The Earth's Changing Glaciers

by Dr. Andrew Klein, *Texas A&M University*

The retreat of the world's glaciers was thrust into the American public consciousness in September, 1997, when Vice President of the United States Albert Gore stood in front of Grinnell Glacier in Glacier National Park, Montana, and declared, "It's retreating before our very eyes."

The Vice President went on to conclude that the rapid retreat of the world's glaciers is one of the most tangible signs of the global warming that has occurred over the last century. While his assertion that the recent glacial retreat is attributable to the so-called "greenhouse effect" is still under debate, the fact that glaciers worldwide are currently in a state of retreat is not.

The declaration comes as no surprise to mountaineers, who have observed the retreat first-hand. Where last century's climbers walked over snow and ice, alpinists at the beginning of the twenty-first century may encounter rocks and loose rubble. Why is this happening? The following article presents a brief synopsis of our current knowledge about the world's glaciers: their retreat, the unique relationship between glaciers and climate and the effects of past and current climatic conditions.

The Earth's Glaciers: Just the Facts

Before we begin examining glacial retreat, a basic overview of the global distribution of glaciers is in order. While glaciers currently exist on six continents (presently, Australia alone has none at all), it may come as a surprise to many mountaineers that the total number and area of the world's glaciers are poorly known. Ignoring the large Antarctic and Greenland ice sheets, which account for the vast majority of the Earth's ice cover, the best estimates are that there are about 160,000 glaciers and 700 ice caps covering an area of 240,000 and 430,000 square kilometers, respectively. (Ice caps differ from glaciers in that they have no confining rock walls.) Of the total number of glaciers and ice sheets, only a quarter have been cataloged, and an even smaller number have been extensively studied.

Through empirical observations, the volume of a glacier has been found to be proportional to its area raised to the 1.36th power. Based on this relationship, the total volume of the Earth's ice caps and glaciers (excluding the Greenland and Antarctic ice sheets) is estimated to be 100,000 and 80,000 km^3, respectively. To put this into perspective, if all these glaciers were combined into a single ice cube, it would be 56 kilometers on a side. This total includes glaciers and ice caps in alpine areas, as well as those bordering the Greenland and Antarctic ice sheets.

Figure 1 shows the distribution of the world's glaciers. It can be seen that, although glaciers exist almost everywhere in the world, not all areas of the world are equally glaciated. For example, glaciers cover a much higher percentage of Europe than they do South America. Generally, the lowest altitude to which glaciers descend increases toward the equator, so glaciers in the tropics are found only on the highest peaks, while glaciers near the poles descend to sea level.

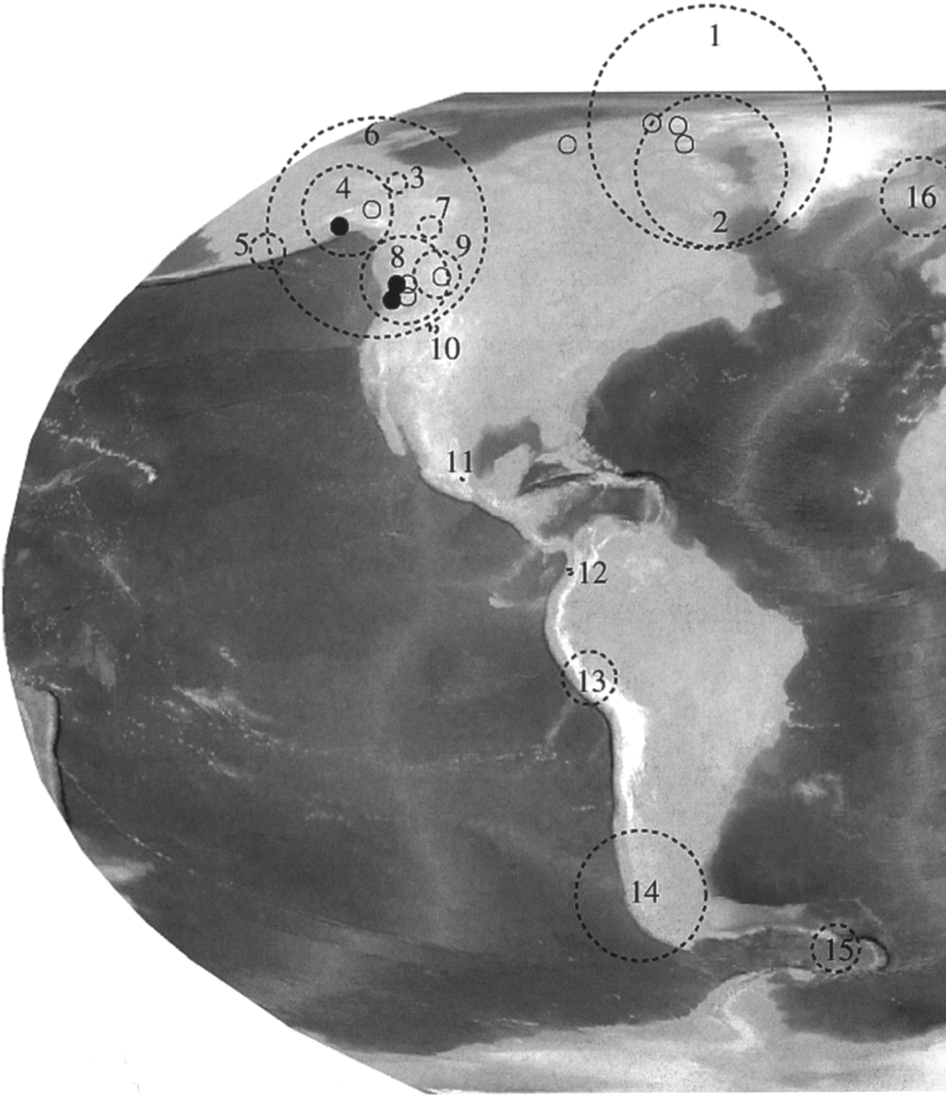
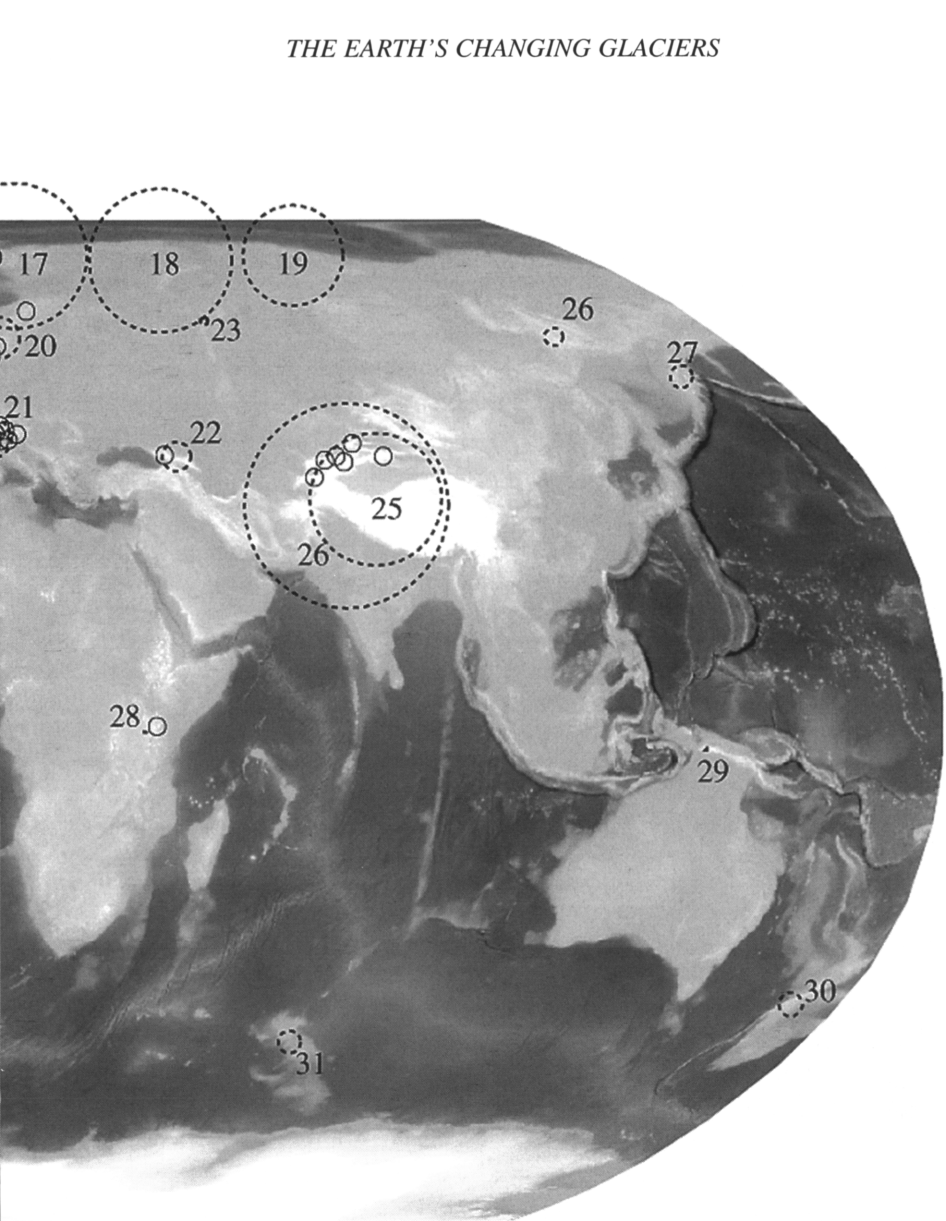


FIGURE 1. *Glaciated regions of the world. Dotted circles represent the area covered by glaciers in different regions (excluding the Greenland and Antarctic ice sheets). The circles are scaled in proportion to the total glacier area they represent. The circles are centered on the geographic center of each glaciated region and may or may not encompass the extent of all the glaciers in the region. The dots indicate whether glaciers with long mass balance records had positive (filled) or negative (empty) mass balances over the period from 1968-1989. Glacier areas are from Meier and glacier mass balance measurements are from Dyurgerov and Meier.*

Numbers and corresponding regions: **1**: *Canadian Arctic-North.* **2**: *Baffin and Bylot Islands, Labrador.* **3**: *Brooks Range, Kigluaik Mountains.* **4**: *Alaska Range, Talkeetna, Kilbuk Mountains.* **5**: *Aleutian Islands, Alaska Pennisula.* **6**: *Coastal Mountains, Kenai Penninusula to 55°N.*



7: Mackenizie, Selwin, Rocky Mountains north of 55° N. **8***: Coast Mountains south of 55° N, Cascades, Olympics.* **9***: Rocky Mountains south of 55° N, Selkirks (Canada), Northern Rocky Mountains.* **10***: Middle and Southern Rocky Mountains, Sierra Nevada.* **11***: Mexico.* **12***: Andes (10° N to 0°).* **13***: Andes (0° to 30° S).* **14***: Andes (30° S to 55° S).* **15***: South Atlantic Mountains.* **16***: Iceland, Jayen.* **17***: Svalbard.* **18***: Franz Josef Island, Novaya Zemlya.* **19***: Severnaya Zemlya and other CIS Arctic islands.* **20***: Norway, Sweden.* **21***: Alps, Pyrenes.* **22***: Caucasus, Turkey, Iran.* **23***: Ural Mountains, Byrranga, Putorana.* **24***: Hindu Kush, Pamir, Alai, Karakoram, Himalaya, Nyainqentangla.* **25***: Tien Shan, Kun Lun, Altai, Qilian Shan, Dzungaria, Sayan.* **26***: Kodar, Orulgan, Chersky, Sun-Kho, Koryasky.* **27***: Kamchatka.* **28***: Africa.* **29***: West Irian.* **30***: New Zealand.* **31***: Kerguelen, Heard Island.*

Out of all the world's glaciers, only 250 (or 0.15%) have their mass balance measured. (A glacier's mass balance refers to the amount of ice gained or lost over a period of time, usually a year.) Out of these 250 glaciers, only about 50 have mass balance records stretching back over 20 years. As seen in Figure 1, glaciers with long mass balance records are clustered in Europe, the United States and Canada. Other areas with considerable glacier area, such as the Southern Andes, have few or no long-term mass balance records. Although the number of extensively studied glaciers is small, they do provide a strong indication that glacial retreat has been pervasive across the globe over the last half century. Unfortunately, even this limited glacial monitoring network is threatened by continuing government cutbacks, both in the United States and beyond.

Glaciers and Climate

While it is easy to observe a casual relationship between glacial retreat and climate changes, understanding the exact physical mechanism linking glaciers and climate is much more difficult. Why is it, and how is it, that glaciers respond to changes in their immediate climate?

Simply put, glaciers are mass balance systems. At any time, glaciers are either gaining (accumulating) or losing (ablating) mass. This net gain or loss of mass over the glacier surface results in changes in glacier shape and size.

During at least a portion of the year, glaciers accumulate mass through snowfall, avalanche activity, wind deposition and a host of other processes. While accumulation occurs during the winter months for glaciers in the European Alps and North American Rockies, the timing of accumulation is more complicated in other parts of the world. For example, the tropical glaciers in the South American Andes receive most of their accumulation during the wet season, which coincides with their warmest time of the year. Portions of the Himalaya, meanwhile, may have two distinct accumulation seasons: winter and the monsoon.

Because glaciers do not continue to grow unchecked, there must be a process that counteracts accumulation. Enter ablation. Ablation includes melting and sublimation (the transformation of H2O directly from solid to vapor form). Glaciers terminating in lakes, rivers or the ocean also lose mass by calving (the breaking-off and drifting-away of ice from the terminus—i.e., the end of the glacier). Ablation is not only affected by air temperature but also by the amount of radiation absorbed at the glacier surface, which in turn is affected by cloud cover and the albedo (reflectance) of the glacier's surface.

If a glacier is in equilibrium, the amount of ice added by accumulation over a year is exactly balanced by the amount of ice lost to ablation. When a glacier is in equilibrium, its size (though not necessarily its shape) remains unchanged. If there is net accumulation, the glacier will thicken and the additional mass will be transferred by glacial flow to the glacial snout, causing it to advance. Thinning and retreat will occur if the glacier loses mass. Because a glacier's mass balance is affected by both accumulation and ablation, glaciers are very complex indicators of climatic change. It is possible for a glacier to experience ablation due to higher air temperatures but still advance if ablation is offset by increased accumulation.

The intricate relationship between glaciers and climate is further complicated by the fact that climatic changes may not be immediately manifested in changes in the glacier terminus. The exact time it takes for a climatically induced change in mass balance to translate into a terminus position is a complex function of the length, geometry and thickness of the glacier itself, as well as the slope of the terrain beneath the glacier. Generally, small glaciers respond more quickly to climate changes than larger glaciers. Small cirque glaciers may respond to a climate variation within a year or two, while larger valley glaciers may take decades to react. In a single area, then, some glaciers may be advancing while others are simultaneously retreating.

Alpine environments are characterized by an inverse relationship between temperature and elevation: as elevation increases, the temperature normally decreases. The rate of this temperature decrease with elevation is termed the lapse rate, which, for most mid-latitude mountain ranges (such as the Rockies and the Alps), is approximately 6.5° Centigrade per kilometer. Thus, ablation typically decreases with altitude.

Over the course of a year, a glacier's lower reaches are commonly characterized by a net ablation and the upper reaches by net accumulation. The altitude at which ablation and accumulation are equal—that is, the elevation at which the net balance is zero—is termed the equilibrium line. The area below the equilibrium line is termed the ablation zone, while the area above the equilibrium line is the accumulation zone.

An easy way for mountaineers to detect the transition between the ablation and accumulation zones is to look for the transition between bare ice and snow. This is termed the transient snowline. The transient snowline is not an immobile delineation, but rather moves up and down the glacier in response to snowfall and melting over the course of a year. At the end of the ablation season when the transient snowline is at its highest altitude, it is often very close to the position of the equilibrium line (which is determined using mass balance measurements described below). Year-to-year variations in the snowline through field observations, aerial photography or more recently by satellite images can give glaciologists an idea of the relative year-to-year health of a glacier.

MONITORING GLACIER HEALTH

Glaciologists have developed several methods to monitor "glacier health." The ideal method is to make mass balance measurements—to directly measure the ice gained or lost over the glacier's surface over the course of a year. This is typically accomplished by installing a network of stakes over the glacier surface and then revisiting them at periodic intervals. Changes are measured in the distance from the glacier surface to the top of the stake, which is a measure of the amount of ice gained or lost (Figure 2).

To determine the total mass balance of the glacier, it is divided into a series of elevation bands and the glacial area (square kilometers) in each band is determined. The total mass balance of the glacier is calculated by multiplying the area of each band by the amount of ice gained or lost at that altitude from the stake measurements. Summing these values for each band produces the net mass balance for the glacier. If this value is positive, the glacier experienced a net gain of ice over the year. If it is negative, the glacier experienced a net ice loss.

The difficult, laborious, expensive and occasionally dangerous field studies (which are being supplemented by newer technology such as satellite remote sensing) are conducted because they provide the information necessary to compare year-to-year changes in glacier mass balance with various climate records (usually temperature and precipitation). This enables glaciologists to understand relationships between the glaciers and their immediate climate.

Unfortunately, these mass balance records are often of limited term. The oldest records extend back only into the 1940s. Longer-term records of glacial change are available from other sources such as glacier terminus positions, which are probably the most familiar to mountaineers. In addition to being a fairly simple measurement to make, glacier terminus positions have an added advantage: there exist numerous sources of information about them,

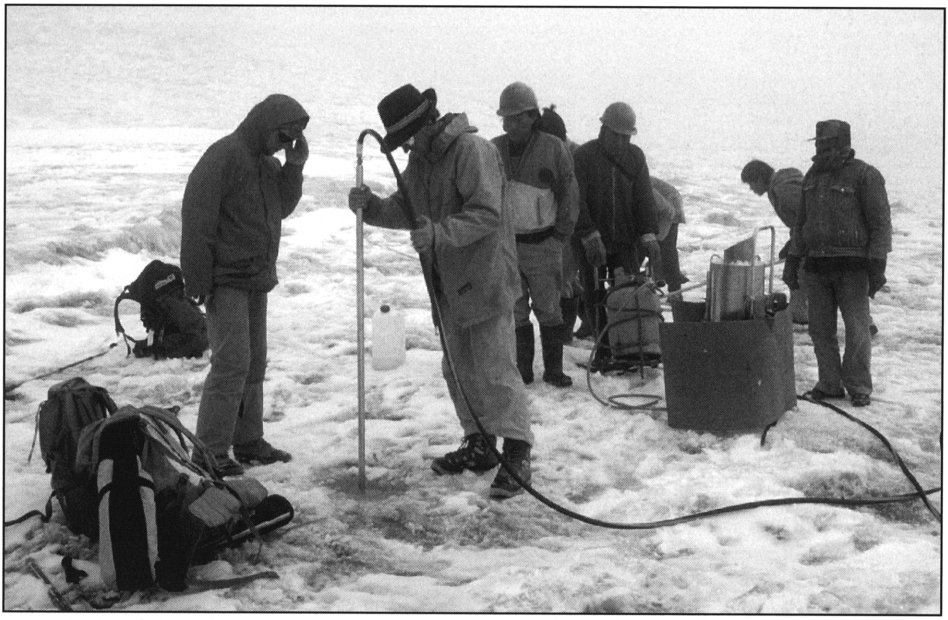


FIGURE 2. *Field glacial mass balance measurements. Glaciologist Bernard Francou prepares to install a stake on Zongo Glacier in Bolivia using a vapor drill.* ANDREW KLEIN

including direct measurements, photographs and sketches. A mountaineer taking a photograph of the terminus of Gangotri Glacier on Bhagirathi III can unknowingly be contributing to glaciology. Figure 3 shows such photographic documentation for a small Andean glacier.

Former positions of glaciers are marked by the locations of moraines (deposits of unsorted and unstratifed sediments produced during glacial advances and left behind as the glacier retreats). The age of the deposits can be determined through a variety of methods, including radiocarbon dating (for older materials), lichenometry (which uses the size of lichens grown on rocks found on moraines to infer the moraines' age) and dendrochronology (which uses tree rings to determine the age). The moraine record can be incomplete, because later glacial advances can wipe away the record of earlier, less extensive advances. However, it is still possible to construct a detailed picture of glacial changes using moraines. One of the most famous records of terminus positions is for Grindelwald Glacier in Switzerland and is illustrated in Figure 4.

Inferring climatic changes from terminus position records can be difficult because of the varying response time of the terminus to climatic changes, difficulties in precisely dating moraines and the multitude of non-climatic factors that can affect the position of the glacier snout. The terminus position of some types of glaciers, most notably tidewater and surging glaciers, are primarily influenced by non-climatic factors.

Still, the fact that glaciers are directly affected by their climates cannot be ignored. The present state of worldwide glacial retreat, even if it not irrefutably tied to the greenhouse effect as Vice President Gore suggests, does offer proof that the world is warmer today than it has been in the past.

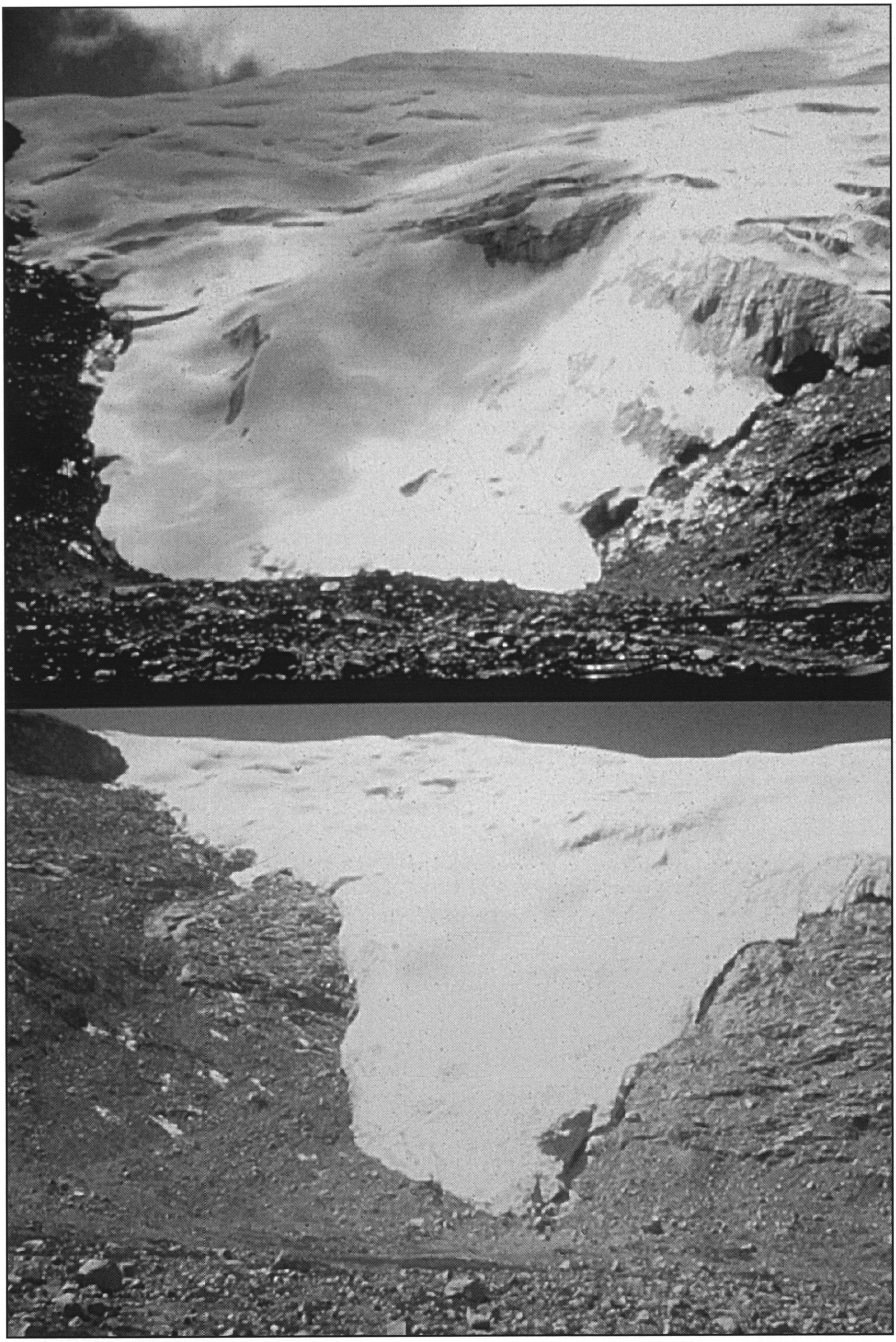


FIGURE 3. *Recent retreat of a small Andean glacier on Cerro Wila Llojeta in the Cordillera Real, Bolivia, from 1989 (upper photo) to 1993 (lower photo).* ANDREW KLEIN

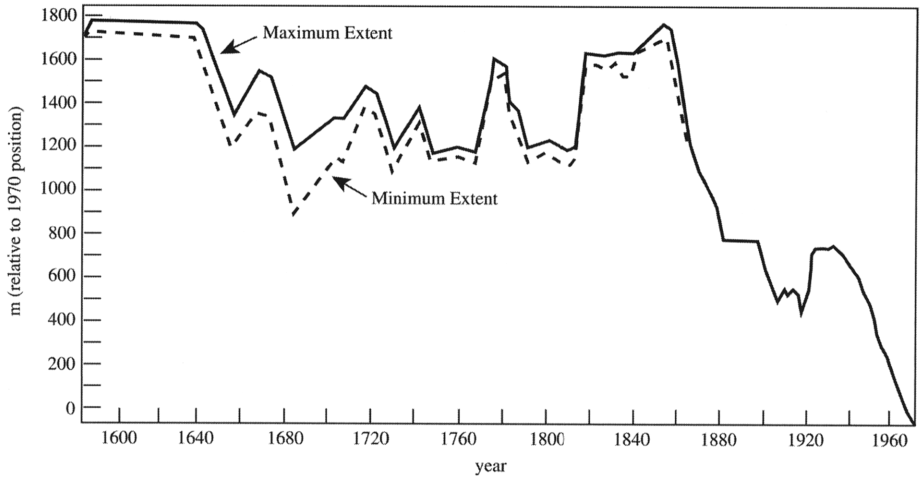


FIGURE 4. *Terminus positions of the Grindelwald Glacier from 1600 to 1975 as measured relative to the 1970 position. There is some uncertainty in the actual position, hence the maximum and minimum boundaries. Adapted from Messerli and others.*

GLACIAL CHANGE FROM THE LAST GLACIAL MAXIMUM TO THE PRESENT

Placing today's current glacier retreat into its appropriate climatic context requires some understanding of how the Earth's climate has changed over the past 20,000 years. Somewhat paradoxically, many of the features we associate with glaciated alpine environments are actually indicative of the largely deglaciated world we currently inhabit. The characteristic U-shaped alpine valleys familiar to today's mountain travelers were carved by numerous advances of glaciers that have long since melted; the moraines upon which many alpine trails run are composed of material deposited by glaciers along their former edges. The picturesque tarns that dot the glacial landscape were originally formed beneath many meters of glacial ice.

Some 14,000 to 20,000 years ago during what is termed the Wisconsin glaciation in North America and the Würm or Weischel glaciation in Europe, ice sheets as deep as two kilometers covered large areas of North America and Eurasia. Alpine glaciers were much larger than at present. In fact, while ten percent of the world is currently covered with ice, at the time when the extent of the large North American ice sheets were at their maximum, the coverage was more than 25 percent. Sea level was also 120 meters lower then, because much water was frozen in the large ice sheets.

Within the last 10,000 years—a period scientists term the Holocene Period—the appearance of the world's glaciers and ice sheets has changed dramatically. Scientists have constructed a detailed picture of the Earth's climate over the Holocene Period by piecing together different sources of paleoclimatic information, including ice cores from ice sheets, ice caps and glaciers around the world; the landforms evidence left behind by retreating glaciers; and analysis of tree rings and ocean sediment cores. The picture that emerges is not one of monotonic glacial retreat since the last global glacial maximum but one of abrupt climatic changes that have witnessed repeated expansion and contraction.

About 6,000 years ago, most of the extensive glaciers and ice sheets of the Wisconsin period were gone. The last remnants of the once-extensive Scandinavian Ice Cap and North American Laurentide Ice Sheet had finally disappeared, and sea level had risen to within a few meters of its present level. Since then, the earth's climate has seen numerous climate variations, though of much smaller magnitude than the large climatic change between the Wisconsin and today's interglacial period.

Between 6,000 and 3,000 years ago during what is known as the Hypsithermal Interval, many regions of the world were warmer and/or drier than at present. At this time, glaciers in many regions of the world were smaller than they are today. Cirque glaciers in the United States and Canadian Rockies and the European Alps disappeared, and larger valley glaciers retreated substantially.

Many of the glaciers we see today are not simply remnants of much larger glaciers left from the Ice Ages, but are glaciers that shrank and then readvanced, or in some cases were reconstituted entirely. This regenerated glaciation during the Holocene is termed "Neoglaciation." There is considerable evidence that, during the Holocene, many regions of the world experienced repeated glacial advances and retreats, though (with a few notable exceptions) evidence for globally synchronous glacial advances is lacking.

The most recent of these Neoglacial events, and for many regions of the world the most extensive, occurred from ca. 1450 to 1850 A.D. Termed the "Little Ice Age," it is well documented in Europe. Looking back to Figure 4, one can see the advances and retreats of the Grindelwald Glacier during the Little Ice Age. Evidence is also mounting for other glacial advances in other regions of the world during this time. Figure 5 shows a recently reconstructed

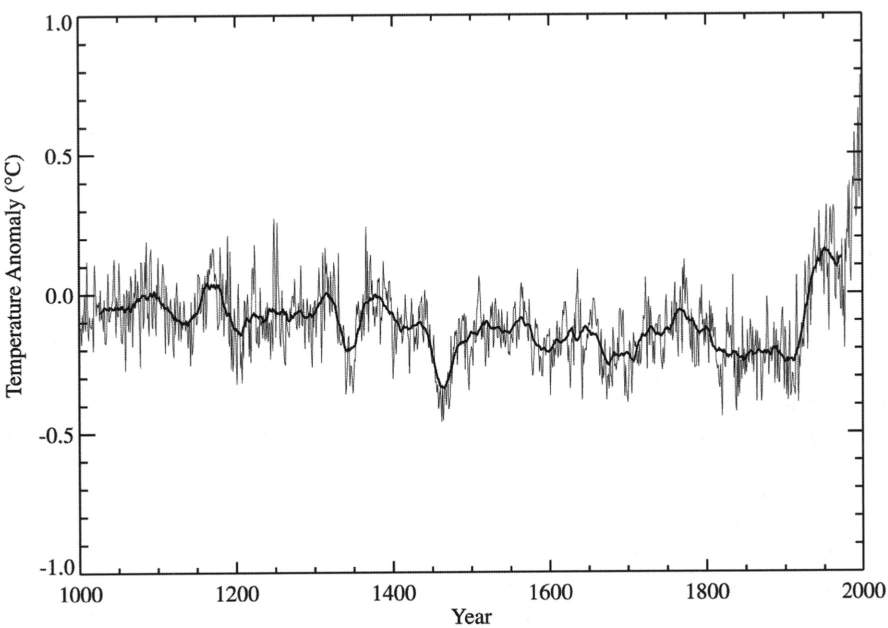


FIGURE 5. *Reconstructed temperature anomalies for the Northern Hemisphere during the last millennium. The anomalies are plotted as departures in degrees Celcius from the 1902-1980 mean. The thin line is annual temperatures and the thick line shows averages for 25-year periods. The period from 1905 to 1998 is from the instrumental record and the period prior is from paleoclimate reconstructions. Adapted from Mann and others.*

Northern Hemisphere air temperature record for the past millenium. Temperatures during the Little Ice Age are a few tenths of a degree Celsius lower than the 1902-1980 mean. The 1800s were especially cold—the coldest period, in fact, of the last millenium.

The glacial advances that accompanied the rather small temperature decrease during the Little Ice Age stand in marked contrast to the pervasive glacier retreat that has marked much of the 20th century. Given the temperature history illustrated in Figure 5, it is not surprising that glaciers have recently been in a state of marked retreat. In particular, the Northern Hemisphere temperature record shows the latter half of the 20th century to be the warmest period in the last 1,000 years. The past decade has continued the trend, and the 1998 temperatures exceeded all annual temperatures in the past 1,000 years! Evidence from ice cores extracted from mid- and low-latitude mountain glaciers suggest that temperatures in the latter half of the 20th century have been warmer than any other 50-year period in the past 12,000 years. Over the course of less than 200 years, alpine glaciers have experienced the most prolonged cold period of the last millenium, followed by the warmest in the millenium and perhaps even of the entire Holocene.

Given that a very small (a few tenths of one degree Celsius) drop in temperature caused large glacial advances during the Little Ice Age, it is not unreasonable to expect that current glacier retreat is related to the warmer conditions that have prevailed during the latter half of the 20th century. During this time, air temperatures have been consistently above those during the previous 950 years of the millenium. However, is it actually the case that increased global air temperatures are leading to worldwide glacial retreat?

The answer is an unequivocal yes. Figure 1 illustrates whether the best-studied glaciers in the world have gained or lost mass, and Figure 6 illustrates the annual mass balances for a few select glaciers. It is interesting to note that glaciers from around the world have witnessed an increased loss of mass between the late 1970s and early 1980s. These data, while scarce, do demonstrate the pervasive nature of the current state of global glacial retreat, and the best recent estimates place the global loss in glacial mass on the order of about 130 mm of ice per year. For the 1961-1990 period, for which the world's mass balance record is the most complete, this is equivalent to the loss of nearly four meters of ice from the surface of the world's glaciers.

THE FUTURE

While mountaineers may be most interested in the consequences of glacial retreat in alpine environments and its effect on, say, the ice routes of the Cordillera Blanca, potentially the most serious repercussions of alpine glacier retreat are felt far afield and at much lower altitudes. Mountaineers might not have asked the question, "What happens to all the glacial meltwater?" But this question has serious ramifications.

As the world's alpine glaciers melt, the water they stored is returned to the oceans. While this melting will not cause a 120-meter change in sea level as did the melting of the large Northern Hemisphere ice sheets, the consequences are still significant. Current estimates place the current rate of sea level rise due to glacial melting at between 0.25 and 0.5 mm per year.

The Intergovernmental Panel on Climate Change represents the consensus opinion of the scientific community on climate change issues; its conclusions are meant to be the standard guide on the subject. As the 1995 IPCC estimates place the current rate of global (eustatic) sea level rise at 1.8 mm per year (± 0.1 mm), current glacier melting is contributing somewhere between 14 and 28 percent of the current sea level rise.

While glaciologists lack a crystal ball that would enable them to predict the future of alpine glaciers, if the current warming trends continue (as is expected), then the world's glaciers will

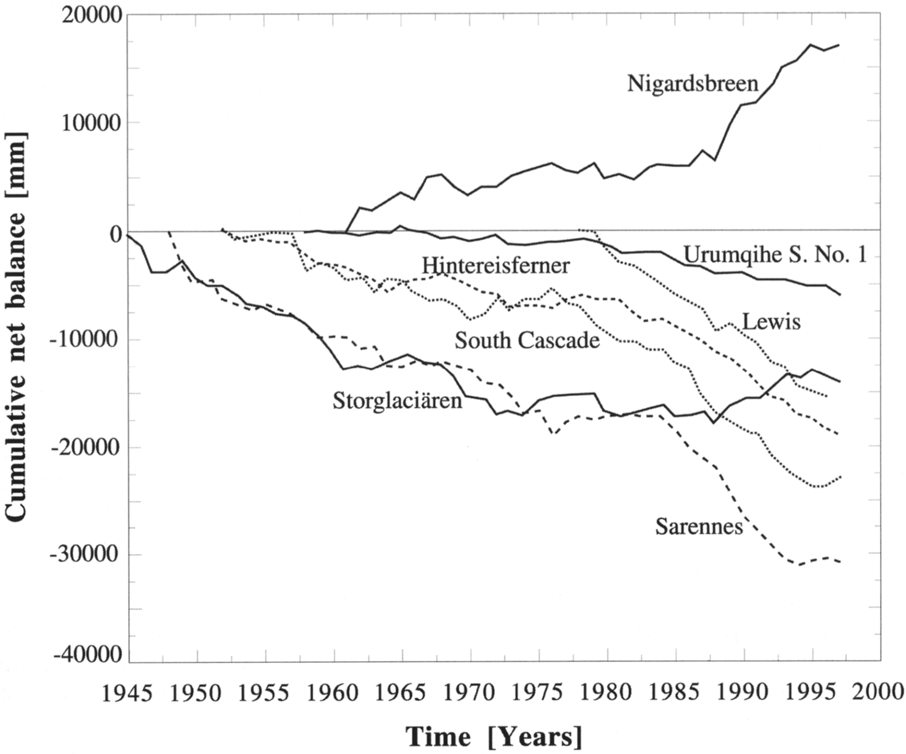


FIGURE 6. *Cumulative mass balance records from selected glaciers around the world. (Data is from the World Glacier Monitoring Service.) The locations of the glaciers are as follows: Nigardsbreen: Southern Norway; Urumqihe S. No. 1: Tien Shan, China; Hintereisferner: Austrian Alps; Lewis: Mt. Kenya, Kenya; South Cascade: North Cascades, USA; Storglaciären: Northern Sweden; Sarennes: French Alps.*

undoubtedly continue to retreat. Thus, as Al Gore said, the future does look bleak for the glaciers in Glacier National Park, and alpine enthusiasts can expect to be witness to continued glacial retreat and the disappearance of some individual glaciers. Still, mountaineers do not need to fear a glacier-less future, as there is no threat that all the world's glaciers will disappear in our—or our children's—lifetimes.

Acknowledgments. The author wishes to acknowledge Baker Perry for encouraging me to write the paper, Bernard Francou and Pierre Ribstein of IRD (ex-ORSTOM) and Geog Kasser of the University of Innsbruck for teaching me much about tropical glaciers, and Joan Ramage of Cornell University and Austin Post for their thoughtful comments on the manuscript.

Further Reading

Dyurgerov, M. B., and Meier, M. F. "Year-to-year fluctuations of global mass balance of small glaiers and their contribution to sea-level changes." In *Arctic and Alpine Research*. 29: 392-402. 1997.

Dyurgerov, M. B., and Meier, M. F. "Mass balance of mountain and subpolar glaciers: A new global assessment for 1961-1990." In *Arctic and Alpine Research.* 29: 379-391. 1997

IAHS(ICSI)/UNEP/UNESCO. "Glacier Mass Balance Bulletin No. 5 (1996-1997)." In *World Glacier Monitoring* Service and ETH Zurich. 1999.

Callender, B.A., Harris, N., Houghton, J.T., Kattenberg, A., Maskell, K . and Meira Filho, L.G. (Eds.) "Climate Change 1995: The Science of Climate Change." *IPCC Second Assessment Report.* Cambridge University Press, UK. 1995.

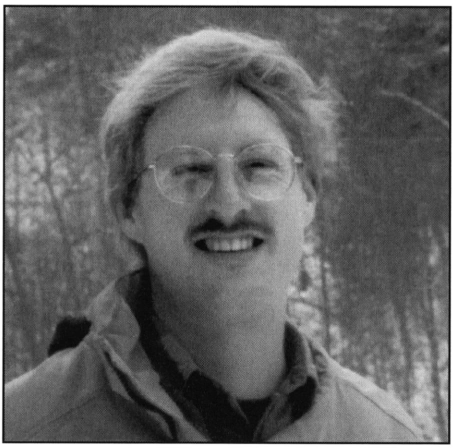
Mann, M. E., Bradley, R. S., and Hughes, M. K. "Northern hemisphere temperatures during the past millennium: Inferences, uncertainties, and limitations." In *Geophysical Research Letters.* 26: 759-762. 1999.

Meier, M. F. "Contribution of Small Glaciers to Global Sea-Level." In *Science.* 226: 1418-1421. 1984.

Meier, M. F., and Bahr, D. B. "Counting glaciers: use of scaling methods to estimate the number and size distribution of the glaciers of the world." In *Glaciers, Ice Sheets and Volcanoes: A Tribute to Mark F. Meier.* S. C. Colbeck, Ed. 89-94. Hanover, New Hampshire: U.S. Army. 1996.

Messerli, B., Messerli, P., Pfister, C., and Zumbuhn, H. J. "Fluctuatons of climate and glaciers in the Bernese Oberland, Switzerland, and their geological significance, 1600-1975." In *Arctic and Alpine Research.* 10: 247-260. 1978.

Thompson, L. G., Mosleythompson, E., Davis, M., Lin, P. N., Yao, T., Dyurgerov, M., and Dai, J. "Recent Warming—Ice Core Evidence From Tropical Ice Cores With Emphasis On Central-Asia." In *Global and Planetary Change.* 7: 145-156. 1993.



Andrew Klein

Dr. Klein is an assistant professor of geography at Texas A & M University, where he applies remote sensing to the cryosphere, including global snow cover and Andean and Himalayan mountain glaciers. He is currently collaborating with other Texas A&M researchers to develop an environmental monitoring program for McMurdo Station, Antarctica. Previously, Dr. Klein was a visiting scientist in the Hydrological Sciences Branch at NASA/Goddard Space Flight Center. He received his Ph.D. in 1997 from Cornell University, where he conducted remote sensing of glaciers and glacial landforms in the Central Andes, an area in which he has a continuing interest.