"With some relatively very simple ways of visualizing and plotting this stuff," he says, "we could immediately see the very nice nature of the traffic: When you looked at the [variation in the] number of packets per millisecond or per second or per minute, it always looked the same." Such self-similarity is a fundamental characteristic of a fractal process, as is the bursty behavior Willinger and Taqqu also observed. "You can see areas where the traffic behaves quite nicely," Willinger says, "and then periods where it's extremely variable and goes up and down like crazy."

> The discovery of fractal behavior "has certainly changed the way we think about network traffic."
>
> —Scott Shenker

Willinger and his collaborators published these findings 5 years ago to mixed reviews. Paxson, for instance, says he was "deeply skeptical" when he first read the paper, then tried to disprove it and couldn't. Now he describes himself as a "missionary zealot." To convince the rest of the community, says Willinger, he had to explain the fractal behavior, not just describe it. He did so with Taqqu, Wilson, and Robert Sherman, another Bellcore researcher, in a paper published in 1995.

To get at the root of the fractal behavior, the researchers looked at traffic between source-destination pairs in a network. They found that characteristics of the traffic—the duration of busy periods, for instance, or the size of the transmitted files—had what's known as a heavy-tail distribution. Whereas telephone call durations, in a Poisson distribution, are tightly clustered around a mean value, heavy-tail distributions include large numbers of values that are arbitrarily far from the mean.

Telephone calls, for example, might have a mean duration of a few minutes, never lasting less than a few seconds and rarely extending beyond 15 minutes—the classic three standard deviations that encompass 99% of the distribution. But machines communicating on a network don't have the same habits as humans on a telephone. The researchers found, says Willinger, that "the busy or idle periods could last from milliseconds to seconds to minutes and even longer." The actual size of the documents being sent also varied by as much as six or seven orders of magnitude. When traffic sources have this heavy-tail behavior, says Paxson, "there are theorems that say that you're going to get fractal correlations in your traffic."

In their latest work, presented this month in Vancouver at a meeting of ACM SIGCOMM, a networking association, Willinger and his AT&T collaborators Anja Feldmann and Anna Gilbert found that the structure of packet networks themselves also contributes to the bursty nature of the traffic, at time scales of less than a few hundred milliseconds. At least one reason for the behavior, says Willinger, is the way the dominant network protocols break up each electronic message into hundreds or thousands of packets before sending them over the network.

As Willinger and Paxson describe in their September article, they and others have now documented fractal behavior for traffic on the Internet as well as on smaller networks. "Everyone buys its existence now," says Shenker. "The only debate is over how much it affects design issues." Willinger and others cite one instance in which it already has: in the design of buffers for Internet routers, which store packets during busy periods until they can be sent onward to their destination. "If you look at first-generation Internet switches," Willinger says, "buffer sizes were very small, maybe big enough for a couple hundred packets. Now, they're two or three orders of magnitude larger, because engineers realized very quickly that with the fractal nature of traffic, buffers have to accommodate much more variable traffic than was assumed in a Poisson world."

Other AT&T researchers are monitoring network traffic to extend Willinger's work, says Calderbank. "Today we're really where Erlang was around the turn of the century," he says. "Like Erlang, we are trying to understand the fundamental nature of data traffic by taking measurements. If we could understand the mechanisms at work, then we could do the engineering so that applications would run better." **–GARY TAUBES**

GLOBAL CHANGE

Among Global Thermometers, Warming Still Wins Out

Recent analyses show that the gap between the satellite temperature record and that of thermometers at the surface is more apparent than real

Summer heat waves, together with forecasts of greenhouse warming, have convinced much of the public that the world as a whole has warmed in recent years. And temperatures recorded by thermometers at the surface show warming of about a half-degree during this century and a couple tenths of a degree during the past 2 decades. But there has been a nagging doubt: The 20-year-long temperature record compiled by satellites looking down into the atmosphere—by far the most complete, global temperature record ever made—has given the opposite answer, showing a slight cooling. Although most climate researchers rely on the longer surface temperature record, a few contrarians have seized upon the satellite data as evidence that the threat of greenhouse warming has been overblown.

The slight surface warming would not prove that greenhouse gases from human activity, rather than natural climate variations, are responsible. Nor would a slight cooling rule out a future greenhouse warming. But the apparent cooling has offered greenhouse skeptics a powerful public relations tool that has been applied from congressional hearings to *Reader's Digest*. If there is no warming in the satellite data—"our only truly global record of lower atmosphere temperature," as greenhouse skeptic Patrick Michaels of the University of Virginia, Charlottesville, puts it—then the surface data must be flawed and the threat of greenhouse warming much exaggerated.

Now, however, in the wake of new analyses of the satellite data, most researchers are more convinced than ever that the satellite cooling trend is not the show-stopper contrarians make it out to be. After considering the effects of El Niños and volcanoes and correcting for decay of the satellites' orbit, researchers are seeing not a cooling but a small warming. The error bars in these new analyses are larger than before, but the trend is close to that in surface records. Although the contrarians still aren't budging, leading satellite analyst John Christy of the University of Alabama, Huntsville—who has been reporting a cooling trend for a decade—agrees that the satellite data are compatible with a slight warming trend. The discrepancy between satellite temperatures and model predictions of moderate greenhouse warming "isn't that large," says Christy.

The satellites in question weren't designed to monitor global warming. Launched starting in 1979 for the National Oceanic and Atmospheric Administration (NOAA), they fly from pole to pole at altitudes of about 850 kilometers carrying instruments called Microwave Sounding Units (MSUs). These pick up the microwave glow of the atmosphere at about a frequency of 60 gigahertz, produced by oxygen molecules at an intensity that is proportional to their temperature. Analysts could fill in data-sparse areas in weather forecast models by inferring daily atmospheric temperatures from the MSU data.

In the 1980s, Christy and Roy Spencer of NASA's Marshall Space Flight Center in Huntsville realized that the global coverage of these data throughout the atmosphere would make them a gold mine for global change studies. They took the daily readings from the series of MSU-bearing satellites—now numbering nine—and spliced them into one long record of atmospheric temperature. By their reckoning of a few years ago, the lower part of the troposphere, centered at an altitude of 3.5 kilometers, had actually cooled at a rate of 0.05°C per decade between 1979 and 1995. That was a far cry from the warming of 0.13°C per decade recorded on the surface during the same period. And greenhouse computer models of that time called for an even larger warming of 0.25°C per decade. So the contrarian complaints began. Michaels began printing a monthly comparison of the cooling satellite data and the warming computer model predictions in his newsletter, *World Climate Report*.

Other meteorologists countered that the surface and satellite measurements wouldn't be expected to give identical values. The two observing systems "are not measuring the same quantity," says meteorologist James Hurrell of the National Center for Atmospheric Research in Boulder, Colorado. "Even if you assume both records are perfect, you're going to get different trends over 20 years." Climatic events such as El Niño's periodic changes in atmospheric circulation can have different effects on surface temperature than on the temperature several kilometers above the surface, he says.

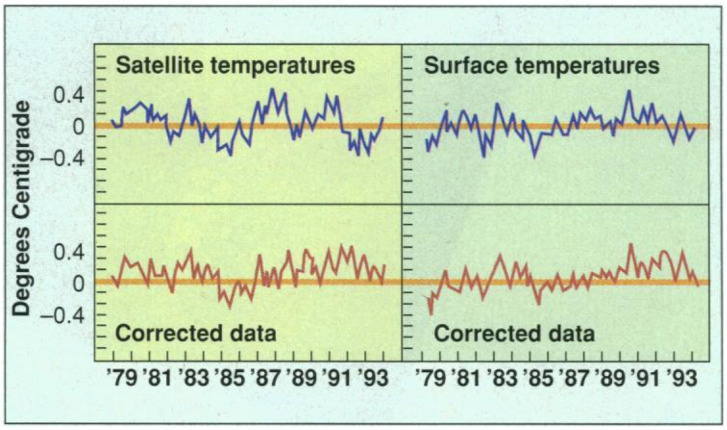
In any case, the satellite numbers are now looking more like those measured at the surface. New analyses of the errors incurred in splicing together the separate satellite records are driving some of the convergence. For example, in June's *Geophysical Research Letters*, remote-sensing specialist C. Prabhakara of NASA's Goddard Space Flight Center in Greenbelt, Maryland, and his colleagues published their own analysis of the satellite data. Prabhakara notes that when his group took full account of the error involved in splicing the record together, they found a distinct warming of 0.12°C per decade. They also estimated an error of ±0.06°C per decade, twice as large as previously assumed.

Then in August, remote-sensing specialists Frank Wentz and Matthias Schabel of Remote Sensing Systems in Santa Rosa, California, published another revised estimate in *Nature*. As atmospheric drag pulls a satellite into a slow descent of about 1 kilometer per year, they reported, some MSU readings that are measured at an angle from the satellite are taken at higher—and therefore colder—altitudes, thus reducing the measured temperature (*Science*, 14 August, p. 930). This orbital decay requires a correction of +0.12°C per decade, say Wentz and Schabel, bringing the 1979 to 1995 trend to +0.07°C per decade.

Once this problem was pointed out, Christy and Spencer immediately accepted the need for a correction. Christy says that when they applied the orbital-decay correction and added other corrections to account for such things as changes in the spacecraft's orientation, which affects how much the sun heats the MSUs, they still got a negligible cooling trend of 0.01°C per decade for 1979 through 1997. However, the team also widened their error bars from 0.03°C to 0.06°C per decade, in line with Prabhakara's estimate.

Christy now also has made an additional set of corrections to try to compensate for a basic problem of the satellite record: its shortness. "Twenty years is a very brief climate period," he says. And as climatologist James Angell of NOAA in Silver Spring, Maryland, points out, trends are "very sensitive to the length of record."

Angell provided a case in point recently when he reanalyzed another temperature record, this one derived from sensors on weather balloons. He found that the trend from 1979 to 1996 is –0.02°C per decade, much like the satellite trend. But when he extended the analysis back to the beginning of the reliable balloon record in 1958, the trend jumped to a warming of 0.16°C per decade. The main reason for the difference, says Angell, is that the satellite record begins too late to include a sharp jump in temperature during the 1970s.



Warming up. Raw temperature records (top) corrected for the effects of El Niños and volcanoes show a small warming trend (bottom).

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Even climate shifts that fall within a short record can skew the apparent trend. For example, if a temporary global warming, such as the one induced by the warm tropical Pacific during the El Niño of 1982–83, happens to fall near the beginning of a short record, any long-term warming trend will be muted or even reversed. The same would happen if a brief cooling, such as that produced by the 1991 eruption of Mount Pinatubo, falls near the end of the record. To help compensate, Christy attempts to remove the effects of El Niños and major volcanic eruptions in the MSU record. After this adjustment, the underlying trend through July 1998 shows a slight warming—between 0.03°C and 0.10°C ± 0.06°C per decade, according to Christy's latest calculation. That overlaps with the observed surface warming and is compatible with a real, albeit modest, global warming.

Despite these results, the contrarians aren't yet giving up. Michaels, for one, has answers for all the new corrections. He points out that after Spencer and Christy's orbital-decay correction, "you still don't see any warming." Nor is he bothered by the satellite record's shortness. The 1970s temperature jump it missed, he says, "is the only warming in the last half-century; if that's global warming, we don't understand it at all."

Most researchers, however, now see no major mismatch between satellite and surface temperatures. None of the temperature records—satellite, balloon, or surface—is ideal, notes climatologist Dian Gaffen of NOAA in Silver Spring. Given the available records, Gaffen and many other climatologists choose the longer ones. The 130-year surface record's 0.5°C warming of the past century (±0.2°C) is "virtually certain," says climate researcher Jerry D. Mahlman of the Geophysical Fluid Dynamics Laboratory in Princeton, New Jersey. In recent decades, the surface record has tracked the modest 0.1°C per decade greenhouse warming now predicted by climate models cooled by the shading of pollutant hazes. Such results don't prove that the strengthening greenhouse is behind the warming, of course—but neither can they be used to support the notion that the greenhouse threat is a fraud.

–RICHARD A. KERR