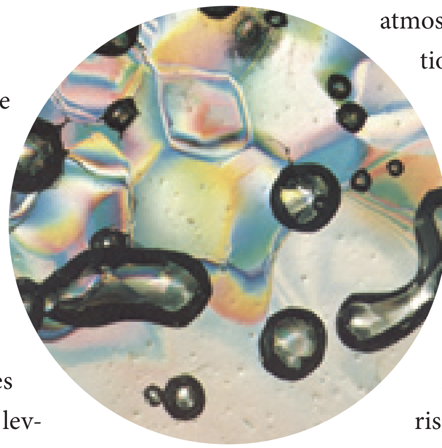
# Why Did Antarctica Warm?



Antarctica is covered by a massive blanket of glaciers. It is difficult to believe that the continent is now quite a bit warmer than it was 20,000 years ago—according to gas bubbles trapped in Antarctic ice. Those bubbles reveal that 20,000 to 17,000 years before present, surface-air temperatures started to rise about 5 to 8°C until they leveled off around 10,000 years ago. About the same time, the Southern Ocean warmed, sea-ice retreated, and $CO_2$ concentrations in the atmosphere rose.

A prevalent view of this "end of the last Ice Age" in Antarctica holds that it was indirectly triggered by more solar radiation striking the Northern Hemisphere in summer. The amount of solar radiation reaching the Northern and Southern Hemispheres varies over the millennia with cycles of Earth's path around the Sun: precession, obliquity, and eccentricity. Around 20,000 years ago, the higher northern latitudes started to receive increasingly more solar radiation during June–August. This increase is thought to have triggered glacial melt, pouring fresh water into the North Atlantic. In numerical model simulations, such freshwater flushing abruptly changes the North Atlantic thermohaline circulation and shifts heat to the Southern Hemisphere, with the result that Antarctica warms up.

Another scenario, however, is possible. About 20,000 to 17,000 years ago, the Southern Hemisphere began to receive more solar radiation during its springtime, September–November. Springtime insolation reached a maximum around 10,000 to 8,000 years ago, and then decreased. Today it is about the same as it was 20,000 years ago. Perhaps this change in solar forcing directly triggered the warming in Antarctica.

**Axel Timmermann**, IPRC co-team leader for research on Impacts of Global Environmental Change, IPRC postdoctoral fellow **Oliver Timm**, and their colleagues **Lowell Stott** at the University of Southern California and **Laurie Menviel-Hessler** at the University of Hawai'i explored this possibility. Their strategy was to simulate the temperature changes over the past 21,000 years in an accelerated global climate model of intermediate complexity called ECBilt-CLIO. They varied over the 21,000 years the ice-sheet cover and atmospheric greenhouse gas (GHG) concentrations in accordance with values estimated by the proxy records, and the solar radiation in accordance with orbital changes computed from astronomical theory.

Figure 1 shows the simulated Antarctic temperature evolution from glacial to interglacial times for the four seasons. There are clear seasonal differences. During December–February, temperatures rise until about 5,000 years ago and then plateau; during March–August temperatures continue to rise from 18,000 years ago to the present. Only for September–November do the changes in the model's mean air-temperatures map well onto the magnitude and phases of the reconstructed isotope-based temperatures from the Antarctic Vostok ice cores. Figure 1 (lower right) and Figure 2a show that the temperature in the model rose from below −34°C to −28°C from 17,000 years to 10,000 years ago (black curve) and then leveled off. The Vostok ice core records show a similar rise of about 6°C above the average long-term record.

To separate the effects of solar radiation, sea-ice albedo feedback, and greenhouse gases on Antarctic temperature evolution, the team ran several simulations in addition to

**Above.** Thin slice of a polar ice sample illuminated through two polarizing filters. Grain boundaries appear in rainbow colors, the gas bubbles enclosed in the ice are dark. The bubbles range from 1 to 3 mm in diameter. Analysis of the gas composition in these bubbles permits reconstruction of greenhouse gas concentrations ($CO_2$, $CH_4$, and $N_2O$) over the past 650,000 years (*Copyright: W. Berner, 1978, PhD Thesis, University of Bern*).

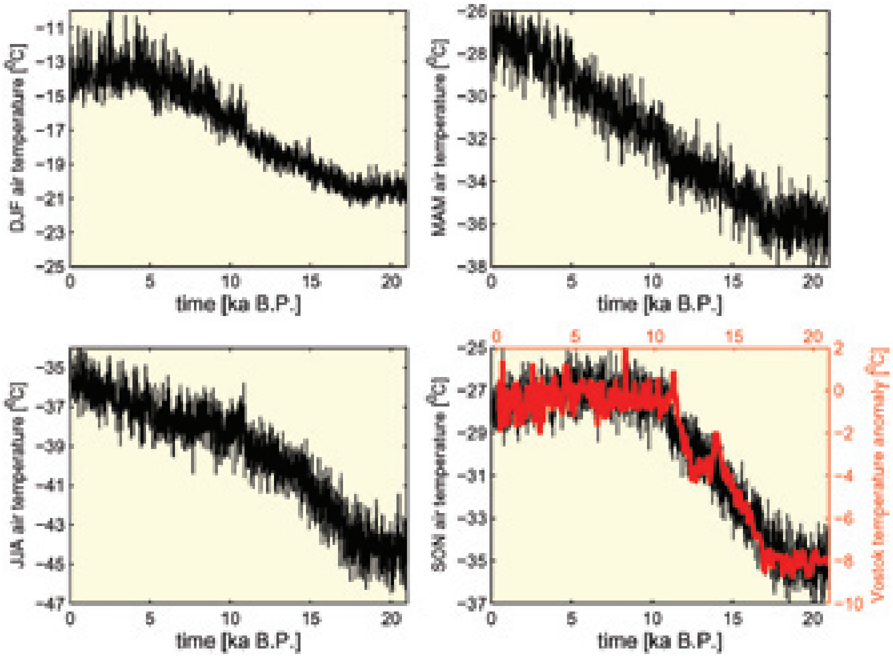



**Figure 1.** Simulated and observed evolution of Antarctic temperature: (**upper left**) simulated surface air temperature for austral summer (December–February) averaged for latitudes 65°S–90°S; (**upper right**) same as upper left but for austral autumn (March–May); (**lower left**) same as upper left but for austral winter (June–August); (**lower right**) same as upper left but for austral spring (September–November). In red, the reconstructed surface air temperature anomalies relative to present-day values for the Vostok ice core (latitude 78°28'S, longitude 106°48'E). The temperature anomalies are reconstructed from the δ-deuterium concentration and are plotted on the GT4 timescale.

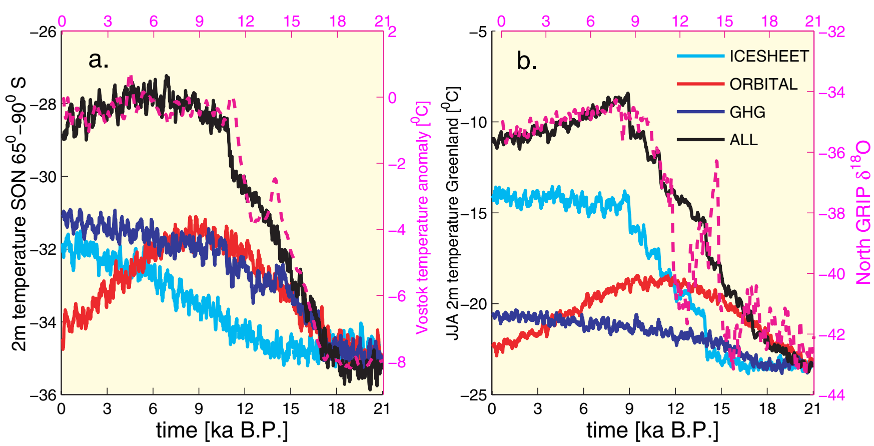



**Figure 2.** Simulated evolution of Antarctic and Greenland temperatures and sensitivity to different forcings. (**left**) Simulated smoothed austral spring surface air temperatures averaged over latitudes 65–90°S for the transient simulation that includes orbital, greenhouse gas, and ice sheet changes (black) and the simulations that capture only the time-evolution of the orbital forcing (red), the greenhouse gases (blue), and the ice-sheet orography and sea-ice albedo (cyan). Reconstructed temperatures at Vostok are represented in magenta. (**right**) Simulated smoothed boreal summer temperatures over Greenland obtained for four forcing integrations and the temperature reconstruction (magenta) from the oxygen isotope ratio $\delta^{18}O$ recorded in the Greenland North Greenland Ice Core Project.

the control that had included all three forcings (ALL experiment). The ORBITAL experiment varied insolation in accordance with orbital changes, while the other variables were kept at values existing around 21,000 years ago. Temperatures first rose and then after 10,000 years before present fell again as springtime solar radiation waned (Figure 2, left panel) red curve). The GHG experiment varied atmospheric greenhouse gas concentrations as indicated in the ice core records, while keeping everything else at the original values (dark blue curve). The temperature changes again did not follow those captured in the ice core. Finally, the ICESHEET experiment included only changes in orography and albedo arising from ice and sea-ice coverage, but again the effect on temperature did not match the ice records (cyan). Only the ALL condition (black curve) matched the temperature reconstructions from the Vostok ice core (magenta curve).

Driving the model with conditions as they had evolved in Greenland, Timmermann and his colleagues studied the Greenland temperature evolution (Figure 2, right panel). When all three variables—orbital changes, greenhouse gases, and sea ice coverage—were included, the model captured the overall evolution of temperature recorded in the Greenland ice core. The phases and the contribution of the three variables, however, differed from those seen in the Antarctic simulation and in the Antarctic records.

The end of the last Ice Age in Antarctica, therefore, does really seem to have been triggered by local changes in the Southern Hemisphere.

**iprc**