Greenland and Antarctica, or "small glaciers and ice caps". This rate of sea level rise is projected to continue through this century. Importantly, much of the acceleration in loss of ice from all ice sources comes not simply from surface melting of the ice, but from a highly nonlinear ice dynamics driven by rapid sliding of the ice at its bed (Anderson et al., 2004). This basal process and its connection, through the hydrology of glaciers, to climate change is ill-understood.

The role of glaciers in freshwater runoff to the Arctic Basin is very poorly defined. Glacier input by direct calving of ice into the Arctic Ocean is the biggest factor in terms of net land-to-ocean transfer of fresh water. The local ecological effects arising from freshening of coastal waters add to the impacts of the loss of sea ice from the basins.

Scholars on mountain glaciers are developing an understanding of the evolution of mountain landscapes and aim to transfer this knowledge to planners, policy makers and the broader public. It is imperative that models are developed that go beyond the cartoons in modern textbooks toward quantitative, process-based simulations that include our present knowledge of ice physics. Improved understanding of the hydrology of glaciers is required to generate the predictive capability needed to address the consequences to water resources as the present glaciers shrink, and to predict the timing and magnitude of outburst floods that could be released. Although substantial work has been completed on the links between glaciers and hydrology throughout mountain regions (e.g. Verbunt et al., 2003) these links need to be quantified more fully because of the considerable local and regional variations that exist. Specific research priorities should include such topics as controls on water storage and annual modulation of water cycles.

The glaciological community is involved in a broad and urgent effort to develop a predictive understanding of two distinct glacier responses: 1) the response to climatic forcing, which dominates glacier changes on century-to-longer timescales, and 2) internal dynamic feedbacks that lead to natural variations in glacier motion even in a steady climate. These latter modes can be independent of

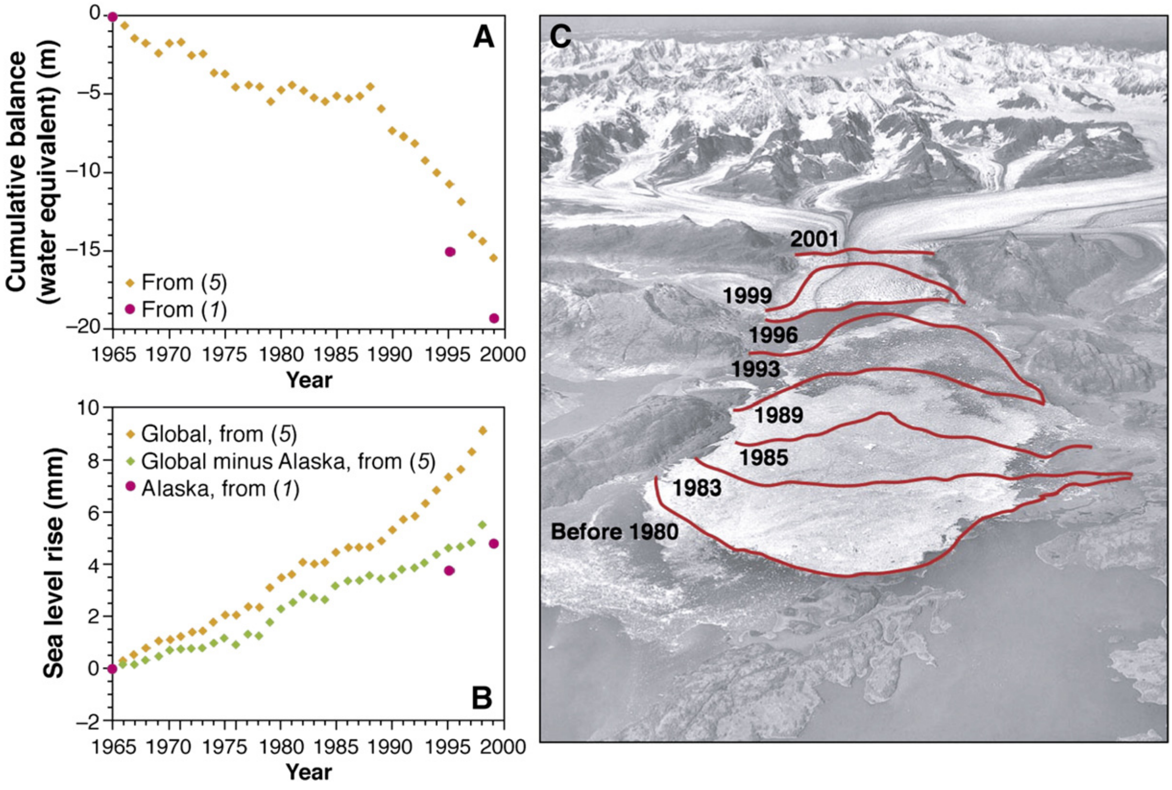

Fig. 2. Examples of the retreat of mountain glaciers and the contribution to global rise of sea level. (A) Surface mass balance of glaciers in Alaska (1, Arendt et al., 2002; 5, Dyurgerov, 2002). (B) Rise of sea level from the melting of mountain glaciers in Alaska, where glaciers have lost an average of ~15 m water equivalent from their surfaces, contributing ~4 mm of sea level during this time period. (C) Recent retreat of the Columbia Glacier, Alaska (from Meier and Dyurgerov, 2002).

climate and can dominate on decadal-and-shorter timescales. Ice loss associated with such “dynamic effects” is accomplishing much of the ice loss from the edges of ice sheets (Rignot and Kanagaratnam, 2006). Prediction of glacier dynamics on short timescales is hampered by lack of basic knowledge of processes, such as subglacial sliding, seasonal and daily evolution of the englacial and subglacial hydrologic system, iceberg calving, and ocean-ice heat and mass transfer. These unknowns must be addressed if future century-scale environmental changes, including the rise of sea level, are to be predicted well enough for responses to be effectively planned.

4. Mountain glaciers as agents of landscape evolution

Glaciers are efficient agents of erosion and produce dramatic mountain landscapes with deep valleys and high peaks. These are exemplified by such places as Yosemite and Glacier National Parks, and the Mt. Everest World Heritage Site. Mountain glaciers occupy the headwaters of catchments and, hence, profoundly influence the water and sediment delivery to the rivers downstream. Alpine landscapes are ornamented with features that are distinctly glacial: horns, arêtes, cirques, U-shaped valleys, and strings of small lake basins. Rates of glacial erosion can be more than an order of magnitude greater than those in landscapes dominated by river and hillslope processes (Hallet et al., 1996). Glaciers can, therefore, significantly influence the evolution of mountain landscapes and modulate the output of sediment.

Glacial erosion generates local relief in the cores of mountain ranges, and can incite rock uplift because of erosional unloading of the crust in the cores of ranges (Figs. 3 and 4). The potential, therefore, exists for significant feedbacks: rock uplift raises peaks, which in turn results in larger glaciers (Molnar and England, 1990; Small and Anderson, 1998; Champagnac et al., 2007). This ability of glaciers to accomplish rapid erosion underlies a proposed explanation for localized rapid rock uplift in the syntaxes of the Himalaya, a phenomenon that has been dubbed the ”tectonic aneurysm” (Zeitler et al., 2001). Significant debate exists, however, over the importance of mountain glaciers versus other processes, such as fluvial erosion and mass movement, in shaping mountain landscapes (Hallet et al., 1996). Topographic data from the Himalaya, the Cascade mountains in Washington, and the Chugach Range in Alaska has given rise to the “glacial buzzsaw” hypothesis: glacial erosion is so efficient that it limits the heights of the peaks (Brozovic et al., 1997; Spotila et al., 2004; Mitchell and Montgomery, 2006). This concept remains to be demonstrated as a universal rule. It is undoubtedly the case that polar glaciers, which dominate in high latitude and very high altitude settings, fail to erode glacial valleys efficiently; the impact on landscapes may be limited to fluvial erosion by glacial meltwaters upon the demise of the glaciers. The influence of glacier thermal regime — temperate, polythermal or polar — must, therefore, be acknowledged. Furthermore, long-term rates of denudation have been shown to be an order of magnitude less than measured short-term rates in some settings, in particular those subjected to tidewater glacial cycles (Spotila et al., 2004). Currently, the questions of what processes limit topography, the temporal and spatial role of glaciers in eroding orographic belts, and the variations of rates of denudation over time, remain unanswered. A stratigraphic and temporal framework is essential to answer these questions and to help quantify and assess the role and importance of mountain glaciers in landscape evolution.

Glaciers have oscillated many tens of times in the last few million years. These oscillations result in periodic changes in erosion and the inputs of sediment to the fluvial systems, making it difficult to argue that such systems can ever achieve a steady state. Glaciated mountain ranges are always in a state of transience, challenging the application of the typically applied, simplifying assumption of steady state. The sediment derived from glacial erosion is carried to the terminus in subglacial streams, which then serve as the top boundary condition of the fluvial system. Cycles of glacial occupation of the headwaters will generate great swings in the sediment delivered to the fluvial system, which in turn drives cycles of aggradation and incision downstream. These can be recorded either as sets of fluvial terraces, as cyclical depositional packages on alluvial fans, or as sedimentary records in fjords or lakes. Sediment eroded from the glaciated cores of mountain ranges, derived either from the glacial regime or from periglacial slopes, is delivered to the remainder of the landscape through the fluvial conduit. In effect, the fluvial and hillslope systems act as filters through which the signal of glacial climate must pass before being recorded in the marine or lacustrine archive. The corresponding timescale of this filter has been dubbed the paraglacial time (Church and Ryder, 1972, 1989). The dominant processes during this time of adjustment are mass movement and fluvial erosion and transport. These are particularly important in the transfer of glacial and proglacial sediments within and beyond the high mountain landscapes, thus, helping to contribute to the net denudation of high mountains (Ballantyne, 2002a,b; Benn et al., 2006). Furthermore, mountain glaciers are very sensitive to climatic oscillations and have fluctuated repeatedly, particularly on millennial timescales, throughout the late Quaternary. The landscapes in glaciated mountain regions are, therefore, expected to be in a state of transient adjustment to changing climatic and environmental conditions. The history of sediment delivery from a glaciated mountain range, therefore, reflects the action of two filters: first, the glaciers act as a filter to the climate,

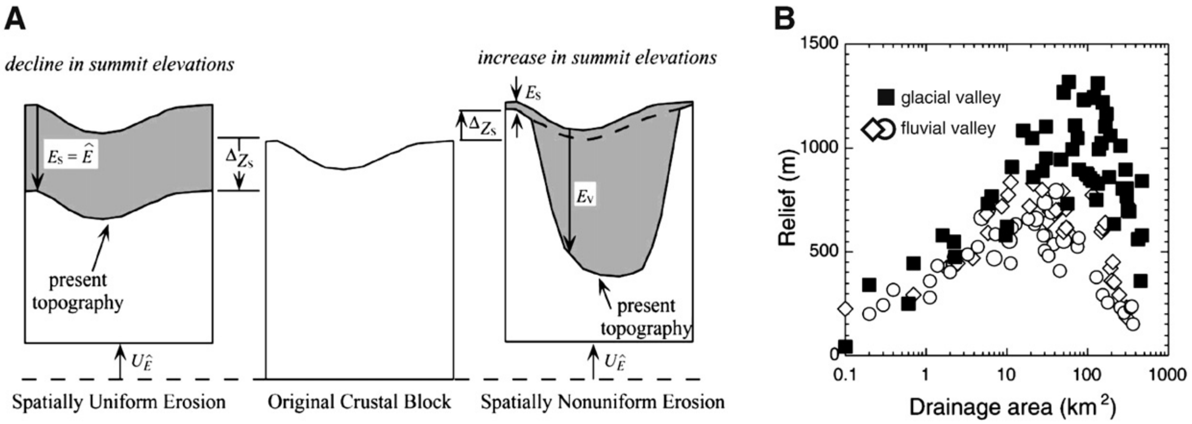

Fig. 3. Examples of the role of glacier occupation, and associated erosion on mountain landscape evolution and relief development. (A) Model of relief generation via glacier erosion (Small and Anderson, 1998; modified from Molnar and England, 1990). (B) Empirical data showing that glacier erosion generates more relief than fluvial incision alone in Olympic National Park, Washington (from Montgomery, 2000).

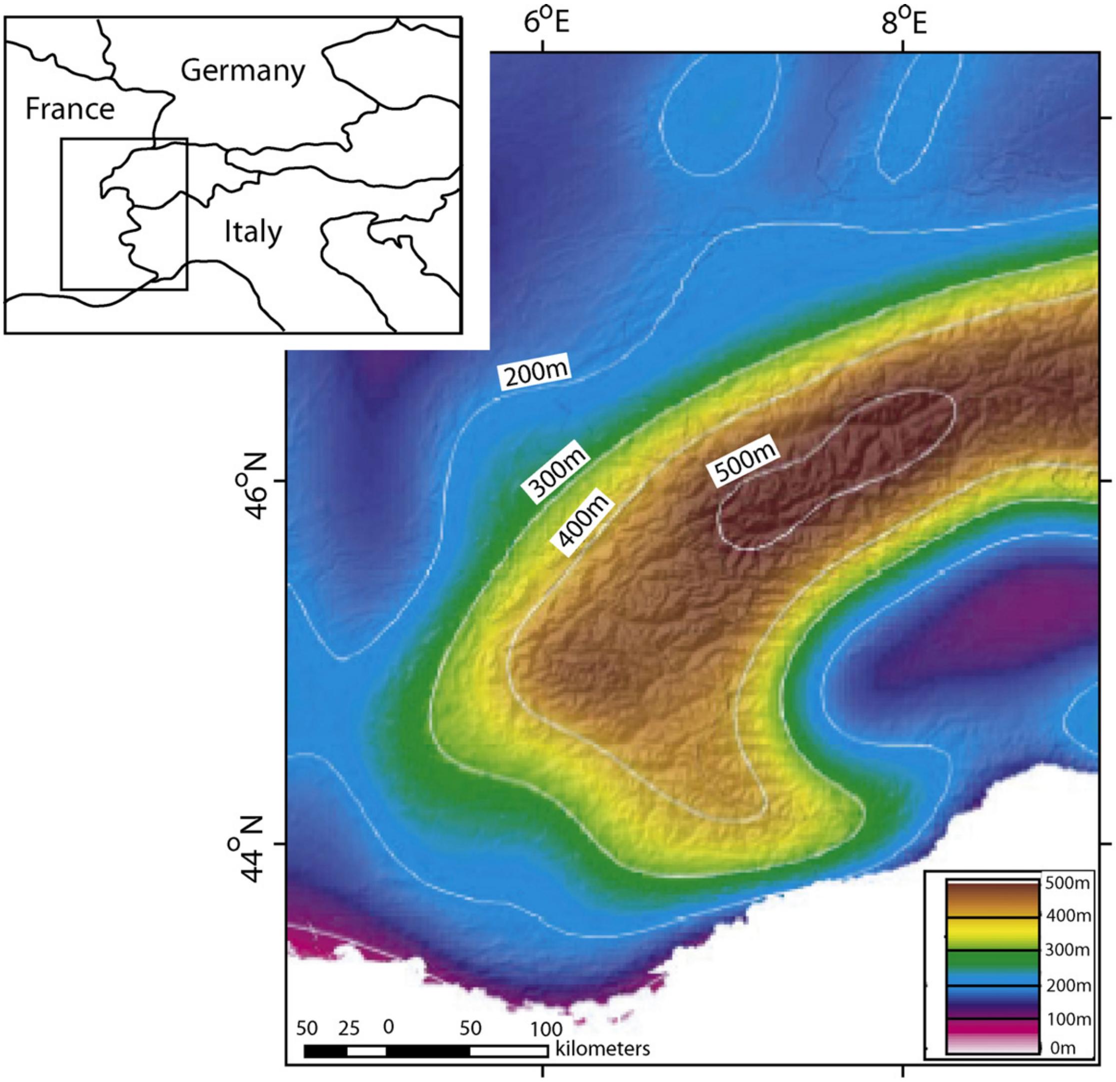

Fig. 4. Isostatic response of the western Alps (inset) to erosional deepening of glacial valleys in the Plio-Pleistocene. In the core of the range, more than 500 m of rock uplift can be attributed to this effect (after Champagnac et al., 2007).

and second, the fluvial-landscape system acts as a filter to the sediment originally eroded by the glacier.

Continued documentation of the pattern and rate of glacial erosion on landform, catchment and mountain range scales is important. We must understand how the atmosphere interacts with the landscape to set the pattern of snow accumulation and of melt that together dictate the pattern of mass balance on a glacier. In addition, we must understand how glaciers accomplish downvalley transport of ice by internal deformation (irrelevant to erosion) and by sliding (all-important in erosion). Furthermore, we must establish how and over what timescale the products of erosion are delivered to sinks that serve as archives of the history of erosion. Moreover, we must address how the variation in rock and ice loads on the landscape is accommodated with flexural and isostatic adjustment. All of these processes are linked, with a rich set of feedbacks. Only when we are able to robustly evaluate all of these processes will we be capable of modeling the impact of glaciers on mountain evolution in the face of repeated glacial cycles (climate forcing), and be able to explore this rich suite of feedbacks. We must find robust tests of glacial and non-glacial (fluvial and other “paraglacial” processes) components of landscape change, using landscapes in which moraines are dated and the sinks for sediment are preserved and documented.

5. The legacy of glacier ice

Mountain glaciers erode rock and deposit sediments, generating distinctive landforms that serve as their legacy in the mountains. The degree to which a glacier can alter the landscape over which it moves depends upon the extent and the thermal regime of the glacier. Polar glaciers, frozen to their beds, achieve little to no erosion, while temperate glaciers, capable of significant sliding, can erode at rates several times higher than rivers. The majority of glaciers are polythermal, with some warm and some cold ice (Blatter and Hutter, 1991). These contrasts in types of ice influence the rate of landscape evolution, and also the amount of sediment generated by the glacier and fed to the river network downvalley, and the degree to which surface exposure-based chronological tools are effective in documenting the timing of glacial occupation of the landscape.

Glaciers leave a record of past extent that is largely written in the positions of terminal moraines (Fig. 5). Whereas most moraines are easy to map, particularly with modern remote sensing tools, these depositional features are notoriously difficult to date. Yet they must be dated well if we are to reconstruct maps of the extent of mountain ice at various time slices in the past. The tools of choice within the last decade have become terrestrial cosmogenic nuclides (TCNs), largely

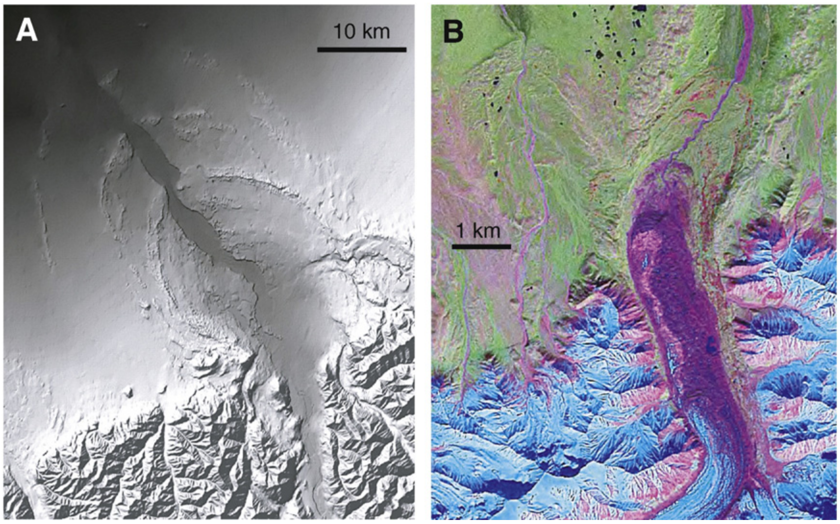

Fig. 5. The depositional record of mountain glaciation in the Alaska Range. (A) Digital evaluation model showing Pleistocene moraines along the Kuskokwim River (National Elevation Data (NED) from http://seamless.usgs.gov/). (B) 2000 LANDSAT image of Holocene and Pleistocene moraines fronting the Peters Glacier as it descends to the north from the highest peak in North America, Mount Denali (from https://zulu.ssc.nasa.gov/mrsid/). Moraines like these delimit the extent of mountain glaciers, and where dated, are used to infer the timing and extent of mountain glacier fluctuations.

^{10}Be and ^{26}Al, measured in moraine boulder surfaces (Fig. 6), in places augmented by OSL dating of sediments. These techniques have become especially useful because they are more widely applicable than radiocarbon dating, which is limited by available organic materials and restricted in geologic time (<50 ka) because of its short isotopic half-life. Although considerable investment has been made through the US National Science Foundation (NSF) and partnering European agencies in documenting the production rates of these TCNs and the scaling factors needed to calculate the dependence on latitude and altitude, operational problems remain in dating specific types of landforms. In essence, the geomorphic reality of evolving landforms and of inheritance of TCNs from prior exposure elsewhere in the environment must be handled well, to interpret properly the measured concentrations of TCN as ages of these landforms (Benn and Owen, 2002; Putkonen and Swanson, 2003).

To meet the challenges outlined above, the mountain glacier community must develop robust, cost-effective strategies to date moraines that address the various sources of error, including inheritance of TCNs, temporal evolution of the topographic form of moraines after deposition, and erosion of the boulders being dated. Finally, we must establish ages of moraines in mountain ranges around the world to define the spatial pattern of glacial extent at specific times in the past.

6. Ice dynamics

The essential role of glaciers in the system of Earth is the transportation of ice from regions where excess ice mass accumulates (principally through snowfall) to regions where that excess mass can melt, be discharged into the ocean, or evaporate. Under long-term steady conditions, a glacier will self-adjust its geometry and velocity such that mass transferred by flow processes in the glacier exactly balances mass sources and sinks, and the glacier geometry remains constant in time. This delicate balance is sensitive to climate and ice physics: the pattern of snowfall, the efficiency of ice transport, and the pattern of ice loss. Transport is accomplished by some combination of

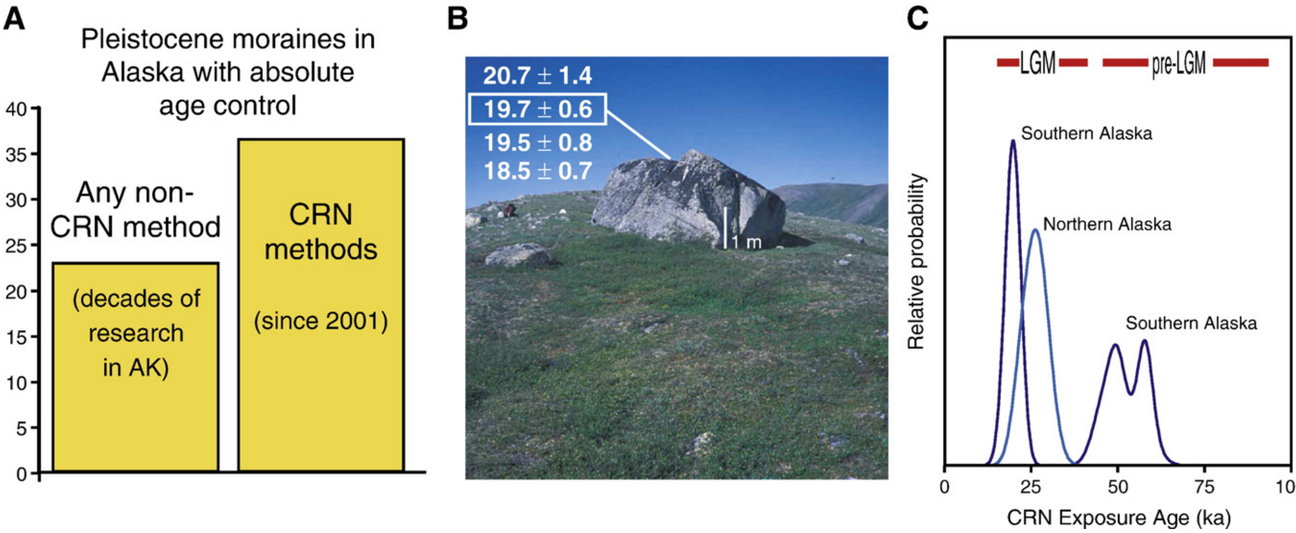

Fig. 6. The increased use of TCN dating compared to other dating techniques (e.g. radiocarbon dating) and its application to dating moraines illustrated for Alaska. (A) The number of dated moraines using TCN compared to other methods. (B) One of four moraine boulders used to constrain the age (ka) of an end moraine. (C) Summed relative probability plots for selected moraines TCN ages showing conclusions not available prior to the availability of TCN dating: 1) differences in the ages of the LGM terminal moraine across the state; and 2) the ages of pre-LGM moraines, at least in south Alaska, are ~50 to 60 ka.

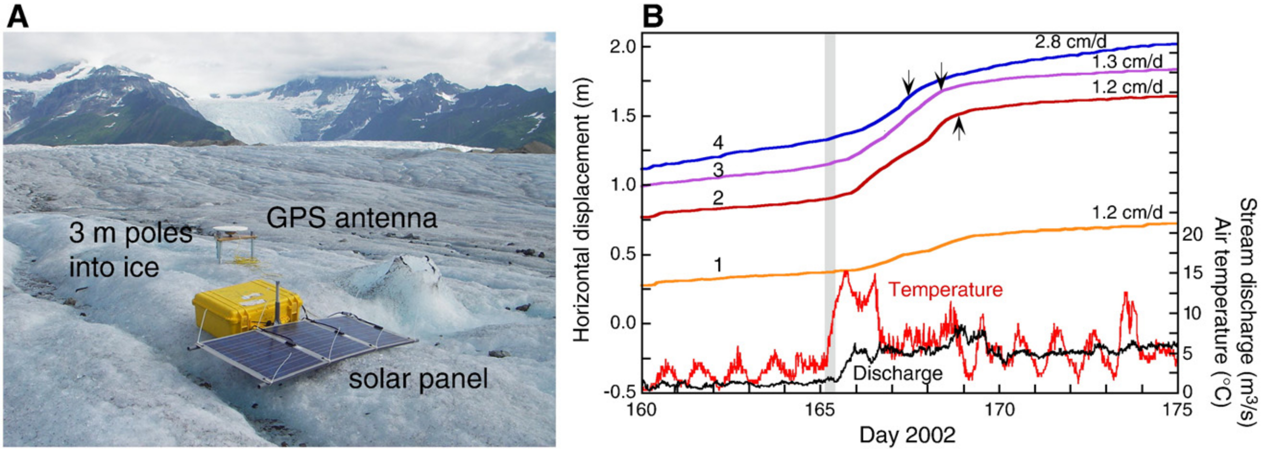

Fig. 7. The Bench Glacier showing (A) ice surface and instrumentation and (B) horizontal displacement record on the Bench Glacier, Alaska, derived from GPS measurements at four sites on the glacier (after Anderson et al., 2004). Speed-up deduced from change in slope reflects a change in sliding at the bed, and is associated with higher air temperatures and associated enhancement of melt input. The discharge of a glacier outlet stream (black) shows a major change in magnitude, as a major drainage channel is extended up glacier. While sliding stops around day 170, high discharges continue, reflecting establishment and maintenance of the new conduit system that serves to bleed water pressure from the subglacial system.

internal deformation and basal sliding, with the partitioning between these mechanisms principally dependent on temperature (Paterson, 1994). Ice deforms as a non-linear viscous fluid whose effective viscosity is strongly temperature-dependent. Basal sliding is accomplished by a variety of complex and poorly understood processes, all requiring the presence of meltwater (Copland et al., 2003a,b). The details of the ice-water interaction are poorly known, owing largely to the difficulties of making direct englacial and subglacial observations, but significant studies include Cohen et al. (2005) and Kavanaugh and Clarke (2006). 'Polar' glaciers, which have internal temperatures below the melting point and no significant liquid water present, flow at different rates and respond differently to climate forcing. 'Temperate' glaciers, and polar glaciers in the process of becoming temperate, are influenced by climate through the complex linkage of surface melt, water mobility and input, and the action of that water in modulating deformation and sliding. Many glaciers, however, are polythermal and, hence, involve a combination of the above conditions and processes.

The broad picture of internal deformation and subglacial sliding is understood through more than 50 years of research on glaciers and ice sheets, and adequate predictions can be made of slowly-changing or steadystate conditions (e.g., the final steady state geometry following a climatic shift). Transient glacier response to forcing, and indeed glacier response on all short timescales, is much more difficult to predict reliably at present. Importantly, these timescales overlap with those associated with internal dynamic cycles, which include the tidewater glacier cycle, the surging of alpine glaciers, and the rapid response of outlet glaciers from ice sheets. These now appear to be dominating some substantial present-day glacier changes (e.g., the volume reduction of the Greenland Ice Sheet and rapid retreat of Columbia Glacier, Alaska) (Meier and Dyurgerov, 2002; Joughin et al., 2004). Whereas new tools are being brought to bear on these critical issues, we lack a complete understanding of the controlling processes. Great care must, therefore, be exercised not to extend modeling predictions beyond the range of meaningful, robust results.

We now have new tools to work these problems, including global positioning systems (GPS) (Fig. 7), Interferometric Synthetic Aperture Radar (InSAR), Light Detection and Ranging (LiDAR), ground-penetrating radar (GPR), and seismic methods. Most weather information is derived from airports, which are not commonly situated in mountains. Remotely operated meteorological stations are becoming more reliable. Recent modification of radar methods now allows us to document the thickness of temperate ice up to about 1 km below the ice surface. Repeat LiDAR surveys can be used to document patterns of snow accumulation if flown in late fall and late spring, and to document glacier change efficiently if flown every few years. InSAR has now been utilized to document the speed of glaciers remote areas, dramatically enhancing our knowledge of surface speeds of ice (Fig. 8;

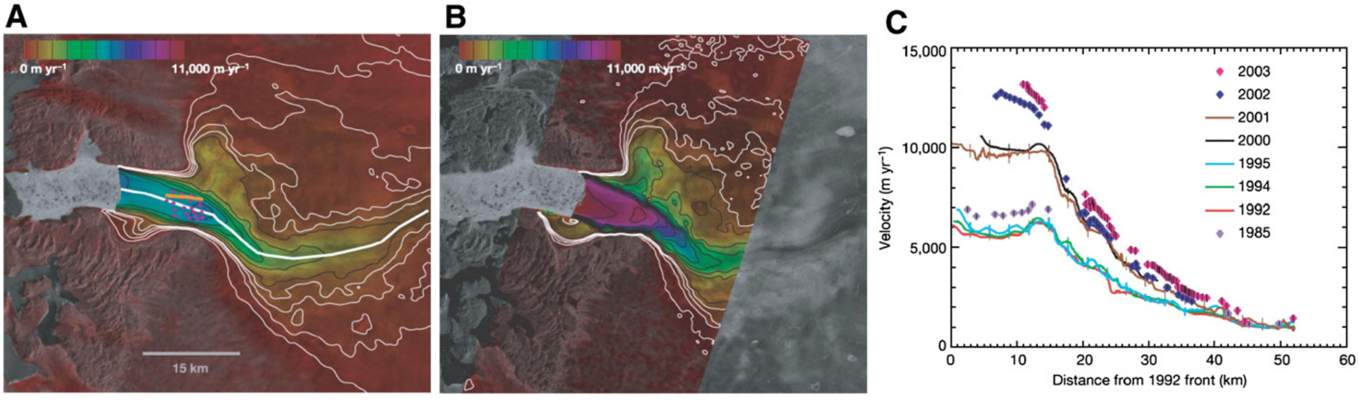

Fig. 8. The speed of ice-flow as color over SAR amplitude imagery of the Jakobshavn Isbrae in February 1992 (A) and October 2000 (B). In addition to color, speed is contoured with thin black lines at 1000 m/yr intervals and with thin white lines at 200, 400, 600 and 800 m/yr. The thick white line shows the location of the profile plotted in panel (C). The locations of velocity measurements made in 1997 (orange line) and 1985 (purple symbols) are also shown. (C) Velocity profiles along the Jakobshavn Isbrae through the last two decades (from Joughin et al., 2004).

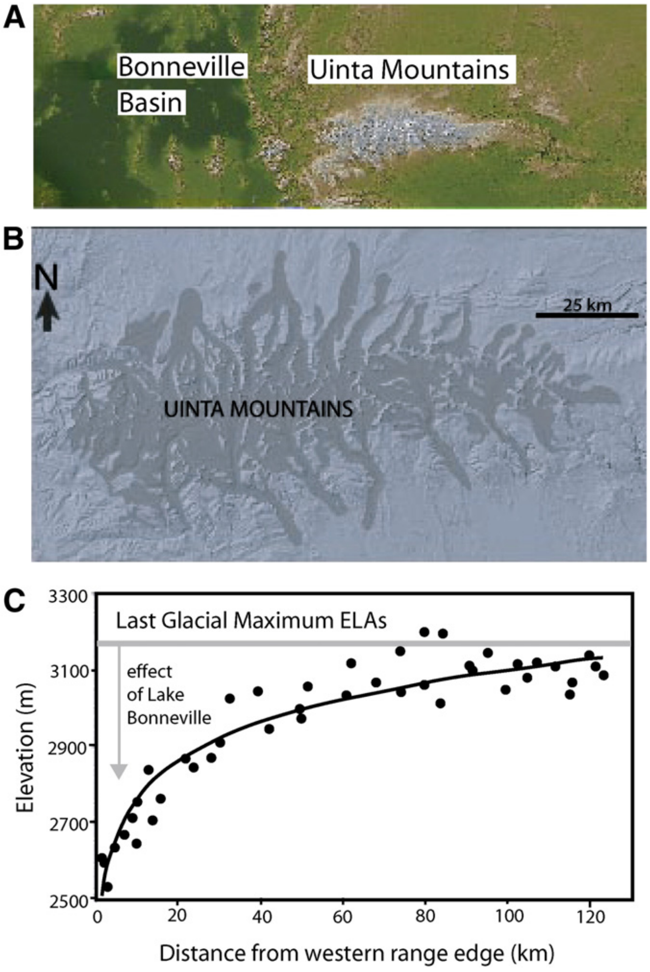

Fig. 9. Changes of equilibrium-line altitudes (ELAs) across the Uinta Mountains for the Last Glacial Maximum (LGM). (A) DEM of northern Utah showing the Uinta Mountains with Lake Bonneville Basin to the west. (B) DEM of Uinta Mountains with the LGM mountain glacier extent recorded by terminal moraines. (C) ELAs of the LGM glaciers along the Uinta Mountains. The pattern shows a dramatic drop in the ELA to the west, attributed to enhanced precipitation because of the lake effect from Lake Bonneville immediately upwind to the west (from Munroe et al., 2006).

Joughin et al., 2004). Whereas these methods document well the variation in the speed of the surface over wide areas, these are averaged over large time intervals, and are incapable of documenting the temporal variation that reflects glacier sliding. This must come instead from GPS deployments on the ice surface, an activity well supported by UNAVCO.

7. Climate–glacier interactions

The local climate dictates the presence or absence of glaciers in a valley (set by whether the equilibrium-line altitude [ELA] is above or below the top of the landscape), the extent of glaciers in the valleys, the ice discharge through the valley, and the style of glacier (polar or temperate or polythermal). The relevant climate is local in several senses: 1) the last glaciers to melt in an alpine landscape are those that hide in nooks that are favorable to the accumulation of snow, and in which the direct radiation is lowest; 2) orographic effects, the interaction of the wind and precipitation fields with the topography, lead to drastic asymmetry of glacial extent (Fig. 9; Roe, 2005; Munroe et al., 2006); and 3) regional variations in atmospheric circulation lead to non-uniform response of glaciers to global climate cycles.

Mountainous terrain dramatically affects patterns of precipitation and ablation down to remarkably small scales. A ridge can capture twice as much snow as the neighboring valley a kilometer away, for example. For many glaciers, wind-blown accumulation during large storms is also an important part of the mass budget. On the ablation side of the mass balance, heat, not temperature *per se*, physically ablates glaciers. This heat results from the energy balance at the glacier surface. Sublimation, turbulent energy fluxes, atmospheric humidity, cloudiness, solar and terrestrial radiation, local slope aspect and shading, and percolation and refreezing of meltwater all play a role in controlling ablation on the surface of the glacier.

Glaciers also alter the local climate through many strong feedbacks. For example, because the glacier surface serves as the lower boundary condition for the atmosphere, as the glacier ice thickens, the elevation of that spot in the landscape rises and cools. This brings more of the landscape into the accumulation zone, and acts as a positive feedback on the growth of the glacier. The intense temperature contrasts between glaciers and adjacent land surfaces drive turbulent fluxes of heat and momentum that, in turn, play an important role in glacier surface mass balance. Katabatic downslope winds, driven by cooling of the air mass against the surface of the glacier, alter the melting regime on the ice surface, and serve to reduce the temperatures downvalley beyond the glacier itself, with attendant impacts on biota. In glaciated valleys, these and other effects play an important role in the local meteorology, and so are of concern to populations within such valleys. They occur at a scale too small to be well represented in current state-of-the-art numerical weather prediction models.

We must understand mountain meteorology well enough to be able to characterize its impact on glacial mass balance in mountainous terrain, including all feedbacks (Braithwaite, 2002; Hock, 2005). The larger-scale challenge for bridging glacial and atmospheric disciplines is to determine how a glacial system responds as a whole to changes in climate, including long-term, orbitally-driven cycles (tens of thousands of years) and shorter-term millennial to sub-annual changes. This cannot be accomplished without attention to the smaller scale glacier–climate interactions. Predicting future responses of the glacier to climate change have mostly been done using 'static' models, which assume unchanging glacier geometry and calculate changes to the mass balance in response to a given climate signal (e.g. Radic and Hock, 2006). The new generation of predictions, however, uses 'dynamic' models, which evolve glacier geometry through time (e.g. Schneeberger et al., 2003; Anderson et al., 2006; Kessler et al., 2006). This is likely to be a major contribution to our understanding of the interaction of glaciers and climate in the future.

8. The present status of knowledge about mountain glaciers

The refinement of existing methods and the development of new tools and technologies (Fig. 10) have led to significant recent progress in the study of mountain glaciers. This progress places the mountain glacier community on the cusp of an explosion of knowledge about responses of mountain glaciers and its relationship with the climate

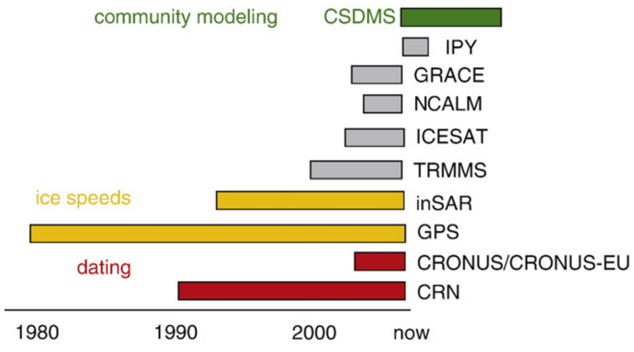

Fig. 10. The evolving toolkit. The emergence of new tools in the last decade has been dramatic. These represent an opportunity for the mountain glacier community to pursue the goal outlined in this paper.

system and longer-term evolution of landscapes, and the hazards it poses for humans.

1) We can now date past ice advances, represented by moraines, in unprecedented detail over the last few glacial cycles using new dating techniques that include surface exposure to terrestrial cosmogenic nuclides (TCN) and optically stimulated luminescence (OSL), methods unavailable to researchers until recently (Gosse et al., 1995a,b; Phillips et al., 1996; Gosse and Phillips, 2001; Owen et al., 2003; Spencer and Owen, 2004; Briner et al., 2005; Owen et al., 2005, 2006). Furthermore, the refinement of methods and strategies for the coring and analysis of glacial-lacustrine and glacial-marine sediment has produced more continuous proxy records of past glacier response.
2) We now have access to a global digital elevation models at a minimum of 90 m resolution; thus, we are in the position to characterize mountain morphology across the globe, including regions difficult to access. Furthermore, data from Aster and Quickbird satellites offer visible and multi-spectral data at exceptional resolution (≪30 m) suitable for local-scale studies.
3) New thermochronologic methods, stemming from improved geochemical and isotopic analytical techniques, allow us to define rates and patterns of mountain exhumation on million year timescales.
4) We have a moderately extensive global inventory of volume and area distribution of glaciers, because of a global effort by the glaciological community, augmented recently by such programs as GLIMS (Global Land Ice Measurements from Space), but the inventory of changes in glaciers is much less extensive. Records of long-term volume changes and long-term seasonal mass balance records (which identify seasonal mass balance components) are scarce. Paleoclimate proxies, extracted from ice cores, provide extremely detailed records of change over timescales greater than 100,000 years, but are available at a very limited number of locations.
5) We can now document the speeds of glaciers in real time on the ground using global positioning systems (GPS), Light Detection And Ranging (LiDAR) and over longer intervals remotely using Interferometric Synthetic Aperture Radar (InSAR), allowing us to document ice discharges, and to probe sliding speeds (Rignot et al., 1996). Using hot-water drills, we can now efficiently drill to the beds of glaciers, and can monitor water pressures, *in situ* stress and strain in the ice, and document the nature of the local bed.
6) We can sense rebound and loading patterns, even down to seasonal hydrological changes, using remotely sensed Gravity Recovery and Climate Experiment (GRACE) data and GPS on the ground.
7) We can sense remotely the hydrologic cycle, for example, using Tropical Rainfall Measuring Mission Satellite (TRMMS) for precipitation in the tropic.
8) We have long records of ocean volume and δ^{18}O from marine and ice core sites that must be reconciled with the terrestrial record.
9) Records of modern changes in glaciers, ice core proxy records, and other stratigraphic climate proxy records (e.g., lake and ocean cores, tree rings, corals) are extremely effective tools for establishing spatially and temporally dense records of environmental change (Fig. 11; Loso et al., 2006). The technology for extracting these records is in hand, but field campaign commitments must be made

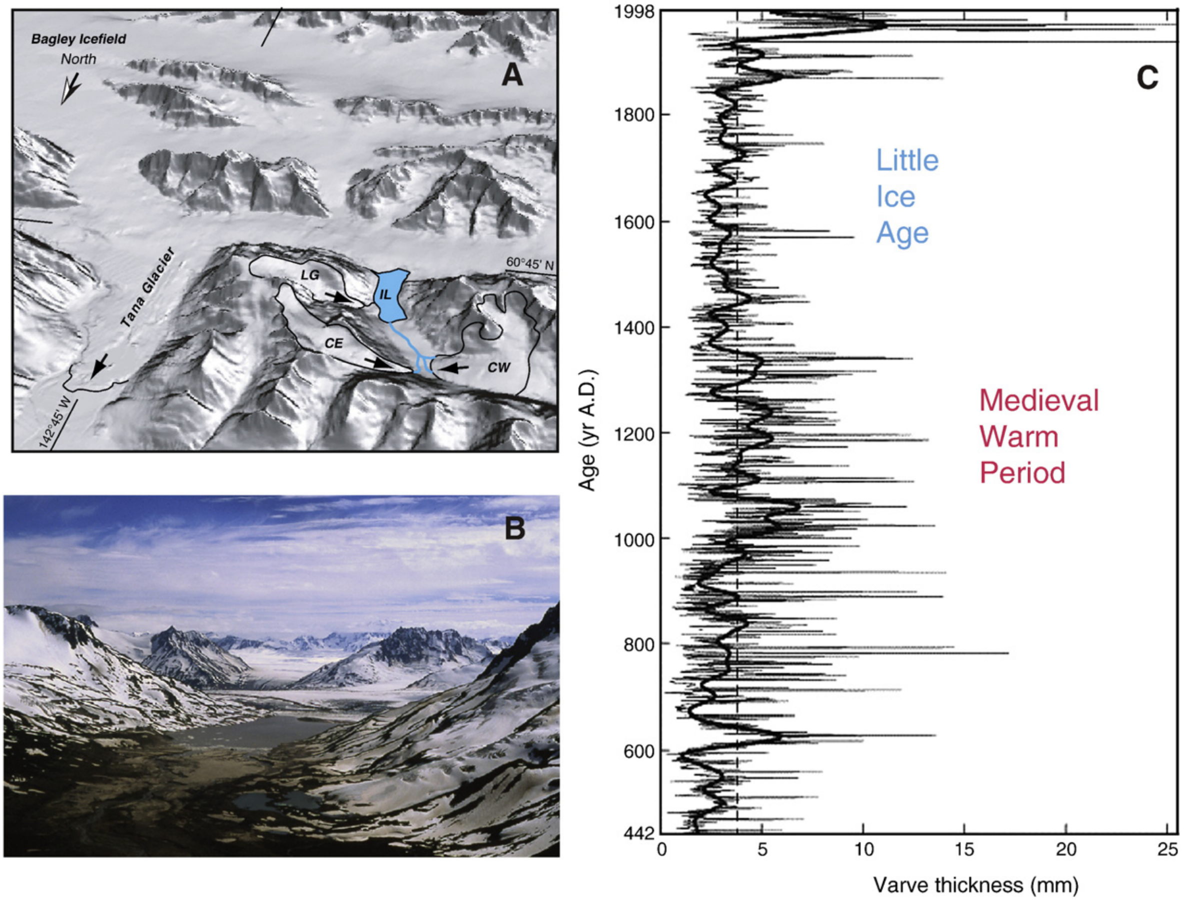

Fig. 11. The record of varve thickness as extracted from Iceberg Lake, Alaska. (A) Index map showing location of the Iceberg Lake basin beside an arm of the Tana Glacier, draining the Bagley Icefield, Chugach Range, Alaska. (B) Iceberg lake after partial draining, exposing delta topset beds and portion of the lake floor. Part of the Tana Glacier dams the lake. (C) Raw record of varve thicknesses, and smoothed record, extracted from lake floor muds, extending over ~1600 years, from AD 442 to AD 1998. Varve thicknesses reflect variations in sediment discharge from small glaciers (CE — Chisma East; CW — Chisma West) (after Loso et al., 2006).

to collect them, and in the case of glacier mass balance studies, long-term (decades) support for continued observation is essential.

10) Climate models exist with timescales that can resolve individual storms, and with boundary conditions that can embrace the range of ice mass conditions over the last glacial cycle.
11) We now have a first generation of glacier models, which operate on detailed DEMs and range in scale from a mountain glacier to an ice sheet. These models are capable of testing the response of mountain glaciers to climate while paying attention to climatic and topographic detail (Fig. 12; Kessler et al., 2006).

9. A global research strategy for mountain glaciers in the 21st century

Based on the above discussion, a set of integrative research priorities can be identified that will allow the mountain glacier research community to tackle the previously highlighted research topics and issues. These will now be discussed in turn.

9.1. Clarify the spatial–temporal fluctuation patterns of mountain glaciers from the last glacial cycle through the present

To meet this goal, we need to develop further two equally important datasets: an accurate reconstruction of the extent of mountain glaciers through time, and an accurate accounting of the timing of fluctuations. The first depends on interpretations of ice-marginal and pro-glacial sedimentary records, especially those stored in fluvial terraces, lakes, and fjords. Sediment cores from ice-proximal lacustrine and marine basins are especially valuable as continuous and often datable archives of glacier activity. Seasonal-scale records are attainable where laminations are known to accumulate annually. Otherwise, accurate geochronological control depends on the availability of suitable materials for particular dating tools, and ideally materials for multiple dating approaches that can be used as cross-checks. In reconstructing fluctuations of mountain glaciers at widespread locations across the globe, particular attention needs to be paid to the style of glaciation, in terms of the geomorphology of the landscape, which is the legacy of the past glacier occupation, and in terms of the climate information that is extracted from the sedimentary record.

9.2. Relate historical and past fluctuations in glaciers to variability in the primary features of ocean-atmospheric circulation

To accomplish this goal, we need to quantify the relationship between climatic variables and ice extent during the interval of instrumental records. We need to interpret fluctuations in past ice volume in terms of past precipitation, temperature, and wind regimes at local and regional scales. As the geomorphic evidence of fluctuations in glaciers is incomplete, we must explore continuous records of glacier activity stored in proglacial sedimentary basins. Robust interpretation of those records will require improved understanding of sediment transfer as it relates to glacial and fluvial sediment transport processes, as well as sedimentation processes in the basins themselves. Similarly, as the instrumental record of climate variability is short, we must exploit other proxy evidence, including tree rings, isotopic, and paleo-ecological indicators from sites nearby the glaciers to document the meteorological forcing. We need to identify the key mountain ranges where climate change can be linked directly to variability in well-documented modes of ocean-atmospheric

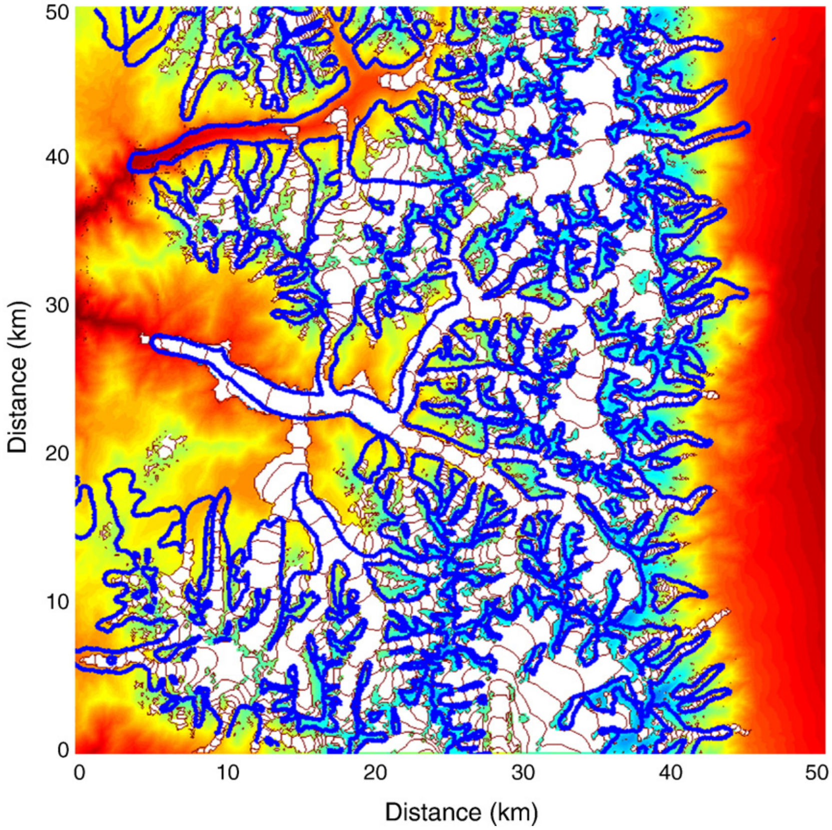

Fig. 12. Model results of King's Canyon National Park, California are from Kessler et al. (2006). This is an example of one of the few existing numerical glacier models that are used to relate the extent of mountain glaciers reconstructed by glacial–geologic studies. The blue outline relates to climate parameters via ice-flow simulations, while the white areas are simulated glacier extent that was "grown" in a numerical model based on first principles of glacier flow. The combination of winter precipitation, summer ablation, and orographic effects lead to a mass balance equilibrium-line, which is optimized for the best match). Models like these are needed to understand the response of glaciers to varying climate regimes whereas the glacier–geologic data are used to validate the model.

variability, such as the strength of the Asian monsoon or the position of the Aleutian low.

9.3. Focus efforts on identifying important but poorly understood processes controlling the motion and erosion of glaciers

Critical non-linear processes must be identified and distinguished from processes that are not significant drivers or modulators. Investigation of these processes must be motivated and steered by tangible long-term goals (principally the development of short- to long-term predictive modeling capabilities), but the research must be based in observation, experimentation, and analysis, guided by realistic assessments of what level of physical detail is needed for a given model application.

9.4. Develop and expand the application of numerical models of glaciers

To meet this goal, the mountain glacier community needs to address several objectives. Firstly it needs to test the physical modeling against field data obtained through activities proposed in Section 9.3 (above). Next the models need to be used to understand the climatic significance of the present distribution and lengths of glaciers. This “training set” is prerequisite to interpreting the climatic significance of past glacier fluctuations. Then the distribution of glaciers needs to be modeled for specific times in the past (e.g., the Global Last Glacial Maximum). Assuming that the glacial geology and geochronology are correct (Section 9.1 above), the reconstructed snapshot of the glacial extent serves to validate the model while facilitating a quantitative understanding of the glacier sensitivity to climate change. Finally, the predicted response of present glaciers to scenarios of climate change, including successful modeling of transient states, needs to be modeled.

9.5. Design specific experiments to explore the most uncertain of glaciologic topics

To use mountain glaciers most effectively as probes of the climate system and determine the specific role in mountain evolution, we need to: a) determine what factors control the rate and spatial pattern of glacial erosion; b) improve our understanding of the role of hydrology in glacier sliding; c) understand calving dynamics in light of widespread retreat of tidewater glaciers and ongoing sea level rise (Benn et al., 2007); and d) record and model the seasonal evolution of the subglacial hydrologic system, especially in cases where significant volumes of water are stored. This step feeds back to Section 9.4 above, and ideally an iterative process emerges with observation and theory informing modeling. Modeling in turn would be used to help set fundamental process-based research priorities. At each iteration, assessment of progress must be made by comparing model performance against observations, as established by clear metrics.

9.6. Model the evolution of mountain landscapes in the face of repeated glaciation

Numerical models of long-term evolution of alpine landscapes require linkage of glacial, periglacial, fluvial and hillslope processes. The glacial models must be defensible, operating on full landscapes with sufficient resolution to capture the meteorological forcing, but they must be capable of eroding the bedrock over which they slide. Given the great need for testing glacial models against available glacial chronologies, we urge early focus on modeling to test more robustly specific hypotheses about the evolution of mountainous landscapes. Clear targets will include quantitative exploration of the origins of specific landforms, such as glacial cirques, arêtes, horns, and stepped valley profiles, and testing of hypotheses for larger scale mountain range evolution, including quantitative evaluation of the “tectonic aneurysm” and “glacial buzzsaw” hypotheses.

9.7. Climate and the balance of energy and mass at a glacier surface

Most modeling of glacier mass balance has employed rather simple empirical relationships. For example, accumulation is assumed constant or a simple function of height, while ablation is often assumed to be simply proportional to integrated summertime temperatures. These parameterizations barely scratch the surface of the real interactions with climate, a situation that must be improved by combining carefully targeted field campaigns with simultaneous modeling efforts. We must develop self-consistent models of the surface energy balance that allow us to assess the controls on the pattern of glacier mass balance. Understanding the present glacial system is a prerequisite for understanding the nature of glaciers in the past, which in turn is required before we can defensibly model how glaciers erode the landscape at long timescales. High-resolution (1 to 4 km) numerical weather prediction models will allow surface energy balance to be studied on a regional scale to explore local variability. It is equally important to evaluate and improve such modeling with concerted field campaigns at different glaciers on which different terms of the energy balance dominate. This exercise is essential if the attribution of observed glacier changes are to be correct.

9.8. Characterize the role of intrinsic climate variability on glacier variations

Climate is defined as the statistics of weather, averaged over some period of choice (30 years is the standard, but it can be any length). Thus, a constant climate has a constant mean and a constant standard deviation (i.e. inter-annual variability). This is important to appreciate because this intrinsic inter-annual variability is integrated by the ice system to produce glacier variability over much longer timescales. Because of this effect, a glacier with a typical dynamic memory of tens of years will naturally undergo century-scale and longer undulations. Subtracting this intrinsic signal is crucial to proper interpretation of the climate changes that the geological record reflects. These natural excursions that are not attributable to climate change have been largely overlooked in the glaciological and the glacial geologic communities; they must be acknowledged and understood.

9.9. Longer term climate changes

Paleoclimate is often motivated by the mantra of ‘past is prologue.’ An alternative and useful change of perspective is that the ‘present is precedent.’ By closely observing and modeling modern systems, we are much better able to put past changes into context. For example, if we understand how modern observed variability of climate leads to intrinsic glacier variability, we can better characterize the magnitude and duration of past climate changes. Then, as we inspect reconstructions of past extent of glaciers from different regions of the world, we will be able to answer in what places the changes are so large as to require that they could not have arisen from the variability of modern climate.

9.10. Glaciers and the future

The observations of near worldwide retreat of glaciers are compelling evidence of a changing climate. Better knowledge of the surface mass balance is needed to understand this change. As noted above, the connection between glacier ablation and temperature is not, and should not be assumed, trivial. We need to identify in detail how the anthropogenic perturbations to the radiation balance of Earth are manifest in the response of glaciers. We can expect the answer to vary by region: for example, at Kilimanjaro, we know sublimation is crucial, while in Norway we cannot rule out accumulation as a significant player. Through better evaluation of the surface energy balance and improved calibration of models, we will make progress in the attribution of current changes, and in our ability to predict future changes. The framework to do so is already in place, and needs to be supported in a broader effort.

10. Conclusions

The mountain glacier community stands on the cusp of large advances toward answering long-standing questions about mountain glacier systems worldwide. We can only achieve our goals by communicating across the ice-related disciplines using the newly enhanced toolkit described above. Our community needs to develop and embrace models that will serve to link, extend, and test more fully our understanding of the nature of the glacial record and the climatic information it represents. We need to think from local to global scales. The glacial response to climate change is heterogeneous; it varies in magnitude, phase and even in direction from region to region as the global climate changes. Clarified mountain glacier science will represent a rigorous test of the broader scientific communities' grasp of global atmospheric response to trace gas and orbital forcing.

Mountain glaciers play a critical role in translating present rapid global change to local and global consequences. The rise of sea level and issues with water supply dramatically affect many civilizations and ecosystems. Society requires quantitative assessment of sustainable water resources and hazards associated with glaciers. In addition, people are inherently interested in high mountains for recreation.

Integrated research on mountain glaciers must focus on important but poorly understood processes that control glacier motion and erosion. To use mountain glaciers as probes of the climate system and determine the specific role in mountain evolution, we must: a) improve our understanding of the connections between glacial hydrology and glacier sliding; b) understand calving dynamics in light of widespread retreat of tidewater glaciers and ongoing rise of sea level; and c) determine what factors control the rate and spatial pattern of glacial erosion.

The community must clarify the spatial–temporal pattern of fluctuations in mountain glaciers in prehistoric times, and relate past fluctuations to variability in the primary features of ocean-atmospheric circulation. To meet this goal, we must: a) develop accurate reconstructions of the extent of mountain glaciers through time, and b) quantify the relationship between climate variables and ice extent over the instrumental era.

It is essential to develop and expand the application of numerical glacier models, and model the evolution of mountain landscapes in the face of repeated glaciations. To meet this goal, the mountain glacier community must: a) test the physical modeling against field data; b) use models to understand the climatic significance of the present distribution and lengths of glaciers; c) predict response of present glaciers to climate change scenarios, including modeling of transient states; and d) develop models that operate on the whole landscape with the capability of eroding the bedrock over which they slide.

The broader public has long been enamored with mountain landscapes. Currently, the world community is rapidly becoming more aware of changing climate and its potential consequences. Taken together, these factors represent an opportunity for the mountain glacier scientific community to engage the public in our efforts to further the understanding of these landscapes. The National Parks and other public lands around the globe, many of which have been or are currently glaciated, are obvious settings in which to engage and expose citizens, students, and foreign visitors to methods and the results of scientific efforts to elucidate these landscapes. Mountain landscapes also offer opportunities that can strengthen scientific education. The science of mountain glaciers integrates physics, chemistry, mathematics, Earth science, and biology. An integrated mountain glacier science community offers Earth-based science that can stimulate students at all educational levels to pursue science as avocations and careers.

These goals are ambitious and achievable. Whereas the research tools exist, success will require significant bridging between the existing research communities involved. Success will also require that the community take advantage of existing infrastructure within funding agencies, and a variety of newly deployed technologies.

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