CLIMATE

Ice Rhythms: Core Reveals a Plethora of Climate Cycles

Researchers have long known that Earth's climate can move in cycles, from the annual rhythm of the seasons to the ponderous waxing and waning of the great ice sheets. They have carefully detailed the stately cycles paced by Earth's slow wobbling on its axis over tens of thousands of years, as well as the rapid shifts called El Niños that skitter through the climate system every few years. But there is a little known intermediate range of climate variation, cycles of a few thousand years that are too slow to be noticed in a human lifetime but frequent enough to have played a role in human affairs. Now this middle realm is being opened up by a full panorama of millennial climate cycles.

Other climate records in polar ice sheets and sea-floor sediments had already revealed some millennial cycles, one or a few at a time. But the reality of some cycles was uncertain, because the records were short and difficult to correlate the cycles. A record of climate extracted from Greenland's ice is changing all that by laying out the whole spectrum of midrange climate variations, from the well-known Milankovitch cycles of about 40,000 and 23,000 years, driven by the tilting and wobbling of Earth's axis, down the scale to cycles of 11,100, 6100, and 1450 years.

It is also sparking a fresh debate about their causes, as evidenced in a report to be published in the *Journal of Geophysical Research* by glaciologist Paul Mayewski, mathematician David Meeker, and their colleagues at the University of New Hampshire. In the case of the longer cycles, they point to possible reverberations of the Milankovitch cycles within the climate system. And for the 1450-year rhythm—which seems to cause abrupt shifts in climate—they make the intriguing suggestion that the waxing and waning of the sun may be the trigger.

That idea is likely to be met with the skepticism that has greeted past claims of sun-driven climate cycles. But even if the causes of these cycles remain controversial, their strength and regularity in the new record are impressing the climate community. "I thought Paul [Mayewski] was nuts at first," jests geochemist Michael Bender of the University of Rhode Island, "but I don't think so anymore. Some of the [cyclic] periods stand out and grab you. ... I think they are onto something important." Still, "there's going to be a lot of disagreement" about the cycles and how they work, says paleoceanographer Gerard Bond of Columbia University's Lamont-Doherty Earth Observatory, who works on climate cycles in marine sediments. "It may be a while before it all gets sorted out."

No one is questioning the quality of the data, which come from a more than 3-kilometer-long core drilled by the Greenland Ice Sheet Project Two (GISP2) (*Science*, 14 May 1993, p. 890). This core consists of snow laid down each year from modern times back

GISP2

Core values. Researchers working on the GISP2 ice core *(left)* extract chemical data that reveal a series of millennial climate cycles.

through the 10,000 years of the current interglacial period (called the Holocene), through the 100,000 years of the last ice age, and beyond. Researchers counted each year's layer of snow-turned-to-ice, marked by a band of summer dust, and so built up an annual climate record. While some studies have used oxygen isotopes to estimate past temperatures, this study monitored changes in atmospheric circulation by analyzing the varying amounts of chemical species blown onto Greenland, such as the sodium and chloride from sea salt, calcium from continental dust, and ammonium from vegetation at lower latitudes. Samples were taken on average every 2 years in Holocene ice and every 50 years in ice up to 110,000 years old.

"It's an amazingly clean data set," says Mayewski. Compared to other records that have pointed to millennial cycles, such as marine sediments and lake muds, GISP2 is relatively undisturbed, better dated, and covers more time. By doing a statistical analysis on eight chemical species in this record, the New Hampshire group traced changes in the circulation around the polar region and from lower latitudes. And they found that the waxings and wanings of these two circulation systems revealed a whole sheaf of periodic cycles.

In addition to the 40,000- and 23,000-year Milankovitch cycles, the team found 11,100- and 6100-year cycles previously reported from marine sediments. Both appear to be higher frequency oscillations somehow induced as the longer Milankovitch cycles reverberate through the climate system, much as overtones can be induced by plucking a taut string. For example, the 23,000-year cycle, driven by the wobbling or precession of Earth's axis, redistributes sunlight so as to alternately intensify summer heat in the Northern and Southern hemispheres. Land masses straddling the equator might then pick up temperature maxima from both hemispheres, producing a maximum in the tropics every 11,000 years or so (*Science*, 14 January 1994, p. 174). Other overtones would appear as diminishing maxima at successively higher frequencies, for example at 1/4, 1/8, and 1/16 of the length of the 23,000-year cycle, although researchers don't have geologic explanations for each one.

The 6100-year cycle is nearly as prominent as the 11,000-year cycle, but has been harder to explain. The New Hampshire group, however, has 12 peaks of this cycle in the past 70,000 years, and notes that seven of these peaks coincide with the seven great gushings of icebergs into the North Atlantic during the last ice age, called Heinrich events (*Science*, 6 January 1995, p. 27). The cycle maxima are also roughly correlated with less dramatic coolings during the mid-Holocene and with the Little Ice Age that froze northern Europe in the 17th century.

Mayewski and colleagues argue that this cycle is indeed a precessional overtone, with its effect amplified during glacial times by the ponderous piles of ice. These react so slowly that their response takes about as much time as the overtone cycle itself, about 5000 to 10,000 years. Similar timing of driving force and response can lead to an amplifying feedback, the way the regular pushing of a swing in synch with its motion can send it higher.

But there are so many possible Milankovitch overtones that almost any climate cycle can be matched with an overtone, whether or not the link is real, says paleoceanographer Scott Lehman of the University of Colorado. In general, "it's very hard to ... demonstrate causality," he says. And when it comes to the shorter cycles, pinning down a cause gets even trickier.

For example, the cycles of 3200 and 1450 years that the New Hampshire group has identified form a regular progression that again suggests precessional overtones. But such overtones are expected to decrease in amplitude toward higher frequencies, and the short 1450-year cycle leaps above this trend, dominating polar circulation on time scales of 3000 years and less. "It's definitely one of the big players," says Mayewski. "It pins every one of the rapid climate change events," abrupt coolings that chilled Greenland by more than 10°C in less than 10 years at intervals during the last ice age.

Too rapid to be tied directly to the behavior of the sluggish ice sheets, the 1450-year cycle may instead be linked to an inconstant sun, Mayewski says, an idea other researchers have suggested for cycles of 80, 208, 512, and 2300 years found in a variety of other records and now in the GISP2 core. Like these other cycles, he says, the 1450-year one also shows up in tree-ring records of carbon-14, which is produced in the upper atmosphere by cosmic rays that vary with solar activity.

"We have an amazingly close correspondence with the carbon-14 record," says Mayewski, a fact he considers to be strongly suggestive of a solar link. What's more, the GISP2 record of beryllium-10—a more reliable measure of solar activity that is produced along with carbon-14—closely tracks that of carbon-14, says Robert Finkel of Lawrence Livermore National Laboratory, who analyzed the beryllium-10 with Kuni Nishiizumi of the University of California, Berkeley.

Still, attributing any climate change to a change in the sun is likely to draw suspicion. Although new studies have fueled a revival in sun-climate links (*Science*, 8 March, p. 1360), such revivals have come and gone before, leaving a hard core of skepticism among many researchers. The beryllium-10 data—which few outside the team have seen yet—will have to be a very good match to win any converts, says Lehman. And some time-series analysts would like to see more statistical work on the identification of the 1450-year cycle, among others. The New Hampshire group's technique "needs to be tested by other methods," says Teresa King of UDP Consulting in Portland, Oregon. And when compared to other types of records, the ice cores don't always yield a perfect match. For example, although Bond sees evidence of Heinrich events in marine sediments, he sees no sign of the 6100-year cycle, for reasons no one can yet explain.

But the 1450-year cycle and others have passed at least one outside test. Pascal Yiou of the CEA-DSM in Saclay, France, applied different statistical methods to the records of a second Greenland ice core, drilled by a European consortium called GRIP, and to the Russian Vostok core from Antarctica and found similar periods as in GISP2. "I don't know if they are real," he says, "but at least they are reproducible." Clearly, the study of climate cycles is on an upswing.

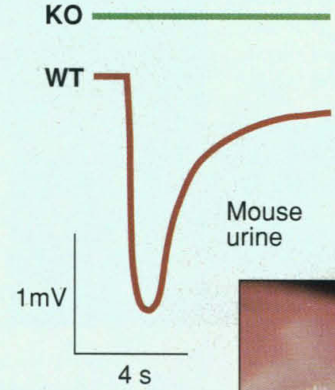
–Richard A. Kerr

NEUROBIOLOGY

Mutant Mice and Worms Help Solve Mysteries of Olfaction

Geoffrey Gold, a physiologist at the Monell Chemical Senses Center in Philadelphia, had wanted for years to put to rest a nagging question: How do odors trigger olfactory neurons to fire off action potentials to the brain? The dogma for the past 5 years had been that odors fall into two categories, each of which acts via a different intracellular messenger molecule. But Gold believed this view was wrong, and that all odors work by increasing the production of the intracellular messenger cyclic AMP (cAMP). One day last spring, Gold got a phone call out of the blue from neurobiologist John Ngai, at the University of California (UC), Berkeley, offering the possibility of answering this question. "It was my dream come true," says Gold.

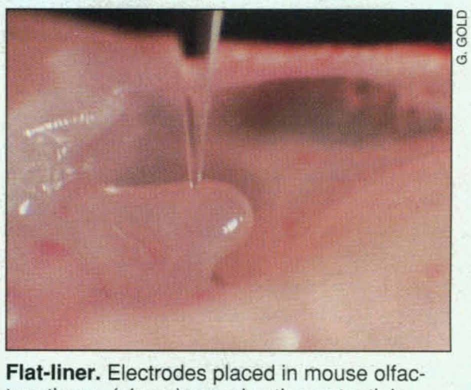
Ngai and his co-worker Lisa Brunet had made knockout mice whose olfactory neurons were missing an ion channel that cAMP must open in order to cause the neurons to fire. He invited Gold to test the mutant animals' response to smells. A month later Gold began the experiment, and the results were stunning—so much so that he thought his equipment wasn't working. "I was getting all these flat traces," he says, "I thought there was something wrong with my setup." But there wasn't anything wrong. The neurons were simply not responding at all to any of the odors Gold tested, implying that the mutant mice couldn't smell a thing. That finding, which is reported in this month's issue of *Neuron*, shows that the cAMP-activated ion channel is essential for the sense of smell. And that, says Gold, means cAMP is in fact the universal intracellular trigger for odor detection in mammals.



While not everyone in the olfaction field agrees with Gold that the case is closed, "the good thing about this [work] is that it activates this controversy and may stimulate people to go back and do more experiments," says Columbia University neurobiologist and olfaction researcher Stuart Firestein. And it has implications that reach far beyond olfaction. "I am excited because it is going to point to the role that these channels play in other organ systems," says neuroscientist William Zagotta, of the University of Washington, Seattle.

Indeed, ion channels activated by cAMP or a related cyclic nucleotide called cGMP may play roles in other sensory systems besides olfaction, and also in embryonic development and heart and brain function. The knockout mice, along with two mutant strains of the nematode *Caenorhabditis elegans* reported in the same issue of *Neuron*, promise to help researchers understand these myriad biological functions. In addition, the complete knockout of smell in the mice will make them useful in answering questions about the role of smell in mammalian behavior.

Ngai and Brunet didn't have such ambitious goals when they began the mouse project. They wanted to study mechanisms of olfaction, including the role of cAMP. Olfactory researchers have known since the late 1980s that many odor molecules raise cAMP levels in olfactory neurons in a variety of animals, and that cAMP can activate an ion channel that causes the neurons to fire. But Heinz Breer and his colleagues at the University of Stuttgart-Hohenheim in Germany had found that some odorants seem to trigger little or no rise in cAMP, and instead cause a burst in concentrations of another intracellular messenger molecule, inositol trisphosphate (IP_3). Breer's finding was complemented by work from Diego Restrepo at Monell and his colleagues, who found an IP_3-activated ion channel in olfactory neurons. That suggested that odor responses fall into two classes, one



Flat-liner. Electrodes placed in mouse olfactory tissue *(above)* record action potentials from normal mice (WT) in response to odors like mouse urine. Knockout (KO) mice show no response.