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WEATHER

WHAT WE CAN AND CAN'T DO ABOUT IT

SPRING 2000 VOLUME 11 NUMBER 1

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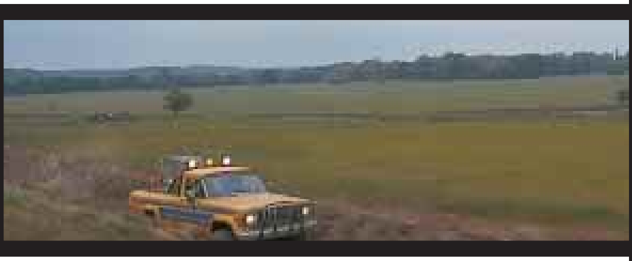

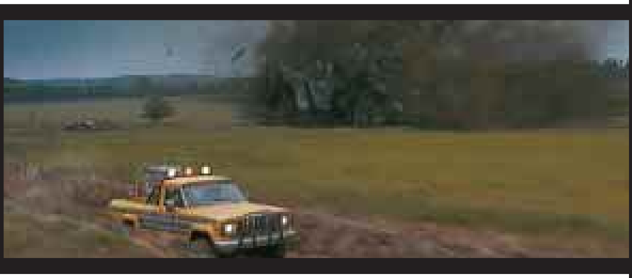

Scientific American Presents (ISSN 1048-0943), Volume 11, Number 1, Spring 2000, published quarterly by Scientific American, Inc., 415 Madison Avenue, New York, NY 10017-1111. Periodicals Publication Rate. Postage paid at New York, N.Y., and at additional mailing offices. Canadian BN No. 127387652RT; QST No. Q1015332537. Subscription rates: one year $19.80 (outside U.S. $23.80). To purchase additional quantities: 1 to 9 copies: U.S. $5.95 each plus $2.00 per copy for postage and handling (outside U.S. $5.00 P&H); 10 to 49 copies: U.S. $5.35 each, postpaid; 50 copies or more: U.S. $4.75 each, postpaid. Send payment to Scientific American, Dept. SAQ, 415 Madison Avenue, New York, NY 10017-1111. Postmaster: Send address changes to Scientific American Presents, Box 5063, Harlan, IA 51593. Subscription inquiries: U.S. and Canada (800) 333-1199; other (515) 247-7631.

SCIENTIFIC AMERICAN® PRESENTS

Weather is published by the staff of SCIENTIFIC AMERICAN, with project management by:

John Rennie, EDITOR IN CHIEF
Gary Stix, ISSUE EDITOR
Ricki Rusting, ASSISTANT ISSUE EDITOR
Michelle Press, MANAGING EDITOR
Tim Beardsley, Steve Mirsky, STAFF WRITERS

Art
Mark Clemens, ART DIRECTOR
Bridget Gerety, PHOTOGRAPHY EDITOR

Copy
Maria-Christina Keller, COPY CHIEF
Molly K. Frances; Daniel C. Schlenoff; Katherine A. Wong; Myles McDonnell; Rina Bander; Sherri Liberman

Contributors
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Rosa Davis, FULFILLMENT AND DISTRIBUTION MANAGER

Subscription Inquiries
U.S. and Canada 800-333-1199; Other 515-247-7631

Business Administration
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President and Chief Executive Officer
Joachim P. Rosler
jprosler@sciam.com

Vice President
Frances Newburg

Scientific American, Inc.
415 Madison Avenue
New York, NY 10017-1111
212-754-0550

SCIENTIFIC AMERICAN

Sandra Ourusoff
PUBLISHER
sourusoff@sciam.com

NEW YORK ADVERTISING OFFICES
415 MADISON AVENUE, NEW YORK, NY 10017
212-451-8523 fax 212-754-1138

Denise Anderman
ASSOCIATE PUBLISHER
danderman@sciam.com

Peter M. Harsham
pharsham@sciam.com
Randy James
rjames@sciam.com
Wanda R. Knox
wknox@sciam.com
Carl Redling
credling@sciam.com

MARKETING
Laura Salant *MARKETING DIRECTOR*
lsalant@sciam.com
Diane Schube *PROMOTION MANAGER*
dschube@sciam.com
Susan Spirakis *RESEARCH MANAGER*
sspirakis@sciam.com
Nancy Mongelli *PROMOTION DESIGN MANAGER*
nmongelli@sciam.com

DETROIT
Edward A. Bartley
MIDWEST MANAGER
248-353-4411 fax 248-353-4360
ebartley@sciam.com

CHICAGO
Rocha & Zoeller
MEDIA SALES
333 N. Michigan Ave., Suite 227
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312-782-8855 fax 312-782-8857
mrrocha@aol.com
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LOS ANGELES
Lisa K. Carden
WEST COAST MANAGER
310-234-2699 fax 310-234-2670
lcarden@sciam.com

SAN FRANCISCO
Debra Silver
SAN FRANCISCO MANAGER
415-403-9030 fax 415-403-9033
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EUROPE
Roy Edwards
INTERNATIONAL ADVERTISING DIRECTOR
Julie Swaysland
Thavies Inn House, 3/4, Holborn Circus
London EC1N 2HA, England
+44 171 842-4343 fax +44 171 583-6221
royedwards1@compuserve.com
jswaysland@compuserve.com

FRANCE
Christine Paillet
AMECOM
115, rue St. Dominique
75007 Paris, France
+331 45 56 92 42 fax +331 45 56 93 20

GERMANY
Maren Scupin Günther
Am Wingertsberg 9
D-611348 Bad Homburg, Germany
+49-7541-66-5959 fax +49-6172-66-5931

MIDDLE EAST AND INDIA
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+44 140 484-1321 fax +44 140 484-1320

JAPAN
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Spektrum DER WISSENSCHAFT
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redaktion@spektrum.com

POUR LA SCIENCE
Pour la Science
Éditions Belin
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tel: +33-1-55-42-84-00

LE SCIENZE
Le Scienze
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redazione@lescienze.it

INVESTIGACION Y CIENCIA
Investigacion y Ciencia
Prensa Científica, S.A.
Muntaner, 339 pral. 1.ª
08021 Barcelona, SPAIN
tel: +34-93-4143344
precisa@abaforum.es

العلوم
Majallat Al-Oloom
Kuwait Foundation for the Advancement of Sciences
P.O. Box 20856
Safat 13069, KUWAIT
tel: +965-2428186

ŚWIAT NAUKI
Swiat Nauki
Proszynski i Ska S.A.
ul. Garazowa 7
02-651 Warszawa, POLAND
tel: +48-022-607-76-40
swiatnauki@proszynski.com.pl

日経サイエンス
Nikkei Science, Inc.
1-9-5 Otemachi, Chiyoda-ku
Tokyo 100-8066, JAPAN
tel: +813-5255-2821

СВІТ НАУКИ
Svit Nauky
Lviv State Medical University
69 Pekarska Street
290010, Lviv, UKRAINE
tel: +380-322-755856
zavadka@meduniv.lviv.ua

ΕΛΛΗΝΙΚΗ ΕΚΔΟΣΗ
Scientific American Hellas SA
35–37 Sp. Mercouri St.
Gr 116 34 Athens GREECE
tel: +301-72-94-354
sciam@otenet.gr

科学
Ke Xue
Institute of Scientific and Technical Information of China
P.O. Box 2104
Chongqing, Sichuan
PEOPLE'S REPUBLIC OF CHINA
tel: +86-236-3863170

OUR NATIONAL PASSION

by KEAY DAVIDSON, Illustrations by Dusan Petricic

Preoccupation with weather reflects both our hunger for constant change and our need to recover a lost sense of awe toward the natural world

A generation ago adolescent meteorologists monitored local weather by turning milk cartons into barometers and Ping-Pong balls into anemometers. But nowadays, simply by tapping a keyboard, their successors can track weather as it happens all over the globe. The World Wide Web offers a jungle of "weather weenie" sites. Its users can stare until stupefied at weather-radar imagery from St. Louis, St. Paul or St. Cloud, satellite pictures of fog hugging the California coast or the Appalachian foothills, charts that depict dry lines and tropical maps that show a long, sinister red band. That band is the thermal signature of El Niño, now mercifully slumbering in Pacific Ocean waters (until it strikes again!). "And Hurricane Floyd probably sucked more people onto the Internet than it did palm trees and street signs into its swirling maw," joked the *Los Angeles Times*.

The modern fascination with weather is also epitomized by tornado chasers on the Plains, politically charged conferences on climate change and the Weather Channel on cable television. In the age of CNN and MSNBC, weather disasters receive the breathless, moment-by-moment, you-are-there coverage once reserved for wars. In the comfort of our living rooms in New York City and San Diego and Dubuque, we watch live TV images from the southeastern U.S. as Hurricane Floyd pounds beach mansions into pulp. Pundits, meanwhile, exploit every atmospheric disaster—a Chicago heat wave, a California monsoon, a Northeastern blizzard—as material for debate: Is the weather changing? Are we to blame?

The weather craze has a historical parallel. More than a century ago geology was the preeminent popular science in Victorian Britain; weekend rockhounds sketched geologic layers exposed on cliffsides and scrutinized granite outcroppings with magnifying glasses. The Victorians' obsession reflected, at least in part, the 19th century's larger fixation with Time—with grand hypotheses of social evolution over thousands of years and biological and planetary evolution over millions and billions of years.

Likewise, I suspect that today's weather craze is no mere craze; rather it reflects the larger cultural mood circa the Millennium. Whereas Half Dome and the Grand Canyon just sit there, mute marvels of geologic change a millimeter at a time, and whereas astronomical objects typically creep at an imperceptible pace across the evening sky, the weather is ever changing—the perfect natural entertainment for the "MTV generation," accustomed to films and videos with high-speed plots and millisecond editing. But the craze also reflects a deeper sentiment akin to the feelings poured into the environmental movement: a desire to escape from our increasingly artificial lives—surrounded as we are, from cradle to grave, by the chrome-and-concrete, claustrophobic womb of Civilization. Our nomadic and agricultural forebears hauled carcasses of woolly mammoths or bags of berries home in the face of blinding rainstorms and shuddered in awe at every flash of lightning. The spirits were angry! True, few moderns would wish to return to prehistory, with its short, brutish lives. But many people today, huddled around "entertainment centers" in their air-conditioned homes, suffering through unhappy marriages and disappointing careers, wish nothing more than to recapture our ancestors' sense of awe—the sense that they were part of something greater.

To devoted weenies, myself included, nothing is more enthralling and educational than the nonstop melodrama of the atmosphere—the skyrocketing growth of thunderstorms, the writhings of the jet stream, the balletic choreography of fronts and air masses. In textbooks, Newtonian equations and Avogadro's law and fluid mechanics look dry and inscrutable, but in the heavens they come to vivid, sometimes violent, life. Nothing dramatizes the physical process of moist adiabatic cooling better than the formation of a cumulonimbus; nothing epitomizes angular momentum more shockingly than a tornado's buzz-saw mayhem. Weenies old enough to have obtained driver's licenses may spend every spring and summer in the Midwest chasing ominous-looking convective clouds that, they pray, will soon sprout twisters. "I have only one purpose in life—to chase and photograph severe storms," one chaser declares on his personal Web site. "I am glad when I can contribute to scientific research and education about storms, but the driving force behind my lifelong passion is the incredible power and beauty of the storms themselves."

Weather fanaticism has spawned its own commercial culture. In *Weatherwise* magazine and in colorful brochures for weather-oriented mail-order boutique stores such as Wind & Weather, one sees advertisements for a "solar-powered weather station" ($990) and a "WeatherPager" that beeps you with weather alerts ("NWS issued severe t-storm watch until 6:00 P.M."). You can even learn how to construct a home "tornado simulator" (which uses fans to generate realistic-looking "tornado" funnels). There are also the usual classified ads for, say, "Tornado-Chasing Safaris" that "will take you on an experience you won't forget as we travel through the Midwest in the spring and summer of 2000."

My First Forecast

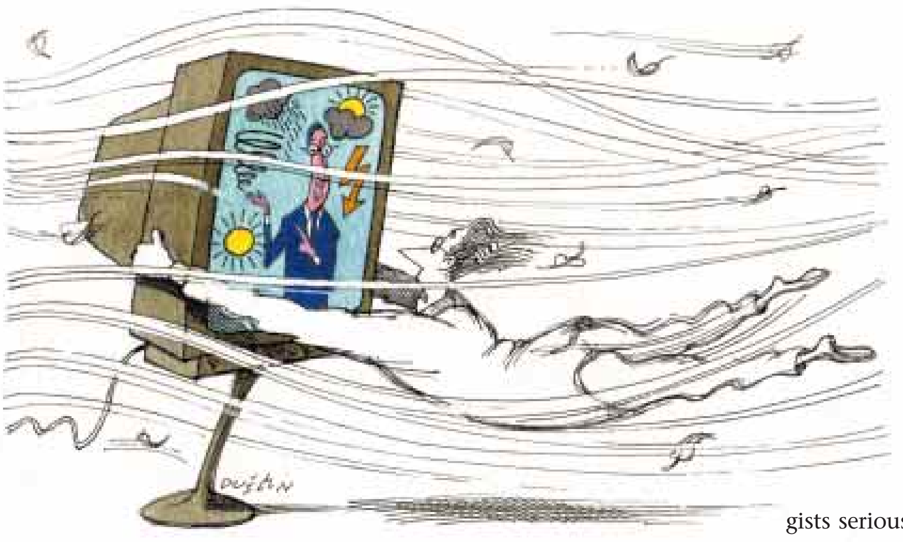
How times change. At age 11, every day after school in southern Ontario, I rummaged through my parents' mail for the latest edition of The Map. Ah, there it was: a thin publication, approximately six by nine inches when folded, with a return address that mentioned the U.S. Weather Bureau and Government Printing Office. I ran to my room, leaped on the bed and happily unfolded it. Before my eyes lay a green-and-white depiction of the U.S. and southern Canada, littered with hundreds of hieroglyphlike symbols. Each town had its own hieroglyph, which sported a little feather and was surrounded by numbers. The Map also featured big grayish blobs and long, bold black lines—some lined with jagged edges, others with little domes—arcing across several states. The blobs marked regions of precipitation. The jagged lines were cold fronts; the domed ones, warm fronts.

Blessed with this wealth of meteorological data, I set to work with a ruler and a pencil. My favorite maps showed major storms over the central plains or Rocky Mountains or American Southwest or Midwest. Western storms often moved toward the northeastern sector of the country and southeastern Canada, sometimes passing over my home in southern Ontario. After a few days of tracking a storm's progress, monitoring its speed and direction, I'd forecast whether it would pass overhead—and if so, when. Unfortunately, thanks to the sluggishness of mail delivery, the maps typically depicted weather that was a few days old; I was frequently upset to discover that the storm had already come and gone. I was too ignorant to take account of other factors such as the jet stream, which refuels and guides storms.

But I've never forgotten my first successful storm forecast: I calculated that a major disturbance would arrive within a few hours, that very evening. I ran to the barometer that hung on my bedroom wall and tapped the glass case: the needle plunged. That night I awoke in the bedroom darkness to hear the faint growl of an approaching thunderstorm. A successful forecast! At a time when most other kids' horizons were defined by the distance to school, the softball diamond and the candy store, I was monitoring humidity in Santa Cruz, rainfall in Madison and wind directions in Orlando. A year or two later the U.S. Weather Bureau (now the National Weather Service) canceled circulation of the daily weather map. Saddest day of my childhood.

We weather buffs descend from a great tradition: Thomas Jef-

To devoted weenies, nothing is more enthralling than the nonstop melodrama of the atmosphere—the skyrocketing growth of thunderstorms and the writhings of the jet stream.



ferson and Benjamin Franklin were serious amateur meteorologists. As every bright schoolchild knows, the latter risked his life by using a kite to figure out the mystery of lightning; he also helped to pioneer the crucial notion that weather systems move over long distances (rather than forming and dying in pretty much the same area). And ol' Ben was also America's first recorded "storm chaser," of a sort. In 1755, while on horseback, he pursued a strong dust devil for almost a mile; he later recalled it as "forty or fifty feet high... [and] twenty or thirty feet in diameter.... I tried to break this little whirlwind by striking my whip frequently through it, but without any effect."

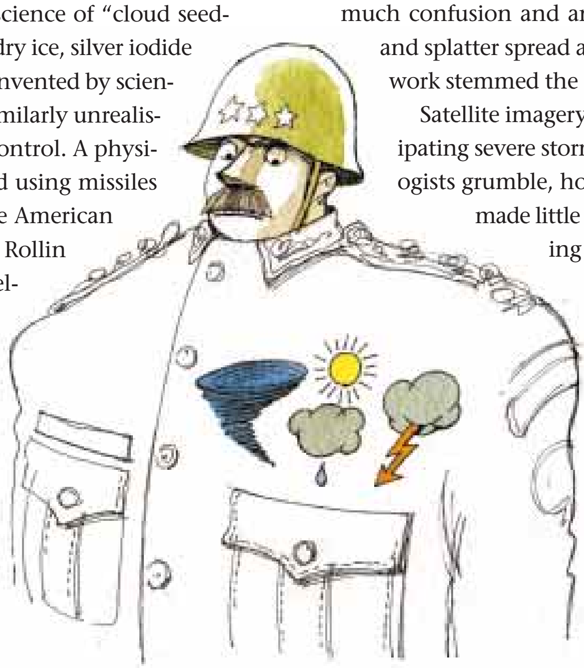
The Cold-Front War

Franklin's behavior was very American: he wished not only to understand the vortex but to control it. The 19th century also brought a swarm of schemes for "controlling" weather, such as meteorology pioneer James Pollard Espy's proposal to fight droughts by starting forest fires, which (he reasoned) would initiate atmospheric convection, triggering rain-bearing thunderstorms. Rainmakers were highly visible hucksters in the farm belt.

In the 1940s, when the modern science of "cloud seeding" to make rain fall (by sprinkling dry ice, silver iodide or other chemicals into clouds) was invented by scientists at General Electric, it inspired similarly unrealistic hopes for the future of weather control. A physicist and an air force officer proposed using missiles to destroy tornadoes. Addressing the American Meteorological Society in 1953, Col. Rollin H. Mayer said the nation could develop "a fleet of airplanes loaded with missiles waiting to attack tornadoes." Nobel laureate Irving Langmuir claimed that cloud seeding could bring about "important changes in the whole weather map," including the diversion of hurricane paths. There were also speculations about warming the Arctic by diverting warmer ocean waters toward polar regions or by sprinkling dark-colored substances (which would absorb sunlight) on the ice to warm it and about washing pollution from Los Angeles skies by finding a way to generate thunderstorms near the city. The military was keeping an eye on weather control, too: Gen. George C. Kenney, former head of the Strategic Air Command, said, "The nation which first learns to plot the paths of air masses accurately and learns to control the time and place of precipitation will dominate the globe."

Before controlling weather, scientists had to understand how it worked. But early meteorologists seriously underestimated the difficulties ahead. In 1895 Mark Walrod Harrington, the director of the U.S. Weather Bureau, expected that "three competent physicists, left to pursue their investigations for ten years without disquiet and given proper encouragement and assistance, would probably be able to so improve our art of weather forecasting as to satisfy all ordinary requirements. The cost would perhaps be $10,000 per year, but the resulting benefit would be a thousand or ten thousand times that annually." Clearly, this was overoptimistic, as can be attested by anyone who has had a picnic ruined by a "20 percent chance" shower.

This is not to deny that meteorology has made progress. Two historic anniversaries are coming up this April: the 40th anniversary of the first weather satellite and the 50th anniversary of the first computerized weather forecast. On April 1, 1960, the first TIROS weather satellite transmitted to the earth blurry but enthralling images of cloud patterns. These images dramatized better than any amount of meteorological data what the "Bergen school" of meteorologists in Norway had argued in the early 20th century: that weather obeys certain geometries, with masses of cold air and warm air engaged in intricate dances, sliding over and under each other, generating specific types and distributions of clouds that had previously seemed like so much confusion and anarchy, so much meaningless fuzz and splatter spread across the blue heavens. (From their work stemmed the concept of cold and warm fronts.)



Satellite imagery has made a big difference in anticipating severe storms such as Floyd. Veteran meteorologists grumble, however, that weather satellites have made little difference, so far, in the understanding of "routine" weather such as precipitation. We lack adequate three-dimensional atmospheric data, both from space-based sensors and from ground-based devices like wind profilers, which can map wind speeds and directions at different heights.

A half-century after the first computerized "weathercast" was made, computers are essential tools of weather forecasting, di-

our understanding of fronts is badly flawed. And the recent recognition of upper atmospheric phenomena called sprites and blue jets—massive electrical events of some kind occurring high in the atmosphere above thunderstorms, some of them many miles across and, incredibly, not scientifically acknowledged until 1989 despite anecdotal reports by airline pilots of their existence—reminds one of 19th-century astronomers' long resistance to accepting the reality of meteorites. In short, there is a great deal yet to learn about our atmosphere.

Jehovah's Wrath

That weather remains so mysterious, so hard to predict, surely accounts for much of its present—and past—popular allure. Early settlers viewed American weather as almost transcendentally majestic, like the national topography: grandiose canyons, a 1,000-mile river, vast mountain ranges, the surreal wind-carved natural monuments that adorn the landscape of the Southwest. Also, American weather was quite unlike anything the ancestors of Native Americans or their European successors had seen in their lands of origin. This is especially true of tornadoes, which are almost uniquely American in their frequency and ferocity: it is hard to think of a weather phenomenon, save lightning, that is quicker to inspire thoughts of the wrath of Jehovah.

gesting Niagaras of data that no one human mind could juggle. Unfortunately, the dream of high-precision, long-term (say, many weeks ahead) forecasting has largely soured, thanks to the discovery in the 1960s of "chaos." (Nowadays every schoolchild has heard of the "butterfly effect," in which a minor weather phenomenon—as trivial as a butterfly flapping its wings—can unleash a far grander phenomenon, extremely disproportionate in energy to the input, perhaps a typhoon half a world away.)

Also, even if chaos did not exist, the computers' crunching is of little value if the assumptions and data fed into them are ambiguous or erroneous—the old GIGO (garbage in, garbage out) problem. In that regard, it is disturbing that so much remains unknown about basic processes in our atmosphere. It startles people when I tell them that we still do not have a fully worked out and generally accepted explanation for why rain falls or why thunderstorms become electrified and spark with lightning. (Popular explanations in schoolbooks are invariably oversimplified and ignore experts' disagreements.) In recent years, some atmospheric scientists have begun to argue that

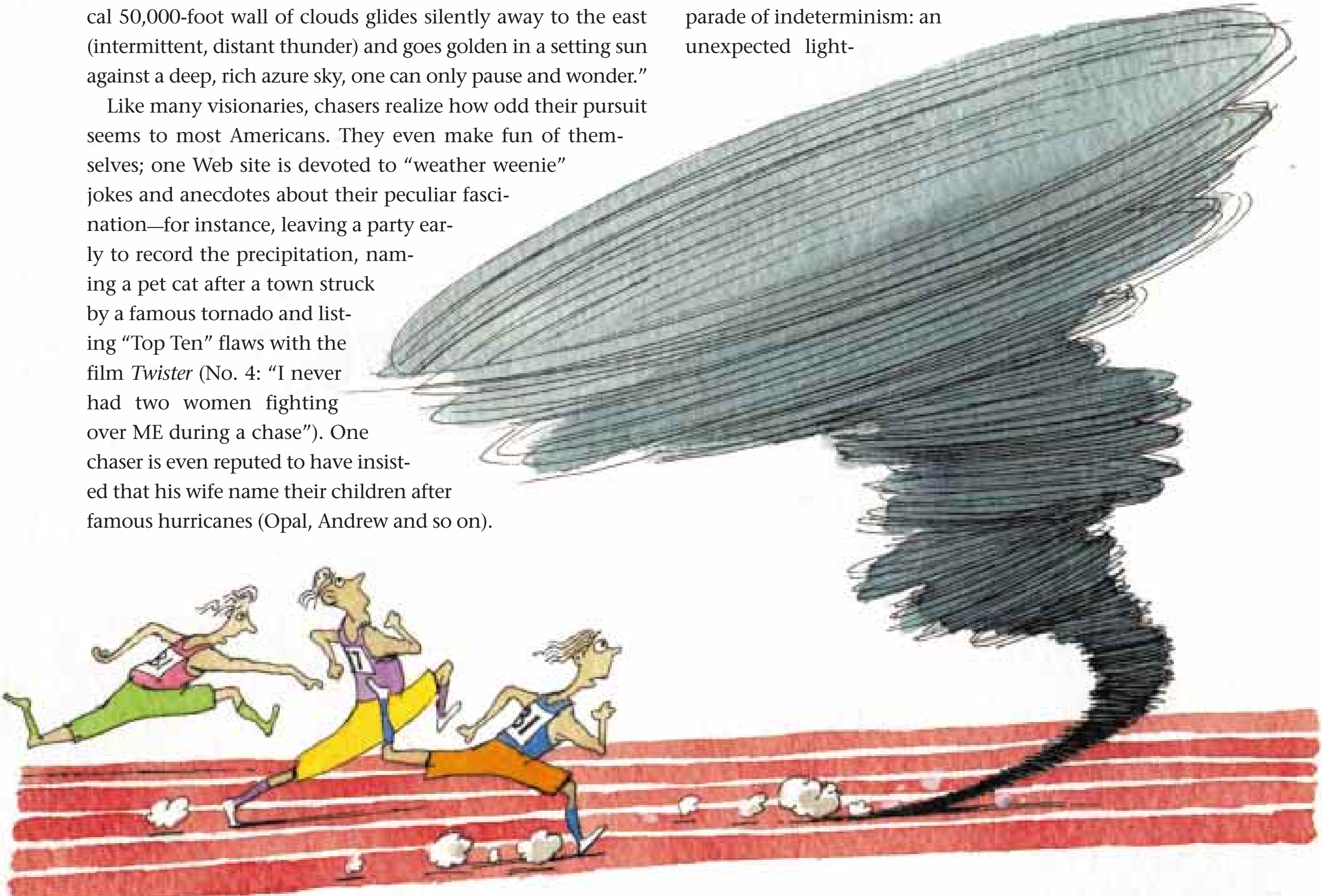
A few years after the presidency of Andrew Jackson, Father Pierre Jean de Smet accompanied settlers from Indiana to California and witnessed a tornado a mile high, a sight surely as baffling to them as Moses' encounter with the burning bush: "In the twinkling of an eye the trees were torn and uprooted, and their boughs scattered in every direction. But what is violent does not last. After a few minutes, the frightful visitation ceased.... All was calm and we pursued our journey." Another twister awed naturalist John James Audubon: "The whole forest before me was in fearful motion. I saw, to my great astonishment, that the noblest trees of the forest bent their lofty heads for a while, and, unable to stand against the blast, were falling into pieces.... The horrible noise resembled that of the great cataracts of Niagara, and it howled along in the track of the desolating tempest." To some, such ethereal visitations embodied God's wrath. A St. Louis tornado in 1927 was "a visitation from a merciful and loving Providence," a preacher assured his flock. "Whom the Lord loveth he chastiseth. Chastisement here is better than chastisement hereafter."

Despite their scientific leanings, I believe that weather fanat-

Early settlers viewed American weather as almost transcendentally majestic, like the national topography: grandiose canyons, a 1,000-mile river, vast mountain ranges, the surreal wind-carved natural monuments of the Southwest.

ics—especially storm chasers—have far more in common with Father Pierre and Audubon than with Gen. Kenney. Ponder the words of pioneering storm chaser David Hoadley, who wrote in *Storm Track* magazine in 1982 that he chased partly for "the sheer, raw experience of confronting an elemental force of nature—uncontrolled and unpredictable.... Few life experiences can compare with the anticipation of a chaser while standing in the path of a big storm, in the gusty inflow of warm moist gulf winds sweeping up into a lowering, darkening cloud base, grumbling with thunder as a great engine begins to turn." His reaction is far more explicitly religious than Father Pierre's: "an experience of something infinite," Hoadley remarks, "a sense of powers at work and scales of movement that so transcend a single man and overwhelms the senses that one feels intuitively (without really seeking) something eternal.... When a vertical 50,000-foot wall of clouds glides silently away to the east (intermittent, distant thunder) and goes golden in a setting sun against a deep, rich azure sky, one can only pause and wonder."

Like many visionaries, chasers realize how odd their pursuit seems to most Americans. They even make fun of themselves; one Web site is devoted to "weather weenie" jokes and anecdotes about their peculiar fascination—for instance, leaving a party early to record the precipitation, naming a pet cat after a town struck by a famous tornado and listing "Top Ten" flaws with the film *Twister* (No. 4: "I never had two women fighting over ME during a chase"). One chaser is even reputed to have insisted that his wife name their children after famous hurricanes (Opal, Andrew and so on).



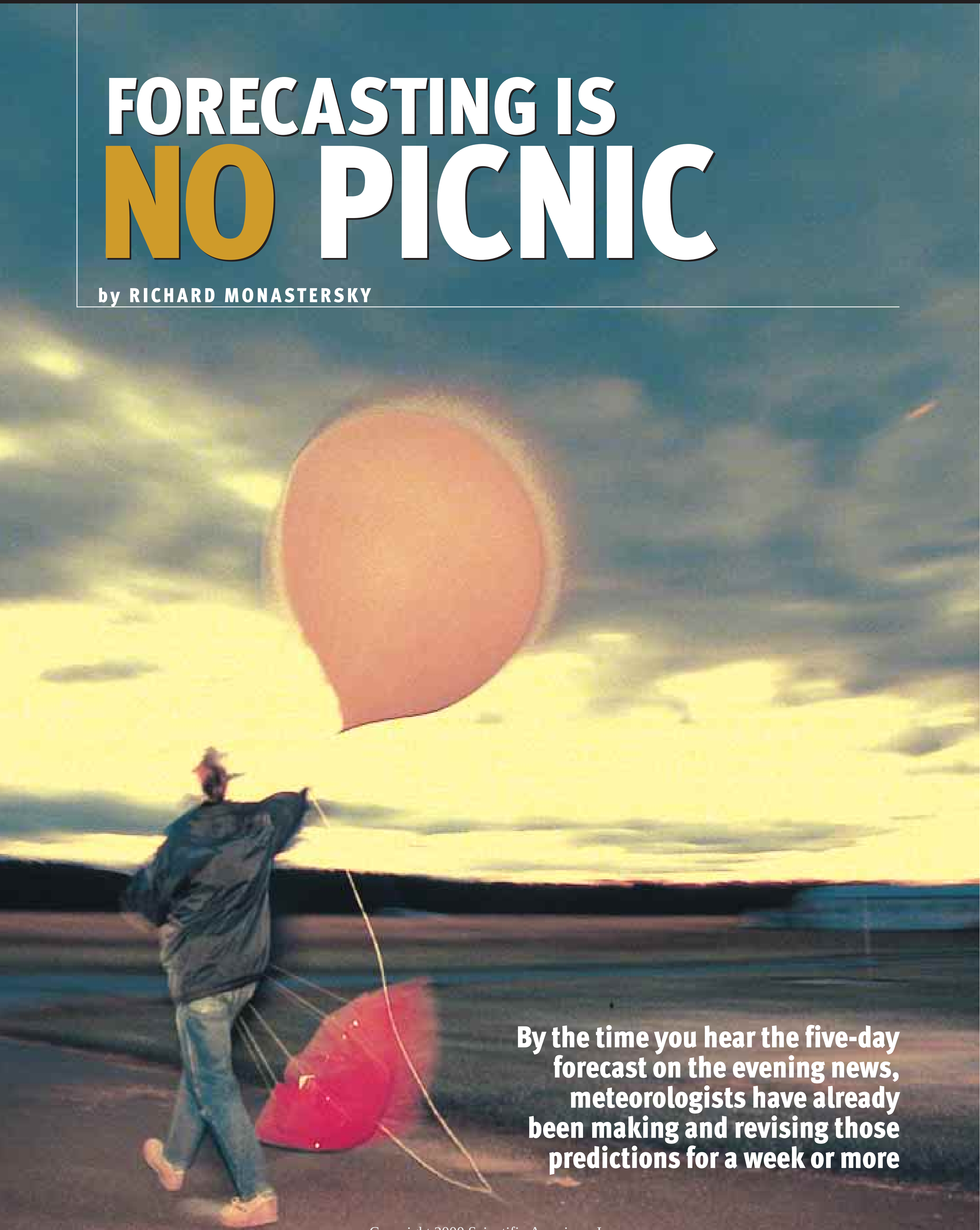
Storm chaser Web sites publish their poetry and songs (a tune called "Inflow," by Taz Fujita: "You see it coming like a nightmare/Darker than your fears/You scream as the gust front overtakes you/But no one hears"). The storm chasers' accounts are not all poetry, yet they are today's folk poets of the nation's heartland, struggling to express in words the same feelings of startled wonderment that welled up within the early pioneers as they confronted the surreal gigantism of both America's landscape and weather.

Weather's unpredictability makes it easier to anthropomorphize; hence much of its fascination. Part of the thrill of watching a hurricane is wondering: "Where will it strike?" We give hurricanes human names and attribute to tornadoes the traits of living creatures—willfulness, cunning, evil. In a sense, our attitude toward nature is psychologically atavistic, a relic of an epoch when we were all animists and believed all of nature was alive, when we imagined gods and spirits hiding atop the thunderclouds and within the raindrops. Nowadays, when faith in gods is far weaker, weather's indeterminism seems to satisfy something in our souls. In an era when science purports to be explaining so much—heredity via DNA, feelings via neurochemistry—it is satisfying to ponder sciences that yield less readily to the determinists' agenda. Turn to the Internet or the Weather Channel and witness the dark parade of indeterminism: an unexpected lightning bolt that ends a life, an unexpected rainstorm that floods a state, an unexpected tornado that devastates a town. Although some observers foresee "the end of science," this purported end—should it ever come—remains very far off for meteorology, the branch of the physical sciences that touches our lives most intimately. W

KEAY DAVIDSON is a science reporter for the *San Francisco Examiner*. His books include *Carl Sagan: A Life* and *Twister: The Science of Tornadoes and the Making of an Adventure Movie*.

FORECASTING IS NO PICNIC

by RICHARD MONASTERSKY



By the time you hear the five-day forecast on the evening news, meteorologists have already been making and revising those predictions for a week or more

Last summer a gaggle of government dignitaries flocked to the end of Thunder Road, a quarter-mile-long strip of asphalt tucked behind Washington Dulles Airport. There, in the shadow of a giant radar dome, the bureaucrats celebrated the end of a nearly 20-year struggle to bring the National Weather Service (NWS) into the information age. This $4.5-billion modernization effort has furnished U.S. federal forecasters with sophisticated Doppler radar, a nationwide communications network, vastly improved computing power and a new suite of satellites.

KAY CHERNUSH

TOP-OF-THE-LINE EQUIPMENT: The Doppler radar tower (*above*) near Washington Dulles Airport is one of the workhorses intended to increase the accuracy and timeliness of weather forecasts. The opposite page shows the early morning launch of a weather balloon.

To test-drive the revamped system, I enlisted the full force of the weather service to answer a simple question: Will it rain on an upcoming picnic planned for my son's birthday in early October?

For a 10-day period before the event, I turned into a weather weenie, keeping in close contact with meteorologists drawing up the forecasts for Saturday, October 9. Aside from helping me plan the picnic, the exercise allowed the weather service to show off its advanced capabilities and to explain exactly how meteorologists go about predicting the weather.

Federal officials were eager to advertise the new system and its benefits. "Our three-day forecast is better than the accuracy of our one-day forecast 20 years ago," asserts John J. Kelly, Jr., director of the NWS. "We've more than doubled the lead times for tornado warnings. We've got a sevenfold increase in flash-flood warning lead times, all by this technology, this modernization."

My test revealed not only the profound improvements but also some bugs in the U.S. forecasting system. At the same time, it demonstrated just how complex a task it is to predict relatively mild conditions, let alone the blizzards, hurricanes, tornadoes and other hazards that strike disastrously from the sky.

A resident of the U.S. would have to hide in bed all day wearing earplugs to avoid hearing some sort of weather forecast. Even if one shunned every type of news media, updates about the weather would invariably slip into daily conversations. How often has a neighbor announced in passing: "They say it'll rain this weekend"?

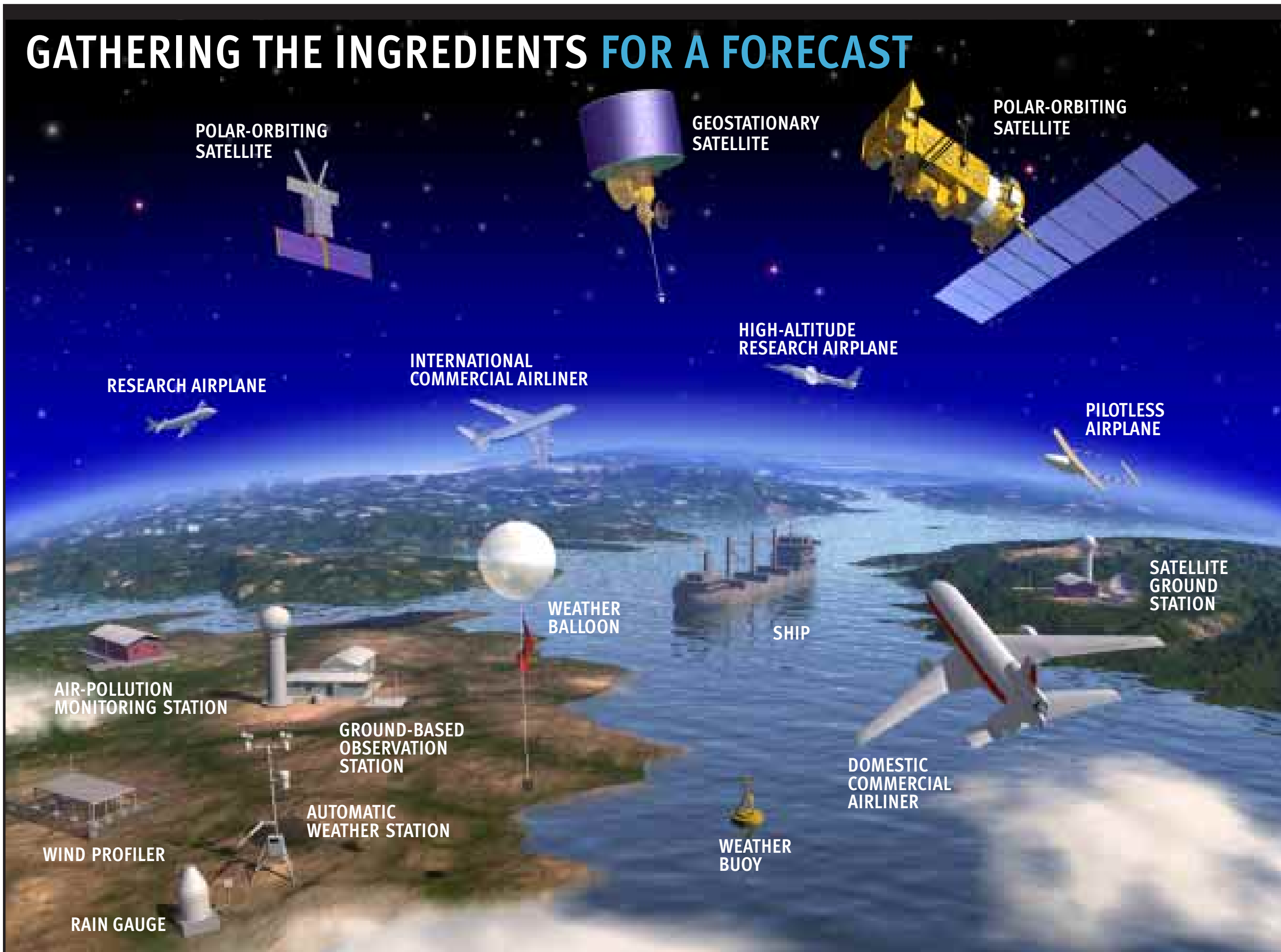
KAY CHERNUSH

To track down the "they" behind all these prognostications, I start off with a phone call to the World Weather Building, a boxy, brown office tower just south of Washington, D.C. The building houses the National Centers for Environmental Prediction, also known as NCEP ("encep") in the abbreviation-crazed federal government.

"Here is where it all begins," says Louis Uccellini, NCEP's head. A balding, brash meteorologist, Uccellini proudly describes how his organization drives the national forecasting effort.

The heart of the weather-prediction process rests deep within the building, where the Central Operations division oversees the computer programs that forecast the weather. More than one million meteorological observations flow into this building from around the world every day and serve as the initial seeds from which forecasts grow.

Every passenger on commercial flights unwittingly takes part in the observation process. Airplanes automatically measure air temperatures and winds and then send those data to an international information network. Weather balloons, ships, satellites, ground-based gauges and other



ALFRED T. KAMAJIAN, AFTER TREVOR RUTH

Computer-modeling programs that form the basis of weather forecasts must be fed meteorological data from a fleet of monitoring devices around the world. Those devices assess such factors as air temperature, moisture and pressure, and wind speed and direction.

instruments all contribute to take the atmosphere's vital signs.

The information eventually funnels into a supercomputer that runs several forecasting programs, called models. Designed to describe the atmosphere's behavior, these models are made up of mathematical formulas that predict how the sun's rays and the earth's rotation move air, heat and moisture around the planet.

The models represent the atmosphere as a spherical grid made up of dozens of vertical layers. At the start of the forecasting process, a program assembles all the meteorological observations into a complete portrait of what the weather looks like at the moment for each point on the grid. Then the models use Newton's laws of motion and other equations to determine how temperature, humidity, winds and other factors will change at every grid point.

That computer output then goes to meteorologists at NCEP, who make their forecasts by comparing the in-house models with those run by other federal agencies and foreign governments. Each model uses slightly different equations, grid spacing, starting times and initial observations. Taken together, they resemble a group of opinionated sports announcers, often producing divergent predictions of how future events will unfold.

When I began planning my son's party in late September, the weather service was using a Cray C90 computer for running its own forecasting models. At the time of its acquisition in 1994, this machine was one of the fastest supercomputers on the market, boasting a peak speed of 16 billion floating-point operations per second (16 gigaflops). Now that pace is downright poky. To build up its computational muscle, the government last year procured an IBM supercomputer that can hit 690 gigaflops. An upgrade planned for fall 2000 will boost the speed to 2.5 trillion flops.

Officials at NCEP planned to retire the Cray this year, but the supercomputer ended up quitting much earlier, and with more drama, than anyone had anticipated. Just 30 minutes after I spoke with Uccellini on Monday, September 27, a fire broke out in the Cray and destroyed the machine. Unfortunately, the IBM computer was not ready, so the weather service had to rely on its own backup systems along with those from the U.S. Air Force, Navy and other nations. For several months, the fire's legacy hobbled the computer division, forcing it to cut back on some of its forecast products.

Because of the fire, I had to wait until 10 days before the picnic to get the first inkling of what the weather would be like. This came from NCEP's Climate Prediction

Center, which is in charge of forecasts longer than a week or so in the future.

Meteorologists at this point can't hope to provide specific information that far ahead. The winds sailing around the globe are just too chaotic and the initial weather observations are too spotty for the computer models to tell whether it will rain at 4:13 P.M. two weeks hence in any particular place. Recognizing these limitations, the Climate Prediction Center staff issues only general projections beyond a week ahead. The information, however, is often accurate enough to warn forecasters that the potential for a major storm system is lurking upstream.

10 Days and Counting

When I check in with the center on September 29, the initial news is slightly sour. The forecast calls for below-normal temperatures and above-normal precipitation in the mid-Atlantic states, where I live. This assessment draws mostly on information from the European Center for Medium Range Weather Forecasts, one of the only organizations running a model out that far.

The European simulation envisions a low-pressure region sitting over the Mississippi by October 9. Called a "trough" by meteorologists, such a system deflects high-altitude winds traveling eastward across the country, forcing them to detour southward and then loop back northward around the low-pressure region. As the winds skirt the eastern edge of the trough, they push warmer, humid air northward, where it rides up and over the colder mass in front of it. The warm air cools as it rises and therefore can hold less moisture, which condenses to form clouds and rain over the Eastern states. So the presence of a trough over the Mississippi valley translates into a soggy party for my family.

Two days later the forecast looks sunnier. Doug LeComte of the Climate Prediction Center foresees normal temperatures and below-normal rainfall, a picture produced by combining the most current European model output with that from the day before. This blending helps to define the large meteorological patterns soon to be rolling across the country.

Instead of establishing a trough over the Mississippi, the most recent European model prediction shoves the system out to the northeast, putting much of the country under a high-pressure ridge eight days in the future. Like a boulder in a river, that ridge will block the atmosphere's currents and keep away storm systems, letting sun shine on my picnic, LeComte says.

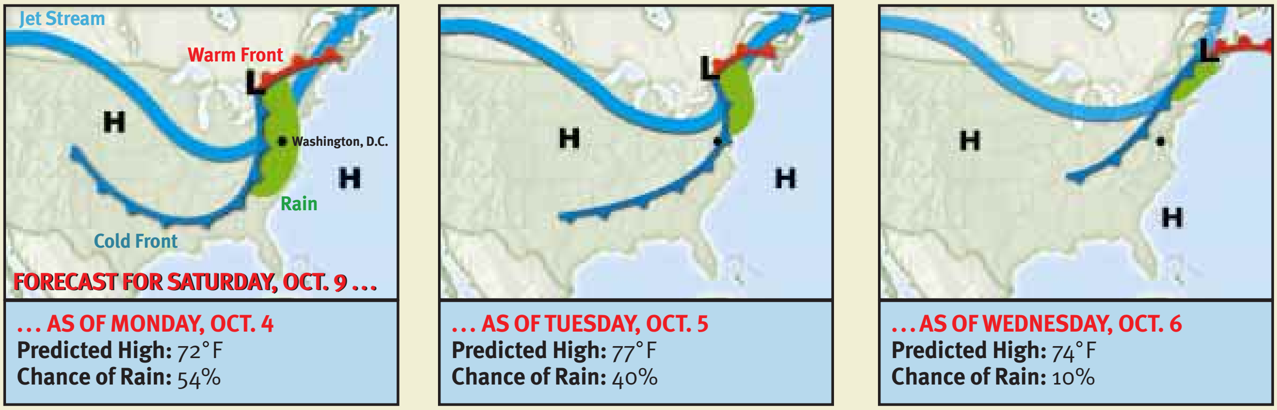
He quickly tempers my optimism, however. With the model changing its forecast so dramatically in just two days, he cautions, "anything I say will have really low confidence."

Despite the warning, I can't help putting some stock in the forecast, especially because it calls for good weather. The very existence of this information, no matter how suspect it may be, seems to give it some authority. That explains why most media outlets do not report the forecasts earlier than five days ahead. People would be tempted to place too much faith in the often inaccurate longer-range predictions.

LeComte's skepticism seems prescient the next day when I phone into the Hydrometeorological Prediction Center, the NCEP office that issues medium-range forecasts seven to two days ahead. "Right now we're looking at a cloudy day with a chance of showers and a high in the upper 60s," says Frank Rosenstein. He forecasts a 48 percent chance of precipitation at D.C.'s Reagan National Airport, the airfield nearest to my house.

The potential spoiler to my son's party is visible in the model run by NCEP. It projects that a low-pressure system will sweep across the country and reach the East by picnic day. Even worse, a couple of models show a storm brewing in the western Gulf of Mexico. The Canadian forecasting model foresees the storm growing into a hurricane and sweeping over the Gulf Coast states, where it could start to merge with the northern low-pressure system. "There is a potential for heavy rain," Rosenstein says.

His message starts to give me heartburn as I wonder how to keep several preschoolers occupied inside for two hours until it's time for cake and ice cream. Before I can get too worked up, though, Rosenstein backpedals on the forecast: "I wouldn't bet on this, especially at this time of year." Fall and springtime are no-



LAURIE GRACE; SOURCE: EDWIN DANAHER *NCEP*

WILL IT, WON'T IT? As part of making advance predictions for October 9, 1999, in the mid-Atlantic region, the National Weather Service tracked the movement of low- and high-pressure systems (*Ls* and *Hs*) across the country (*maps*). Low-pressure systems often bring rain. As the date approached, the author felt increasingly confident that no rain would mar his son's outdoor birthday party on that day. He—and the forecasts—were a bit wet.

toriously difficult seasons to predict for the models because the atmosphere is flip-flopping between a summertime mode of circulation and a wintertime pattern. What is more, the European and NCEP models do not agree on where the weather systems will be. Such discord among the computers makes forecasters' jobs more difficult because they have to figure out which model prediction to trust—a subjective process that relies in part on recalling how models have fared in similar situations before.

The following day Rosenstein and his partner Michael Schichtel have not changed the forecast appreciably. The only difference is that most of the models downplay the risk of a hurricane hitting the Gulf Coast. The NCEP medium-range model still shows a low-pressure trough moving slowly across the country and arriving on Saturday. Other models push the system along faster, which means the rain would start earlier. Either way it doesn't look good for the picnic.

After giving the forecast, Schichtel provides the by now expected caveats: "For day six and seven, we're looking at storms that haven't even developed yet." The seeds to these systems are still floating over eastern Asia as we speak. "There is a lot of room for the models to change things," he says.

The next morning—Monday—the forecasting activity begins to pick up its pace, with only five days left before the picnic. This is when the news media start to get involved, issuing their own forecasts or reporting the official predictions provided by the weather service.

The *Washington Post,* for instance, calls for a "chance of rain," on Saturday, with a high of 68 degrees Fahrenheit. This weather information comes from a commercial firm called AccuWeather in State College, Pa., which supplies the forecasts to some 660 newspapers and 250 radio stations around the country.

Bad News, Good News

I'm eager to see what the government's forecast will be, so I go to the World Weather Building. James E. Hoke, head of the Hydrometeorological Prediction Center, leads me into a long, open room filled with more than 100 monitors displaying weather maps, satellite photographs and radar images. The shades are drawn, and the hum of computers fills the air as a shift of 40 people track the nation's weather for the next week.

Hoke takes me to a work area of 10 monitors and two chairs, where a pair of meteorologists is developing the forecast. Earlier this year the scene would have been very different. "Up until April 1, we used to do all of the charts by hand with light tables and grease pencils," he says.

Now the forecasters use a network of computer workstations called the Advanced Weather Interactive Processing System, or AWIPS. Often called the central nervous system of the weather service, this system connects all the offices around the country, allowing meteorologists to display model maps and weather observations, create their forecast charts, and instantly transmit them.

The Department of Commerce began work on AWIPS back in the early 1980s, but the system's development did not progress smoothly. Its cost has reached nearly double the original budget, and the government has lagged several years

behind in completing the system, which is still not fully functioning, according to the General Accounting Office. Despite the problems, forecasters say it has revolutionized their work.

As for the picnic, the news has grown slightly worse. NCEP's medium-range model still shows the trough moving east, and it appears even stronger than in yesterday's run. The European model goes to the opposite extreme again, keeping upper-level winds blowing straight east-

...AS OF THURSDAY, OCT. 7
Predicted High: 76°F
Chance of Rain: 20%

...AS OF FRIDAY, OCT. 8
Predicted High: 74°F
Chance of Rain: 0%

ACTUAL CONDITIONS AT PICNIC
Cloudy, cool, drizzle after 3 P.M.

ward, with no deviation around a trough. The U.S. Navy, Canadian and U.K. models portray something in between these two pictures. Rosenstein takes a middle-of-the-road approach, calling for a trough to arrive farther north and weaker than the medium-range model wants it to. He gives better than even odds of a shower on Saturday.

Given the dismal prospect of drizzle, I start looking up the telephone number of a professional juggler I had met, thinking he could entertain the kids indoors. But it quickly becomes clear that our low ceilings would cramp his routine, especially the bit involving scimitars and cantaloupes.

On Tuesday morning, four days before the picnic, my mood brightens when I speak with NCEP's Steve Flood, whose name in this case is entirely inappropriate. "Today it looks pretty good that it will not rain on Saturday. We're missing some of our models, but from what we can see, the system is not coming as far south in the country. Most of the energy is staying in Canada."

The big change since yesterday is in the U.S. medium-range model, which has repositioned the trough northward, giving Washington only a slight chance of showers, Flood says. The U.S. Navy and U.K. models have remained the same since the day before, while the poor Canadian model is still on its own trying to pull the Gulf storm north toward the states.

Flood explains how he sorts out the different predictions of how weather patterns will move across the U.S.: "We start from an anchor position that all the models agree on, and then we work from there to see what happens downstream and upstream from those anchor points to try to determine what's reasonable or not."

The next day the news keeps improving. The U.S., European and U.K. models are all in agreement in calling for relatively undisturbed air over the Eastern states on Saturday. Flood and his colleagues have dropped the chance of precipitation down to 10 percent in Washington.

That matches the prediction coming out of AccuWeather. Eliot Abrams, a senior meteorologist there, gives me the news by phone: "Right now the forecast is for a fine day with mixed clouds and sun, partly sunny. High 72, low 58. It's a good day for outdoor activity, and a good breeze will be blowing."

With a penchant for puns and a sonorous voice, Abrams seems a natural for radio forecasts. His sunny disposition clouds over only when asked about the recent fire at NCEP. "It's outrageous," he says,

PHOTOGRAPHS BY KAY CHERNUSH

FORECASTERS IN ACTION: Doug LeComte (*left photograph*) of the Climate Prediction Center at the National Centers for Environmental Prediction (NCEP) constructs a long-range forecast more than a week ahead. Michael Schichtel (*at left, above*) and Frank Rosenstein confer on a medium-range forecast (seven to two days out) at NCEP's Hydrometeorological Prediction Center. At the National Weather Service office in Sterling, Va., John Billet (*right photograph*) consults depictions of winds, pressures and such to compile a short-range forecast for the D.C. area.

"that the government of the United States is so vulnerable to one computer."

Abrams's boss, Joel N. Myers, contends that the government should get out of much of the weather-forecasting business, leaving it to private companies like the one he owns: "My vision of what will happen 10 or 15 years out is that the need for the government weather services might almost disappear." The government, Myers adds, should focus on issuing severe-weather warnings and leave the routine forecasts to private companies.

Uccellini of NCEP takes issue with that forecast of the future: "Our warnings are made by the same people who issue the day-to-day forecasts." The forecasters have to stay on top of the daily weather in order to recognize when thunderstorms, tornadoes, hurricanes, floods and other threats are looming, he asserts. What is more, the forecasts put out by private companies rely heavily on information issued by the NWS. Often, he notes, meteorologists working for news outlets use the government's official forecast verbatim.

What will happen a decade hence, however, fades in importance as the picnic looms only 48 hours away. At noon on Thursday, I drive out past Dulles airport to visit the weather service office at Sterling, Va., which issues forecasts for the Washington area.

John Billet, the lead forecaster on duty, walks me through the information he uses to predict the weather for the next two days. An avuncular man with a face like a young Charles Kuralt, Billet starts off with the NWS's most sophisticated computer models. The AWIPS system lets him click quickly through 12-hour steps in the model simulations to see the virtual weather evolve.

The models show a strong low-pressure trough over New Mexico moving eastward, drawing moisture from the Gulf of Mexico into the center of the country. Another trough lurks near the Canadian border. "There's quite a bunch of moisture—80 to 90 percent—over Louisiana and all the way up into Illinois," Billet comments. "My question for Saturday is: How much of this moisture is going to get hooked up with that trough we saw coming down and make it in to here?"

The next few screens of model predictions help him answer that question. The moisture will hit us on Friday and Saturday, but there won't be any force causing that air to rise, Billet says. Without the vertical motion, the moisture won't condense to form precipitation on Saturday, he predicts. The rain will come later.

He checks out the weather satellite images and refers to the computer projections of temperature and precipitation. Then he moves to another computer to type out his forecast. The official prediction for Saturday: "Partly sunny and warmer, with highs in the mid-70s." The chance of precipitation at Reagan National Airport is 20 percent.

The following day the specter of rain disappears completely. The Sterling office predicts a 0 percent probability of precipitation at Reagan National Airport. The skies will be partly sunny with a high of 74 degrees F, says Phil Poole, the lead forecaster on Friday afternoon.

The update from AccuWeather differs only slightly from the weather service's. "More cloudiness, high of 74," says Abrams in a voice-mail message. "It will be 60 to 70 percent cloudy. A one- or two-out-of-10 chance for showers. A one-out-of-100 chance for raining more than an hour." He signs off with his trademark line: "Have the best day you've ever had."

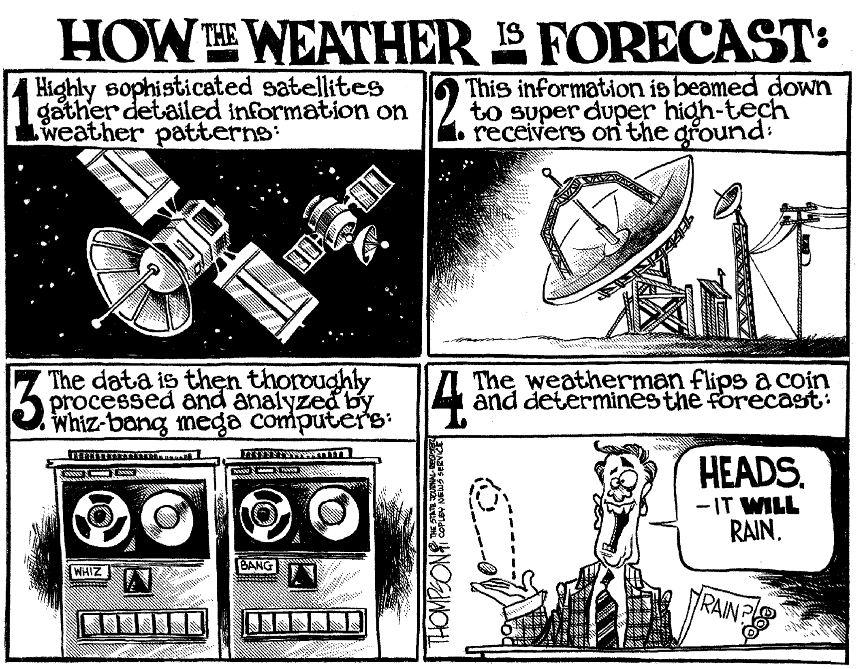
As I drift to sleep Friday night, the outdoor party seems a sure bet. The forecasts for the past five days have been getting increasingly sunnier and more consistent. Tomorrow should be warm and rain-free, with even some blue sky peeking through the clouds—perfect weather for letting the kids run around until they tire.

Flawed Forecast, Great Party

At dawn on Saturday, the forecast looks like a bull's-eye. The air feels softer than it has in days, a sign that the moisture has arrived in the region right on schedule. Fluffy white clouds stand out against a bright blue sky. I don't realize it then, but this will be the last clear sky I see all day. Within 30 minutes, a sheet of midlevel clouds moves in from the southwest to stay. As a result, the temperature never rises above 68 degrees F, making the air chillier than expected.

The party goes off well, although the clouds, mosquitoes and cool air combine to drive people indoors soon after the meal ends. That turns out to be a fortunate move. By 3 P.M. the sky darkens and a light rain starts falling, confounding the forecasts that I have heard. The morning's weather report from Sterling had said "rain likely after midnight" but did not mention precipitation during the day.

At 4:45 P.M. I call Poole and ask whether



MIKE THOMPSON *Copley News Service*

ABLE TO TAKE IT: Showing a sense of humility, the NWS posted this cartoon on its Web site.

he would consider this a blown forecast. He sighs and takes a long pause before answering: "Let's put it this way—if I had made the forecast and called for an absence of precipitation and there was precipitation from three o'clock on, I wouldn't be very satisfied with that forecast."

At the same time, however, he notes that the rain is extremely light and has not hit all parts of the forecast area. In fact, by midnight on Saturday, Reagan National Airport will record only a trace of rain, less than $^1/_{100}$ of an inch. By the weather service's standards, any rainfall less than that amount does not officially count as precipitation, even if other parts of the forecast area measure more.

Still, the temporary drizzle is enough to keep us inside for the rest of the day. Poole feels compelled to alter his forecast for the evening. Instead of predicting that the rain would arrive after midnight, he says, "Rain likely overnight." The strong precipitation does wait for Sunday.

Several days later Jim Travers, head of the Sterling office, explains that part of the problem on Saturday came from interpreting the models: "The models in general seem to be a little slow in bringing in the precipitation, which is not unusual. They go through periods when they're too fast or too slow." The forecasters must spot these biases and make adjustments, a tough task in borderline cases such as Saturday's drizzle. "Any forecaster would tell you that the most difficult forecasts we have to make are marginal situations," Travers says. "There aren't many big events that we or the models totally don't know are coming."

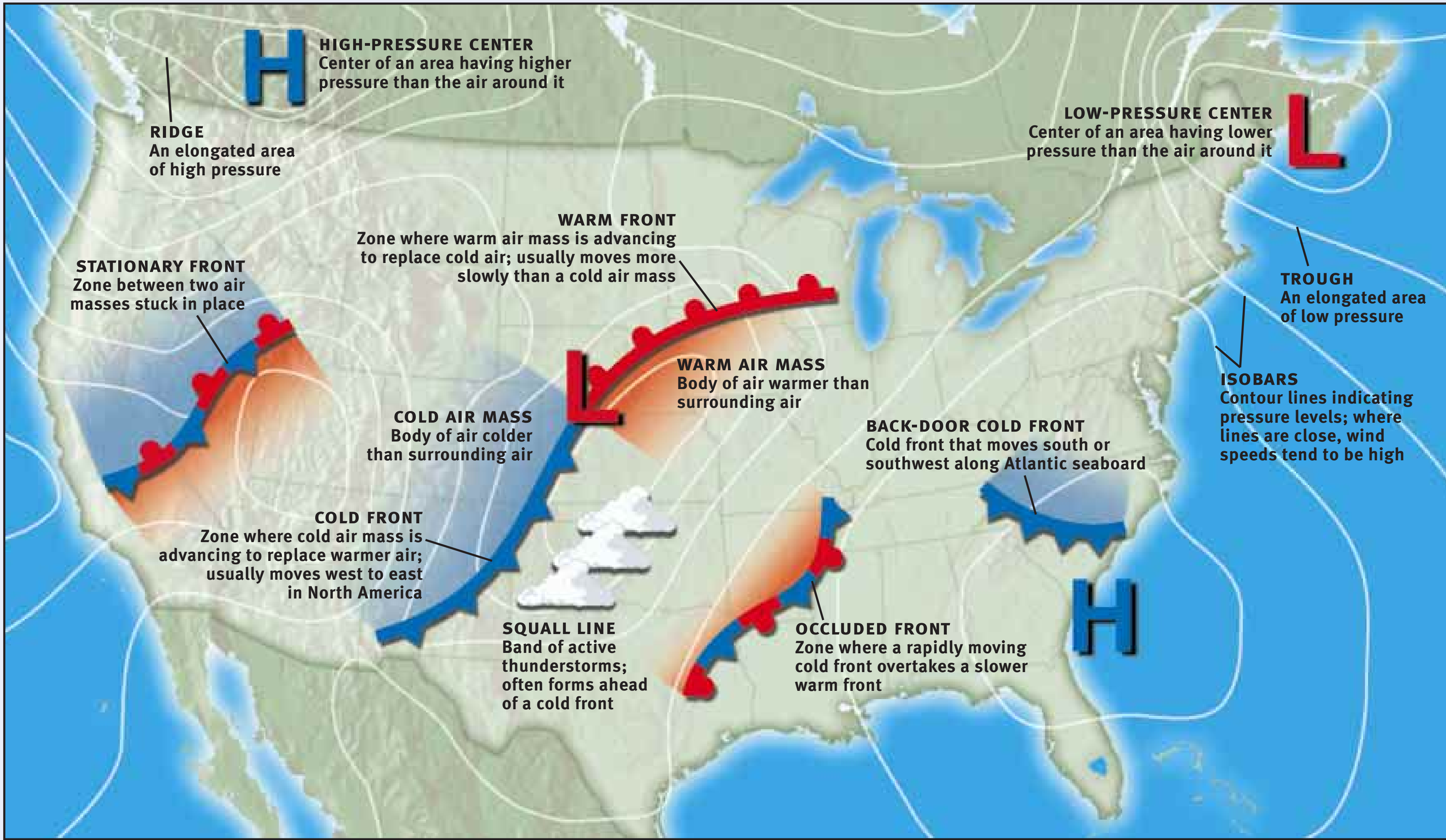
As computer power improves and models can better tune into local geography, the accuracy of forecasts continues to edge upward, as it has for several decades. Yet benign conditions will continue to be the bane of meteorologists, in part because the radar, satellites, models and other tools cannot give forecasters 20/20 insight into the atmosphere's future movements. The potential for rain will always lurk in the unseen currents of air swirling over the heads of picnickers. W

RICHARD MONASTERSKY is the earth science editor for *Science News.*

DECODING THE FORECAST

Compiled by EUGENE RAIKHEL
Illustrations by LAURIE GRACE

A glossary of common weather terms



WINDCHILL

How cold the air feels when the effects of temperature and wind speed are combined

TEMPERATURE (DEGREES FAHRENHEIT)

WIND SPEED	20	10	0	−10	−20	−30
5 mph	16	6	−5	−15	−26	−36
10 mph	3	−9	−22	−34	−46	−58
15 mph	−5	−18	−31	−45	−58	−72
20 mph	−10	−24	−39	−53	−67	−81
25 mph	−15	−29	−44	−59	−74	−88
30 mph	−18	−33	−49	−64	−79	−93

Windchill	Frostbite Risk
0 to −20	Medium
−21 to −60	High
Below −60	Imminent

HEAT INDEX

How hot the air feels when the effects of temperature and humidity are combined; also known as apparent temperature

TEMPERATURE (DEGREES FAHRENHEIT)

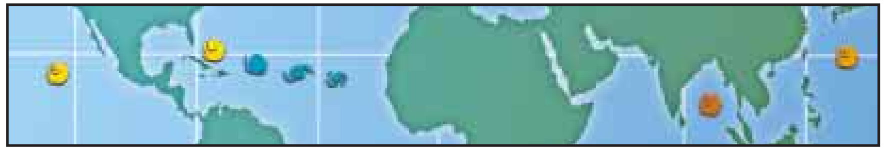
RELATIVE HUMIDITY	70	80	90	100	110	120
30	67	78	90	104	123	148
40	68	79	93	110	137	
50	69	81	96	120	150	
60	70	82	100	132		
70	70	85	106	144		
80	71	86	113			
90	71	88	122			
100	72	91				

Apparent Temperature	Health Effects
80 to 90	Fatigue
91 to 105	Heat cramps and exhaustion possible
106 to 130	Heatstroke possible
131 and higher	Heatstroke imminent

TROPICAL CYCLONES

Large low-pressure weather systems that typically form over warm oceans

Name	Wind Speed	Description
Tropical Disturbance	Below 23 mph	A mass of storms with relatively low wind speeds, out of which hurricanes sometimes develop
Tropical Depression	23 to 38 mph	A more organized cluster of storms
Tropical Storm	39 to 73 mph	A well-organized storm system
Hurricane	74 mph and up	A storm system with counterclockwise winds in the Atlantic or eastern Pacific
Typhoon	74 mph and up	A tropical cyclone arising in the western Pacific
Cyclone	74 mph and up	A tropical cyclone arising in the Indian Ocean



MORE WEATHERSPEAK

Degree days A calculation used by utility companies to determine how much energy is used for heating or cooling. They count one heating or cooling degree day, respectively, for each degree Fahrenheit below or exceeding 65: the temperature at which people are unlikely to run either heaters or air conditioners. Any day can have more than one cooling or heating degree day.

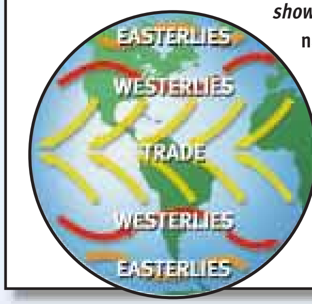
Dew point The temperature at which air becomes saturated and moisture condenses into dew.

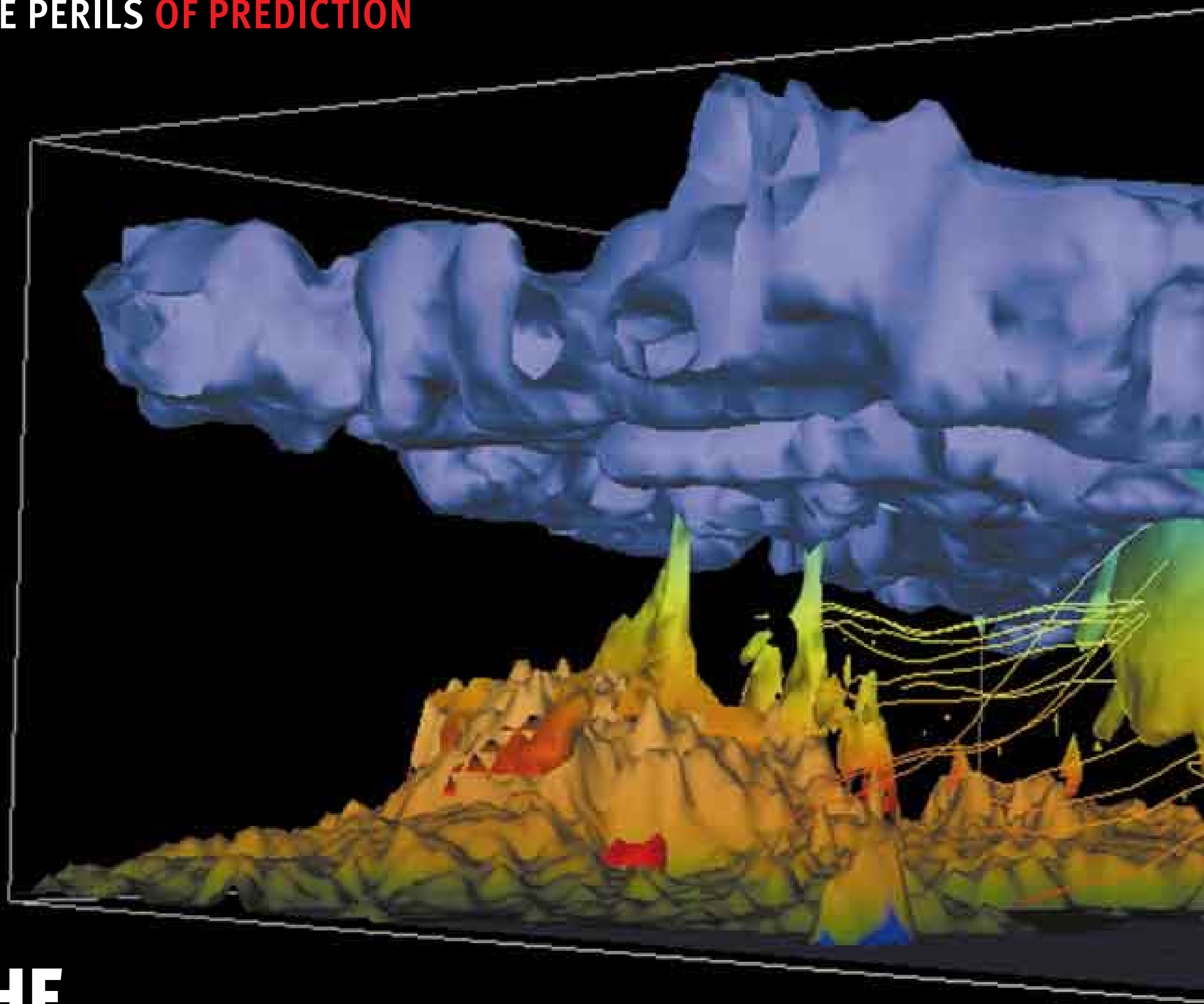
Dry line A boundary separating warm, dry air from warm, humid air.

Relative humidity An indicator of moisture in the air. A 50 percent relative humidity means the air is half-saturated.

GLOBAL WINDS

Surface winds (*below*) are often described by the direction from which they originate: easterlies move from east to west, westerlies from west to east. Trade winds typically travel from subtropical, high-pressure zones to areas of low pressure near the equator. Jet streams (*not shown on map*) are narrow bands of wind that move rapidly high up in the atmosphere (generally from west to east) over midlatitudes.

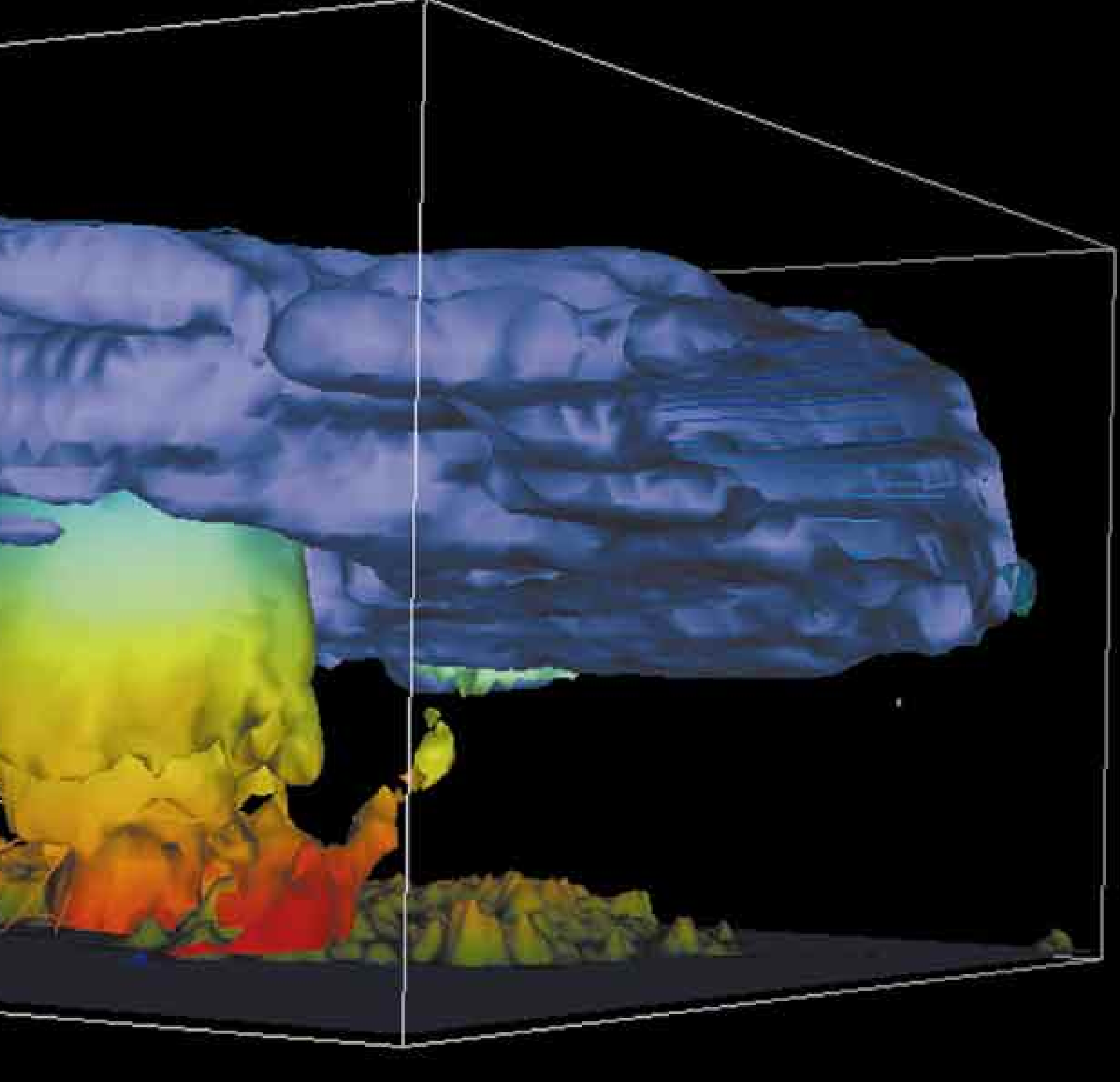




THE BUTTERFLY THAT ROARED

by JEFFREY ROSENFELD

To improve weather forecasting, meteorologists have learned to pay attention to the effects of chaotic airflows in the atmosphere



CYCLONE OFF ASIA: This computer model, developed at Pennsylvania State University and the National Center for Atmospheric Research, shows a storm brewing over the Yellow Sea off the coast of China. Beneath the upper deck of icy clouds, the model creates an imaginary cloudscape (the tints represent temperature) that shows the areas where airflow is most contorted.

BILL KUO *NCAR Mesoscale and Microscale Meteorology Division (computational modeling)*; HONGQING WANG *University of Peking* AND TIM SCHEITLIN *NCAR Scientific Computing Division (visualization)*

Weather forecasters are a frequently humbled bunch. No matter how far their science advances, the atmosphere finds ways to defy prediction. In 1998, for example, sophisticated computer models helped the National Weather Service (NWS) achieve the highest forecast accuracy in its 130-year history. But a disturbing number of meteorological events that same year proved how fragile that achievement was.

Take what happened on Thursday, February 19, 1998. The models predicted a stormy weekend in Louisiana. Fortunately, though, meteorologists were flying over the Pacific Ocean for a special research mission and reported one small correction. The jet stream was moving much faster than expected far off the coast of Alaska. Rerunning the models with the new information, NWS meteorologists saw that storms would probably strike central Florida, not Louisiana.

By Sunday at 2 P.M., confident forecasters issued a tornado watch—seven hours ahead of a deadly tornado outbreak in the Orlando area. A little discrepancy in the pattern of air flowing more than 4,000 miles away had made the difference between an accurate forecast and a bust. The change in the winds in Alaska had displaced storms in the southeast by several hundreds of miles—endangering people living near Orlando, not New Orleans. Blame what happened on chaos, the way small uncertainties in atmospheric conditions in one place can produce enormous consequences at a huge distance. Chaos is the bane of weather forecasters because it adds untold complexity to the models they use to make predictions.

Through the 1970s, few meteorologists anticipated the impact of chaos on the accuracy of forecasting. They had once assumed that they could gain a handle on the weather simply by accumulating a better understanding of such phenomena as lunar phases and solar cycles. The growing use of the computer facilitated this search by making it possible to construct statistical models that made predictions based on historical trends. Ironically, however, the computer age quickly displaced these models as a tool for day-to-day forecasting. Statistical models took a backseat with the rise of another type of computer prediction called dynamic modeling.

Like a motion picture, a dynamic model consists of a series of frames, each one a slight alteration of the previous one. The first frame is a numerical snapshot of the weather—the "initial conditions," a collection of the latest temperatures, pressures and other observations. The initial conditions are entered for each of a series of evenly spaced points of a grid that is superimposed onto a map of the area for which a forecast is being made. Then the model subjects the conditions at each grid point to basic equations describing motions (dynamics) of air and heat. The results of these calculations form the next frame, a simulation of the atmosphere usually a few minutes into the future. Each subsequent frame is produced by running the conditions in the previous frame through the equations of the model. As in a movie, time passes in small jumps from frame to frame. Eventually the computer arrives at the frame representing the time in the future that meteorologists are hoping to forecast—say, a day ahead. Meteorologists interpret this last grid of forecast conditions to predict whether tomorrow will be sunny or gray.


M.I.T. MUSEUM

FATHER OF CHAOS: Edward N. Lorenz came up with crucial insights that place a theoretical limit on how far in the future it is possible to predict the weather.

The growing use of dynamic models paved the way for the discovery of chaos. In 1961 Edward N. Lorenz of the Massachusetts Institute of Technology made a pivotal finding. Lorenz's dynamic model proved surprisingly sensitive to fluctuations in initial conditions. Slightly altered initial conditions changed the model results drastically. Lorenz realized that the real atmosphere, too, has this strange characteristic, which scientists now call chaos. Because of chaos, the weather never repeats itself exactly, so forecasting based solely on past trends is doomed. In addition, because it is impossible to know initial conditions perfectly, chaos forces dynamic models to spit out gibberish if stepped forward too far into the future.

Over time, Lorenz formulated a limit: beyond about two weeks, no one can tell where it will rain on a given day. Most of the time forecasters can't even get close to the two-week limit. Even the short-term predictions are dicey: tornado warnings—now averaging a lead time of about 12 minutes—are often false alarms. And most experts think chaos will bar warnings even a few hours in advance. Yet that hasn't discouraged meteorologists. By developing a savviness about chaos—even exploiting it—forecasts can continue to improve despite limits.

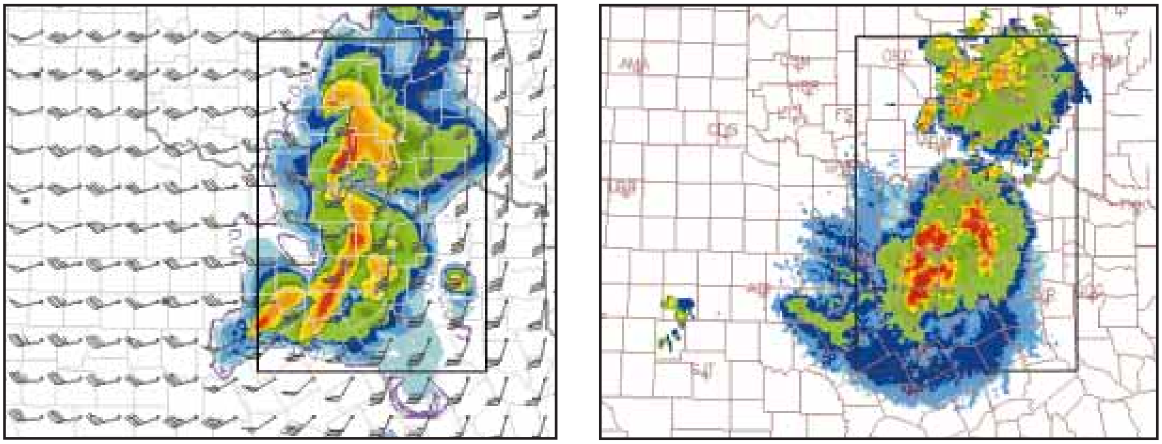
Breaking Up Gridlock

Lorenz described sensitivity to initial conditions as the "butterfly effect." Theoretically, a butterfly flapping its wings in Beijing could cause a storm over New York City. Such small motions slip through most model grids. Computer power has improved enough to take models from 200-mile spacing between points on a grid in the 1950s to 20-mile spacing in the finest resolution used today at the NWS. Anything in the 20 miles between grid points is lost to the computer. In other words, a butterfly as big as Manhattan could elude detection. But continued efforts to narrow grid spacings—with improvement in specification of initial conditions—is one way meteorologists can minimize the impact of chaos on forecasts.

Already model grids have tightened enough to handle big storms like East Coast blizzards of up to 1,000 miles across. Sometimes meteorologists can project their development five days in advance. Until recently, model forecasts of thunderstorms have not had much success. These storms—usually about 10 miles across—respond quickly to subtle motions.

Finer grids should assist models in forecasting severe storms. But devising better grids requires improving observations (the initial conditions). Right now so few observations represent the roughly 25 million cubic miles of U.S. weather that an accurate forecast for any given small area seems miraculous. For upper air conditions, 108 balloons rise simultaneously twice a day and radio back data. A few

ADVANCED REGIONAL PREDICTION SYSTEM



CENTER FOR ANALYSIS AND PREDICTION OF STORMS, UNIVERSITY OF OKLAHOMA

A high-resolution computer model devised at the Center for Analysis and Prediction of Storms at the University of Oklahoma predicts weather conditions over a very localized area. It forecast where thunderstorms that generated tornadoes would crop up over Oklahoma on May 3, 1999 (*left*). The projections corresponded closely to where the storms actually occurred (*right*).

dozen upward-pointing microwave beams add information about what winds are aloft. These beams are supplemented by automatic readings from commercial airliners that cover temperature, pressure and winds at high altitudes along popular routes. Information gathering is rarely as good elsewhere, especially over the oceans, long the Achilles' heel of global models.

To obtain better information, the National Oceanic and Atmospheric Administration experiments with getting better data out of observing systems, such as one that tracks clouds with satellites to derive wind speeds. Signals from the Global Positioning System can also roughly index atmospheric moisture content. Unfortunately, explains Thomas Schlatter of NOAA's Forecast Systems Laboratory, data are sustenance for models: if they eat too much, they can get sick; if too little, they can die. Most of these new data sources provide only indirect information and thus lack much nutritional value. Satellites, for instance, measure various wavelengths of radiation from the atmosphere, ranging from the infrared to the microwave end of the spectrum. From these emissions, meteorologists can detect the presence of moisture, but they then have to make a cumbersome conversion to derive humidity, the parameter to be input into the model. Even then, to ensure that the humidity figure is accurate, the scientists must adjust the model or the data to get usable results—unappetizing fare for those seeking to minimize errors in the initial conditions that lead to chaos.

In some cases, new uses of observing systems can help tighten grids to heretofore unheard-of resolution. At the Center for Analysis and Prediction of Storms (CAPS) at the University of Oklahoma, meteorologists recently made a breakthrough in their ability to model initial conditions. CAPS uses NWS radar data routinely to run a grid with five-mile spacing over the central U.S. The CAPS model also benefits from special observations across Oklahoma that track moisture and heat exchange between the soil and the atmosphere, which helps show where sunshine might trigger new updrafts for storms. On May 3, 1999, in the worst outbreak of tornadoes in Oklahoma history, CAPS predicted correctly where individual thunderstorms (though not the tornadoes themselves) would pop up over the landscape—two hours before they actually appeared on radars.

Benefits of a Better Diet

For three years, CAPS teamed up with American Airlines to test the new storm modeling. On January 6, 1999, for example, NWS models led forecasters to believe that the early morning might be clear at American's hub at the Dallas/Fort Worth airport. The fine-scale grid in the CAPS model picked up a small disturbance nearby, however, so the airline meteorologist predicted that fog would begin at the hub at 6 A.M. With three hours' warning, some incoming planes had time to add fuel for holding over Dallas/Fort Worth, thereby saving American at least $4.5 million in costs to divert flights to other airports.

Fine-scale models such as CAPS that make forecasts for a limited area are a proliferating breed. The most widely used fine-scale forecasting model is distributed by the National Center for Atmospheric Research (NCAR). With it, meteorologists at the University of Washington forecast Pacific Northwest weather daily. Part of the area is resolved by two-mile grid spacings. This grid resolution allows simulation of important terrain features that determine local atmospheric properties. "The mountains produce all kinds of features," explains Clifford F. Mass, an atmospheric sciences professor at the University of Washington. The fine-scale model can forecast local events, such as winds that collide behind mountains, the paucity of rain or snow on slopes sheltered from storms, and winds that pick up velocity and temperature as they descend a mountain.

In the central U.S., terrain effects are less pronounced. But there the storms themselves cause complicated local winds. Thunderstorm outflows—cool air spreading from rain shafts—

can kick up new storms. To model this, says CAPS director Kelvin K. Droegemeier of the University of Oklahoma, it seems likely that grid points about a mile apart are necessary. But Mass points out that increased resolution yields diminishing returns if the observations needed to specify initial conditions aren't plentiful. In the West, bordered by the sparsely observed Pacific, the absence of atmospheric readings is already a problem for fine-scale modeling. "If you aim a very fine rifle well enough but in the wrong place, then you don't hit the target," Mass says. Without better initial conditions, "the models are frequently not aimed in the right place."

Another difficulty with high-resolution modeling is that the results can mystify meteorologists. At five-mile resolution, Droegemeier says, a model might produce a storm that, unrealistically, does not dissipate. Increase the resolution to 500 yards, and the simulation might create a storm that oddly varies its strength. At even finer resolutions, the simulated storm can exhibit behavior that scientists have yet to see in nature. Meteorologists have trouble determining whether these results are caused by chaos, by model errors or by the weather itself.

One reason for this confusion is that no one is sure what limits chaos imposes on fine-scale modeling. Lorenz studied the atmosphere on a global scale, in which turbulence is distributed relatively evenly. But thunderstorms are concentrated areas of frenetic activity, with relatively vast spaces of minimal turbulence in between. "It's kind of scary," Droegemeier says. "We're not sure what resolution we need."

Increasing resolution decreases uncertainty only to a point: for every model, meteorologists ultimately must devise shortcuts to stand in for some hard-to-resolve atmospheric phenomena. A global model (a name for a model that usually has a grid with more than 30-mile spacing) simulates shifts in the jet stream and large storms, such as blizzards. But the model does not represent thunderstorms. Instead it must use a shortcut that consists of a simple calculation to approximate the effects of a thunderstorm on existing weather conditions. Even the sophisticated CAPS model—which uses basic equations of heat and motion to simulate thunderstorms—must resort to shortcuts. At one-mile resolution, it must take into account individual raindrops, a task beyond the capabilities of the modeling software. So it uses a shortcut to calculate the effects of rainfall evaporation, an important model input.

Shortcuts don't just fill the gaps in the grid—they also incorporate new knowledge from researchers, another way meteorologists improve forecasts despite the limits of chaos. One hazard that models do not resolve is supercooled drizzle—liquid droplets less than half a millimeter in diameter that float in clouds at subfreezing temperatures. Undetected supercooled drizzle iced the wings of a commuter plane over Roselawn, Ind., in 1994 and caused it to crash, killing all 68 people on board. At NCAR, Ben Bernstein and his colleagues subsequently developed an algorithm that incorporated human expertise at forecasting aircraft icing from supercooled drizzle, knowledge developed during recent National Aeronautics and Space Administration test flights. This software considers many different variables, such as cloudtop temperatures and surface precipitation, then weighs the evidence as an expert would.

Another team of NCAR researchers, led by Rita Roberts, James Wilson and Cynthia Mueller, recently developed an automated system to predict the motion of thunderstorms about half an hour ahead. They combined satellite and radar information, local surface observations and a model that analyzes thunderstorm outflows, the cooled air that emerges from areas where rain is falling. The system improved severe-weather warnings in tests at the NWS.

One of the most elaborate meteorological expert systems

ENSEMBLE MODEL

Each colored line on these maps represents a separate prediction for the same atmospheric pressure pattern. Combined, the lines constitute an ensemble of forecasts. Every prediction is slightly different because the computer runs the model each time with slightly different input conditions. At first the tiny differences in input conditions matter little: the resulting lines trace nearly identical paths (*left*). In later predictions (*center* and *right*), however, the lines diverge. If the divergence occurs rapidly, as it does here, meteorologists know that atmospheric conditions are chaotic and that their predictions may be uncertain.

ENVIRONMENTAL MODELING CENTER, NATIONAL CENTERS FOR ENVIRONMENTAL PREDICTION consists of real flesh and blood: the forecasters of the Hydrometeorological Prediction Center (HPC) at the National Centers for Environmental Prediction (NCEP), the NWS's modeling hub. They tell the local forecasters how much rain to expect—

New techniques for improving forecasts take into account the inherent limits of scientific certainty.

not just where and when—by interpreting the models carefully. One NCEP model, for instance, approximates thunderstorms in a way that makes too much rain on the East Coast and too little in the High Plains and West. The HPC staff members adjust accordingly at the times they think storms will appear.

The HPC forecasters are attuned to theoretical advances that might improve on the model output. In recent years, researchers have characterized the interaction of the high-altitude jet stream with low-level channels of moist air. These interactions elude most models, so the HPC must predict these rainy areas and then adjust the model results.

Ensemble Work

The HPC forecasters have learned that their expertise can tempt them to become overly precise in making predictions. In April 1997 the Red River began to rise at Grand Forks, N.D. Based in part on HPC outlooks, the NWS predicted a record flood of 49 feet. Unfortunately, citizens of Grand Forks didn't pile the sandbags high enough for what turned out to be a 54-foot flood, and the city's downtown district was overwhelmed, forcing more than 5,000 people to evacuate.

Forecasters correctly foresaw that the river would reach a record crest, but critics assert that predicting the full range of possible water levels might have saved Grand Forks. New techniques for improving forecasts take into account the inherent limits of scientific certainty. HPC will begin issuing advisories estimating the chance—either 75, 50 or 25 percent—that a given prediction is likely to be exceeded. Probabilities help people decide how much risk they wish to take.

Assessing the likelihood of a meteorological event has grown easier with a technique called ensemble forecasting, which makes it possible to assess the atmospheric uncertainties produced by chaos. An ensemble is a collection of nearly identical simulations using a particular model. For example, the ensemble of NCEP's two-week model includes 14 different versions of the forecast, each with slightly different initial conditions. Scientists check the ensemble's predictions every few hours against observations of the actual weather to gauge accuracy. In a sense, they are intentionally breeding chaos. If the ensemble forecasts diverge from the real weather quickly, the forecasters know that the atmosphere is particularly sensitive to its initial conditions and that the forecast is uncertain.

Errors in prediction that result from chaos can often render the four-day outlook meaningless, says Zoltan Toth, a General Sciences Corporation modeler at NCEP. But sometimes the atmosphere seems relatively insensitive to initial conditions. "In some cases, we can actually get to the two-week limit," Toth says.

Ensemble studies and similar analyses show that predictions are often enhanced when the environment forces the atmosphere to behave in a consistent manner—limiting the influence of chaos. Recent El Niño–based climate predictions have been successful, partly because of the overwhelming influence (or "forcing") of the ocean on wind patterns. Once a strong El Niño (periodic warming of the equatorial Pacific off South America) appears, the atmosphere above it settles into a reasonably predictable routine, affecting winds elsewhere around the world as well.

Such oceanic forcing may determine hurricane intensity. Hurricane Opal in 1995 gained 20 miles per hour in wind strength in just 14 hours over the Gulf of Mexico, only to weaken again before landfall. A recent modeling study by scientists at M.I.T. suggests that warm ocean waters triggered Opal's intensification. The hurricane's winds then forced cool water to rise to the surface, which would have quelled the storm quickly if Opal had not moved so fast. Researchers with the University of Rhode Island and NOAA have now coupled an ocean circulation model to a hurricane model to simulate the upwelling. In 1999 the new coupled model—which also boasts more realistic cloud simulations—showed it could improve intensity forecasting by 30 percent.

Ensembles not only reveal which environmental features—a warm ocean eddy, for instance—can enhance prediction but also help meteorologists isolate where uncertainty is overwhelming a model. Then scientists can try to improve predictions by obtaining more observations from a critical area. The flights over the Pacific that discovered the strong jet stream in February 1998 tested this strategy.

But chaos can fool even the ensembles. Once at NCEP, two of the 14 simulations in the ensemble nearly began to duplicate each other day after day. With the varying initial conditions, each simulation, as it progresses, is supposed to differ increasingly from other simulations—an essential characteristic of chaos. When the rogue pair began to dance too closely together, Toth and his fellow chaos breeders had to stop the music, ending the simulations. Somehow the chaos they had created had lost its way. The NCEP model masters had to start over with a fresh set of initial conditions. "We didn't understand why it was happening," Toth says. So researchers faced another puzzle among the unanswered questions related to chaos. Finding answers may help scientists avoid the destruction that can be unleashed by a storm misplaced on a computer model grid. W

JEFFREY ROSENFELD is a freelance writer who lives in El Cerrito, Calif. He is the author of the book *Eye of the Storm: Inside the World's Deadliest Hurricanes, Tornadoes and Blizzards* (Plenum Trade, 1999) and a contributing editor at *Weatherwise* magazine.

DO WE NEED THE NATIONAL WEATHER SERVICE?

by JEFFREY ROSENFELD

Private forecasters are taking over more and more of the responsibilities that were traditionally fulfilled by government meteorologists

You're getting ready for an adventure, packing up for a pleasure cruise from New England to the warmer climes of Bermuda. Next to your life vest, your charts and your provisions, what you need most is an accurate weather forecast. The forecast had better last you a good four days, close to the limit of reliable prediction.

"Most people know it's risky behavior to take a boat out into the open ocean," says Ken McKinley of Locus Weather, a one-man meteorological bureau in Camden, Me., that helps mariners reduce that risk. Every year hundreds of them plunk down about $100 for McKinley's advice before embarking on an ocean voyage, even though they can get a free five-day forecast from the National Weather Service (NWS). They prefer McKinley's customized assessments of wind shifts and wave heights to the generalized statements from the government agency. Even crusty old Yankee skippers, self-sufficient types who can make their own forecasts, will hire McKinley for a consultation.

McKinley's business is proof that when the stakes are high, people are willing to pay for a forecast. To decide whether to take an umbrella to work, people tune in to the TV or radio or check a newspaper or Web site. In turn, these media buy their forecasts from commercial meteorologists. The private forecasters purchase the weather data they use to make predictions from commercial data vendors who have contracts to obtain and process the raw radar, weather balloon and satellite readings from the NWS. In addition to supplying the basic data, the NWS also makes its own forecasts.

The way some leaders in the forecasting business are talking, this supply chain will change dramatically in the new century. Today the NWS is the hub of the nation's weather infrastructure. But if the speculations of Joel N. Myers, chairman of AccuWeather, the largest private forecasting company, turn out to be true, the NWS may eventually cease to exist. Last October, in a speech at NWS headquarters in Silver Spring, Md., Myers suggested that private firms might eventually launch their own satellites, run their own models of weather conditions, merge disparate private radar networks and expand their deployment of observing instruments, all jobs currently carried out by the NWS. The implications of what Myers depicts are clear: technology and efficiency will render the NWS redundant.

Anticipating Crowds at the Mall

In this vision, the broadened capabilities of private services would expand coverage greatly, supplying a neighborhood-by-neighborhood picture of what the weather is doing. In this new world, a few large private companies like AccuWeather, by assuming these responsibilities, would substantially increase the size

ACCUWEATHER.COM

NWS, INC.: AccuWeather, the largest private forecasting firm, employs a team of 93 meteorologists in its operations room at State College, Pa. Companies like AccuWeather may take over more of the government's weather responsibilities.

of their markets, mainly by selling meteorological data and forecasts to smaller weather services companies.

These ideas may seem farfetched, but in fact at least 300 firms nationwide already sell meteorological services of some kind. Most are small and make do with NWS forecasts, or else they focus on consulting, such as providing expert testimony in weather-related court cases. But others, especially bigger firms, also make their own forecasts using NWS data on wind speeds, temperatures and other observations. Based in State College, Pa., AccuWeather employs 93 forecasters. "I think most people don't realize that 85 percent of their weather information comes from private weather providers," says Jeffrey Wimmer, who is both president of Fleet/Compuweather, a forecasting firm in Dutchess County, New York, and current chairman of the forecasting industry's lobbying arm, the Commercial Weather Services Association (CWSA). The industry tops $1 billion in sales each year, at least 50 percent more than the annual budget of the NWS itself.

Private firms add value to the government information by tailoring weather forecasts to serve specific customers' needs. McKinley's clients have included movie production companies looking for on-location sunshine; other meteorological firms advise such clients as local TV and radio stations, retailers, construction firms and amusement parks.

Despite the availability of free government forecasts, the private services find clients because they are so good at handholding. Many forecasting firms offer unlimited telephone consultation in addition to sending a forecast daily to the client's e-mail. School districts hire forecasters to predict icy road conditions; the meteorologists will call the superintendent at a specified predawn hour to help make cancellation decisions. Other conveniences include beeper services that relay NWS announcements and 900 numbers for windsurfing or skiing outlooks.

Specialization is another rationale. At EarthSat in Rockville, Md., meteorologists examine government satellite imagery that gauges vegetation quality, then put together daily updates of harvest expectations. Commodities traders buy these images to make estimates about crop yields and ensuing fluctuations in commodity prices. Similarly, Climaton Research in Fairfax, Va., gives utilities a daily updated report of projected weekly energy demands based on expected temperatures.

The CWSA and its 33 member firms continually press Congress to bar the NWS from supplying services that companies can provide on their own. They lobby for legislation to reduce the role of the NWS over time as technology progresses. They want to limit the agency to running computer models, performing data collection and research management, and issuing public warnings to save life and property. Confining itself to these tasks would let the NWS avoid competing with the private sector, which it promised not to do in a 1991 policy statement.

But privatizing weather forecasting presents its own hazards. In 1996 the CWSA helped to persuade Congress to eliminate the frost-warnings program of the NWS. Many farmers were reluctant to pay for services that had been free for decades. The repercussions were harsh when a cold snap hit Florida in 1997 and caused $100 million in crop damages. Private weather services say they saved some of their clients from the freeze, for fees from $50 to $100 a month. They claim, moreover, that the NWS would not have done much better. But too many farmers were hurt by the freeze.

Severe-weather warnings pose the biggest challenge to those who advocate taking over NWS responsibilities. Even the most diehard advocates of privatization often acknowledge that there is a legitimate place for the government in making these warnings. It's not that private firms can't issue hurricane warnings, given proper resources, but any company that mistakenly puts out a warning might face huge litigation exposure. Every mile of coastline evacuated erroneously costs coastal economies close to $1 million.

The idea of getting rid of the NWS starts to break down when Myers talks about taking over the government's data-gathering responsibilities. Developing and launching weather satellites (now a duty of the National Aeronautics and Space Administration) costs hundreds of millions a year; the upgrades of NWS radar and computers in the 1980s and 1990s required an investment of billions. No private company could bear the burden of these expenses.

Myers's vision suggests that, as private weather services grow, a firm like his own might be able to muster the necessary financial wherewithal to supplant government data services. Such a development, however, might have the unwanted consequence of endangering the existence of smaller forecasting firms. Those companies might end up paying dearly to the company with the biggest data-gathering network, resulting in less competition in the field. Worse yet, all meteorologists would lose government involvement in incubating the basic science that drives their predictions: the history of forecasting in America shows that progress at the NWS helped to hatch the very industry that may ultimately destroy it.

ACCUWEATHER.COM

TWISTER BEEPER: AccuWeather sends severe-weather updates to word-message pagers.

The National Weather Service was born in 1870, when Congress directed the U.S. Army to begin forecasting weather. The act was a direct response to two years of maritime disaster on the stormy Great Lakes: 500 people drowned and more than 3,000 ships sank or ran aground in 1868 and 1869. The new service immediately reduced the tragic losses, and by 1891, when the army handed weather duties over to civilian oversight, Americans considered their free weather forecasts essential to daily life.

Over the next 50 years, however, the U.S. Weather Bureau (as the NWS was then called) advanced sluggishly. It refused to issue tornado warnings, which were still unreliable. It was slow to focus on tailoring fog and thunderstorm prediction to the needs of aviators. Worst of all, old-guard forecasters at the bureau ignored helpful new discoveries about the basic science of meteorology, such as the existence of cold fronts. They clung to the belief that forecasting was an art, not a science. They weren't alone: the public shared their view, and so did many scientists. As a result, few universities bothered to teach meteorology. This attitude partly explains why private forecasting was practically impossible at the time: without objective standards, the most prominent private weather practitioners (outside the airline industry) were con men who claimed that they could make rain.

In the 1930s the Weather Bureau rapidly modernized, remaining an oasis of credibility while shedding its former scientific malaise. After World War II, the reputation of meteorology improved dramatically. The technology of battle bred tools for science—radar, satellites and computers, to name a few. The Weather Bureau helped to adapt them to meteorology. Computerized predictions in particular transformed weather forecasting into an objective, scientific process. Finally, private meteorologists had something worthwhile to sell, and a few of the thousands of soldiers trained in meteorology during the war went into business for themselves, making forecasts using data from the government.

In the 1950s their annual sales only amounted to a few million of today's dollars, but private meteorologists were primed for new business by the mass media in the 1970s and 1980s. For this development, they could again thank advances at the NWS and associated federal agencies. Government satellite imagery proved immensely popular on TV, and better severe-storm warnings from government radar enticed competitive broadcasters to begin installing their own radars for local forecasting. Private companies supplied the graphics and forecasting necessary to adapt this technology for a wide audience.

AccuWeather now furnishes forecasts to more than 1,000 TV and radio stations, all from its headquarters in Pennsylvania. The advent of the Weather Channel in 1982 spurred broadcasters to rely even more heavily on private meteorologists to retain their edge in local forecasting. To compete, local broadcasters had to turn to private services to improve their reports, introducing high-powered

THE WAY THE WIND BLOWS: Windsurfers turn to private weather services to learn about the winds they might encounter while cavorting in the Columbia River Gorge.

WARREN MORGAN *Corbis*

graphics that showed weather conditions in their small markets.

By serving the media's special needs, private forecasters usurped the presence of the NWS in making direct forecasts. Today the forecasts that come straight from the NWS are mostly severe-weather warnings for hurricanes, tornadoes and the like, which can be seen scrolling across the bottom of television screens when a storm is approaching. As eminent free-marketers, Myers and others criticize the freely accessible NWS Web pages that disseminate and discuss routine forecasts, radar imagery and more. The business leaders say that the pages compete with Web sites supplied with weather information and forecasts from commercial vendors—the government, they reason, should not be doing something that the private sector can do better.

Betting on the Thermometer

NWS-driven expansion of the private sector continues. When the NWS enhanced climate modeling in the 1990s, it could make generalized predictions covering an unprecedented year into the future. Private firms quickly adopted similar techniques and assisted in interpreting the new forecasts, refining the basic reports they received from the NWS. This work became more prominent when El Niño turned into a household word in 1997—a result, in part, of the success of computer modeling at the NWS and research institutions. This event gave the financial industry the confidence to back a new form of investment: "weather derivatives." These contracts, written months in advance, pay a designated amount when temperatures are abnormal. In particular, derivatives help utilities hedge against widespread losses from weather-influenced price changes. An over-the-counter market for derivatives developed, prompting the Chicago Mercantile Exchange to begin electronic trading of them in September 1999. Corporate clients have also turned to private forecasters for advice on pricing and trading these new financial instruments.

Government-funded university researchers have contributed to the expansion of the capabilities of the private firms as well. Windsurfers in the West routinely place calls to forecasting companies plugged into the results of high-quality computer modeling programs run at the University of Washington that discern tricky local wind patterns. And the latest advances in modeling thunderstorms—made at a National Science Foundation–sponsored center at the University of Oklahoma—were tested in a partnership with meteorologists at American Airlines.

Perhaps someday computers will be so fast and cheap that all firms will be able to run their own forecast models. But private firms will only outstrip the NWS if the weather service stands still—and many have no wish to unbalance the status quo. Says Lee Branscome of Environmental Dynamics Research, a Palm Beach Gardens, Fla., meteorological firm that chooses not to make its own forecasts: "We'll always be a step behind them. Our approach is, 'Why reinvent the wheel?' The real key is to interpret the forecasts."

In this sense, both the forecasting business and the NWS are likely to occupy complementary niches: predicting windsurfing conditions in the Columbia River Gorge may remain the bailiwick of private specialists. But the NWS still has a major role to play in improving forecasts. Its funding and expertise mean that it may be the only institution able to develop and implement new observing systems and computer models. Despite the dreams of Joel Myers and the like, the outlook for a continuing role for the National Weather Service is fair to good. W

JEFFREY ROSENFELD is a freelance writer based in El Cerrito, Calif.

BILLION-DOLLAR TWISTER

by ROBERT HENSON

Oklahoma, America's most frequent victim of tornadoes, suffered more twister-related destruction on May 3, 1999, than ever before. What are we learning from this epic event—and could it happen somewhere else?

For drama's sake, it's tempting to say there was something spooky in the air. But as dawn broke across Oklahoma on May 3 of last year, the conditions weren't especially ominous. True, it was a bit humid and breezy, but nothing special for springtime. Wheatfields near Oklahoma City were tossing in a 25-mile-per-hour wind by midafternoon, but wind is to Oklahoma as snow is to Alaska. It's part of the fabric of life and—usually—of little consequence.

Five hours later some 8,000 buildings in central Oklahoma lay in partial or total ruin. A seemingly endless swarm of tornadoes had ravaged a 150-mile-long belt running from southwest Oklahoma diagonally across the state to near Wichita, Kan. Across this swath, at least one twister was spinning on the ground at every moment from 4:45 to 10:45 P.M.—except for a two-minute lull midway through the period, as if nature were catching its breath.

Even for storm-savvy Oklahomans, this swarm was a catastrophe beyond most people's experience. All by itself, the twister that touched down in Oklahoma City was the nation's first billion-dollar tornado. It damaged almost three times as many structures as any previous American tornado had.

As the twisters descended on Oklahoma, storm chasers, including some of the world's top tornado experts, went out in droves to meet them. Their mobile radars and other instruments collected a year's worth of data in a single day. Already the tornadoes of 1999 have provided some intriguing avenues for research and shattered a hypothesis or two along the way. The work is helping to explain why the twisters of May 3 became so fierce. It is also providing new insights into how tornadoes form and sustain themselves.

PAUL HELLSTERN *The Oklahoman*/SABA

A Cloudy Forecast Becomes Clear

Forecasters didn't exactly see apocalypse coming on the morning of May 3, but they knew there could be a twister or two. Oklahoma gets more tornadoes per square mile than anyplace else on Earth, and May is when they are most likely. A few basics, largely identified more than 50 years ago and clarified more recently, lie at the root of severe weather (including tornadoes) across the plains. Warm, moist, ground-hug-

PAUL B. SUTHERLAND *The Oklahoman*/SABA

A NEIGHBORHOOD VANISHES: The spring tornadoes that hit Oklahoma and Kansas damaged thousands of buildings, including these homes in Moore, an Oklahoma City suburb.

PAUL HELLSTERN *The Oklahoman/SABA*

PAUL B. SUTHERLAND *The Oklahoman/SABA*

THE AFTERMATH: Volunteer rescue workers in southwest Oklahoma City labored for half an hour to remove Renee Faulkinberry from the rubble of her home after it was leveled by a tornado.

ging air from the Gulf of Mexico sweeps beneath a cooler, drier layer several miles high, creating instability. Often a warm, dry layer in between serves as a buffer, preventing the layers from meeting and thus keeping a lid on the instability until late afternoon or evening. Then the air warmed by the sun breaks through this separation layer. A tornado may occur if certain other conditions are also present at that point. One is wind shear at upper levels: the wind strengthens with height or changes direction with height, or both. Another is a nearby front or other air-mass boundary (where winds collide) near the ground. And the pot is stirred if a knot of vorticity, or rotation, in the jet stream approaches the area of these disturbances.

This recipe holds up well for predicting when severe weather is possible. But what causes multiple tornadoes, known to meteorologists as a "tornadic swarm"? "We don't understand exactly why some days are prolific and others aren't," says Harold Brooks, a researcher at the National Oceanic and Atmospheric Administration National Severe Storms Laboratory (NSSL) in Norman, Okla. Singling out the really bad days in advance can be like trying to pick the future criminal out of a group of mischievous 10-year-olds.

May 3 did not stand out from the pack at first. At 6:30 A.M., forecasters at the Storm Prediction Center (SPC)—another NOAA unit based in Norman—assessed the day as having a "slight risk" for severe weather across parts of Texas, Oklahoma and Kansas. Every morning SPC rates the day's severe-weather potential as slight, moderate or high. (They also issue the nation's tornado watches.) On this Monday morning there were some indications that a tornado would be unlikely. Forecasters thought a sheet of cirrus clouds evident on satellite images might limit heating over the expanse of the southern plains. Upper-level winds were blowing at only around 50 mph, a marginal speed for supporting twisters. And a dry line in west Texas, separating sultry Gulf air from its desert-toasted counterpart, was not moving much.

It took until early afternoon for the day's true colors to become apparent. A swirl of upper-level energy, packing winds of close to 100 mph, was heading east from New Mexico. This kink in the jet stream, called a short wave, was small enough to have escaped detection by almost 100 weather balloons launched across the U.S. at 7 A.M. Oklahoma time. The next national balloon launch would not be until 7 P.M. But at midday, as the short wave approached the plains, it ran into a posse it couldn't evade: a network of 30 wind profilers. Scattered across the central U.S., these upward-pointing radars plot wind speed and direction as do the twice-daily weather balloons, but the profilers report every hour. From the profiler data, SPC could tell that upper winds would strengthen dramatically across Oklahoma that evening.

By late morning SPC had upgraded the level of risk in the southern plains to moderate. A patch of clearing skies across southwest Oklahoma and northwest Texas provided even more cause for concern: nothing in the sky would block that region from heating up enough to generate storms. Most convincing was output from a high-resolution computer forecast model that showed storms charging across Oklahoma and southern Kansas by evening. At 3:49 P.M., SPC bit the bullet and placed the area under high risk—a red-flag rating reserved for only a few days per year.

Even at this point, nobody could say which towns would be flattened two or three hours later. It's one of the fondest dreams of storm scientists to be able to provide hard numbers in advance on tornado likelihood. Brooks and his colleagues at NSSL and SPC are testing one tool that shows promise. The most familiar example of a probabilistic outlook is the percent-chance-of-rain statements that entered public forecasts in the 1960s. Each of the experimental tornado forecasts pegs the likelihood that a twister will strike within 25 miles of any given point. Last year provided a slew of tornadoes for calibrating the test

F5 TERROR: Some of the May 3 tornadoes reached F5 (261 to 318 miles per hour), the highest intensity on the Fujita scale of tornado severity (*top*). In contrast, an F0 (*bottom*), the lowest on the scale, produces winds of 40 to 72 mph.

JERRY LAIZURE *Newsmakers/Gamma Liaison* (*top*)

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH/UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH/NATIONAL SCIENCE FOUNDATION (*bottom*)

outlooks. “The response from forecasters in the field has been very positive,” Brooks says. Probabilistic tornado outlooks may become a standard tool of forecasters as early as next year, although it’s unlikely they will become part of public statements until more work is done.

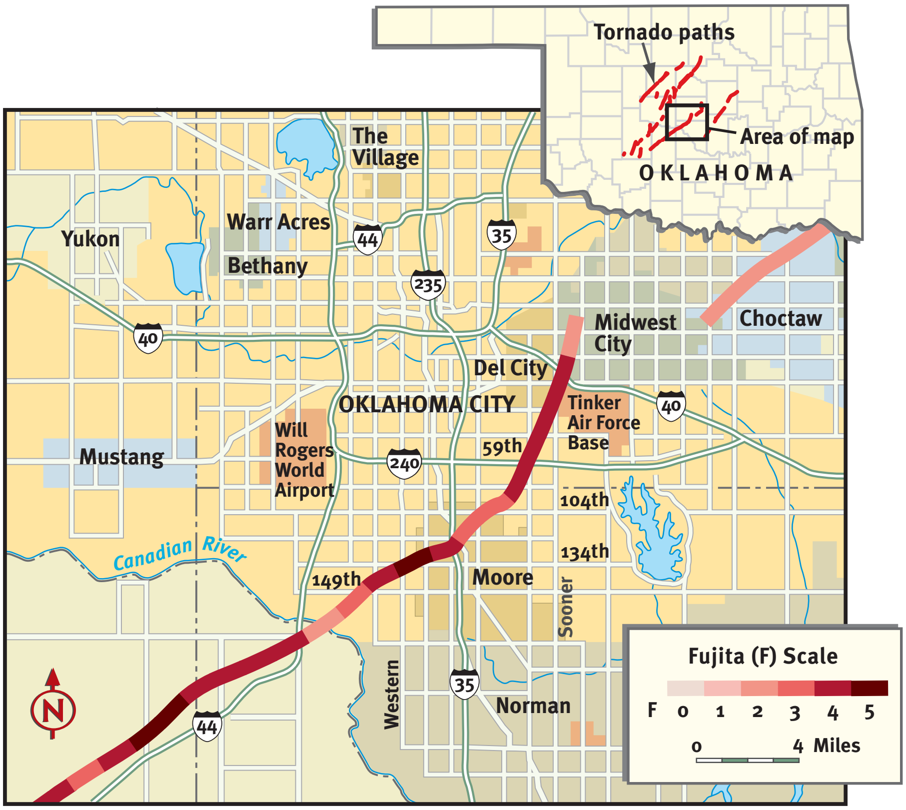
Ground Zero in an F5

The worst havoc on May 3 occurred with the tornado that sliced across the southern outskirts of Oklahoma City and the suburb of Moore. Its 38-mile-long path was three quarters of a mile wide in spots. On the F-scale of tornado damage created by T. Theodore Fujita (the eminent University of Chicago meteorologist who also discovered microbursts), this twister was rated by surveyors as a rare F5, which corresponds to top winds from 261 to 318 mph. It destroyed more than 1,000 buildings (including 22 homes swept completely off their foundations) and damaged many more. Any F5 is unusual, but one that plows into an urban area is even more rare; this was Oklahoma City’s first. Together F4s and F5s represent only 2 percent of tornadoes, but they cause two thirds of all tornado-related deaths. Even people sheltered in a small interior “safe room” may not survive an F5.

Street after street of ruined homes revealed as much about building practices as they did about the tornado itself. Typically the garage door folded inward and the windows shattered, followed by the roof lifting off and the walls caving in. A damage survey team led by Texas Tech University also found, not surprisingly, that even homes built to code—able to withstand 70- to 80-mph winds—were no match for this twister. Among the more unusual finds: a bathtub holding two shelter seekers that was airborne for almost a city block. (Both passengers survived.) The team also found significant damage up to a mile from the tornado’s path. On a closer look, they noticed something new: cones of damage that flanked the tornado’s path at right angles. Each one sketched the trajectory of a single chunk of debris (such as a roof blown off an especially weak building) that pelted structures in its wake as it was sucked from well outside the tornado’s path into the funnel by 100-mph winds.

Mobile homes fared even more poorly. Despite their folk reputation as tornado magnets, mobile homes tend to act more like iron filings—they scatter to the wind with haste. “Trailers are good at detecting tornadoes that would otherwise not be noticed,” says tornado climatologist Thomas Grazulis. An F1 tornado (winds of 73 to 112 mph) can overturn a mobile home; an F2 can demolish it. In the Oklahoma City storm, mo-

PATH OF DESTRUCTION



Sixty-five tornadoes on May 3 cut their way across Oklahoma; the paths of some of those funnels appear on the map at the upper right. The most severe twister plowed through Oklahoma City and its environs, with a rating that varied from an F5, at its most intense, down to an F2.

MATT KANIA

bile homes accounted for less than 2 percent of the structures damaged but a quarter of the deaths.

Although the property toll was enormous, the number of deaths was actually surprisingly low. Several tornadoes earlier in this century took more than 100 lives at once, yet the May 3 strike in Oklahoma City took far fewer. Why were so few killed? For one thing, the tornado itself was huge, visible and audible. At times, its dull roar could be heard more than half a mile away. Also, local radio and television went into saturation coverage once the first twister touched down. Warnings from the National Weather Service (NWS) gave an average lead time of 32 minutes in the Oklahoma City area, more than double the national norm.

Radar to the Rescue

The prompt warnings were made possible in part by wind-sensing radar devices. Doppler radars have been peering inside tornadoes for more than 25 years. Whereas traditional radars use the energy returning from radio waves to map precipitation, Doppler radars sense the change in frequency of those radio waves to plot winds as well. Over the past decade a national network of Dopplers has been installed at NWS offices. With software that can identify some tornadoes as they develop, the radars have helped boost lead times for tornado warnings.

In the past decade Dopplers have gone mobile. Howard B. Bluestein, a storm-chasing pioneer and a professor at the University of Oklahoma, started the ball rolling. In the late 1980s he brought to the plains a compact, continuous-wave Doppler radar developed at Los Alamos National Laboratory. (A newer version comes from the University of Massachusetts.) This radar's narrow antenna can't see beyond about six miles with clarity. Close up, though, it can dissect a tornado by measuring wind speed at points separated by as little as 20 feet. In April 1991 Bluestein set a world record for near-ground wind measurement when his radar detected 287-mph winds in an Oklahoma twister.

Four years later Joshua Wurman (now a University of Oklahoma professor as well) created Doppler on Wheels (DOW) with help from NSSL and the National Center for Atmospheric Research. Mounted on a flatbed truck, the DOW resembles a flying saucer on a pedestal. It is harder to maneuver into place than Bluestein's radar, but it can see farther. The addition of a second DOW in 1997 allows for a quick three-dimensional picture of wind vectors when both DOW units are trained on the same storm.

Both Wurman and Bluestein struck pay dirt with the Oklahoma City tornado and others that dropped earlier from the same storm. One DOW unit caught a wind gust near Moore initially estimated at between 300 and 320 mph—near the edge of the F6 category that Fujita originally labeled as "inconceivable." Once analysis has deciphered the actual speed, it's expected to be the highest tornadic wind on record.

Another tornado in the swarm set a record as well. In Mulhall, about 40 miles to the north of Oklahoma City, an F4 tornado measured roughly 1.2 miles across. "It was the most fearful-looking tornado I've ever seen," Wurman says. "If it had passed through a populated area, it would certainly have been the worst tornado of the day."

Beyond sending off much needed "take cover" alarm bells, the radars provided a new look at the interior of tornadoes. On May 3 and in two storms thereafter, Bluestein discovered that a tornado's center may not be a perfect cylinder. His radar has found cross sections that look more like squares. The corners

HOWARD B. BLUESTEIN

STORM TRACKERS: The mobile Doppler radar operated by University of Oklahoma professor Howard B. Bluestein and his colleagues measured wind speeds for a May 3 tornado.

appear to be waves or minivortices swirling around the main vortex. Multiple vortices have been photographed for decades, but Bluestein is still not sure just what the surprising radar indications really mean.

One of the key puzzles left in the debris of May 3 is why that day's storms were so durable. Almost every storm across the heart of Oklahoma that evening was a supercell—a long-lived, steady-state severe thunderstorm. And almost every supercell dropped tornado after tornado. There were 65 twisters in all, more than Oklahoma usually sees in a whole year. In southern Kansas three other tornadoes killed six people and damaged several thousand structures.

When multiple storms develop in proximity, they often interfere with one another's tornadic potential. One storm might hog the supply of atmospheric fuel, or it could dump rain-cooled air onto another. Often storms will solidify in an hour or two into a line or cluster that is ill suited for producing tornadoes. Yet at least five supercells coexisted across Oklahoma and Kansas on May 3.

A project called VORTEX (Verification of the Origins of Rotation in Tornadoes Experiment) has been studying the birth of twisters ("tornadogenesis") for the past five years. Its leaders—NSSL tornado specialist Erik Rasmussen and University of Oklahoma professor Jerry M. Straka—are hoping that analyses of the Oklahoma swarm will help explain why the atmosphere was so efficient at producing tornadoes and why this swarm in particular took so long to run out of steam. As part of the project, Rasmussen and Straka oversee a fleet of cars with full weather stations attached to their hoods. These mobile laboratories take measurements near supercells every six seconds—a critical reading for tracking the rapid-fire shifts in pressure and wind that occur just as a tornado forms.

Data collected since the project's inception in 1994 already indicate that temperature gradients along minifronts on the east side of a storm are not as important as once thought. Rasmussen believes instead that downdrafts wrapping around the south end of the storm are key to spinning up twisters. The violently descending air may help stimulate a compensating updraft and enable this lifting air to tighten from a larger-scale circulation into a tornado.

Street after street of ruined homes revealed as much about building practices as they did about the tornado itself.

The May 3 event has added a new wrinkle: rain-cooled air was virtually absent. Nearly all the downdrafts observed by VORTEX were warmer than the surrounding low-level air, as compared with a typical downdraft, which is several degrees cooler. "This is broadly consistent with a new hypothesis we're testing," Rasmussen says. Warmer downdrafts may allow low-level air to stay juiced, enhancing odds for an outbreak of long-lived twisters. If so, forecasters might be able to judge a day's probable downdraft temperature in advance and use it as an outbreak prediction tool.

For all their brute force, tornadoes appear to thrive on a mysterious and delicate balance of forces. Computer models of the future may be able to better diagnose the preconditions for a tornado hours in advance. To do so, however, they will have to be fed with better observations, including information from a wider net of profilers, more sophisticated radars and the kind of dense surface networks now in place across Oklahoma. There more than 100 automated stations in a state-sponsored "mesonet" cover the area formerly served by a handful of human-operated stations. A new set of portable research radars is now under development by NSSL and several universities. Small, remotely piloted aircraft (one prototype is being built at the University of Colorado) may provide a different look inside a twister and its surroundings.

Safety in a Closet

Technology is also working to protect people in their homes. Safe rooms, designed to withstand the ravages of both hurricanes and twisters, have become a hot item as storm-stricken areas begin the process of rebuilding. These rooms, which run $2,500 to $5,500, often double as closets and can be retrofitted into existing homes. They feature walls of steel-reinforced concrete, typically measuring six inches thick.

HOWARD B. BLUESTEIN

METEOROLOGICAL BOMBER: A supercell, a long-lived thunderstorm such as this one that formed May 3, 1999, may drop tornadoes.

In one survey of the Oklahoma City tornado, six of 40 rebuilt homes included safe rooms. But engineer Timothy P. Marshall found plenty of shoddy workmanship elsewhere among the 40 homes that had to be constructed anew. "In general," he says, "construction was no better in quality after the tor-

WHAT WOULD AUNTIE EM DO?

Pity Dorothy. The *Wizard of Oz* heroine ran into her home in the face of an approaching "cyclone" after being locked out of the storm cellar. Standing and stewing by her bedroom window, she was easy prey for the window's frame to blow in and knock her unconscious (and send her on to Oz).

In the real Kansas and its neighbors, people know better. Safety rules (which are not necessarily all correct all the time) have been ingrained for decades, especially at schools. The average 10-year-old can recite the basics in a flash: go to a basement or to an interior room on the lowest floor, such as a bathroom or closet; cover yourself with a blanket or mattress; don't try to drive away from the storm; and head for a ditch if you're caught in the open.

About half of all U.S. residents come under a tornado warning each year, but weather-weary Oklahoma City is the world capital of tornado awareness. The events of May 3 bore this out. Despite unprecedented destruction, the fatalities there were relatively low. If the same tornado had struck a city of the same size in the 1940s, before the existence of modern warnings, it would most likely have killed more than 600 people, according to Harold Brooks of the NOAA National Severe Storms Laboratory.

What's even more notable is that nobody between the ages of four and 24 died. The odds of this happening by chance, according to Brooks, are more than 4,000 to 1. A poststorm survey showed that 85 percent of the kids in harm's way did something to preserve their safety and that more than 95 percent of those actions were in line with the recommended rules. One mother re-

J. PAT CARTER *Associated Press*

NO REFUGE: Civil defense officials and meteorologists are trying to dispel the myth that overpasses, such as the one shown here, can provide a safe haven from a tornado.

TIMOTHY P. MARSHALL

STORM BUNKER: Steel-reinforced concrete "safe rooms" can sometimes provide protection against the fury of tornado-strength winds.

nado than before, and in some cases, the quality was worse."

What happens when a family of F4 or F5 twisters strikes the Dallas/Fort Worth metropolitan area, the St. Louis vicinity or Chicago? Each has been the victim of major tornadoes before. The Dallas/Fort Worth area is particularly at risk. Its two big cities lie only 30 miles apart on an east-west axis, so a long-lived F5 twister could chew on homes and businesses for over an hour. With any luck, forecasters of the future will be able to identify such a worst-case scenario as a possibility hours before it actually happens.

Weak tornadoes—the most common kind—will remain hard to predict, and they can do as much harm in the wrong place as an F5 in the countryside can. On August 11 a freak twister touched down in the heart of Salt Lake City with no advance notice by sight or radar. It killed one person and injured dozens more. Only eight other people had been reported hurt by tornadoes in Utah before that day. Sometimes "it can't happen here" means only "it hasn't happened here yet."

ROBERT HENSON, a meteorologist and freelance writer, grew up with tornadoes in Oklahoma City and chased them while he was still a graduate student. He now enjoys photographing severe weather and writing about it, as he did in "Only a Storm," a contribution to the anthology *Soul of the Sky* (Mount Washington Observatory, 1999). He works as a writer/editor in the communications department at the University Corporation for Atmospheric Research in Boulder, Colo.

turned home in a panic after the storm to find her 12-year-old daughter tucked into a bathtub, a mattress over her head. In her arms were a teddy bear and a weather radio.

Does it ever make sense to drive away from your home before a tornado hits? Instinct might say yes, but official guidance says no, and there aren't yet enough data to know for sure. Several deaths in the Jarrell, Tex., tornado of May 27, 1997—another F5 with ample warning—occurred when people had come home specifically for shelter, only to be swept away with their houses. By all accounts, many people in the Oklahoma City area left their soon-to-be destroyed homes and survived. On the other hand, others were injured in traffic accidents as they fled.

Tornado-packing storms often produce large hail, and it's now common across the plains for motorists to stop in traffic beneath an overpass in an effort to protect their car's finish from damage. Horrendous traffic jams often result, and motorists become sitting ducks for tornadoes. Problems may persist even after the storm: rescue operations in the Oklahoma City area were hindered by clots of damaged cars clustered around bridges.

Just as worrisome is the "overpass issue." Thanks to an endlessly televised 1991 video from Kansas, in which a film crew experienced the winds at the fringes of a twister under a bridge's girders, overpasses have gained a false reputation as a place of safety. Many overpasses are built without girders, providing no chance of protection. Moreover, the Kansas film crew was in a rural area, and the tornado's core never passed overhead. On May 3 in Oklahoma, 17 people took shelter under an Interstate 35 overpass. All but one were blown out from their refuge; one was killed, and 14 were seriously injured. A few miles away another person was dismembered after being sucked from an overpass. In short, "overpasses are not a safe place to be," Brooks says.

Mobile homes tend to be unsafe at almost any tornadic speed; nearly half of all tornado deaths since 1975 have occurred in them. Yet few mobile-home residents have access to shelters. One recent damage survey led by Thomas W. Schmidlin of Kent State University hints that for tornadoes of F2 to F3 intensity, it could be safer for mobile-home residents to stay in parked cars than to remain in their homes. The cars, being more aerodynamic, appear far less likely than mobile homes to tip over and disintegrate when lashed by the wind. In an F4 or F5, of course, all bets are off. (Taking shelter in a ditch may not be the answer either: Schmidlin notes that this longtime recommendation has yet to be backed up by research.)

How far can we go in tailoring warning advice to fit the storm? New technology at the National Weather Service already allows forecasters to craft warnings on the fly using preworded statements. Oklahoma City's NWS office added the words "tornado emergency" on May 3 to convey the gravity of the situation. But most tornado outbursts are not so clear-cut. "We can't and don't forecast intensity now. May 3 illustrates that this is an important potential research area," Brooks says.

In the meantime, public-safety officials are loath to change warning advice too quickly or too often. After all, it's taken decades to dispel a bit of old tornado gospel—the idea that opening windows away from an approaching twister helps to equalize air pressure and reduce damage. In fact, houses don't "explode" from the pressure drop, which at best runs only about 10 percent below normal atmospheric pressure. Buildings usually disintegrate as they are unroofed and walls collapse. As Dorothy discovered, a window is no match for the onslaught of a serious cyclone. *—R.H.*

STORMS

1. DEADLIEST TORNADO IN THE U.S.
Missouri, Illinois and Indiana
On March 18, 1925, a twister cut a 219-mile path through three states, killing some 689 and injuring nearly 2,000.

2. LARGEST TORNADO OUTBREAK IN THE U.S.
Ohio River Valley
On April 3 and 4, 1974, a storm system spawned over 125 tornadoes from Indiana to northern Georgia, nearly a quarter of them rating as fearsome F4s or F5s.

3. DEADLIEST HURRICANE TO HIT THE U.S.
Galveston, Tex.
Not expected to be destructive, the 1900 storm ravaged the island with 100-mph winds and a 20-foot storm surge; an estimated 8,000 people died.

4. DEADLIEST FLOOD CAUSED BY A STORM SURGE
Bangladesh (East Pakistan)
In November 1970 a cyclone in the Bay of Bengal killed about 300,000 people.

5. COSTLIEST METEOROLOGICAL DISASTER
Bahamas, Florida and Louisiana
In 1992 the small but destructive Hurricane Andrew caused an estimated $25 billion worth of damage.

6. LARGEST TROPICAL CYCLONE
Western Pacific
At its height on October 12, 1979, Typhoon Tip had gale-force winds extending over a radius of 675 miles. The 870 millibars recorded in Tip's eye is the lowest sea-level pressure ever recorded on Earth.

7. LONGEST-LASTING TROPICAL CYCLONE
Pacific Ocean
The storm system known as John wandered the Pacific for 31 days in August and September 1994.

CORBIS

PRECIPITATION

1. WETTEST PLACE ON EARTH
Lloro, Colombia
An estimated average of 523.6 inches of rain falls each year.

2. DRIEST PLACE ON EARTH
Arica, Chile
Averaged .03 inch of rain each year for half a century.

3. GREATEST 24-HOUR RAINFALL
Foc-Foc, Réunion Island
Between January 7 and January 8, 1966, 72 inches of rain fell.

Compiled by **EUGENE RAIKHEL**

EXTREME WEATHER

A tour of the most dramatic weather on the planet

4. GREATEST 12-MONTH RAINFALL
Cherrapunji, India
1,042 inches of rain fell between August 1, 1860, and July 31, 1861.

5. MOST INTENSE DROUGHT IN THE U.S.
Great Plains
From 1930 to 1938 agriculturally induced erosion, heavy winds and a lack of rain turned 50 million acres of farmland into the Dust Bowl.

6. BIGGEST 24-HOUR SNOWFALL IN THE U.S.
Silver Lake, Colo.
Storms dropped 76 inches of snow between April 14 and 15, 1921.

TEMPERATURE

1. HIGHEST TEMPERATURE
Al-'Azīzīyah, Libya
Mercury reached 136° Fahrenheit on September 13, 1922.

2. LOWEST TEMPERATURE
Vostok Research Station, Antarctica
Temperature of –129° F was recorded on July 21, 1983, outside this Soviet research station.

3. HOTTEST PLACE ON EARTH
Dallol, Ethiopia
Average temperature from 1960 to 1966 was 94° F.

4. COLDEST PLACE ON EARTH
Sovietskaya Research Station, Antarctica
Average temperature in 1957 and 1958 was –71° F.

ROBERT PICKETT *Corbis*

5. GREATEST 24-HOUR TEMPERATURE FALL IN U.S.
Browning, Mont.
Temperature fell from 44° to –56° F between January 23 and 24, 1916.

6. MOST VARIABLE TEMPERATURE ON EARTH
Verkhoyansk, Russia
Temperatures have ranged from –90° to 94° F, although Verkhoyansk is usually extremely cold.

7. LONGEST STREAK OF STABLE TEMPERATURES
Garapan, Saipan Island, Northern Mariana Islands
From 1927 to 1935 the temperature never rose above 88.5° F and never dropped below 67.3° F.

OTHER

ROBERT DOWLING *Corbis*

1. HIGHEST WATERSPOUT
Eden, New South Wales, Australia
Estimated to be 5,014 feet high, it was spotted on May 16, 1898.

2. FOGGIEST PLACE IN THE U.S.
Cape Disappointment, Wash.
An average of 2,552 hours (106 days) each year are heavily foggy.

3. MOST HUMID PLACE ON EARTH
Aseb, Eritrea
Average afternoon dew point is over 84° F.

4. STRONGEST WINDS OUTSIDE OF A TORNADO
Mount Washington, N.H.
Gusts of 231 mph were measured on April 12, 1934.

ALL THE FIGURES ARE THE MOST EXTREME EVER RECORDED, WITH THE EXCEPTION OF SOME ESTIMATES. SOURCES: *WEATHER AND CLIMATE EXTREMES*, BY P. KRAUSE AND K. FLOOD; *GUINNESS BOOK OF RECORDS*; *FAQ: HURRICANES, TYPHOONS AND TROPICAL CYCLONES*, BY C. LANDSEA; http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqE.html

FLEEING FLOYD

by JIM REED

Thousands who tried to race to safety before Hurricane Floyd hit last year ended up going nowhere fast, stuck in traffic. Were such problems a fluke or a glimpse of the future?

RIC FELD AP Photo

Last September Hurricane Floyd became one of the largest tropical cyclones to form over the Atlantic Ocean. As it threatened to incapacitate several major cities along the southeastern coast of the U.S., the nation's civil defense system snapped into gear. Sirens howled, schools and courthouses closed, and navy ships headed to sea. Along barrier islands, soldiers darted among houses instructing residents to clear out, while the National Aeronautics and Space Administration battened down its shuttles.

As the 600-mile-wide storm bore down on Florida with winds of 155 miles per hour—just one mile per hour below the threshold of the fiercest, Category 5, storms—the specter of its potency chilled coastal residents and alarmed local emergency managers. "Floyd had the potential to be the worst hurricane to ever strike the East Coast," says James Lee Witt, director of the Federal Emergency Management Agency (FEMA) and a cabinet adviser to President Bill Clinton on natural disasters. "This is the first time we have ever had an evacuation that involved so many states at one time. It was my worst fear."

Dreading casualties, officials in more than 60 counties urged residents to move to higher ground. In response, an estimated 3.2 million Floridians, Georgians and North and South Carolinians rolled their vehicles onto the highways, yielding the largest single evacuation on U.S. soil.

Yet the question remains: Was the evacuation a success? Not surprisingly, the answer depends on one's perspective. Many emergency managers, the people who oversee such operations, consider it a qualified success—insofar as early warnings sounded, residents complied, and large numbers of imperiled people moved from

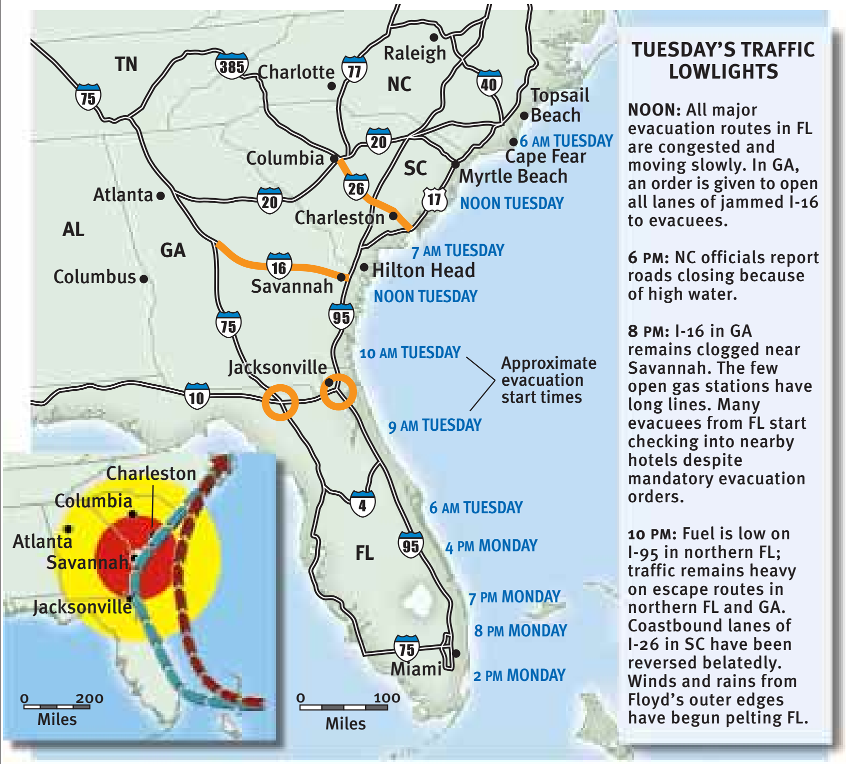
NATIONAL HURRICANE CENTER/AP PHOTO

HURRY UP AND WAIT: Even the opening of all lanes of Interstate 16 in Georgia to evacuees failed to free up traffic on Tuesday, September 14, 1999 (*above*). Meanwhile Floyd, shown on Monday evening (*left*), hovered menacingly off the coast.

Floyd's dangerous path with time to spare. But not all knowledgeable observers concur. Critics note that traffic gridlock kept many evacuees from reaching their designated shelters. Thousands of families were stranded in rest stops, strip malls and parking lots—even inside their cars on low-lying bridges. Mercifully for them, Floyd veered slightly east, sparing the most inhabited areas before its eye made landfall in southeastern North Carolina.

Both boosters and critics agree, however, that Floyd has lessons to teach for the future and that the need for smooth evacuations may be becoming increasingly critical. The number and intensity of hurricanes bombarding the U.S. Southeast have risen in the past couple of years. Moreover, the size of the at-risk population is climbing. According to FEMA, the

ESCAPE ROUTES?



GRIDLOCKED ROAD OR INTERSECTION
TROPICAL STORM–FORCE WINDS; SUSTAINED SURFACE WINDS OF 39 TO 73 MPH
HURRICANE-FORCE WINDS, 74 TO 155 MPH AND GREATER. WIND GUSTS COULD BE AS HIGH AS 190 MPH
ACTUAL PATH
WORST-CASE-SCENARIO PATH

Major evacuation routes in Florida, Georgia and South Carolina (*above*) became clogged after many regions issued mandatory or voluntary evacuation orders within a short time on Monday and Tuesday, Sept. 14 and 15. Floyd's eye stayed offshore until it reached the Cape Fear, N.C., vicinity at about 3 A.M. on Thursday. Had the storm sped up and veered significantly to the west (*inset*), its winds and rain could easily have harmed hundreds of evacuees who did not reach safe shelters by Tuesday night.

LAURIE GRACE

number of people living in hurricane-prone locations has reached nearly 50 million, with new families migrating daily to the coast. More people live in or near Miami today than lived in all 109 coastal counties from Texas to Virginia in 1930.

Best-Laid Plans

Although the traffic and other difficulties that bedeviled Floyd's refugees may seem to suggest a lack of forethought by officials, each state involved in the evacuation actually had—and put into effect—a detailed hurricane evacuation plan, which is part of a state's overall emergency plan.

"The state emergency manager has replaced the civil defense man, who used to drive around in an army car with a blue light," says Bill Massey, hurricane program manager at FEMA's Regional IV Office in Atlanta. "Only now, instead of worrying about the atom bomb, we're worried about bad weather."

Evacuation procedures can vary among states but are all quite specific. In Florida, for example, evacuations occur in four phases. In the initial (standby) stage, officials determine which regions are most likely to be affected. In the next stage, the decision to evacuate is rendered, and the governor declares a state of emergency. At that point, crisis telephone lines are set up, shelters prepare, and hundreds of support organizations get ready to help.

As the third stage—the evacuation itself—begins, emergency managers call on HURREVAC, a restricted-use U.S. government computer program used to help coordinate local evacuations. Launched in 1988, the program integrates lessons from previous evacuations and research by the federal government and the U.S. Army Corps of Engineers. The software tracks hurricanes on computer plot maps and assists in determining when to evacuate individual high-risk areas.

Two key factors influence the start times. One is clearance time—how long it will most likely take to get all cars to safe havens after the first evacuees enter an evacuation route. The other factor is the prelandfall time, or the lapse between the onset of tropical storm–force winds and the arrival of the storm's eye over land. Emergency managers aim to relocate all at-risk populations before high winds ensue, because people remaining on the roads during the prelandfall phase are vulnerable to injury from the winds, flooding and tornadoes. The final stage, the return home, begins when conditions are no longer hazardous.

The National Hurricane Center has identified three major hazards that most require evacuation: storm surges, high winds and heavy rain. Historically, storm surges—wind-pushed swellings of ocean water, sometimes measuring up to 20 feet high and 100 miles wide—have been the deadliest of all storm hazards, accounting for up to 90 percent of all hurricane-related fatalities. High winds can prove treacherous as well, especially to mobile homes and other lightweight dwellings or to structures with unprotected windows. When glass shatters, soaring shards become lethal projectiles. Rushing wind can blow a house apart. And torrential rain can cause fatal floods, depending on a hurricane's size, strength and path.

Consequently, residents of barrier islands, which have limited roads to the mainland, are among the first evacuees, followed by coastal inhabitants and mobile-home dwellers. Depending on the expected hazards, a county may totally or partially evacuate, first urging voluntary evacuation, then issuing an order to leave. Residents with special needs, such as those reliant on oxygen, dialysis or specialized medical care, usually relocate during the voluntary phase. Typically, officials guide evacuees to state-authorized shelters 20 to 50 miles inland.

Taking the Floyd Test

Last September Hurricane Floyd put the hurricane evacuation plans of the Southeast to a severe test. During the four-state evacuation millions competed for rapidly vanishing space on local roads. Floyd's wide range of possible landfall locations stymied evacuation timing. No one wants to order an evacuation unless it's absolutely necessary, and so orders cannot be given too early.

As it turned out, many areas began to evacuate within the same 24-hour period. Between 2 P.M. on Monday, September 13, and noon the next day, an estimated 47 at-risk counties sounded sirens, evacuating within hours. "Our infrastructure can't handle an evacuation with the kind of participation that took place during Floyd," says Massey in Atlanta. "There just weren't enough roads to hold everybody." Among the roads that clogged quickly were I-75, I-95 and I-10 in Florida, I-20 (spanning South Carolina and Georgia) and the most jammed of all: two main evacuation arteries heading away from the Atlantic Ocean, I-16 in Georgia and I-26 in South Carolina.

On Tuesday afternoon, with hundreds of thousands of Floridians caravaning into southern Georgia (many joining 350,000 Georgians heading west), Georgia's emergency managers reversed all normally coastbound lanes on I-16, hoping to ease traffic. But the effect was limited. As Floyd hovered offshore, local roads became clogged with vehicles.

In Savannah, Sheila Watson and her family, including a baby, discovered to their horror that they had driven from one evacuation region (in Florida) to another. Exhausted and ignoring the order to leave, the Watsons collapsed in a motel that required them to clean their own rooms, because maids had fled.

In South Carolina, where close to a million coastal residents were ordered to evacuate by Governor Jim Hodges, vehicles were also at a standstill. Hurricane castaways lounged in beach chairs beside cars and campers, shuffling cards in the drizzle as others cursed La Niña. But unlike Georgia officials, who initiated a lane reversal, disaster planners in South Carolina spent much of Tuesday arguing over whether or not to reverse coastbound lanes of I-26, the primary evacuation route for the citizens of Charleston and Hilton Head Island. By Tuesday night, I-26 was paralyzed with traffic at a time when the dangerous prelandfall period was fast approaching.

Meanwhile local DJs announced to evacuees stranded along I-16 and I-26 that the nearest available rooms were in Chattanooga—some 200 miles away. (Indeed, shelter options for evacuees had dwindled rapidly. By 8 A.M. Tuesday, even before evacuations became mandatory in Savannah, Hilton Head Island, Charleston and Myrtle Beach, hotels and shelters in Georgia and South Carolina were already packed.) Hearing the news reports, angry, exhausted motorists took the risk of pulling over to sleep, parking at highway rest stops. Some evacuees even began making U-turns and heading back toward the ocean.

"People were irate," remembers Lynn Willhite, a National Park Service real estate appraiser from Kennesaw, Ga., who spent the night in his car at a strip mall in South Carolina after moving only 87 miles in 10 hours. Emotions often reach a high pitch in an evacuation. During Hurricane Georges, the second deadliest cyclone of 1998, roughly 15 hours into the state of emergency some 14,000 evacuees sheltered in the Louisiana Superdome decided that they had had enough. When authorities said that conditions outside remained unsafe, armed National Guardsmen blocked exits—provoking frustrated evacuees to smash glass, rip up seats and destroy $50,000 in property.

Briefed on the developing Floyd mutiny, South Carolina's governor issued an emergency executive order compelling officials to open all lanes of I-26 to evacuees by 10 P.M. Tuesday. But time was running out. Gasoline supplies, too, ran short. Because of heat and humidity, motorists revved engines for hours to power air conditioners, overheating engines. Abandoned cars littered local roads.

Officials were sweating as well by the time the lane openings took place. Rain was falling in Florida and Georgia, storm winds were already whipping the Florida peninsula, and refugees in Georgia and

STEPHEN MORTON *AP Photo* (*top left*); COREY LOWENSTEIN *The News and Observer* (*bottom left*); CHUCK LIDDY *The News and Observer* (*right*)

SCENES FROM FLOYD: In addition to traffic, refugees endured lines for buses (*top left*) and crowded shelters (*bottom left*) to avoid being trapped and hurt by Floyd. After the storm hit North Carolina, a trucker had to be airlifted to safety because his vehicle had floated off I-95.

ANSWERS BLOWING IN THE WIND

While public officials squabbled over how to evacuate residents, scientists struggled to predict when and where the storm would make landfall. "The 72-hour forecasts were as good as we'd expect the 24-hour forecasts to be," says Hugh E. Willoughby, director of the National Oceanic and Atmospheric Administration's Hurricane Research Division, which provides forecasters with real-time wind analyses. Willoughby himself has flown into the eyes of hurricanes and typhoons more than 400 times.

As Floyd approached Cape Fear, N.C.—roughly where the eye eventually came ashore—three hurricane reconnaissance planes were aloft, assessing the speed, direction and behavior of the storm's threatening winds. Two NOAA WP-3D Orion turboprop planes traversed Floyd at altitudes between 1,500 and 10,000 feet, with airborne Doppler radar recording the wind's rapidity. Each plane also sports sophisticated instruments bolted to its underside to measure fluctuations in sea-surface movement; storm-blown waves are reliable indicators of wind velocity. Since 1997 a modified Gulfstream IV-SP jet has also soared over hurricanes at altitudes above 35,000 feet, releasing 16-inch-long instruments—dropsondes—that bear Global Positioning System receivers to relay wind velocity data every five seconds.

On the ground, through stream-flow gauging stations, the U.S. Geological Survey tracked rising waters, which closed 600 roads and 40 bridges in North Carolina during Floyd. Satellites relayed up-to-the-minute data on river levels to the National Weather Service, which issued warnings on storm surges and waves along the southeastern coast.

JIM REED

INTO THE BREACH: The Doppler on Wheels truck is able to measure wind speed and direction from within a hurricane.

Meanwhile in North Carolina, Joshua Wurman of the University of Oklahoma took to the road in Doppler on Wheels (DOW), a state-of-the-art mobile laboratory and radar that is designed to penetrate super-high-velocity winds and to relay wind measurements directly to the National Hurricane Center. During Floyd, Wurman and his crew parked the 12.5-ton mobile radar near the shore of Topsail Beach, N.C., north of Cape Fear, readying to scan the storm from within—using both the rotating radar and a 30-foot hydraulic pole bearing three anemometers (two high-speed, one regular) that measure wind speed.

"When a reconnaissance aircraft flies toward radar on the ground, you can cross the airborne Doppler with the ground-based beam and get a 3-D wind profile," Willoughby says. "The DOW cuts a sample of the boundary layer wind underneath the aircraft, which [airborne scientists] can't see because of the beam's geometry."

Beyond helping with storm tracking, information gathered by the DOW is expected to result in a better general understanding of hurricane behavior and in improved models for determining when, and if, a county should evacuate. *—J.R.*

South Carolina were still on the roads. If the hurricane had suddenly changed course, as Hurricane Andrew did in 1992, thousands of evacuees could have been exposed to two of the three most lethal hazards: high winds and flooding.

"If Floyd had made landfall in Savannah, it would have traveled right up parts of I-16 and I-26 and killed people sitting or sleeping in their cars," says Michael Phelps, a meteorologist at the Weather Channel, the Atlanta-based 24-hour cable channel. "I think we would have seen a death toll of at least 500."

Fearing for their lives, more than 500 stranded evacuees sought shelter at Georgia's brand-new, state-of-the-art visitor center along I-20, near the South Carolina state line. Officials transformed the center, which is typically closed after 5:30 P.M., into a makeshift storm shelter; it remained open for more than 33 hours straight. From early Wednesday morning through Thursday afternoon, evacuees watched hurricane highlights on a super-wide TV screen normally reserved for showing tourism videos on the joys of living in the Southeast.

Shortly after 3 A.M. on Thursday, many officials issued a collective sigh of relief as Floyd made landfall near Cape Fear, N.C., and weakened. The monster storm pummeled North Carolina, but the worst of it bypassed most of Florida, Georgia and South Carolina.

Pinpointing Causes of Problems

Ironically, the jamming of roads and shelters stemmed in part from disaster plans that worked only too well. "About 90 percent of the people in mandatory evacuation areas actually evacuated," says Robert S. Lay, director of the Office of Emergency Management in Brevard County, Florida. "I think people looked at the hurricane on TV and said, 'I'm leaving!' "

Reviewing poststorm reports, some disaster planners contend that certain residents also evacuated unnecessarily. How Americans view breaking news has changed since Hurricane Andrew. Real-time information beams into living rooms and offices around the clock. Massey believes TV coverage actually alarmed the wrong people—stirring up thousands who really didn't have to leave ("shadow" evacuees) and further snarling traffic. A survey after Floyd by David N. Sattler, a psychologist at the College of Charleston, suggests citizens trust local weather forecasters more than they do state officials.

This is not to say that officials want

people who should flee to stay. On the contrary, they worry a great deal about those who remain behind in mandatory evacuation areas. Commonly, it is the elderly or those of low income who insist on staying put, and indeed, during Floyd a number of nursing home residents refused to go. Too often those who stay live in areas prone to storm surges, and many pay a price for their resistance.

"During Floyd, there were some people on the Outer Banks who didn't evacuate," says FEMA director James Lee Witt. "Then all the roads got washed out, and they didn't have any power or phone service. The state then had to airlift food and water in to them."

Of course, not all the problems stemmed from high responsiveness. In South Carolina, Governor Hodges called the I-26 part of the evacuation "inexcusable," apologized to state residents and pledged to open all lanes in the future. So upset were residents over the botched I-26 Floyd evacuation that motorists slapped bright yellow bumper stickers on their vehicles exclaiming "Evacuate Hodges." Department of Transportation director Morgan Marton apologized for not properly advising the governor, and the state's top Highway Patrol officer, Wesley Luther, a 27-year veteran of the force, resigned under controversy. A "traffic czar" has now been appointed to ensure that evacuations run smoothly in future emergencies.

Yet even if all needed lanes were opened promptly and all shadow evacuees stayed home, the possibility exists that gridlock may be unavoidable during huge evacuations. Despite the American Society of Civil Engineers's 1994 statement that the interstate road system is one of the "seven wonders" of the U.S., impenetrable gridlock has plagued every hurricane evacuation since Camille in 1969, prompting traffic experts to question the feasibility of a multistate evacuation altogether.

Roger A. Pielke, Jr., a social scientist with the Environmental and Societal Impacts Group of the National Center for Atmospheric Research, warns that after decades of low hurricane frequencies, U.S. citizens live with a false sense of security, dwelling in hurricane-vulnerable regions without fully appreciating the risks. "The issue is, What level of risk are we willing to take?" he asks. "People look to Mother Nature as the cause for our problems, when the decisions we make every day actually underlie our vulnerabilities."

One thing people can do to improve their odds of survival is to strengthen their homes against storms. In 1997 FEMA launched Project Impact, a nationwide initiative to help homeowners shore up disaster protection. Arguing that homeowners can save two dollars in repairs for every dollar spent on prevention, FEMA urged residents of vulnerable regions to become more self-sufficient, trim trees, strengthen roofs and install a "safe room" able to withstand violent winds. Such measures cannot guarantee safety to those in the path of a storm surge, however.

The Outlook

Leading meteorologists say the question is not if but when a lethal storm will incapacitate a major U.S. city. "A Category 5 hurricane will make landfall in a heavily populated area," Pielke, Jr., warns. "It shouldn't surprise anyone." Witt agrees, emphasizing that scientists believe the U.S. has entered a busy hurricane period, reminiscent of the 1950s.

Between 1995 and 1999 an unprecedented 41 hurricanes formed in the Atlantic, 20 of them major. In fact, last year's Hurricane Lenny was the first Category 4 hurricane to occur in November since Greta in 1956. Ominously, with at least 9,000 hurricane-related fatalities, 1998 was the deadliest hurricane season in North and Central America since the Galveston, Tex., hurricane killed more than 8,000 in 1900. (In the Galveston episode, officials did not expect the hurricane to hit hard and so did not order an evacuation.) Moreover, the 1999 hurricane season was the first on record to spawn five major hurricanes with winds of at least 131 mph (1926 was the last year that four such hurricanes arose in one season). And Floyd was the first single hurricane to turn 10 states into major disaster areas (and that was after it weakened).

Researchers at the Benfield Greig Hazard Research Center in London predict that at least three tropical storms and one hurricane will directly strike the U.S. mainland between June 1 and November 30, 2000. Other regions are also at risk.

Disaster planners hate to think of what might have happened if the eye of Floyd had made landfall near Savannah or Charleston. Few people appreciate a tropical cyclone's capacity to kill and destroy property inland. In the case of Hurricane Andrew, the storm actually strengthened as it moved over Dade County, Florida. In September 1989 the remnants of Hurricane Hugo traveled 175 miles inland, pounding Charlotte, N.C., with 100-mph gusts, uprooting trees, shredding power lines and disrupting the city.

Although Floyd weakened, its torrential rains, flooding and winds still claimed 75 lives, making it the deadliest hurricane since Agnes in 1972. Thousands of unsheltered Floyd evacuees might have been injured had Floyd taken a more western track, Pielke, Jr., observes. Because of Floyd's enormity, its winds would have lashed evacuees even if the eye had remained offshore. Toppling trees might have crushed evacuees dozing in cars, downed power lines could have electrocuted pedestrians, and flash flooding might have swept others away, given that a packed I-26 rest stop stands next to a swamp and that I-16 intersects four rivers.

Gridlock may be unavoidable during huge evacuations. It has plagued every hurricane evacuation since Camille in 1969.

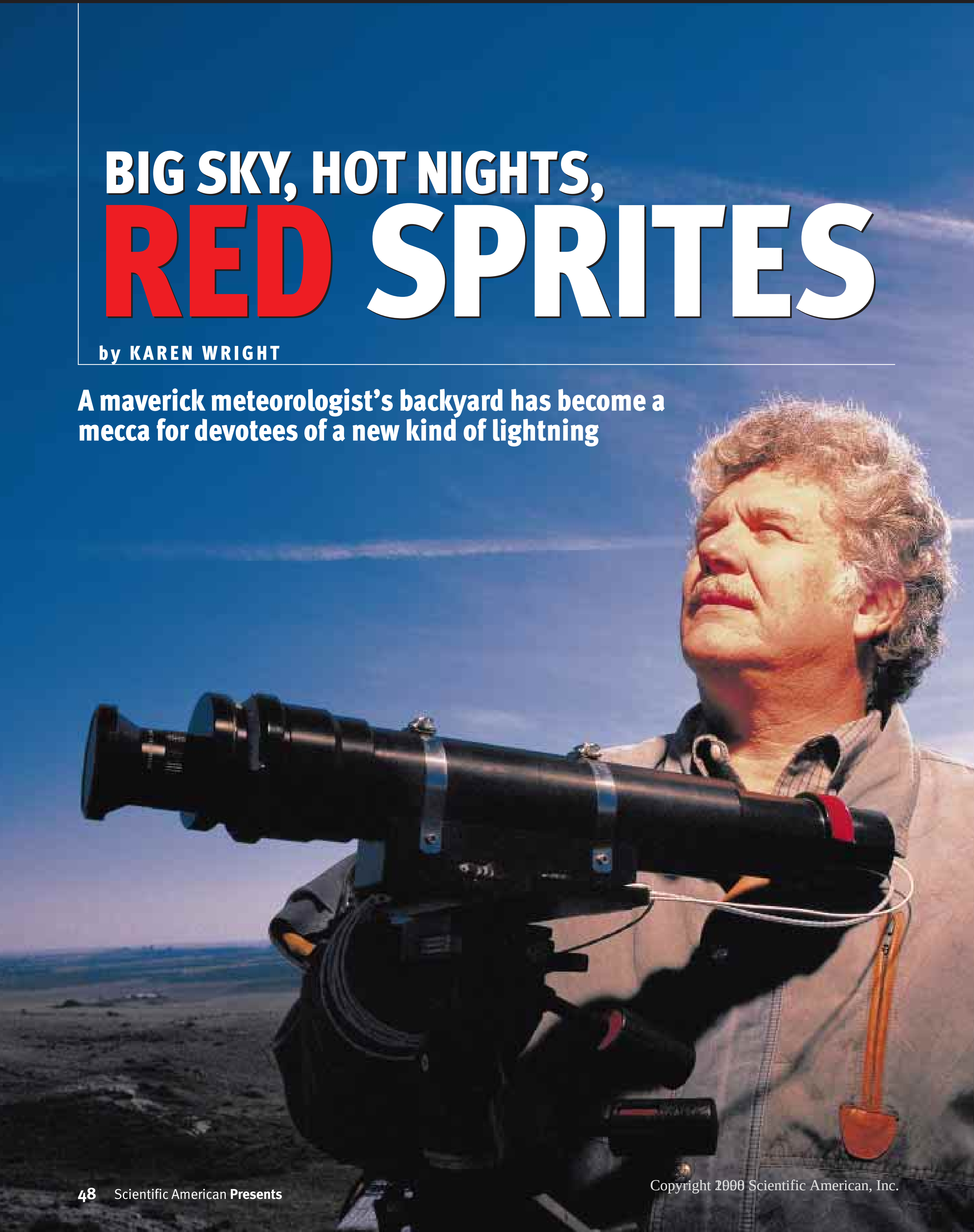
"If you go through an evacuation and the hurricane turns out to be weaker than forecast, just thank God and prepare for the next one," says the Weather Channel's Michael Phelps. Floyd, it seems, was a good trial run for the Big One. W

JIM REED (JimReedWX@aol.com) is a freelance writer and photographer specializing in severe weather.

BIG SKY, HOT NIGHTS, RED SPRITES

by KAREN WRIGHT

A maverick meteorologist's backyard has become a mecca for devotees of a new kind of lightning



When speeding along the straight arrow of State Highway 14 outside Fort Collins, Colo., it's easy to miss the turnoff onto the dirt road that runs past Walt Lyons's house. From the dirt road it's easy to miss his driveway, too, which winds up a low bluff to the east. The land here is like an open palm, its contents—prairie, farms, horses and cattle—standing in plain view. Even so, roads and houses are inconspicuous, dwarfed by the sheer scale of their expansive surroundings.

On a clear, still morning in October, it's hard to imagine summers at the Lyons place, when hordes of scientists from all over the globe converge on a rooftop deck for all-night skywatching sessions. The sky they're watching stretches from North Dakota to Texas and hosts some of the largest, most energetic thunderstorms on the planet. High above those storms, split-second flashes of colored light dance in bewitching displays that have escaped the notice of trained observers for millennia. Only a decade has passed since the phenomena—a kind of cross between lightning and auroras—were discovered. Yet they may play a pivotal role in passing energy between the earth and space, helping to maintain an ethereal network known as the global electrical circuit and making gamma rays in the bargain.

And through a combination of storm savvy, people skills and serendipity, freelance meteorologist Walt Lyons has become a central figure in efforts to understand these enigmas of the upper atmosphere. His prairie home observatory serves as both technical training ground and conceptual watering hole for the people who study them. "Never underestimate the role of pure dumb luck in science," jokes Lyons, a towering nimbus of a man with a genial smile and cloud-gray curls. He is referring to the day in 1989 when a physics professor at the University of Minnesota called to tell him about a videotape he had made

THE LONG VIEW: Walt Lyons surveys the sky from the deck of his Colorado home, which offers a panorama of the Great Plains, the vast arena for the thunderstorms that produce sprites, elves and blue jets.

STEVE STARR *SABA*

STEVE STARR SABA

SPRITE CENTRAL: The office in Lyons's house serves as a control room for sprite investigators, who come to observe from as far away as Russia, Japan and New Zealand.

while testing a low-light camera for a rocket launch. Lyons was spending his daytime hours at the university's supercomputer center developing a national lightning-detection network and his nights at a local TV station doing the weather for the evening news. His colleague John R. Winckler wanted to show him a frame of the tape that seemed to have captured by chance the image of a giant column of light rising above a thunderstorm near the Canadian border.

On viewing Winckler's video, Lyons decided that the strange light show was no technical glitch. He had heard rumors of such things before, eyewitness accounts in the fringe literature of phantom lightning that apparently went upward from the tops of clouds rather than downward to the ground. Here, he recognized, was the first and only hard evidence of these sightings. "To make a long story short, this was the first time that a sprite had ever been actually caught on videotape," Lyons explains.

Stupid Hurricanes

Sprite is the name the experts later gave to the branching columns and plumes that appear above thunderclouds at heights up to 55 miles. They typically glow orange-red and last just one tenth of a second—long enough to be seen with the naked eye but not quite long enough for the viewer to be sure what has been seen. Because their light is so faint and fleeting (hence the name), catching sprites in the act proved to be a technical challenge. In the years following Winckler's report, a few dedicated teams of atmospheric researchers would document their existence using ground-based video cameras, photographs and videos taken from airplanes, and images collected from the space shuttle's payload-bay camera.

These investigations also turned up two more varieties of luminous high-altitude phenomena that came to be called elves and blue jets. Elves are enormous expanding rings of light that can extend more than 250 miles in diameter but that pulse for a millisecond at most—too briefly to be seen without special equipment. Blue jets, by far the rarest member of the menagerie, shoot up from cloudtops at speeds of more than 60 miles a second to heights of 30 miles. All three of these phenomena are now known to occur primarily in conjunction with giant storm systems called mesoscale convective complexes. These megastorms have thousands of times the cloud volume of the average thunderstorm, last up to 20 hours and make lots of lightning. "They're basically hurricanes too stupid to form over the ocean," Lyons says.

It just so happens that these giant storm complexes are responsible for much of the summer weather on the Great Plains. And it just so happens that from Yucca Ridge, his home on the range since 1990, Lyons has an outstanding view of the sky above the Great Plains. The ridge is the highest point for 20 miles, and it's all downhill to the east. Because of the rural environs, the horizon in that direction is dark at night (the only time that light from sprites and so on can be detected). These facts were not lost on Lyons when, in 1993, he got a contract from the National Aeronautics and Space Administration Kennedy Space Center to study the potential hazards to space shuttle launches posed by the newly found flashes.

Lyons suspected that his backyard might be an ideal place to catch a sprite. He borrowed a low-light video camera from a California optics company and pointed it out the window of his office on the second floor one dark and stormy night in July. "There was a big thunderstorm complex over eastern Kansas," he recalls. "You could see the lightning flashing on the horizon." He aimed above the clouds, and for two hours nothing much happened. Then, around midnight, a sudden spark broke the black field on the video monitor. A few minutes later it happened again. "By the time the sun came up, we'd seen 248 of them," Lyons declares.

By the end of the season, Lyons had taped hundreds more sprites, and his home office had earned a reputation as "Sprite Central." In the following summers, rotating squadrons of physicists, engineers, meteorologists and sundry students of the atmosphere camped out at Yucca Ridge for weeks or months, eagerly awaiting the big storms that would launch their nocturnal vigils. In the beginning they set up their equipment on Lyons's wood-shingled roof while his wife, Liv, experimented with sleep beneath it. "One night we had five people up there, plus one very big dog," Lyons remembers. In 1996 he built a 400-square-foot observation deck and expanded his office to a full-fledged control room, complete with rolling swivel chairs, stacks of computer screens and video monitors, and black cables looping down from open panels in the ceiling.

Lyons's colleagues come from as far away as Russia, Japan and New Zealand to learn how to anticipate the timing and location of sprite formation and to gather and integrate data from a variety of instrument sources. "It's an amazing collection of people—

everything from theoreticians who have come up to see what the real world looks like, to the people working on spectroscopy, all sorts of photometric measurements, also some radio-wave propagation," Lyons says. "My job is to predict which storms are going to make sprites and tell everybody to look there."

It sounds simpler than it is. Scientists still don't agree on exactly what sprites and their kin are. Sprites and elves happen in a part of the atmosphere that was thought to be electrically inert and so wasn't of much interest—the mesosphere (or "ignorosphere," as Lyons calls it), above the meteorologically active troposphere and the ozone-laden stratosphere. Because so little is known about that part of the sky, it's not clear what effects the electric fields and electromagnetic energy generated by thunderstorms might have in the thin air above the flat tops of cloud anvils. Indeed, until sprites were discovered, most experts assumed that thunderstorm effects stopped there.

But they don't. Blue jets, according to one theory, can occur above almost any kind of storm cloud that has whipped up enough positive charge. A spark will leap between the positively charged anvil and the negatively charged air just above it, and a column of current will form above the cloud by a sort of domino effect that culminates in the release of short-wavelength photons. Yet if the chain of events is this simple, then why are blue jets so rare? What distinguishes a storm that spawns blue jets from one that doesn't?

Sprites and elves pose similar conundrums. Both are known to occur immediately after strokes of so-called positive cloud-to-ground lightning, which drain positive charge from the tops of thunderclouds as negatively charged electrons rush up from the ground. Positive lightning is the exception, not the rule: the vast majority of lightning strokes issue from the lower part of a cloud, which is negatively charged, and deliver negative charge to the ground. Positive lightning carries far more current than negative lightning does. When it flashes, it creates an electromagnetic pulse that rises in an expanding ring. The ring meets the free electrons above cloudtops, boosting their energy, and the collisions of these electrons with nitrogen molecules release the reddish light that characterizes an elf.

At least that's the theory hatched by physicist Umran S. Inan and his colleagues at Stanford University, who first recorded the color spectra of elves at Yucca Ridge in 1996 using a photometric array called the Fly's Eye. Designed explicitly for sprite- and elf-watching, the Fly's Eye can detect both the movement of an elf and the wavelengths of light in it—no mean feat, considering that elves come and go in less than one thousandth of a second. Based on analyses of the energetics of lightning, Inan's group had posited the existence of elves several years before finding one. "They turned out to be remarkably close to what we had predicted," Inan notes.

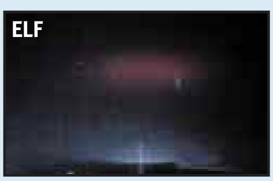
A-Bombs and Carmen Miranda

Sprites are the subject of the most fervid study, in part because they are more plentiful and easier to detect than their psychedelic sisters. Sprites come in a seemingly endless variety of shapes and sizes that have spawned descriptors such as broccoli sprites, octopus sprites, A-bomb sprites and Carmen Miranda sprites. They seem to be caused by an upward flow of accelerated electrons that occurs after a positive lightning stroke drains charge from the cloudtops. But how does the architecture of a thundercloud influence the shape of a sprite? And what causes the sprite "clusters" that can stretch for 200 miles and last for more than half an hour? To answer these questions, experts from a number of fields are sharing their knowledge—and confronting their ignorance.

"This area of research has broken us out of our traditional disciplines," observes Davis D. Sentman, an atmospheric researcher

STEPHEN B. MENDE AND R. L. RAIRDEN, COLORIZATION BY LAURIE GRACE (*sprite*); STEPHEN B. MENDE (*elf*); PATRICE HUET (*blue jet*)

DIFFERENT STROKES: CATALOGUING NEW TYPES OF LIGHTNING



Name	Color	Shape & Size	Duration	Visible to the Naked Eye
Sprite	Salmon red fading to purple or blue in lower tendrils	Blobs, columns and plumes extending from 30 up to 55 miles in altitude	10 to 100 milliseconds	Yes
Elf	Red	Flattened rings up to 250 miles in diameter rising from 45 to 60 miles in altitude	Up to 1 millisecond	No
Blue jet	Indigo blue	Narrow fountains of light shooting between 10 and 30 miles in altitude	10 to 100 milliseconds	Yes, but very rare and faint

COURTESY OF WALT LYONS

SPRITE GALLERY


CARMEN MIRANDA


DIET SPRITE

NAME THAT SPRITE: Researchers compete to come up with the most whimsical name for this bizarre atmospheric phenomenon.

at the University of Alaska Fairbanks who was part of the team that first photographed sprites from airplanes. "The lightning specialists know a lot about lightning, although this isn't exactly lightning. The space and ionospheric physicists are experts in plasma physics, but this isn't really your normal kind of plasma. And the atmospheric chemists aren't used to dealing with the electrical aspect of chemistry, so they're scratching their heads over it, too. It's interdisciplinary in the extreme."

Lyons's colleagues credit him with creating a sense of community among these disciplines by bringing researchers together. "Walt's big contribution was, first of all, providing a place where people could come," Sentman comments. "He's got all the infrastructure there that you need to do a complete study. Once we learn how to do it, working at Walt's place, then we wander off and find our own dark place."

"Yucca Ridge has really been a clearinghouse for the sprite work," says physicist David M. Suszcynsky of Los Alamos National Laboratory, who witnessed the spectacle of a sprite induced by a meteor from Lyons's deck in 1998. "Walt is kind of a spiritual leader in that sense."

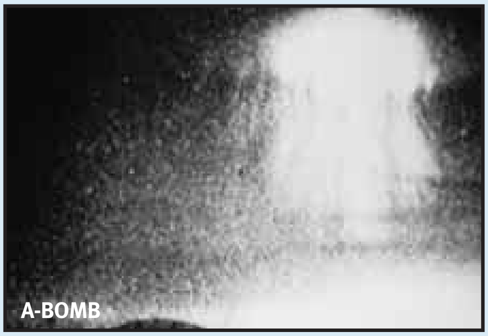
Lyons describes himself as a meteorologist by nature as well as by training. His earliest memory is of measuring snowfall as a four-year-old during a record-breaking storm in New York City that dumped three inches of the white stuff in one hour. "December 26, 1947," Lyons relates, with the chronological precision that is his habit. Although neither of his parents were meteorologically inclined, "there was never an issue of what I was gonna be when I grew up."

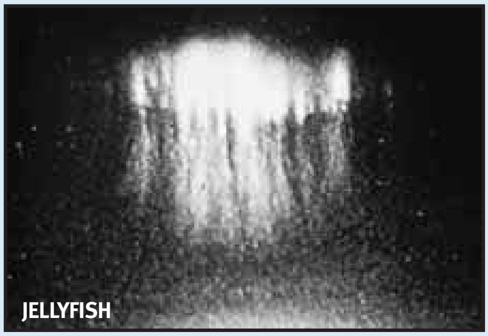
After attending St. Louis University for what was then one of the country's rare undergraduate programs in meteorology, Lyons went on to the University of Chicago to continue his studies under the late T. Theodore Fujita, an iconoclastic weatherman who devised the F scale used to rank the ferocity of tornadoes (as featured in the movie *Twister*). Fujita emphasized a pragmatic approach to observation combined with broad thinking. "One thing I learned from Ted is that you can't just look within one narrow discipline for answers," Lyons says. "And the other thing I learned from Ted is simply to look out the window."

Out the two-story windows of Lyons's den, the Front Range of the Rockies is visible to the west and south, a hazy-gray massif sprawled under the sun's autumn glare. But the business end of the house faces east, over the tawny, rolling fields that introduce the vast expanse of the Great Plains. The sameness of the view makes the horizon seem deceptively close. In the immediate foreground, half a dozen rare varietals of garlic grow in small brown plots, and turkeys named Thanksgiving, Christmas, New Year's and Easter poke about in a wire pen. The garlic is part of a commercial sideline; the turkeys are for private consumption. "We can see forever from here—or at least a thousand miles," Lyons remarks.

The pleasures of a home office in a rural setting are offset by the difficulty Lyons has had getting funding for his freelance sprite research. "The phrase 'blood from a turnip' comes to mind," he concedes. Although in the course of his career he has remained loosely affiliated with academia, his official title is president of Forensic Meteorology Associates and FMA Research. He subsidizes his pet projects with government and industry contracts for pollution research and with forensic work for attorneys and insurance companies. In short, when it comes to sprites, he's an outsider studying a freak phenomenon. "This is basic, pure science that only peripherally meets any of the [funding] agencies' needs," he says.

Sprite research has already overturned several fundamental assumptions about the planetary energy budget and its relationship with space. By sending columns of current into the atmospheric outback, for example, sprites are fueling the so-called global electrical circuit, an electric field maintained in air during fair weather by the difference in charge between the ionosphere and the ground. During studies of the circuit in the 1920s, Nobel Prize–winning Scottish physicist Charles T. R. Wilson proposed that upward flows of current probably accompany the downward discharges in thunderstorms and that such flows might glow at high altitudes. Wilson even claimed to have witnessed such an event in 1956, but his speculations on the subject were largely ignored. Now it seems that sprites do in fact deliver current to the upper atmosphere and that they may cause localized disturbances in the chemical and electrical properties





of the ionosphere. They may also be contributing high-energy particles to the Van Allen radiation belts that surround the earth; researchers used to believe that these particles came exclusively from the sun. "Sprites provide visible evidence that electrical effects extend all the way up into space," Sentman observes.

Homegrown Gamma Rays

In a truly remarkable development, sprites are now suspected of generating gamma rays, the most energetic radiation in the universe. Before the discovery of sprites, all gamma-ray sources were presumed to be buried in deep space. In 1994, though, a satellite observer detected bursts that seemed to be emanating from the earth's atmosphere. Acting on a hunch, Inan and his colleagues later matched the timing of such bursts to that of sprite-producing lightning bolts. The evidence, though circumstantial, suggests that sprites give rise to high-energy beams of "runaway" electrons, Inan says, that create gamma rays as they dodge molecules in the air.

Skeptics point out that the number of homegrown gamma rays seems to be a small fraction of the number of sprites produced. But current satellites can barely see earth-generated rays, Inan comments, because they are designed to detect rays coming from space. "We think there may be a whole lot of gamma rays out there waiting to be detected," he notes.

No one's sure yet just how many sprites are happening around the world, either. To answer that question, one of Lyons's closest collaborators, Massachusetts Institute of Technology physicist Earle R. Williams, is conducting a sprite census by monitoring fluctuations in ultralow-frequency radio waves. Ordinary lightning strokes, which occur at a rate of about 100 per second worldwide, produce a constant radio "hum" in the earth's atmosphere at these ultralow frequencies. During a long telephone conversation one night in 1994, Williams and Lyons discovered that each sprite Lyons observed from Yucca Ridge corresponded with an abrupt spike in the radio hum that Williams was reading at his oscilloscope station in the Rhode Island woods. The source of these spikes, called Q-bursts, had eluded physicists for decades. Williams has since determined that the Q-bursts occur because sprite-producing lightning strokes last thousands of times longer than ordinary lightning strokes, making an extralong pulse of electromagnetic energy that synchronizes with and amplifies the extralong radio waves.

"Sprite lightning is the biggest lightning on the earth's surface, in the biggest storms on the earth's surface," Williams marvels. "Every time there's a sprite, the whole earth resonates—it rings—for some fraction of a second." This resonance can be detected with equipment positioned almost anywhere on the planet. According to Williams's studies, sprites probably occur somewhere on the earth every 30 seconds or so.

Whereas experts like Williams stick to their specialized domains, Lyons has made it his mission to champion storm observations rather than abstract notions of upper-atmosphere effects. He's convinced that a more detailed understanding of thundercloud architecture and the electrical forces within will help reveal the secrets of sprites. Paul R. Krehbiel of the New Mexico Institute of Mining and Technology is already planning remote sensing of the lightning patterns within clouds to help expand knowledge of thunderstorm dynamics. Lyons points out: "That will keep the theorists from running off and saying silly things."

Meanwhile the theoretical disarray that plagues research on sprites, elves and blue jets is evident in the difficulty experts have had in coming up with a single name for the electromagnetic menagerie. "Above-ground discharges" was popular for a while, Los Alamos's Suszcynsky remarks, although sprites and whatnot probably aren't discharges in the usual sense. "So we gave up on that name." "Cloud-to-stratosphere discharge" suffered a similar fate. "They don't always go from the cloud up to the stratosphere," he says. "Certain parts go from the stratosphere down to the cloud." Ditto for "upward lightning."

Lyons recounts that he was happily deploying the acronym TLEs, for transient luminous events, until a colleague pointed out that "transient electromagnetic events" would better describe the full range of observed phenomena. So Lyons switched to TEEs. Then a friend at the National Oceanic and Atmospheric Administration told him that TEEs may also produce acoustic signals, at infrasound frequencies of several hertz, as well as electromagnetic emissions. "We may be able to hear them, too!" Lyons enthuses. But name them? Not yet. W

KAREN WRIGHT is a freelance writer who lives in New Hampshire.

IT'S RAINING EELS:

A Compendium of Weird Weather

Compiled by RANDY CERVENY
Illustrations by Dusan Petricic

May 19, 1780

DARKNESS AT NOON: A smoky blackness settled over the New England states, possibly the result of massive forest fires in Western states. It was so dark that by noon, people had to light candles and lamps to see. Even with the aid of lanterns, farmers could scarcely get to their barns to care for their livestock.

March 1876

JERKY FROM HEAVEN: *Scientific American* reported that many witnesses in Bath County in northeast Kentucky observed "flakes of meat" drifting down from a clear sky. One investigator declared that some of the flakes tasted like mutton or venison. The cause: Lightning may have roasted a flock of birds.

March 1884

WIND-POWERED TRAIN: A gale-force wind carried a train of six loaded coal cars on the Burlington & Missouri Railroad some 100 miles in three hours. The railroad deployed a locomotive that finally caught the runaway cars, coupled to them and brought them to a stop.

January 28, 1887

BIGGEST SNOWFLAKES: On the ranch of Matthew Coleman in Fort Keogh, Mont., a mail carrier observed snowflakes that were "larger than milk pans," apparently measuring as much as 15 by eight inches.

May 29, 1892

EEL RAIN: An enormous number of eels fell during a rainstorm in Coalburg, Ala. Farmers quickly drove into town with carts and took the eels away to use as fertilizer for their fields. The eel deluge—similar to other such peltings—may have resulted from a waterspout's lifting and jettisoning the fishes.

May 11, 1894

TURTLE HAIL: The last turn of the century was a good time for falling meat. A large hailstone that fell during a thunderstorm near Vicksburg, Miss., encased a six-by-eight-inch gopher turtle. A waterspout may have lifted the amphibian, which subsequently became the nucleus for the formation of a hailstone.

May 27, 1896

WAKE ME WHEN IT'S OVER: A massive tornado that hit the St. Louis area picked up one sleeping resident along with his bed and mattress, carried him more than a quarter of a mile and left him unharmed—if unable to remember how he got there.

November 15, 1915

AIRMAIL: The tornado that hit Great Bend, Kan., was noted for many oddities, but perhaps greatest among them was the discovery of a canceled check from Great Bend in a cornfield 305 miles to the northeast near Palmyra, Neb.

June 22, 1918

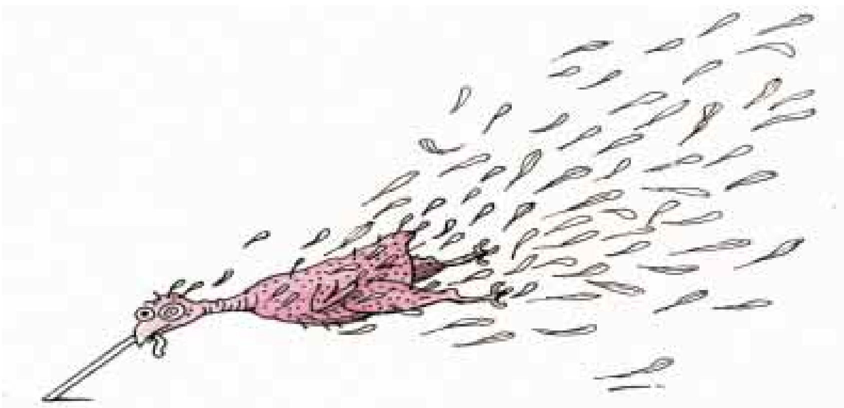
CELESTIAL SLAUGHTER: In the Wasatch National Forest in Utah, park rangers discovered the carcasses of more than 500 sheep, evidently killed by a single stroke of lightning.

January 22, 1943

THE GREAT SOUTH DAKOTA CHINOOK: In the Black Hills of South Dakota, temperatures in the small town of Spearfish fluctuated from –4 to 45 degrees Fahrenheit in two minutes because of blistering chinook winds during the morning hours. This rapid change in temperature was so pronounced that many plate-glass windows cracked simultaneously.

June 8, 1958

MORE THAN ONE WAY TO PLUCK A BIRD: A tornado tore off the feathers of a chick in Flint, Mich., and the local newspaper showed a photograph of it "pecking around a truck twisted like a steel pretzel." The National Severe Storms Forecast Center remarked on the story: "While it is not [our] mission ... to record tornadoes which deplumed fowls, enough events of this phenomenon have been documented over the past 140 years to warrant its acceptance."



June 14, 1960

A NIGHT IN HELL: After a distant thunderstorm sent a blistering downburst into the town of Kopperl, Tex., the temperature apparently shot up to near 140 degrees F, roasting ears of corn on their stalks, wilting cotton plants and drying fields of grass so that they were ready for immediate baling.

November 17, 1971

ELECTRIC SANDS: At White Sands, N.M., during a violent windstorm, three-foot-long sparks shot up from the tops of the gypsum sand dunes of White Sands National Monument. The friction of fierce winds and blowing sand apparently created huge static charges on the dunes, which triggered the sparks.

April 3, 1974

THE PICKY TORNADO: Despite demolishing an entire farmhouse in Xenia, Ohio, one of the worst tornadoes ever to hit the country left untouched a mirror, a case of eggs and a box of highly fragile Christmas ornaments.

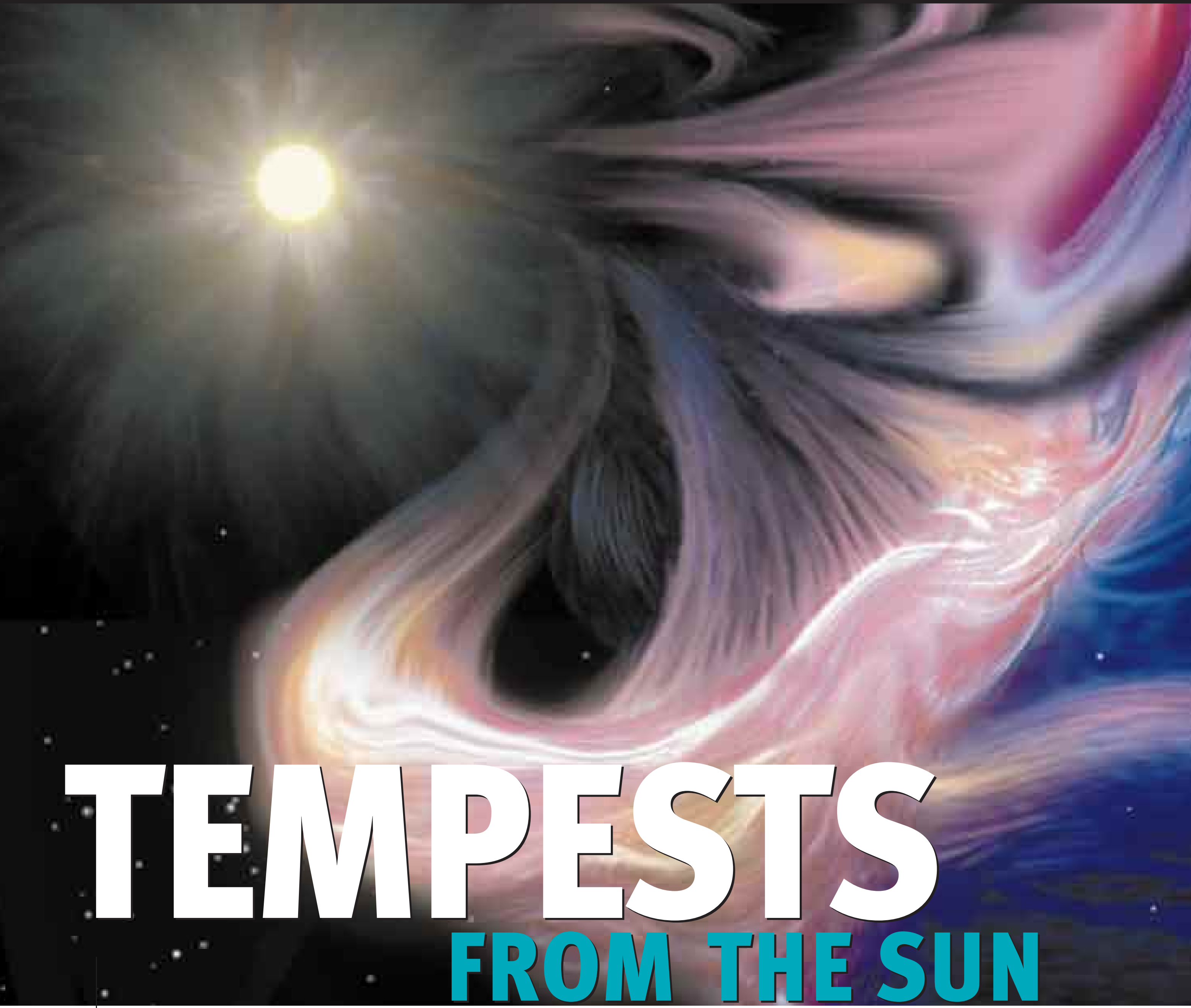
January 19, 1985

FROZEN ALIVE: When two-year-old Michael Troche wandered outside his home in Milwaukee, the morning temperatures had plummeted far below zero due to a record-breaking cold snap. When his father discovered the boy's body several hours later, young Michael's limbs had hardened; ice crystals had formed on and beneath his skin, and he had stopped breathing for an unknown time. His core temperature had fallen to 60 degrees F. At the hospital, a massive recovery operation began. Over a period of three days, the boy recovered; he suffered no brain damage. Apparently the windchill had frozen him so rapidly that his metabolism required very little oxygen.

July 9, 1995

NO SAFETY ANYWHERE: Lightning from a storm in Bristol, Fla., struck a tree, sending a power surge through the water in a nearby septic tank. The exploding water catapulted a 69-year-old man sitting on his toilet into the air. A hospital treated and released the man, who suffered only elevated blood pressure and tingling in his lower extremities. W

RANDY CERVENY is assistant professor of geography and meteorology at Arizona State University.



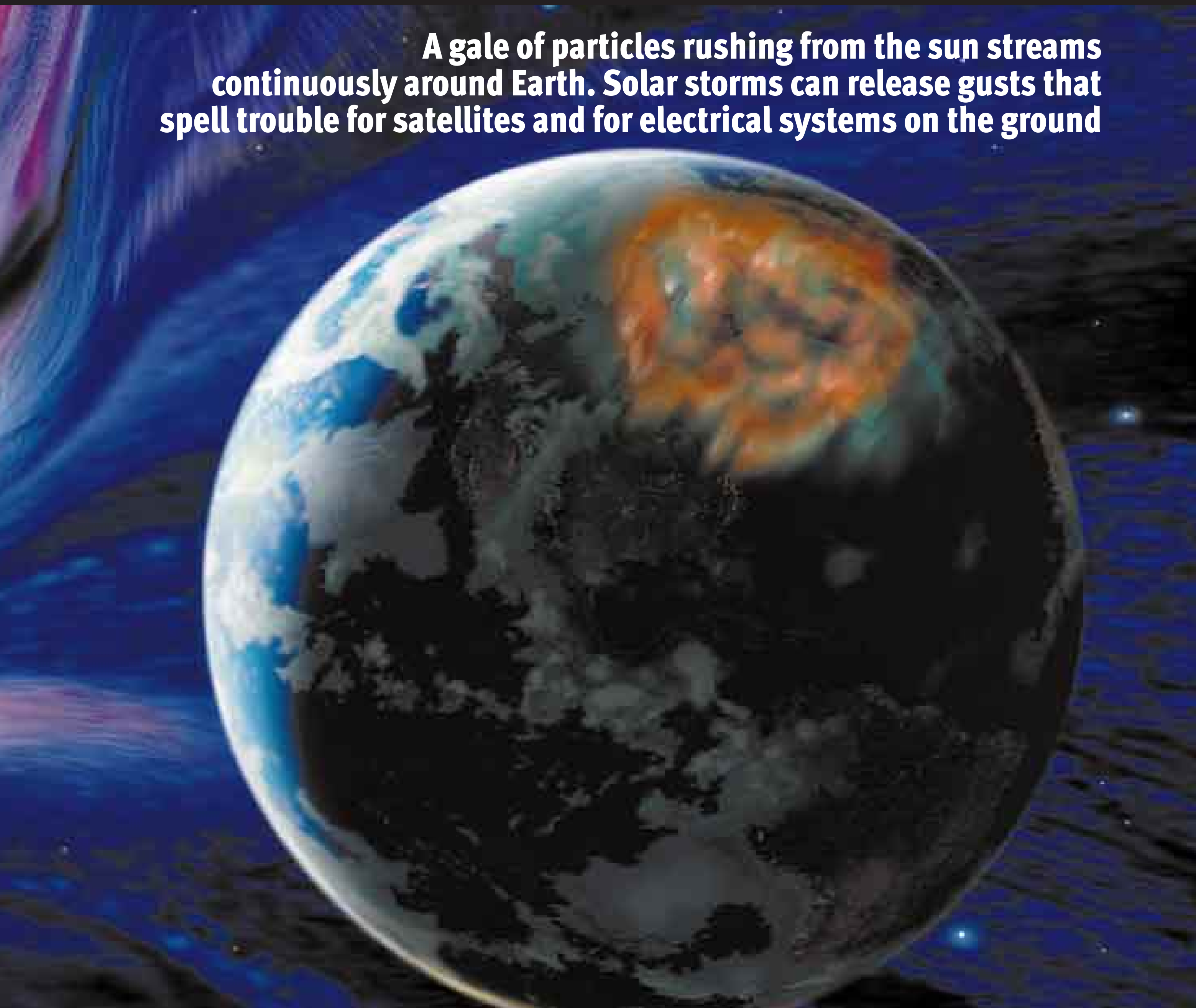
TEMPESTS FROM THE SUN

by TIM BEARDSLEY

In a sheltered Arctic valley in Greenland, a pulsing radar beam emanates from a 32-meter dish antenna. As I watch, the dish sweeps across the night sky, probing the ionosphere, a huge part of the atmosphere above 50 kilometers where atoms dissociate into electrons and ions. The antenna collects faint reflections that reveal distinct layers where electrons and ions swirl in unusual numbers.

An hour earlier the radar, located at the Sondrestrom Upper Atmospheric Research Facility, had detected prominent signals bouncing back from 140 kilometers up. They were coming from the aurora borealis, visible patches in the ionosphere where high-energy particles from space strike oxygen and nitrogen atoms. The collisions excite the atoms and cause them to emit light of different colors, producing the spectacular displays known as the northern lights. But now, as midnight approaches, the aurora has dissipated. It is a quiet night in Earth's near-space environment.

A gale of particles rushing from the sun streams continuously around Earth. Solar storms can release gusts that spell trouble for satellites and for electrical systems on the ground



SPACE WEATHER IN SPADES: A bundle of plasma (ionized gas), known as a coronal mass ejection, may escape from the sun (*far left*) during cataclysmic disturbances on its surface. The plasma—which weighs billions of tons but is too sparse to see—arcs through space and may pass by Earth, where it can trigger electrical storms in Earth's space neighborhood.

DON DIXON

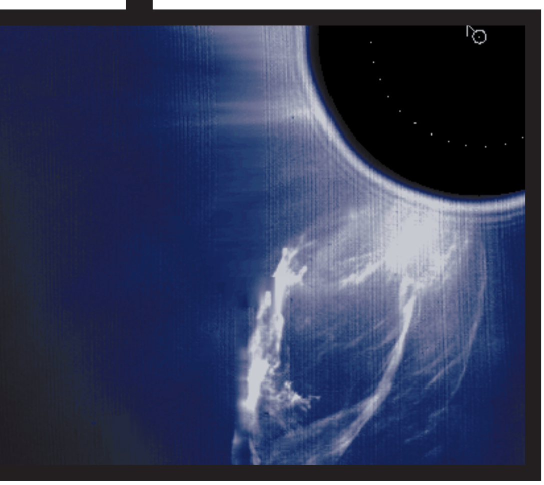
Inside the facility, though, scientists are still active. The radar, originally built to monitor aboveground nuclear explosions, is today a key component of a worldwide effort to understand space weather and its effects. Investigators at the research station—which is run by the Danish Meteorological Institute and SRI International on behalf of the National Science Foundation—hope the information they collect will provide clues about processes not only in the ionosphere, which ends at about 600 kilometers, but also far beyond it.

Earth has a magnetic field that extends all the way through the atmosphere and then tens of thousands of kilometers farther into space. In different parts of this vast region, called the magnetosphere, electrically charged particles whiz around in complicated patterns that can change or intensify in response to conditions on the sun. These effects out in space often induce changes nearer to Earth, in the ionosphere—at times causing all manner of trouble for enterprises on the ground and for the satellites on which we have become increasingly dependent. A better understanding of space weather should help researchers devise ways to avoid or limit its destructive effects.

One consequence of space weather disturbances is that the layers of free electrons in the ionosphere may shift unpredictably or fade. As a result, some radio trans-

CRAIG J. HEINSELMAN *SRI International*

PROBING THE SKIES: The Sondrestrom Upper Atmospheric Research Facility (*top*) sits in a prime location—Greenland—for studying events related to space weather. The dish antenna is part of a radar that charts phenomena occurring in the ionosphere. One of these phenomena is the aurora borealis, or northern lights (*glowing patches in sky*). The green laser beam is from a separate instrument that detects specific chemical elements in the ionosphere. The image below captures a coronal mass ejection in the process of forming.



SOLAR MAXIMUM MISSION/HIGH ALTITUDE OBSERVATORY/NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

missions that are deliberately bounced off these layers may be interrupted.

During especially violent episodes known as geomagnetic storms, particles become more energized throughout the whole magnetosphere, sometimes for several days. These electrical storms in our region of space can cause voltage swings on Earth that disrupt sensitive measuring instruments used in semiconductor manufacturing, says John W. Freeman of Rice University.

Geomagnetic storms can even take out power grids. In one of the most notorious storms, in March 1989, millions of people in eastern Canada were left without power for many hours after voltage swings brought down Hydro Quebec's grid. Even fiber-optic cables under the ocean are vulnerable to space weather events, because abnormal currents can be generated in copper wires that run alongside the cables carrying power to amplifiers.

Another space weather effect arises when storms on the sun cause it to emit more ultraviolet radiation than usual. The extra radiation can warm and swell Earth's atmosphere. In this condition, it may slow satellites that are normally beyond its clutches in low Earth orbit, including the Hubble Space Telescope and the space shuttle. Such an unexpected puffing up in 1979 caused Skylab to plummet to Earth years before it was intended to. Planners of the International Space Station assembly have had to take careful precautions against similar events.

The quest to understand space weather has gained urgency with the realization that geomagnetic storms also threaten many satellites that are in high orbits well above the atmosphere. The most susceptible are in a crowded orbit called geosynchronous, 36,000 kilometers above the equator. Satellites at this height move around Earth at the same speed as the planet rotates, so antennas on the ground can be aimed at an unmoving point in the sky.

Zap!

Unfortunately, this lofty perch places the satellites within the Van Allen radiation belts, which occupy a vast doughnut-shaped region that buzzes with energetic particles and encircles Earth's midlatitudes outside the ionosphere. During a geomagnetic storm, electrons and ions in the belts have more energy than usual. Then they deposit electrical charges in circuitry within spacecraft and charge up exterior surfaces. The buildup provokes discharges that can damage hardware and produce spurious commands.

Unmanned spacecraft are not the only orbiters at risk. Astronauts building the space station might receive substantial doses of radiation in a geomagnetic storm. Other highly energetic particles—notably protons that come directly from the sun during solar disturbances—also threaten spacefarers and can rapidly degrade solar panels on spacecraft.

Just how much space weather threatens satellites is controversial and shrouded in secrecy, because the owners of such expensive items of hardware—which may be worth hundreds of millions of dollars each—are reluctant to advertise their vulnerabilities. Some insurers may refuse to pay for a satellite lost through an "act of God." Others won't pay for satellites destroyed by weather events, so laying the blame for losses is a delicate matter.

According to Daniel N. Baker of the University of Colorado at Boulder, several notable satellite failures in recent years were caused by high-energy electrons, including major problems that occurred with two Canadian Anik communications satellites in January 1994. Baker suspects high-energy electrons may also have been involved in the failure of the Galaxy 4 satellite in May 1998 (although the satellite's owner disagrees). That event caused a widespread loss of pager services and other communications links. All in all, economic losses attributable to space weather are estimated in the high tens of millions of dollars a year—but could potentially climb much higher in a year in which storm activity is more intense.

Scientists expect some violent space weather in the months to come, because this year the sun is reaching a solar maximum: a peak in the number of violent outbursts on its surface. Such peaks occur roughly every 11 years. At these times the sun is more likely to emit energetic particles that create havoc if they near Earth.

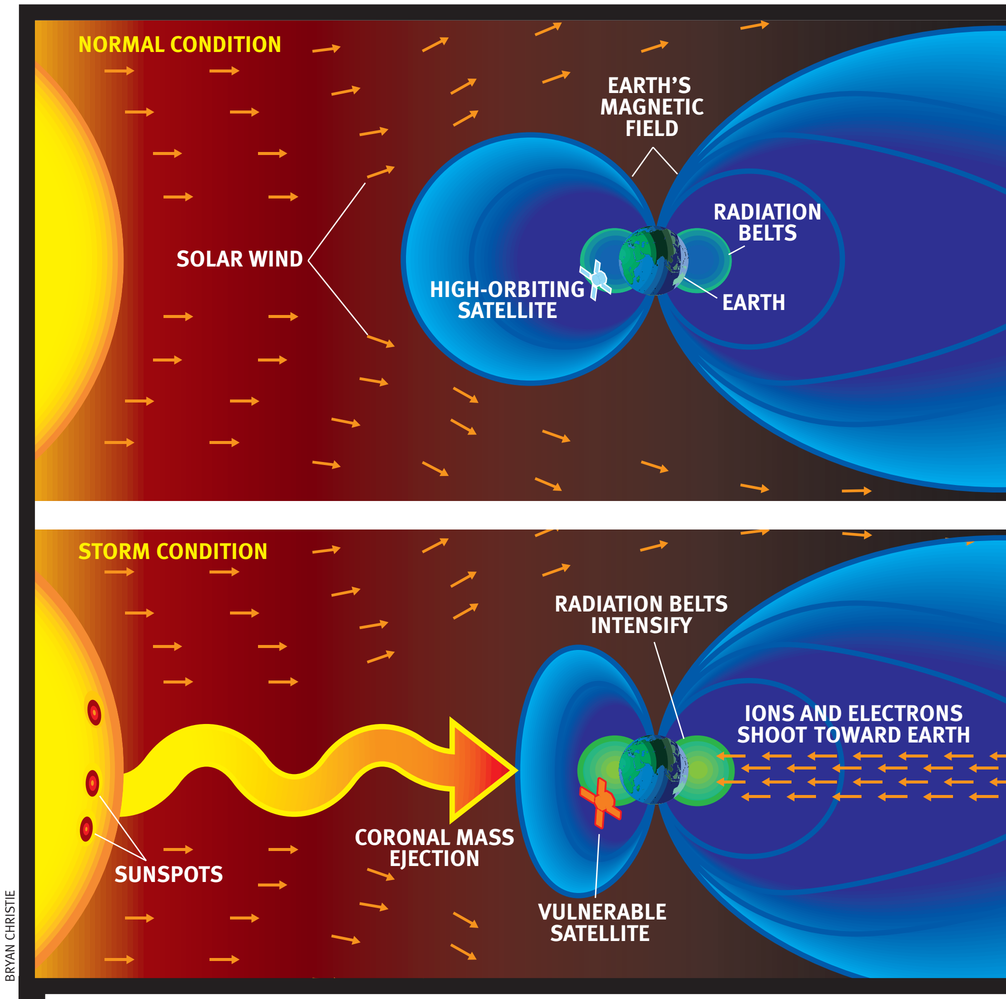
Researchers would like to issue daily forecasts that would warn of geomagnetic storms and other space weather disturbances, just as meteorologists predict storms in the lower atmosphere. Civilization is now more reliant on sensitive technological systems such as telecommunications satellites and the Global Positioning System than it was during the last solar maximum in 1989, so good forecasts could avert much damage. But scientists have a long way to go before they can produce dependable predictions.

Storm Sources

Although researchers at Sondrestrom and related facilities can hardly predict space weather disturbances, they do have some ideas about what is involved. A tenuous gale of electrons and protons—the solar wind—gusts continuously from the sun's corona, its very hot outermost layer. These particles carry a magnetic field with them from the sun. As they approach Earth, the magnetosphere normally serves as a *Star Trek*–style force field, parting and deflecting the wind so that it rushes past the planet. When storms are agitating the sun's surface, however, massive loops of ionized gas, or plasma, may blow off from the corona. The plasma energizes the solar wind and shoots through space at around one million kilometers per hour in an arc that follows the lines of the solar magnetic field. Plasma from a coronal mass ejection near the sun's midlatitudes may pass close by Earth and so trigger a geomagnetic storm.

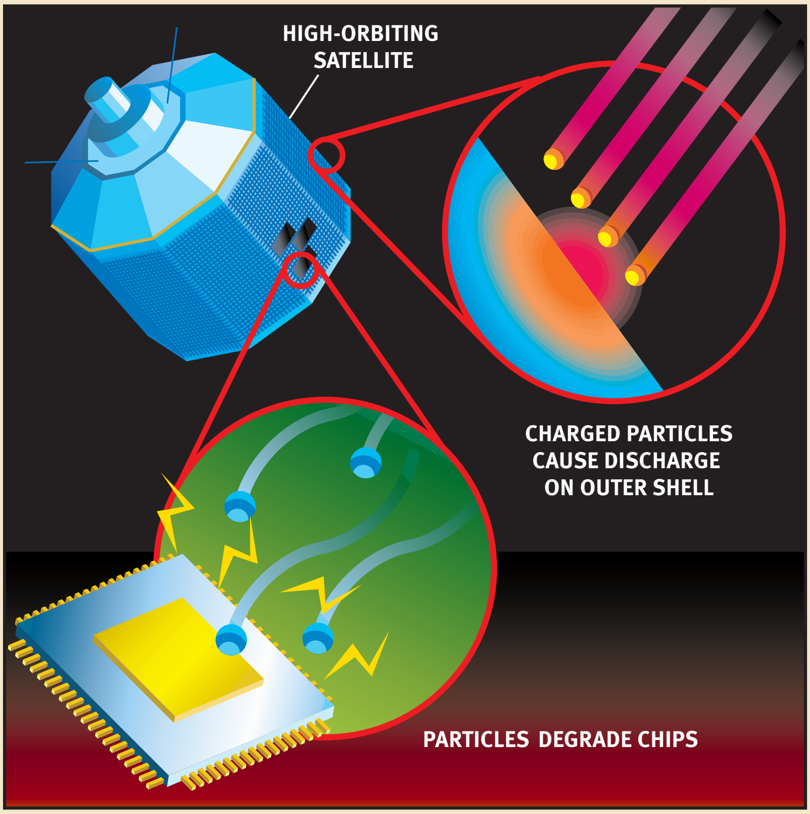
During these extreme conditions the wind distorts the magnetosphere, and the magnetic field that the wind has carried from the sun interacts with Earth's own field to generate a backlash of particles that shoot in the opposite direction to the wind. More specifically, on the side of Earth that faces away from the sun, the magnetosphere is permanently stretched out to form a long tail. In a storm, electrons and ions moving past the tail in the solar wind somehow penetrate the tail, reverse course and zoom back toward Earth. "It's like a giant dynamo that deposits energy on Earth's dark side," says Jeffrey P. Thayer, program manager at Sondrestrom. That is why the instruments at the Greenland site operate mainly at night; some of the most interesting phenomena can be detected when the devices are looking into the sky away from the sun. Operators fueled with coffee and prepackaged frozen food often work into the hours before dawn.

The charged particles in the backlash rushing toward Earth's dark side in a storm energize the Van Allen belts, which is why the radiation levels there may suddenly rise and disturb spacecraft. The particles may also produce a titanic electric current that circulates the entire globe. It is this current that can induce fluctua-



HOW SOLAR STORMS AFFECT EARTH: A gale of particles constituting the solar wind blows continuously from the sun, but Earth's magnetic field, shown in blue, mostly deflects the barrage (*top*). Occasionally, the sun generates a coronal mass ejection that reaches Earth (*bottom*). The ejection distorts the planet's magnetic field and makes particles from the wind rush toward Earth's night side in a backlash. These inrushing particles intensify the radiation belts around the planet, markedly increasing the danger they pose for satellites. The torrent of inrushing particles also brightens the aurora, which is not shown here. Coronal mass ejections occur most often when sunspots are visible.

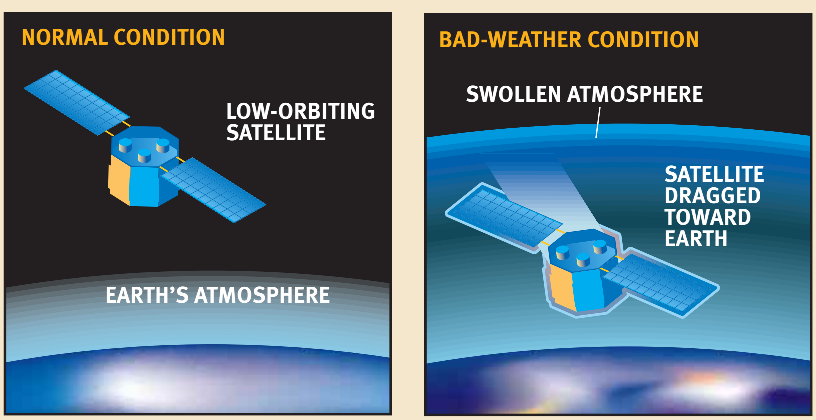
WHY SATELLITES SUFFER



Space weather can threaten satellites in several ways.

High-orbiting satellites (*above*) pass through the Van Allen radiation belts. During bad space weather, electrically charged particles in these belts become more energetic, so they charge spacecraft surfaces, causing sparks that can damage those surfaces and disrupt circuits. Other particles directly degrade the chips in the satellites' onboard computers.

Low-orbiting satellites (*below left*) face a different space weather hazard. When the sun is disturbed, it emits more ultraviolet radiation than normal, which warms Earth's atmosphere and makes it swell. The atmosphere then acts as a brake on satellites that are normally beyond its clutches, bringing them into a lower orbit (*right*). Operators must expend valuable fuel to reboost the orbiters, thus shortening their service lifetimes.



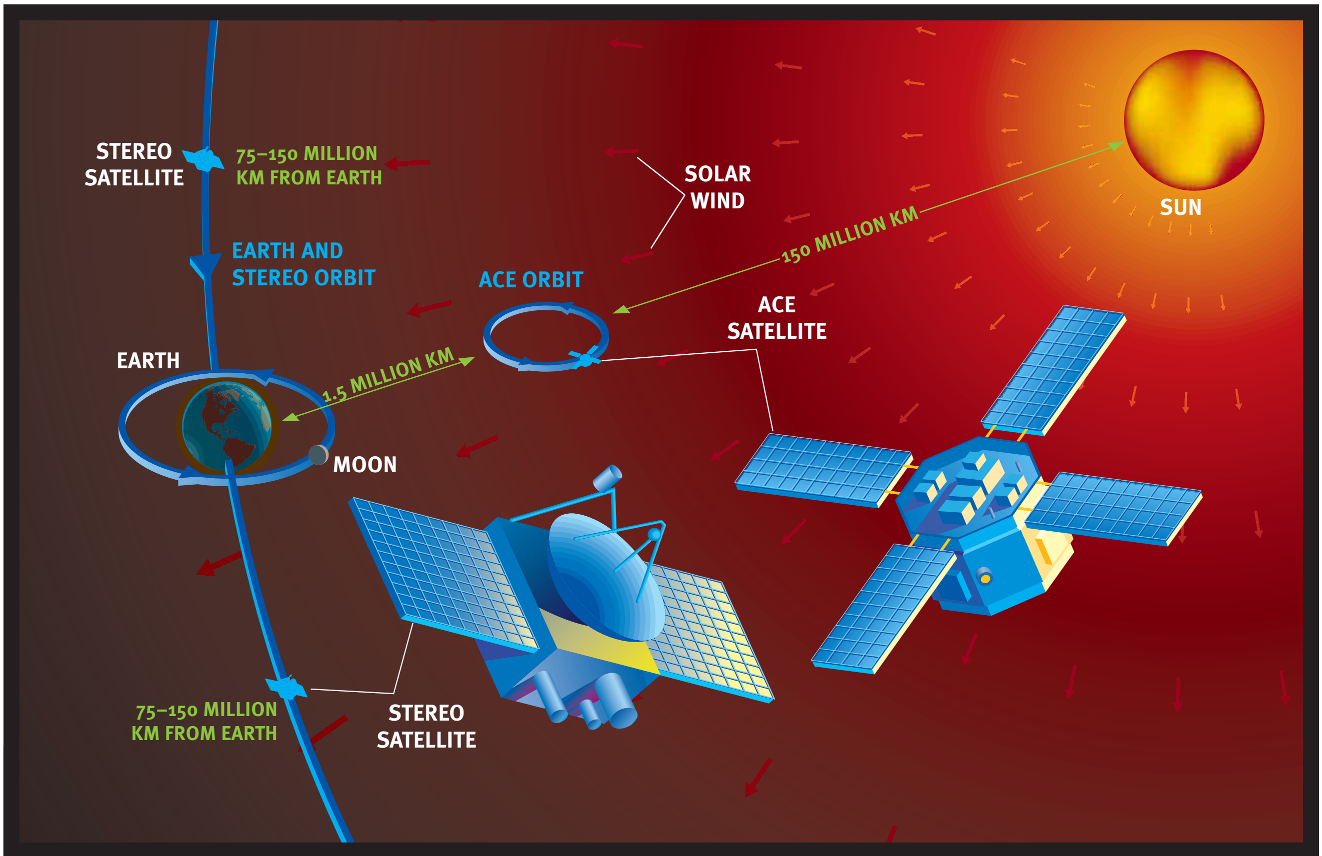
BRYAN CHRISTIE

tions in sensitive instruments on Earth.

The backlash flow of ions and electrons also funnels particles onto two rings at the top of the ionosphere, one around each of Earth's magnetic poles. The rings, known as auroral ovals, are a few thousand kilometers across. Charged particles continuously plough into the ovals, creating the aurora borealis and its southern counterpart, the aurora australis, in the ionosphere. But when a geomagnetic storm is in progress, this torrent of particles intensifies, brightening the auroras. Less delightfully, a storm may give rise to tremendous electric currents in the ionosphere around the poles. These currents can then bring about the voltage swings that can knock out long-distance power lines at the terrestrial surface.

Even when the sun is being well behaved, parcels of plasma shoot sporadically toward Earth's dark side, prompting a bright aurora and intensifying radiation belts. These events, called substorms, last only a few hours, but they occur several hundred times a year and are quite capable of disrupting satellites, according to Baker. The Sondrestrom facility, near the settlement of Kangerlussuaq, is within the northern auroral oval, so it is excellently positioned to detect any ionospheric changes that happen in this sensitive part of the world. Indeed, its radar is one of only three comparable instruments studying space weather inside the Arctic Circle. Detectors at Sondrestrom continually register fluctuations in Earth's magnetic field caused by substorm-induced currents.

One of the most important capabilities of the Sondrestrom radar is that it can detect horizontal motions of plasma within the ionosphere, which is too high to be reached by balloons carrying instruments. This ability could be crucial for unveiling some of space weather's most perplexing phenomena. The ionosphere plays a crucial role in dissipating electrical energy created by the interaction of the solar wind and Earth's magnetic field, SRI's Craig J. Heinselman says. Currents arising in the ionosphere can heat the sparse plasma there and trigger bulk movements of neutral gases. Enormous patches of partly ionized gas hundreds of



DEFENSIVE MANEUVERS: Specialized satellites can help predict bad space weather. ACE monitors the particles in the solar wind from its orbit directly between Earth and the sun. Gusts pass the spacecraft about an hour before they reach Earth, so ACE can radio a warning that severe space weather is on the way. Two Stereo satellites scheduled for launch in 2004 will provide stereo views of the sun from vantage points farther from Earth. Their viewing angles will enable scientists to better predict when the sun is likely to shoot off an especially vigorous burst of particles, giving perhaps a full day's warning of a potentially disruptive space weather event.

kilometers across often drift over the poles from the planet's day side to its night side, for example, interfering with satellite communications. The radar can map those movements and may thus eventually enable scientists to anticipate worrisome plasma shifts.

Keeping an Eye on the Sun

Monitoring Earth's near-space environment can help scientists understand space weather, but better forecasting also demands scrutiny of the sun, where disturbances originate. Some of the most useful instruments for observing the sun detect wavelengths of electromagnetic radiation that cannot penetrate through the ionosphere and stratosphere to Earth-based detectors; consequently, the most useful sun-watching instruments are borne by spacecraft way past even the most distant wisps of the atmosphere.

In recent years a satellite known as SOHO (Solar and Heliospheric Observatory) has greatly refined ideas about links between the sun and our planet. SOHO does not orbit Earth; rather it circles around a gravitationally stable point in space about 1.6 million kilometers from the planet in the direction of the sun. From there SOHO can observe our local star 24 hours a day. It sees onrushing plasma from coronal mass ejections as a characteristic halo around the corona. Unfortunately, plasma ejected on the far side of the sun and plasma moving toward Earth present identical appearances, so SOHO images are far from ideal as predictors of episodes that might have consequences to earthlings.

Since early 1999 scientists have been able to get another type of advance warning of bad space weather. A satellite called ACE (Advanced Composition Explorer), positioned in an orbit like SOHO's directly between Earth and the sun, monitors the particles in the solar wind and its magnetic field. The spacecraft sends warnings that arrive an hour before a gust. ACE's data have to be incorporated into computer models before they can supply forecasts, but even so they provide about 30 minutes' notice of when a satellite might be vulnerable to high-energy particles. That is enough for operators to take some steps to protect sensitive systems, although they may be reluctant to reconfigure satellites that lack immediately available backups, notes Baker of Boulder. Furthermore, some of the most dangerous particles, notably energetic protons, travel from the sun to Earth in just a few minutes—too fast for any warning.

Researchers are learning some tricks to improve prediction. They can, for example, sometimes see in the corona reflected light from solar storms occurring beyond the edge of the sun's visible disk.

CHASING EXTRATERRESTRIAL STORMS

by TRACY STAEDTER

Even on its stormiest days, Earth's weather pales next to that on other worlds. Gigantic dust devils stampede across Mars. Gasolinelike liquids rain onto Saturn's moon Titan. A high-pressure system approximately the size of two Earths reels around Jupiter. And unimaginable winds rage against Neptune at more than 1,300 kilometers an hour. It's no wonder some scientists prefer to chase extraterrestrial storms rather than bother with any Earth-bound ado.

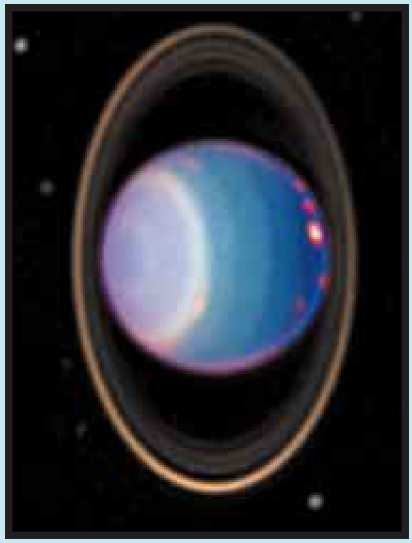
But tracking alien weather is a daunting task. Astronomers must look across vast distances of space at worlds whose very atmospheres enshroud storm activity. And any viewing from the ground must be done during brief observing sessions on just a few large telescopes. But surprisingly, scientists have gotten remarkably close to their quarry. With advanced telescopes and computer models, they are peering deeper than ever before into otherworldly atmospheres and even gaining insight into weather phenomena right here at home.

Some of the latest advances are being made on the outer planets. Recently a team of scientists from Lawrence Livermore National Laboratory used the 10-meter Keck telescope to image Saturn's moon Titan and discovered possible methane seas. The presence of these seas suggests that the tiny moon may undergo something similar to Earth's water cycle. On Earth, water condenses into clouds, then rains onto the surface. On Titan, methane could be condensing and raining onto the surface to make seas of liquid hydrocarbons.

"It's like what Earth was like four billion years ago before there was life," says team member and astronomer Bruce Macintosh. If so, Titan presents scientists with a natural laboratory for examining our own planet's earliest atmosphere.

In many cases, such parallelism is why scientists study the extreme conditions of extraterrestrial atmospheres. Those harsh environs represent how weather varies in ways that cannot be duplicated by experiments on Earth. "Generally the way we learn about how true our models are is by having more conditions to compare them to," Macintosh notes. The more comparisons scientists can make out there, the more they understand how things work down here.

Take lightning. On both Jupiter and Earth the phenomenon seems to occur only in



ERICH KARKOSCHKA *University of Arizona AND NASA*

URANUS: This false-colored 1998 Hubble Space Telescope image highlights clouds toward the right of the sphere.

water clouds, says theoretician Seran Gibbard of the Livermore laboratory. Observing bursts on more than one planet has helped scientists to narrow down the conditions that create lightning.

Some phenomena are not so clear-cut, however. One thing that remains a mystery is how the outer planets generate weather so far from the storm-producing energy of the sun. On Earth the sun's radiation warms the planet's surface considerably, creating clouds and winds that eventually lead to

And one team of investigators, headed by Richard Canfield of Montana State University at Bozeman, has identified a particular visible structure that often appears on the sun's surface before a violent outburst. The pattern, evident in images made with soft x-rays, is an S-shaped bright region. Canfield and his collaborators believe it represents a twisted magnetic field that is readying to resolve itself into a coronal mass ejection.

Above the Crowd

The growing concerns about space weather have spurred several new initiatives. The government has inaugurated a national space weather program, and additional specialized satellites are in the works. One, not yet funded, is called Geostorms. Like ACE and SOHO, it would be positioned directly between Earth and the sun. But because it would have a solar sail to intercept energy from the sun, it could hover about twice as far from Earth as those spacecraft, which must remain close to a specific gravitationally stable point. Geostorms could thus extend notice of a threatening blast of solar wind to a couple of hours—enough for utility companies to put circuits in their safest configurations and to alert personnel.

A more ambitious space mission, approved for launch in 2004, is Stereo (Solar and Terrestrial Relations Observatory). It would consist of two sun-gazing satellites following orbits like that of Earth's around the sun, with one of the pair leading our planet and the other, about 200 million kilometers distant, lagging. The two satellites would jointly provide a stereoscopic view of the sun that would reveal storms in three dimensions and allow scientists to see more of the sun's disk than they can from near Earth. That capability should allow them to be much more confident about which events are most likely to produce repercussions.

Stereo could also help ensure the safety of astronauts who might one day travel to Mars. An interplanetary journey will expose spacefarers to potentially dangerous quantities of high-energy solar protons. If they had some warning of a threatening solar event, however, they might be able to take refuge in a shielded compartment.

Other planned satellites will focus on deepening scientific understanding of the effects of the solar wind on the mag-

VOYAGER 2 NASA

NEPTUNE: Voyager 2 produced the first clear images of long cirrus-type clouds (white streaks) over Neptune in 1989.

dramatic storms. But the outer planets are incredibly distant from the sun.

Neptune, for example, is 30 times farther from the sun than Earth is. Yet Neptune has clouds and nearly supersonic winds. In 1989 Voyager 2 revealed cirrus-type clouds there. In May 1999 Macintosh and his team of scientists used Keck to create the highest-resolution infrared images of Neptune's clouds and of atmospheric bands in the planet's southern hemisphere. Before then, even the biggest clouds on Neptune looked like fuzzy blobs from ground-based telescopes. The secret to the improved resolution is computer-controlled adaptive optics, which dramatically reduces image distortions introduced by Earth's atmosphere.

So how do clouds and high winds form on a planet so far from the sun? Scientists speculate that even the weakest amount of sunlight can make a difference on a planet with surface temperatures of about –130 degrees Celsius. The meager energy upsets the precarious balance of temperature and chemicals in the gaseous layers of the planet, leading to atmospheric disturbance. Weather-producing energy may also come from inside Neptune. Like all the planets, Neptune formed when gases in the solar nebulae condensed and collided with one another, accreting into a planet. The energy generated during those collisions is still emanating from the interior.

But the forces apparently at work on Neptune do not convincingly explain the clouds scientists see on its neighbor, Uranus. "Uranus seems to have no internal heat source," comments planetary scientist Heidi Hammel of the Space Science Institute in Boulder, Colo. Even so, Hammel and researchers from New Mexico State University and the Massachusetts Institute of Technology found 20 clouds—one brighter than had ever been seen before—when they observed Uranus with the Hubble Space Telescope.

Scientists theorize that changes in Uranus's atmosphere might arise in part from how the planet spins. Like the other gas giants, Uranus rotates especially fast, turning full circle in less than 18 hours. The rapid spinning sets up flow patterns in the gaseous atmosphere similar to those observed in fluid dynamics. "When you spin a ball of fluid, you get streaky patterns; in between you get eddies and currents," Hammel explains. "That is the weather."

Observations made from Hubble, Keck and other telescopes, combined with computer models, offer valuable insight into extraterrestrial atmospheres. By digesting a multitude of variables such as temperature, wind speed, chemical composition and more, the models can play out plausible weather scenarios.

Ultimately, scientists would like to have one model that works for all the planets, including Earth. With such a model, they could change variables such as carbon dioxide levels and fast-forward to the most likely outcome. That would provide us with a clearer picture of our planet's atmospheric future, a forecast critical to our own well-being.

TRACY STAEDTER is managing editor of *Scientific American Explorations*.

netosphere. A notable example in that category is known as Image. Image, scheduled for launch early this year, will use specialized detectors to visualize plasma around Earth, thus providing a real-time picture of space weather's effects.

Heads Up

Space weather does ultimately affect weather down on the ground—but the link is well established only for effects that span very long timescales. From the mid-17th to early 18th century, the sun was unusually inactive, a period known as the Maunder Minimum. The result, most scientists agree, was an extended cold spell on Earth. An earlier period of heightened solar activity might explain how Europeans were able to colonize Greenland in the 11th century: the country was warmer then than it is today.

On a shorter timescale than centuries, Harry Van Loon of the National Center for Atmospheric Research in Boulder, Colo., and Karin Labitzke of the Free University of Berlin have demonstrated to the satisfaction of many scientists that the 11-year cycle of solar activity affects temperatures and pressures—and thus winds—in the stratosphere. Such an effect might, for example, explain links between winter temperature on Earth and the phase of the solar cycle. What is more, the solar cycle controls the inflow of cosmic rays to the atmosphere, through its effects on the magnetosphere. Some researchers believe cosmic rays could influence cloudiness, because they may provide nuclei for droplets to condense around. But the suggestion is controversial. Although space weather deposits a lot of energy into the upper atmosphere, very little is transported into the lower regions, says Ron Zwickl, assistant director of the National Oceanic and Atmospheric Administration Space Environment Center.

Space weather forecasting is unlikely to ever help people plan vacations or decide whether to take an umbrella to work. But as those who study it at Sondrestrom and elsewhere are well aware, its importance to civilization seems likely to grow in coming decades as systems become more complex. For electrical utilities, military and civilian communications planners and others, accurate space weather forecasts cannot come too soon. W

TIM BEARDSLEY is an associate editor of *Scientific American*.

Will efforts to change the weather ever attain scientific legitimacy?

CLOUD DANCERS

by DANIEL PENDICK

Water. Everybody needs it. Almost everybody who has it could use more of it. And those who don't have it would do almost anything to get it. For millennia, the traditional technology for obtaining water was simple enough—a hole in the ground. Shamans and charlatans alike also appealed to the sky to boost their water supplies. Half a century ago in a laboratory in Schenectady, N.Y., scientists came up with an entirely new version of the tribal rain dance: cloud seeding. By scattering chemical "seeds" in rain clouds, they hoped to augment natural rainfall to replenish water tables and reservoirs.

Rainfall enhancement, as its practitioners like to call it, remains just one variation of the much older dream of controlling the weather. Taming tornadoes with A-bombs, short-circuiting lightning storms with metal chaff, smothering hurricanes at sea, quashing damaging hail—all have been proposed or attempted since that fateful day in Schenectady.

Decades of equivocal research have failed to quell enthusiasm for weather modification. True, the U.S. government all but abandoned investigations into cloud seeding five years ago. But in 1998, reports the National Oceanic and Atmospheric Administration, 48 nonfederal weather modification projects in 10 states were under way. And according to the most recent statistics from the World Meteorological Organization, 26 countries were conducting a total of 84 projects in 1995. Although many such projects are for hail reduction—reducing potential damage by making hailstones smaller—cloud-seeding projects still abound and are motivated by thirst for water. "They always say the same thing," notes Thomas J. Henderson, head of weather modification firm Atmospherics in Fresno, Calif. "The value of water is so high that we can't afford not to do it. If there's any indication at all of positive results, they've got to keep doing it."

Rainmaking has generated renewed optimism lately because of field trials in South Africa, Mexico and Thailand of a technique called hygroscopic cloud seeding, which accelerates the natural raindrop-forming process in clouds. One proponent, Nico J. Kroese of the South African Weather Bureau, has characterized this method as the most exciting development in cloud-seeding research in the past 50 years. But before hygroscopic seeding lives up to its initial billing, a stubborn question needs to be answered: If you seed a cloud and it rains, how can you be sure that it would not have rained anyway?

SEEDING THE SKY: Flares from a two-engine propeller airplane contain microscopic particles, often silver iodide, that are emitted in a flare and blown by updrafts into clouds. Larger than normal water droplets may form around the particles, some of which may grow big enough to fall to the ground as rain.

The rainmaker is a well-ensconced figure in U.S. history. In 19th-century America, where agriculture was king, itinerant rainmakers found willing dupes in times of drought. On the scientific front, kites and balloons were used to set off explosions to see if the concussion might coax a few extra drops from the clouds—an attempt to probe whether there was any validity to the lore that rain followed big battles. Indeed, the U.S. Congress appropriated $9,000 in 1891 for rainmaking experiments under the direction of an agent of the Department of Agriculture, Robert Dyrenforth. Experiments continued sporadically into the 20th century, involving everything from igniting fires to stimulate updrafts and spawn new rain clouds to scattering shovelfuls of sand into the clouds from the open cockpit of an airplane.

Eureka! It's Snowing

In 1946 at the General Electric Research Laboratory in Schenectady, the dark ages of rainmaking came to an end. Nobel Prize–winning chemist Irving Langmuir and junior researcher Vincent J. Schaefer were studying airplane-wing icing in supercooled clouds—clouds in which tiny water droplets were chilled to below the freezing point of water. Schaefer had rigged up an electric freezer and breathed into it to create a miniature cloud. Intending to cool the chamber even more, he slipped some dry ice (at –109 degrees Fahrenheit) into the

THOMAS J. HENDERSON *Atmospherics*

LET IT RAIN: Unseeded clouds (*top*) have less moisture content than the same bank of clouds after seeding (*bottom*). The seeded clouds managed to produce rain showers.

SCHENECTADY MUSEUM ARCHIVES

SNOWSTORM IN A BOX: General Electric scientists Irving Langmuir (*left*) and Bernard Vonnegut look on while Vincent J. Schaefer performs a snowmaking experiment. All three scientists were involved in developing the field of weather modification.

chamber. Eureka! The droplets precipitated out as a blizzard of tiny ice crystals—the researchers had produced a pint-size snowstorm inside a box.

Thus was born glaciogenic (ice-forming) cloud seeding. If supercooled cloud water could be made to grow into large enough clumps, they would fall out of the sky as snow or—if they passed through warm air—as raindrops. Physical chemist and meteorologist Bernard Vonnegut (the brother of writer Kurt Vonnegut) joined the effort. He reasoned that a substance with a similar crystal structure to that of ice might also work as a glaciating agent. He found that the smoke from burning silver iodide did the trick brilliantly in laboratory experiments. Way up in the frigid tops of clouds, supercooled droplets cannot freeze until they encounter a bit of ice, a mote of dust or a fleck of soil. The crystals of silver iodide in the smoke mimic ice, providing a nucleation site for the water to freeze onto.

The rainmakers had found their seed, and the sky was the limit. By the 1950s commercial cloud-seeding companies actively hawked their services on the open market in the American West. In those heady early days as much as 10 percent of the sky over the U.S. may have been under cultivation by cloud seeders, who claimed increases in rainfall of up to 15 percent or more. This development caught the skeptical eye of Congress, which in 1953 established the Advisory Committee on Weather Control to look into the matter. Its 1957 report stated that based on data provided primarily by commercial cloud seeders, seeding seemed to have real potential to enhance precipitation. But statisticians and others attacked the report for the poor quality of data and the statistical methods on which its conclusions were based. What was needed, the scientists said, was better science.

The cloud seeders obliged. Throughout the 1960s and 1970s—the glory days of weather control—they expanded the scope of their activities. Researchers mounted a number of major campaigns in what became a veritable war on weather. They explored techniques to clear fogs from airports, either by seeding from above or heating the air from below. Hailstorms were targeted, too, in the hope of slowing the growth of the large, damaging stones that form when cloud droplets transform into crystals. In the Soviet Union, hail-suppression researchers even fired artillery shells impregnated with silver iodide into storms.

In the U.S., the war on weather took on an even more formidable enemy: Atlantic hurricanes. Starting in 1962, the federally funded Project Stormfury tried an approach called dynamic seeding. The thought was that heavy seeding with silver iodide would release large amounts of latent heat in the inner rainbands of storms as liquid droplets were converted to ice—perhaps enough heat to destabilize the storm and blunt its winds. In addition, the military has always mused on the tantalizing possibility of weather modification as a tool of warfare. During the Vietnam War, American pilots secretly doused clouds with silver iodide over Vietnam, Laos and Cambodia, hoping to bog enemy supply lines in mud.

These attempts at weather control were not entirely in vain. The seeders learned much about clouds and rain. They failed, however, to achieve the level of certainty they needed to gain broad and lasting scientific respectability. "There have been so many experiments, and a few looked sort of encouraging," says

SIGNAL CORPS PHOTO

EARLY EXPERIMENTS: In preparation for a cloud-seeding test near Schenectady, N.Y., in 1949, soldiers crushed dry ice, the first seeding material, which was later displaced by silver iodide.

K. Ruben Gabriel, an emeritus professor of statistics at the University of Rochester. "But the sum total of 30 years of experimentation with silver iodide is that there is so little that is positive that I don't feel optimistic about it at all."

One experiment in particular—the seeding of wintertime clouds over Israel—highlights some of the gremlins that tormented virtually all attempts at rainmaking. In the early 1960s Gabriel devised the statistical design for a major series of cloud-seeding experiments conducted by the late Abraham Gagin of Hebrew University in Jerusalem. The experiment included target and control areas, randomly assigned seeding days, and other features to minimize bias and shuffle the deck enough that Gagin and his colleagues would be unlikely to mistake the effects of silver iodide with the natural wax and wane of rainfall.

The first set of experiments, dubbed Israeli I, ran from 1961 to 1967. The scientists reported a 15 percent increase in rainfall in one of the two target areas. "That experiment looked good," Gabriel recalls. "It was statistically significant, and that was just fine." To confirm these apparently successful results, the scientists undertook a second trial in 1969, focusing on the catch basin of the Sea of Galilee. Israeli II concluded in 1975. Again, the scientists reported positive results: it rained more in the northern target area when clouds were seeded.

For a time, the Israeli experiments were considered the best evidence to date for traditional silver iodide seeding. But in 1995 two atmospheric scientists from the University of Washington, Peter V. Hobbs and Arthur L. Rangno, called into question, with a lawyerly eye for detail, seemingly everything about this much-heralded project.

Not So Fast

Hobbs and Rangno argued that many of the targeted clouds were already rich in ice crystals. The clouds were most likely not the fertile fields of supercooled droplets the Israelis had assumed they were. Therefore, seeding may have affected some clouds but probably not nearly the number the Israelis thought. Hobbs and Rangno also raised doubts about the statistical evaluation of the seeding data. By analyzing regional climate patterns, they determined that the Israeli seeding coincided with greater rainfall over the whole area. Was the extra rainfall the Israelis measured because of a natural upturn or the seeding?

The debate does not end there. Daniel Rosenfeld, a former student of Gagin and currently head of the Laboratory for Cloud Physics at Hebrew University, has rebutted Hobbs and Rangno point for point. Even now Rosenfeld does not accept a word of the critique—except maybe that the Israeli clouds were rich in natural ice and therefore less seedable. "The seeding must have worked differently than what was thought a priori," Rosenfeld acknowledges. But even if the critique was not correct in all the details, the end result has challenged the faith in the Israeli results and, more generally, in silver iodide seeding.

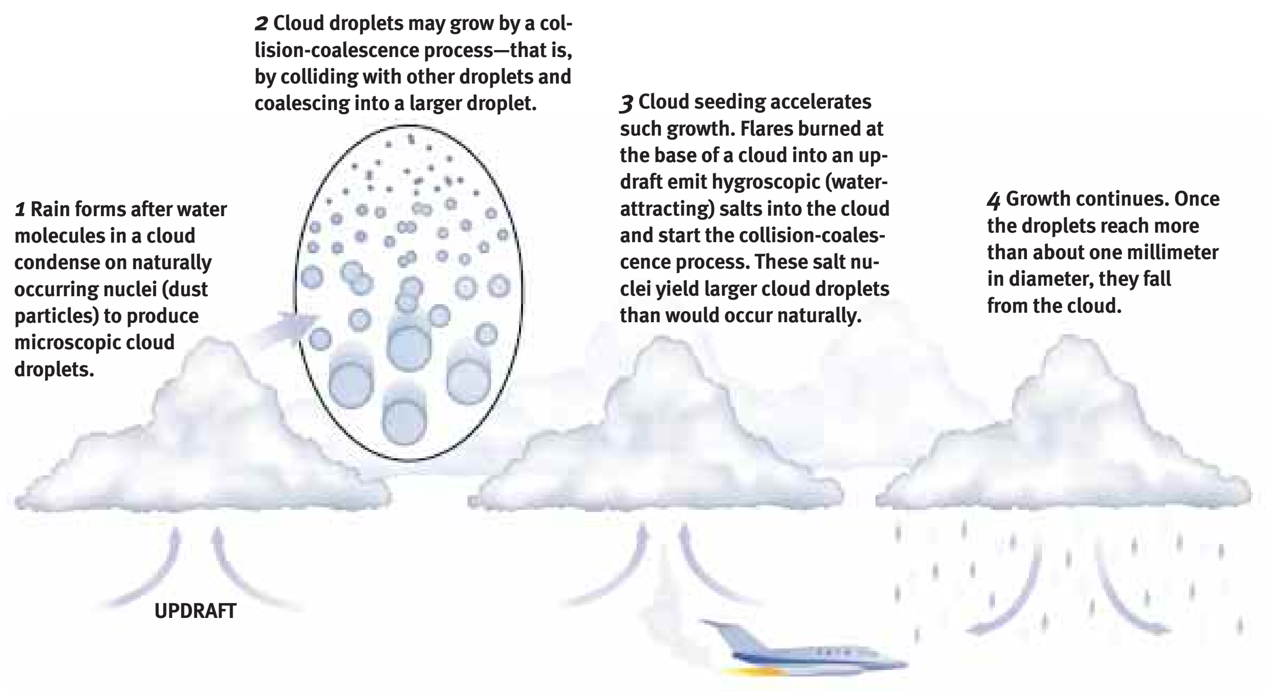
Notwithstanding past disappointments, meteorologists retain hope. The latest make-or-break test of cloud seeding is

SIGNAL CORPS PHOTO

SIGNAL CORPS PHOTO

DOES THIS WORK?: Cloud-seeding trials in the late 1940s by the U.S. Air Force and the U.S. Weather Bureau raised questions about the technique. An air force sergeant filled a hopper with dry-ice pellets for an experiment in Wilmington, Ohio, that showed seeding to be relatively ineffective (*left*). Stratus clouds seeded with dry ice in another experiment displayed a characteristic racetrack pattern (*right*).

BOOSTING RAIN BY HYGROSCOPIC CLOUD SEEDING



LAURIE GRACE

happening in Mexico. In the state of Coahuila meteorologist Roelof T. Bruintjes of the National Center for Atmospheric Research in Boulder, Colo., along with researchers from Mexican and American universities, is testing a technique for seeding warm clouds that has shown heartening results.

It could be said that the single best thing the Mexican experiment has going for it is that it does not involve silver iodide, given the material's checkered history. The technique involves warm rain clouds, where droplets do not go through a freezing phase to form precipitation. The clouds are seeded with microscopic salt particles that attract water and form larger droplets. The particles collide with still more droplets, eventually growing large enough to fall to the earth. Scientists and commercial rainmakers have for decades used this technique, hygroscopic (water-attracting) seeding, in which salt particles make water vapor condense into little droplets. In a key new development, flares that supply large quantities of salt crystals when they burn have supplanted the relatively unproductive liquid sprays of particles used in the early experiments.

The flares were first tested in South Africa in the early 1990s. The late Graeme K. Mather and his colleagues in the government-sponsored National Precipitation Research Program claimed increases in the size of particles within individual clouds of 30 to 60 percent. Bruintjes decided to see if he could back up the South African results in the most rigorous way possible. In 1996, with funding from Coahuila and a local steel mill, Bruintjes began a new round of experiments. To avoid uncertainty about whether the clouds were seedable (whether they had enough liquid in them), the first year of the program focused entirely on studying the characteristics of the clouds. The seeding itself, conducted in 1997 and 1998, was modeled after double-blind clinical trials used to test new pharmaceuticals. The researchers incorporated randomly assigned "placebo" flights: instructions from envelopes unsealed after takeoff would sometimes tell them to fly through a targeted cloud without actually lighting the flares that release the hygroscopic chemical salts in their smoke. They even hired the same pilots who had flown in the South African experiments.

After two seasons of seeding, with observations of 48 seeded clouds and 52 placebo clouds, the research team was encouraged to find that the preliminary results from Coahuila matched the South African findings. Over time, the seeded clouds appeared to be producing significantly more precipitation than the unseeded clouds were. Furthermore, Bruintjes says, it appeared to rain over a larger area and for a longer time. The Bureau of Royal Rainmaking in Thailand has just completed trials with hygroscopic seeding that also seem to back up the results from South Africa and Mexico.

Despite the promise, Bruintjes cautions that the studies have shown only that hygroscopic flare seeding makes wetter

In Mexico, researchers are testing a technique for seeding warm clouds that has shown heartening results.

THOMAS J. HENDERSON *Atmospherics*

A FLARE FOR RAIN: Weather modification company Atmospherics uses hygroscopic seeding to increase precipitation over a reservoir near Fresno, Calif. Flares emit microscopic salt particles onto which water vapor condenses into droplets.

clouds, not that it necessarily produces more rain for crops and drinking. In Mexico and South Africa the effect of seeding was not measured as rainfall on the ground but as radar reflections. Stronger reflections off a seeded cloud mean that the cloud contains more precipitation—near the base of the cloud. So what does that mean in terms of more raindrops falling on our heads? The only direct test of rainfall enhancement is the amount of water that actually reaches the ground. Bruintjes says that the Coahuila seeding did involve a network of gauges, which he hopes to use to calibrate the radar measurements of rain volume.

If hygroscopic seeding proves itself, the story is not over. Even if more rain falls from a given cloud, "the next logical question is whether you really increase rainfall over an area," Bruintjes comments. "Is this a worthwhile alternative, or should we build more reservoirs? Should we build a desalinization plant?" In the Mexican state of Durango, where the project has relocated, researchers want to observe a watershed to determine if increases in precipitation in the clouds can be linked to increases in the water supply. "If we can show that it doesn't work, that will still be a tremendous result," Bruintjes remarks. "Then I know I've gone through all the necessary steps, and people wouldn't be wasting their money on this."

Deploy the Thunderheads

Assuming that warm-cloud seeding bucks the 50-year trend in weather modification research—promising results followed by dashed expectations—it would seem that the prospects for weather control in the 21st century have begun to improve. Even some in the military have had a rapprochement with weather control, despite a 1976 United Nations agreement against the hostile use of "environmental modification," in part a response to the military seeding in Vietnam. In a 1996 report, "Weather as a Force Multiplier: Owning the Weather in 2025," the projected scenarios for weather warfare included unmanned cloud-seeding planes that would loose thunderstorms on enemies or throw a "cirrus shield" of cloud cover over friendly forces.

Yet the apparent optimism does not guarantee public acceptance of rainmaking, even among the farmers who would most stand to gain. Cloud seeders have at times found themselves at odds with farmers. Often the disputes have involved accusations that seeding in one area robs moisture from adjacent fields—an atmospheric variation on robbing Peter to pay Paul. In northwestern Kansas, some are now questioning the wisdom of fiddling with natural forces for human benefit.

A group of farmers in Rawlins County, Kansas, has formed Citizens for Natural Weather to speak out against a regional hail-suppression program. The opponents of the program, based on their own anecdotal observations, believe the seeding has robbed them of rain. "If we miss out on an inch of rain, the impact of that in a dryland county is phenomenal," says Keith Downing, a dryland farmer in Colby, Kan., who heads the group. "We do not want to take the risk of that." In July 1999 citizens in the county voted nearly 4–1 to ditch the seeding program. "Nobody can prove anything about this," Downing notes. "It's not scientific. It's strictly experimental, particularly on the rainfall end of it." Ironically, the same uncertainty that has allowed commercial cloud seeders to operate despite the absence of sound scientific backing is coming back to dog them.

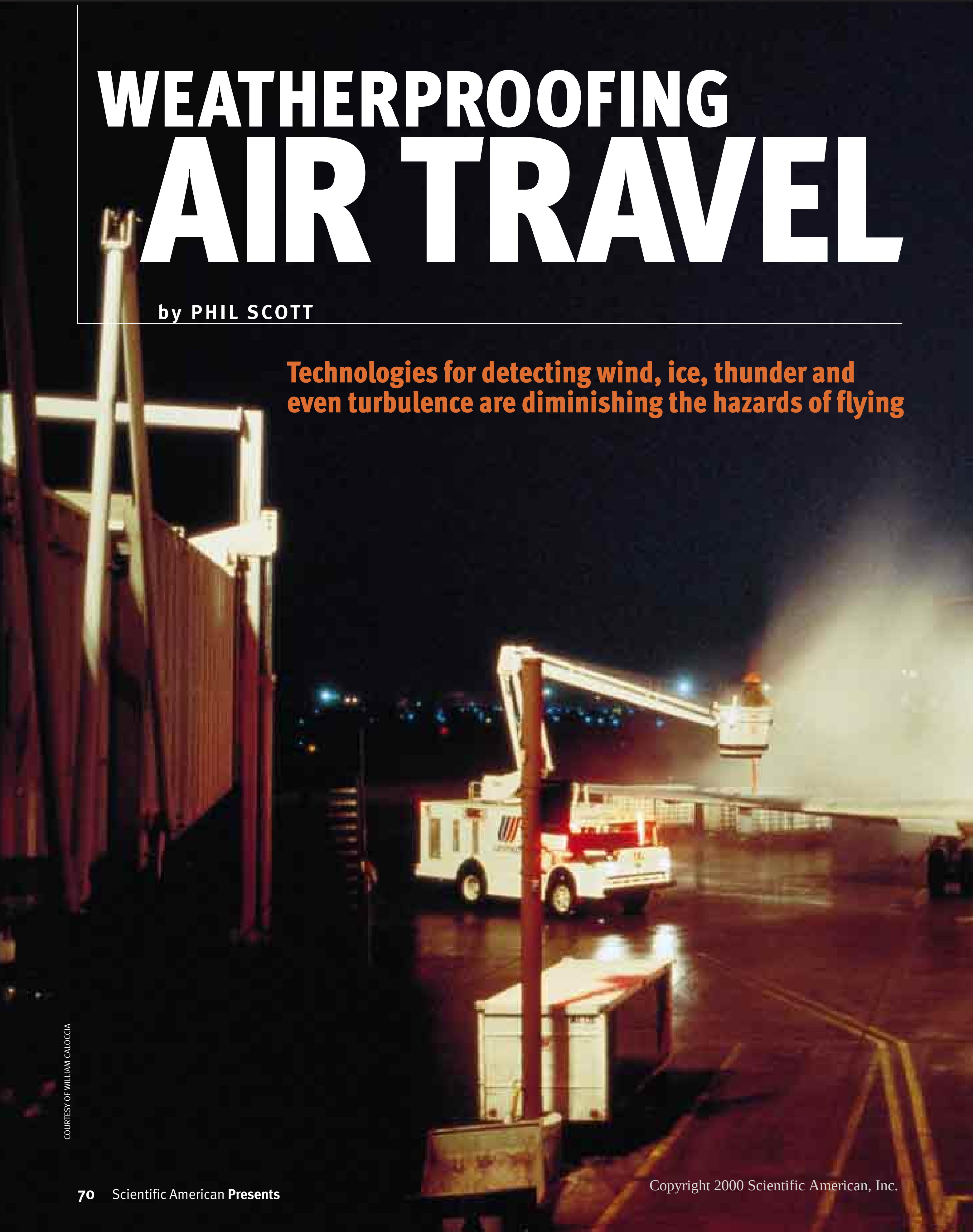
Downing has also raised a more fundamental objection to cloud seeding. Kansas's Groundwater District No. 4, which includes his property, is supposed to manage the aquifer, he remarks, not create one. "They are spending way too much time on cloud seeding and not enough time on managing the depletion of the groundwater," he says. Downing would like the seeders to hang up their silver iodide burners and water managers to adopt a policy of zero depletion, allocating as much water to farmers as possible yet maintaining the water table at current levels. "I'd just as soon let Mother Nature take care of the weather," he urges. Even if Downing's view becomes the consensus, the age-old dream of human control of the forces of nature will probably never die. But the underlying science has failed to move the technology far enough beyond its shamanistic origins to quell the skepticism that still surrounds the rainmaker's art. W

DANIEL PENDICK is a freelance writer living in Brooklyn, N.Y. He was formerly an editor at *Earth* magazine.

WEATHERPROOFING AIR TRAVEL

by PHIL SCOTT

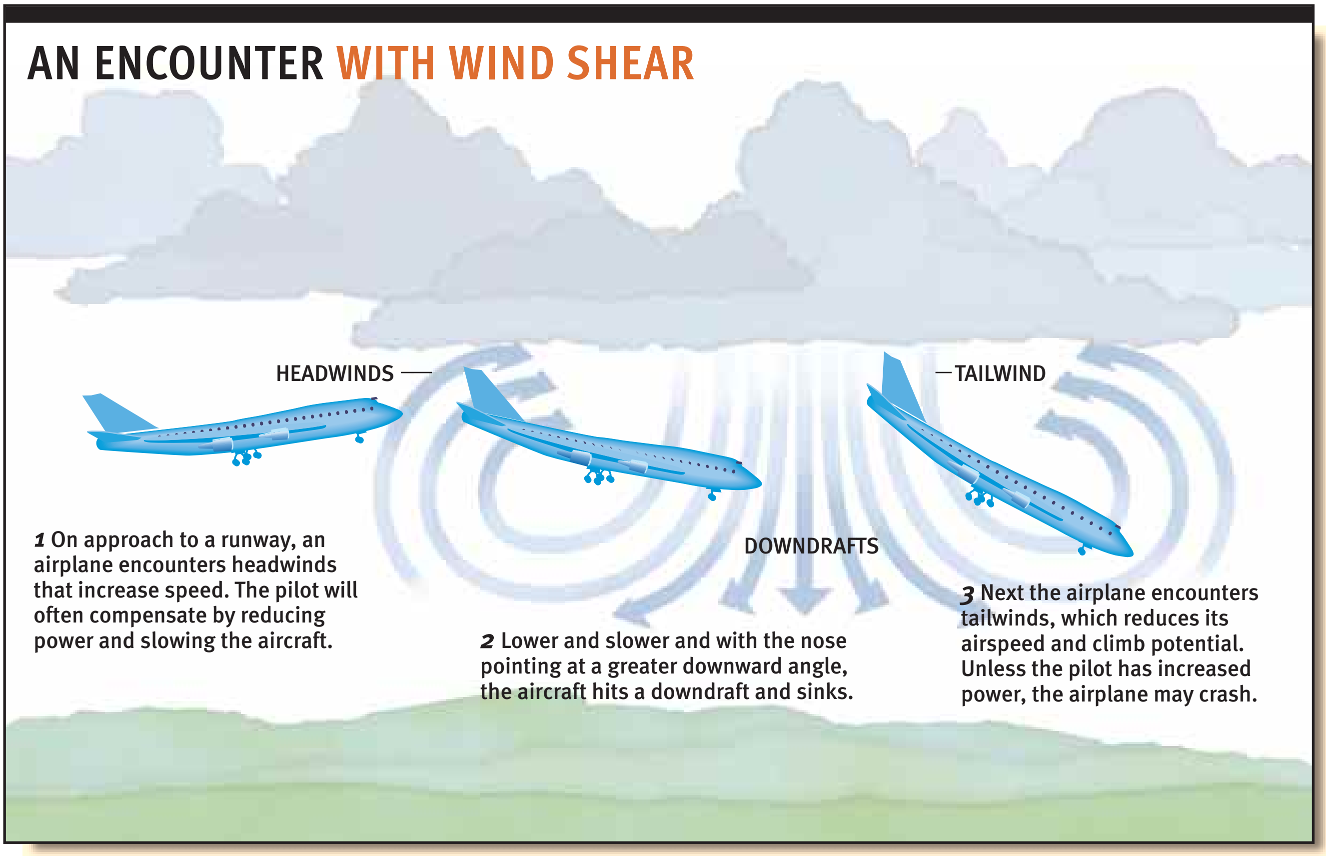
Technologies for detecting wind, ice, thunder and even turbulence are diminishing the hazards of flying



COURTESY OF WILLIAM CALOCCIA

The modern commercial airliner is a symbol of sleek modernity, an emblem of our success in conquering the elements. Yet few commonplace human endeavors place people so thoroughly at the mercy of nature quite like aviation does. In fact, 26 percent of commercial airline accidents and almost 20 percent of all general aviation—small aircraft—accidents list weather as a contributing factor. Weather also helps lead to flight delays and wreaks unexpected havoc with the hub-and-spoke system, which flies travelers into a central

RITE OF WINTER: Deicing with a solution of antifreeze prevents ice accretion that can change the shape of the wing and rob the aircraft of the necessary aerodynamic lift on takeoff.



LAURIE GRACE

port to change planes. A storm in Atlanta can delay flights out of San Francisco. And with air traffic scheduled to increase by nearly 50 percent over the next decade, smooth flow of flights will rely on weather and modern forecasting.

In aviation, however, an unfortunate, oft-cited aphorism preaches that it takes a major accident to spur the government to improve the system. "It's called tombstone technology," explains John McCarthy, a meteorologist at the National Center for Atmospheric Research (NCAR) in Boulder, Colo. NCAR works with the Federal Aviation Administration (FAA), the National Weather Service (NWS), research universities and private enterprise to push aviation weather forecasting to new limits. And over the past three decades McCarthy has often been in the middle of such efforts. "We have an old maxim in the aviation weather business that weather is not a big problem until it is a big problem," he adds.

Numerous accidents have demonstrated how existing technology—which provides nationwide forecasts around the clock—needs improvement. Pilots confronted by severe weather up ahead might make better decisions if they knew what was likely to happen during the next half an hour. Traditional forecasting predicts up to 36 hours ahead, but greater accuracy is required over short spans of an hour or less. To provide nearly immediate weather information, the FAA and government and university researchers are developing "nowcasting" techniques that can predict whether a thunderstorm is likely within the next 30 minutes. Called the Integrated Terminal Weather System (ITWS), it uses information from GOES weather satellites, NEXRAD radar and NWS computer model data to make its predictions.

Four prototypes are up and running, and the first production version will be available to air traffic controllers in 2001 or 2002. Simultaneously, another research team is working on enhancing the ITWS by extending the prediction out to one hour. "One hour turns out to be a very big deal," says Dave Sankey, the FAA's program manager for aviation weather research. "The software taking it out to 30 minutes or so does a fairly good job, but beyond that you have to have a model to account for the decay and growth of thunderstorm cells. And cells have a lifetime of only about an hour."

Isolating a Killer

Optimism about the benefits of the newest weather-related research stems in part from researchers' track record in alleviating wind shear. Wind shear was still a problem on August 2, 1985, when a Delta Air Lines L-1011 on final approach to the Dallas/Fort Worth International Airport began behaving as though it were possessed by some supernatural evil: the fully loaded airliner began rising suddenly, forcing the pilot to pull back on the power and lower the plane's nose in order to return to the approach path to the runway. Then, just as suddenly, a huge blast of wind from above slammed the jet toward the ground. With its power settings too low and without enough time for the engines to spool up, the plane struggled in vain to stay aloft. It clipped two cars on a highway, killing a driver, then crashed into a field short of the runway. All 137 people on board perished.

Amid a tremendous public outcry, the government began an intensive search to isolate the killer. McCarthy, a pilot as well as a meteorologist, was one of the scientists drafted for the effort. He and his NCAR colleagues began by building on the research of legendary storm investigator T. Theodore Fujita, a.k.a. "Mr. Tornado." Fujita, while inspecting damage from a superoutbreak of tornadoes in 1974, had stumbled on a curious pattern: instead of flying around in a swirl, trees and plants had been blown outward from a central point, as if flattened by an explosive blast. Then, the next year, Eastern Flight 66 crashed mysteriously at New York's John F. Kennedy International Airport, and Fujita suspected that the two incidents had had similar causes, which he called downbursts. Although the idea of such a weather phenomenon was controversial at the time, two research projects were funded to detect and study downbursts.

In one, set up at Denver's Stapleton International Airport in 1982, researchers theorized that they could use Doppler radar to log perhaps an instance or two of this seemingly rare phenomenon. They got more than they could ever hope for. "We found that we could detect microbursts [the name that replaced downbursts] unambiguously with Doppler," McCarthy recalls. Over the test's 86-day duration, they logged 186 of them.

The NCAR team went to work developing the technology to warn pilots and controllers of microbursts. In its first real-world test, at Denver Stapleton, on July 11, 1988, the Doppler system detected an 80-knot microburst; air traffic controllers waved off five airliners while it lasted. "All of them believed the system saved their bacon," McCarthy says. As a result, 47 Terminal Doppler Weather Radars have been ordered for at-risk airports across the nation; today all but two, one for New York and one for Chicago, are up and operating. The effort didn't stop there: the FAA ordered the airlines to install cockpit wind-shear detectors by 1993. The earliest was the so-called passive-warning system, which analyzed an aircraft's vertical and forward speed and its power settings and would audibly warn crews of wind shear. The latest wind-shear alert systems being integrated into all new airliners use a forward-looking microwave Doppler channel tied to existing onboard weather radar; they show microbursts in the aircraft's path.

The NCAR team also helped to establish a microburst training program now required for commercial pilots. The scenarios in the simulator program that teach pilots how to fly through wind shear were developed from the flight data recorders taken from the accident at the Dallas/Fort Worth airport. "In the mid-1980s low-altitude wind shear was the largest cause of aircraft accidents," McCarthy says. "In the U.S. now, it's a rare event, but 10 or 15 years ago that was all we talked about."

Ice on the Wing

The problem of ice formation on aircraft wings now occupies researchers' attention the way wind shear once did. "We're a reactionary agency," Sankey says. "The joke here has been that icing is the number-one thing—until an aircraft crash occurs because of something else."

The best-known recent icing accident occurred near Roselawn, Ind., in the autumn of 1994: busy controllers at Chicago's O'Hare International Airport directed an inbound American Eagle ATR-72 turboprop to fly holding patterns in freezing rain for more than an hour. With its wings iced over—ice deforms the wing into a shape that robs an aircraft of necessary lift—the commuter plane nosed over and crashed into a field, killing all 68 on board. "Up to then, icing accidents had been in small airplanes with one to three people killed," says Marcia Politovich, an NCAR project scientist. "Prior to Roselawn, icing

CHARLES BENNETT *AP Photo*

FATAL DELAY: Investigators inspect the remains of an American Eagle ATR-72 that crashed when its wings iced over while it was flying in a holding pattern, waiting to land at Chicago's O'Hare International Airport. All 68 passengers aboard the aircraft died in the crash.

studies had been backburnered; such a rare event was not high on the priority list, but it got moved up to priority in a big hurry."

In the past, pilots had no way to anticipate icing. Only after they saw ice begin to form on the wing did they activate various heaters on the windscreen, propellers, wings and control surfaces. But Politovich and her colleagues at NCAR have focused their efforts toward predicting the conditions that lead to icing. To find out more about how and where such conditions occur, researchers repeatedly fly a heavily instrumented de Havilland Otter, a twin-engine commuter airplane, into cold clouds and see how much ice they can pick up. Such flights have helped NCAR create the Integrated Icing Diagnostic Algorithm, which combines ground-based radar and satellite data to paint a three-dimensional grid that indicates where icing is present, information that is then fed to pilots. Today, Politovich says, it's a fairly well developed product, used by several of the airlines as well as missions flown by atmospheric researchers.

And the National Aeronautics and Space Administration, along with NCAR, is trying to put in place onboard sensors to help warn pilots that they could be flying into ice-producing clouds. Although no one is exactly sure what form the instrument should be—radar, radiometer or laser—it will send a signal in front of the aircraft that will aid the instrument's sensors in measuring the moisture and temperature of the clouds ahead. If the levels are within the known range found in supercooled droplets that freeze when they make contact with aircraft surfaces, the pilot will be able to decide to activate the plane's deicing equipment or to plan the best path through the weather system.

Icing also takes place on the ground, and one accident underscored the necessity of better understanding the effects of earthbound freezing moisture: Air Florida Flight 90 departed from Washington, D.C.'s National Airport on January 13, 1982, during a snowstorm and immediately struggled to stay airborne. The Boeing 737 struck a bridge and plunged into the freezing currents of the Potomac River. Only five out of 79 on board the jet survived to be plucked from the icy water; four motorists were killed on the bridge. The National Transportation Safety Board investigation revealed that although ground crews had sprayed the aircraft with antifreeze, the 737 had remained on the ground 50 minutes after the treatment, too long for it to remain effective.

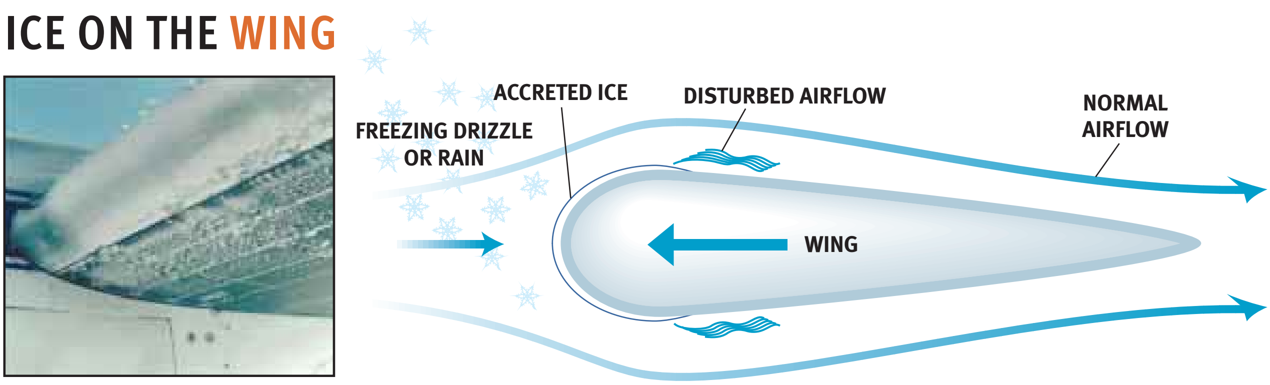
As a result of Air Florida's and subsequent icing-related accidents, the FAA and NCAR have funded the development of a system called Weather Support to Deicing Decision Making, also known as WSDDM. Using NWS and FAA Doppler radar data and a network of snow gauges and observation data, WSDDM lets airport operators know how much snow has fallen, how much is going to fall and its liquid content. "It can predict 30 minutes ahead of time what the intensity of the snowfall is going to be," Sankey says. With that kind of knowledge, ground crews can spray aircraft with the best, most economical antifreeze solution for its takeoff conditions.

Bump Detectors

Perhaps it's an indication of how much progress scientists and researchers have made in such traditionally deadly areas as wind shear and storm detection—or perhaps it's a sign that the hidebound FAA is trying to better anticipate problems—but today much energy is being focused on detecting upper-air turbulence. "It's rarely a killer, but it does kill," McCarthy explains. And it's the leading cause of injuries in the air. From 1981 through December 1997, major air carriers reported that turbulence caused 769 minor injuries, 80 serious injuries and three deaths. Every year an average of 58 people are hurt—50 percent of them flight attendants—costing the airlines $100 million. But there's also a significant psychological factor. "Turbulence is the largest cause for fear of flying in the U.S.," McCarthy adds. "People don't seem to be afraid of a catastrophic event, but they get upset when the ride gets exceedingly rough. It's a distressing environment."

Until recently, reporting turbulence has been up to the discretion of pilots flying en route, and thus gathering data can be spotty and tenuous. "For turbulence, the main thing we rely on

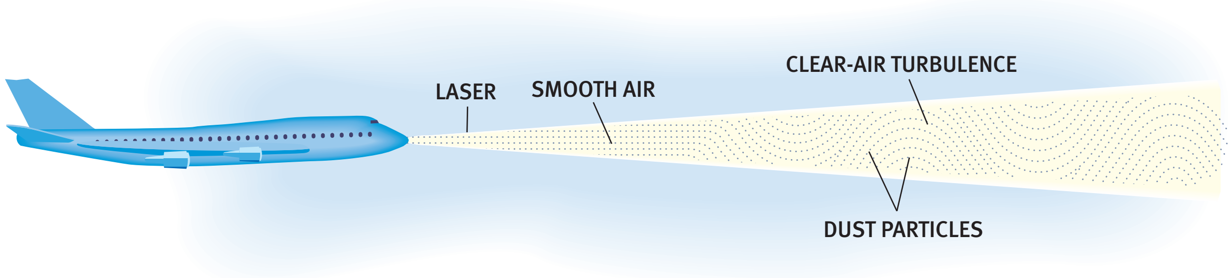
ICE ON THE WING



NASA GLENN RESEARCH CENTER (*photograph*); LAURIE GRACE

Freezing rain or drizzle can lead to ice buildup on the wings, which can disturb the air flowing over their surface and can sometimes affect the ability of the pilot to fly the aircraft. Onboard sensors may eventually warn pilots of ice-producing clouds.

DETECTING CLEAR-AIR TURBULENCE



A sensor on board an aircraft detects unseen turbulence by measuring the shift in frequency of laser light transmitted from the nose of the airplane and scattered by dust particles in the agitated air ahead. The frequency of light reflected back to the airplane is compared with that of light transmitted to determine whether turbulence is present, so that the pilot can warn passengers.

LAURIE GRACE

are pilot reports from commercial and general aviation aircraft," says James H. Henderson, deputy director of the NWS's Aviation Weather Center in Kansas City, Mo. "But it's a subjective thing and aircraft dependent. 'Severe turbulence' for a pilot flying a four-seat Cessna may be 'light turbulence' to a Boeing 737."

By October 2000, some 200 Boeing aircraft will be equipped with software that uses deviations from expected flight characteristics (such as pitch, roll and yaw) to detect turbulence and report it to air traffic controllers on the ground. Such remote sensing feeds data to NWS computer models whose output provides guidance to other planes.

In addition, NASA is looking at developing an onboard sensor that will warn the pilot of turbulence up ahead. Detecting thunderstorm-generated turbulence is fairly easy: beefing up current onboard weather radar with new software and enhanced processing technology allows it to detect foul-weather turbulence. But clear-air turbulence, which has no moisture off which a radar signal can be reflected, presents a stickier problem. So NASA is experimenting with LIDAR, or Light Detection and Ranging. In it, a laser beam bounces off dust particles in the clear air and measures the scattering of the air. Onboard processors analyze the return for signs of roiling currents in its path. Thus far the results are promising. "Now we're looking at how to get more range out it," says Bruce Carmichael, NCAR's manager for FAA and NASA programs. "Instead of a one-minute warning, we want to get several minutes. We want to be able to give enough warning for the pilot to do something: get the passengers seated and belted and the drink carts tied down."

The Skyway Ahead

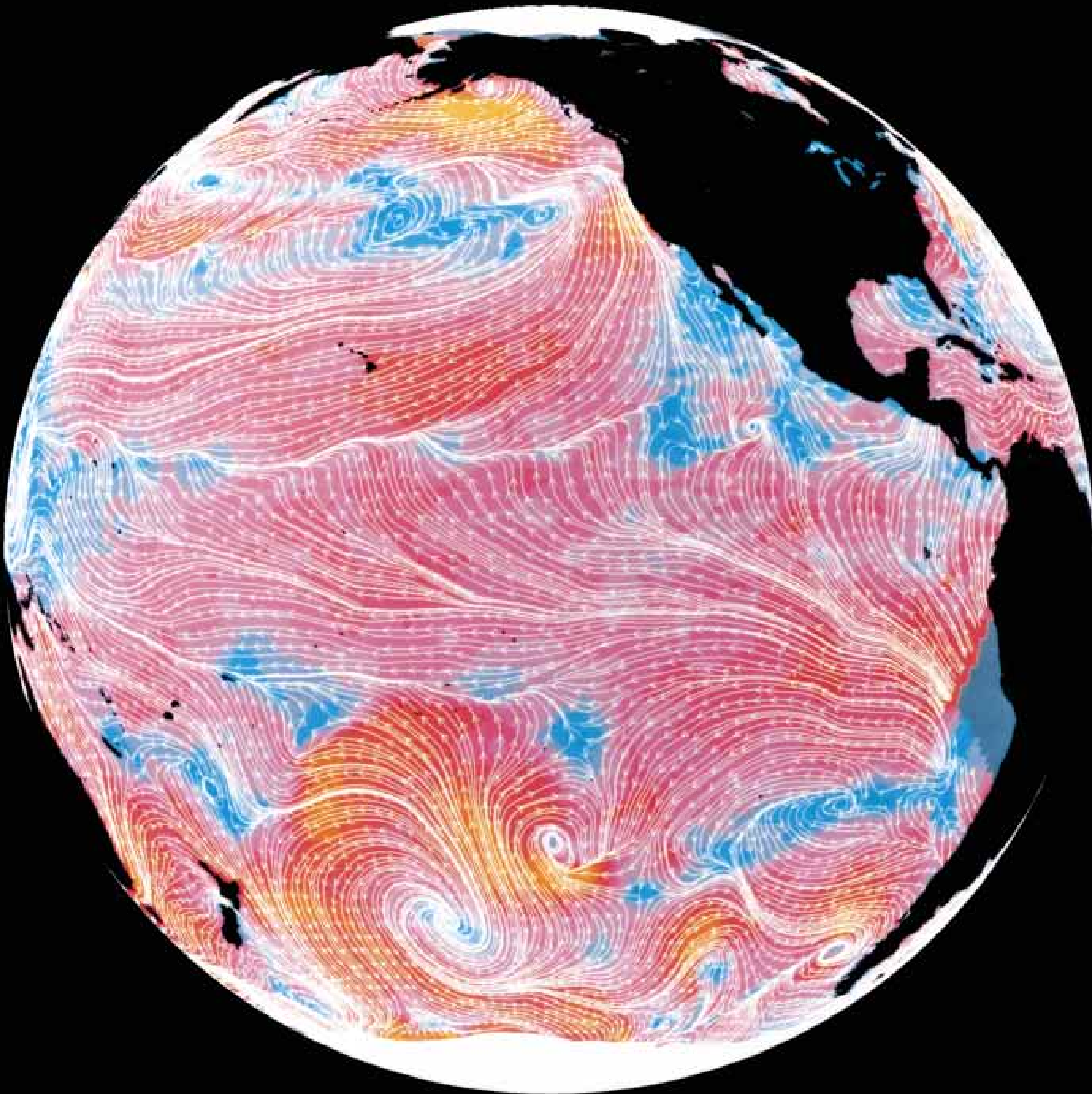
While investigators were laboring to give travelers a smoother ride, the FAA received a mandate last summer from its administrator, Jane F. Garvey, to get more weather information into all cockpits. "In fact, an airline passenger equipped with a satellite digital cell phone and a laptop computer with a modem can receive real-time weather data that the crew flying the airplane cannot receive in the cockpit," testified Capt. Paul McCarthy last July to the House Aviation Subcommittee of the Transportation and Infrastructure Committee. McCarthy is executive air safety chairman of the Air Line Pilots Association International.

Airline pilots get their weather briefings while they file their flight plans at the airport, whereas general aviation pilots who are not flying solely by reference to instruments are responsible for familiarizing themselves with the level of information appropriate to their flight. In the air they can radio a service called FlightWatch for further updates.

To bring more advanced technology to small, private airplanes (which have been technologically stagnant in recent years), NASA, in concert with avionics manufacturers, formed a project in 1994 called AGATE, for Advanced General Aviation Transport Experiments. Part of it, Flight Information Services-Broadcast, or FIS-B, is a system that broadcasts—on aviation VHF bands—weather information directly to a display system in the cockpit. In the most basic version, that information comes across in the ancient alphanumeric teletype code that all pilots still learn in primary ground school. For a subscriber fee, however, the broadcast can include a weather radar overlay on a moving map display. "Flying along, the pilot will be able to see where the weather is," says Scott C. Asbury, AGATE project engineer at the NASA Langley Research Center in Hampton, Va. A similar project directed toward commercial carriers is also under way there.

But cooler heads warn against overloading the pilot with information, cautioning against adding yet another warning device to the overcrowded instrument panel of the modern airliner. "Pilots need a lot of weather information, but the information needs to be well integrated," Capt. McCarthy says. "If you've got all hell breaking loose in the cockpit, with all these bells and bonks and gongs going off, it doesn't mean you did the job right." In other words, if all that the new weather technology does is add more stress to the pilot's job, then the solution could well be worse than the problem. W

PHIL SCOTT is a freelance writer who lives in New York City. His most recent book is *The Pioneers of Flight: A Documentary History* (Princeton University Press, 1999).



BEYOND El Niño

El Niño is not the only oceanic and atmospheric event that profoundly affects climate. Several other seesawing conditions have also been uncovered

by LAURENCE LIPPSETT

Long before anyone ever heard of the Pacific warming called El Niño, a guy named Joseph demonstrated the enormous value of a reliable climate forecast. His discovery wasn't published in a scientific journal but rather in a book called Genesis.

The pharaoh of Egypt had a disturbing dream: seven cows, sleek and fat, emerged from the Nile River. Seven gaunt and thin cows followed and ate the fat ones. Joseph interpreted the dream, warning that Egypt would have seven years of plenty followed by seven years of famine. He urged the pharaoh to take advantage of the good years to store surplus grain. So it was done. After seven years of bumper crops throughout the region, "there was famine in all lands; but in all the land of Egypt there was bread."

All human endeavor hinges on the vicissitudes of climate, and it is deep within the human race to defend itself against nature and to seek some sign, divine or otherwise, of next season's weather. Sacrifices to the rain gods notwithstanding, until recently climate forecasting hadn't advanced much in the millennia since Joseph's time. Only 17 years ago one of this century's most powerful El Niños took us completely by surprise.

In 1982 scientific experts had come to a consensus that no El Niño was forming, even as waters in the eastern tropical Pacific Ocean near Peru were already heating with inevitable and catastrophic momentum. It sparked a host of climate changes: devastating droughts and fires in Australia, flooding in normally arid regions of Peru and Ecuador, unusual storms that rearranged California beaches, and widespread mortality of fish and birds. All told, the El Niño that wasn't going to happen led to thousands of deaths and an estimated $13 billion in damage.

But from the ashes of that El Niño, which persisted from the winter of 1982 into the spring of 1983, emerged a scientific breakthrough. Caught off guard, scientists renewed efforts to figure out the riddle of El Niño. They began to see how the ocean and atmosphere are intimately linked in an oscillating rhythm. Like two people going up and down on each side of a seesaw, the ocean and atmosphere continuously shift in response to each other. The two never achieve equilibrium; one side of the seesaw is either up or down. Each "position" creates its own distinct set of climate conditions. The rhythm is complex—but it isn't random. If you could decipher it, you could anticipate

NASA

WIND EVERYWHERE: Arrows indicate wind direction at the surface of the Pacific Ocean as detected by a satellite on a single day; colors denote speed, which rises as the underlying colors shift from blue to pink, orange and yellow. Swirls reflect storms. Scientists are learning that the atmosphere and the oceans continuously interact to generate recurring patterns that influence weather and climate around the globe.

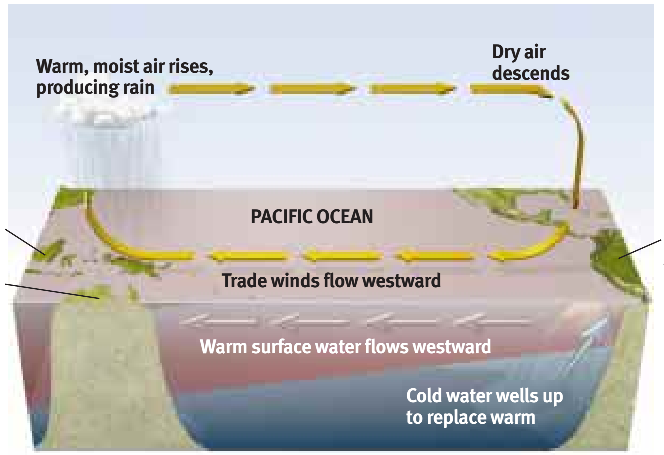
where the climate was headed. At a breathtaking pace, researchers did just that, predicting the next El Niño: 1986–87.

"That marked the beginning of the modern era of climate forecasting," says Nathan J. Mantua, a scientist at the University of Washington. Initial success with El Niño has inspired a feverish search for other oscillations. And sure enough, amid the apparent cacophony of Earth's ever-changing climate, more patterns are materializing. Shifting over months or decades, these newly identified patterns may spawn different climate changes in different parts of the globe.

"People in the field realized that El Niño was just the loudest and most obvious oscillation," Mantua says. Persuaded that the oceans help to regulate our climate in quasiperiodic but potentially predictable ways, scientists around the world are mobilizing to deploy a global network of instruments—including a flotilla of several thousand buoys—that can monitor oceanic conditions. Much the way networks of land-based meteorological observatories track atmospheric conditions to give us five-day forecasts, this ocean-based array promises to give us Joseph-like warnings that next winter may be colder and snowier than usual, that next year's hurricane season may be fierce, that we should look for fish in this part of the ocean and prepare for disease outbreaks in that part of the world or that rains will not return in the spring to water our crops.

THE EL NIÑO/SOUTHERN OSCILLATION

NORMAL CONDITION



Oceanic and atmospheric conditions in the equatorial Pacific generally flip-flop between two states: a normal condition (*left*) and an El Niño condition (*center*), which brings extra rain to parts of South

DAVID FIERSTEIN

The Search for Patterns

The annual monsoon rains that farmers in India depended on never came in 1877 and 1899, each time resulting in devastating famine. In 1904 Gilbert Walker was charged with finding a way to predict the monsoon fluctuations that made life in India such a lottery. In his 30-year quest, he collected and analyzed meteorological observations from stations all over the globe. He found that the air pressure at sea level in the Pacific seesawed up and down across a region ranging from Australia to South America. Most notably, when it was high in Darwin, Australia, in the western Pacific, and low in Tahiti, in the central Pacific, there was heavy rain in the central equatorial Pacific, drought in India, a warm winter in southwestern Canada and a cold one in the southeastern U.S. Every few years the air pressures in Darwin and Tahiti reversed, and so did climate conditions in various regions in the world.

Walker called this atmospheric pattern the Southern Oscillation, but critics derided his theory, doubting that such far-flung climate changes could be linked. It didn't help that Walker had no scientific explanation for his pattern. Despite his zealous data gathering, he took no account of the ocean and made no connection with El Niño, which had been documented as early as the 16th century.

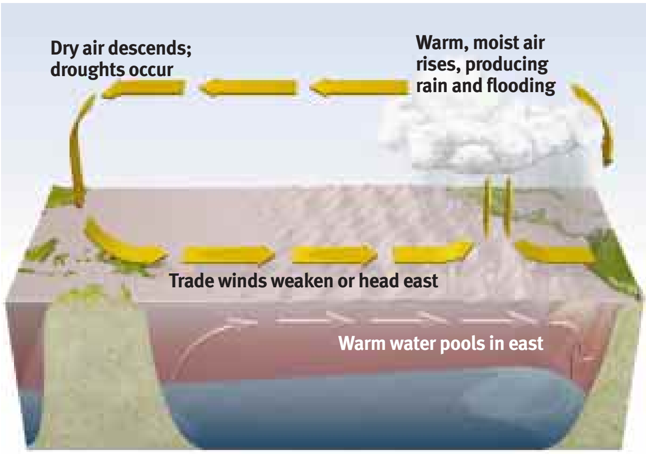
Originally, the term "El Niño" referred specifically to a warming of coastal waters off Ecuador and Peru that arrived around Christmas—the celebration of El Niño, the Christ child. In most years the warming was mild and benign, but then as now, occasionally severe warmings led to heavy rains, catastrophic flooding and the disappearance of fish from local waters.

It was not until the 1960s that anyone realized El Niño and the Southern Oscillation were related. (Today they are collectively referred to as the El Niño/Southern Oscillation, or ENSO.) Using measurements of the atmosphere and the tropical Pacific gathered during 1957–58, Jacob Bjerknes of the University of California at Los Angeles discovered that El Niño warming of sea-surface temperatures was not confined to the western coast of South America but extended thousands of miles into the central Pacific. Moreover, it was accompanied by all the atmospheric changes observed in Walker's Southern Oscillation.

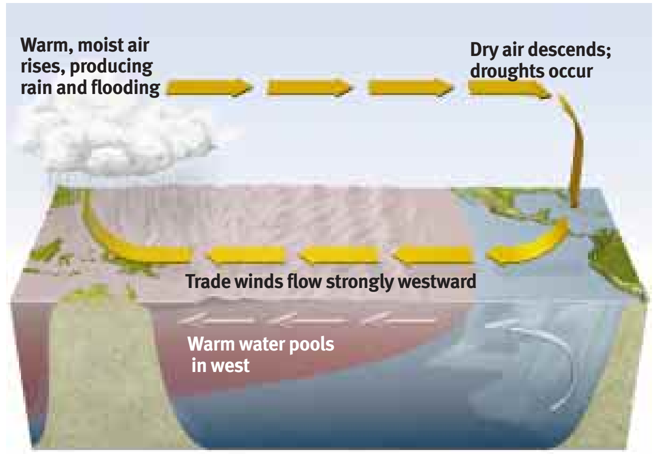
In non–El Niño years, Bjerknes noticed, sea-surface temperatures in the eastern, South American end of the Pacific are remarkably cold for such a sun-drenched equatorial region and contrast sharply with the great warmth in the western Pacific. Nature moves to even out the temperature gradient. In the west, the ocean heats the air above it. The heated air rises and draws in beneath it cooler and denser air that flows along the sea surface from the cooler eastern Pacific. These are the trade winds. (The readily evaporating waters in the west also supply moisture to the air, yielding rainfall.) Bjerknes called this equatorial circulation system—generated by the temperature and air-pressure gradients between the eastern and western Pacific—the Walker Circulation.

At the same time, Bjerknes said, the prevailing trade winds drive tropical Pacific

EL NIÑO CONDITION



LA NIÑA CONDITION



America and dry conditions to Indonesia and Australia. Sometimes, instead of returning to normal after an El Niño, the eastern Pacific cools excessively, signaling the onset of La Niña (*right*), which is accompanied by excessive rain in the west and abnormally dry conditions in the east. The shifting conditions in the Pacific also affect weather elsewhere in the world.

waters westward as well as northward and southward toward Earth's two poles. To replace those departing waters, deeper (and colder) waters upwell in the eastern Pacific. These cold, nutrient-rich waters not only allow fish to thrive, they also reinforce the east-west temperature gradient, keeping the winds blowing westward and warm waters pooled in the west.

But this air-sea interaction could flip-flop, as it does in El Niño years. If the trade winds diminished, warm waters could migrate eastward, reducing the east-west temperature gradient, which would reduce the trade winds further, and so on in a chain reaction.

Thus, Bjerknes married the circulation of the ocean and the atmosphere together in a continuous feedback loop with two alternative modes. Every few years, for reasons Bjerknes didn't figure out, the loop reverses. Warm surface waters that usually pool in the western Pacific expand dramatically throughout the tropical Pacific until they gird a quarter of Earth's circumference. Rain clouds that accompany the warm waters migrate eastward, taking rain from places where it is expected and dropping it unexpectedly in other areas. Prevailing trade winds diminish, thus rearranging global atmospheric circulation patterns and worldwide weather.

On average, an El Niño occurs about every four years, but the cycle is irregular. Sometimes there are only two years between events, sometimes almost a decade. In the early 1990s an El Niño seemed to last two years. The intensity of the events and their climatic effects vary considerably. Sometimes, in an El Niño's wake, eastern Pacific waters not only return to a cool state but also become unusually cold—a condition called La Niña, which packs its own climatic repercussions.

Only in the past decade have researchers gotten a tentative handle on why the system flips back and forth. The upper few hundred feet of the ocean stores 1,000 times more of the sun's heat than the atmosphere does. Huge masses of heat-storing water move through the depths at their own sluggish pace, uninfluenced by the much faster-moving interactions described by Bjerknes that transfer heat near the surface. The two heat-transferring processes are perpetually out of sync—continuously seeking but never achieving equilibrium.

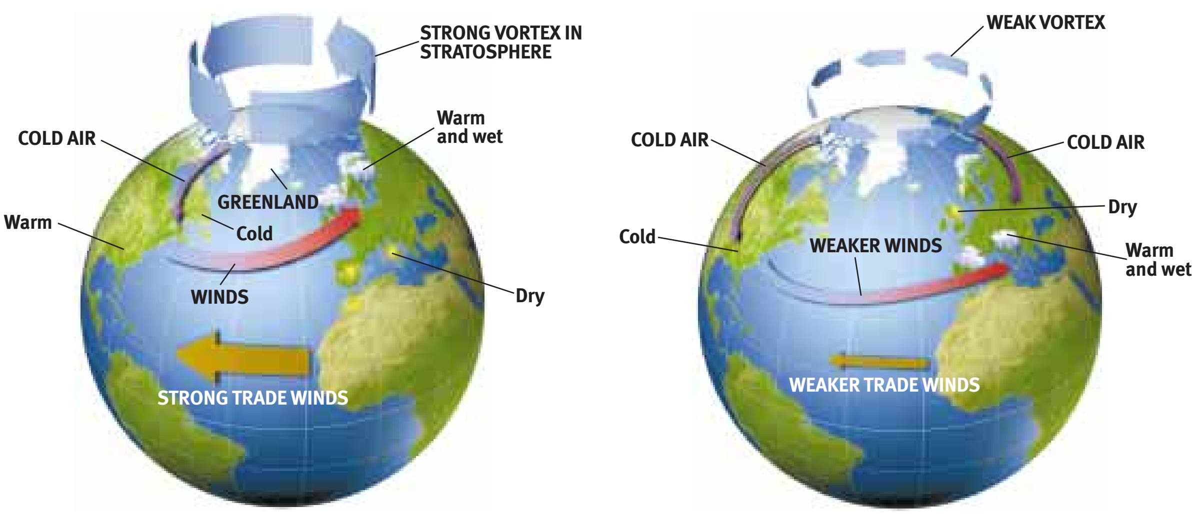
In the atmosphere, even a small change in wind direction, air pressure or temperature could launch an unpredictable sequence of events that would doom reliable weather forecasts beyond two weeks. But the oceans transfer heat around the globe in less ephemeral pulses, setting the stage to make one kind of climate condition more or less likely than another. By about 10 years ago the search was on for other oscillations—perhaps driven by many of the same air-sea dynamics that had been uncovered by studying ENSO. Scientists have only begun to explore the mechanisms driving these newly recognized oscillations. "The science right now is more like our understanding of El Niño 15 to 20 years ago," Mantua says.

The North Atlantic Oscillation

Early in the 1990s investigators revisited with a vengeance another climate pattern first identified decades ago by Walker: the North Atlantic Oscillation (NAO). Like ENSO, the NAO flip-flops between two modes, but unlike ENSO, its defining signals are primarily atmospheric.

In the "positive" mode, a huge low-pressure system sits over Iceland, circulating winds counterclockwise around it. A high-pressure system with clockwise-circulating winds lodges near the Azores off Portugal. Like interconnecting gears, the two systems steer strong winds through

THE ARCTIC OSCILLATION



STRONG VORTEX CONDITION

WEAK VORTEX CONDITION

The Arctic Oscillation is a shift between two patterns of wind flow. In one state (*left*), a strong stratospheric vortex swirls over the North Pole, increasing the flow of surface winds across the Atlantic. The winds warm as they cross the ocean to Scandinavia and Siberia, which become warmer and wetter. When the vortex weakens (*right*), cold air seeps out across the northern lands. Meanwhile the winds originating over North America take a more southern track over the ocean, bringing some warmth and wetness to the Mediterranean.

DAVID FIERSTEIN; SOURCE: DAVID THOMPSON AND JOHN M. WALLACE *University of Washington* AND FRITZ HEIDE AND JACK COOK *Woods Hole Oceanographic Institution*

the lane where they intersect—eastward across the North Atlantic toward Europe. In winter, when northern air temperatures go down, the air-pressure contrast between the two systems increases, creating stronger winds. The winds bring polar air down through the eastern U.S. and Canada, making winters colder on average there, but then they pick up heat and moisture from ocean waters warmed by the Gulf Stream, making European winters wetter and milder.

When the NAO flips into its "negative" mode, the low-pressure system moves down over the Azores. The warm, moisture-laden winds are diverted southward, making northern European winters cooler but bringing warmth and rain across the Mediterranean region all the way to the Middle East. Winters are generally warmer in the eastern U.S. and Canada but colder in the southeastern U.S.

The NAO can switch modes over days, weeks or months, but viewed over years or decades, it essentially stays one way or the other. With the exception of 1995, the NAO has been in the positive position since 1980. The effects have been pervasive. Strong winter winds have whipped North Sea oil rigs with higher waves, for example. But they have brought more rain, increasing Scandinavia's hydroelectric output. Warmer temperatures have lengthened growing seasons but hurt the ski industry in Scandinavia and other parts of northern Eurasia.

Farther south, lack of rain has disrupted grape and olive harvests on the Iberian Peninsula and diminished stream flow in the Tigris and Euphrates rivers, which bring coveted water to the Middle East. Less rainfall in the Sahel region of Africa has brought famine to Ethiopia, Sudan and Somalia, causing starvation, expensive disaster relief, wars and mass migrations of populations (not unlike the Israelites' migration, in search of food, to Egypt following Joseph's prediction and their subsequent exodus). Interestingly, Heidi Cullen and Peter deMenocal of Columbia University's Lamont-Doherty Earth Observatory have suggested that the NAO, locked in the positive mode about 4,200 years ago, may have been at the root of the history-changing drought that archaeologists believe caused the collapse of the great Akkadian civilization of Mesopotamia.

Researchers haven't figured out what causes the NAO to switch modes, but Michael S. McCartney, an oceanographer at Woods Hole Oceanographic Institution, believes the ocean plays a critical role. Measuring ocean temperatures in the North Atlantic, he and his colleagues found large, persistent masses, or "pockets," of unusually warm or cold waters that flow in a ring of currents up the western coast of Ireland and Scotland, west to Iceland and Greenland, on to the Labrador Sea and eastward again with the Gulf Stream to Ireland. As these pockets are transported along this oceanic pathway over decades, they release more or less heat to the overlying atmosphere. McCartney found a good correlation between the fluctuations of the NAO and the heat moving through the ocean.

Arctic and Antarctic Oscillation

The NAO, however, may be encompassed by a more fundamental phenomenon—the Arctic Oscillation—that affects climate over the entire Northern Hemisphere, as John M. Wallace and David Thompson of the University of Washington pointed out in 1998. In general, winds a mile or more above Earth's surface spin counterclockwise around the polar cap. In winter, frigid air temperatures greatly strengthen the winds in the stratosphere 10 to 20 miles high, creating a powerful polar vortex that extends all the way down to Earth's surface over the North Atlantic region. When the vortex strengthens, it increases the flow of winds that bring warm, wet Atlantic Ocean air eastward toward Europe and Siberia, making winters warmer and wetter on average in those regions, say Wallace and Thompson. Those are precisely the conditions ascribed to the warm phase of the NAO.

Periodically, though, the stratosphere above the pole warms, sometimes by 50 to 60 degrees in a week. When that happens, the great swirling wall of stratospheric winds surrounding the pole partially or completely breaks down. Polar air leaks out and penetrates southward into parts of North America, Europe and Asia, making winters chillier in the affected areas. Meanwhile, eastward-blowing winds closer to the surface often weaken or shift southward, bringing rain to the Mediterranean region.

"The NAO and AO are different names for the same phenomenon," Wallace asserts. "The NAO represents a 'bottom-up' perspective that presumes that the ocean is the key player, whereas the AO is a more 'top-down' perspective," which assumes the phenomenon is driven by atmospheric changes that occur independently of the ocean.

Interestingly, the AO has an identical twin operating around the South Pole called the Antarctic Oscillation, although fewer people live within range of its climatic effects. The AO and the Antarctic Oscillation shift over weeks, months and years, but overall they seem to have become "stuck" over the past decade or two in the mode that favors strong polar vortices. But scientists have only just begun exploring in detail the long-term patterns, underlying causes and far-flung climatic impacts of these polar oscillations.

Investigators are also looking into evidence that the AO may be getting stuck because of the buildup of industrial greenhouse gases. High in the stratosphere, the gases are not trapping heat in but are radiating it out to space. The colder stratospheric temperatures may also be doing other damage: stimulating chemical reactions that destroy the ozone layer, which shields Earth from dangerous ultraviolet solar rays.

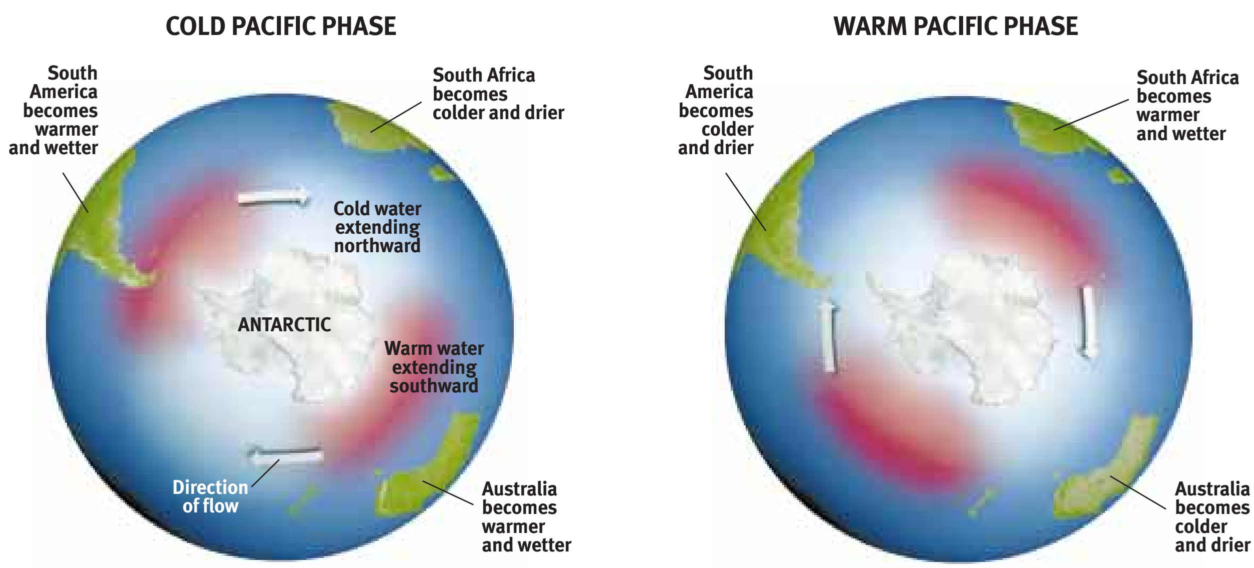
The Pacific Decadal Oscillation

In the mid-1990s Wallace and his University of Washington colleague Yuan Zhang began to notice a climate pattern over the Pacific. This pattern seemed to shift in 20- to 30-year cycles. At the same time, Steven R. Hare and Robert L. Francis, also at the University of Washington, discerned similarly timed boom-and-bust cycles in Alaska salmon. In 1997 these teams realized that they were looking at the same phenomenon and labeled it the Pacific Decadal Oscillation (PDO).

In the PDO's "warm" mode, the vast central interior of the North Pacific is colder than usual, while a narrow band of warmer than average sea-surface temperatures hugs the coastlines of Alaska and the western U.S. and Canada. In the PDO's "cold" mode, ocean temperatures are warmer in the interior and colder along the coast.

When the PDO is warm, a low-pressure system forms with a bull's-eye over the

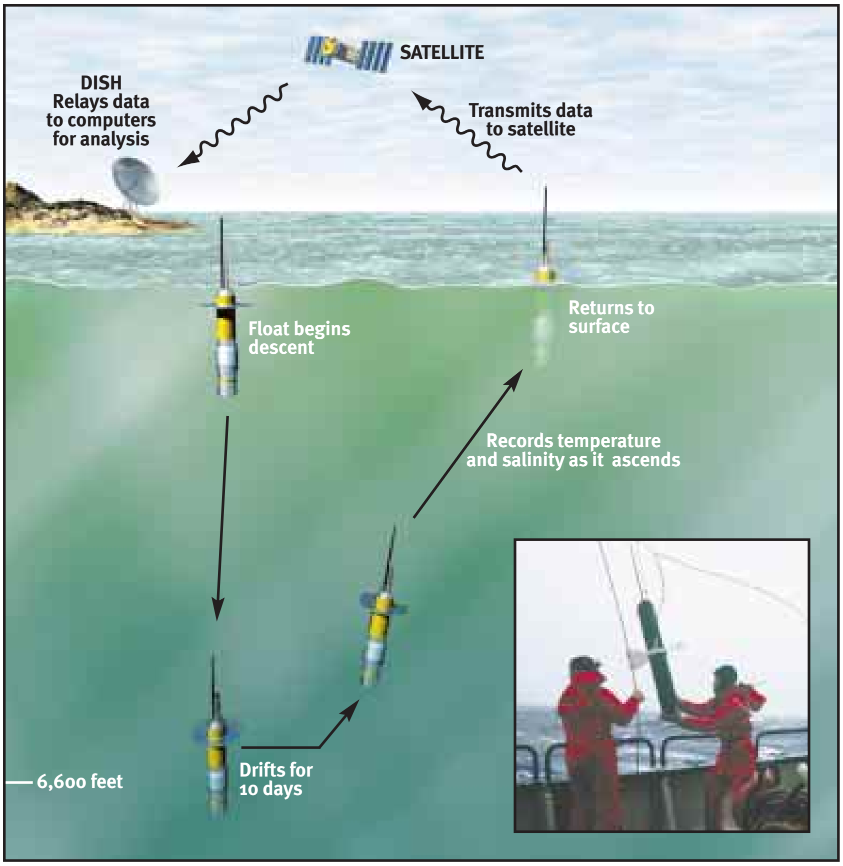
THE ANTARCTIC CIRCUMPOLAR WAVE



The Antarctic Circumpolar Wave, shown highly schematically, is composed of alternating masses of cold polar waters (that have spread northward) and warm subtropical waters (that have spread southward) propagating slowly around Antarctica. When the wave, which takes about eight years to go full circle, is in its cold Pacific phase (*left*), South Africa has colder and drier weather, whereas South America and Australia become warmer and wetter. When the wave is in its warm Pacific phase (*right*), weather conditions reverse.

DAVID FIERSTEIN; SOURCE: WARREN B. WHITE *University of California, San Diego*

THE ARGO FLOAT SYSTEM



DAVID FIERSTEIN (*diagrams*); GEORGE TUPPER WHOI (*photograph*); SOURCES: JACK COOK WHOI, JEFF SHERMAN U.C.S.D. (*detail*)

Hoping to improve weather prediction, an international collaboration is launching Argo, an array of 3,000 floats. The devices will measure the temperature and salinity of the ocean, two features that influence atmospheric conditions, and will relay the results every 10 days to a satellite for analysis (*cycle above, starting at left of center*). The floats (*shown in cutaway view*

Aleutian Islands, near Alaska. It circulates strong winds that bring warm, dry air and warmer winters to the Pacific Northwest. But water supplies suffer from diminished precipitation and snowpack in the mountains. With few interruptions, the PDO has been in this mode since 1977, as it was between 1925 and 1946.

But from 1947 to 1976, water supplies were 20 percent higher on average in the Northwest. The PDO was in its cold mode, as it had been between 1890 and 1924. During that time, the Aleutian low dissipated, less warm air flowed to the Northwest, and winters were colder. But salmon fishing was terrific from California to Vancouver. “One of the most fascinating and important aspects of these oscillations is how they prompt huge reorganizations of marine ecosystems,” says the University of Washington’s Mantua.

Mantua, Hare and Francis found that PDO warming of coastal waters creates detrimental conditions for West Coast salmon (except in Alaska, where they thrive). The warmer, buoyant waters lay atop the ocean surface, creating a boundary between deeper, colder, nutrient-rich waters. The upper layer is no longer replenished by upwelling nutrient-rich waters. Phytoplankton and zooplankton populations crash. Juvenile salmon migrating from streams into the coastal ocean either starve or become easy prey for hungry predators.

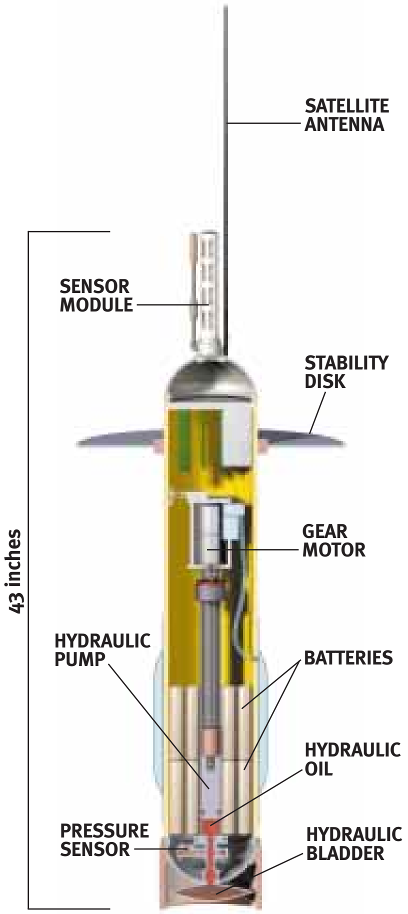
Up in Alaska, the same changes benefit phytoplankton. The northern waters, though warmer, are still cold enough to be nutrient-rich. The more stratified waters keep phytoplankton near the surface and near the life-giving sunlight that is limited in Alaskan winters. Alaskan salmon have a banquet. Similar PDO-related boom-and-bust cycles also affect important fisheries across the Pacific in Japan, Korea and Russia.

On the lookout for possible oscillations in other oceans, scientists are also exploring the tropical Atlantic Ocean and the Indian Ocean, where a still fuzzy pattern tentatively dubbed the Indian Ocean Dipole may shift warm pools of water in a smaller version of ENSO. Down under, workers are excited about a newly discovered oscillation in the Southern Ocean, which surrounds Antarctica. Called the Antarctic Circumpolar Wave (ACW), this pattern was unveiled in 1996 by Warren B. White and Ray G. Peterson of the Scripps Institution of Oceanography.

The Antarctic Circumpolar Wave

Analyzing measurements of sea-surface temperatures and sea-level pressure in the Southern Ocean, the two researchers found something rather curious: you can draw a wavy line, with two peaks and two troughs, completely around Antarctica between latitudes 40 and 70 degrees south; ocean temperatures are warmer above the line and colder below it. Warm tropical waters flow southward into the troughs, and polar waters flow northward in the peaks. This pattern results in four alternating regions (two each) of relatively warm or cool ocean waters that span thousands of miles. These regions are embedded in the Antarctic Circumpolar Current, which moves clockwise around Antarctica, completing one circumnavigation every eight to nine years.

Every four years or so (with a frequency similar to ENSO’s, oddly enough), a peak or trough passes over a given region in the Southern Ocean, shifting winds and rainfall accordingly as it progresses—in much the same way that ENSO’s shifting warm and cold pools do. When a warm trough nears Australia, winds coming off the ocean bring warm, moist air and warmer and wetter than average winters, says Peter Baines of the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. Cold peaks



***above*) can be launched over the rail of a ship (*inset photograph on opposite page*) and, in remote areas, might be deployed from aircraft.**

passing along this traveling wave make Australian winters cooler and drier.

"Soon everyone in Australia will know about the ACW," White predicts. "It will be common knowledge on the street, just as ENSO is now." The ACW may also prove helpful for forecasts in New Zealand, South Africa and southern South America. And because it encircles the globe unimpeded by continents, it could be acting as a link to transmit climate patterns around the world, White and Peterson say. The ramifications and importance of the ACW remain untested, however.

More evidence that Earth's climate tends to oscillate between two different states arrived last November. Lamont-Doherty geochemist Wallace S. Broecker and his colleagues revealed telltale clues that the circulation of the entire world ocean oscillates in a regular pattern that produces centuries-long cold spells every 1,500 years. The most recent one was the "Little Ice Age"—a well-documented period between 1350 and 1880 of generally colder European winters that expanded alpine glaciers, froze rivers and harbors, and disrupted farming.

Today warm Gulf Stream waters flow into the North Atlantic, where they release their heat and keep Europe noticeably warmer in winter than comparable latitudes in North America. The warm waters are "pulled" from tropical latitudes into the north to replace cold, salty, dense waters that sink to the ocean bottom. Like a hand pushing downward in a bathtub, the sinking cold water propels a conveyor belt of deep-ocean currents throughout the world's oceans and eventually back to the Atlantic. When this "Great Ocean Conveyor" is pumping strongly, it draws more tropical waters northward and warms Europe. Conversely, when a smaller amount of cold North Atlantic waters sinks, less tropical water is pulled northward, and Europe receives less heat.

The conveyor receives a boost near Antarctica, the only other place on Earth where the ocean is cold and salty enough to sink. Until now, cold waters were assumed to sink at the same rates in both the North Atlantic and Antarctica. But Broecker's new study suggests that when one site revs up, the other one slows down—in a 1,500-year oscillation that generates worldwide climatic consequences.

"Wiring" the Ocean

Over the next decade, scientists should be quite busy figuring out the validity and significance of all these newly recognized oscillations. "One of our big challenges is determining the extent to which all these phenomena are linked, and how," says Stan W. Wilson, deputy chief scientist of the National Oceanic and Atmospheric Administration.

But whether the ocean drives or is driven by the atmosphere, it plays a critical role in creating our climate. Consequently, in the aftermath of the disastrous 1982–83 El Niño, NOAA, the National Science Foundation and scientific agencies of other nations deployed a string of moored buoys to monitor oceanic conditions spanning 10,000 miles of the equatorial Pacific. Satellites operated by NOAA and the National Aeronautics and Space Administration also track shifting winds and sea levels. Together these instruments provide a continuous stream of observations that feed climate forecasting models and have allowed forecasters, for instance, to give plenty of warning of the powerful 1997–98 El Niño, as well as the La Niña that followed it.

"The time is ripe to take the next obvious step," Wilson notes. With international partners, NOAA plans to cast 3,000 buoys throughout the oceans, dropped overboard from ships or parachuted by airplanes in remote regions. Each four-foot-long torpedo-shaped buoy will sink about a mile deep, drift with ocean currents for 10 days and then rise, measuring water temperature and salinity along the way. On the surface, each so-called Argo float will radio its data and position to orbiting satellites before sinking again and continuing another cycle. The satellites will relay buoy data to help make "weather maps" of the ocean, along with other satellites that will continuously measure sea levels and wind speeds and directions. The buoys are built to last five years, says W. Brechner Owens of Woods Hole, who helped to design them. "Because the ocean is so incompressible, the buoys won't clump," he adds.

"Once fully deployed, Argo will give us for the oceans what meteorologists have had for the atmosphere—a worldwide observing network," Wilson exclaims. "If we can observe and understand the oceans, we have the potential to forecast six to 12 months in advance." Forecasters will not be able to say that it will snow on Christmas in New York, but they may be able to predict that the Northeast will probably have more snow than usual next winter and give people a chance to prepare for it. The old saying—that everyone complains about the weather but nobody does anything about it—may not be quite so true anymore. W

LAURENCE LIPPSETT is science editor at the Woods Hole Oceanographic Institution.

A FAMILIAR SIGHT: Flooding, such as this inundation north of Seoul, South Korea, in 1998, may become more common with global warming.

WARMING TO CLIMATE CHANGE

Global warming is upon us, scientists say—and some communities are ready to react. Together researchers and local leaders are planning for hot, wet—or just plain bizarre—weather to come

by KATHRYN S. BROWN

For geophysicist Gunter Weller, getting to the office is a real trip. On weekday mornings around 7 A.M., Weller gingerly backs his black Toyota SUV down the driveway and into the icy fog that shrouds Fairbanks. His car creeps, antlike, for three miles to the University of Alaska. It's not the morning darkness—or even the icy air—that puts Weller on guard. Rather it's the sudden lurches and gaping cracks that emerge from nowhere in the road—scars of the permafrost melting below the ground.

Record warm temperatures are gnawing away at the masses of ice that lie beneath Alaska and other Arctic areas—and, in the process, buckling roads, tilting trees and threatening homes. Eventually much of the boreal forests that color Alaska could dissolve into wetlands, which could, in turn, become grassland. This ecosystem makeover is a dramatic show of climate change—and perhaps a distressing harbinger of things to come. "We are beginning to see the greenhouse effect—and it's not pretty," notes Weller, director of the university's Cooperative Institute for Arctic Research.

Most scientists now agree that global warming is quite real. The past decade has been the Northern Hemisphere's warmest in 1,000 years, and solar variability and other natural phenomena cannot alone explain the temperature patterns, researchers say. At the same time, freaky weather events—from permafrost thaw in the Arctic to El Niño–driven drought in Indonesia—are putting climate on the radar screen in a new way. Last fall North Carolina residents endured three hurricanes in two months. "After that, we have newfound respect for storms, and we're more open to looking at the possibilities of global warming," remarks Barbara Blonder, a site manager of North Carolina's Division of Coastal Management.

Forecasting regional climate changes—the future temperatures, storms or landscape shifts in the midwestern U.S., say, or along the Australian coast—isn't easy. Climate models are coarse, and zooming

YONHAP AP Photo

in on any given region does not provide an accurate picture. Still, many scientists would like to help communities brace for—and in some cases even benefit from—global warming. So they are teaming up with local leaders—including farmers, forestry managers and government officials—to sidestep the gaps in climate models and encourage resourceful strategies for protecting communities. "Uncertainty about climate change isn't going to be erased for a long time," remarks Richard H. Moss, a climate scientist based at the Pacific Northwest National Laboratory in Washington, D.C. "Even so, there are ways to manage the risk that you face."

STEVEN SPRAGUE *Panos Pictures*

ARBOREAL SEAWALL: Vietnam has cultivated mangrove trees for firewood and honey—but scientists say these plantings yield an indirect benefit of holding back rising seas.

Preparing Now

Management strategies range from simply getting out of nature's way—moving people out of a floodplain, for example—to building up wetlands, investing in diverse crops and rethinking water markets. The best solutions depend on a community's unique resources, economy and concerns—things scientists can pin down only by leaving the lab and talking to people. The largest such effort is the U.S. Global Change Research Program's National Assessment, in which a team of scientists from various disciplines fan out across the country, holding town hall–like meetings and writing reports on climate's potential impact in various states. "We're trying to find out how climate affects people, listening to their questions, thinking of solutions," remarks Michael MacCracken, head of the assessment's coordination office.

In the Mid-Atlantic region, Pennsylvania State University agricultural economist Ann N. P. Fisher has found that area residents are worried about global warming's effect on the coastline. Will more raging storms flood nearby farms and carry runoff into drinking water? What about the opposite problem, drought? "Win-win" strategies can be deployed that make sense on either front, Fisher says—more tightly regulating farm waste, for example, and conserving water. One solution might be metering city water in Pennsylvania, so that residents pay for the amount of water they use and are thus encouraged to use less.

Indeed, conserving natural resources, whether water or land, often emerges as a way to grapple with climate change. Climate models predict that higher temperatures will turn white winters into wet ones in the western U.S., with more precipitation coming down as rain than snow. Warmer temperatures may also hasten the melting of snow crowning the Rocky Mountains, causing winter floods and leaving less of the spring/summer snow melt normally used for drinking water and crop irrigation across much of the West. To adapt to any impending change, water managers may need to rethink the way they operate existing reservoirs to capture more winter flood flow, whereas farmers might favor drought-tolerant crops or more efficient irrigation techniques, comments Peter Gleick, director of the Pacific Institute for Studies in Development, Environment and Security in Oakland, Calif. "We don't necessarily need new tools to cope with climate change—we just need to be better at figuring out where and when to apply the tools we have," Gleick adds.

In some cases, old tools may come back into vogue. Before Europeans established farms across the U.S., Native Americans had their own ways of growing crops in a harsh climate. One strategy was pebble mulching—layering gravel over crop fields to soak up scarce rainfall. Some Pueblo Indians can still recall pebble-mulched farms along the Rio Grande. A similar style is the grid garden, a rectangular slice of field covered with cobblestones that collect water. "It's not designed to feed Phoenix," concedes anthropologist Richard P. Watson of San Juan College in Farmington, N.M. But Watson observes that such techniques could sustain small communities—particularly Native Americans living on federal reservations, who would find it difficult to simply move to more fertile ground.

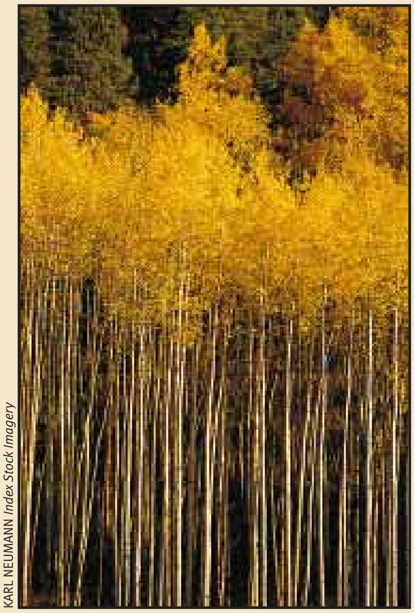
As is true of water, conserving land from development can sometimes protect a community, a lesson that North Carolina residents learned the hard way. Last fall hurricane-whipped floods soaked hog and poultry farms in the state's floodplains, bloating animal waste lagoons and threatening private wells with water awash in feces and urine. Landfills, trash dumps and wastewater treatment plants, too, all went under, littering the floodwaters with their contents, says Larry Ausley, a water quality supervisor for the state. "Above all, we've learned that we really don't own these floodplains; we just borrowed them for a while," Ausley notes. In the aftermath of Hurricane Floyd, North Carolina's Department of Environment and Natural Resources announced that farmers would not be allowed to rebuild waste lagoons that were severely damaged in the

LIFE IN A HOTTER WORLD

Nothing screams "New England" like the sugar maple—a showy, sappy tree crowned with fiery orange leaves every fall. This autumn flush is New Hampshire's very personality. But the hand of global warming may dull the region's orange luster—mixing in more subdued yellow, as aspen trees take over the landscape. In much the same way, climate could redecorate backyards worldwide, shifting the scenery like a painting in progress—and dabbing away at our very sense of place.

This is the personal side of climate change—and it worries researchers almost as much as do the logistics of planning for higher seas or less rainfall. "We know the world can ultimately deal with climate practicalities, like changing crops in the face of drought," says agricultural economist Richard M. Adams of Oregon State University. "But how will global warming change the color or culture of a region? Maybe you won't see all the dairy cows on the hills in Switzerland, or maybe you'll find the wine market moving from northern California into Canada. The question is, How will these changes in regional identity play out?"

Climate change isn't new, of course—the earth is forever evolving, and ecosystems naturally surge and fade over time. But scientists suggest that global warming is speeding up the process. And in a mere 50 years, they say, familiar landscapes could take on a whole new look. The so-called prairie peninsula—a blanket of yellow grasses softening the horizon in the Midwest—could fill up with trees as increasing rainfall stifles the periodic fires that normally clip prairies. Further south—across Arizona, Texas and into Mexico—summer rains have already begun littering grasslands with squatty mesquite. And in a future New England, "people may be nostalgic for those beautiful falls," predicts ecologist Steven P. Hamburg of Brown University.



KARL NEUMANN *Index Stock Imagery*

SUBDUED YELLOWS: A warmer climate may encourage the growth of more aspens and fewer maples in New England, blunting the colors of fall there.

These shifting landscapes pay no heed to our sense of boundaries, such as those marking the edges of national parks. Across Canada, more than two dozen parks protect caribou, whooping cranes and other endangered species—not to mention treasured habitat, such as rain forest and prairie grass. But warmer temperatures may lure both animals and plants north, outside a park's protective borders. "The park can't just up and move," remarks Roger Street of the Atmospheric Environment Service in Ontario. And no one knows how park inhabitants—from birds to bears—will fare in the real world, outside the shelter of their existing homes. Some species probably will disappear entirely, while others hopscotch north in unpredictable patterns.

Ironically, in Europe, global warming could mean a decades-long cold snap—thanks to changes in the North Atlantic Ocean. Normally, salty, dense water on the North Atlantic's surface sinks predictably, creating a current of warm air that wafts toward Europe. But as the globe warms, increasing rainfall in high latitudes will lead to less salty water in the North Atlantic, disrupting the ocean's normal circulation patterns—and cooling the air currents above. Some researchers even suggest that London will become more like Copenhagen, with winters that average at least 10 degrees Fahrenheit cooler than they do now.

In most places, though, climate change will merely blur the borders of regional identity, scientists say. The U.S. corn belt won't suddenly relocate to Canada—but it could creep 50 to 100 miles north, into Michigan and Minnesota. And at the southern end this farm belt could become more sorghum than corn, because sorghum tolerates heat well. "Few people will stand up and yell, 'Aha! The climate has changed!'" Hamburg says. "But we may well notice that our world looks oddly different than it used to." *—K.S.B.*

floodplain. Many coastal managers argue that flood insurance also should be abandoned, because it encourages people to put their houses right back in harm's way.

The North Carolina disaster also shows how important wetlands can be: they give rivers and oceans room to swell harmlessly. In the Chesapeake Bay, rising sea level—one of global warming's more discernible effects—will swallow today's wetlands, says Donald F. Boesch, president of the University of Maryland's Center for Environmental Science. "That's something we can plan for," Boesch comments. He tells water managers that the time to build up intertidal wetlands in the Chesapeake is now. Similarly, British scientists are lobbying to place mangrove forest barriers on Vietnam's coast, and Australian researchers are warning coastal governments in Queensland to factor more intense tropical cyclones into flood management programs.

Saving water and setting aside land are safe bets for dealing with climate change. A greater challenge, perhaps, is rolling with nature's punches—heat waves, dry spells and other weather patterns that turn an ordinary season into a roller coaster of extremes. And such schizo-

Heat waves, dry spells and other schizophrenic weather patterns that turn an ordinary season into a roller coaster of extremes could increase in frequency with global warming.

phrenic weather patterns could increase with global warming, because warmer temperatures are likely to disrupt the normal water cycle, causing more frequent violent storms and, paradoxically, more prolonged droughts in some regions. Scientists still cannot forecast climate variability decades down the line, but they are learning how to predict it on a seasonal basis. And agencies like the National Oceanic and Atmospheric Administration are eager to put these climate forecasts to use. To that end, NOAA has sent dozens of scientists to remote communities across the globe.

In Zimbabwe, agronomist Jennifer G. Phillips of the National Aeronautics and Space Administration Goddard Institute for Space Studies and her colleagues have surveyed more than 200 farmers to see how they use climate forecasts to plan such crops as corn, millet and sorghum. Like those elsewhere, Phillips remarks, farmers in Zimbabwe say mercurial weather makes planning for crops difficult—seasons may start dry yet end in floods, thanks to weather events like El Niño. Many African farmers plant up to eight crops, so a reliable dry climate forecast might prompt them to focus on the use of drought-tolerant grains such as millet, sorghum and certain types of hybrid corn, Phillips says: "If farmers know that chances for a bad year are high, they might figure that into their yearly planning—saving back some seed stock, maybe selling more oxen or moving cattle to a neighboring farm that boasts a better pasture or better water."

The southern Africa research has only begun, but investigators have already endured one hard lesson: the impact of an incorrect forecast. Climate scientists predicted relatively dry conditions for much of southern Africa during the 1997–98 rainy season, but radio reports had exaggerated the potential drought. Many farmers planted less land than they would have normally, Phillips points out. These farmers lost out when normal levels of rainfall trickled over their unused land. Forecasts can backfire, Phillips notes: "If we tell farmers to invest in a little fertilizer or plant more rice and we're wrong, we may be exposing them to more risk than if we said nothing at all." Still, she is optimistic that climate forecasts will continue to improve and that farmers can benefit.

Crop Snapshots

NASA, too, has a high-tech take on climate variability. It funds the Upper Midwest Aerospace Consortium at the University of North Dakota, which is offering more than 200 farmers and ranchers in the northern Great Plains weekly satellite images of their fields. These snapshots from space may help guide crop decisions (say, how much fertilizer or fungicide to spread on crops) or ways to plan land use for livestock. As earth systems scientist George A. Seielstad of the University of North Dakota explains, the idea is to see whether farmers and ranchers can use remote images of their land throughout the course of the growing season to maximize crop yields. This kind of flexibility could be critical in the future. "For most of this decade in North Dakota, it has been exceptionally wet," Seielstad says, "and, as a result, fungi are feasting on spring wheat and potato crops. The lesson is that when the weather takes a turn, it affects agriculture in a big way, and people have got to adapt."

What ranchers want most is resiliency—the ability to bounce back from whatever nature lobs their way, according to Robert Ravenscroft, a cattle rancher in Valentine, Neb., and a participant in the National Assessment. One strategy already being implemented is diversification. Ravenscroft maintains his own adult cattle herds and takes in groups of calves from other ranches. He also keeps careful watch over the plants that make up his rangeland, checking for a good mix of grasses that favor cool and warm seasons or a fair blend of plants with root systems that tap into shallow soil or snake further down. "These kinds of diversity give us staying power," Ravenscroft comments.

Resiliency also counts on the urban frontier. Climate shocks to the world's most important cities—such as New York,

J. SCHMID *Tropix*

ADJUSTING TO EXTREMES: Southern African farmers would benefit greatly from more accurate climate forecasts that would allow them to better plan for inevitable droughts, such as this one that struck fields in Zimbabwe in recent years.

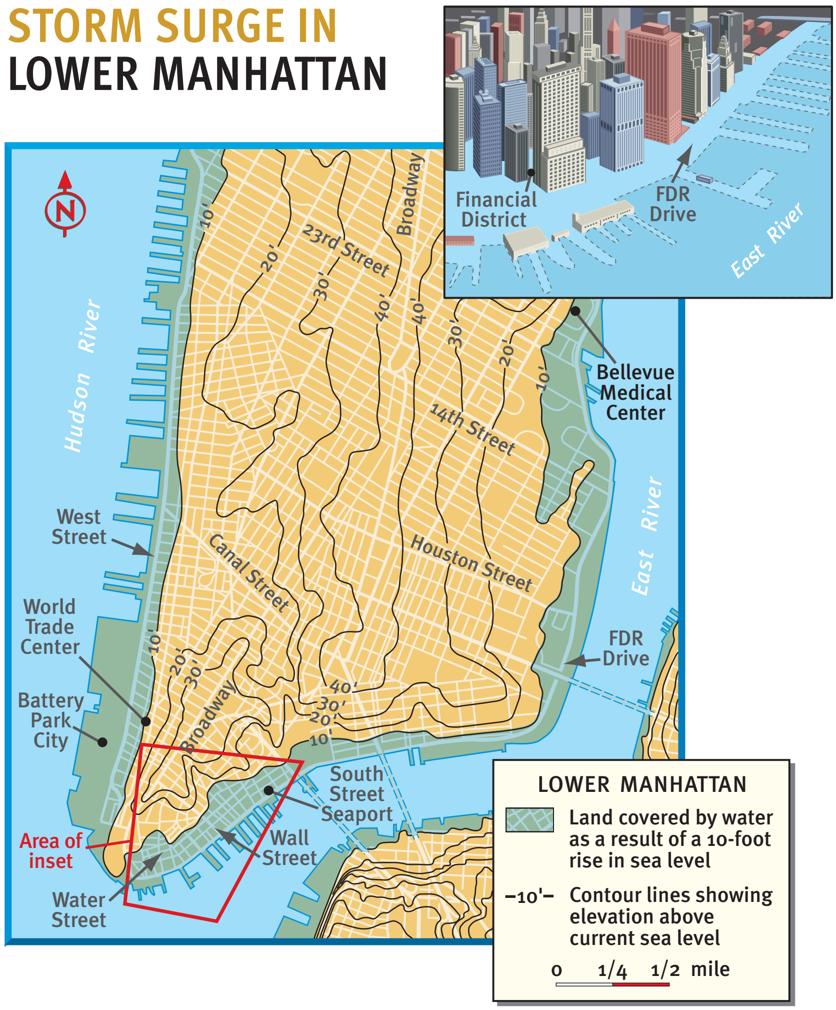
Tokyo and London—could shake up economies worldwide. By 2090 increasing storm surges could dunk lower Manhattan under water every few years, flooding the World Trade Center and other financial district skyscrapers and threatening the water supply with salty sludge from the Hudson River, according to Cynthia E. Rosenzweig of Columbia University and the NASA Goddard Institute for Space Studies. New Yorkers might stave off disaster by taking these forecasts into account when renovating buildings or transportation systems. Already, the Port Authority of New York and New Jersey has factored the possibility of future sea-level rise into projects at John F. Kennedy International Airport, boosting the drainage end of a storm sewer system by more than a foot. "With a little planning, we can make the city more robust," contends Rosenzweig, co-chair of the National Assessment's metropolitan East Coast team.

The trick, researchers assert, is to seek out these "no-regrets" strategies—logical ways to manage the environment that will pay off if climate forecasts come true. In the southeastern U.S., timber companies are engineering loblolly pine trees that can endure drought, an especially useful trait, given the sandy soil and dry skies that can leave forests in the area parched. If the area does happen to grow hotter and drier in the future, these trees—and other genetically engineered species yet to come—should adapt better to the new climate conditions.

That's not to say that climate strategies come easy, or even at all, for some people who may be affected. Forestry managers can't use today's climate models to plan 30 years down the line, according to Lloyd C. Irland, a forestry consultant in Winthrop, Me. "Will there be more oak trees farther north?" Irland asks. "How are white pines going to change in their range? Timber is a regional market, and climate models can't tell us precisely how regions are going to change. That makes it hard to plan ahead."

To forecast regional climate changes, scientists try to scale down results from popular global circulation models (GCMs). But sometimes these models do not agree. For the Great Lakes region, the Canadian

STORM SURGE IN LOWER MANHATTAN



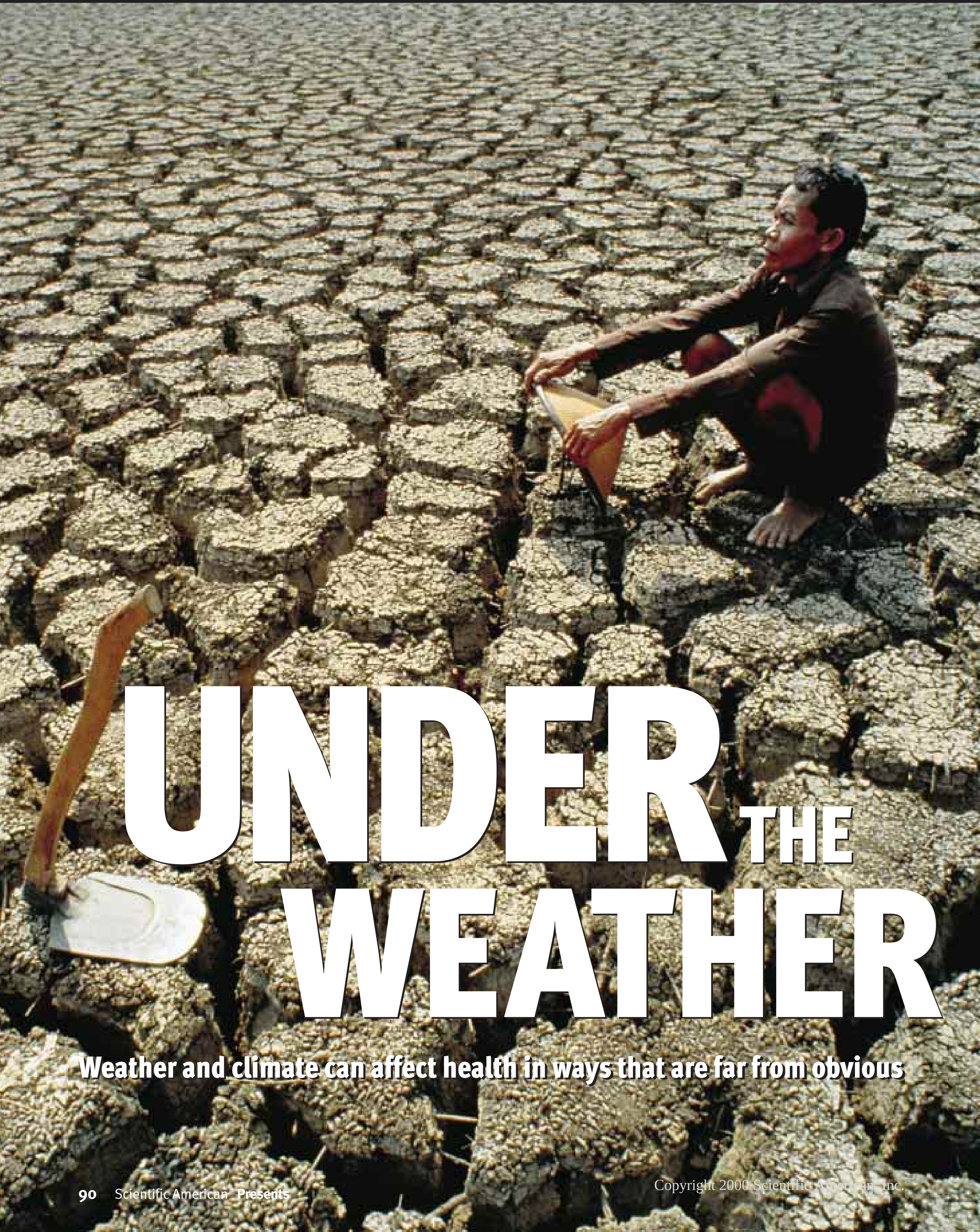
MATT KANIA

Rising waters could be submerging lower Manhattan periodically by 2090 if global warming proceeds as at least one climate analysis has projected.

Climate Model suggests a warmer and drier future than another simulation, the Hadley model, does. The contradiction results in different scenarios for crops or even area lake levels, critical to Michigan's $5-billion recreational boating industry. "We have to fine-tune the models to get a clearer picture of the future," says meteorologist Peter J. Sousounis of the University of Michigan. Until then, he hesitates to give anyone advice for adapting to the coming climate.

In Alaska, residents are getting a crash course in climate change—and adapting isn't simple. Local governments are spending a fortune ripping up roads, digging out the chunks of permafrost—sometimes 15 feet deep—and relaying the pavement. Life is even more challenging on the coast, where native Alaskans live in isolated hunting and fishing villages. These villagers report that melting ice along the coast of the Bering Sea is ever harder to navigate on snowmobiles and that seals, walruses and whales are growing more scarce, reports the University of Alaska's Weller. There are plenty of practical, though expensive, solutions, he notes: relocating villages to higher ground, building sea walls or importing food. But these logistical strategies are of little comfort to native villagers. "We're talking about drastically altering the lifestyle and cultural traditions of these people, and they are reluctant to give it up," Weller says. And for that, he declares, there is no scientific solution. W

KATHRYN S. BROWN is a freelance writer who lives in Columbia, Mo.



UNDER THE WEATHER

Weather and climate can affect health in ways that are far from obvious

by RITA BARON-FAUST

The wind has different names: the poison *simoom* of North Africa, the bad-tempered *melteme* of the Aegean, the violent *mezzar-ifoullousen* of Morocco. Cultures throughout time have reasonably feared dangerous winds and other weather catastrophes because of the immediate effects on fortune and health: high heat can kill directly, as can rampaging floods from hurricanes or monsoons. Yet weather works less overt mischief as well, such as when it fosters the proliferation of pests that transmit infectious diseases or when it disrupts the integrity of water supplies.

The weather's power over health was demonstrated dramatically several times in the space of just a few weeks in 1999:

- In three states along the U.S. East Coast, weeks of drought and intense heat created ideal breeding conditions for mosquitoes that turned out to be carrying an encephalitis virus never before seen in the Western Hemisphere. Fifty-six cases were reported, with seven deaths.
- Runoff from heavy rains in late August apparently swept a dangerous strain of *Escherichia coli* bacteria into a well at a county fair in upstate New York. More than 1,000 fairgoers became sick after sipping drinks made with the well water; two died.
- In Asia, from China to the Philippines, torrential rains during an unusually severe monsoon season unleashed floods, leaving thousands dead and compromising water supplies and already weak sanitation systems.
- The summer of 1999 was among the hottest ever in the U.S. More than 250 people died during its heat waves. Hot weather and high pressure also trapped air pollution for up to three weeks in some locations, crowding emergency rooms with people suffering from asthma and other chronic respiratory conditions.

CHARLES DHARAPAK *Associated Press*

WITH DROUGHT COMES DISEASE: Drought in Indonesia (*opposite page*) has apparently contributed to the spread of several infectious disorders. About two years ago a dry spell brought increases in cholera, malaria and dengue fever—the last of which afflicted the child above and killed hundreds of others.

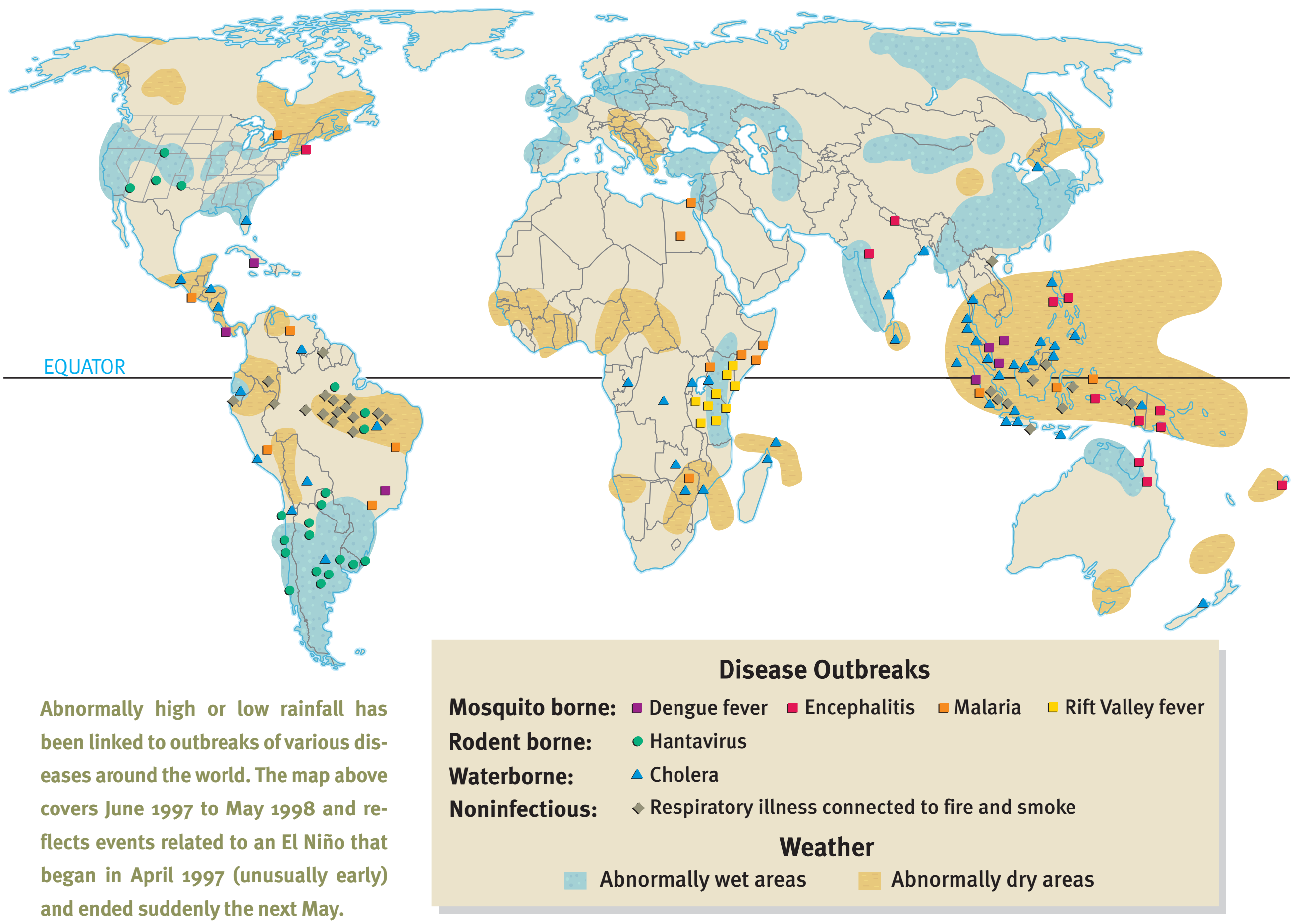
Weather can influence the range and activity of insects and other animals that transmit diseases, thereby affecting the timing and intensity of disease outbreaks, notes Paul R. Epstein, associate director of the Center for Health and the Global Environment at Harvard University. And changes in climate (long-term weather patterns) are a concern as well: "One of our most important tasks right now is to understand the climate change and instability now occurring and what this means for human health."

Of course, humans can also tip the balance of nature, Epstein adds. Loss of forests to indiscriminate logging and depletion of buffering coastal wetlands lead to more severe flooding and death when heavy rains hit. Clogging freeways with more cars, vans and trucks creates more pollution and ozone, exacerbating respiratory disorders during hot spells.

The infamous El Niño and its opposite, La Niña, seem to be major sources of the

SHENG UNEP/Still Pictures/Peter Arnold, Inc.

WEATHER EXTREMES AND DISEASE OUTBREAKS



Abnormally high or low rainfall has been linked to outbreaks of various diseases around the world. The map above covers June 1997 to May 1998 and reflects events related to an El Niño that began in April 1997 (unusually early) and ended suddenly the next May.

MATT KANIA; SOURCES: PAUL EPSTEIN *Harvard University*; NOAA CLIMATE PREDICTION CENTER; http://chge2.med.harvard.edu/enso/disease.html

ill winds that blow no good in many parts of the world, including in the U.S. El Niño, the cyclical warming of the central and eastern Pacific Ocean, occurs every three to seven years around Christmastime and usually lasts for about a year. It is "the strongest driver of regional weather conditions around the world next to the seasons and has major effects on human health," says Jonathan Patz, director of the Program on Health Effects of Global Environmental Change at Johns Hopkins University.

El Niño can produce warmer and wetter years in certain regions around the world and can lead to a drastic drop in rainfall, causing drought conditions and wildfires, in other areas. La Niña's tropical Pacific chill can set up atmospheric pressure changes that keep rainfall away from land or that whip up an especially strong hurricane season (as happened in 1998 and 1999).

The health effects of these climate patterns are diverse. For instance, torrential downpours from El Niño can promote the growth of plankton that harbor the cholera bacterium *Vibrio cholerae* in coastal estuaries and rivers. Floods can then flush the diarrhea-causing bacteria into water systems. Cholera epidemics linked to El Niño have occurred across Africa and South America. "At the other extreme, drought conditions leading to water shortages can make it hard to maintain hygiene, also increasing the incidence of diarrheal diseases," Patz notes.

Dramatic increases in the incidence of malaria—a parasitic disease marked by fever and chills—have been tied both to excess rainfall and to drought caused by El Niño. In normally dry regions, heavy rain leaves pools of water in which parasite-carrying *Anopheles* mosquitoes can breed, explains Paul J. Beggs, secretary-general of the International Society of Biometeorology. "In areas that are normally very wet, a decrease in rainfall allows rivers and streams to stagnate, providing a breeding ground for mosquitoes."

In fact, a report by the Center for Health and the Global Environment at Harvard noted that in 1998 increased malaria outbreaks coincided with above-average rainfall in South America and in Rwanda and with below-average rainfall in Sri Lanka. The report also linked outbreaks of a number of other disorders to extreme weather that occurred between June 1997 and May 1998 [*see map above*].

A Killing Heat

When people think of weather as a killer, they often recall major disasters, such as the La Niña–related floods that killed more than 3,000 people in China in 1998. In the U.S., however, the largest numbers of deaths related to weather are caused by extreme heat. The elderly are usually hardest hit.

During a record-breaking heat wave in 1995, as many as 1,000 people died, 522 of them in Chicago alone, according to the Centers for Disease Control and Prevention (CDC). In the unusually hot summer of 1999—when Chicago and New York City suffered consecutive days of temperatures exceeding 100 degrees Fahrenheit and when Cincinnati saw temperatures above 90 for three weeks in July and August—at least 256 heat-related deaths occurred.

The cities likely to have the most heat-related fatalities are actually those in the midlatitudes, such as New York, Philadelphia, Chicago and St. Louis, which have irregular but intense heat waves, says Laurence S. Kalkstein, a University of Delaware climatologist. In New Orleans or Miami, he points out, fewer heat-related deaths occur because people have already acclimated to higher temperatures and humidity. Extremely hot and dry weather can at times be more deadly than the sultry weather in the South, because perspiration evaporates more rapidly when the air outside is dry. "If you do not replenish fluids, you can become dehydrated, and your ability to maintain a cool core temperature is diminished," Kalkstein explains.

Another problem in Northern and Midwestern cities, he notes, is that low-income housing tends to be multistory brick tenements with a flat tar roof that holds heat in. With the sun beating down, a room could get to be 120 degrees F, and many people can't afford air-conditioning. In the South, poorer people tend to live in one-story, white frame buildings with windows on all sides and a metal roof that deflects heat, keeping interiors cooler.

The number of consecutive days of heat is also significant. Ongoing elevations in daytime and nighttime temperatures have a cumulative effect on body stress, which in turn can contribute to heart attacks and stroke as well as to heat exhaustion, Kalkstein says.

Experts generally agree that our world is getting warmer, although they do not agree on whether the cause is human activity (such as the burning of fossil fuels) or a natural process. What this climate trend will mean for human health is still unclear. "We don't know whether global warming will simply make each day warmer or bring more frequent extreme heat events, which are the most dangerous for human health," Kalkstein adds.

SHEZAD NOORANI *Still Pictures/Peter Arnold, Inc.* (*top*); MARK EDWARDS *Still Pictures/Peter Arnold, Inc.* (*bottom*)

RUINOUS RAINS: Floods, such as those that swamped Bangladesh in 1998 (*top*), promote infectious diseases by contaminating water supplies and encouraging the breeding of mosquitoes and other transmitting agents. Cholera is a major risk. In the bottom photograph, a resident of Bangladesh carries his cholera-stricken wife away from a flooded area.

Something in the Air

Heat has another killing effect: hot, sunny weather bakes the emissions of cars, trucks, power plants and factories into a thick, ozone-laden smog. Ground ozone is a powerful lung irritant and a major hazard for people with asthma and chronic obstructive pulmonary disease (COPD), both of which can hamper breathing. Wind patterns and humidity can help trap pollution for days or weeks. Last summer's heat waves made 1999 one of the worst years for ozone pollution in recent memory.

Ozone alerts have been correlated with increased numbers of hospital admissions and emergency room visits for asthma attacks and exacerbations of COPD. According to the Clean Air Network, a nonprofit watchdog group based in Washington, D.C., federal data on 37 Eastern states show that in 1997 (the latest year available), Texas had the highest number of ozone-related hospital admissions, ER visits and reported asthma attacks. Florida beat out New York State for second place, but citywide totals put populous New York City squarely on top.

"Air pollution certainly worsens asthma for people who have asthma, but there's a question as to whether it actually causes it," says George D. Thurston, an environmental scientist who heads the community outreach program of New York University's Nelson Institute of Environmental Medicine in Tuxedo, N.Y. "While tailpipe emissions have declined, asthma rates continue to rise. So there may be other compounds in air pollution that we haven't measured. For example, diesel particles and tiny particles generated by wear and tear of tires can become windborne. Tire-wear particles contain latex, which can be allergenic. Asthmatics are especially at risk."

Paul Beggs, who teaches environmental and life sciences at Macquarie University in New South Wales, Australia, believes weather and climate can also influence levels of other allergens that provoke asthma attacks, such as pollen.

N. RICHMOND *The Image Works*

HIDDEN PERIL FROM HEAT: Hot, sunny weather can increase levels of ozone in the air, which in turn can aggravate asthma.

Came the Deluge

Heavy rains in areas along the U.S. East Coast during the 1999 hurricane season (made worse by La Niña) may not have produced floods of biblical proportions, but they were bad enough, coming on the heels of record summer heat and drought.

According to the U.S. Geological Survey, rainfall in September 1999 from Hurricanes Dennis and Floyd in some areas of North Carolina added up to nearly half the state's average annual rainfall total. Floyd dumped 20 inches of rain on parts of the state, killed at least 49 people and left two million livestock dead. A month later Hurricane Irene dropped another half foot of rain along the Carolina coast.

Concerns have been raised about the possible long-term health effects of bacteria and dangerous chemicals flushed into the state's waterways. Floyd flooded 24 municipal sewage treatment plants and 46 hog-farm waste pits, caused spills from gas stations, farms and chemical plants, and left the landscape littered with rotting animal carcasses. There were only a few reports of waterborne illnesses, although state health officials worried about molds as residents returned to waterlogged homes. In New Jersey, extraordinary flooding forced nearly two million residents to boil drinking and bathing water for more than a week, but again no major outbreaks of illness occurred.

That outcome contrasts sharply with the aftermath of torrential rains in many developing nations, such as Bangladesh (where massive flooding from monsoons also hit in September). Bangladesh has no central water filtration or chlorination, and fuelwood to boil water is scarce, so epidemics of cholera and other diarrheal diseases are commonplace, notes Rita R. Colwell, director of the National Science Foundation (NSF), who has studied cholera for 25 years.

In 1998 flooding in Bangladesh was very severe. At its peak, as many as 1,000 people a day entered the central cholera hospital, Colwell recalls. Plankton from coastal estuaries was swept into inland waterways, carrying along *V. cholerae.* "We wouldn't see this happen in a developed country unless there was a massive breakdown in our sewage and water treatment systems," Colwell says. She is spearheading tests of simple filtration systems in Bangladesh in hopes of curbing future outbreaks.

Even with the best water filtration and treatment systems, dangerous organisms can still slip through. Chlorination does not kill the parasite *Cryptosporidium parvum,* which causes the intestinal illness cryptosporidiosis, and standard filtration systems do not keep it out. In 1993 an outbreak of cryptosporidiosis occurred in Milwaukee after severe rains and flooding along the Mississippi River overwhelmed water treatment and sanitation facilities. In excess of 400,000 people came down with the illness after drinking contaminated water; more than 100 died.

Even small gaps in the system can be vulnerable to weather. Health experts believe a downpour the night before the opening of the Washington County Fair, a century-old agricultural event held in Easton, N.Y., led to an outbreak of illness from a virulent strain of *E. coli* (0157:H7). This strain releases powerful toxins into the blood and can kill quickly. At least 1,050 who attended the fair in late August were affected, among them a little girl and an elderly man who died. The most likely source was a cattle exhibition; fecal matter mucked out from the stalls was probably swept up in runoff that leached into an unchlorinated well. The state has issued new regulations for water and food vendors at mass gatherings.

Unhealthy Confluences

Sometimes it may not be a single kind of weather but an unlucky combination of weather and environmental factors that causes illness. For those whose lives are lived close to the land, there's nothing new about the notion that weather, health and the environment are bound up in a delicate balance. Such is the belief of the Navajo, who saw this interconnectedness play out dramatically during an outbreak of hantavirus—a deadly hemorrhage-causing infection—on reservations in New Mexico and Arizona several years ago.

In 1993 the CDC drafted Ben Muneta, a Navajo physician with the Indian Health Service, to help track down the source of the disease. "The investigation was going slowly, and I decided on my own to talk to medicine men and women on the reservation," Muneta recalls. "They believed the illness was caused by heavy rains that had caused the piñon trees to bear too much fruit, upsetting the bal-

TODAY'S FORECAST: INCREASED COLD AND HEART ATTACKS

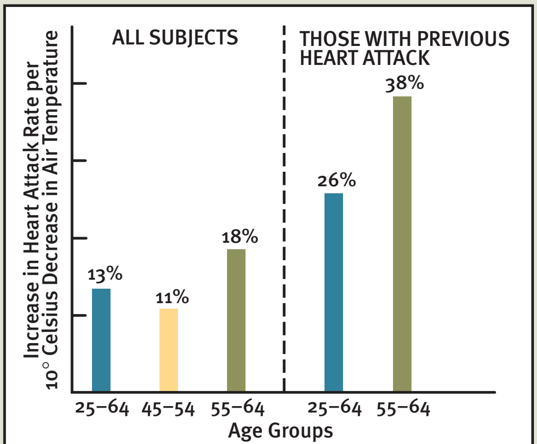
People with heart disease, migraines or circulatory disorders may want to listen more closely to weather forecasts. Two 1999 studies, including a large one published in the journal *Circulation,* found that below-normal air temperatures may trigger heart attacks in vulnerable people, especially those living where climates are normally moderate.

"If you have a 10-degree [Celsius] decrease in any temperature, you will have an increase of 13 percent in the rate of myocardial infarction, or heart attack, for a particular region," says Philippe Amouyel, a professor at INSERM and the Pasteur Institute of Lille in France, who was lead author of the *Circulation* report.

That study, which looked at 10 years' worth of data monitoring 257,000 men aged 25 to 64 living in the north of France, found that extreme atmospheric conditions, such as a big drop in atmospheric pressure with an approaching storm, may also pose a risk. "When atmospheric pressure increases from almost sea-level atmospheric pressure or decreases from that point, heart attack increases. In each age group we have this same relationship for temperature and atmospheric pressure. But it was stronger in older ages, 55 to 64," he notes.

The second study, from Scotland, finds that cold temperatures can increase blood pressure, make blood more likely to clot and strain the heart, especially in overweight or sedentary individuals. It's also believed that cold weather can trigger irregular heartbeats and enhance pain syndromes, such as migraines.

Amouyel advises older people, particularly those with heart disease, to take precautions during very cold weather—and maybe have the neighbor's kid shovel the walk. *—R. B.-F.*



SOURCE: P. Amouyel, INSERM U508, Pasteur Institute

CASUALTIES OF THE COLD: When air temperature declines by 10 degrees Celsius (18 degrees Fahrenheit) in a temperate region, the heart attack rate goes up, according to a study of men aged 25 to 64 living in northern France.

SARAH L. DONELSON

ance of nature. They were also very clear that the mode of transmission was the deer mouse, whom the Navajo believe should not live in proximity to man."

The medicine men and women turned out to be right. Piñon nuts are food for the deer mouse, which carries the deadly virus. An unusually mild winter and excessive rains had produced an abundance of piñon nuts, and six years of drought conditions had also decreased predators, such as owls and coyotes, that limit mouse populations. The result: a 10-fold increase in deer mice and an outbreak of the hantavirus strain dubbed Sin Nombre ("without name" in Spanish). Hantavirus is spread when people inhale aerosolized virus particles from the saliva, urine and feces of mice that have invaded a home or other building.

Since 1994 the CDC has continuously monitored rodent populations at nine sites in Arizona, Colorado and New Mexico. Weather is one of the factors used in tracking hantavirus, and it helped the agency to prepare for another outbreak.

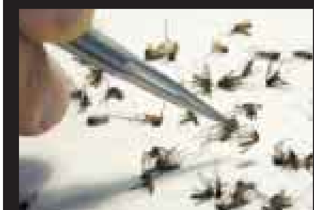
"We had increased rainfall from El Niño in 1997. Then in the spring of 1998, we saw tremendously increased populations of rodents at many of the sites. Even though not that many were infected, we had 16 cases of hantavirus," recalls James N. Mills, chief of the Medical Ecology Unit of the CDC's Special Pathogens Branch. In the spring of 1999 the rodent population grew again, although not as much as before. Now up to 40 percent of the animals were infected, because many mice carrying the virus had survived the unusually mild winter; another 16 people were diagnosed. "This," Mills adds, "is compared to only three to five cases a year in 1995, 1996 and 1997. So the preliminary evidence was that weather was definitely a factor… in both outbreaks."

An imbalance in nature caused by weather may have also promoted an outbreak of encephalitis in New York, New Jersey and Connecticut in August and September of 1999. After two dozen people became ill, investigators discovered that the cause was West Nile virus, which had never been found in that part of the world. Experts still don't know how the virus got there, whether it arrived in infected birds or perhaps in mosquitoes that found passage by ship or airplane.

In any case, the weather seems to have cooperated with the virus. In June, July and much of August, parts of the area were hit with the worst drought in years, coupled with long bouts of hot weather. Together these events created the ideal conditions for the spread of the virus, which is transmitted by *Culex,* the common northern house mosquito, an insect that breeds in stagnant water.

"The hot weather helped incubate the virus in birds and breed larger numbers of mosquitoes that bit the birds, which spread the virus further. And, at some point, the mosquitoes transmitted it to humans," says Durland Fish, an epidemiologist at Yale University, who has studied diseases borne by insects and other pests for 30 years.

Northern house mosquitoes spend the winter in damp basements, walls and



CITY UNDER SIEGE: Last summer health officials began spraying insecticide in New York City (*above*) and its suburbs after a cluster of encephalitis cases led to the discovery that mosquitoes (*left*) were transmitting a dangerous virus. The West Nile virus apparently flourished in last year's heat and drought.

PHOTOGRAPHS BY ED BETZ *Associated Press*

tunnels, so there is a huge possibility that the virus could reemerge in the spring of 2000, Fish warns. Problem is, there is no wide-scale system in place for monitoring mosquitoes in New York State.

"Vector-borne diseases are multifactorial. You have to have a susceptible population, the virus has to be present, and weather conditions have to be right. It's important to look at climate in the context of these other factors," Patz says. In the case of malaria in the U.S., he notes, "it's more an issue of having the parasite being transported into this area through international travel, rather than having certain weather conditions that favor the mosquito."

Early-Warning Systems

Forecasting weather can be an inexact science. Forecasting the future of our climate and its effects on our health may be almost impossible. But biometeorologists are taking a stab at it.

A consortium of government agencies and research teams from many regions in the U.S. is expected to issue a National Assessment of Climate Variability and Change this year, along with steps that need to be taken to maintain the health of humans and the planet, including establishing early-warning systems.

"We have the technology to help monitor climate and predict disease outbreaks, so we can take preventive measures and not have to operate in crisis mode," says Cynthia E. Rosenzweig, a research scientist at the National Aeronautics and Space Administration Goddard Institute at Columbia University. Rosenzweig also heads the Metro–East Coast study group for the national assessment.

Global monitoring via remote-sensing satellites of sea-surface heights and temperatures and of atmospheric and weather conditions helped to predict the 1997–98 El Niño event almost a year ahead, allowing some advance warning of extreme weather conditions. In the fall of 1999 this same technology indicated that La Niña would influence weather in the winter and spring of 2000 in ways that could affect health. For example, it predicted warmer than normal temperatures interspersed with bouts of bitter cold and storms for the Northern, Central and Eastern states; these conditions might be hazardous to people's hearts [*see box on preceding page*].

Remote-sensing satellites are also being used to detect plankton blooms that could threaten coastal areas with cholera during rainy seasons. The goal, again, is an early warning, so resources can be deployed to lessen, if not prevent, epidemics of cholera, says the NSF's Colwell.

At Johns Hopkins, computer simulation models of air pollution and climate change are being used to try to predict future patterns of temperature, air inversions (which trap pollution) and pollution. This could help alert health systems to prepare for conditions that might be deadly for people with COPD or asthma.

Kalkstein has developed a system of air-mass categories for use as an early-warning system for heat waves. In many Midwestern cities, the most dangerous is a dry, tropical air mass, which leads to 30 to 40 percent more deaths from all causes. "We can predict two to three days in advance whether excess deaths will occur," he notes.

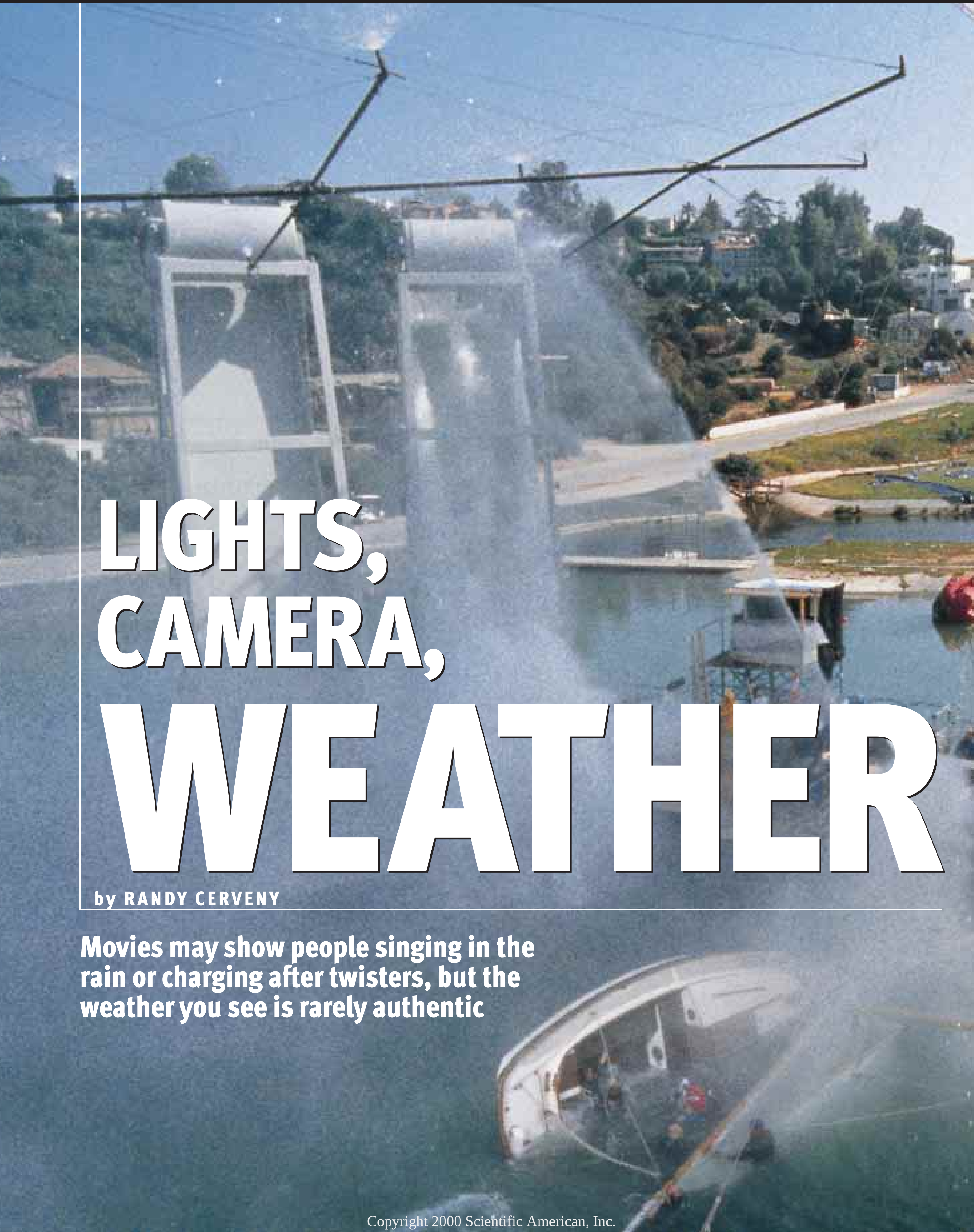
The hot-air-mass early-warning system was used in Philadelphia during 1995 and did save lives by prompting quicker deployment of measures such as establishment of air-conditioned centers where the elderly poor could congregate, Kalkstein says. He is now working with the United Nations to develop heat-warning systems for Rome and Shanghai.

As for mosquito-borne diseases, long-range climate and weather forecasting can provide some early warning of danger as well. And local monitoring can track the numbers of mosquitoes and whether they carry a virus, so that public health authorities can institute control measures.

It's conceivable that daily weather forecasts of the future will include a health outlook. In addition to pollen counts and ozone alerts, your local biometeorologist might report the global warming index or might issue a hot-air-mass warning coupled with advice to ward off heatstroke. Mosquito, rodent or tick alerts might also give a heads-up about disease-bearing pests, so you can get out the bug spray and long pants.

Until then, as scientists advised in one old sci-fi movie: look to the skies. W

RITA BARON-FAUST is a medical journalist and author of books on women's health.



LIGHTS, CAMERA, WEATHER

by RANDY CERVENY

Movies may show people singing in the rain or charging after twisters, but the weather you see is rarely authentic

In much the same way that Jim Carrey's character in the 1998 film *The Truman Show* suffered through simulated lightning, thunder and rain, believing they were real, moviegoers often fail to realize that the weather in motion pictures is almost always fake. Movie weather—as with all aspects of a film—must be at the beck and call of directors and producers. Unfortunately, the desired storms rarely occur on schedule and usually don't film particularly well. Consequently, directors typically rely on special-effects wizards to re-create the variety of weather they need.

Celluloid weather has entertained moviegoers for more than 60 years. Indeed, the very first Academy Award for special effects honored the spectacular monsoon scenes of the 1939 movie *The Rains Came*. During that feature's soggy climax, an astounding 10,000 gallons of water drenched the actors every minute. If that had been real rain, the deluge would have corresponded to an incredible rate of 40 inches a day. Such massive simulated downpours are produced by pumping water from large tanks into sprinklers set high above the action; the water is then captured for reuse in additional takes.

The watery effects were actually even more astonishing in John Ford's Oscar-winning 1937 movie *The Hurricane*. Particularly exciting was a gargantuan storm-generated "tidal" wave, made by dumping 2,000 gallons of water down chutes and then blowing it onto the actors with two huge airplane propellers. For safety, the actors were tethered to trees.

These unnatural disasters were especially impressive because even heavy rain is rather translucent and thus extremely difficult to capture on film. That's why news footage on hurricanes often depicts the storms' results (flooded roads, rapidly working windshield wipers) rather than focusing on the rain itself.

DUNKING TRUMAN: A rainstorm in *The Truman Show* came not from the sky but from a complex system of faucets, pipes and fans.

PARAMOUNT PICTURES CORP./PHOTOGRAPH BY MELINDA S. GORDON

STURM'S SPECIAL EFFECTS (www.snowmaker.com)

WHITEOUT: A blizzard in 1998's *The Hi-Lo Country* (*above*) actually swirled in an indoor studio. After spreading two kinds of white material over the ground and sticking white fibers onto fake trees and rocks (*far left*), a crew filled the studio with white fog (*left*) and released plastic flakes, foam particles and more fog into machine-generated winds.

In older films, "rain" was often made more visual by mixing water with milk. Today many moviemakers employ a series of carefully positioned overhead sprinklers above the actors. Frequently, water from these sprinklers is sprayed upward, instead of directly downward, to yield a more realistic falling effect on screen. When a riveting movie car chase during a fierce thunderstorm ends with the car skidding wildly out of control into a wall, the untold story is usually that, just off-camera, a water tanker is driving alongside with pumps spraying water skyward over both road and car.

Sometimes the application of watery special effects has extra benefits. When designers created the main set for the 1995 movie *Congo,* about the discovery of great gorillas in the wild, they fashioned a rain forest from more than 2,500 live tropical plants. They then had to construct a sophisticated overhead misting system to maintain the lush greenhouse foliage properly. Director Frank Marshall noted that Allen Daviau, director of photography, found the misters a wonderful alternative to the smoke generators conventionally used in Hollywood to create a hazy atmosphere.

Fog is another atmospheric phenomenon that can be problematic to photograph in its natural state but can be simulated in various ways. In old movies, "ground fog" and the visible breath of people in the cold were manufactured by simply vaporizing frozen carbon dioxide, or dry ice. Unfortunately, carbon dioxide can be lethal if inhaled for prolonged periods, and dry ice (which is colder than –100 degrees Fahrenheit) can be extremely dangerous to hold. In scenes in which breath needed to be visible, actors used to pop a safely boxed cube of dry ice into their mouths and let their breath gently warm the carbon dioxide, which would then evaporate, producing a visible mist. An actor unaware of the dangers once decided to skip the box because of its effect on his speech. He simply slipped the chunk of dry ice into his mouth—and ended up with severe cold burns.

Special-effects artists are often asked to produce convincing footage of other cold-weather phenomena as well. In early movies, falling snow was often, in fact, minced chicken feathers. The feathers did float realistically, but they also collected in the poor actors' nasal passages. Since those days, "snow" has been made from a wide range of materials, including shredded polyethylene, painted balsa wood, powdered detergent or even bleached cornflakes. Snow cover for backgrounds may consist of permanent materials, such as plastic bits, rock salt crystals or even plain old white paint. Close-up foreground shots, though, might feature temporary but more realistic-looking foams (such as the stuff in fire extinguishers) or ice shavings.

Directors have complained about pseudo snows, however, because of their regrettable failure to melt. Watch carefully, for instance, the snow on Jimmy Stewart in the last scene of the 1946 Christmas classic *It's a Wonderful Life*. The white stuff often sticks unrealistically to the actors' clothes long after actual precipitation would have melted. So today special-effects companies commonly employ actual snowmaking equipment capable of turning any landscape into a winter wonderland—that is, when they don't simulate snow entirely by computer.

A Tankful of Clouds

Clouds pose yet another challenge to moviemakers. The typical solution is the cloud tank, a large aquariumlike glass structure that is filled with a mixture of saltwater and freshwater. The saltwater, being denser, stays at the bottom of the tank, thereby creating two distinct but visually similar layers. Next, an injection device, carefully placed into the boundary between the layers, feeds an opaque tempera or a thinned latex paint mixture into the tank. Cloudlike shapes form as the paint billows out and swirls in the fluid. Cameras positioned outside the tank take the shot, which is later combined with the live action.

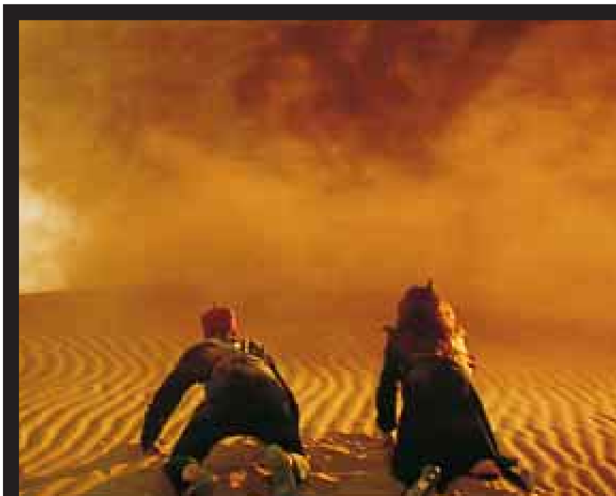
The cloudy skies can also be enhanced in several ways. Notably, spotlights arranged beside the tank can illuminate or shadow specific parts of the paint clouds. Gels of various kinds can confer color and texture to thunderclouds. And strobe lights above or behind the tank can simulate lightning in the clouds. Although the cloud tank is mechanically simple to operate, the texture of the final "sky" is satisfyingly complex. This method for manufacturing clouds, thunderstorms and lightning has been exploited in a number of popular movies, including *Close Encounters of the Third Kind, Raiders of the Lost Ark* and *Star Trek II*.

Surprisingly, movie lightning—in contrast to other atmospheric phenomena created for film—frequently fails to abide by basic physical laws. In the real world, the difference between the speed of light and the speed of sound means that a viewer rarely experiences lightning and thunder at the same time. An interval of five seconds between a flash and the corresponding thunderclap means the lightning is a mile away, 10 seconds of separation corresponds to two miles, and so on. Directors, however, often have their lightning and thunder occurring simultaneously—something that would happen in real life only if the lightning were directly overhead. Portrayal of an accurate separation, they say, would disrupt the mood they want to set.

Sometimes effects normally employed to produce ersatz weather are enlisted to achieve other tricks. For example, the alien spaceships in the 1977 movie *Close Encounters of the Third Kind* are first seen as amorphous balls of light. If filmed under normal conditions, the neon-lighted alien ships would have appeared very flat and mechanical. To make them seem softer and more organic, Douglas Trumbull and his special-effects company, Future General Corporation, filled a model studio

MUSEUM OF MODERN ART FILM STILLS ARCHIVE

AS WET AS RAIN: ***The Rains Came*****—a 1939 feature starring Myrna Loy and Tyrone Power—won the first Oscar for special effects. Its manufactured monsoons consisted of thousands of gallons of water pumped through sprinklers.**



EVERETT COLLECTION

DUST MUMMY: A dust storm that later morphed into an evil face in 1999's ***The Mummy*** **was created by computer.**

with an amount of smoke that, in other movies, might have been used to simulate fog or haze. In this case, the smoke diffused the brilliant lights of the alien UFOs.

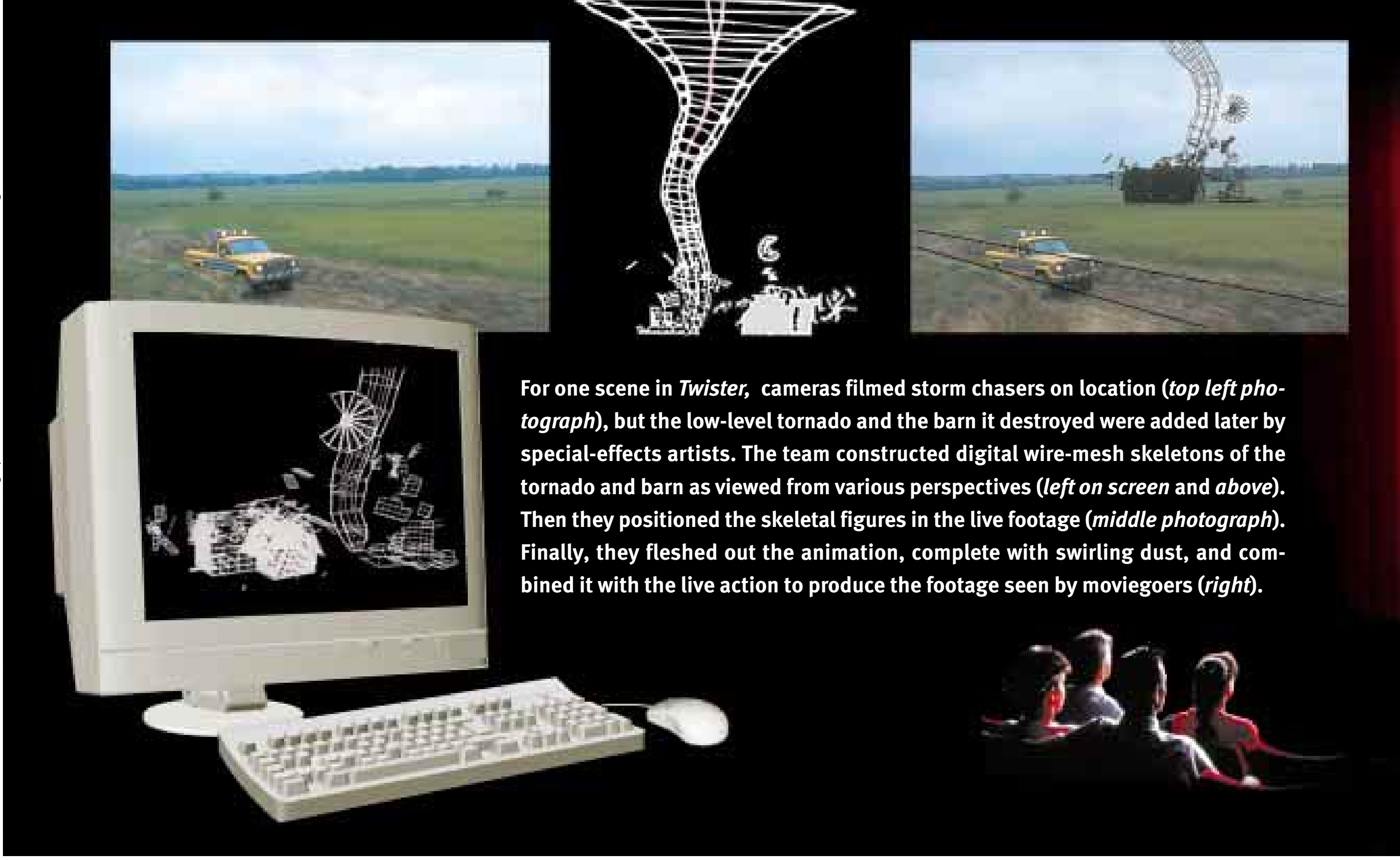
Computers Reign

Today movie depictions of meteorological phenomena are often achieved through a clever combination of imagination, miniatures and computer graphics—a trend that has gained increasing momentum over the past 20 years. For example, James Cameron's special-effects team, Digital Domain, created a number of cold-weather effects in 1997's *Titanic*. The film's infamous iceberg that sank the ill-fated ship was a classic small-scale model; the chunks of ice that cascaded from it onto the *Titanic*'s deck were created with computer graphics. Even more amazing, in contrast to the dry-ice antics of past films, the cold-breath exhalations of the *Titanic*'s passengers and crew were added seamlessly by computer into the real-action footage, which had been filmed earlier in warm Mexico.

In the past, disparate elements had to be combined, or composited, optically by masking some parts of frames on a film, superimposing other images on the masked areas and then creating a new piece of film with all the images combined. If the various elements were not merged with exacting precision, the material added to a live scene looked disconnected from the rest of the image and therefore unconvincing.

Optical compositors did have some help from a technique called rotoscoping, which tracks individual elements in a given movie sequence. The rotoscope, developed in 1917 by animation genius Max Fleischer, is simply an elevated device that projects film sequences, frame by frame, down onto a flat surface. For each frame, animators using a classic rotoscope must manually trace every element to be added or altered. The finished product is a series of drawings that indicate where the special effects need to go on each frame. In *Star Wars,* for example, a rotoscope was used to trace the blade of each light saber, thereby showing the animators precisely where the various color

COMPOSITING IN ACTION



For one scene in *Twister,* cameras filmed storm chasers on location (*top left photograph*), but the low-level tornado and the barn it destroyed were added later by special-effects artists. The team constructed digital wire-mesh skeletons of the tornado and barn as viewed from various perspectives (*left on screen* and *above*). Then they positioned the skeletal figures in the live footage (*middle photograph*). Finally, they fleshed out the animation, complete with swirling dust, and combined it with the live action to produce the footage seen by moviegoers (*right*).

WB/UNIVERSAL CITY STUDIOS INC./INDUSTRIAL LIGHT & MAGIC (*imagery*); KNOWLEDGE MEDIA DESIGN (*illustration design*)

glows of the swords were to be positioned. After the saber lights were created as separate elements, they were optically composited into the live-action sequences.

To facilitate the creation of seamless compositing, moviemakers commonly record the live scenes in front of a "blue screen," an evenly lit, blue-colored background. Later, all blue in the picture is eliminated and replaced with other images. The blue-screen process is familiar to all those who watch the evening weather report on television. Meteorologists who seem to be pointing to a colorful weather map are actually gesturing to a blank screen. The busy weather maps behind them are composited in the TV studio to produce the final image of map and person. Blue has been the standard screen color because its elimination from film does not distort human skin color. Other colors, however, especially green and red, are now in use as well. Each hue has its own advantages in the film industry. Green, for instance, is highly reflective and therefore easy to find and drop out of a scene.

Today's special-effects artists usually use digital compositing methods, which are far superior to optical techniques, both in the labor involved and in image quality. Movie directors have their film negatives scanned into digital form. Next, the composite image is created on a computer (which can add in any additional visual elements the director requires). Then the completed images are scanned back onto film. One of the greatest advantages of digital compositing is that it allows near-perfect registration of the scene components, so that the viewer cannot distinguish between what is real and what is computer-generated. More important, the technology allows the director more direct control to add, alter or move objects.

The rotoscoping step in the digital age is also a much faster, computerized process. Animators can now indicate the position of a specific element in one frame and its subsequent position a few frames ahead. The computer then interpolates the element's positions for intermediate frames. After the positions of all elements are charted, the special effects, many of which are now created digitally, are inserted into the film sequence.

Digital techniques for creating special effects and fusing them with live-action scenes allowed the natural-disaster movie *Twister,* which was nominated for the 1996 Academy Award for Best Visual Effects, to be so convincing. Powerful Silicon Graphics computer workstations enabled each tornado in the movie to be crafted as a multitude of individual moving objects, rather than as a single figure. First, the computer experts at Industrial Light & Magic (ILM) constructed a virtual wire-mesh skeleton of the tornado's funnel. Then they applied complex fractal programs to create the rough texture of the vortex's ever changing surface. Finally, they "motion-blurred" the entire debris cloud of each tornado to simulate the natural blurring we perceive when viewing fast-moving objects. This new

type of effects artistry far exceeds the feats that could be accomplished when A. Arnold (Buddy) Gillespie resorted to a fan-blown, 35-foot muslin wind sock to create the famous, and surprisingly believable, Kansas tornado of 1939's *The Wizard of Oz.*

(Modern computer-generated compositing of images also frees the creators to have a bit of personal fun and digitally add features never present in the actual live filming of the scene. As *Twister*'s visual-effects producer Kim Bromley related, "One of the modelers' nicknames is Edsel, so he modeled a grille from an Edsel and made it into a piece of debris." This fictitious remnant of the tornado was then digitally inserted into the movie.)

Similar computer-generated effects breathed life into the monstrous and memorable dust storm incarnation of the title character in the 1999 blockbuster *The Mummy*. To make a huge outdoor dust storm morph into a large malevolent face, the effects people at ILM, under the supervision of John A. Berton, improved on the methods they developed in *Twister.* Instead of portraying the dust storm's components as disjointed clusters of particles, Berton's team created a specially designed particle renderer that gave the storm a continuous flowing character. The dust storm images were composed on computer workstations and then digitally merged into live-action sequences, which had been filmed in Morocco.

A second weather-related phenomenon in *The Mummy* was also computer-generated. The sinister "sand-devil" aspect of the Egyptian mummy Imhotep—the sudden indoor formation of the villain from the very sands of the desert—was created by making digital sand particles from various parts of the scene target specific areas of a wire-frame model of a human figure. The visual effect was further enhanced by generating streams or ribbons from these digital particles that then wove themselves around the human framework.

Sounds Scary

Sound is as important as visuals in generating realistic weather on the screen. So far, though, the art of producing sound effects remains rather more low-tech and empirical than the art of making images. For *Twister,* foley artists—the professionals who assemble the distinctive sounds for movies—used an imaginative variety of materials to simulate the monstrous noises of severe weather. They simply but effectively produced the clattering sound of icy hailstones by dropping pea-size gravel and clinking swords onto metal and wooden surfaces.

To craft the tornado's characteristic moaning and whistling sounds, *Twister*'s audio engineers built an ingenious contraption consisting of different-size pipes and lengths of fishing line. The device was then placed onto a truck and driven at highway speeds so that digital recordings could be made of the wind whipping through and over the pipes and wires. Yet even those masterful sounds didn't completely satisfy the movie's director and sound-effects artists. *Twister*'s tornado screams eventually included other digitally mixed sounds, including the squeals of pigs and camels as well as a classic audio effect used in *The Wizard of Oz:* the noise of loose paper flapping around on the outside of a large rotating barrel.

Of course, the field of special-effects weather is hardly static. As directors demand more and better effects, the bar keeps getting raised. For example, moviemakers have recently started placing more emphasis on indirectly enhancing the main action by introducing seemingly invisible secondary effects behind it. Images of planet surfaces seen in the latest *Star Wars* epic, *The Phantom Menace,* included moving waterfalls and other background motion to impart a more realistic feeling. And the use of computer graphics is still in its infancy. Indeed, the eventual future of feature movies may well be the computerized creation of the entire production—including the total physical environment and perhaps even the actors themselves in a way that makes everything and everyone seem compellingly authentic.

What will be the end result of such work? Many special-effects artists maintain that the greatest compliment they can receive is when, after seeing or hearing a movie effect, the audience simply believes it was real. To paraphrase the classic line, the masters of movie special effects want to be sure that neither rain, nor sleet, nor dark of night will prevent them from achieving the goals of their directors.

RANDY CERVENY is associate professor of geography and meteorology at Arizona State University and a contributing editor to *Weatherwise*, where he has also written on this subject.

Talking about the weather isn't so simple—on TV

CHANNELING THE WEATHER

by STEVE MIRSKY

The easiest job in America is probably being a television weather forecaster in San Diego. If you can say the words "sunny" and "70" without ejecting your dentures, go ahead and fill out a job application. Or so you'd think. Actually, performing on television is a lot more difficult than it looks. I know. That guy in the picture is me. Fortunately for the good people of Pennsylvania, my single appearance as a TV weather guy projected no farther than the studio control booth at Pennsylvania State University.

Only about half of America's TV weather folk are certified meteorologists, a statistic that annoyed meteorologist Fred Gadomski enough for him to offer senior meteorology majors at Penn State a class on how to be on TV. "In a perfect world, everyone who told you about the weather on television should be a meteorologist," Gadomski says. "They know the most about it, and there are a few times each year when the weather gets really serious, and it can mean something to your life or your property. You don't want some Joe Schmoe handling it."

Gadomski understands, however, that TV watchers want more than facts. "All those other times when the weather is not so serious," he says, "you want someone interesting telling you about it. And that's what we're trying to get across here."

I visited Gadomski's class a few years back and got to try my hand, which is pointing at my hometown. About 20 seniors enroll every year, most of whom will nonetheless pursue conventional meteorology careers at the National Weather Service or airports or in the military. But five or six will go on to TV.

Gadomski's class meets twice weekly. The first session covers the technology currently available for creating compelling television graphics that help explain the weather better. For that discussion, students sit in a classroom, wearing jeans and T-shirts. A couple of days later, however, they move into the TV studio. Then they go from looking ratty to looking natty, donning suits to strut their stuff in front of a camera.

On the day of my visit, the students were practicing the kind of one-minute forecast that a local weatherperson does during a network morning news program. After exactly one minute, the network broadcast reasserts its dominion and cuts off the local weather, whether or not. So you'd better have wrapped it up in that 60 seconds. Finish in 52 seconds, and you're facing the unblinking eye of a TV camera for eight seconds that will feel longer than a Minneapolis winter.

Add to that time pressure the fact that there's actually no map behind the weather guy. Instead there's a big, blank, blue wall and TV magic, which replaces that wall with an image of a map. Weatherpeople have to look at an offscreen monitor to see where they should be pointing their own hand, which in fact is flailing at something that is not really there (kind of like being a Congressman figuring out how to spend the budget surplus). Predicting the course of a low-pressure front can thus be simple compared with finding Philadelphia with your finger. (The blue wall can also lead to horseplay, as the monitors are insensitive to anything that same shade of blue. "You can throw a blue ball at someone," says one student, "and it won't show up on camera, but the guy will flinch.")

The toughest battle aside from invisible dodgeball, however, is the delivery. Television demands an unusual combination of attitudes: relaxed and conversational but energetic and upbeat. The biggest, phoniest smile you can possibly imagine plastering on your face will seem just about normal on TV, whereas your typical facial expression and speech pattern may make you look like you've just returned from delivering the eulogy at your dog's funeral. For the average student, the semester in front of the camera is thus a slow peeling away of layers of performance inhibitions.

Those are the rules of the TV game, and anyone who wishes to play has to abide by them. The benefits, however, are worth the arduous investment. Students who do not pursue TV careers nonetheless enhance their communication skills, which will serve them well wherever they wind up. And those students who do wind up on a newscast serve all of us well, by being something rare and positive: trained scientists appearing on television daily. W

STEVE MIRSKY is an editor and columnist at *Scientific American*.

PENNSYLVANIA STATE UNIVERSITY

WEATHER ON THE WEB

Compiled by DIANE MARTINDALE

DUSAN PETRICIC

STATEMENT OF OWNERSHIP, MANAGEMENT AND CIRCULATION (required by 39 U.S.C. 3685). 1. Publication title: Scientific American Presents. 2. Publication number: 0017-429. 3. Filing date: November 16, 1999. 4. Issue frequency: quarterly. 5. Number of issues published annually: 4. 6. Annual subscription price: U.S. and its possessions, 1 year, $19.80; all other countries, 1 year, $23.80. 7. Complete mailing address of known office of publication: 415 Madison Avenue, New York, NY 10017. 8. Complete mailing address of the headquarters or general business office of the publisher: 415 Madison Avenue, New York, NY 10017. 9. Full names and complete mailing address of publisher, editor and managing editor: Publisher, Sandra Ourusoff, 415 Madison Avenue, New York, NY 10017. Editor, John Rennie, 415 Madison Avenue, New York, NY 10017. Managing Editor, Michelle Press, 415 Madison Avenue, New York, NY 10017. 10. Owner: Scientific American, Inc., 415 Madison Avenue, New York, NY 10017; Holtzbrinck Publishing Holdings Limited Partnership, 123 West 18th Street, 8th Floor, New York, NY 10011: (a) Holtzbrinck Publishing Group, Inc. (General Partner), 100 West 10th Street, Wilmington, DE; (b) Georg von Holtzbrinck GmbH & Co. (Limited Partner), Gaensheidestrasse 26, 70184 Stuttgart, Germany. 11. Known bondholders, mortgagees and other security holders owning or holding 1 percent or more of total amount of bonds, mortgages or other securities: none. 12. Tax status: not applicable. 13. Publication title: Scientific American Presents. 14. Issue date for circulation data below: September 1999. 15. Extent and nature of circulation: a. Total number of copies (net press run): average number of copies each issue during preceding 12 months, 378,223; actual number of copies of single issue published nearest to filing date, 355,036. b. Paid and/or requested circulation: (1) Paid and/or requested outside-county mail subscriptions (including advertiser's proof and exchange copies): average number of copies each issue during preceding 12 months, 16,685; actual number of copies of single issue published nearest to filing date, 22,851. (2) Paid in-county subscriptions (including advertiser's proof and exchange copies): 0. (3) Sales through dealers and carriers, street vendors, counter sales and other non-USPS paid distribution: average number of copies each issue during preceding 12 months, 143,802; actual number of copies of single issue published nearest to filing date, 165,000. (4) Other classes mailed through the USPS: average number of copies each issue during preceding 12 months, 6,787; actual number of copies of single issue published nearest to filing date, 14,254. c. Total paid and/or requested circulation (sum of 15b(1), 15b(2), 15b(3) and 15b (4)): average number of copies each issue during preceding 12 months, 167,274; actual number of copies of single issue published nearest to filing date, 202,105. d. Free distribution by mail (samples, complimentary and other free): average number of copies each issue during preceding 12 months, 4,372; actual number of copies of single issue published nearest to filing date, 3,500. e. Free distribution outside the mail (carriers or other means): average number of copies each issue during preceding 12 months, 0; actual number of copies of single issue published nearest to filing date, 0. f. Total free distribution (sum of 15d and 15e): average number of copies each issue during preceding 12 months, 4,372; actual number of copies of single issue published nearest to filing date, 3,500. g. Total distribution (sum of 15c and 15f): average number of copies each issue during preceding 12 months, 171,646; actual number of copies of single issue published nearest to filing date, 205,605. h. Copies not distributed: 206,577; actual number of copies of single issue published nearest to filing date, 149,431. i. Total (sum of 15g and 15h): average number of copies each issue during preceding 12 months, 378,223; actual number of copies of single issue published nearest to filing date, 355,036. j. Percent paid and/or requested circulation (15c/15g £ 100): average percentage of each issue during preceding 12 months, 97.45%; actual percentage of single issue published nearest to filing date, 98.30%. 16. Publication of statement of ownership is required. Will be printed in the March 2000 issue of this publication. 17. I certify that all information furnished above is true and complete. I understand that anyone who furnishes false or misleading information on this form or who omits material or information requested on the form may be subject to criminal sanctions (including fines and imprisonment) and/or civil sanctions (including multiple damages and civil penalties). (Signed) Joachim P. Rosler, President and CEO. Date: January 14, 2000.