Abstract

Taken together, evidence from east Greenland’s mountain moraines and results from atmospheric models appear to provide the answer to a question which has long dogged abrupt climate change research: namely, how were impacts of the Younger Dryas (YD), Dansgaard–Oeschger (D–O) and Heinrich (H) events transmitted so quickly and efficiently throughout the northern hemisphere and tropics? The answer appears to lie in extensive winter sea ice formation which created Siberian-like conditions in the regions surrounding the northern Atlantic. Not only would this account for the ultra cold conditions in the north, but, as suggested by models, it would have pushed the tropical rain belt southward and weakened the monsoons. The requisite abrupt changes in the extent of sea ice cover are of course best explained by the turning on and turning off of the Atlantic’s conveyor circulation.

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1. Introduction

During the past couple of years one of the key mysteries surrounding the abrupt changes in climate which punctuated glacial time appears to have been solved. The mystery has to do with the teleconnection which allowed the impacts of these events to be so quickly propagated throughout the northern hemisphere and the tropics. The breakthrough came about as the result of the combination of a field study and a model simulation.

2. The Younger Dryas

The field study was conducted in the mountainous region surrounding Greenland’s Scoresby Sound. The participants (Denton, Alley, Comer) focused their attention on a set of moraines first studied by Funder (1989). Pending additional radiometric dating, Denton et al. (2005) accepts Funder’s conclusion that these moraines are Younger Dryas (YD) in age. Based on the highest elevation of lateral moraines, the Denton team was able to estimate the extent of the associated snowline lowering and hence the magnitude of the YD cooling. At first they were puzzled by how small (4° to 6 °C) it was. It was clearly at odds with the 16 °C YD cooling obtained by Severinghaus et al. (1998) based on isotopic measurements on N₂ and Ar in air bubbles trapped ice from the Greenland’s Summit station. But Denton et al. (2005) soon realized that while the Severinghaus et al. estimate yielded the mean annual temperature, theirs reflected primarily summer conditions. During YD time ablation of mountain glaciers must have been confined to the warmest months. Further, as suggested by the oxygen isotopic record preserved in the Summit ice, little snow fell during YD winters. Assuming that the 4 to 6 °C cooling reflected summer conditions, Denton et al. (2005) concluded that
Fig. 1. Measurements by Jeff Severinghaus of the isotopic composition of the nitrogen and argon trapped in Summit Greenland ice provide a firm estimate that the mean annual air temperature was 16 °C colder than today’s during the Younger Dryas. In contrast, the lowering of the snowlines in the mountains surrounding Scoresby Sund suggests only about a 4 °C cooling. The explanation for this large difference appears to be that winters during the Younger Dryas were so cold that little snow fell in the mountains of eastern Greenland. Therefore the snowline lowering records only summer conditions. Together, this 4 °C summer cooling and a hypothesized 28 °C winter cooling would yield the mean annual cooling documented by Severinghaus. The red dots represent the location of the Summit cores and of Scoresby Sund. The ultra cold winter conditions require a climate akin to that in Siberia. This could only have been possible if the northern Atlantic was totally ice bound during winter months. During glacial time, a shutdown of the Atlantic’s conveyor circulation would have starved the northern Atlantic of ocean-borne heat and permitted sea ice to form. In the presence of sea ice, no heat could escape from the ocean to the atmosphere. Not shown on the Younger Dryas map are either the glacial ice which covered much of Canada and Scandinavia, or the expansion of sea ice in the northern Pacific. The purpose of this omission is to focus the readers’ attention on the northern Atlantic. The map showing the boundaries of Arctic sea ice at the end of the winter of 2004 was provided by Gunnar Spreen (Kaleschke et al., 2001).
the YD winters must have been 26 to 28 °C colder than today (see Fig. 1). In this way, taken together with the moraine-based summer cooling, the Severinghaus et al. 16 °C mean-annual cooling could be explained. Based on a review of the literature, Denton showed that while pollen, beetle and snowline evidence suggested a 4 to 6 °C YD summer cooling in northern Europe, periglacial features (such as ice polygons) suggested ultra cold winter conditions. Hence, the idea that the YD winter cooling must have been far greater than that in the summer is not new.

There is only one way that winters in Greenland and northern Europe could have gotten so cold during the Younger Dryas, namely sea ice must have covered the entire Norwegian Sea extending perhaps to the southern end of the British Isles (Fig. 1). This ice cover would have choked off any heat release from the underlying ocean and created winter conditions akin to those in today’s Siberia.

This scenario fits well with the idea that the Younger Dryas was triggered by the catastrophic release to the northern Atlantic of meltwater stored in proglacial Lake Agassiz (Kennett and Shackleton, 1975; Broecker et al., 1989). The resulting dilution of the salt content of the surface waters in the northern Atlantic would bring to a halt deep water formation (Rooth, 1982). The combination of a low-salinity cap and a large reduction in the delivery of ocean heat allowed sea ice to form.

The other half of this breakthrough comes from an atmospheric modeling study conducted by Chiang et al. (2003) who showed that, if sea ice was introduced into the northern Atlantic, the model’s tropical rain belt was shifted southward. This nicely explains the records in the Atlantic sector of the tropics (Chiang and Koutavas, 2004). Modeling studies by Barnett et al. (1988) suggest that more extensive and longer lasting snow cover in Eurasia would weaken the monsoons. This would nicely explain the results from the Arabian Sea sediments (Schulz et al., 1998; Altabet et al., 2002) and from Chinese stalagmites (Wang et al., 2001).

Not only do these modeling studies suggest a means of exporting a signal from the northern Atlantic to the tropics, but they account for the prompt response to that signal. Once the delivery of conveyor heat was shut down by the meltwater flood, the northern Atlantic could freeze over during the following winter.

3. Heinrich events

As was the case for the Younger Dryas, the sudden injection of meltwater to the northern Atlantic appears to have produced a shutdown of the conveyor circulation after each Heinrich event (Hemming, 2004). The difference is that, in the case of the Heinrich events, the fresh water was generated in place by the melting of armadas of icebergs launched into the northern Atlantic from eastern Canada.

The Chiang et al. (2003) suggestion that freeze-overs of the northern Atlantic push the tropical rain belt to the south clarifies something that has puzzled me: namely, how to account for the difference between the distribution of Heinrich (H) impacts on one hand and Dansgaard–Oeschger (D–O) impacts on the other. Records in eastern Brazil and central Florida record only H impacts. By contrast, the records in Greenland ice and that in Cariaco Basin sediment are dominated by D–O impacts. Falling in between are records from the Arabian Sea, western Mediterranean sediments and Chinese stalagmites in which both sets of impacts appear, with those associated with the H events being stronger than those associated with the D–O events (see Table 1).

<table>
<thead>
<tr>
<th>Map No.</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Medium</th>
<th>Proxy</th>
<th>Driver</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Summit, Greenland</td>
<td>71° N</td>
<td>40° W</td>
<td>Ice</td>
<td>18O</td>
<td>Ice</td>
<td>Temperature</td>
</tr>
<tr>
<td>2</td>
<td>Santa Barbara basin</td>
<td>34° N</td>
<td>120° W</td>
<td>Sediment</td>
<td>18O</td>
<td>Forams</td>
<td>Temperature</td>
</tr>
<tr>
<td>3</td>
<td>Alboran Sea, W. Med.</td>
<td>36° N</td>
<td>3° W</td>
<td>Sediment</td>
<td>Alkenones</td>
<td>Temperature</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Lake Tulane, Florida</td>
<td>28° N</td>
<td>82° W</td>
<td>Sediment</td>
<td>Pollen</td>
<td>Rain</td>
<td>Grimm et al. (1993)</td>
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<tr>
<td>5</td>
<td>Cariaco basin</td>
<td>11° N</td>
<td>65° W</td>
<td>Sediment</td>
<td>Color</td>
<td>Rain</td>
<td>Peterson et al. (2000)</td>
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<td>6</td>
<td>Brazil margin</td>
<td>4° S</td>
<td>38° W</td>
<td>Sediment</td>
<td>Fe/Ca</td>
<td>Rain</td>
<td>Arz et al. (1998)</td>
</tr>
<tr>
<td>7</td>
<td>S.E. Brazil Cave</td>
<td>10° S</td>
<td>40° W</td>
<td>Calcrete</td>
<td>18O</td>
<td>Rain</td>
<td>Wang et al. (2004)</td>
</tr>
<tr>
<td>8</td>
<td>Arabian Sea</td>
<td>18° N</td>
<td>58° E</td>
<td>Sediment</td>
<td>15N</td>
<td>Monsoon</td>
<td>Altabet et al. (2002)</td>
</tr>
<tr>
<td>10</td>
<td>Hulu Cave, China</td>
<td>32° N</td>
<td>119° E</td>
<td>Calcrete</td>
<td>18O</td>
<td>Monsoon</td>
<td>Wang et al. (2001)</td>
</tr>
<tr>
<td>12</td>
<td>Off Chile</td>
<td>42° S</td>
<td>76° E</td>
<td>Sediment</td>
<td>18O</td>
<td>Temperature</td>
<td>Ninnemann, pers. comm.</td>
</tr>
</tbody>
</table>
This geographic pattern might be explained if it is assumed that the sea ice expansion associated with the H events exceeded that associated with the cold phases of D–O events (see Fig. 2). If so, the observation that H coolings in the western Mediterranean were larger than those associated with the D–O events could be explained: more sea ice — greater cooling. Further, more sea ice following H events would mean a larger southward push of the tropical rain belt producing H-associated wet events in currently dry eastern Brazil (see Fig. 3). The shifts associated with D–O events, while too small to impact the cave site in Brazil, were large enough to impact the Caribbean’s Cariaco Basin. In records from China and from the Arabian Sea, both H and D–O events are recorded. However, the impacts associated with H events are larger. This could be explained by the greater magnitude of the northern cooling and hence larger snow extent in Asia associated with H events.

This geographic model is also consistent with the muted response in the south temperate region (i.e., that part of the globe beyond the reach of the tropic rain belt). The main impacts in the south appear to be offset from those in the north perhaps as the result of a seesawing in the relative strength of deep water formation in the Southern Ocean relative to that in the northern Atlantic (Broecker, 1998; Stocker, 1998). Ule Ninneman of the University of Bergen has results (as yet unpublished) which clearly demonstrate that off Chile (~42°S) the

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Fig. 2. Shown here are the locales of selected paleoclimate records. Those records indicated by circles are dominated by Dansgaard–Oeschger (D–O) events; those by triangles by Heinrich (H) events. In those indicated by squares, both are present but the H events stand out as more extreme than the D–O events. The diamonds show sites in the southern hemisphere which appear to follow the deglacial pattern recorded in Antarctic ice rather than that recorded in Greenland ice. In the locales designated by filled symbols, the record appears to be dominated by temperature changes while at those designated by open symbols, rainfall changes appear to dominate. Details are given in Table 1.

Fig. 3. Map showing the locations of the Cariaco Basin and of Wang et al.’s (2004) eastern Brazil’s stalagmite record. Also shown by the dotted line are the present-day positions of the ITCZ’s northern limit (September) and its southern limit (March). As can be seen, even small southward excursions of these boundaries would leave the Cariaco Basin and the adjacent land in Venezuela outside the rain belt. By contrast, as the stalagmite locale lies to the southeast of the southern limit of today’s ITCZ, a modest southward shift is required to bring rainfall to the area of these caves. As shown by Wang et al. (2004), this happens for brief periods at the time of Heinrich events #1 and #4.
temperature during the last deglaciation in both surface waters and in waters at intermediate depth follows the pattern seen in Antarctic ice cores. Also, it now appears that the Waiho Loop glacial advance on New Zealand’s South Island reached a maximum during the latter part of the Antarctic cold reversal rather than during early in the YD (Denton, personal communication).

4. Discussion

In this case, as for many scientific discoveries, there is room for debate as to whom the credit should be awarded. I have already mentioned that a number of earlier studies suggested that changes in winter temperature were considerably larger than those for the summer. One of the reviewers of this paper pointed out earlier studies that called on the northward transport of heat in the Atlantic as a means to force a southward displacement of the ITCZ. It is not the purpose of this paper to pass judgment in this regard. I will say, however, that the conjunction of the convincing field evidence presented by Denton et al. (2005) with the model results of Chiang et al. (2003) convinced me that a mystery about which I had long puzzled had been solved.

References


