ow of a New York auto importer. And her bequest had fallen into limbo when she tragically died less than 24 hours after shaking hands on the deal—and before signing the papers.

The project's money worries were not resolved until January 1985, when Caltech bought itself an equal partnership with a \$70-million donation from the Keck Foundation, administered by the sons of the late oilman W. M. Keck. This also solved the problem of what to name the telescope. And of course, it enriched the project with Caltech's own powerful cadre of astronomers—who would now have to get half the observing time. "At the UC, everybody was disappointed to lose half the telescope," says Nelson. "But half of a real telescope is a lot better than all of an imaginary one." (Ten percent of the observing time will actually go to the University of Hawaii, which controls access to Mauna Kea.)

Then, however, came the truly difficult challenge: mass-producing the mirror segments. Forty-two would be needed in all, 36 for the full 10-meter mirror and 6 spares. "We always knew it would be hard," says Nelson. "But we had no idea it would be as hard as it turned out to be."

The difficulties became apparent almost as soon as work on the segments began in 1985 at Itek Optical Systems in Lexington, Massachusetts. The stress polishing worked well enough. But when the edges of the polished disks were trimmed to make them into hexagons, they warped. The warping was not entirely unexpected, says Nelson, but it was certainly more than the opticians could handle with touch-up polishing. So he and the Keck team had to redesign the mirror support structure, adding a "warping harness" behind each segment to bend it back into shape.

Next, the apparatus that Itek was using to measure the accuracy of the mirror surfaces turned out to have serious optical flaws of its own. After a loud and extensive debate, Smith overruled Nelson and decreed that rebuilding the apparatus would take too long and cost too much. So instead, the final test results are now obtained by taking the raw data and running them through a computer program that supposedly eliminates the effects of the flaw. Nelson is keeping his fingers crossed.

In fact, manufacturing the segments has proved so tough that the scientists have been forced to compromise slightly on their goals for optical quality. Presumably the telescope's users will never notice except on the most crystalline nights. But the images will be just a bit fuzzier than they ought to be.

Fortunately, however, as a slow but steady stream of finished segments has begun to arrive on Mauna Kea, things seem to be going more smoothly. The project passed a major milestone in early August when the team temporarily put three of the segments into the telescope and, for the first time, activated the computer-controlled alignment system. It worked beautifully.

The next, and most important, milestone will be the first light images later this autumn. Not only will these images tell the Keck team how good their segments really are, says Nelson, but if all goes well they will be Exhibit A in the project's fund-raising efforts for a second, identical telescope. No commitments have been made yet. But Caltech physicist Edward Stone, who is serving as chairman of the partnership, has gotten expressions of interest from the Keck Foundation and is deep in negotiations with other possible partners.

The possibility of a Keck 2 has actually been in people's minds for a long time, says Nelson. The site has already been laid out with space for a second dome. And the control room building adjacent to the existing dome has even been built with a tunnel running underneath, so that the two telescopes could combine their light into ultra-high-resolution images using a technique known as optical interferometry.

"Building a second telescope just like this one doesn't need me," says Nelson, who says he hopes to go back to being an astronomer when the first one is done. And yet—nobody actually knows how to do optical interferometry. And then there's the challenge of developing "active optics" for the telescopes to eliminate the distortion of the atmosphere and give their images space-like clarity. That sounds hard, says Nelson. "And *that's* what might interest me."

■ **M. MITCHELL WALDROP**

The Climate System as a Ticking Clock

The discovery of a 2-year "ticking" in the record of El Niño is fueling a growing awareness of biennial climate variations

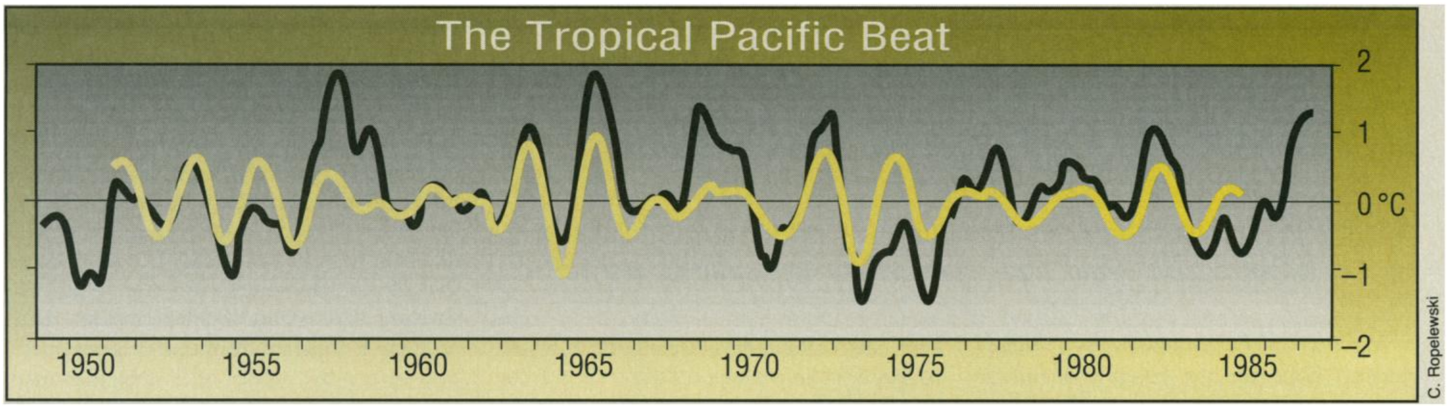
THE COOLNESS OF NIGHT follows the heat of the day; winter follows summer: these are the obvious short-term cycles of climate change. Now, climate researchers are detecting a periodicity that extends beyond these familiar rhythms of the day and of the seasons. They are picking up a more or less regular 2-year beat to the global climate system—one that seems to be heard from every quarter.

The Amazon tends to surge every other year, as does the Mindanao Current east of the Philippines. Winds over New Zealand tend to pick up and abate on a biennial schedule, as does the pace of the bimonthly cycle of cloudiness in the tropical Pacific. And the most recently discovered example of this climatic ticking—and perhaps the most intriguing—comes from the very core of El Niño. Researchers have found that some aspects of this cycle of alternating warm and relatively cold waters along the equatorial Pacific have a tendency to repeat every 2 years. The overlying winds pulsate at the same pace, as do the globe-girdling effects of the El Niño cycle, from winter warmth in Alaska to heavy rains in Peru and drought in Australia.

The climatic ticking in the tropical Pacific is hardly as reliable as the changing of the seasons. Sometimes it is muted, and occasionally it skips a beat. But some researchers nevertheless see hope of using it in the prediction of El Niño and its global effects. In any case, climate researchers are eager to determine what makes El Niño tick. The answer could be an underlying pacemaker of this crucial atmospheric cycle.

The biennial aspect of the El Niño cycle has been glimpsed now and again for more than a decade, but conventional wisdom has always maintained that El Niño displays an irregular rhythm. The intervals between strong tropical Pacific warmings range from 2 to 7 years and average 3 to 4 years, so how can it have a 2-year cycle? The answer, according to two recent studies, is that El Niño is paced by two different clocks—one with a 2-year beat and the other with a less well defined beat of 4 to 5 years. It is the combination of these two cycles that produces the appearance of a highly irregular rhythm.

In a recent paper, Eugene Rasmusson and Xueliang Wang of the University of Maryland and Chester Ropelewski of the National Oceanic and Atmospheric Administration's Climate Analysis Center of Washington, D.C., report the detection of a 2-year oscillation in the strength of the winds blowing over the surface of the western Pacific Ocean and eastern Indian Ocean.



The 2-year beat in the climate system (yellow curve) can be separated from the record of ocean temperature (black curve) in the central Pacific. The biennial cycle both contributes to the warmer than normal years that are El Niños, as in 1982–83, and counteracts cooling tendencies, as in 1974–75.

That is where wind shifts cause El Niño's ocean temperature shifts across the Pacific. These researchers also found variations in tropical winds on a time scale of 4 to 5 years that were superimposed on the biennial cycle.

These observations are supported by another study of the western equatorial Pacific. There, Tim P. Barnett of Scripps Institution of Oceanography has found similar short- and long-period variations in atmospheric pressure, winds, and the temperature of the sea surface. In both cases, the groups find that the biennial variation, rather than the longer cycle, resembles the climate extremes traditionally labeled El Niños.

The interplay between the biennial cycle and the longer period variation helps explain, in hindsight, two recent anomalous El Niños, says Rasmusson. In 1982–83 the biennial and the long-period variations of 4 to 5 years were in phase, both being at their strongest. When the two added together, the most powerful El Niño of the century resulted, Rasmusson notes. This Pacific warming, along with such disastrous effects as the worst Australian drought in 200 years, caught observers by surprise. On the other hand, El Niño watchers thought they saw signs of a Pacific warming in the works in 1974. They even mounted a hurried oceanographic expedition to probe what they assumed would be a growing El Niño. But the biennial cycle was out of phase and so snuffed out the warming.

Yet Rasmusson is quick to suggest that the 2-year component of the El Niño cycle cannot be relied upon in forecasting. The regularity of the biennial variation "is not like a pendulum's," he notes. "It misses a beat now and again." And Barnett has shown that its strength waxes and wanes on a roughly decadal time scale.

Conclude Rasmusson and his colleagues: "Thus nature, in a rather perverse fashion, has presented us with a biennial component of [El Niño cycle] variability that is regular enough to be identified and studied, but variable enough to significantly limit its use as an empirical prediction tool." Barnett, who has had some success in the El Niño prediction business, is more sanguine. He sees some prospect of extrapolating the behavior of the biennial variation perhaps a year ahead to decide whether a major warming event is in the cards or not.

While the biennial variation's usefulness in prediction may be open to question, meteorologists are already busy trying to figure out what is driving it. There are two schools of thought. According to one view, the fundamental pacemaker is found within the tropical Pacific Ocean itself. There, two types of slow-moving ocean waves bouncing back and forth along the equator combine to create a clock that, through changes in sea level, switches the ocean—and thus the atmosphere—from warm phase to cold phase and back again (*Science*, 11 December 1987, p. 1507).

To test this hypothesis, Matthias Münnich, Mark Cane, and Stephen Zebiak of Columbia University's Lamont-Doherty Geological Observatory built a computer model containing the bare essentials of the internal clock mechanism. When they ran the model, they found that it does indeed produce a 2-year oscillation in the ocean and atmosphere. This oscillation, which Cane sees as the fundamental period of the Pacific system, is determined by the time it takes the slow ocean waves to cross the Pacific basin and by how strongly the winds and the ocean interact. The model even generates a 4-year cycle when atmospheric disturbances from beyond the equatorial region destabilize the shorter cycle.

Some modelers may prefer an internal pacemaker for El Niño, but another camp emphasizes an external clock—the annual cycle of the changing seasons. Rasmusson sees the seasonal cycle as a fundamental pacemaker for El Niño because the biennial cycle he sees in the Pacific is often in step with the seasonal cycle. But just how the annual cycle impresses itself on the tropical Pacific to produce a biennial variation is far from clear. Every meteorologist favoring a role for the annual cycle seems to have his own theory. One is that with the seasonal cycle rhythmically driving the climate system once a year, this annual cycle would excite a sympathetic oscillation having a 2-year period, the so-called subharmonic of the annual cycle. Or, maybe a year of subdued seasonal changes in the tropical Pacific could set up conditions favoring extreme seasonal shifts the next year that in turn favors another weak cycle the third year.

These conundrums haven't discouraged climatologists from taking a fresh look at other 2-year cycles of regional weather patterns. "You can hardly pick up a long-term observation series that doesn't have some sort of biennial oscillation in it," says meteorologist John Anderson of the University of Wisconsin. "It's strong in everything and we don't know why."

But the general mystification has not stopped an intrepid few, such as William Gray of Colorado State University and Tetsuzo Yasunari of the University of Tsukuba in Japan. Indeed, these two see biennial variations in the lower atmosphere being orchestrated by a well-known cycle called the Quasi-Biennial Oscillation (QBO). The QBO is a cyclic wind shift of the lower stratosphere. Gray sees a link between the QBO and hurricane intensity, and Yasunari has suggested that the tropical Pacific also responds to the QBO. Others say it can't be so; all the biennials are unrelated regional responses to the annual cycle. Sorting out the possibilities will be a problem that surely won't be solved on a biennial time scale.

■ RICHARD A. KERR

ADDITIONAL READING

E. M. Rasmusson, X. Wang, C. F. Ropelewski, "The biennial component of ENSO variability," *J. Mar. Sys.* **1**, 71 (1990).