RESEARCH FOCUS

Rapid climate change and Arctic Ocean freshening

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The idea that global climate can change rapidly has been clearly demonstrated on the basis of oxygen isotopic stratigraphies from the deep ice cores drilled at Summit, Greenland (Greenland Ice-core Project [GRIP] Members, 1993; Taylor et al., 1993). Because δ^{18}O measured in the ice is a proxy for the temperature of the air from which Greenland precipitation is derived, the ice sheet itself acts as a "paleothermometer," one that may be accurately calibrated using gas isotope data and air thermal diffusion constants (e.g., Gatchev and Severinghaus, 2005). These records make it clear that extremely rapid excursions in the air temperature over Greenland have been characteristic of both Northern Hemisphere glacial conditions during oxygen isotope stage 3 (OIS3, 65– 25 ka) and of the last glacial-to-interglacial transition (ca. 21–10 ka). The variability during these intervals has been characterized by millennial-timescale excursions from warm to cold and cold to warm conditions in which the local temperature variations associated with the individual events have been on the order of 10 °C. Individual fluctuations have been characterized by a "sawtooth" form, rather like the 100 k.y. Late Quaternary ice-age cycle itself, with the transition from cold to warm atmospheric conditions occurring on a time scale that is short compared to the time scale of cooling. This two-timescale characterization of the individual pulses suggests that they are the consequence of a physical process that involves what is referred to in the language of dynamical systems as a "relaxation oscillation."

The most compelling explanation of these events is in terms of variability in the strength of the thermohaline overturning circulation (THC) of the Atlantic Ocean, which is primarily driven by the formation of deep water in the Greenland-Iceland-Norwegian seas (e.g., Broecker et al., 1989). The atmosphere is warmed over the North Atlantic adjacent to Greenland when the THC is strong, but is cooler when the THC is weak. The fast time scale of the relaxation oscillation is determined by the convective destabilization of the water column that occurs when the THC flips from an "off" to an "on" mode. The long time scale is determined by a slow, diffusion-dominated process that determines the time needed to re-establish convective instability of the water column in the Greenland-Iceland-Norwegian seas after the THC has collapsed (e.g., see Peltier and Sakai, 2001).

The millennial-timescale event that has been most studied is actually the most anomalous in character. This is the so-called Younger-Dryas cold interval that began at ca.12.8 ka, during which the general climate warming that occurred during the transition from Last Glacial Maximum to Holocene conditions was interrupted by a return to the cold conditions of the glacial that lasted ~1000 yr. Until recently it was generally accepted that this event was linked to a freshening of surface conditions over the Greenland-Iceland-Norwegian seas, due to a massive release of fresh water from glacial Lake Agassiz into the North Atlantic Ocean that occurred when the flow of fresh water from the waning Laurentide Ice Sheet was diverted from the south, through the Mississippi River System, to the east, through the Great Lakes and the St. Lawrence river system (Broecker et al., 1989). Very recently, this explanation for the Younger-Dryas event has been called into question by the difficulty encountered in identifying the spillway(s) through which the required massive flood of fresh water is suggested to have passed (Lowell et al., 2005). This led to a recent detailed analysis of the time-dependent deglacial routing of meltwater to the sea, based upon the application of a carefully calibrated continental-scale ice dynamics model which was coupled to a detailed model of the glacial isostatic adjustment process and superimposed upon a hydrologically self-consistent digital elevation model (Tarasov and Peltier, 2005, 2006). This analysis strongly suggested that the meltwater flood that occurred at the Younger-Dryas onset did not occur as a consequence of a switch in flow direction from the south to the east, but rather from the south to the north through the McKenzie River outlet onto the Arctic Ocean surface over the Beaufort Gyre. Peltier et al. (2006) showed that such freshening of the surface of the Arctic Ocean would have been as efficient a means of shutting down the Atlantic THC as would direct Atlantic freshening. Figure 1 illustrates the different geographical regions over which freshwater forcing was applied in order to demonstrate this equivalence. Direct paleoceanographic evidence also shows an Arctic source of the freshwater loading event that triggered the Younger-Dryas cold reversal. Figure 2 compares the results of a sequence of Arctic and Atlantic "water hosing" experiments, performed using the National Center for Atmospheric Research (NCAR) Climate System Model (CSM 1.4), that demonstrate the almost identical response of the strength of both the Atlantic overturning circulation and North Atlantic surface air temperature (SAT) to the application of the same intensities of freshwater forcing over the two regions.

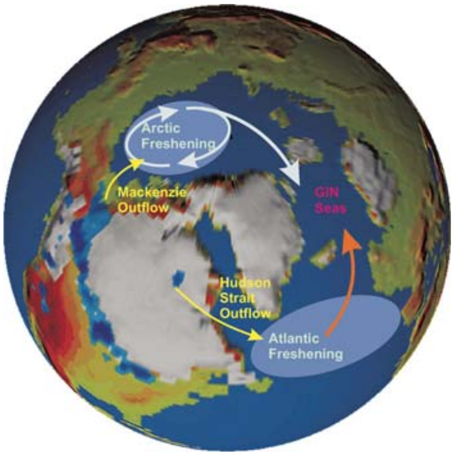

Figure 1. Freshwater "hosing" areas over the North Atlantic and Arctic Oceans employed for the purpose of comparing the impact of surface ocean freshening on Atlantic thermohaline circulation.

The study by Knies et al. (2007, p. 1075 of this issue) considers the question of Arctic Ocean freshening from the perspective of the entire Late Pleistocene interval of time. They employ calcium carbonate records from deep sea cores raised from the vicinity of Fram Strait, through which Arctic Ocean surface water flows southwards onto the surface of the Greenland-Iceland-Norwegian seas. They discuss an 800 ka record that covers the time from the mid-Pleistocene climate transition, following which the 100 k.y. glacial cycle dominated climate system variability. The quality of this record has enabled them to identify a strong imprint of Arctic-derived freshwater pulses that have passed through the Fram Straight. Such events appear to have been an enduring sub-Milankovitch–timescale characteristic of the glaciation-deglaciation process, and are shown to have been strongly linked to covariation in the strength of the THC. Knies et al.'s summary comment, that "most spectacular are freshwater pulses during glacial terminations" (p. 1077 of this issue), suggests that Younger-Dryas–type cooling events may have been a rather common feature of the variability that occurs when the climate system undergoes a glacial-to-interglacial transition.

Knies et al.'s work is especially interesting because it raises the question of why Arctic freshening events may be especially efficient in their ability to impact the THC and thus

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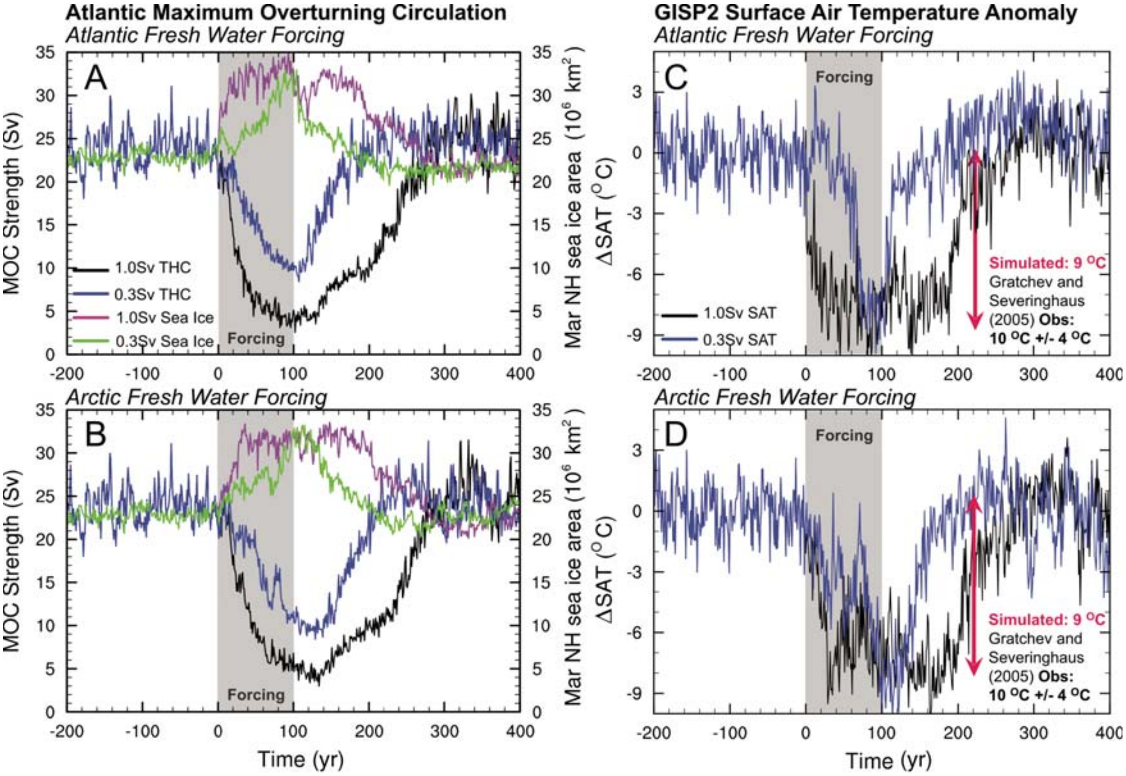

Figure 2. A–B: Response of Atlantic thermohaline circulation and Northern Hemisphere sea ice extent to 100 yr of freshening at the rate of either 1 Sv (1 Sv = 10^6 m^3/s) or 0.3 Sv applied to the Atlantic and Arctic Oceans, respectively, over the areas illustrated in Figure 1. C–D: Variations in surface air temperature predicted at Summit, Greenland, due to the alternative freshening scenarios. Note that the response to Atlantic and Arctic freshening in both the strength of the thermohaline overturning circulation (THC) and surface air temperature is essentially identical.

Northern Hemisphere climate. It is now clear, for example, that even massive floods of fresh water into the Gulf of Mexico, such as occurred during meltwater pulse 1a at ca. 14.2 ka, synchronous with the onset of the Bölling warm interval, failed to impact the strength of the THC. I have previously argued, citing the laboratory experiments of Parsons et al. (2001), that this was most probably due to the heavily sediment-laden nature of the riverine outflow, which caused the meltwater plume to enter the ocean hyperpycnally (i.e., the fresh water flows under the salt water rather than over the surface). This hypothesis has since been verified by Aharon (2006) based upon time-synchronous analyses of δ^{18}O in both planktic and benthic forams from Gulf of Mexico sediment cores. The efficiency with which a given freshwater pulse may impact the strength of the THC therefore depends upon the mechanism by which the fresh water is delivered to the Greenland-Iceland-Norwegian seas. During Heinrich events, the mechanism is efficient because this delivery occurs through the intermediary of "armadas of icebergs" whose tracks are preserved on the ocean floor in the form of the North Atlantic Ice Rifted Debris belt (e.g., Hemming, 2004). Arctic freshwater outflow may be especially effective because the stability of the water column in the Arctic Ocean is especially strong. Freshwater outflows, even if heavily sediment laden, are therefore unlikely to enter the ocean hyperpycnally. When the surface water thus produced is forced through Fram Strait, most probably as pack ice, it is then delivered to the Greenland-Iceland-Norwegian seas where it melts and is as effective in arresting the THC as are the Heinrich event-related armadas. The Knies et al. study is extremely useful in establishing this process as having operated ubiquitously under glacial conditions. However, more detailed analysis is warranted to establish that Younger-Dryas–type events were characteristic of the glacial-interglacial transitions that preceded the most recent such event.

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