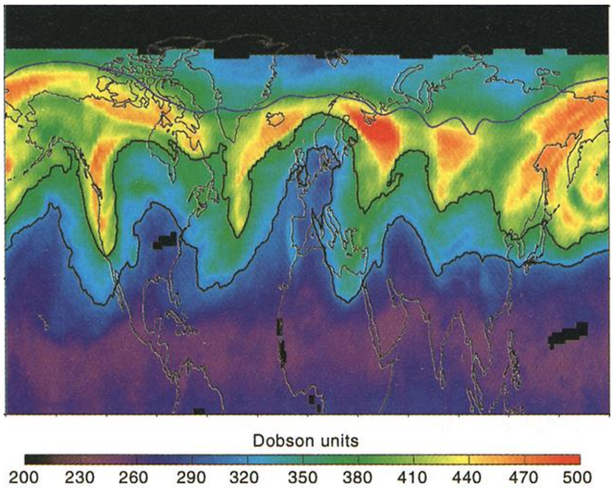
MEETING **AMERICAN GEOPHYSICAL UNION**

Of Ozone, Teapots, And Snowballs

BOSTON—Almost 3000 earth scientists of every stratum gathered here late last month for the spring meeting of the American Geophysical Union. Topics ranged from what's happening to the stratospheric ozone over Boston to how mysterious gullies formed on Mars and whether Earth really was one big snowball 600 million years ago.

Less Ozone Without Pollutant Chemistry?

Chemicals from refrigerators and air conditioners have long been the prime suspects in the erosion of the protective ozone shield over our heads, letting more and more ultraviolet radiation stream down. But one group presented evidence at the meeting implicating another perpetrator in the loss of stratospheric ozone over the midlatitudes: climate change, possibly the strengthening greenhouse. Researchers still see chlorofluorocarbons (CFCs) as the villains behind the destruction of ozone over the poles every spring, however.



Ozone palette. Shifting low (dark blue), moderate (blue-green), and high (yellow-red) ozone may be behind a midlatitude ozone decline.

CREDIT: R. HUDSON *ET AL.*

Based on an analysis of 15 years of satellite ozone measurements, "most of the ozone trends we're seeing [at midlatitudes] aren't due to chemistry," says ozone researcher Robert Hudson of the University of Maryland, College Park. "I think this is pretty firm." Others are intrigued but not yet convinced. "I take it very seriously," says atmospheric chemist James Anderson of Harvard University, "but it needs to be tested."

Hudson and his Maryland colleague Alexander Frolov used the downward-looking TOMS ozone sensor on the Nimbus 7 satellite to map out the global pattern of ozone abundance between 1978 and 1992. Typically, there is less stratospheric ozone overhead in the tropics, more at midlatitudes, and the most in the polar region, thanks to a thickening of the ozone-laden stratosphere from one zone to the next. That thickening occurs at the boundaries between the three zones: the subtropical front between tropics and midlatitudes and the polar front between midlatitudes and polar regions.

When researchers looked at ozone in the northern midlatitudes as they are usually defined—between 25° and 60°—they found that levels fell at a rate of 2% to 4% per decade through the period, the decline leveling off in the mid-1990s. But when Hudson and Frolov defined midlatitudes meteorologically, as the area between the two ever-shifting fronts, they found a very different picture: The amount of ozone overhead did not change at all through 1992. By their count, over time the geographical midlatitudes included more and more meteorologically tropical air, presumably because the subtropical front moved northward. "We think we're seeing a climate change here," says Hudson. "If we're right, and most of the ozone trend in midlatitudes is due to frontal movement, then even if we cut back the [CFCs], we aren't necessarily going to see a change in ozone trends at midlatitudes."

The redefinition of midlatitudes is getting a tentative reception. "It's a neat new way, a better way, of looking at ozone trends," says atmospheric physicist Paul Newman of NASA's Goddard Space Flight Center in Greenbelt, Maryland. However, he cautions, "it's still a little bit early" to conclude that climate rather than chemistry is to blame.

One thing researchers would still like to see is independent evidence of a northward shift of the fronts. By chance, that's what turned up in the June *Journal of Climate* paper by climatologist Gregory McCabe of the U.S. Geological Survey in Denver and his colleagues. They tallied the storms that tended to track along the Northern Hemisphere's polar front from 1959 to 1997 and found "a pretty large decrease in the frequency of cyclones in midlatitudes and an increase in high latitudes," says McCabe. That implies a northward shift in the storm track and in the polar front the storms follow, he says. And that's just what meteorologists would expect to have happened as the atmospheric seesaw known as the Arctic Oscillation drifted to the positive side over the past 20 years (*Science*, 9 April 1999, p. 241), drawing the fronts northward. Even farther along the meteorological chain of causation, some climate models have the Arctic Oscillation under the sway of increasing greenhouse gases. In that case, human activity could still be behind the decline of midlatitude ozone, but through climate rather than chemistry.

An Alternative to Snowball Earth

When a proposed scenario for a chapter of Earth's history is so catastrophic that most researchers balk at the sheer audacity of it, a milder alternative won't be long in coming. At the meeting, three researchers put forward just such an alternative to snowball Earth, the 10-million-year-long cold spell that some earth scientists believe iced over land and sea 600 million years ago. The group proposed tossing the snowball and substituting a slush ball. According to this milder view, it was cold in the tropics—indeed, permafrost was pervasive there—but not so cold that the ocean froze over, and life would never have been in danger of extinction. "They're starting to make a case" for milder glacial episodes in Earth's Neoproterozoic era, says paleontologist Bruce Runnegar of the University of California, Los Angeles.

In the prevailing picture of snowball Earth, ice averaging 1 kilometer thick sealed off the ocean from the atmosphere. It took 10 million years of volcanic outgassing to rescue the planet, building up enough carbon dioxide to create a supergreenhouse that eventually melted the ice. The rigors of the snowball, according to this view, may have triggered the evolution of multicellular organisms. But paleontologists have wondered how life could have withstood these rigors, and climate modelers have complained that the more realistic the models they used, the more difficult—even impossible—it was to freeze over the model globe (*Science*, 26 May 2000, p. 1316).

Avoiding these perceived difficulties, as well as others, geochemist Martin Kennedy of the University of California, Riverside, and geologists Nicholas Christie-Blick and Linda Sohl of the Lamont-Doherty Earth Observatory in Palisades, New York, reinterpret two key observations that underlie the snowball Earth hypothesis. The first is a dramatic enrichment of carbon's lighter isotope at the time of tropical glacial deposits. Geologist Paul Hoffman and geochemist Daniel Schrag of Harvard University had linked this abrupt isotopic shift to the sudden mixing of atmospheric, isotopically light carbon dioxide from volcanoes into the ocean as its ice cover melted. But Kennedy and his colleagues attribute it to the release of microbially produced, isotopically light methane gas long frozen in permafrost. In their scenario, as glaciers melted, rising seas would have flooded the land, warmed the icy methane hydrates locked in the permafrost, and released its methane into the shallow seas. Kennedy notes that light carbon is produced in arctic permafrost in quantities that, if extrapolated to Neoproterozoic glacial times, would account for the carbon shift. And bursts of methane from subsea hydrates have been linked to isotopic shifts in younger sediments (*Science*, 18 August 2000, p. 1130).

Their second reinterpretation concerns the odd carbonate sediments lying above the glacial deposits. Hoffman and Schrag argued that these "cap carbonate" sediments were precipitated from the supergreenhouse's carbon dioxide after it weathered continental rock and washed into the sea. But Kennedy and his colleagues believe they were produced by biological oxidation of the released methane. They think they can see traces where gases—presumably methane—rose through now-filled tubes in the cap carbonate from glacial deposits below. They also see disruption of sediments by gas flow and sediments once glued together by mucilaginous mats of microbes. In fact, it appears to them that cap carbonates most resemble deposits that form on the sea floor today where methane seeps up to be oxidized by microbes at so-called cold seeps.

The methane scenario got a mixed reception. "I think it's a much more viable mechanism myself," says geologist Maarten De Witt of the University of Cape Town in South Africa. "It's a very good way to produce a negative carbon [isotopic] spike." But the particulars of cap carbonates came in for more criticism. "I've seen a lot of fossil seeps," says paleontologist David Bottjer of the University of Southern California in Los Angeles. "From a distance, it's a reasonable guess these cap carbonate structures are seep-related, but on closer inspection it's likely not seeps at all." Tiny layers across the tubes might have been formed by microbial mats blocking gas from seeping through, he and others suggest. Proving they were seeps will probably require finding the powerful isotopic signature of methane in carbonate cements laid down directly from escaping gas. So far, no one has seen that proof.

Gullies and Lobes on Mars

The gullies of Mars, which have been appearing in images sent back from Mars Global Surveyor since 1998, are proving difficult to explain. The initial suggestion that they formed by water gushing out of the rock from subterranean aquifers seems unlikely, given the current deep freeze on the planet's surface; dry ice deposits bursting out seem too exotic, melting snow too prosaic. Now comes the giant teapot hypothesis.

A study of the gullies of Dao Vallis by planetary scientist Martha Gilmore and undergraduate Avi Stopper of Wesleyan University in Middletown, Connecticut, conjures up that analogy. Dao Vallis is a good area for gully spotting: Gullies turned up in 23 of 31 high-resolution images returned by Mars Global Surveyor, and the 600-kilometer-long valley's varied geology also allowed them to compare gully formation in different types of rock in the same background climate. Running down the valley, the exposed rock grades from the heavily layered lavas of the volcano Hadriaca Patera, through a mix of sediments, layered lavas, and impact debris, to nothing but jumbled impact debris near the great Hellas impact basin.

Drips from a teapot? Water distilled from deep within Mars may form gullies like these in Dao Vallis.

Gullies, it appears, much prefer layered rock. Gilmore and Stopper reported that they are common in the layered volcanic rock, less abundant in the area of mixed geology, and absent in the unlayered impact debris. And even within the volcanic rock, gullies prefer one or two particularly solid-looking layers. Gully formation, Gilmore and Stopper conclude, requires an impermeable layer of the sort volcanic lavas can provide but impact rubble cannot.

Gilmore and Stopper also see a relation between layering and another mysterious martian feature, the so-called "lobate structures," which have been interpreted as ice or ice-rich material. Lobate structures lie in alcoves as gullies do and appear to flow down from the same layers as gullies, sometimes side by side with them. Lobate structures seem to prefer valley walls with the least exposure to the sun, while gullies are more common on the sunniest, and therefore warmest, exposures.

All this reminds one of a teapot, albeit a chilly one. Water kilometers below the martian surface is gently warmed by the planet's meager interior heat, Gilmore and Stopper note. What little vaporizes could then diffuse upward through pore space toward the top of the "teapot." There it would condense and freeze near the surface. During times of climatic warmth, this ground ice could melt and percolate downward. If this water encounters an impermeable layer below, it could move laterally along it—as if out the teapot's spout—to a valley wall. If further warmed by the sun, the water might erode the wall to form an alcove and carry the debris downslope to form the gullies. If the sun weren't up to keeping the water liquid, it could freeze at the wall to form an icy lobate structure. The teapot mechanism could even work where aquifers are unlikely to feed gullies, note Gilmore and Stopper, such as seen on the central peaks of impact craters.

The teapot mechanism of gully formation "is a viable alternative" to the aquifer mechanism (*Science*, 30 June 2000, p. 2295), says planetary scientist James Zimbelman of the Smithsonian Institution's Air and Space Museum in Washington, D.C. It is also an alternative to snow nestled on the valley wall simply melting in the spring and washing downward (*Science*, 6 April, p. 39). But it isn't everybody's cup of tea. It leaves open the question of how the climate ever gets warm enough for water to approach the martian surface, notes planetary scientist Stephen Clifford of the Lunar and Planetary Institute in Houston. Periodic extreme tilting of Mars to warm the summers is the most promising idea so far.

Viable gullying alternatives aside, says planetary scientist John Mustard of Brown University in Providence, settling the origin, or origins, of martian gullies seems a distant prospect. Soon "we're going to have a half-dozen views equally supported by the observations," he says. Then researchers will have to ask themselves, "What data do we need to resolve it?" —RICHARD A. KERR

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