Did Ocean Waves Transmit Abrupt Changes in Glacial Climate?

Mountain avens (*Dryas octopetala*) loves cold arctic climates.

The climate of the last glacial period, 80,000–11,000 years ago, is of particular interest for climate research because it furnishes a testing ground for scientific hypotheses about how climate changes. The large continental glacial ice sheets that covered North America and Europe affected climate greatly. Being 2,000–4,000 m high, they acted as a topographic barrier for the atmospheric circulation. They also changed Earth's albedo. Insolation from the sun, fluctuating with Earth's orbital paths around the sun on periods of 21,000, 41,000 and 100,000 years, was also different. Although the North American ice sheet accumulated snow only gradually, it was very unstable, melting and surging into the North Atlantic every 7,000 to 10,000 years.

Our understanding of the nature of these surges, their abruptness and their effects on climate, started with a tiny flower—the mountain avens (*Dryas octopetala*)—that flourishes in arctic climates. Paleo-botanists, studying sediments in Scandinavia in the early 20th century, found to their surprise fossils of this tundra flower right on top of soils on which trees had grown during a mild recovery from glacial conditions 14,000–11,800 years ago. The close proximity of such different vegetation layers could only mean that the climate had abruptly grown colder again.

We now know that this so-called Younger Dryas climate transition is one of the main hiccups of the glacial climate period. Data from ice cores in Greenland and sediment cores from the North Atlantic reveal that the Younger Dryas was not the only abrupt transition during the glacial period but that it belongs to a series of similar climate fluctuations. In 1988, Hartmut Heinrich discovered glacial debris deposits in sediment cores of the North Atlantic Ocean, which must have come from huge numbers of icebergs flowing into the North Atlantic. The surges were accompanied by global sea level rises of up to 20 m, and the impact of these so-called Heinrich events on climate is found in proxy records all over the globe: Greenland temperatures dropped rapidly several degrees; deep-sea ventilation—the exchange of water properties between the surface and the deep-ocean circulations—halted temporarily; and Antarctic temperatures rose by up to 3°C. In the tropics, Heinrich events were associated with a saltier Pacific warm pool and less monsoon rainfall over India.

The quest for mechanisms that cause such global climate swings is now on. Some researchers believe the observed synchronized climate effects seen around the globe during these ice-sheet surges result from atmospheric adjustments. Others are looking at oceanic adjustments, particularly the effects of the infusion of so much cold fresh water into the North Atlantic.

At the IPRC, **Axel Timmermann**, co-leader of the Impacts of Global Environmental Change Team, and his European colleagues are using an efficient global coupled atmosphere-ocean-sea ice model (ECBilt-Clio) to study the oceanic adjustment to changes in freshwater inflow into the North Atlantic under glacial conditions. More specifically, to mimic a Heinrich event, such as the Heinrich event II, they injected into the northern North Atlantic a glacial meltwater pulse of about 0.6 Sv [1 million m^3/s] for about 200 years. In response to this freshwater pulse, the thermohaline circulation in the North Atlantic collapsed and the North Atlantic cooled several degrees; in the Southern Hemisphere,

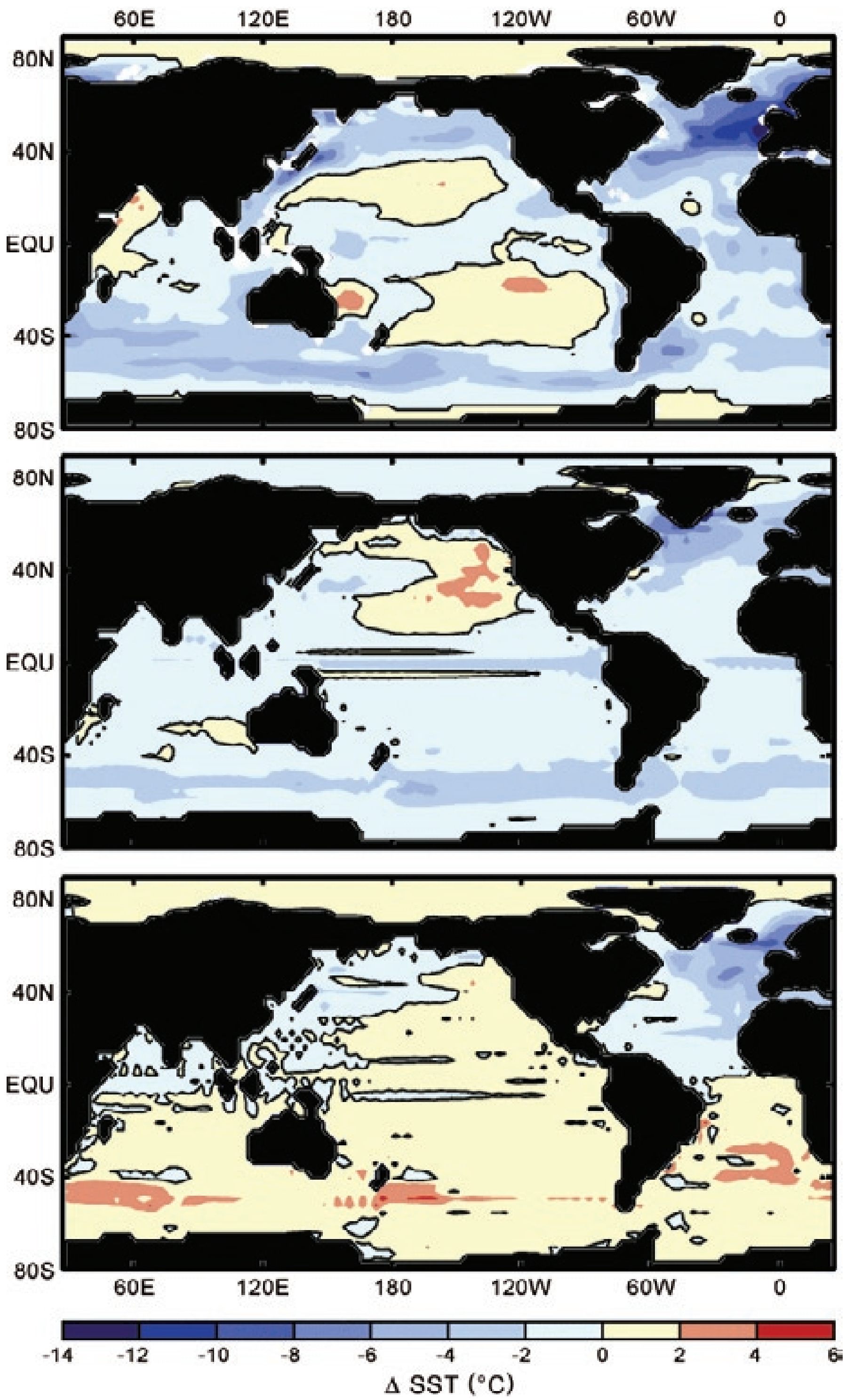


Figure 1. Top: Difference between sea surface temperatures (SST - average of February and August temperatures) reconstructed for the Last Glacial Maximum (LGM), and present-day observations. **Middle:** Difference between annual mean SSTs in the LGM experiment and in a pre-industrial control experiment. **Bottom:** Difference between SSTs during thermohaline circulation shutdown and normal LGM conditions. The North and South Atlantic temperature seesaw is apparent.

oceans warmed by as much as 3°C (Figure 1, lower panel). The simulated glacial climate is similar to recent climate reconstructions for the Last Glacial Maximum (Figure 1, upper panel). The model underestimates, however, the cooling of the North Atlantic during that period because of its weak climate sensitivity and strong glacial thermohaline circulation.

In agreement with the reconstructions of paleoclimates, the warm pool in the model grew saltier during Heinrich events, and the Indian monsoon grew weaker. The simulation not only showed the seesaw in North and South Atlantic temperatures that has been described and explained in detail in Knutti et al. (2004), but also a North Pacific–North Atlantic seesaw. That is, when the North Atlantic cools, the eastern North Pacific warms, and *vice versa*.

To see whether these changes can occur through purely oceanic adjustments, the researchers conducted the same simulation experiment except that the connections between the atmosphere and ocean were prevented world wide. This resulted in climate changes in the Pacific Ocean that were much like those noted in the first experiment. Analyses of the model output show that the ocean circulation can account for many of the synchronized changes seen in the global ocean over 100 to 1000 years in response to Heinrich events.

When the thermohaline circulation in the model weakens, the tropical thermocline in the Indian and Pacific oceans deepens as a result of a global baroclinic wave adjustment: The density changes stemming from the influx of freshwater generate Kelvin waves in the North Atlantic that travel to the equator. At the equator, they are forced to move towards the coast of Africa, where they split into a northern

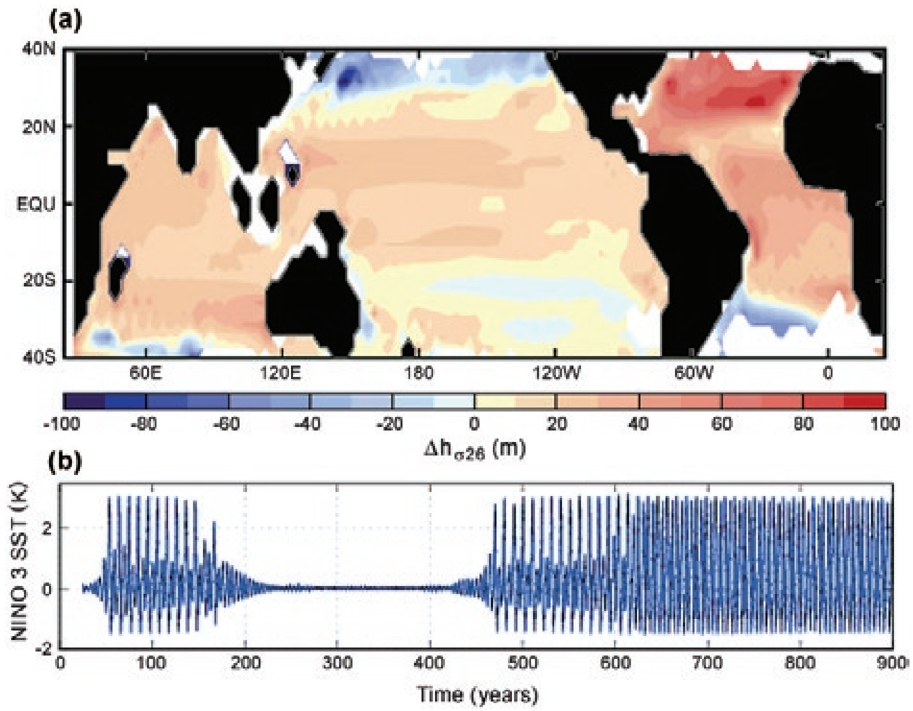
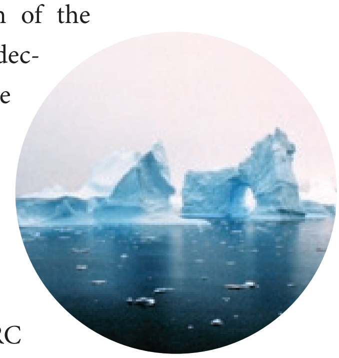


Figure 2. Top: Difference in the depth of the isopycnal 26.0 kg/m^3 surface during shut-down and normal thermohaline circulation (THC) in the LGM experiment. This isopycnal surface separates upper-ocean thermocline waters from deep-ocean waters. **Bottom:** Response of ENSO to the thermohaline circulation-induced changes: time-series of the NINO 3 SST anomalies [K] simulated by the intermediate ENSO model. The back-ground thermocline depth is updated every year to capture the spatial and temporal thermocline changes that correspond to a collapsed thermohaline circulation in the North Atlantic during Heinrich events.

and southern branch. While moving poleward, they radiate Rossby waves, which readjust the interior transport of the North and South Atlantic after reaching the western boundary. The southern wave branch travels around the southern tip of South Africa into the Indian and subsequently into the Pacific Ocean. The global baroclinic adjustments to the initial density anomaly in the North Atlantic happen within a few years to decades, whereas adjustments due to advection of the density anomalies are much slower. The overall sea level and thermocline-depth changes can be viewed as a standing wave pattern—a global seiche as Cessi et al. (2004) have called it.

In the model, the collapse of the thermohaline circulation in the North Atlantic deepens the tropical Pacific thermocline about 20–30 m. What will happen to El Niño–La Niña, a major mode of modern-day climate variation, when the tropical Pacific thermocline lies deeper? In a simulation with an intermediate model of the El Niño–Southern Oscillation (ENSO), Timmermann and his colleagues found that the temperature variability in the tropical Pacific also collapsed, and there were no El Niño and La Niña events for many years (Figure 2). Several elements of the ENSO suppression mechanism, however, may be model-dependent. Paleo-reconstructions for ENSO may soon become available for the Younger Dryas event or other Heinrich events to confirm or disprove this ENSO collapse. Timmermann also plans to conduct sensitivity experiments with more realistic state-of-the art coupled general circulation models to test the robustness of the results.

Are similar oceanic adjustment mechanisms operating under present-day climate conditions? Timmermann is now exploring how much of the Northern Hemispheric interdec-adal variance in temperature and ocean currents seen in instrumental records can be explained by oceanic global adjustments or atmospheric bridges such as the Arctic Oscillation. **Oliver Timm**, IPRC postdoctoral fellow working with Timmermann, is conducting transient glacial interglacial simulations using a global atmosphere-ocean-sea ice model. He hopes to understand why our present Holocene climate is so much warmer and more stable than climate during glacial times.



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