Does the Trigger for Abrupt Climate Change Reside in the Ocean or in the Atmosphere?

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Two hypotheses have been put forward to explain the large and abrupt climate changes that punctuated glacial time. One attributes such changes to reorganizations of the ocean’s thermohaline circulation and the other to changes in tropical atmosphere-ocean dynamics. In an attempt to distinguish between these hypotheses, two lines of evidence are examined. The first involves the timing of the freshwater injections to the northern Atlantic that have been suggested as triggers for the global impacts associated with the Younger Dryas and Heinrich events. The second has to do with evidence for precursory events associated with the Heinrich ice-rafted debris layers in the northern Atlantic and with the abrupt Dansgaard-Oeschger warmings recorded in the Santa Barbara Basin.

The abrupt changes that are of interest fall into two main categories, those associated with Dansgaard-Oeschger (DO) events and those associated with Heinrich (H) events. The former are jumps between a state of intense cold and a state of intermediate cold that dominate portions of the Greenland ice-core 18O record. In addition to local air-temperature changes, the ice cores record abrupt changes in the infall of dust and sea salt (2) and in the content of methane in the atmosphere (3). The climate system remains trapped in a given state for many centuries. H events (4) show up in the northern Atlantic Ocean as sedimentary layers dominated by ice-rafted debris spaced at roughly 7000-year intervals during the last glacial period. They have been shown to result from the melting of armadas of ice launched from eastern North America. Although not prominently recorded in the Greenland ice record, impacts associated with H events are seen in records from distant places, including the tropics (5).

In a category all its own is the Younger Dryas (YD), a millennium-long cold snap that punctuated Termination I (i.e., the transition from the last glacial period to the Holocene). Although in many ways similar to the DO events, the YD is of particular interest because the global pattern of its impacts is by far the best documented, and also because it appears to have been triggered by a catastrophic release of fresh water to the northern Atlantic (6). Because there is no evidence that a similar millennium-long cold episode punctuated earlier glacial terminations, the YD appears to be a one-time event made possible by a quirk in the relation between the glacially excavated topography and the position of the retreating ice front. The Antarctic ice-core methane record is particularly relevant in this regard, because there is no repeat of the prominent YD methane drop associated with the three earlier terminations (7).

The Younger Dryas

The prevailing view of this cold snap is that it was triggered by a catastrophic release of fresh water stored in proglacial Lake Agassiz (6). This release was initiated when the retreat of the Laurentide ice sheet opened a lower outlet, allowing much of the lake’s stored water to flood across the region now occupied by the northern Great Lakes into the St. Lawrence valley and from there into the northern Atlantic (Fig. 1). On the basis of reconstructions of the pre- and post-diversion shorelines of Lake Agassiz, it has been estimated that ~9500 km³ of water was released (6). If released over the course of a single year, this flood would match today’s net annual input of fresh water to the Atlantic Ocean region north of 45°N. In most ocean models, an input of this magnitude cripples the conveyor of deep water in the northern Atlantic (i.e., it greatly weakens or even shuts down the model’s conveyor circulation).

In support of such a shutdown is evidence for a dramatic rise in surface-ocean 14C to 12C ratio. As documented by radiocarbon measurements on planktonic foraminifera from calendar-dated annual layers in a core from the Cariaco Basin, immediately after the onset of the YD (marked by a sharp change in the color of the sediment), the 14C to 12C ratio in the local surface water began to rise (8). This rise continued for about 200 years and reached a ratio ~5% higher than that before the YD’s onset. Such a rise is consistent with a shutdown of deepwater production in the
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northern Atlantic, because currently this pathway supplies ~75% of the radiocarbon atoms needed to balance radiocactivity in the entire deep sea (9). On the basis of the 10Be record in Greenland ice, a claim has been made that at least part of the 14C increase was the result of an increase in the production of 14C rather than a shutdown of deepwater formation (10). The evidence for this is inconclusive, and Hughes’s conclusion that the 14C rise was primarily the result of a shutdown of the conveyor seems more likely to be correct.

Except for the Antarctic continent, everywhere on the globe where an adequate record has been obtained, conditions during the YD appear to have been more glacial-like than those characterizing the preceding Bolling-Allerød warm period. Summarized in Fig. 2 are sites where the YD has been documented and its onset adequately radiocarbon dated. In Antarctic ice cores, a marked departure is seen (11–13). In seven out of eight of these records, the YD is a time of pronounced warming. Those who favor the ocean-based scenario call on an alternative in the relative strengths of deepwater formation in the northern Atlantic and in the Southern Ocean as the cause for Antarctica’s anomalous behavior. However, it must be stated that the record in the Taylor Dome core located near the margin of the Antarctic cap more closely resembles those from Greenland (14). The importance of this curious departure remains to be understood.

A test of the flood hypothesis is to make use of radiocarbon dating to determine when the release of Agassiz water occurred at the time of the YD onset. However, a complication must be taken into account: the radiocarbon clock is imperfect. For a period of about 200 years before 11,100 14C years ago, the clock stalled (because of a decline in the atmosphere’s 14C to 12C ratio) and subsequently to this time, for a period of 200 or so years, the 14C clock ran three times too fast (because of a rise in the atmosphere’s 14C to 12C ratio). This anomalous behavior complicates a novel approach by Hajdas et al. (15) to precisely date the onset of the YD. This approach takes advantage of the late Allerød Laacher See tephra, which is found in Swiss and German lake sediments. Counting annual layers in these sediments shows the interval between the tephra layer and onset of the YD to be about 200 years. On the basis of 12 terrestrial plant macrofossil 14C ages derived from above and below the tephra in sediments from Soppensee, Holzmaar, and Schalkenmehrner Maar, these authors inter-

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could be as large as 500 years. Hence, this seemingly clever way to establish the 14C age of the onset of the YD turns out to be fraught with uncertainty. A better strategy is based on 14C ages for both late Allerød and early YD sediments in the same sediment sections. An age of 10,900 ± 65 14C years on a sample from 300 calendar years above the tephra layer suggests that the eruption occurred toward the beginning of the plateau and, hence, that the 14C age of the YD onset must be close to 11,000 years (15).

With one exception, the radiocarbon ages for the onset of climatic impacts associated with the YD at widely separated places on Earth cluster around 11,000 years. The exception is dates on wood from the Waiho Loop moraine on New Zealand’s South Island (17). As shown in Fig. 3, these ages range from 10,650 to 11,520 years. Twenty-seven out of 37 ages are greater than 11,000 years (i.e., they predate the onset of the YD). Perhaps most of this wood formed during the Allerød time and was preserved in avalanche deposits formed during that time and subsequently exhumed by the advancing YD ice. However, these results could equally well be taken to indicate that the glacia-

tion in New Zealand began as much as 500 years earlier than the onset of the YD in the Northern Hemisphere. Resolution of this question is of utmost importance, because hanging in

the balance is the documentation of interhemispheric synchrony.

One approach to resolving this question is the comparison of ages based on the in situ production of 10Be in quartz from superficially exposed erratic boulders present in moraines in the Swiss Alps and in the New Zealand Alps. Although questions remain regarding the exact dependence of 10Be production on latitude and elevation, because these locales are nearly equidistant from the equator and at nearly the same elevation, the age differences are not dependent on the exact calibration. 10Be measurements obtained for the Swiss Alps and for the New Zealand Alps show no notable differences (18). However, the uncertainty in this age difference (~500 years) is still too large to allow the YD cooling to be declared synchronous between the hemispheres. The mean of the nine 10Be ages on

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Wind River range (Wyoming, United States) boulders (19) is consistent with those from the Swiss Alps.

The age of the Agassiz flood is based on radiocarbon measurements on three wood samples from the beaches of the lake’s Moorhead low-water phase formed after its outburst into the Great Lakes and the North Atlantic. The ages are 10,960, 10,820 and 10,810 years (20–22). These ages set a minimum for the flood. An independent estimate comes from the age of 11,110 years on mixed planktonic shells in Gulf of Mexico sediment cores marking the onset of the interval indicating the shutdown of the flow of low 18O Agassiz water into the Mississippi drainage (21). To the measurement uncertainty of 130 years on this shell sample must be added the uncertainty associated with the assumed 400-year reservoir correction to the marine shell date. Thus, although the documentation remains somewhat thin, the 14C age of the flood is consistent with the hypothesis that it triggered the YD.

The most definitive chronological information comes from Greenland’s ice. Here, no need for radiometric dating exists. The time differences of interest can be obtained by directly counting annual layers in the ice. The large increase in dust content at the YD onset (2) coincides exactly within the time of Greenland’s 18O-based cooling and drop in snow accumulation rate (23). Because the dust has been shown to come from the Asian deserts (24), this suggests that the increase in the frequency of intense windstorms occurred there at the same time as the cooling in Greenland. The concentration of NaCl in the ice underwent a similar increase (2). Thus, it appears that storminess over the ocean also increased at this time. Of course, both of these changes could be attributed to washout efficiency rather than source strength. Of even greater interest is the observation that the drop in atmospheric methane content as measured in the gas trapped in the ice occurred within decades of the time of the Greenland cooling that heralded the onset of the YD. The uncertainty resulting from the ~70-m initial offset between the ice record and the trapped-gas record was eliminated by measuring the 15N to 14N ratio in N2 (25). During the abrupt air temperature rise, an enrichment of 15N due to thermal diffusion in the firm is seen (25–27). The onset of the associated methane rise lags the warming by no more than a few decades (26). Severinghaus and Brook (26) have found a corresponding thermal diffusion–induced decrease in 15N resulting from the cooling at the onset of the YD. This methane drop (3, 28) is thought to be largely the result of a decrease in the extent of tropical wetlands (29). Hence, a case can be made that the tropical climate change accompanying the onset of the YD was nearly synchronous with that at the high northern latitudes. Because the Greenland ice-core record cannot be directly radiocarbon dated, a small leap of faith is required to postulate that the abrupt YD onsets at other sites on the planet were coincident with that in Greenland. Indeed, the Greenland ice-core dust and methane records lend support to this assertion.

There is another way to assess the timing of these changes. On the basis of the methane records (28), events in Antarctica can be closely tied to those in Greenland. This tie tells us that the pause in Antarctic warming and the pause in the atmospheric CO2 rise (30) that characterize the Bölling-Allerød time interval came to an end very close to the onset of the YD. The warming and CO2 rise then continued throughout the course of the YD. Thus, although the YD temperature change in Antarctica was in the opposite sense as that in Greenland, it began at very nearly the same time.

In summary, it can be said that, with the exception of that for New Zealand, the chronological evidence is consistent with a sudden global onset of the YD impacts at about 11,000 14C years B.P. Further, the radiocarbon age of the release of 9500 km3 of water stored in Lake Agassiz is indistinguishable from that for the YD onset. If advocates of a tropical trigger discount the role of the Agassiz flood as the trigger for the YD, then they must attribute this apparent synchronicity either to coincidence or to a climate change initiated elsewhere as the cause of the flood.

Heinrich Events

Six layers dominated by ice-rafted debris have been identified in a series of cores extending from the Hudson Straits across the northern Atlantic to the coast of France (4). This material has been shown to have been released during the melting of armadas of ice launched from eastern Canada. Although the hypothesis that these armadas resulted from gigantic surges of the Hudson Bay lobe of the Laurentide ice sheet (31, 32) is widely accepted, alternate hypotheses involving Jökulhlaups (33) and shattered ice shelves have been proposed. Regardless of their mode of origin, it is clear from the associated reduction in planktonic 18O accompanying each event that the melting of these ice armadas reduced the salinity of northern Atlantic surface waters by a large enough amount to impact conveyor circulation. Indeed, as for the YD, far-field climatic impacts roughly matching the times of each H event have been documented (34). Far-field impacts include times of the greatest glacial cooling in the Mediterranean Sea (35) and in the Atlantic Ocean off the Iberian Margin (36), sediment-discharge events off eastern Brazil (37), pine events in central Florida (38), and sharp weakenings of the monsoons in the Chinese Hulu Cave record (39). Thus, it is tempting to conclude that these impacts were triggered by disruptions of thermohaline circulation caused by freshwater inputs to the northern Atlantic.

Precursory Events

Perhaps the most important means of distinguishing between the oceanic and tropical hypotheses is through a search for and study of precursory events. The first demonstration of the existence of such events was the discovery of the presence of pulses of volcanic glass and hematite-stained mineral grains just
before the onsets of the deposition of each of the Heinrich layers (40). Because both lithic types originate far to the north of the core sites, a cold ocean favors their delivery by ice rafting. Further, the relative abundance of cold-loving *Neogloboquadrina pachyderma* (left coiling) reached a maximum during these precursory events (41). The existence of such events must certainly be troubling to those who view the Heinrich’s ice armadas as stochastic events whose onset is dictated by conditions at the base of the Hudson Bay lobe of the Laurentide ice sheet (i.e., isolated from the overlying climate). However, even if the armadas were somehow triggered by a cooling, one could still contend that the far-field climate impacts were the result of a shutdown in conveyor circulation induced by the freshwater input rather than by the precursory cooling event itself.

Evidence for precursory events associated with the DO events as recorded in Santa Barbara Basin sediment has been recently discovered (41). If the abrupt warmings found at the base of each of the anaerobic layers (recorded by sharp decreases in planktonic $^{18}O$) are correlated with the DO warmings in the Greenland record, then one could look for precursory events in the bioturbated sediment immediately underlying each of these sudden warmings. For two of the warmings, there is clear evidence (based on $^{18}O$ measurements in benthic foraminifera) for a precursory warming of the deep-basin water (41). This warming is attributed to a strengthening of the contribution of thermocline water moving northward from the tropics. Clearly, if proven correct, this hypothesis will be music to the ears of the advocates of a tropical trigger.

Conclusions

Although model-based simulations provide useful clues to what might lie behind these abrupt climate changes, they do not provide compelling proof that any given hypothesis is the correct one. Such proof, if it is to be obtained, must come from the record created by these events. The key to success will be the determination as to whether the far-field climate changes predate the changes attributed to ocean reorganizations. Ideally, this evidence would come from precise dating of the times of onset of the far-field impacts. But, because of the abrupt nature of these transitions, this quest may be doomed, for if the changes happened at very nearly the same time everywhere, it will not be possible to obtain a definitive answer. Hence, a more promising approach may be the search for and study of precursory events.

So where do we stand? First, the evidence that reorganizations of the ocean’s thermohaline circulation accompanied the YD and H events appears to be very strong. Although these ocean reorganizations could well be consequences of climate changes initiated elsewhere, there are good reasons to believe that they constitute the primary trigger. Somehow these oceanic changes must have perturbed tropical dynamics which, in turn, drove the global atmospheric changes. Missing, of course, is the link necessary to meet the requirement that the message was transmitted from the deep ocean to the tropical atmosphere on the time scale of a few decades.

In any case, we are still a long way from understanding how our climate system accomplished the large and abrupt changes so richly recorded in ice and sediment. However, despite this ignorance, it is clear that Earth’s climate system has proven itself to be an angry beast. When nudged, it is capable of a violent response.

References and Notes


49. Although conversations with many people have influenced my thinking, those with J. Teller, G. Denton, B. Kromer, J. Severinghaus, S. Rahmstorf, S. Hemming, and G. Bond stand out in my mind. Further, the ongoing biannual meetings of the National Oceanic and Atmospheric Administration (NOAA)-sponsored Changeling Group have broadened my perspective and, in particular, have made me think more seriously about the tropical scenario. This research was supported by a grant from NOAA’s Global Change Program (NA17RJ1231, UC5O.P.0609607-003). The views expressed herein are those of the author and do not necessarily reflect the views of NOAA or any of its subagencies. This is Lamont-Doherty Earth Observatory contribution number 6461.