Perspective

Sensitivity and rapidity of vegetational response to abrupt climate change

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Rapid climate change characterizes numerous terrestrial sediment records during and since the last glaciation. Vegetational response is best expressed in terrestrial records near ecotones, where sensitivity to climate change is greatest, and response times are as short as decades.

The last two decades of scientific research have seen a pronounced increase in studies of abrupt climate change. Understanding past "flips" in climate becomes a priority as we examine reasons for climate change and the interrelationship of the biosphere with the atmosphere-ocean-cryosphere. The realization that modern climate appears to be changing at a rapid rate has challenged scientists to look at past records of abrupt climate change. How rapidly can vegetation respond to climate shifts? What magnitude of vegetational change has been seen in the past? How widespread were these changes and how do they compare with shifts in the polar ice cores and the ocean? A selection of vegetational records that reveal rapid shifts during the last deglaciation, the glaciation itself (marine isotope stage 3), and the Holocene are examined here. The most sensitive histories are from sites near an ecotone, a transition zone between vegetational communities.

Deglacial Pattern of Abrupt Climate Change. This paper focuses on terrestrial (sediment) records of abrupt vegetational change, which actually represent the earliest detected evidence of rapid climate shifts. European macrofossil investigations in Scandinavia about the turn of the last century identified a series of late-glacial climatic oscillations named the Bölling (warming), Alleröd (warming), Older Dryas (cooling), and Younger Dryas (YD) (cooling). This same pattern of abrupt shifts in climate is seen in great detail in the Greenland oxygen isotope pattern (1). Some recent papers highlighting the pattern of abrupt late-glacial climatic shifts in sediment records as similar to this Greenland pattern include the European pollen, beetle, and isotopic lake records (2), midge (chironomid) larvae response to lake water temperatures estimates in maritime Canada (3), shifts in stable isotopes in central North America (4), antiphasing between rainfall in North America's Great Basin and Africa's Rift Valley (5), and patterns of vegetation response in the central Appalachians (6). These terrestrial patterns of shifts parallel marine records from the North Atlantic (7) and the tropical Atlantic (8).

The "Bölling" Abrupt Warming Shift. The first of the most pronounced events in the deglaciation sequence is the "Bolling" warming, which occurs ≈12,700 ^{14}C yr before present (15,000 calendar yr before present). This major "step" appears in many pollen records from ≈41°N to 29°N along the North Atlantic seaboard (6), as increases in temperate forest (oak, hickory, beech, ash, hornbeam) pollen abruptly rise from sites in New York and Connecticut and throughout the southeastern U.S. to as far south as Florida (9). This North American temperature increase appears to parallel the European rise in many of the same genera, as far south as Monticchio, Italy (10). Evidence of even earlier deglacial warming on both continents is apparent when one considers the retreat of the Laurentide and Scandinavian ice sheets and montane glaciers in order for the lakes and bogs that record the Bolling event to be ice-free.

The Younger Dryas Cold Snap. The YD is the best documented example of an abrupt climate change, primarily because of its millennial duration and its extensive geographic coverage. The Younger Dryas was first discovered around the turn of this century in an examination of plant macrofossils in a stratigraphic section in Denmark. The tiny leaves of *Dryas octopetala* (Rosaceae family) were found above remains of shrubs and trees that indicate the climate was warming after the ice age (11). This return to *Dryas*, which is an arctic–alpine tundra indicator, indicated that the vegetation was responding to a dramatic cooling. By the 1940s, as the science of palynology (the study of pollen and spores) was established, many investigated sites all over Europe showed signs of this pollen change from shrub/tree to tundra and back again. Evidence for glacial advances during the cold snap were mapped in Scandinavia and even in Scotland, where glaciers actually reformed. By the early 1980s, the Younger Dryas was considered a significant event that took place 11,000–10,000 ^{14}C years ago throughout Europe (12). When looking for the event elsewhere in the world, this ^{14}C time interval is considered a radiocarbon "chronozone." Complications to these correlations occurred with the recent discovery of differences in the radiocarbon time scale and the calendar time scale. Several radiocarbon "plateaus" exists in the interval, and thus the YD interval actually spans more than 1,500 calendar years. Thus, in calendar years, it is considered to be between ≈13,000 and 11,600 years ago (1).

The estimates of the magnitude of the YD cooling range from 10°C in northern Europe to 2°C in southern Europe. By the end of the 1980s, paleoclimate research in Greenland ice cores also showed this as a major climatic cooling event of from 7 to 15°C, and the subsequent warming at its close took place in Greenland in a decade or less (1).

North American YD Evidence. The first strong evidence for the YD in North America came from Atlantic Canada in the 1980s, when stratigraphic sections and lake records showed shifts in lithology, pollen, and macrofossils, suggesting a summer temperature decline of at least 5°C (13, 14). In some cases, chironomids

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suggest an air temperature decrease of as large as 6–20°C (3), implying a dramatic temperature decline and large sensitivity of midge larvae to water temperature change. The return to warmer conditions was quite rapid at most sites. At the same time, pollen, macrofossil, and accelerator mass spectrometry (AMS) ^{14}C ages from southern New England documented the occurrence of a YD average July cooling of 3–4°C and, at its close (the Holocene boundary), a shift back to warm conditions within ≈50–75 years (15, 16). This estimate of a response time of the vegetation to the Holocene warming is taken from the 5-cm interval of a high sedimentation rate Linsley Pond, CT core section that represents 50 years of the entire YD core span of 1 meter. The boreal spruce, fir, larch, paper birch, and alder trees, which had increased during the YD, were suddenly replaced by oak and white pine. Similar pollen and macrofossil stratigraphy has been AMS-dated in two additional sites in southeastern New York (17, 18). Oxygen isotopes in diatoms suggest the YD temperature shift was as large as 6°C (19). Thus, different paleoindicators give a YD temperature decline in eastern North America ranging from 3 to 20°C.

To the south, in the central Appalachians, an interesting pattern of vegetational change occurs during the late-glacial and early Holocene. In Virginia, the YD is apparently marked by slightly warmer, wetter climate as hemlock dominates at Browns Pond (6). This pattern of climate change can be consistent with a cold reversal in the northern North Atlantic region if one considers the steep temperature gradient that may have occurred between cold subpolar waters and the adjacent warmer subtropical waters close to the latitude of Virginia. This steep temperature gradient would favor storm track frequency and consequently might be responsible for this vegetational response of a wetter climate. The only other published southeastern U.S. record that may record a YD appears to be Jackson Pond, KY, which shows a slight cooling with the recurrence of spruce (20). More sites with detailed AMS chronology are needed to firmly establish the late-glacial timing and magnitude of climatic oscillation.

Sites in the midwestern U.S. show a YD oscillation, primarily through an increase in spruce in some sites, and the suggested cooling is ≈1–2°C in summer (21). Oxygen isotope shifts from the Great Lakes region match the Greenland ice core and some European lake records, suggesting the Bölling, Alleröd, and YD climate changes, although the records are not well dated (4). However, the vegetational response is very minimal, probably because of the lack of ecotones, and the lack of good chronology prevents estimates of response times.

On the western coast of North America, evidence for a YD cooling is found in many coastal records (22, 23). On Kodiak Island, AK, several AMS-dated sites record a regional cooling correlative with the YD, and the striking lithology shows a pronounced warming at the Pleistocene–Holocene boundary. The pollen and macrofossil record reveals a YD increase in crowberry (Empetrum), which indicates cooling, followed by the dominance of ferns in the Holocene, indicative of warmth and moisture (24). The magnitude of the temperature response is difficult to estimate, but the response appears quite rapid. Supporting evidence from the Bristol Bay region also suggests a cooler, drier YD (25). The possibility of North Pacific circulation changes associated with the Younger Dryas (i.e., Santa Barbara Basin, Sea of Japan, Gulf of California) greatly enlarges the geographic pattern of ocean circulation change and calls into question the role of this major ocean in the climate forcing for this event (26).

Global Distribution of YD? Peteet (27) summarized the possibility of scattered late-glacial palynological evidence for the YD around the globe and concludes that, at this point, there is not enough evidence to indicate that the YD is an obvious global event as defined by vegetational change. Although the evidence for the northern hemisphere is very convincing, tropical and southern hemisphere data is more controversial, primarily because the data must support a regional vegetational and climatic change with robust AMS chronology. Until a clear regional response from more than one site is well dated, the question remains an open one, and an estimate of timing and magnitude of the vegetation response to climate is difficult. Areas such as southern South America are especially critical for our understanding of the leads and lags and responses of northern and southern hemispheres.

Marine Stage 3 Rapid Climate Shifts. The high-resolution Greenland ice cores indicate that the Younger Dryas is just one of many pronounced and rapid climate changes that have occurred in the last 50,000 years. Major changes during these earlier times such as dust flux increase and snowfall declines in Greenland as well as methane declines during the coolings demonstrate the variety of atmospheric effects that took place. Longer terrestrial records such as those from Florida (28), coastal Washington (29), and Chile (30) demonstrate that rapid shifts have taken place before and during the last glaciation, and that the magnitudes of some of these events are as large as 6°C. Better resolution and dating is needed to tie them to the marine and ice core records.

The Holocene 8,200-Year Cold Event. A cooling event during the Holocene, ≈8,200 calendar years ago (7,500 ^{14}C) is recorded in Greenland ice cores (31) and is apparent in European sediment records (32, 33). A recurrence of spruce and the decline of thermophilous species in a pollen record from Browns Pond, VA records this event along the Atlantic seaboard (6), and oxygen isotope shifts are seen in Minnesota between 8.9 and 8.3 calendar years, before this event (34). Further detailed investigations are needed to document the Holocene abrupt changes both in North America and Europe, and elsewhere around the globe.

Sensitivity to Rapid Climate Change. The best examples of abrupt climate change recorded by vegetational records suggest that, where a sharp ecotone exists, the pollen/macrofossil records provide a sensitive and rapid response to a climate change. This is true of records in southern New England and the southern Appalachians, where a mixture of boreal and deciduous species during the late-glacial provided the mixture of species for immediate response to a temperature change—either a rapid decrease (YD, 8,200-yr event) or a rapid warming (Holocene change) that occurred within a century (6, 15–18). This rapid response to the Holocene warming is also seen in coastal Alaska, where cold, windswept tundra is rapidly replaced by tundra species that favor moisture and warmth (24). In these cases, there is very little migrational lag because all of the response species are already in the region, unlike the midwestern U.S. These sensitive vegetational records then parallel the response to climate from the isotopic records—either from ice cores, lake carbonate records, or diatoms. They also parallel the records from animal responses: i.e., midge larvae or beetles. However, the estimates of the magnitudes of the temperature shifts seem to vary widely among biological indicators. Thus, multiproxy, high-resolution studies in sensitive ecotones are essential for a better understanding of abrupt events.

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