1

The Place of Glaciers in Natural and Cultural Landscapes

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In the first half of the nineteenth century, glaciers taught us a great lesson about the earth. In the 1820s and 1830s, Swiss naturalists established the existence of the Ice Age. Their key insight was the fact that the small glaciers found at high elevations in mountainous regions were remnants of vast sheets of ice that once had covered large portions of the earth's surface. They combined many sources—Alpine villagers' intimate knowledge of mountain landscapes, earlier research by other geologists, and their own extensive explorations—to document the remote periods of the past, when areas that now are towns, fields, and forests had lain under miles of ice. Once they understood that this now-vanished ice had transformed the earth's surface, they were able to explain features such as the parallel scratches found on rock faces that were engraved by glaciers and the long walls of rocks, stretching across valleys, that were carried by glaciers. Later researchers traced multiple Ice Ages and linked them to the cyclical fluctuations in the earth's orbit. This first lesson, then, was of the dynamic quality of the earth. Geologists found common elements in the study of the ice sheets and other discoveries that were made around the same time, such as the formation of rocks from sediments deposited on the floor of the sea. They came to understand that the earth was immensely old and always changing. This first lesson faced many challenges, particularly from those who held to a literal interpretation of the Bible, but finally received broad acceptance.

Now, at the beginning of the twenty-first century, glaciers are teaching us a second lesson, one that may be even larger than the first and that certainly is more somber and more urgent. That lesson is of the susceptibility of the earth to human impacts. The nineteenth-century picture of an earth whose surface is continually being modified by very slow natural processes is being replaced by the image of a planet that is being altered by rapid processes caused by humans. Once again, glaciers are playing a major role in shaping our understanding of our planet, since the retreat of glaciers around the world is a clear and dramatic example of this vulnerability. This retreat has come to public attention only recently. Through the 1970s, glaciologists—the intellectual heirs of the early Swiss geologists—observed that some glaciers expanded and others shrank and spoke of glacial “fluctuations” rather than a coherent, unidirectional process. By the 1980s, though, they had noticed the consistency with which many glaciers in different regions were becoming smaller. Glacier retreat became headline news in 1991. In that year two hikers discovered Oetzi, a Bronze Age man who had died high in the Alps and whose body, soon covered with snow that turned into ice, had rested frozen for 5,000 years until melting ice exposed it to view. Another such ice man appeared at the edge of a receding glacier in Canada in 1999 and received the name Kwaday Dan Ts’inchi (Long Ago Person Found) from the indigenous people of the region. Other lines of evidence pointed in the same direction: the series of measurements, released in 1998, that documented the shrinkage of the glaciers for which Glacier National Park in Montana is famed; the announcement in 2001 that scientific models predicted the complete disappearance of the famous snows of Kilimanjaro by 2020; the dramatic melting of Alpine glaciers in the unusually warm European summer of 2003. It became clear that many of the glaciers that had seemed permanent features of the landscape for millennia will not survive for many decades. Geoscientists are finding common elements in the study of glaciers and other recent discoveries, such as the warming of Arctic regions and the rise of sea level. We are coming to understand that human impacts can be more significant than we had realized. This second lesson, like the first, is also facing many challenges, particularly from those with an unwavering trust in the power of technology to solve problems.

There will not be a third lesson, or, at least, it will not come for a very long time. Current research suggests that the addition of large amounts of greenhouse gases to the atmosphere will postpone any future glaciation by tens or hundreds of thousands of years (Berger and Loutre 2002; Archer and Ganopolski 2005; Cochelin, Mysak, and Wang 2006). Looking up at mountains on the horizons, future generations will see bare rock where we still see gleaming snow and ice; traveling to the high country itself, they will find the dry beds of streams that once were filled with meltwater. One crucial and cherished part of our world will be gone.

The nature, history, and consequences of these changes form the subject of this volume. Reduced to its essence, each of the major aspects of glacier retreat can be summarized by a single term. The first term, *perception*, evokes the ways in which people know glaciers and form mental images of them, whether by seeing them or by hearing about them from others. The second, *observation*, might seem to be virtually a synonym of the first, but we use it in the specific sense of scientific observation—the systematic collection of measurements of glaciers. These two terms provide the basis for the third, *trends*, which includes both the reconstruction of glacial dynamics in the past and the projection of these dynamics into the future, indicating the probable state of glaciers in coming decades and centuries. As the fourth term, *impacts*, suggests, people are affected by glacier retreat in a variety of ways. We identify the major areas where new dangers—and perhaps new opportunities—have emerged. We highlight the vulnerability and resilience of societies in the face of significant changes to their landscapes and livelihoods. The final term, *responses*, indicates the action that people take on the basis of their perceptions of these trends and of their impacts. These responses may include different forms of accommodation and adaptation, as well as the adoption of policies by government agencies.

To guide our broad overview of glacier issues, we present some concepts and basic terms in the field of glaciology. Glaciers occur in places where, over a period of time, winter snowfall amounts exceed summer melting, so that snow accumulates on the surface and is transformed to ice. Once it reaches a critical thickness (about 30 m) and density (about 0.85 g/cm^3), this ice can deform and move downslope under the influence of gravity, forming glaciers. The state of health of a glacier can be defined by its mass balance. When annual snow and ice accumulation exceeds the loss by melting and other processes such as the calving of icebergs, the glacier has a positive mass balance and increases in mass. When the snow and ice loss exceeds the mass gain, the glacier has a negative mass balance. Generally the headward part of the glacier (the accumulation area) has a net gain, and the lower part of the glacier (the ablation area) has a net loss. The line separating these two zones is the equilibrium line, and the equilibrium line altitude (ELA) is the elevation at which the net accumulation in a given year is zero. Glacier flow transfers ice from the accumulation area to replace ice lost from the ablation area. If loss at the toe exceeds replacement by downvalley flow, the position of the toe recedes upvalley (the glacier "retreats"); if the ice delivered to the toe exceeds melt on an annual basis, the glacier front advances. Generally, glaciers with a negative mass balance exhibit frontal recession, although they may also lose considerable mass by thinning without frontal recession. Direct measurement of mass balance is expensive and time-consuming, but crude estimates of mass balance may be obtained from inspection of the equilibrium line elevation at the end of the melt season: Glaciers with a positive mass balance have, on average, more than two-thirds of their total area above the equilibrium line; this fraction is known as the accumulation area ratio (AAR).

A significant portion of the earth's land surface, roughly one-tenth of the total area, is permanently covered with ice, but it is heavily concentrated in distant and uninhabited regions (Barry 2006). The Antarctic ice sheets hold most of this ice, about 85% of the total area. About two-thirds of the remaining 15% is located in the Greenland ice sheet. In other words, all the other glaciers make up only about 5% of the world's ice-covered area.

Nonetheless, these glaciers account for a significant area, 680,000 km² by a recent thorough estimate (Dyurgerov 2005). These, too, are concentrated in remote areas at high latitudes and elevations (Table 1.1). Over half of this area consists of glaciers located on islands near Antarctica and in the Arctic Ocean or on Antarctica and Greenland but not contiguous with the major ice sheets. Within Europe, about two-thirds of the glacierized area is in Iceland. Patagonia holds a similar proportion of South America's glaciers, and the bulk of them are located in the more remote South Patagonian icefield rather than in the North Patagonian icefield, closer to towns and roads. New Zealand's glaciers are concentrated in the distant southwestern corner of the less populated South Island. Despite their concentration in cold places where few or no people live, however, glaciers play an important role in human societies.

PERCEPTION OF GLACIERS AND GLACIAL PROCESSES

Two attributes of glaciers shape the ways in which human perceive them: They are visible, and they are subject to cultural framing. The first attribute is a simple one. As large, slow-moving objects, glaciers can be directly seen. Though this point may seem so obvious that it does not merit being mentioned, it is quite significant. There are many other environmental concerns that involve entities that cannot be seen by the naked human eye. One cannot gaze up into the sky and tell whether ozone thinning has taken place, nor can one feel whether one is exposed to harmful levels of radioactivity. Genetically modified crops cannot be distinguished from other crops simply by looking at them. However, a person who returns to a glacier after an absence of several decades or who compares photographs of it taken at different times can easily note glacier retreat.

The direct accessibility of glaciers to human vision has helped to make them a topic of personal and public concern. Moreover, many glaciers can be seen for long distances, as can be attested by the tourist-brochure photographs of gleaming peaks rising beyond fields and forests in the southern Andes or in the Alps or of Mt. Kilimanjaro standing high above the dry plains of East Africa. People have adopted glacierized peaks as icons of particular regions: Residents of the city of Seattle have a special

TABLE 1.1

Distribution of Glaciers in the World, ca. 2000

REGION	TOTALS AND SUBREGIONS	GLACIERIZED AREA (KM^2)
World	Total	680,000
Europe	Total	17,800
	Alps	2,900
	Scandinavia	2,900
	Iceland	11,300
	West Caucasus	700
	Other	10
North Asia and Siberia	Total	3,500
Central Asia	Total	114,800
	Tien Shan	15,400
	Pamir	12,300
	Karakoram	16,600
	Himalaya	33,000
	Hindu Kush	3,200
	Other	34,300
Middle East	Total	830
	East Caucasus	780
	Other	50
Arctic islands	Total	315,000
	East Arctic islands	56,100
	West Arctic islands	36,700
	Canadian islands	151,800
	Greenland small glaciers	70,000
North America	Total	124,200
	Alaska	74,600
	Canada	49,000
	Other U.S.	530
	Mexico	10
South America	Total	25,000
	Patagonia	17,200
	Peru	1,800
	Other	6,000
New Zealand	Total	1,200
Sub-Antarctica	Total	77,000
	Sub-Antarctic islands	7,000
	Sub-Antarctic glaciers	70,000
Other	Total	9
	Africa	6
	New Guinea	3

NOTE: Figures include some rounding. Source: Dyurgerov (2005).

relationship with Mt. Rainier and will stop, when walking on a busy street, if the ordinarily cloudy skies clear and offer a view. The great height and pure whiteness of this mountain, featured on the city's Web site, evoke the natural beauty and abundant resources of the Pacific Northwest. At the center of the coat of arms of the Republic of Armenia is an image of Mt. Ararat, which now lies within Turkey but whose massive glacierized peak, visible from much of Armenia including the capital, Yerevan, serves as a symbol of the Armenian people and nation, of their greatness and of their indomitable will to survive.

However, not all glaciers capture the imagination. One may contrast the great fame of Kilimanjaro in Tanzania with the utter obscurity of the glaciers on Mts. Baker, Speke, and Stanley in the Ruwenzori Mountains of Uganda. First explored in 1906 by a team led by an Italian nobleman, they are less well known than Kilimanjaro, not only because they are somewhat smaller but also because they are much harder to view. In contrast to Kilimanjaro, a free-standing volcanic cone in an area of dry climate, these peaks lie behind other ridges in a moist region, almost constantly obscured by clouds. In other regions as well, some glaciers are seen only infrequently. Local residents in the Val Bavona in the Italian-speaking region of Switzerland only rarely view the nearby Basodino Glacier, even though it is the largest in the region (Madden 2003). It is difficult even to discern the glacier from the narrow and curved valley; over one-fifth of the valley's adult inhabitants have never seen it. No major ski facilities have been established in the high country above the valley, and therefore only the small number of men, less than one-tenth of the population, who work at a high-altitude hydroelectric power plant have any direct relation to the glacier or even see it on a regular basis.

Perception of glaciers does not rest on physical visibility alone. Cultural framing can also shape the ways in which glaciers are perceived, both by influencing the patterns of movement that can bring people close to them and by shaping their understandings (Knight 2004). Local populations in Uganda have generally considered the Ruwenzori Mountains unappealingly cold and damp. Even the Bakonjo people, who live closest to the peaks, identify themselves and are identified by others not with the peaks but with the forests of the lower and middle slopes, where they grow crops in clearings, gather wild plants, and maintain a series of shrines (Oryemoriga et al. 1995). Though the Batoro, one of the precolonial kingdoms that continued under British rule and after independence, have sought to impose their rule over this area and to tax its gardens, its rough terrain and its image as a wild, uncivilized place have supported the autonomy of the Bakonjo (Alnaes 1967, 1969; Cooke and Doornbos 1982; Horowitz 1977, 1881). Bakonjo men have occasionally obtained employment as porters and mountain guides, but this work is considered physically demanding and dangerous because of the possibility of angering the spirits that inhabit the high mountain zone (Busk 1954). If tourism brought foreign travelers more regularly to the glaciers, it might lead the local people to become more involved with them, but tourists coming to this region tend to visit the lakes and observe the wildlife in the lower, forested zones. In this case, cultural framing reinforces the limited physical visibility to keep the glaciers out of mind as well as out of sight.

In the Val Bavona, local residents may not see the nearby glacier, but they are quite conscious of glacier retreat and express concern about it. Over four-fifths of the people, including some who have never seen the Basodino Glacier, are aware that it is shrinking, since it is a topic of at least occasional conversation in the valley and those who see it often enough to notice the change have commented about it to others. Moreover, the glacier retreat has significance for them because they are generally concerned about climate change. The residents recognize other aspects of local climate change, such as drier summers, as well. They express their concern about its potential impacts elsewhere in Switzerland and throughout the world, but this concern stems from exposure to the national and international media. They are relatively untroubled by possible local repercussions such as the genuine risk that the reservoir of the power plant would receive insufficient inflow as glacier retreat continues. Nor do they attribute the increased number of rockfalls to glacier retreat, since the rockfalls that most affect them do not come from the area near the glacier. In the case of Val Bavona, then, cultural framing is influenced by global rather than local perceptions and leads to a greater level of awareness of the glacier than would result from its physical visibility alone.

Recent research thus confirms the variety of forms of cultural framing of glaciers. Cruikshank's work (2005) with the indigenous communities of the Yukon in Canada documents their frequent travel on glaciers, which they use as paths to cross the high ranges of the region in which they live. Cruikshank notes as well that they consider glaciers to be sentient beings who can observe and respond to human behavior. Native people express concern that white researchers will not demonstrate proper respect for the glaciers (by avoiding certain foods and ways of speaking), thus raising the risk of glacial surges. In this case, the local perceptions of glaciers come not only from the proximity that travel brings and the attentiveness required to avoid crevasses but also from the rich stock of stories that provide information about glacier movement in the past. Research with indigenous groups in the southern Peruvian highlands documents a long tradition of pilgrimage to a glacierized peak. In this region, native communities recognize spirits that live in the high mountains and make offerings and recite prayers to them. A glacierized peak, Sinakara, is the site of a pilgrimage that dates back to the eighteenth century (Sallnow 1987; Bolin 2001).The pilgrimage lasts several days and includes visits to a number of churches and chapels; one crucial element is the climb by costumed pilgrims to the glacier itself, where, until recently, they carved off blocks of ice, believed to have medicinal properties. The glacier itself was divided into different sections, each allocated to the pilgrims of a specific region. The retreat of the glacier has been a matter of great concern to the local people; their regular pattern of visiting ensures that they see the location and shifts of the glacial front, and the ritual significance of the travel leads them to pay close attention to it. Troubled by the thought that the mountain spirits are withdrawing the ice from them, they have resolved to stop cutting blocks from the glacier.

Cultural framing by these various indigenous groups thus influences both the ways people physically see the glacier and the ways they understand it, but it is by no means restricted to indigenous cultures and to earlier times. As Wolf and Orlove (this volume) show in their study of Mt. Shasta in California, many contemporary Americans attribute a kind of consciousness or awareness to the mountain itself. They note in particular the comments made by many locals that the mountain protects itself from encroachment by sending avalanches through current or proposed ski resorts, as it did in 1978 and 1995. In her ethnographic study of several German-speaking villages in the northern Italian province of Alto Adige, Jurt (2007) describes the economic importance of glaciers in this region heavily dependent on tourism. She notes that the villagers attribute the recession of the glaciers to many material factors, such as physical removal of surface ice and snow by skis and snowmobiles and the deleterious effect of disposing of rubbish by throwing it in crevasses. They also speak of the glaciers as being sentient; they comment that the numerous visitors "stören" (trouble, distress) the glaciers and that to avoid further retreat "man sollte sie in Ruhe lassen" (one should leave them [the glaciers] in peace).

Researchers have shown that these cultural framings of glaciers can change over time. Strauss (2003) documents the terrifying Swiss folktales that portrayed glaciers as physical sites of residence of souls of dead people, trapped in purgatory. There were stories as well of the villagers' ability to alter the glaciers through magical means. One such story told of a stranger who traveled to a valley and advised the residents to send a young maiden to the mountains at dawn;

if she removed a piece of ice from each of seven glaciers and assembled these pieces above the valley, a new glacier would form, increasing the flow in the local river.

These stories were ancient and conveyed fears of real hazards. During the nineteenth century, advancing glaciers increased the level of danger by blocking entire valleys, damming rivers to create lakes that burst out in devastating floods (Wiegandt and Lugon, this volume). Close attention to these developments led to more systematic observation of glaciers and ultimately contributed to the beginnings of the science of glaciology. Once glaciers began to be monitored regularly, the growing data sets allowed researchers to trace the movement of glaciers and to examine hypotheses to account for their shifts. The scientific observation of glaciers, deriving in part from the concerns of the populations living closest to them and in part from the interest of scholarly individuals and associations, is a new form of perception of glaciers.

OBSERVATION

The regular gathering of data about glaciers involves repeated and coordinated visits to particular glaciers, usually on a fixed schedule, and the systematic recording of their attributes. This observation is nearly always conducted in the context of scientific research, though it has significant premodern and prescientific antecedents. Cruikshank (2005) has recounted how Native peoples near the Yukon-Alaska border preserve stories describing the movement of the Lowell Glacier, including the advances that blocked the Alsek River to create lakes that accumulated behind the ice dam before bursting out in floods. In a similar vein, Quechua-speakers in highland Peru have visited a glacier in yearly pilgrimages, noting the shifting location of several tongues in relation to fixed features in the surrounding mountain landscape. Nonetheless, the stories remain largely oral and local and, as Cruikshank points out, require significant translation to be incorporated into the body of scientific knowledge.

Though measurements of glaciers had been made since the first half of the nineteenth century (Haeberli, this volume), it was not until near the close of that century that the modern systematic collection of data about glaciers began in Switzerland and Norway. The International Glacier Commission was established in 1894 and sought to coordinate the recording of the length and areas of glaciers (Radok 1997; Braithwaite 2002). The particular form of glacier monitoring reflected the nature of the groups involved: People living close to glaciers were often concerned about glacial hazards, while the members of national scientific communities and international scientific organizations were interested in understanding the motion and characteristics of glaciers and their history. In countries such as Switzerland and Norway, extensive monitoring is a measure of the importance of glaciers to the national identity, economy, and society. In Switzerland, densely populated valleys are exposed to glacier hazards, and major hydropower resources depend on the amount and timing of glacier meltwater. Cantonal forest services, natural-hazard managers, and university scientists work together to observe glacier dynamics. The mix of factors is similar in Norway, where the research has been conducted by national institutes, particularly those involved with polar exploration and with the extensively ice-covered archipelago of Svalbard, an international zone of whaling and coal mining over which Norway came to exercise a predominant role. The country's great pride in its accomplishments in ice-cap exploration (including the first crossing of the interior of Greenland and the first successful expedition to the South Pole) initially contributed to support for glacier research, though the national hydropower authority has played an increasingly important role (Andreassen et al., this volume). Glacier monitoring in Peru, by contrast, began several decades later. Disastrous floods, in which thousands of people died, directed attention to the monitoring of glacial lakes in the regions in which the risks of floods are greatest (Carey, this volume). Government services have sought to gather data on glaciers to assess stream flow in areas where glacial meltwater has high economic value as a source of hydropower and the supply of irrigation water to arid regions (Carey 2005).

Though glacier monitoring began over 100 years ago, its history has not been smooth (Macdougall 2004). Governments sometimes fail to provide steady funding, and the contribution of effort by local volunteers has similarly proved to be unreliable in a number of cases. For example, the Canadian government began an ambitious program of glacier inventory in the 1960s but abandoned it in the 1970s; it has yet to be resuscitated. International organizations were disrupted during the two world wars, and funding was often scanty in the intervening decades. Some expansion of glacier monitoring began after world war II, particularly with advances in mass balance studies. In contrast to earlier work, which concentrated on measuring the frontal positions of glaciers and their surface areas and lengths, this research examined the changes in volume of glaciers by measuring accumulation and ablation (Schytt 1962). Many such studies were set up during the International Hydrological Decade of 1965–74.

Glacier observation has expanded greatly in the past two decades (Knubel, Greenwood, and Wiegandt, this volume; Bowen 2005). The concern about global warming in the 1980s brought attention to glaciers as a valuable indicator of environmental change. The creation of the World Glacier Monitoring Service (WGMS) in 1986, centered at the University of Zurich and the Swiss Federal Institute of Technology, combined earlier organizations, systematized data collection, and extended it to new areas. The WGMS coordinates closely with the United Nations Environment Program, the United Nations Educational, Scientific, and Cultural Organization (UNESCO), and international bodies in the geosciences. The International Geosphere-Biosphere Program (IGBP), also founded in 1986, has vigorously promoted research linking glacial data with climate change. The data sets assembled by the WGMS have documented the dramatic glacier retreat around the world and have received specific mention in such major reports as the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report of 2007.

As glacier observation has become an increasing priority and attracted more funding, new techniques have allowed more efficient and detailed data gathering and analysis. These methods provide much better information than the aerial photographs, some dating back to the 1930s, which offered poor resolution and uneven coverage. New remote sensing methods have improved the collection of data on glacier area. Aircraft-based laser altimetry and satellite-based kinematic global positioning system (GPS) measurement allow mass balance to be studied by observing shifts in the height of glacial surfaces. The rapid advances in computational power permit analysis of the new data sets. New modeling techniques have led to better projections of glacial mass balance by integrating data on glacier area and elevation with meteorological data on temperature and precipitation and energy-input data from solar radiation at a high degree of spatial resolution (Paul et al., this volume). This modeling work has also led to assessments of the effects of different scenarios for climate change on hydrology in glacierized watersheds (Corripio, Purves, and Rivera, this volume; Schneeberger et al. 2003) and on changing hazards such as debris flows (Huggel et al. 2004).

TRENDS

Much of the current interest in glaciers rests on the linkages between trends in climate and trends in glacier extent (length, area, or volume). The consensus reported in the most recent IPCC report is that glaciers around the world are shrinking primarily because of global warming (Lemke et al. 2007). The linkage between glacier extent and temperature is not quite as direct and immediate as this account suggests. The effects of warming can be influenced by other variables such as topography and cloud cover, which both affect exposure to sunlight, and the nature of the bed of the glacier, which can favor or delay the downslope flow of ice. Changes in precipitation, also associated with climate change, can influence accumulation in the upper portions of a glacier and ablation in the lower portions. Moreover, many glaciers are quite large, so it can take a long time for them to respond to shifts in temperature; though warming takes place on their surfaces, their interiors can remain cold for some time. Nonetheless, the simplest account—glaciers are melting because temperatures are rising—is a fair summary.

The recent improvements in glacial observation and the growth of longer-term data sets have supported more detailed studies of glacier history, recent recession, and modeling of future changes. Recent glacier history can be reconstructed from a variety of geologic and geomorphic techniques that rely on the morphologic and stratigraphic evidence. Steiner, Zumbühl, and Bauder (this volume) present a classic study of the reconstruction of glacier history from a wide variety of documentary sources and show how, using modern cartographic techniques, some of the early, high-quality topographic mapping can be used to develop accurate three-dimensional images of the glacier surfaces over 100 years ago for comparison with detailed modern records of changes. Tree-ring data have been used in the past to date glacier fluctuations and to provide reconstructions of temperature and precipitation from mountain areas. For example, Watson et al. (this volume) use tree-ring data from several tree species to develop proxy records for summer and winter mass balance that can be used to examine the controls and past history of glacier fluctuations over the last 300 years in the Rocky Mountains in North America. These reconstructed mass balance records can be verified against the discontinuous record of glacier fluctuations based on more traditional geomorphic techniques and dating of moraines. This work allows the authors to reconstruct glacial fluctuations at a finer time scale for the eighteenth and nineteenth centuries than is possible from the morphological record. Their results demonstrate that warming in the twentieth century has been an important cause of glacial retreat, though fluctuations in precipitation have also had an effect.

Similar efforts to link climate variables with mass balance models have supported connections between global warming and glacier retreat in other regions. In particular, models indicate that shifts in temperature—especially in temperate regions but in many high-latitude regions as well—have a stronger effect on glacier extent than shifts in precipitation, which tend to be more localized. As Oerlemans (2005) documents, the small increase in temperature that has taken place in many parts of the world, on the order of 1°C, is sufficient to create significant melting. It would require a large increase in precipitation, about 25%, to offset it; no model of climate change suggests long-term increase on such a scale. In the Alps, the area in the world for which the most detailed records are available, the basic pattern—general retreat for the past 150 years, with an accelerated pace in the past two decades—is consonant with atmospheric warming, though individual glaciers show different rates of response to this process, depending on orientation, topography, and several other factors (Zemp et al., this volume). These studies have also shown that small glacial advances in the 1990s in a few regions of the world, such as the South Island of New Zealand, far northern California, and portions of Norway, occurred in response to augmented winter precipitation due to changes in storm trends in areas of heavy precipitation. Glaciers in these areas are nevertheless sensitive to temperature increases and have also seen retreat since 2000 or so (Andreassen et al. 2005; Chinn et al. 2005) or are projected to retreat in coming decades (Wolf and Orlove, this volume).

Temperature increases are also associated with glacier retreat in the tropics, particularly in the Andes, where the great majority of the tropical glaciers in the world are found (Wagnon et al. 1999; Francou et al. 2003). However, the situation is more complex for Kilimanjaro. As Mölg et al. (this volume) show, the well-known shrinking of the glaciers there has more to do with changing precipitation patterns in East Africa linked to shifts in Indian Ocean circulation than with increasing temperature.

Recent research points to the significant impact of warming on glacier size and mass balance in the future. From estimates in the 2007 IPCC Fourth Assessment Report, glacier retreat will cause a rise in sea level of 0.076–0.152 m between 1990 and 2090 (Meehl et al. 2007). A recent study points to a figure just below the lower end of that estimate (Raper and Braithwaite 2006), but even this level would be accompanied by further reduction in glacier extent far beyond what has been experienced to the present. Projections for specific regions of the world also indicate such shrinkage (Hall and Fagre 2003). On the basis of different scenarios for greenhouse-gas emissions, one article forecasts that 73–94% of mountain glacier volume will be gone by 2400 (Wigley and Raper 2005). Any projection that far into the future must necessarily rest on assumptions about changing levels of greenhouse-gas emissions, a difficult matter to anticipate. Here we will not adopt such a distant time horizon but will instead look at the impacts of the glacier retreat that has already taken place and note the responses to them.

IMPACTS

In general, the study of physical processes associated with glacier retreat is more advanced than the study of the impacts of these processes on human societies; indeed, the question of impacts constitutes an important gap in our knowledge. Nonetheless, current research has progressed to the point of being able to recognize four broad categories of impacts: global environmental change, economic resources, hazards, and cultural landscapes.

The most frequently discussed impact of glacier melting on global environmental change is its contribution to sea-level rise, a factor with the potential for major effects in coastal regions. There is strong consensus that sea level rose about 15 cm in the twentieth century and that the rate increased in the last decades of that century. This rise can be attributed partly to the melting of glaciers, though other factors, particularly the small but positive tendency of water to expand as it warms, have been important. The IPCC report suggests, with some uncertainty, that glaciers contributed about 27% of the rise in the last decades of the twentieth century (Bindoff et al. 2007). Sea levels are projected to continue to rise in the twenty-first century, with an estimated increase of three times the twentieth-century rate. Of this rise perhaps 30% will be attributable to glacier melt. Though glaciers will shrink in later centuries, projected sea-level rises are higher at that time, since the ice sheets in Greenland and Antarctica, which hold considerably more water than glaciers, are likely to melt more rapidly by then. Recent research has pointed to faster rates of current melting of the Greenland ice sheet (Rignot and Kanagaratnam 2006; Ekström, Nettles, and Tsai 2006), and it is likely that new findings will continue to alter our understandings of sea-level rise (Parkinson 2006).

Glacier retreat may also lead to other forms of global environmental change, particularly through its impact on biodiversity, including plants and invertebrates in high mountain regions. Two major research efforts are monitoring these changes in biodiversity. The first of these is Global Change in Mountain Regions (GLOCHAMORE), with many international partners under the auspices of several UN programs, the University of Vienna, and the Mountain Research Institute. The other, the Global Observation Research Initiative in Alpine Environments (GLORIA), is linked to the International Geosphere-Biosphere Program (IGBP) and the University of Vienna (Pauli et al. 2005).

The economic sectors directly affected by glacial retreat are primarily related to water and, to some degree, tourism. Changes in water resources occur both in time (since an early phase of glacier retreat increases water flows as glacial ice is converted to water but then reduces these flows when the glacial volume is much reduced) and in space (since the water is used in different ways in different parts of watersheds). All users may receive considerable water in the short run but face likely shortages in the future. The specific economic impacts and possible adjustments will be different for hydroelectric power generation, often in the upper portions of watersheds, and for irrigation and urban consumption, usually in the middle and lower sections. Tourism may also be affected by glacier retreat, since in some glacierized regions, especially in the Alps and Scandinavia, in western North America, and in New Zealand, tourists visit glaciers for hiking and sightseeing. The capacity of glaciers to extend the ski season also attracts many recreational visitors (Smiraglia et al., this volume). However, the direct relation between tourism and particular landscapes must also be put in the context of price factors and changing tastes.

Hazards in the form of floods and landslides constitute another important impact of glacier retreat. Though these floods have several causes, including expansion of rivers, swollen beyond their banks by glacial melt, one particular form is important. The lakes that form below glaciers are often dammed by relatively weak glacial moraines that can collapse or be breached and create devastating floods. These are known either by their Icelandic name, *jökulhlaups*, or as glacial lake outburst floods. A single outburst flood that occurred in Peru in 1970 killed more than 10,000 people (Carey, this volume). Other disasters caused by glacier retreat include landslides, rockfalls, and debris falls. As the sides of valleys formerly filled with ice become exposed, the material in their slopes is prone to slip and fall. Moreover, temperature changes may result in the degradation of mountain permafrost that can also lead to instability in accumulations of loose surface debris, for example, moraines or talus, formerly bonded by ice. These also provide loose debris accumulations that can be mobilized during intense summer rainfall events and produce major debris flows that destroy communities in the valleys below (Wiegandt and Lugon, this volume).

These three impacts of glacier retreat have economic as well as physical consequences, since they reduce or destroy productive resources and interfere with economic activities (Agrawala, this volume). In addition, there are cultural impacts of glacier retreat. Many human societies have strong attachments to glaciers, as they do to other features of the natural environment. These features have strong symbolic significance, and people identify with them. Brenning (this volume) discusses a case in Chile in which many people opposed the destruction of a glacier by a mining company that proposed to exploit ore deposits not only because of the impacts of such actions on water resources but because they cared about the glacier itself. If a rather extreme parallel may be drawn, many people experienced deep distress over the attacks on the World Trade Center in New York not merely because thousands of people were killed, not merely because valuable property was destroyed, but also because of the symbolic importance of the buildings themselves and because of the key place of the buildings in the built urban landscape. In a similar vein, the white summits of lofty peaks play a special role in natural landscapes—landscapes that, because of the meanings connected with them, are also cultural landscapes. In some instances, this role is clearly religious and ritual, as is shown by the cases of pilgrimages to glacierized regions. In other instances, glaciers become representations of regional or national identity. The glacierized peaks of Illimani lie within clear view of La Paz, the capital of Bolivia; they also are featured prominently on the city's official shield, on the seal of the major university in the city, on the labels for the beer brewed there, and in countless other forms. The residents identify not only with the city and with the nation but also with the highland region of the country, embodied in the summits of Illimani. As do the residents of Seattle and Yerevan mentioned earlier, the Paceños identify not only with a mountain but with the glaciers that make it distinctive. Though glacier retreat in Illimani will reduce the hydropower that La Paz uses and greatly limit the skiing season for local enthusiasts, the cultural impacts of a dark Illimani rather than a gleaming white mass that watches over the city seem as serious as the economic ones (Vergara et al. 2007).

These different areas of impact are closely related. Tourism, for example, links the economic aspects of purchasing goods and services with the cultural aspects of establishing and maintaining social identities. Case studies in this volume indicate that outburst floods and other glacial lake hazards have destroyed hydroelectric plants in Nepal and Peru and periodically injured or killed villagers in Switzerland and tourists in Italy and New Zealand. It is therefore difficult to disentangle linkages between hazards and resources, since economic activities can be disrupted by natural catastrophes.

RESPONSES

Of the different themes discussed here, the question of human responses to glacier retreat is the one for which there is the smallest amount of empirical research, but we can make some general observations and present some examples.

Of the observations, three are particularly important. First, the global scale of climate change means that the people most directly affected by glacier retreat make a very small direct contribution to the worldwide emissions of greenhouse gases that are its root cause. As a consequence, their behavior will have little impact on the future course of this shrinkage. In contrast to the situation with many other environmental issues, local or regional responses cannot directly affect the causes of the problem. This fact can contribute to what might be termed a narrative of victimhood, in which the people affected by glacier retreat passively suffer the consequences of actions of others (Adger et al. 2001). Such accounts rightly capture certain aspects of climate change and its effects, but they also tend to reduce complex historical changes to an overly simple story. Carey's account of glacial hazards in the Peruvian highlands (2005 and this volume) offers a particularly good example of moving beyond simple narratives of victimhood by considering the wide range of actors, interests, and beliefs involved in shaping responses to changing glacierized landscapes.

A second reality about responses is that people who live in glacierized watersheds respond not only to glacier retreat but also to other environmental, economic, and political factors. Luterbacher et al. (this volume) present a particularly clear instance in which Central Asian republics in general and Kyrgyzstan in particular make decisions about water use based not only on projections of glacier retreat but also on their own and other nations' economic goals and geopolitical interests in the current unstable post-Soviet period. These elements all become part of complex negotiations with neighboring countries about future glacier-generated water use.

Third, responses to glacier retreat are complicated by the fact that they involve balancing multiple concerns (Agrawala 2004 and this volume). The long time horizon of glacier retreat and the uncertainty about its trajectory make it difficult to calculate the economic value of glaciers. Moreover, the extraeconomic value represented by the cultural significance of glaciers means that decisions are not made with economic criteria alone. Institutional aspects are yet another factor that intervene to shape responses to changing landscapes and resources. Property rights are particularly ambiguous and ill defined for glaciers. In remote areas, they often constitute a no-man's-land. Incidents such as the example cited by Agrawala (this volume) of a Chinese military truck's being washed into Nepal by a glacial lake outburst flood highlight dilemmas of transboundary adjudication. The problem of glaciers' water resources is even more general and compelling because of their considerable value. The attribution of rights is therefore particularly important. However, the domain of water rights is fraught with complexities, ambiguities, and hence potential conflict. Although agreements exist for specific river systems or lakes, there is no general international water regime. The Kyrgyz case (Luterbacher et al., this volume) illustrates the general problem of resolving asymmetric power relations inherent in upstream-downstream relations, where upstream users can simply prevent access by downstream users. There have been many efforts to have glaciers themselves designated as protected areas managed by agencies concerned with conservation and tourism, but the question then arises of what happens to a protected entity that is disappearing because of global climate change. This problem parallels the global commons issue that climate change represents.

Despite these complicating factors, some responses can be noted in each of the impact areas discussed earlier. The most widely noted aspect of global environmental change is sea-level rise, though this is due to a number of factors and not only to glacier retreat. Planning for this rise has been active in many countries, such as the United Kingdom and the Netherlands. Recent unusual and extreme events such as the tsunami of December 2004 and the deaths and destruction associated with Hurricane Katrina in August 2005 brought attention to the vulnerability of coastal regions and led to efforts to develop early warning systems for tsunamis and to improve defensive works against storm surges.

Responding to the shifts in water resources that follow glacier retreat poses significant challenges. Andreassen et al. and Rhoades, Zapata Ríos, and Aragundy Ochoa (this volume) offer interesting counterpoints. Andreassen et al. show that Norway carefully manages the reservoirs that produce hydroelectric power, the country's principal source of electricity, and this monitoring forms one piece of complex planning that includes consideration of incorporating other energy sources such as wind power (Kristiansen 2006; Hagstrom, Norheim, and Uhlen 2005). The country seeks to balance economic efficiency and environmental sustainability in its energy policy (Johnsen 2001). The Ecuadorian case described by Rhoades, Zapata Ríos, and Aragundy Ochoa is a sobering instance of glacier retreat that has proceeded to the point of glacier disappearance. The indigenous farmers in Ecuador who relied on glacial meltwater for irrigation have invested considerable amounts of labor and capital in linking with other irrigation systems. Their expenses have increased, but their access to water is less secure, since they join these systems, themselves under stress, as latecomers with less effective claims to water. These examples, taken together, point to the great human capacity for adaptability but also to its limits and to the substantial differences among countries. Ecuador is much poorer than Norway. Its possibilities for water storage are limited by the configuration of the Andean volcanic cones, with fewer reservoir sites than the deep canyons of Scandinavia, and its ability to develop strategies for substitution is considerably limited by economic factors. However, in an increasingly globalized world, robust national economies may not be sufficient to withstand the parallel pressures of climate change and market forces, as the resistance to electricity market liberalization in Switzerland demonstrates (Wiegandt and Lugon, this volume).

Tourism constitutes another sector responsive to natural conditions and wider market forces. The effects of glacier retreat on skiing can be dramatic. In the summer of 2005, the Swiss ski resort of Andermatt covered a small portion of a glacier, less than a hectare, with a reflective blanket to slow its melting; this unusual effort attracted considerable attention in the press. Other ski resorts make different efforts. As Smiraglia et al. (this volume) document, one Italian resort on the Vedretta Piana glacier moves firn (snow that has been partially transformed into ice) from the higher portion of the glacier to the lower sections in which skiing takes place, a policy that is in effect accelerating the shrinkage of the glacier. In the United States, a number of resorts, including those on the glaciers of Mt. Hood in Oregon, participate in "Keep Winter Cool," a program run jointly by the U.S. National Ski Areas Association and a large environmental nongovernmental organization (NGO), the Natural Resources Defense Council, encourages skiers to drive in carpools to the resorts and to purchase tags that subsidize the efforts of ski resorts to run lifts with power produced from renewable sources. Though this program, at least in its early stages, appears to set weak standards and to lack enforcement, it does point to the growing awareness of climate change and glacier retreat (Rivera, de Leon, and Koerber 2006). Other ski resorts, however, seek other adaptations, such as emphasizing the use of mountain bikes on snowless trails. All these efforts must also be viewed in the context of comparative costs of travel and lodging that will influence tourists' choices of venues in ways completely unrelated to landscape and activity.

Hazards associated with glacier retreat have very local effects and must be addressed to protect residents as well as visitors. In some instances, the hazards can be directly reduced. Glacial lakes that present high risks of jökulhlaups can be drained, as has been done in Nepal (Agrawala, this volume) and Peru (Carey, this volume). These efforts are extremely expensive, however, and cannot keep up with all the dangerous glacial lakes in the world. The uncertainties associated with these outburst floods also make it difficult to prioritize lakes for draining. Warning systems are another possibility, though these, too, are expensive and difficult to implement in regions in which populations are scattered. Moreover, they are prone to the problem of false warnings. For example, U.S. National Aeronautics and Space Administration (NASA) scientists issued a warning in 2003 after reviewing satellite imagery that appeared to indicate a fissure in a glacier above Lake Palcacocha in Peru, the site of an earlier outburst flood. Many people fled the zone after this warning, and tourism declined. This panic was followed by frustration when it was discovered that the interpretation of the imagery was erroneous (Georges 2005; Vilimek et al. 2005). This case raises the problem of the differences between expert and lay assessments of risk, a topic reviewed by Wiegandt and Lugon (this volume).

A response to hazards that appears to be simpler than direct reduction or warning systems is the use of hazard mapping to indicate zones where travel, construction, or other activities should be limited. Though such mapping has proved an effective means of addressing other geophysical hazards, such as flooding, the evidence for its use to address glacial hazards is limited. Personal interests, as well as objective knowledge, can be involved in making these judgments. Often the desire to create value for sale to tourists or to attract industry leads to the minimization of risks in key zones. Agrawala (this volume) offers the problem of siting hydroelectric power plants because few sites in Nepal present both sufficiently high rates of return of energy production to investment and satisfactorily low vulnerability to outburst floods. In cases where restrictions are imposed, there are enforcement problems; it can be difficult to curb travel in such zones, as is apparent from the accidents that have occurred in areas clearly marked with warnings in New Zealand (Hay and Elliot, this volume) and Italy (Smiraglia et al., this volume). Limits on construction are also very difficult to enforce, as shown by studies in Georgia (Huggel, Haeberli, and Kääb, this volume), Peru (Carey, this volume), and Switzerland (Wiegandt and Lugon, this volume).

The cultural resonance of glaciers creates additional challenges in formulating responses to glacier retreat. Rhoades, Zapata Ríos, and Aragundy Ochoa (this volume) note the great sadness with which highland villagers describe the darkness of the formerly glacierized peak of Cotacachi and their efforts to ensure that younger generations will know of the beauty of the peak when it was still white. Other sources describe a strong concern for retreat in other, less traditional societies, such as Switzerland (Haeberli, this volume) and the United States (Wolf and Orlove, this volume). As Brenning (this volume) notes, many people are troubled when they learn that mining operations are destroying glaciers in remote regions of the world. Though some of their regret comes from the waste of water that could otherwise be used for irrigation, drinking, or other purposes, they can be distressed even when this destruction occurs in remote areas with few inhabitants. As Ehrlich (2004) points out, glaciers often seem to have an intrinsic value beyond any immediate usefulness that they might offer; their loss, whether through unregulated mining or global warming, constitutes a wanton destruction of nature that borders on or crosses into the realm of immorality.

Indeed, human responses to glacier retreat may be shaped as much by this cultural attachment as they are by the economic issues of resources and hazards. The economic impacts should certainly not be minimized, but the cultural impacts, felt outside mountain regions, merit attention as well. It is not only the inhabitants of La Paz or Yerevan or Seattle for whom glacierized peaks are a sign of their connection to their home. Many people around the world care deeply about seeing these mountains on the horizon or in photographs or even in their mind's eye. Eternally white, rising high above the places where people live, they are one of the treasures of our world, a sign for all of a connection to the planet that is our common home.

We may try to imagine the world as it will be a few hundred years from now. It may well be that waves will lap the lower stories of skyscrapers in former coastal cities and that people will understand that the ocean's rise, due principally to the great shrinkage of the ice caps in Greenland and Antarctica, began with the reduction of mountain glaciers to small fragments. But it may also be that new technologies and new patterns of consumption, elements of which can be discerned at present, will avert this change and others just as extreme. If the world does address the great challenge of global warming, it will be in part because of the way that glaciers serve as icons to make this challenge visible.

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