between the electrical and mechanical properties of nanotube NEMS in the Coulomb blockade regime. In both studies, a nanotube is suspended above a substrate, which acts as a gate (see the figure, panel A). Lassagne *et al*. use an electromechanical mixing scheme that takes advantage of the change in current with gate voltage. This scheme is particularly well suited to the Coulomb blockade regime, in which conductance oscillations lead to a large signal, providing single-atom mass sensitivity (*12*). Steele *et al*. measure the dc conductance, which is sensitive to the second derivative of the current with gate voltage. Motion of the nanotube modulates the capacitance to the gate, and therefore the charge state (and conductance) of the nanotube.

As voltage is applied to the gate, electrostatic force induces tension in the nanotube and increases the resonant frequency (see the figure, panel B). However, the frequency does not change smoothly, but shows discrete jumps (see the figure, panel C), which are correlated with the charge state as determined by the Coulomb blockade measurement. This occurs because the charge on the nanotube, and therefore the electrostatic tension, changes in discrete amounts; Steele *et al*. term this effect "single-electron tuning," as the mechanical analog to single-electron tunneling. In addition, the resonance softens and broadens at each jump. Both effects are a direct result of the fluctuating charge at the boundary between states with N and $N \pm 1$ electrons.

Although the discussion so far has addressed the effects of charge transport on the mechanical measurement, the opposite also can be interesting. Steele *et al*. find that in the regime of strong coupling to the leads (rate of tunneling larger than resonant frequency), electron tunneling may spontaneously drive the nanotube into resonance, and consequently distort the dc transport features.

The work of Lassagne *et al*. and Steele *et al*. beautifully demonstrates the rich physics that arises from the coupling of NEMS and electron transport in quantum dots. In addition to the results described in these two studies, such strong electronic-vibrational coupling may be used to investigate interesting physics such as negative charging energy (*13*). Moreover, the newly achieved high Q's make nanotubes very attractive candidates for detecting the quantum limit of motion and subsequent manipulation of quantum states at macroscopic scales.

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ATMOSPHERE

Antarctica's Orbital Beat

Peter Huybers

What do Antarctic ice core records really record?

Alternating glacial and interglacial conditions have dominated Earth's climate for at least the past 800,000 years (*1*, *2*). Such a global rhythm of glaciation is surprising—at least if summer solar radiation controls glaciation (*3*)—because variations in Earth's orbit cause opposite changes in the intensity of northern and southern summer radiation. Deciphering the origins of the orbital period variations found in Antarctic proxies of climate may tell us why glaciations are global.

Earth's orbit around the Sun is not steady. The tilt of its spin axis varies with a period of 41,000 years, the eccentricity of its orbit changes at time scales of 100,000 to 400,000 years, and the orientation of the eccentric orbit precesses with respect to the seasons about once every 21,000 years. One implication of the orbital geometry is that at the time when precession aligns Earth's closest approach to the Sun (perihelion) with Northern Hemisphere summer, Earth is farthest away from the Sun (at aphelion) during Southern Hemisphere summer. But if the north and south are alternately near and far from the Sun during summer, why has glaciation been globally synchronous?

A clue lies in Antarctica's ice, as illustrated by the δD record from Dome C (see the figure) (*4*). δD is the normalized deuterium to hydrogen ratio of the ice and is sensitive to air temperature over Antarctica, as can be roughly understood in that colder temperatures lead to greater distillation of heavy isotopes out of atmospheric moisture. The exact δD of the snow accumulated at Dome C depends on detailed evaporation and precipitation histories (*5*), but similarities between the δD variability and other Southern Hemisphere climate records (*6*, *7*) suggests that this signal represents regional and hemispheric climate variations.

The Dome C δD record (*4*) indicates that Antarctic temperature increases with the tilt of Earth's spin axis. This is as expected, because greater tilt increases the annual incoming solar radiation (insolation) at high latitudes. More puzzling is that temperature also seems to be higher when aphelion occurs during Antarctic summer (*1*, *2*, *4*, *6*). This contrasts with the Northern Hemisphere, which warms when perihelion aligns with northern summer (*2*, *3*). The northern response can be understood as more intense summer insolation reducing ice cover, leading to lower surface reflectivity and higher temperatures (*2*, *3*), but what mechanism governs the southern temperature response?

The answer to this question may also tell us why glacial/interglacial cycles are global. There are at least five possibilities.

Perhaps the most basic prediction can be traced from Milankovitch (*3*), who used simple radiative equilibrium calculations to explore how orbital variations influence temperature and ice volume. He dismissed Antarctica as too cold for changes in southern insolation to influence its ice volume, but applying his radiative equilibrium approach to mean annual temperature does suggest that Antarctica will be warmest when aphelion coincides with Southern Hemisphere summer (*8*). Aphelion is associated with less intense summer insolation, but it also corresponds to a longer summer and shorter winter, as follows from Kepler's second law. Simple radiative equilibrium indicates that the longer summer more than compensates for a lower intensity, giving temperature variations that are consistent with—albeit smaller in amplitude than—those derived from the ice core records (*9*).

Alternatively, if increased Southern Hemisphere spring insolation drives a reduction in sea

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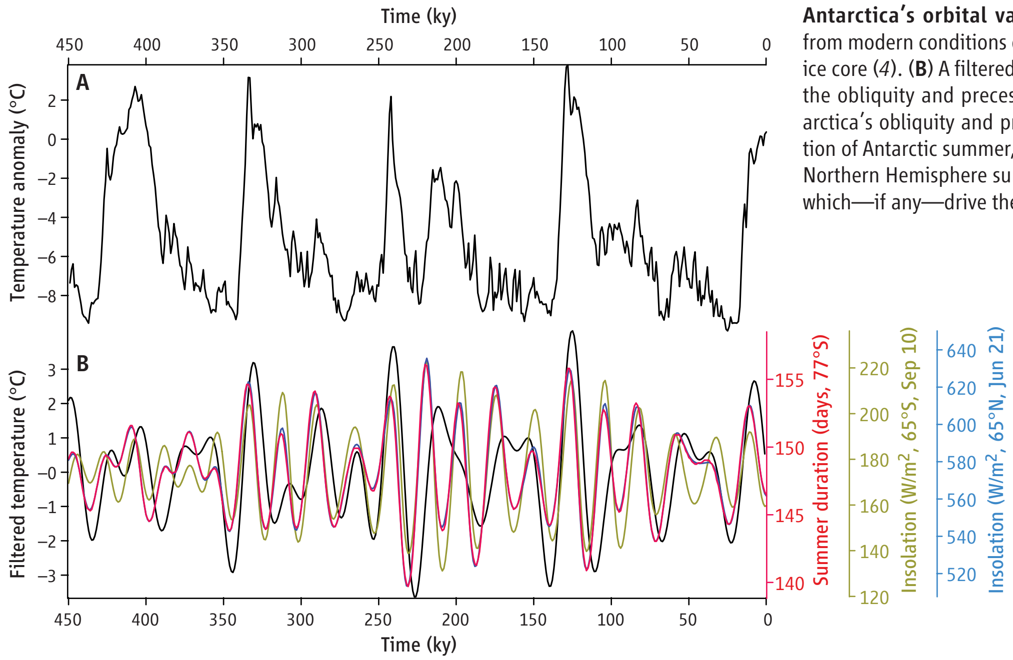

Antarctica's orbital variations. (**A**) Temperature anomalies away from modern conditions derived from δD isotopic ratios in the Dome C ice core (*4*). (**B**) A filtered version of the temperature record highlights the obliquity and precession period variability in temperature. Antarctica's obliquity and precession period variability mimics the duration of Antarctic summer, Southern Hemisphere spring insolation, and Northern Hemisphere summer insolation (*17*), raising the question of which—if any—drive the observed changes?

ice, then heat transport into the interior of Antarctica is expected to increase and cause temperature changes like those inferred from the ice core records (*10*). The intensity of Southern Hemisphere spring insolation is closely related to the duration of summer, and the two quantities are similar when suitably defined (*11*); as a result, signal processing alone will not discern between these scenarios.

A third possibility is that Antarctic climate marches to the beat of northern insolation (*2*, *6*). The intensity of northern summer insolation might influence Antarctica by changing cross-equatorial atmospheric or oceanic heat transports, although such a causal mechanism must be reconciled with evidence that southern climate changes occur slightly earlier than those in the north (*2*).

Atmospheric carbon dioxide (CO_2) concentrations also vary with obliquity and precession, but as for Antarctic temperature, the exact orbital forcing that drives these changes remains unclear. Regardless, CO_2 is observed to amplify Antarctic orbital period temperature variability, accounting for perhaps as much as half the amplitude (*12*). Furthermore, CO_2 is well mixed in the atmosphere and appears to be a good candidate for orchestrating global climate changes.

The relative importance of each of these mechanisms is still debated, although their basic outlines have been known from Southern Hemisphere marine proxies for at least 25 years (*1*). More recently, attention has turned to a fifth possibility: that ice core proxies unevenly record the seasonal cycle of temperature.

If temperature is unevenly recorded across the seasons, the orbital influence on seasonality will tend to appear in the record as precession- or obliquity-period climate variability (*13*). For example, Laepple recently showed (*14*) that as a result of lower summer accumulation rates on the East Antarctic Plateau, fall, winter, and spring temperatures are more heavily recorded in ice cores than are summer temperatures. In this case, even if orbital variations do not actually influence Antarctica's annual average temperature, the uneven recording of the seasonal cycle is expected to result in orbital period variations in δD similar to those observed. Furthermore, Hutterli recently suggested (*15*) that sublimation substantially influences the isotopic composition of Antarctica ice. Perhaps Antarctica's orbital beat tells us more about how the seasonal cycle gets recorded than about long-term changes in temperature, although similarity between ice core records and Southern Hemisphere marine proxy records (*2*, *7*) suggests that the orbital signal is not wholly an artifact of the recording process.

Arguments then exist that the orbital variability recorded in Antarctic ice core proxies relate to the seasonal distribution of Southern-Hemisphere insolation or to Northern-Hemisphere summer insolation; and that the signal could indicate temperature, the seasonal cycle of accumulation, or post-depositional effects. This confusion stems from the fact that many aspects of the insolation forcing have essentially identical variability. The fact that the orbital bands account for only a few of the ~10°C changes between glacial and interglacial conditions (*16*) does not help either. Coming up with orbital scenarios that look like the Antarctic record is too easy. If we are to use Antarctica's orbital beat to better understand the orchestration of global changes in glaciation, we must first decipher which elements of the climate system are in play and how their responses get recorded in Antarctica's ice.

Some promising lines of research include analyzing the modern seasonal cycle of snow accumulation and its isotopic composition (*14*), along with postdepositional effects (*15*), to better constrain the environmental controls on ice core proxies. Inclusion of water isotopes and other proxies in numerical simulations of climate (*5*) will push our understanding of the climate record forward. Further integration of the Antarctic record with other continental and marine proxies (*7*) will also prove useful in synthesizing Antarctica's orbital beat into the full climate song.

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17. A fourth-order Butterworth filter with a passband between 1/41,000 and 1/19,000 years was used for filtering. The insolation variability has statistically significant coherence with the Antarctic δD record (*9*), which also holds when the full 800,000 years of the record is used.

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