As climate changes, so do glaciers

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Understanding abrupt climate changes requires detailed spatial/temporal records of such changes, and to make these records, we need rapidly responding, geographically widespread climate trackers. Glacial systems are such trackers, and recent additions to the stratigraphic record show overall synchronous response of glacial systems to climate change reflecting global atmosphere conditions.

Of the numerous physical systems on Earth, glaciers are one of most responsive to climate change. During the Quaternary, the repeated transition from an ice age when glaciers covered a significant portion of the Northern Hemisphere, thereby dropping global sea level more than 100 m, to an interglacial when glaciers cover only limited areas has followed global temperature changes on 100,000-year cycles. But how do shorter, abrupt climate changes (~1,000 years or less) affect glacial systems? The answer allows glacial features in the geological record to provide essential clues about past behavior of climate.

Glaciers flow from their zone of accumulation into an ablation zone where the removal of ice is completed at the terminus. The position of the glacier terminus or margin, which leaves a distinct geological signature, may reflect one of three processes: (i) internal mechanics such as surges, which rapidly and repeatedly extend glacier margins out within broad limits; (ii) equilibrium accommodation of a long-term climate change, which requires time scales proportional to the size of the glacier (1); or (iii) direct marginal responses preceding equilibrium accommodation. Because the latter adjustments take only a few years or decades to be expressed, they form the basis for extracting paleoclimate information. The actual position of the glacier margin reflects a balance between mass influx from flow and ablation. During climate warming, increased marginal ablation (largely a function of summer temperature for land-based glaciers) overwhelms the mass supplied, forcing a glacier margin to retreat. Conversely, during a climate cooling, the reduced loss of mass allows the margin to extend. Although direct tracking of the glacier margin and associated climate changes is the best way to demonstrate the relationship of climate change to glaciers (2), such data sets extend back only for several decades. Analogs from a climate event called the Little Ice Age provide a bridge from historical observations to the more distant past and justify the use of glacial deposits to help reconstruct older abrupt climate changes.

A Climate Change Event: The Little Ice Age. Relatively minor climate changes during the Little Ice Age (A.D. ~1200–1850) impart significant glacial responses. A recent Northern Hemisphere temperature reconstruction indicates an oscillating temperature drop from A.D. 1000–1850 of about 0.2°C with a subsequent and still continuing warming of nearly 0.8°C (3). Although the Little Ice Age earns its name because glaciers expanded worldwide (4), two site-specific examples illustrate the overall patterns. First, investigations of glacier forelands around Prince William Sound have recovered well dated records of glacial expansions and contractions over the last 1,000 years (5). Fig. 1 shows three periods of glacial growth associated with the three coolest temperature oscillations and the rapid demise of these systems accompanying the warming since the turn of the century.

Second, fieldwork on the western margin of the Greenland Ice Sheet provides evidence of rapid recessions of both the large Greenland Ice Sheet and adjacent small independent glaciers (6). Within the last 150 years, 94% of the lobes along the western edge of that ice sheet withdrew, whereas 70% of the independent glaciers retreated. Increased summer ablation and a concurrent rise of 140 m (~1.5°C) in the equilibrium line altitude drove these massive recessions. All of these Greenland glaciers retreated by comparable amounts, ~2 km, showing that marginal retreat is independent of the size of the ice mass and precedes and equilibrium adjustments.

Additional examples would confirm that, during the Little Ice Age, glacial systems expanded in concert and then withdrew together. Termiin of glaciers of

Fig. 1. Advance and retreat patterns of glaciers in coastal Alaska linked to the regional climate signal. Northern Hemisphere temperature reconstruction (3) is shown with a 50-year smoothing. Times of glacier expansion, constructed from radiocarbon, tree-ring, lichen, photographic, and historic data are shown in blue with the number of systems expanding from both the western and eastern flanks of the Kenai Mountains indicated for each episode (26). The collapsing caused by the warming since A.D. 1880 left moraines (red bars). The number of moraines is a measure of the overall strength of retreat from the Kenai Mountains and other areas in the Gulf of Alaska region (27).

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all sizes, including ice sheets, responded to temperature changes of 0.2°C on decade time scales. Indeed, the dependence of glacier retreat on rising temperatures is strong enough that estimates of temperature increase have been extracted from fluctuations in glacier length (7). Because many glacial margins began retreat (A.D. 1850–1900) before the introduction of significant amounts of human-induced greenhouse gases, at least the initial part of the warming is a natural swing in the climate system. The continued warming and subsequent glacial retreat have uncovered buried forests in the Canadian Rockies (8) and elsewhere that are several thousand years old, which would require that these glaciers were once smaller than their present size. Such observations help define the range of natural climate variability.

Global Responses? Do glacial systems respond to global climate changes? In addition to the global behavior during the Little Ice Age, two major glacial events at the end of the last Ice Age showing similar patterns from the midlatitudes in both polar hemispheres and from the South Pacific and North Atlantic basins suggest that they do. The last event, the Younger Dryas, is the major rapid warming of some 2–3°C, marking the transition from the ice age world to our interglacial world. The Younger Dryas is best documented in Europe with additional records emerging from elsewhere (9–11). The comparisons made below and in Fig. 2 must employ both calendar years before present (cal yr BP) and radiocarbon years before present (14C yr BP) because of the different dating techniques used to capture the records. In the Swiss Alps, the glaciers in Julier Pass retreated at about 11,860 ± 210 cal yr BP (12), and in North America, the Pinedale glacier pulled back from the Inner Titcomb Lakes moraine in the Wind River Range at 11,400 ± 500 cal yr BP (13). In the Southern Alps of New Zealand, the Lake Misery moraines in Arthur’s Pass formed at 11,720 ± 320 cal

![Fig. 2. Reliable chronological assignment of glacial events is essential yet presents at least three challenges. (i) Obtaining a tight stratigraphy of the events. Glacial sediment that encases relic grasses or other plant material living on the land surface is ideal to bracket the age of a glacial expansion. Because moraines form at the peak of expansion, they supply suitable surfaces for cosmogenic techniques whereby the total accumulation of 10Be, 26Al, or 36Cl in boulders provides a means to estimate the age of surface stabilization. These are always minimum ages for the recession. (ii) Obtaining a valid age for selected stratigraphic levels. With radiocarbon dating, contaminants can yield analytical ages several hundred years apart from the same stratigraphic level. Multiple samples and removal of the outliers before averaging increases the precision of the age assignments. Likewise, nonglacial processes can reduce the amount of accumulated isotopes, but a clustering of ages verifies a result. (iii) Converting the radiocarbon age to the calendar time scale. Variations in the production of 14C (28) and plateau effects from the ventilation of old carbon stored in the ocean reservoir (29) currently require an empirical conversion between 14C yr BP and cal yr BP (30). All of these principles are employed in the data points of the figure. Data sources: New Zealand (12, 31, 32), Chile (16, 17, 33), Western U.S. (10, 14, 15), and Switzerland (12, 34). The age of the Younger Dryas is 11,550–12,700 cal yr BP and is shown as a shaded band (35).](www.pnas.org)
yr BP (12). These ages reflect marginal recessions from a down-valley position intermediate between that of Little Ice Age moraines and full Ice Age moraines and typically represent an equilibrium line altitude increase of about 500 m from present values (14). These similar-magnitude, synchronous equilibrium line altitude rises and associated ice retreats again illustrate the strong sensitivity of glaciers to climate.

Before the Younger Dryas at the time of maximum continental ice volume (and hence the approximate low stand of global sea level; ref. 15), glacier systems made one final push. The subsequent extensive collapse formed many of the spectacular lakes ringing glaciated mountain chains around the globe and this final expansion may provide clues to what caused the end of the last ice age (16). In the Southern Hemisphere, at least four adjacent but independent lobes of the Patagonian Ice Cap spread over 2° of latitude and reached maximums together about 14,880 14C yr BP (17), with retreat well underway within several hundred years.

Half a world away, in Washington State, an advance of the Cordilleran Ice Sheet in the Puget Lowland was nearly complete about 14,500 13C yr BP (18). This maximum ice stand was held for only ~100 years, and the retreat in the marine basins of both Chile and Washington occurred at the same time that alpine glaciers left the Tioga 4 moraines in the Sierra Nevada (19). Therefore, along the eastern side of the Pacific, glaciers pulsed together, indicating a common climate forcing. In Chile, coeval vegetation changes suggest a warming of 3–4°C (20) at this time.

An Ice Age Rhythm. A review of glacial records shows a distinct rhythm extending from the Little Ice Age back into the Ice Age (21), and for reasons yet unknown, this rhythm seems amplified during the latter. Whereas land-based glaciers leave only fragmentary evidence, tidewater glaciers send out detrital material transported by floating icebergs to signify times of glacial activity. During the last ice age, the ice-rafted debris (IRD) concentrations in the North Atlantic were two orders of magnitude higher than they are at present and reached maxima in small and large peaks known as the Detrital and Heinrich events, respectively (Fig. 3).

Continued mapping (22) of deep sea cores shows that these IRD increases cover a wide geographical distribution with the varied lithologies reflecting multiple sources. Thus, the total influx of IRD provides another indication that glacial activity occurs in different source areas simultaneously. Comparison of these IRD peaks with the oxygen isotope signal recorded in Greenland (23) showed a similar rhythm in both (24), but its phasing is difficult to extract. Spectral analysis of this IRD signal from both the Ice Age and the Holocene shows an IRD maximum every 1,470 ± 500 years (21).

A similar rhythm occurs in the Sierra Nevada (25). At Owens Lake, downstream from alpine glaciers, the total organic carbon varies according to the dilution of aquatic organic production by glacial melt water silts and varies inversely with magnetic susceptibility. Variations in carbon content track some 11 glacial cycles from 52,500 to 23,500 14C yr BP that correspond with the number of peaks in the IRD fluxes in the North Atlantic. Glaciers with a wide geographical coverage dance to this rhythm. That a cyclic pattern continues through both the Ice Age and the...
present under very different boundary conditions suggests that external forcing must be involved in abrupt climate changes.

Rapid Responses—Questions and Answers.

Changing glaciers interact with the climate system in ways not completely understood. For example, icebergs discharged at times when the ocean surface was cool (22). Does this relationship occur, (i) because the cooler oceans allowed the icebergs to carry material further from the source; (ii) because the cooler oceans allowed the expansion of marine margins and hence increased iceberg fluxes; or (iii) because the high volume of iceberg flux cooled the oceans?

Likewise, a remaining question is the role of the massive Laurentide Ice Sheet covering North America in abrupt climate changes. Once suggested as a fresh water source to induce ocean circulation changes, the synchronous IRD fluxes derived from this ice sheet and others around the North Atlantic basin remove it as a single trigger. In fact, several expansions of the land portions of the ice sheet seem to lag (Fig. 3) expansions elsewhere.

Glacial records do show that the global equilibrium line altitude drop during abrupt climate changes is about the same magnitude at widely scattered locations. Such distribution implies an overall cooling of the atmosphere, not simply a regional redistribution of the heat balance. With such a viewpoint, exploration of more detailed phasing questions such as those listed above will contribute to an explanation for the causes of abrupt climate changes.