Carbon dioxide drove the ending of the last glacial epoch

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geometry allowed them to spectroscopically probe the wire's density of states in the gap. Fortunately, the InSb wire abutting the edge of the NbTiN retained enough semiconducting character that a series of capacitively coupled gates could be attached to it. One gate voltage created a barrier through which normal gold electrons could tunnel into the wire; others acted as knobs to tune the wire's Fermi energy. The team then applied a bias voltage between the normal metal and superconductor and looked for a peak in the supercurrent conductance through the wire.

Usually, a normal electron cannot tunnel into a superconducting gap. But if a Majorana resides there, the electron can tunnel into that state, adding to the circuit's conductance. As shown in figure 2, the expected conductance peak appeared only when the bias voltage was tuned to zero, and it began to do so at a critical value of the magnetic field consistent with theory. What's more, the peak remained stubbornly pinned at zero bias voltage over a broad range of magnetic field intensities and gate voltages.

Must this be evidence for a Majorana? Kouwenhoven acknowledges that other physics, including the Kondo effect, antilocalization, and reflectionless tunneling, could give zero-bias features. His team systematically considered those in an effort to rule them out. Not everyone is convinced. But as Harvard University's Charles Marcus points out, "Showing that an idea is right is difficult, if not impossible, to do with a single experiment—much harder than showing that an idea is wrong—so the natural response to this important result will be a series of further refinements of both theory and subsequent experiments. This is just the start of the experimental program. Stand by for a lot more."

Mark Wilson

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A worldwide assemby of proxy paleothermometers has addressed the disputed role of greenhouse gases in periodic deglaciations.

Antarctic ice-core records covering the past million years show temperature rising and falling with a principal periodicity of about 100 000 years, closely tracked by corresponding rise and fall of the atmospheric concentration of carbon dioxide. The Antarctic temperature troughs and peaks roughly mark the maxima and minima of successive epochal advances and retreats of ice sheets and glaciers in both hemispheres.

In common parlance, the intervals of extensive ice coverage are called ice ages. But geologists classify the entire Quaternary Period—from 2.6 Myr ago to the present—as an ice age because, unlike most of Earth's history, it has had year-round polar ice caps. It's thought that the timing of the Quaternary's 100-kyr cycle of glaciation and deglaciation is set by cycles of Earth's orbital and axial parameters due to gravitational nudges from other planets.

But the Antarctic ice-core data made it clear that CO_2 was somehow also intimately involved. Was the increasing CO_2 an important driving mechanism of the glacial retreats, or was it mostly just a consequence of those retreats? The question has obvious resonance for our time.

The Antarctic data, in isolation, seem to show CO_2 increase generally lagging temperature rise by a few centuries, thus suggesting that CO_2 may have been more a passenger than a driver. Indeed, that lag is often cited by critics of the argument that greenhouse gases contribute importantly to global warming. Retreating ice can, in fact, trigger events that lead to increased atmospheric CO_2, the most important of which are thought to involve warming of the carbon-rich depths of the Southern Ocean around Antarctica.

Now Jeremy Shakun and coworkers have put together a temperature record of unprecedented global scope and temporal resolution for the most recent deglaciation, which began about 20 kyr ago and leveled off 10 kyr later to initiate the present "interglacial" Holocene Epoch. They report that the newly constructed global record shows global mean temperature, unlike local Antarctic temperature, clearly trailing CO_2 increase during most of the last deglaciation.[1] (See figure 1.)

The team also used the global data to distinguish between warming in the Northern and Southern Hemispheres and thus reveal a plausible mechanism for why Antarctic temperature rise tends to precede the mean global rise. Then, attempting to fit various simula-

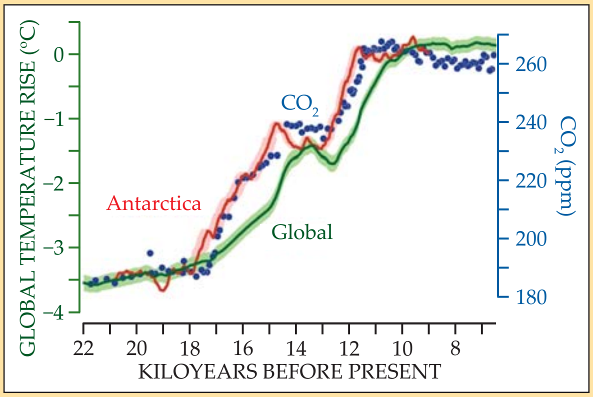

Figure 1. Global mean temperature, Antarctic temperature, and atmospheric CO_2 all rose dramatically during the great deglaciation that ushered in the present Holocene Epoch 10 000 years ago. Global temperature, as measured by proxy data from 80 core sites worldwide, is plotted as differences from the early-Holocene mean. The Antarctic temperature rise is scaled for comparison. During the periods of steepest warming, the CO_2 rise precedes the global temperature by several centuries, but it lags the Antarctic temperature. (Adapted from ref. 1.)

tion models to the global and hemispheric records, the team concludes that the rising concentration of CO_2 in the atmosphere was the principal driver of the last deglaciation.

Shakun, now a postdoctoral fellow at Harvard and Columbia Universities, initiated the undertaking while he was a still a PhD student at Oregon State University.

The global record

To compile its temperature record, the team availed itself of sedimentary and ice-core data from 80 locations worldwide, collected and analyzed in recent years by various groups who then made their databases available. Most of the cores came from sea-floor and lake-bottom sediments. Temperature proxies in the cores ranged from isotopic indicators such as deuterium abundance in ice to biogeochemical indicators such as the magnesium–calcium ratio in fossil microshells. The primary time tag was carbon-14 abundance. With its half-life of 5700 yr, ^{14}C makes an excellent chronometer for the last deglaciation.

For the global CO_2 record, air bubbles trapped in the Antarctic ice cores are sufficient, because CO_2 is well mixed throughout the atmosphere. ”But from the temperature proxies at 80 widely dispersed locations, you'd expect a mess of wiggly lines due to local climate effects,” says Shakun. “And that's indeed what we found. The surprise was that this hodgepodge yielded a global average temperature that clearly mirrors the CO_2 rise.” And, as figure 1 shows, the global temperature starts lagging CO_2 after the sharp upturn of both about 17.5 kyr ago.

Why did the Antarctic temperature record rise more abruptly and steeply at that point than the global record? The answer could clarify the role of north–south differences in earlier Quaternary deglaciations, for which the record is much less detailed. Figure 2 strongly hints that the rapid early warming of Antarctica was caused by the disruption of an oceanic circulation pattern that normally ships heat northward.

Figure 2a shows the separate hemisphere mean-temperature chronologies deduced from the 80 proxy cores. Their difference, shown in figure 2b, calls attention to two prominent troughs of northern temperature that appear to mirror troughs in the strength of the Atlantic meridional overturning circulation (AMOC), chronicled in figure 2c.

The AMOC is a branch of the global thermohaline pattern of surface and deep ocean currents driven by winds and density gradients due to temperature and salinity variation (see the article by Robert Toggweiler in PHYSICS TODAY, November 1994, page 45). In particular, the AMOC is a conveyor belt perennially transferring net heat from the South Atlantic to the North Atlantic. The proxy for the strength of the AMOC current in figure 2c is the ratio of thorium-230 to protactinium-231 in equatorial Atlantic sediment cores. Both are long-lived daughters of uranium in ocean water. But their chemical affinities are such that ^{231}Pa is preferentially swept away when the AMOC is strong.

When the AMOC suddenly weakens,

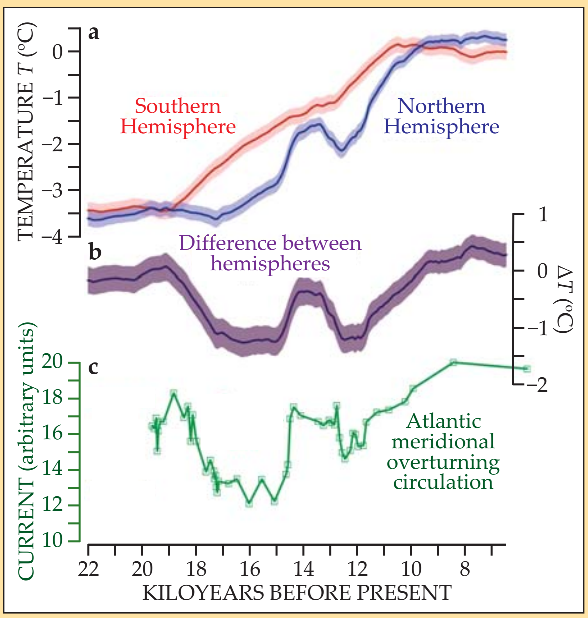

Figure 2. The worldwide array of paleothermometers makes possible **(a)** separate mean-temperature chronologies for the Northern and Southern Hemispheres. **(b)** The difference (north minus south) between the measured hemispheric temperatures. **(c)** The variation of the Atlantic meridional overturning circulation, a northward surface current that perennially transfers heat from the South Atlantic to the North Atlantic. (Adapted from ref. 1.)

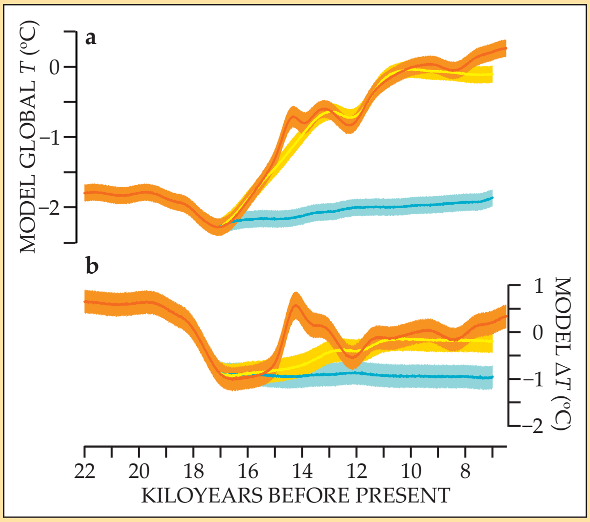

Figure 3. Three model simulations of **(a)** measured global mean temperature and **(b)** the temperature difference between hemispheres. The most inclusive simulation (orange curves) is driven by changing concentrations of CO_2 and other greenhouse gases, changing solar irradiation, and other forcing agents discussed in the text. The other two simulations branch off at 17 kyr. One (yellow) considers only subsequent greenhouse-gas changes, and the other (blue) considers only changes in solar irradiation. (Adapted from ref. 1.)

as it appears to have done about 19 kyr ago, the southern hemisphere retains much of the heat that it normally ships north. The most plausible explanation for that weakening is the recession of ice sheets in and near the far North Atlantic during the gradual warming of the preceding three millennia. Excessive melting in the north inhibits the AMOC because the less dense, low-salinity meltwater sinks less readily to form the southward deep current that's needed to complete the thermohaline circuit.

Simulations

To assess the validity and relative importance of the various mechanisms adduced to explain the last deglaciation, Shakun and company used a National Center for Atmospheric Research climate model to simulate the temperature record for the period from 22 to 7 kyr ago with three different suites of inputs and driving mechanisms. Figure 3 shows the simulation results for the global mean temperature and the mean-temperature difference between the hemispheres.

The most inclusive simulation, shown by the orange curves, is driven by the measured record for CO_2 and other greenhouse gases, the calculated changes of solar irradiation at various latitudes due to orbital and axial cycles, the measured ice-sheet coverage, and estimates of freshwater fluxes from melting ice sheets. The other two simulations branch off the inclusive one at 17 kyr. The yellow curves consider only subsequent changes in the greenhouse-gas concentrations, and the light-blue curves consider only changes in solar irradiation.

The inclusive simulation fits the global and hemisphere-difference temperature records quite well. But so, in broad strokes, does the greenhouse-only simulation—except for the short-term wiggles attributed to AMOC interruption. By contrast, the solar-only simulation yields only a small fraction of the steep global warming that started at about 17 kyr. "So on that time scale," says Shakun, "it seems clear that CO_2 was the principal driver." The simulations don't try to reproduce the CO_2 rise; it's simply taken as an input. "That's because we don't yet understand in sufficient detail how the CO_2 took off so abruptly at 17.5 kyr," he explains.

The likely trigger

Although rising CO_2 seems to have been the driving force of the last deglaciation after that takeoff, the team concludes that it probably was not the initial trigger. After all, global temperature had been rising steadily, if slowly, since 21.5 kyr, with a slight steepening at 19 kyr, just when the AMOC started weakening.

Exploiting their unique temperature-proxy database covering all latitudes in the early millennia of the deglaciation, Shakun and company tentatively offer the following trigger scenario: Starting around 22 kyr ago, gradually increasing summer insolation at high northern latitudes—due to increasing axial tilt and the precession of the June solstice toward Earth's perihelion—began melting enough ice to start disrupting the AMOC by 19 kyr. As the AMOC's northward heat transport continued to weaken, the consequent warming of the carbon-rich Southern Ocean could have unleashed the steep ascent of CO_2 concentration that took over and accelerated the global warming some 1500 years later.

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Classical vortex beams show their discrete side

Researchers twist sound, testing a fundamental law of the quantization of orbital angular momentum.

Faced with danger, the Doctor, protagonist of the science fiction television series *Doctor Who*, often availed himself of a tool known as a sonic screwdriver. A bit larger than an ink pen, the sonic screwdriver was, among other things, a lock pick, a remote control, and an alien-detection device. The Doctor's tool was fictional, of course, but now Michael MacDonald and colleagues at the University of Dundee in the UK, in collaboration with Gabriel Spalding of Illinois Wesleyan University, have developed a real-life sonic screwdriver—an ultrasound device capable of generating high-angular-momentum acoustic vortices. With it, they've obtained an elusive measurement of the ratio of orbital angular momentum (OAM) to energy in a vortex beam.[1]

The notion that propagating waves can possess OAM is just 20 years old. First advanced by Les Allen and coworkers for the specific case of electromagnetic waves, the conclusion follows from the observation that a light beam's momentum is always perpendicular to its wavefront.[2] A beam having a helical wavefront should therefore have some OAM about its axis, and a beam made up of several intertwined helical wavefronts should have even more. Each photon, Allen and his colleagues asserted, must have OAM of $l\hbar$, where the integer l is the topological