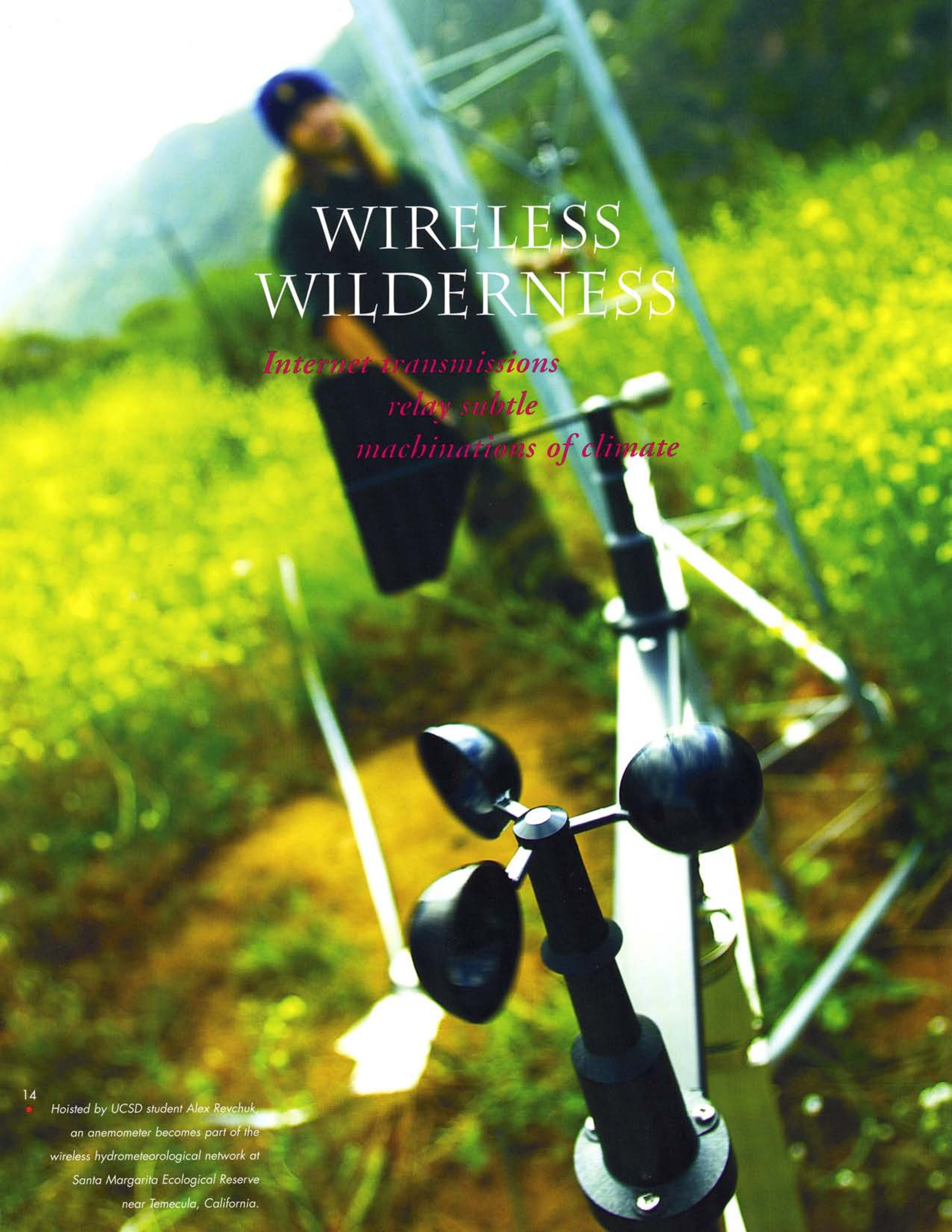
WIRELESS WILDERNESS

Internet transmissions relay subtle machinations of climate



Hoisted by UCSD student Alex Revchuk, an anemometer becomes part of the wireless hydrometeorological network at Santa Margarita Ecological Reserve near Temecula, California.

OBSERVATION

BY ROBERT MONROE

AROUND THE FIRST OF APRIL, the rivers of the Sierra Nevada seemingly reawaken like the hibernating wildlife around them. As if inhaling and exhaling, the rivers swell and subside, varying in height by as much as 20 percent every spring day. The flux is caused by the melting of mountain snow as the days get warmer and sunnier. The snow refreezes at night only to melt again when exposed to the next day's light.

In 2001 the director of the Scripps Climate Research Division, Dan Cayan, and colleagues published a discovery that, for California lawmakers and the general public, put this annual spectacle of nature in a new and disturbing light. Cayan had found that throughout the second half of the twentieth century, spring seemed to be coming earlier each year. Two very different measures—the timing of initial snowmelt in western rivers and the blooms of temperature-sensitive flowering plants—each suggested that the spring time clock had advanced by one to two weeks.

The shift to earlier snowmelt means that the source of water for much of California was trickling away earlier than in previous decades. While one to two weeks earlier doesn't seem very substantial, the trend could lead to drastic consequences. Cayan's study also suggested that in a place particularly at the mercy of climate trends,

the global warming that scientists had been predicting might already have begun to express itself. The analysis relied on daily averages of the flow of western rivers recorded by the U.S. Geological Survey. Cayan and colleagues believe, however, that there's more to be learned with finer grained spatial coverage and more frequent sampling of the West's hydrology.

"We need to know where snow accumulates and how it melts—when, where, and how much. We need a more extensive set of observations to enable us to detect and understand how these characteristics will change over the next few decades," Cayan said.

PRECISE MEASUREMENTS IN PRISTINE PLACES

On Cayan's laptop computer at his Scripps campus office, a future version of mountain climate observation manifests itself in a time-series readout showing spiky fluctuations of water pressure and temperature. On screen are measurements taken every half hour from several sites spaced out about 10 kilometers (6 miles) apart along a river. The measurements represent clues to understanding the mountain ecosystems that act as natural reserves of water and absorbers of carbon dioxide. At places like Yosemite National Park and the Santa Margarita Ecological Reserve near Temecula, California, Cayan and his team are installing and operating dozens of automated hydrometeorological stations that will eventually telemeter real-time data back to Scripps.

What's to be gained from such precise record keeping? At the group's field sites along the Merced and Tuolumne rivers in central California, detailed measurements of water pressure and temperature, the amount of precipitation distributed across the upstream river catchment, and where and when snow began to melt provide an account of the water that has accumulated in river basins from Pacific storms and other climate influences. The Scripps team can even detect the daily lowering in river height that represents the uptake of water by vegetation in the watershed during the spring and summer growth period. Repetition of these measurements reveals a detailed profile of a river's response to climate that should prove useful for calibrating models of future climate changes. An ongoing flow of such information could provide early warning of impending flooding or future droughts. "If we know enough about it, we hope to detect subtle changes in climate acting on a snowmelt basin," Cayan said. "Although we're looking at high-frequency wiggles in river flow, we

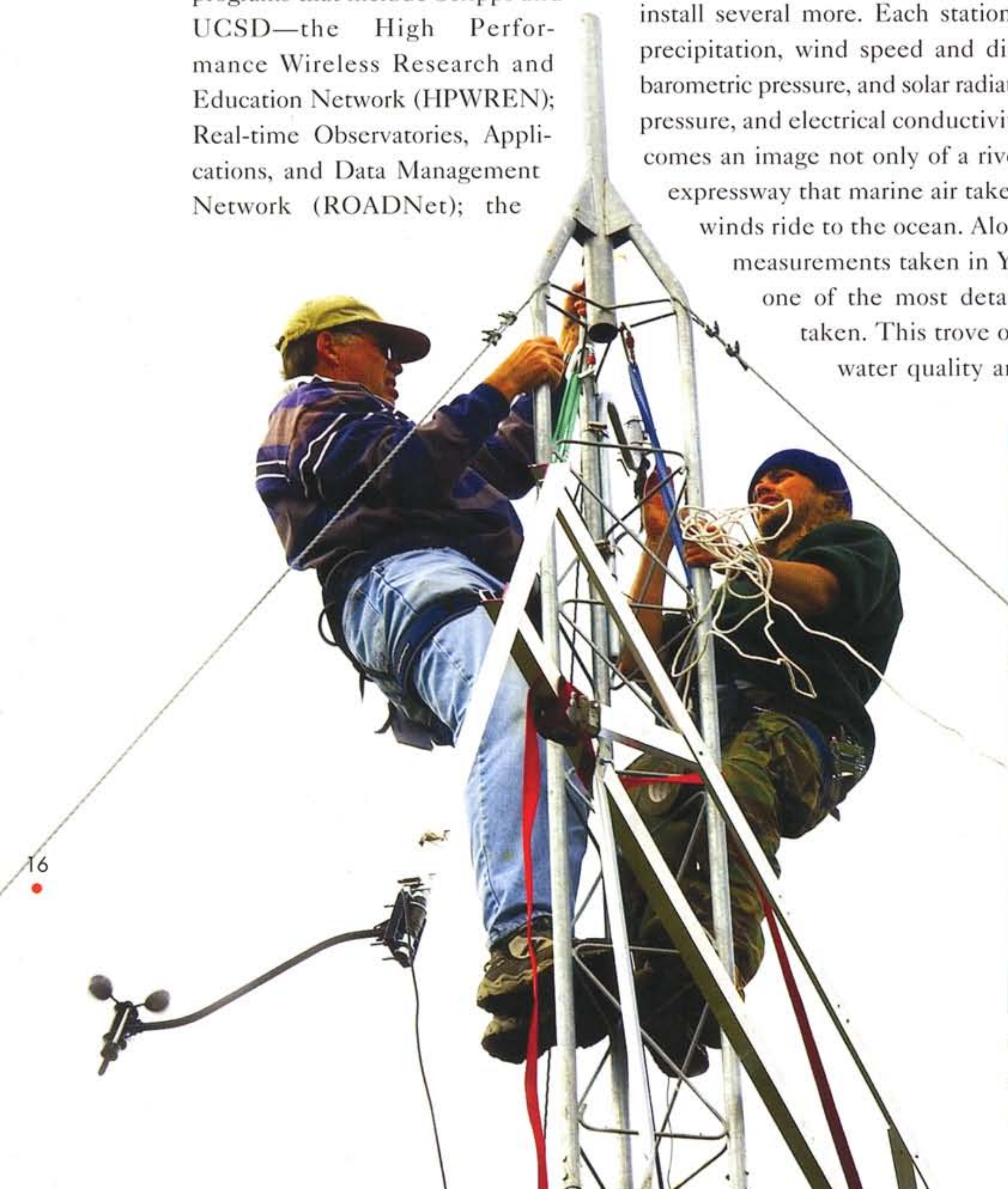
will use the pattern of these wiggles to get a fix on the trajectory of change over time caused by climate forcing."

Nearly 650 kilometers (400 miles) to the south of Yosemite, the Santa Margarita Reserve just might be the world's most technologically advanced patch of wilderness.

About 65 percent of the reserve's 1,700 hectares (4,300 acres) have wireless Internet coverage provided by several multi-institutional programs that include Scripps and UCSD—the High Performance Wireless Research and Education Network (HPWREN); Real-time Observatories, Applications, and Data Management Network (ROADNet); the Santa Margarita Ecological Reserve; and the California Institute for Telecommunications and Information Technology (CAL [IT]²). The Scripps group has established a network of meteorological stations throughout the reserve. The stations collect measurements every second that are averaged out every minute and then posted to the Internet, where Scripps researchers and anyone else who is interested can view the data.

Above, *Alex Revchuk (left) and Dan Cayan talk strategy at Santa Margarita.*

Some 20 stations now dot the reserve and the researchers hope to install several more. Each station houses instruments that measure precipitation, wind speed and direction, air temperature, humidity, barometric pressure, and solar radiation. Stream sensors log temperature, pressure, and electrical conductivity. From this suite of measurements comes an image not only of a river channel but also of the two-lane expressway that marine air takes to the interior and that Santa Ana winds ride to the ocean. Along with the different types of river measurements taken in Yosemite, the network could deliver one of the most detailed portraits of a watershed ever taken. This trove of data will help policy makers with water quality and fire management decisions and



Left, *Cayan and Revchuk add an anemometer-bearing platform to one of the reserve's 20 stations.*

EL NIÑO AND HIS BROTHERS

The year was 1994. El Niño would be peaking the following winter, and in the offices of the Climate Research Division (CRD) at Scripps, a cabal of scientists dared for the first time to dabble in futures on the Chicago commodities exchange. The scientists' own weather forecasts provided them with what they thought was the ultimate legal insider-trading information.

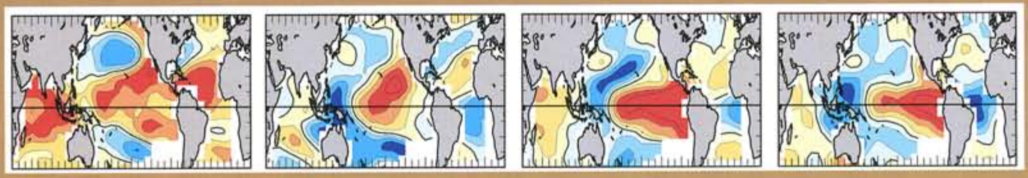
The forecast was for less than normal rainfall in the upper Midwest states, thereby reducing the winter soybean yield from farms west of the Great Lakes. The scientists invested in soybean futures and waited patiently for prices to reach record highs.

Even though they got the forecast right, nature foiled their investment plan. The following winter El Niño occurred as forecasted and led to a terrible soybean yield in the Midwest. The bumper crop, however, simply went south along with the scientists' plans for a big score. This same El Niño enabled Brazil to experience one of the best soybean production years in its history.

If only multiple-taper-method–singular-value decomposition (MTM–SVD) analysis had been around then to aid the CRD researchers. This analysis, developed by a pair of researchers at the University of Massachusetts and Yale University in the mid-1990s, has quietly revolutionized the way scientists visualize climate change. They found that climate variability is composed of a finite number of global modes and processes that evolve slowly to produce climate change over most of Earth's surface.

MTM–SVD has allowed a full global view of climate variability, said Scripps climate scientist and erstwhile soybean investor Warren White, who has gained a new appreciation of such perspectives.

Since then, climate scientists like White have revealed the existence of other global climate signals besides El Niño that influence year-to-year changes in temperature and precipitation. The well-known El Niño–Southern Oscillation has a cycle of about 3.5 years but is only one in a hierarchy of global signals that occur on different time scales.



Above, *El Niño, shown second from right, characterized by sea-surface temperature.*

Other signals include the quasi-biennial oscillation with a 2.2-year cycle, the quasi-decadal oscillation with a near-11-year cycle, and the bidecadal oscillation on a 15- to 25-year cycle.

White's own contribution is transforming climate observation from still photo to motion picture animation. He is a pioneer in modeling the propagating-wave nature of these global signals. Despite their different frequencies, these signals produce remarkably symmetrical patterns of sea-surface temperature and pressure that travel slowly eastward around the globe, taking years to make a complete revolution. White's work has opened a door to improved long-term prediction.

For collaborators like Gregory McKeon, a rangeland scientist with the State of Queensland Department of Natural Resources and Mines in Australia, such predictions have tremendous potential benefits. McKeon provides drought alerts to ranchers, whose sheep and cattle graze vegetation in the country's rangeland. Eight times in the past century, Australia has suffered through severe, multiyear droughts responsible for plant and livestock die-offs, erosion, and weed infestations termed "degradation episodes."

With White's help, McKeon is linking the interdecadal cycle of Australian drought to the evolution of the global signals observed in the MTM–SVD analysis. This is expected to give Australia's producers of beef, wool, and other key exports crucial advance warning.

"Warren White's work is the first sign of hope that we might be able to explain and perhaps predict the occurrence of these extended drought periods and thus save Australia from the nightmare of another degradation episode in the rangelands," McKeon said.

White and McKeon have found that Australia's rainfall is affected less by El Niño, once the main source cited for drought, and more by the quasi- and bidecadal oscillations, especially during multiyear periods when the two signals superimpose constructively. These observations would have been indistinguishable to climate scientists 10 years ago.

Using the MTM–SVD analysis, White and collaborators have found that many of the drought indices over land respond to the evolution of these global signals over adjacent oceans. White and Scripps's Alexander Gershunov are working to predict seasonal precipitation anomalies at lead times up to three months, though White hopes someday to give forecasters like McKeon as much as a one-year head start on drought preparation.

—*Robert Monroe*

A HISTORY LESSON

If he had the guts when he was younger, Alexander Gershunov would have been a history major. He was worried about his ability to find a job after graduation and majored in math en route to becoming a climate scientist. But in time, all things can be reconciled and, now, Gershunov is getting to be a historian of sorts after all.

To understand possible human effects on climate change, Gershunov is reconstructing the climate of recent centuries through the use of proxy records such as tree-ring formations.

"The trouble with understanding anthropogenic climate change is that you have to first understand what natural climate variability is like," Gershunov said. "The point of this research is to understand past climate variability in the Pacific Ocean without which anthropogenic forecasts for North America are basically meaningless."

While the concept of using tree rings, coral growth, or gases trapped in glacier ice to look for past El Niños is not new, Gershunov believes that proxy records hold much more information. Spatially extensive chronologies can be used to reconstruct not just individual climate indices but spatial patterns of climate hallmarks like temperature and precipitation over vast areas and lengthy periods of time. Using the statistical modeling techniques employed in forecasting, Gershunov relates patterns in the records to the sea-surface temperature field of the entire Pacific, a major determinant of climate in the Americas.

Gershunov was working on making regional forecasts seasons in advance when his look at the past began. He and Scripps colleagues have been increasingly successful in creating forecast tools that utilities and other resource managers can use to predict events like heatwaves or heavy rains.

The forecasts are the result of two kinds of models. Statistical models relate the spatial patterns of key climate drivers such as sea-surface temperature to seasonal statistics of a weather variable over an area of land. In Gershunov's case, he links patterns in Pacific Ocean temperature to frequencies of extreme weather events in the United States.

Gershunov also uses a hybrid dynamical–statistical model to make similar forecasts. This approach uses the atmospheric circulation computed by a global dynamical model and statistically downscales the large-scale circulation patterns to regional weather statistics of interest. The statistical downscaling component provides a reality check for his forecasts.

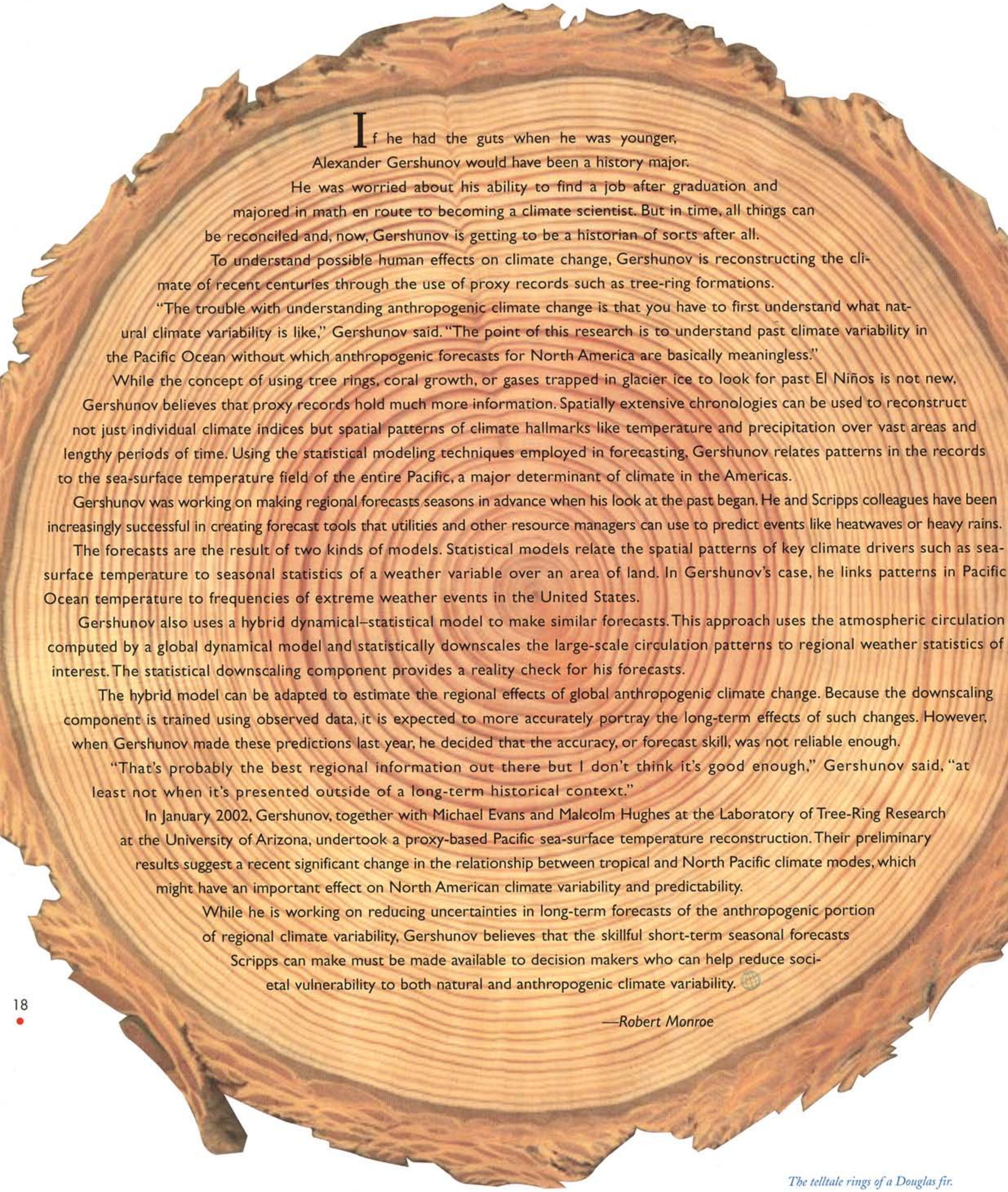
The hybrid model can be adapted to estimate the regional effects of global anthropogenic climate change. Because the downscaling component is trained using observed data, it is expected to more accurately portray the long-term effects of such changes. However, when Gershunov made these predictions last year, he decided that the accuracy, or forecast skill, was not reliable enough.

"That's probably the best regional information out there but I don't think it's good enough," Gershunov said, "at least not when it's presented outside of a long-term historical context."

In January 2002, Gershunov, together with Michael Evans and Malcolm Hughes at the Laboratory of Tree-Ring Research at the University of Arizona, undertook a proxy-based Pacific sea-surface temperature reconstruction. Their preliminary results suggest a recent significant change in the relationship between tropical and North Pacific climate modes, which might have an important effect on North American climate variability and predictability.

While he is working on reducing uncertainties in long-term forecasts of the anthropogenic portion of regional climate variability, Gershunov believes that the skillful short-term seasonal forecasts Scripps can make must be made available to decision makers who can help reduce societal vulnerability to both natural and anthropogenic climate variability.

—Robert Monroe



The telltale rings of a Douglas fir.

Top, *Graduate student Jessica Lundquist stores river water samples.*
Bottom, *Volunteer Julia Dettinger.*

should be invaluable for understanding the ecology of a southern California chaparral community.

As impressive as the level of detail the scientists are retrieving are the means by which they gather the data. The near-real-time transmission of data from the ecological reserve is envisioned for Yosemite as well. This will first require improving communication capabilities in a remote part of California. As it is, Scripps researchers and students are participating in several annual expeditions to the Sierra Nevada to retrieve data loggers out of icy streams. Team members extract months of data from the nondescript instrument packages, noting their location for future retrieval. The growing southern Sierra Nevada network is situated in an environment that is for the most part far away from people but at the center of important hydrologic activity. "We're trying to provide the seeds of a better western observation-

PHYTOPLANKTON COLORS CLIMATE

Above, *Different colored species of phytoplankton swirl in the Black Sea as dust from the Sahara Desert blows in from the west.*

The intensity of tropical monsoons and desert sandstorms could be linked to the aggregation of tiny ocean creatures.

Phytoplankton blooms are enough of a presence to redistribute solar heat on the upper levels of the ocean and in turn influence atmospheric circulation, said Scripps climate scientist Robert Frouin.

In a unique study, Scripps graduate student Karen Shell and Frouin used satellite imagery that detects phytoplankton levels by observing ocean color. They fed that information into an atmospheric circulation model and determined that phytoplankton absorbs enough sunlight that warming at the ocean surface can be amplified and warm the lower troposphere by as much as one degree Celsius (1.8 degrees Fahrenheit). In computer simulations, the air-temperature change at ocean surface level is enough to measurably affect summer rain on the Indian subcontinent and dust transport from the Sahara Desert.

"You have a warmer summer and a cooler winter in the presence of phytoplankton," Frouin said.

The study takes on added significance in light of recent findings that, in many parts of the world's oceans, phytoplankton exist in quantities large enough to damage marine ecosystems. The increase is believed to have been at least partly caused by human activities such as the use of fertilizers, which make their way into the ocean, stoking phytoplankton growth.

Frouin said that their findings can help make future studies of climate change more accurate by correctly accounting for a factor whose significance was unknown until now.

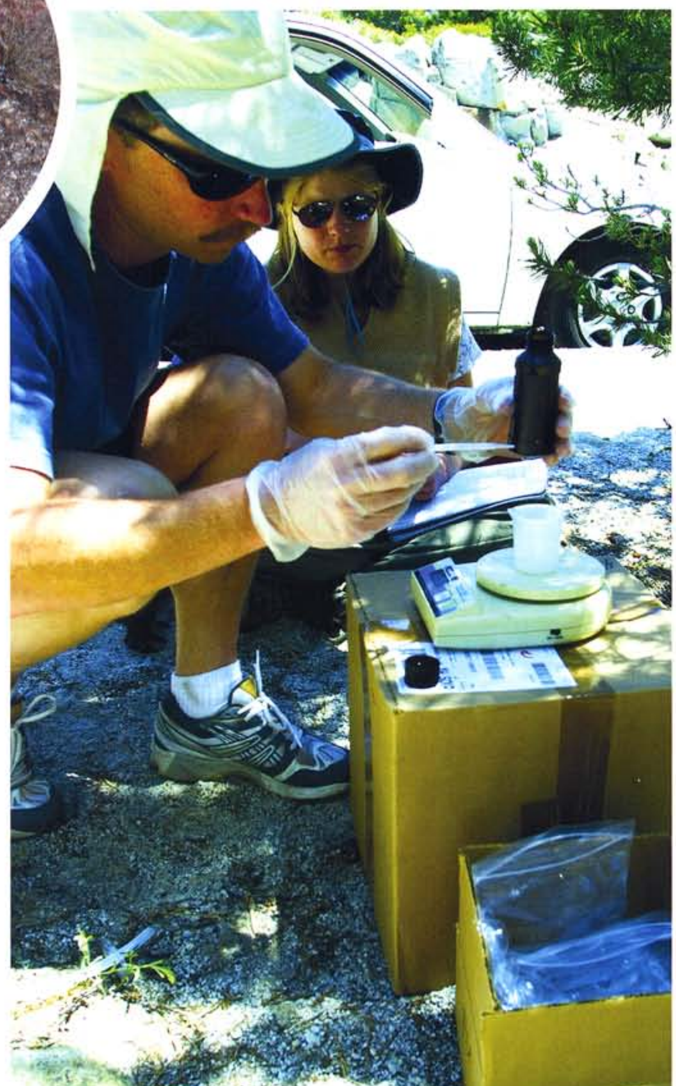
"Especially on regional scales, this would have a significant effect," Frouin said.

—Robert Monroe

al network where we can observe a lot of processes in much better detail," Cayan said.

Cayan estimates that the data loggers, communications transmissions, and basic sensors will cost less than $1,000 each when their development is complete. The loggers run on nothing more than a package of D-cell batteries. At prices like that, intense coverage of California wilderness becomes affordable. Given the challenges California resource managers face in ensuring the state's water supply, a lack of understanding of such key processes is something its millions of residents cannot afford.

Before joining Scripps meteorologist Cayan's research team as a graduate student, Jessica Lundquist camped in Tuolumne Meadows in Yosemite National Park many times as a child. Today's visits to the meadows include wading into river waters barely above freezing to take measurements or deploy instruments. Her urgency of understanding the hydrology of the region is based on her own experience. From her camping trips as a child, she remembers the area's temperatures falling to freezing or below each night, even in July. This past summer, after a snowstorm at the end of June, July was quite warm. On July 18, a series of thunderstorms hit the Sierra Nevada region, and for the rest of the month the lowest temperature



Opposite, *Jessica Lundquist takes readings from a flowmeter in a Tuolumne Meadows creek.* **Above,** *Mike Dettinger, Lundquist, and Dan Cayan look on as dye is poured into Yosemite Creek. Its downstream dilution is another indicator of flow rates.* **Right,** *Dave Clow of the U.S. Geological Survey measures dye before use.*

Lundquist experienced there was six degrees Celsius (43 degrees Fahrenheit). She found out later that this July had the highest recorded minimum temperature in 46 years. The average July temperature was the third warmest in 45 years.

Additionally, during her nine-week stay in Yosemite during the summer, a group of vertebrate biologists visited her base camp in Tuolumne Meadows. They were revisiting a survey of mountain fauna that had been performed 100 years earlier. Among the preliminary

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Below and opposite top, *Joel Norris used millions of ship log entries dating from 1952, the year of Scripps's Capricorn Expedition.*

39.9 MILLION LOG ENTRIES CAN'T BE WRONG

A recent study of cloud cover suggests that nature is doing what it can to counteract global warming—but the earthbound might want to seek out shade anyway.

Scripps atmospheric scientist Joel Norris has found that in the past 50 years, a time period in which scientists have observed a marked increase in global temperatures, cloud cover at higher levels in the atmosphere has diminished. The decline of such clouds has had a net cooling effect on the planet because more thermal radiation emitted by the earth can escape to space.

The historical perspective on cloud-cover change might help researchers understand a big variable in global-warming scenarios. Current estimates of warming over the next century forecast an increase ranging between 1.5 and 4.5 degrees Celsius (2.7 to 8.1 degrees Fahrenheit). Scientists can't be any more specific, in large part because of researchers' limited knowledge of clouds.

"This is the biggest physical uncertainty in our understanding of climate change," said Norris, whose interest in cloud variability goes back to his days at the University of Washington, where he received his doctorate in 1997. "How much warming there will be depends on what the clouds will do."

Norris is the first researcher to paint a long-term portrait of ocean cloud-cover change. To do such, he processed data from weather logs maintained by crews on ocean-going vessels. Some data precede the advent of satellite observations, making the handwritten records the only source of information about day-to-day cloud conditions in existence.

The practice of noting cloud cover and types dates back to the mid-nineteenth century. The original purpose of the observations was to help ships improve their navigation across busy trade routes by enhancing understanding of currents and winds. Crew members would note temperature, wind speed, and other conditions about every six hours. To this day, the best-documented areas of ocean are the tracks regularly traveled by commercial vessels. By contributing to weather reports along their routes, all ships receive better forecasts of upcoming storms and other inclement conditions.

In 1949, the modern code for reporting cloud types was implemented. Aided by a cloud chart, observers mark stratocumulus (the common morning overcast cloud) as a Type 5, a cumulonimbus (thunderstorm cloud) as a Type 9, and so on. Norris used 39.9 million weather reports made between 1952 and 1997 to create his record of cloud-cover change. The observations had previously been collected and digitized into computer files that allow easy sorting.

When beginning his research, Norris could not be sure how accurate the weather logs would be. For one thing, the observations were not made according to the rigorous parameters of a scientific survey.

"Basically it's just this guy out on a ship. How much training does he have? Yet I've found that the observations are remarkably realistic," Norris said.

Norris divided the oceans between 60 degrees latitude south and 60 degrees north into a grid. Into each 10-degree grid box for each 72-day time interval, he averaged data from the weather reports to create cloud cover values at specific locations between 1952 and 1997. Upper-level clouds such as cirrus, altocumulus, and altostratus were the ones crucial to Norris's study because they trap thermal radiation within the atmosphere, thus creating a greenhouse effect. Clouds at all levels also reflect sunlight back to space. Norris used a simple calculation to convert variations in cloud cover to variations in outgoing thermal radiation and reflected sunlight.

He found that the observational data agreed surprisingly well with the satellite cloud data, which has only been available since 1985. The satellite data

confirmed a trend of declining high-level cloud cover that Norris could confidently date back to 1952.

Though fewer high-level clouds means that more sunlight has been reaching Earth's surface, it also means that the clouds are trapping less outgoing thermal radiation.

"You have two competing trends here," Norris said. "Letting more radiation out seems to be slightly dominant." Because the oceans cover 70 percent of Earth's surface, changes taking place above them likely represent what is occurring elsewhere on the planet.

Norris has not yet determined whether the decrease in cloud cover is human-made or natural. Before he reaches any conclusions about the cause, his study will likely have more immediate value elsewhere. For example, it can be used as a measure of the accuracy of the computer models that create global climate change forecasts. The millions of measurements taken by deckhands around the world for more than 50 years now have a new place in the scientific canon.

"A change in the fractional area covered by clouds of a percent or two could have as much influence on the climate as a doubling of carbon dioxide," said Dennis Hartmann, chair of the University of Washington's Department of Atmospheric Sciences, "so careful measurement of trends in cloud amount or type is of central interest in assessing the likely magnitude of warming that we expect from greenhouse gas increases."

—*Robert Monroe*

Below, *From left, Dan Cayan, Jessica Lundquist, and Mike Dettinger back at camp in Yosemite.*

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findings they mentioned to her in passing was the discovery of a particular breed of mouse not mentioned in the 1903 study. Historically, the mice had only been found at lower elevations, now they were found living 914 meters (3,000 feet) higher than they had before.

Despite the possible meaning of such changes, there is still basic research to be performed to determine just where water comes from in California's mountains and where and how it travels.

"Right now we know so little about mountain hydrology," Lundquist said. "We're not rewriting the textbooks. We're just trying to begin to fill in the missing gaps."