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Mt. Washington's wild weather sheds light on aircraft icing

by Bob Henson and Anatta

Researchers from several institutions spent most of April working at the Northeast's highest, coldest, and windiest peak. The Mt. Washington Icing Sensor Project (MWISP) tested methods for remote sensing and improved prediction of in-flight icing conditions, particularly freezing drizzle and freezing rain, which can down aircraft.

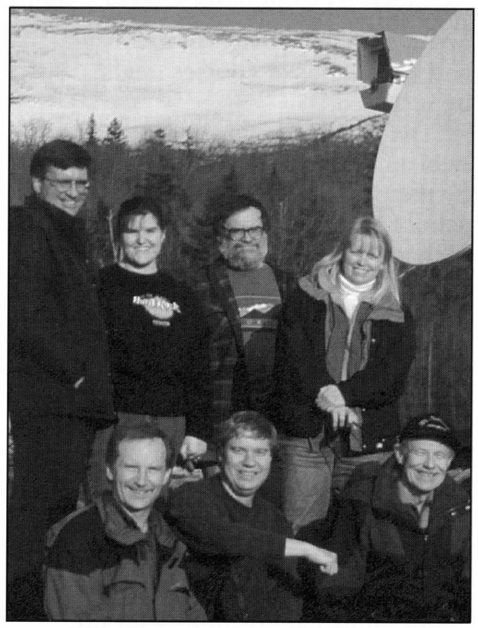
MWISP was the largest field program ever conducted on New Hampshire's Mt. Washington, where some of the first research on icing began in the 1930s. During April, the summit—best known for its high winds—is typically enclosed in clouds over 60% of the time. "It's a wonderful late-winter, early-spring cloud lab," says NCAR's Marcia Politovich (Research Applications Program). She joined Charles Ryerson (U.S. Army Cold Regions Research and Engineering Laboratory, or CRREL) and Kenneth Rancourt (Mount Washington Observatory, or MWO) in leading the field campaign.

During mid-April, the peak saw prolonged snow and cold, with winds gusting above 160 kilometers per hour (100 miles per hour). "The fast-moving clouds provided constantly changing conditions that were a challenge for the radars to track," says Politovich. The researchers found "very dynamic features, even in clouds that were pretty uniform visually." The month ended with ten intensive study days.

The group hopes to be publishing early results from Mt. Washington by this fall. "This is a very rich data set, and we'll be working on it in one form or another for several years," she says.

The goal of MWISP is to improve in-flight icing detection, mainly from remote sensors, and to improve forecasts issued by computer models. Pilot reports can be used for long-term, large-scale comparisons with a model. However, "To get down to smaller scales, like the terminal areas around airports, we need measurements with more detail than just the pilots' 'yes' or 'no' for icing," says Politovich. Better icing-prediction

(Continued on p. 5)



Top: Two of the NOAA radars used in MWISP. Seated on the radar trailer are, left to right, Robert Kropfli, Carroll Campbell, Roger Reinking (all NOAA); standing, l to r, Duane Hazan, Michelle Ryan, Bruce Bartram (all NOAA), and Marcia Politovich (NCAR). (Photos by Bob Henson.)

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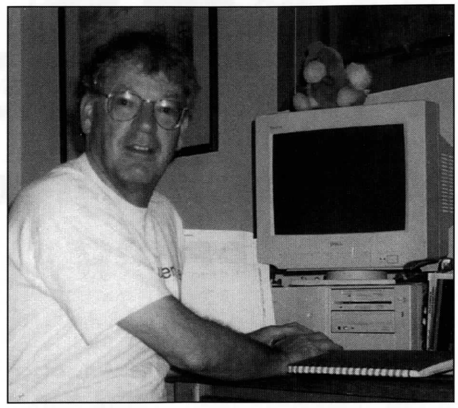
President's Corner

This column is devoted to an editorial that originally appeared in the April–June 1999 issue of the Network Newsletter, *published by NCAR's Environmental and Societal Impacts Group (ESIG). I thought it deserved circulation to the larger university community. Mickey Glantz is the former director of, and currently a senior scientist in, ESIG.*



Michael Glantz.

Climate affairs program: A notion whose time has come?

by Michael Glantz

I have been wondering this past year if there might be a need for the development of a climate affairs program at universities and colleges. I think the notion is a good one, but whether it can be realized in a university setting is an unaddressed question. I received some seed funding from NSF's Atmospheric Sciences Division to assess the feasibility of developing a "model" or template for such an academic program. An e-mail advisory group has been discussing whether and how to go about developing such an activity (in theory) and what kinds of courses might be included.

The idea for a climate affairs activity in an academic setting was inspired by the University of Washington's School of Marine Affairs. Invited to its 25th anniversary celebration in spring 1998, I became acquainted with many of its graduates, now ecologists, political scientists, legal scholars and practitioners, engineers, sociologists, fisheries experts, urban planners, coastal zone developers, among others. They all came out of the same program over the years and were thriving in their chosen careers.... Well, they were getting along in spite of their different political and ideological persuasions about human interactions with the marine environment. So, I thought, could this program serve as a model for those of us focused on climate and climate-related issues? Is the development of a School of Climate Affairs too far-fetched for consideration?

As of the mid-1960s there was not one formally established academic marine affairs program. Today there are more than 50 of them. The first ones emerged in the late 1960s, and I suspect that their development had a lot to do with the ongoing discussions to develop a Law of the Sea. In those deliberations within and among countries, a need was recognized for expertise in many aspects of the marine environment. Academics with some degree of foresight realized that this area was fertile for research, application of research findings, and therefore employment opportunities.

Today, one could argue that governments are in the midst of creating a "Law of the Atmosphere." Concern about greenhouse gas emissions and global warming of the atmosphere, stratospheric ozone depletion, tropical deforestation, El Niño forecasting and impacts, and extreme climate-related events (droughts, floods, fires, infectious disease outbreaks, severe storms) have been added to the traditional concerns about the atmospheric environment: air pollution, transboundary atmospheric pollution, acid rain.

The IPCC (Intergovernmental Panel on Climate Change) focuses scientific research on climate science, climate impacts, and climate policy needs. The Conference of Parties (COP) has met on several occasions over the years to discuss the Protocols to the FCCC (Framework Convention for Climate Change). As a result of concern about global warming, there has been a sharp increase in attention to the human aspects of climate variability and climate change. Aside from the climate change issue, concern has recently grown—thanks in part to El Niño and La Niña—about how well societies cope with interannual climate variability. The point is that there is now, and will continue to be, a growing thirst by societies worldwide for information about the physical, biological, and societal aspects of the climate system. Industries as well as governments will need expertise that may not now exist.

The question, then, is as follows: Is it time for the academic community to consider whether students would benefit from an academic program that focuses on climate affairs—a program, like marine affairs, that encourages scientific study and the application of that science to address societal needs. I think so. Do you?

I would appreciate receiving your thoughts on this issue. Contact me at glantz@ucar.edu or 303-497-8119. ❋

How Unidata helps small schools tackle big projects

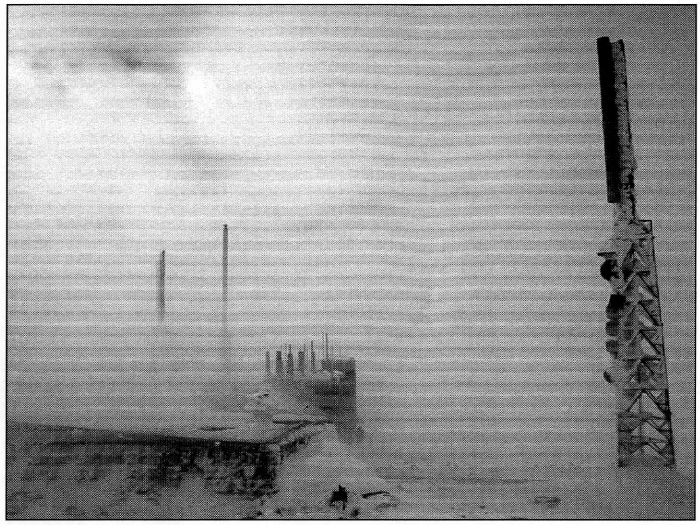
by Bob Henson

When there's cramming or partying to be done, some undergraduates don't get to bed till dawn. All the more noteworthy, then, that a handful of meteorologists-to-be in New England roused themselves at 5:00 a.m. each morning—weekdays and weekends alike—to make forecasts for the Mt. Washington Icing Sensor Project (MWISP) during the month of April.

"I was amazed," says assistant professor Pamela Grube of Lyndon State College in Lyndon, Vermont. The forecasts for Mt. Washington were issued at 8:00 a.m. each day by student teams at Lyndon State and at Plymouth State College, about 80 kilometers (50 miles) to the south in Plymouth, New Hampshire. Both groups predicted cloud depth, base, and height, as well as the heights of the temperature layers at 0, -10, and -20°C (32, 14, and -4°F), all at six-hour increments. "It's a rather detailed forecast," says Grube. "It's good experience because the deadline is very operational."

The meteorology programs at both Lyndon and Plymouth are among the best-known academic units at their schools. However, they are small in funding and enrollment compared to research behemoths such as the Universities of Washington or Oklahoma. How do these smaller departments maintain a high-quality educational experience with limited dollars? Part of the answer is UCAR's Unidata program. Unidata provides over 140 colleges and universities with access to real-time weather data and software for analyzing those data. To support their day-to-day teaching as well as special projects like MWISP, smaller schools rely heavily on Unidata.

"To put it bluntly, without Unidata, I doubt if our program would be here today, at least if we want to have the students look at current weather information," says professor James Koermer, the department head at Plymouth State. Both Lyndon State and Plymouth were among the institutions that helped plan the creation of Unidata with NSF and UCAR in the mid-1980s. They were also among the first 20 to obtain Unidata broadcasts of satellite imagery through the University of Wisconsin's McIDAS system. Today, Plymouth State maintains a Ku-band satellite feed from Alden Electronics for printing and posting large maps and gathering basic observational data. Most of its other real-time data, and all of Lyndon's, arrive through Unidata's Internet Data Distribution (IDD) system.


A typical April day on the summit of Mt. Washington. (Photo by Bob Henson.)

Rather than having data shipped from a single center, the university community banded together—with Unidata guidance and support—to build a national distribution system that uses Unidata software at each school's site. Member institutions assume the responsibility for relaying data to each other from various sources so that no one computer or network link gets overburdened. Users "subscribe" for each data stream of interest; the products in the stream are delivered as soon as they are available from the source. "The IDD may have been the original example of Internet 'push' technology," says Unidata program manager Ben Domenico, referring to data that are sent to the user through prearrangement rather than sought out a la carte.

"Unidata gives us a vast amount of data that wouldn't be gotten any other way," says Harry Maybeck, who oversaw Plymouth State's forecasting team for MWISP. Although many weather products can be retrieved from the Web, says Maybeck, the user might have to go to ten or more Web sites to get the required data, and even then it might not be in a useful form. "When we get it [from Unidata], it's already been put in a package we can use. It's a great time saver and a greater source of accuracy."

In October 1993, Don Murray—now at Unidata, then at Lyndon State—launched a Gopher server to help get weather information to local schools. The following spring, Plymouth State and (a few months later) Lyndon State leaped onto the Web with real-time public weather pages that were among the nation's first. Much of the sites' content is produced through Unidata-supported software, such as its Local Data Manager and McIDAS. For instance, Lyndon uses McIDAS-based scripts to produce an animated global jet-stream image, a popular stop on the college's Web page. McIDAS-derived products are freely placed on the Web for public access at both schools, although licensing restrictions prohibit (except for local Web access) some radar and lightning products obtained through IDD feeds from Weather Services Incorporated and the State University of New York at Albany.

Along with many of its fellow Unidata institutions, Lyndon State makes extensive use of the Linux operating system, a university-based offshoot of UNIX that operates as free software. After Lyndon and other schools began using Linux, Unidata responded by providing support for the system. Meanwhile, Plymouth State is the first Unidata school to try a similar operating system called FreeBSD on PC-based systems. The department spent $2,000 for one non-FreeBSD system software upgrade last year, says Koermer. "Especially for the smaller schools, it's sometimes hard to come up with even $2,000 for an upgrade." The school is taking Unidata source codes and adapting them to FreeBSD; for instance, Unidata's Steve Chiswell recently helped port GEMPAK, an analysis program, to the FreeBSD system.

Many of today's television weathercasters honed their forecasting skills by using Unidata products at their alma maters, including Lyndon State, which produces more than its share of TV weathermen and weatherwomen. The broadcast program is among several career tracks at Lyndon that prepare students for either the National Weather Service, private industry, or graduate school. Plymouth State, which has a single, traditional degree track for its B.S. in meteorology, also uses Unidata resources to help train students who want broadcast experience; they produce a nightly weather segment for their local community access channel by combining Unidata products with chromakey and other television technology.

"It's really all possible because of the Unidata support," says Koermer. Mark Tucker, who manages computing systems at Lyndon State, concurs: "It's about the best support I've ever seen for anything computer-related." Lyndon State averages 100 meteorology majors per year, according to faculty member William Fingerhut. This makes the assistance from Unidata critical for a high-quality program. "We don't have the financial resources and the in-house support to maintain all the high-tech equipment and software you need these days," says Fingerhut, who has worked with Unidata for over a decade. "We just couldn't do it without Unidata, and I think all the smaller schools would say the same thing."

The Lyndon State weather page is at http://apollo.lsc.vsc.edu. Plymouth State's weather page is at http://vortex.plymouth.edu. ❋

Science Bit

Arctic snow chemistry is more complex than previously thought

Purdue University and Michigan Technological University research teams studying natural processes that affect ozone in the Arctic atmosphere have discovered that snowpacks not only absorb chemicals from the atmosphere, but also can help produce them. The findings, published in two papers—one in *Nature* and the other in *Geophysical Research Letters*—cast a new light on scientists' perceptions of how atmospheric gases are processed, says Paul Shepson, professor of atmospheric chemistry at Purdue.

The new findings also may affect the way that scientists view data from ice core studies, because researchers have assumed that the air trapped in ice provided representative samples of atmospheric conditions at the time the ice was formed. "Ice core studies designed to look at reactive species such as nitrates may have to be revisited, as the air bubbles found in these ice cores may not be the mirrors of atmospheric composition that we suspected they were," Shepson says. This is not a concern for more stable greenhouse gases such as carbon dioxide and methane, which have been extensively studied in ice cores, because those gases are less likely to react with other compounds in snow or ice.

Shepson led a research group to the Canadian Arctic last spring to observe how sunlight interacts with various gases in the atmosphere to reduce near-surface ozone levels. (For a report on NCAR's participation in this project, see the Fall 1998 *UCAR Quarterly*, http://www.ucar.edu/quarterly/fall98/ozone.html.) In the Arctic spring, after several months of total darkness, atmospheric ozone may be completely depleted at times. From the Environment Canada research site at the Canadian Forces base at Alert, the group tracked levels of formaldehyde and other atmospheric compounds. Formaldehyde is an important part of the atmosphere's self-cleaning mechanism because when it absorbs light, it breaks apart to produce hydroxyl radicals.

Previous studies of formaldehyde in the Arctic had shown concentrations up to ten times higher than expected. The Purdue team's measurements of formaldehyde in the snowpack and in the atmosphere, published in the *Nature* article, suggest that the compound is produced through photochemical reactions at the snow surface. "The data account for much of the discrepancy between the high concentrations of formaldehyde found in the Arctic and the amounts predicted by our models," Shepson says.

The paper in *Geophysical Research Letters* reports on studies at an ice core site at Summit, Greenland, led by Richard Honrath of Michigan Technological University, in which the Purdue group also participated. That team found that concentrations of nitric oxide and nitrogen dioxide—collectively known as NO_x—were actually higher within the snowpack than in the atmosphere. The findings suggest that nitrate ions in the snow can interact with sunlight to produce NO_x, a pollutant derived largely from the combustion of fossil fuels and a critical precursor to the production of ozone in the atmosphere.

"This observation changes the way we look at atmospheric chemistry in a fundamental way, in that deposition of nitric acid to the snow was previously regarded as the final fate of NO_x," Shepson says. "Now it appears that nitric acid in the snow can be reprocessed by interactions with light, causing re-release of a variety of pollutants back into the atmosphere."

In addition to forcing a re-evaluation of data from ice core studies, the new findings call into question model treatments of the interaction of gases with surfaces, Shepson says. "Although we are starting to do better with atmospheric particles, it is important to remember that a potentially important atmospheric surface is the surface of the earth."

Purdue University, Michigan Technological University

MWISP (continued from p. 1)

software is expected to become part of the proposed weather research and forecasting model (see p. 10).

Remote sensors at MWISP included a five-channel, fully polarimetric radiometer at the summit that sensed radiation emitted by clouds. Another set of instruments was located near Bretton Woods, a few miles west of the peak. These included X-, K-, and W-band radars; a lidar; and a second multichannel radiometer. Balloon-borne instruments were launched from various points by a mobile unit from NCAR. Plymouth State and Lyndon State Colleges provided weather forecasts (see related story on p. 3).

The NASA Glenn Research Center flew its Twin Otter aircraft through clouds above the peak to help document the uniformity in time and space of summit-cloaking clouds. Scientists from NCAR, NOAA, CRREL, and Quadrant Engineering analyzed data from remote sensors and compared the results with on-site measurements from the summit and aircraft.

A previous set of WISP experiments took place across northeast Colorado in the early 1990s. However, few tests had been done on supercooled clouds with relatively high liquid-water content, rare across Colorado but more common in the Northeast. Because of this geographical bias, says Politovich, "This is one of the first documentations of the effect of freezing rain on flight over an extended period." According to NCAR scientist Ben Bernstein (Research Applications Program), "Much of the research and development of operational forecast tools on supercooled drops has focused on freezing drizzle and ignored freezing rain." Bernstein has analyzed a case from February 1998 in which the same NASA Twin Otter aircraft now flying in MWISP suffered over 90 minutes of exposure to freezing rain above the Midwest. The result was a major degradation of the plane's performance, including an increase in drag of up to 200%.

The U.S. Army's participation in MWISP through CRREL stems in part from the huge number of Army helicopters and other aircraft vulnerable to weather. "The Army has the largest fleet of airborne vehicles in the military," notes Ryerson. Although airport weather safety has increased in recent years, he adds, "helicopters don't use airports." CRREL has joined NASA and the Federal Aviation Administration (FAA), along with scientists at NCAR and elsewhere, for an ambitious ten-year program to develop an in-flight safety system that addresses icing, wind shear, and thunderstorms. The next collaborative icing study is being planned near Ottawa, Canada, for next winter, with participation from that nation's Atmospheric Environment Service. And "we are thinking of going back [to Mt. Washington] in two years," Politovitch says. "That gives us time to analyze the data, see what different or new instruments to deploy, and do some more homework."

MWISP was funded largely by the FAA and NASA, along with CRREL and MWO. Providing instruments were NCAR; NOAA's Environmental Technology Laboratory; the University of Massachusetts; the Defense Research Establishment at Val Cartier, Canada; ATEK Data Corporation; and Stratton Park Engineering. ✻

Science Bit

Antarctic ice shelves breaking up due to decades of higher temperatures

Two ice shelves on the Antarctic Peninsula known as the Larsen B and Wilkins have lost nearly 3,000 square kilometers (1,200 square miles) of their total area in the last year, according to researchers at the University of Colorado at Boulder's National Snow and Ice Data Center (NSIDC) and the British Antarctic Survey. The scientists attribute the retreats to a regional warming trend that has caused the annual melt season to increase by two to three weeks over the last 20 years.

"We have evidence that the shelves in this area have been in retreat for 50 years, but those losses amounted to only about 7,000 square kilometers," said David Vaughan, a researcher with the Ice and Climate Division of the British Antarctic Survey. "To have retreats totaling 3,000 square kilometers in a single year is clearly an escalation. Within a few years, much of the Wilkins ice shelf will likely be gone." The Larsen B shelf is currently about 7,000 km^2, and the Wilkins shelf is about twice that large.

Satellite photos monitored by NSIDC show that the Larsen B ice shelf has continued to crumble after an initial small retreat in early 1998. In a series of events that began in November 1998, an additional 1,714 km^2 of shelf area caved away. On the opposite side of the peninsula, the Wilkins Ice Shelf retreated nearly 1,100 km^2 in early March of last year.

Scientists looking at weather satellite imagery at that time suspected a breakup was under way and had their suspicions confirmed by radar satellite images. "The radar images showed a large area of completely shattered ice, indicating an ice front 35 kilometers back from its previous extent," said Ted Scambos of NSIDC. "The sudden appearance of thousands of small icebergs suggests that the shelves are essentially broken up in place and then flushed out by storms or currents afterward."

The British Antarctic Survey scientists had predicted one of these retreats, using computer models to demonstrate that the Larsen B was nearing its stability limit. Where ice shelves are supported by islands and sheltering coastline, they can become stable, long-term features. Surface features on the Larsen B indicate that it has existed for at least 400 years. But with the small breakup observed last spring, the shelf had already retreated too far to continue to be supported by adjacent islands and shorelines.

The British researchers, who have monitored the peninsula's climate warming for decades, report an increase in mean annual temperature of about 2.5°C or roughly 4.5°F since the 1940s. Average summertime temperatures have inched to just above 0°C. Both groups of scientists concur that ice shelf breakup is a direct result of local climate warming.

Images of the Larsen B and Wilkins ice sheets are available on the Web at http://www-nsidc.colorado.edu/NSIDC/ICESHELVES/lars_wilk_news.

University of Colorado, British Antarctic Survey

Upgraded Doppler on Wheels is ready for the road

by Bob Henson

Built on a shoestring four years ago, Doppler on Wheels (DOW) hasn't been stingy with its data. This pack of portable weather radars has crisscrossed the country, peering inside tornadoes, hurricanes, and winter storms. This spring the DOW II and DOW III units received a major upgrade at NCAR, preparing them for field work on two continents over the next year and expanded use by university scientists.

"They don't look [much] different, but their brains and hearts are different," says Josh Wurman, an assistant professor at the University of Oklahoma. Wurman maintains the two existing DOW units with support from NSF's Major Research Infrastructure fund. (The original DOW was retired over two years ago.) NSF also paid for the recent improvements with in-kind assistance from NCAR staff, including technicians Jeff Bobka, Al Phinney, Tim Rucker, and Joe Vinson (Atmospheric Technology Division, or ATD).

Each radar is mounted behind a mini-processing room at the back of a flatbed truck. The most visible addition to DOW III is an extensible weather station to be used to verify conditions at the radar site. Mounted on a hydraulic pole between the antenna pedestal and the truck's cab, the station can be lofted 10 meters (30 feet) above ground level. "The idea is that in very high winds, the pole will stay rigid," says Wurman.

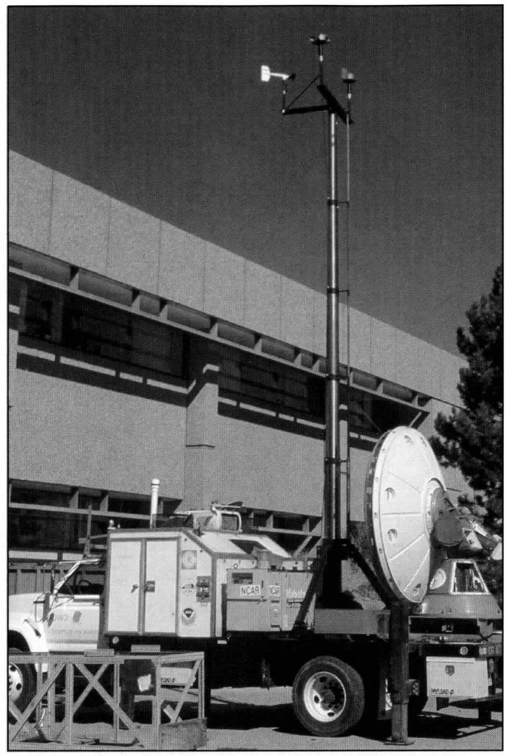
On the inside, DOWs II and III have received processor transplants. They now feature the second generation of the PC integrated radar acquisition board (PIRAQ) developed by ATD engineers Mitchell Randall and Eric Loew. PIRAQ made DOW possible by allowing radar data to be processed in real time through a personal computer rather than a costly, room-sized set of equipment. PIRAQ II has twice the computing power of the original, and "there's a pretty long list of other changes," says Randall. "When we did the first PIRAQ, we didn't realize where it would be used." The new version is compatible with coherent lidar and FM-CW radar, and it can transform a conventional weather radar into a Doppler radar.

Both DOWs have also gotten new antenna controller systems, developed by ATD's Jonathan Lutz. These will allow for faster and more precise pointing and scanning with the radar beam. Radar receivers have also been improved. Together, all of the upgrades should allow for winds to be sampled at an ultra-crisp resolution of 12.5 meters (38 feet).

Just as important to Wurman as the new features is improved reliability. "Our goal is to have it work every time," he says. The very success of the DOWs is one reason why a tune-up was needed: "Life on the road is very difficult. The radars get shaken a lot going down a lot of bad roads."

During last year's devastating tornado at Spencer, South Dakota, on 30 May, two DOW units got within 1.7 km of the twister. Then the antenna of one unit refused to spin. The DOW team ended up obtaining single- rather than dual-Doppler data, which prevented a full two-dimensional wind analysis. Still, the team obtained a peak wind of 115 m/s (258 mph) about 50 meters above the surface. According to Wurman, this was the most disastrous tornado strike for which high-resolution measurements were collected—that is, until the central Oklahoma twisters of last month (see sidebar).

These events may also help to confirm the Fujita tornado-damage scale. The scale gives numerical ratings (F0 to F5) based on observed damage. In turn, these damage ratings are connected to wind-speed ranges, but there have been few data to confirm



The upgraded DOW with its new extensible weather station in front of NCAR's Foothills Lab. (Photo by Carlye Calvin.)

whether the higher wind ranges are in fact accurate. The peak DOW wind from Spencer corresponds to a strong F4 rating, "which is what they found in the damage survey," says Wurman. Similarly, the F5 wind measured in Oklahoma on 3 May was backed up by F5 damage at ground level.

Wurman led the conceptualization and construction of the first DOW unit, which has since been cannibalized for its two newer siblings. To build the original DOW, he and colleagues pulled together expertise and surplused material from NCAR, OU, and the National Severe Storms Laboratory (NSSL). The first DOW made its debut in the southern plains for the 1995 field session of VORTEX (Verification of the Origins of Rotation in Tornadoes Experiment). Twisters remain at the top of the DOWs' priority list. The radars traversed the plains this spring for the second year of the field project ROTATE (Radar Observations of Thunderstorms and Tornadoes Experiment, http://aaron.ou.edu/rotate.html).

Later this summer, one DOW will set its sights on landfalling hurricanes. In 1996's Hurricane Fran and last year's Bonnie and Georges, DOW data verified the presence of small-scale horizontal rolls that transport upper-level winds downward. These may be the cause of localized streaks of intense damage such as those discovered after Hurricane Andrew. DOWs II and III measured gusts over 55 m/s just above the surface while parked at airports in Gulfport and Keesler Air Force Base, Mississippi, during Hurricane Georges last September. "We like airports in hurricanes," says Wurman. "They're treeless and flat, with no debris."

The other DOW will be shipped across the Atlantic in August to join the Mesoscale Alpine Programme in northern Italy and southern Switzerland for three months. (See the Winter 1998 *UCAR Quarterly*, http://www.ucar.edu/quarterly/winter98/sampler.html.) Matthias Steiner (Princeton University) will oversee the DOW's deployment in the Toce (Italy) and Tocino (Switzerland) river valleys, close to the NCAR S-Pol dual-polarization radar. Air flow in the valleys will be invisible to S-Pol, so the DOW will gather smaller-scale measurements beneath the larger radar's coverage area. "Just getting [the radar] down some of those mountain roads will be interesting," Wurman adds. "It's not Oklahoma."

Researchers are invited to contact Wurman about using one or more DOWs outside of the radars' springtime commitments for tornado research. "We're really anxious to have the science community use these," he says. Interested scientists may contact Wurman directly (303-325-0589, jwurman@ou.edu). The DOW Web page is at http://aaron.ou.edu/dow. ❋

Oklahoma twister yields a world-record wind

Wurman and his DOW team often drive hundreds of miles to snag a tornado, but one of the fiercest on record paid a visit to their own backyard on 3 May. The Oklahoma City area and several other points in Oklahoma and Kansas were raked by tornadoes that evening that killed more than 45 people and caused up to $1 billion in damage.

The strongest tornado of the day was a long-track F5 that plowed through portions of Oklahoma City and its suburbs. The two DOWs were positioned on either side of this twister (one unit within one mile of it) as the tornado took shape near Chickasha, about 65 km southwest of Oklahoma City, around 5:45 p.m. The DOWs tracked the storm over the next hour, measuring winds as high as 142 m/s (318 mph) a few dozen meters above ground. Should these wind speeds hold up in later analysis, they will be the highest ever measured in nature.

Also within a mile of the tornado was a separate portable Doppler radar, deployed by OU professor Howard Bluestein in conjunction with the University of Massachusetts and support from NSF. With a wavelength of 3 millimeters, this UMass radar offers limited range but very high spatial resolution, as fine as 5 x 5 x 15 m at a range of one mile. As they tracked the tornado, close to a point where most of a house was swept from its foundation, Bluestein's team saw wavelike features—possibly multiple vortices—along the edge of the tornado. "These are the highest-resolution images ever obtained of the inside of a powerful tornado," says Bluestein, who is collaborating with Andrew Pazmany from UMass. "We hope to combine our data with Josh [Wurman]'s and those from the mobile mesonet [operated by OU's Jerry Straka] to form a more complete picture of tornado structure."

DOW followed other tornadoes until after midnight, including a mile-wide twister that damaged or destroyed every building in the town of Mulhall. Afterward, the DOW team caught its breath and contemplated the vast task of sifting through observations from the portable Dopplers as well as the UMass radar, stationary radars, and other equipment that documented the tornado. "We're reeling with the volume of data we've collected," said Wurman. Preliminary DOW data and a map of the tornado's initial path with radar locations can be found at http://bigmac.metr.ou.edu/dow/image.

Left: The destruction in southeast Oklahoma City was ranked F5, as was the tornado's wind speed.

Right: This shattered billboard is on I-240, one of three interstate highways in Oklahoma City struck by the 3 May tornadoes. (Photos by Bob Henson.)

INDOEX finds surprisingly dirty air

by Carol Rasmussen

Investigators in the Indian Ocean Experiment found the atmosphere over the Indian Ocean both dirtier and more complex than they expected. Although the INDOEX data, collected around the Maldive Islands in February and March, have not been released yet, some of the UCAR participants in the multinational experiment described their initial findings for the *UCAR Quarterly*.

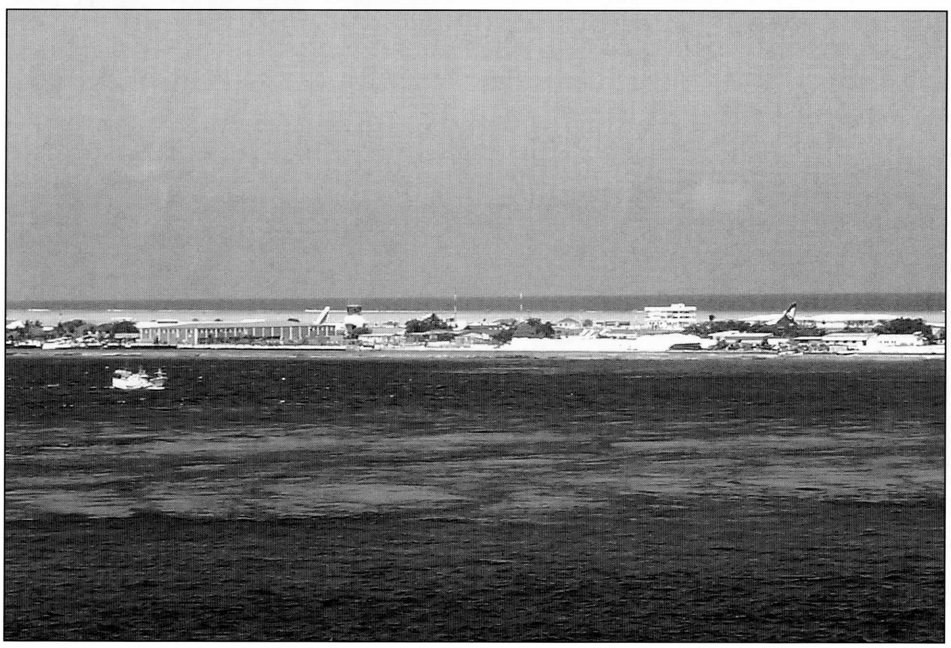
A thick layer of very polluted air, extending more than 1,000 kilometers (600 miles) offshore from the Indian subcontinent, covered the ocean almost constantly during the six-week observing period. The NSF/NCAR C-130 aircraft recorded aerosol optical depths, a measure of murkiness, as high as 0.7—equivalent to a bad day in downtown Los Angeles. Visibility was often under ten kilometers. Aerosols of soot, sulfates, nitrates, organic particles, fly ash, and mineral dust made up the haze, which was accompanied by the gases carbon dioxide and sulfur dioxide. The presence of these compounds is "conclusive evidence that the haze layer is caused by pollution," according to project director Bruce Gandrud (NCAR Atmospheric Technology Division and Scripps Institution for Oceanography).

"Clearly, this is global change at its worst," said V. Ramanathan (Scripps), the co-chief scientist and U.S. coordinator for INDOEX. "We can only hope that INDOEX data will have a beneficial policy impact."

Away from the haze over the Southern Hemisphere, the C-130 sampled almost completely clean air, with an aerosol optical depth of 0.1. James Moore (UCAR Joint Office of Science Support, or JOSS), the aircraft coordinator for INDOEX, noted that some researchers "got very interested in studying the interface between the much cleaner air from the Southern Hemisphere and the very polluted air coming from the north—how rapidly the chemistry changed and what a distinct line there was between the two. We were treated very well by Mother Nature in that she brought the clean air close enough to us that the scientists could study that interface a bit more than they thought they would be able to do."

Although the extent of the polluted air was a surprise, the circulation pattern that carried it out to sea is fairly well understood, according to INDOEX participant Joachim Kuettner. Kuettner holds the UCAR Distinguished Chair for Atmospheric Science and International Research, funded by NSF. He explains that in the Hadley Cell atmospheric circulation, air rises over the Southern Hemisphere ocean, flows northeast, descends over the Indian subcontinent, and moves toward the southwest. As the air descends and warms, it dries out; and with no precipitation to clean the air, it becomes dirtier and dirtier. Polluted air flowing southwest from Burma and Indochina compounds the problem. This heavily polluted low-level air is carried all the way to the Southern Hemisphere, where it meets the clouds of the intertropical convergence zone and finally dissipates.

Hulule Island in the Maldives was the C-130's base during INDOEX. (Photo by Gene Martin, JOSS.)



Cloud complexities

Since one focus of INDOEX was the indirect effects of aerosols—how the particles interact with clouds—the scientists were looking forward to sampling in and around clouds. But that turned out to be more complicated than they had anticipated. Ramanathan cited "two major complexities which will have to be sorted out in the coming year or two." The first is that clouds in the region were often embedded in the band of haze, which was up to about four kilometers deep. The radiative interaction between the clouds and haze is not clear yet, according to Ramanathan; "The direct effect of aerosols in such cloudy and hazy regions has not been looked at before and needs very detailed study." The second difficulty was that cirrus clouds often overlay the low clouds, a situation that is also not well understood.

Principal investigator Bill Collins (NCAR Climate and Global Dynamics Division, or CGD) mentioned another surprise. "We had been examining cloud cover in that region using satellite observations for some time, and the satellites were always telling us the total amount of cloud was very small. That's because the clouds were smaller than the finest satellite resolution. There are a lot of tiny little cumulus clouds."

During the experiment, Collins, Philip Rasch, and Brian Eaton (both from CGD) produced forecasts of aerosols over the region using a combination of a chemical transport model and a system for assimilating satellite aerosol observations. With the data from INDOEX, they will create a three-dimensional aerosol analysis for the experiment period. "This allows you to create a large-scale picture of the aerosols that is consistent with the observations," Collins said. "We can use that to extrapolate the in situ observations to a very large region, and then we can begin computing the direct rate of forcing of aerosols over the Indian Ocean."

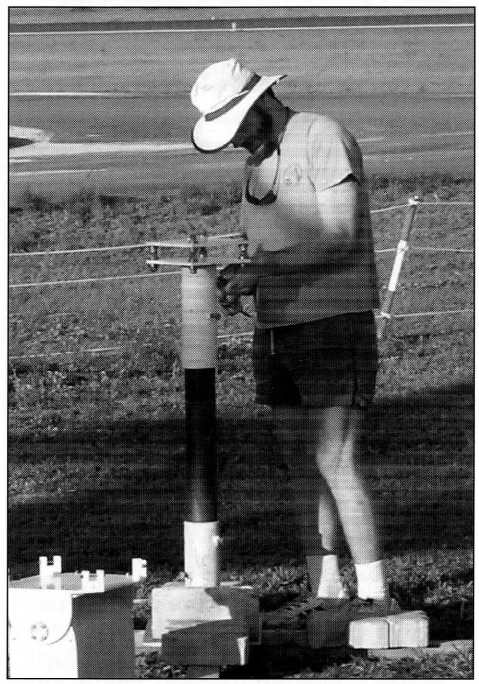
INDOEX principal investigator Richard Shetter (NCAR Atmospheric Chemistry Division) supplied the experiment with up- and down-looking spectroradiometers that flew on the C-130. The sum of the up- and down-looking data gives the actinic flux—all the radiation that reaches a point in the atmosphere from any direction. Teresa Campos, also of ACD, operated the instrument because Shetter and the rest of ACD's Atmospheric Radiation Investigations and Measurement Group were busy running spectroradiometers in PEM-Tropics B, a concurrent NASA experiment in the South Pacific. During INDOEX, "We saw similar things to what we'd seen in other missions in terms of enhancements of radiation around clouds," said Shetter.

"Our instrument performed well, and we got lots of data," Shetter summarized. Having the same kind of data from both tropical experiments is likely to create some synergy. "Combining the INDOEX data with the NASA data set, we're going to start establishing a climatology in what we'll see for photolysis frequencies."

A unique data set

Not only Shetter but all of the principal investigators were satisfied with their data, according to Ramanathan. Previous observations in this part of the world have been few; the last major field project in the area was the Monsoon Experiment, 20 years ago. Thus the INDOEX data will be useful for answering other questions besides the role of aerosols in climate. For example, the data may offer an increased understanding of the monsoon cycle and its connection with other global cycles such as the El Niño/Southern Oscillation. Any improvement in predicting the intensity of the monsoon would be a socioeconomic boon for the millions of inhabitants of India and Southeast Asia, as well as allowing improved global climate models and the potential for better simulation of future climate change.

JOSS is responsible for INDOEX data management, and all the data will eventually end up there. It will be accessible at a link from the JOSS Web site for field-project data, http://www.joss.ucar.edu/cgi-bin/codiac/projs. The INDOEX catalog, giving daily operations summaries, is currently on line at http://www.joss.ucar.edu/indoex/catalog. ❋



Craig Motell (University of Hawaii), one of about 80 INDOEX participants supported by JOSS, installing a satellite antenna to receive data from NASA's Sea-viewing Wide Field-of-View Sensor (SeaWiFS) instrument. (Photo by Gene Martin, JOSS.)

Science Bit

Changes in El Niño show up in the Nile

Hydrologists at the Massachusetts Institute of Technology have used records of the Nile River's height to put recent occurrences of El Niño into historical perspective. The researchers, led by associate professor Elfatih Eltahir, compared records from 1872 to 1997 of both the Nile River—indicating years of flooding or drought—and Pacific Ocean sea-surface temperatures—indicating El Niño years. They found that 30% of the natural variability in the Nile's water-level fluctuations could be linked to El Niño. Based on that information, they analyzed records of Nile water levels for the past 1,000 years. These levels have been measured since 622 A.D. using a simple gauge, the nilometer.

Using the Nile's height as an indicator of El Niño years, the researchers determined that El Niño has occurred more often and with longer duration in the past two decades than in most similar periods during the last millennium. Continuation of this trend for a few more decades would indicate a shift in global climate, but Eltahir cannot say whether that shift is the consequence of human activity. The research, funded by NSF, NASA, and the Alliance for Global Sustainability, was published in *Geophysical Research Letters*.

Massachusetts Institute of Technology

Weather Research and Forecasting Model

by Carol Rasmussen

For the past couple of years, a group of scientists from the research and forecasting communities has been taking the first steps on the long road to a new kind of model—one designed for all of them. Joseph Klemp of NCAR's Mesoscale and Microscale Meteorology Division (MMM) reported on the proposed weather research and forecasting (WRF, pronounced "warf") model at the U.S. Weather Research Program's conference this spring.

Why develop a new model now? Klemp says, "Certainly numerical weather prediction models have been evolving over the past 30 years and have been improving dramatically in their capabilities. However, we still have a long way to go." Existing models cannot fully use some of the new, small-scale observational data that are now available. Model treatments of some physical processes have proved to be inadequate. Perhaps most important, though, is the chance to combine expertise from both types of modelers. Klemp explains, "The model's purpose is both to improve our understanding and prediction of mesoscale weather and to promote closer ties between the research and operational forecasting communities. It isn't going to be your model or my model, it's going to be our model."

Participants come from four organizations: MMM, NOAA's National Centers for Environmental Prediction (NCEP), NOAA's Forecast Systems Laboratory (FSL), and the University of Oklahoma's (OU) Center for Analysis and Prediction of Storms (CAPS). "Each of the organizations involved supports a state-of-the-art model, but they all recognize the need for new and better ways of doing things," says Klemp. "If we pool our resources we'll end up with a better outcome." Scientists from other institutions are also contributing, including Lou Wicker at FSL, Bob Wilhelmson at the University of Illinois, and Dave Dempsey at San Francisco State University.

The participants anticipate that:

- MMM will maintain the model, freely distribute it to and support its use by the community, and migrate its own research to the new model. The new model will take the place of the NCAR/Pennsylvania State MM5 model.
- FSL will gradually transfer its development efforts from its RUC model to the WRF model, which will replace the RUC model when it achieves operational status.
- NCEP will implement the WRF model as a high-resolution nest within its operational regional forecast model (Eta) and consider it as a replacement for its regional model, based on the merits of its performance.

Science Bit

When waffling on flood control is a good thing

North Dakota's Red River of the North, which flooded catastrophically two years ago, is the site of a proposal to protect an entire river basin by using existing road networks to create temporary floodwater storage instead of spending millions of dollars to build more dikes.

"There are two types of dikes: Those that have been topped and those that will be topped," says Gerald Groenewold, director of the University of North Dakota (UND) Energy & Environmental Research Center (EERC) in Grand Forks. "The waffle is a cost-effective option that doesn't rely on new permanent structures to control flooding. It would also benefit everyone living within a drainage basin during times of droughts and floods."

The idea behind waffle flood control is to use existing, raised road networks that crisscross rural areas—resembling the grid pattern on a waffle—as temporary microstorage basins. Just as each individual square on a waffle can hold syrup, each area enclosed by roads is capable of storing water. During major flooding, the water would be held for several days and then released gradually, lowering river crests by an estimated 30%.

In times of drought, water captured from winter snow could be used for irrigation, to recharge depleted aquifers, or to improve topsoil and subsoil moisture on farm land.

Implementing waffle control would require gathering highly accurate location coordinates and elevations of road crests, drainage structures, bridges, and land surface in areas of the basin thought to have potential value as floodwater storage areas. Using a combination of global positioning system and geographic information system technologies, a three-dimensional picture of the drainage basin would be created. The data would be used to model the water storage potential and characteristics of the basin. If model simulations showed that the idea was feasible, a floodwater storage and release plan would be developed for use by policy-making organizations in the Red River Valley

Groenewold says the idea of using the waffle in the Red River Valley is receiving strong support in the United States and Canada from farmers, farm groups, water management organizations, local and state elected officials, urban and rural residents, and federal agencies. In the 1999 North Dakota legislature, an amendment authorizing $2.25 million in state funding to study the waffle concept has been added to a bill containing a variety of water and flood control projects throughout the state.

Leon Osborne, director of the Regional Weather Information Center at UND, says that based on studies of regional climate cycles, it appears that the potential for major flooding in the Red River Valley could continue through 2005. An EERC study on climate cycles based on geological evidence indicates that the northern plains region is in a wet cycle that occurs about every 160 to 170 years. But "we have done virtually nothing to prepare ourselves for a truly great flood," according to Groenewold.

"We can't continue to address this issue on a town-by-town basis," says Groenewold. "The consensus is growing for meaningful, basinwide flood protection. This requires the development of strategic partnerships—local, state, national, and international—within the Red River drainage basin."

University of North Dakota

- CAPS will conduct fundamental studies in small-scale data assimilation and parameter retrieval appropriate for use in the new model.

What will it look like?

The model developers have outlined their priorities for the WRF model. It should be accurate and efficient over a broad range of scales, from cloud-sized to synoptic scale. However, design emphasis is on a high-resolution model with a horizontal grid of one to ten kilometers. "If we're forced to make compromises between coarse resolution and fine resolution, we'll put the emphasis on fine," says Klemp. The model will have improved physics, especially cloud microphysics and representations of convection and turbulence. Data assimilation will be improved, with an emphasis on making better use of small-scale observations. The model will adhere to FORTRAN 90 standards and use standard interfaces for its physics so that scientists can "plug and play" their own physics packages within the model. The scientists envision developing components in steps so that individual parts can be evaluated without slowing the overall process. Finally, Klemp emphasizes, "We are not starting from scratch. We will adapt the best features of existing models and develop new techniques where deficiencies are identified."

The developers are currently wrestling with "numerical model issues," Klemp reports, such as the prognostic equation set, grid staggering, vertical coordinates, terrain representation, and time integration. They are testing alternative approaches to some of these problems on idealized simulations "where we know what the correct answer is."

The groups have also made progress in developing the overall software framework for the model so that it can run efficiently on various types of parallel computers, such as distributed memory and shared memory. "There's a driver layer on top that figures out how to work with the machine, so that the model code that scientists work with remains as simple as possible," Klemp explains.

Nine WRF working groups have been created to formulate detailed plans and begin the development work in their respective areas:

- Dynamical model framework, led by Bill Skamarock (MMM)
- Software architecture, led by John Michalakes (MMM)
- Standard model initialization procedures, led by Stan Benjamin (FSL)
- Data assimilation system, led by Jim Purser (NCEP)
- Model physics, led by John Brown (FSL)
- Testing, verification, real-time implementation, led by Kelvin Droegemeier (OU)
- Postprocessing software, led by Henry Neeman (OU)
- Community model support, led by Jimy Dudhia (MMM)
- Operational implementation, led by Geoff DiMego (NCEP)

Although the collaborators are poised to continue the testing and decision-making needed to develop the model, ongoing funding is still in question. Klemp hopes that a full-physics, research-quality model will be available within two or three years and that the model will be operational in about five years. Achieving this time line, however, will be contingent on establishing a nucleus of support for each of the four organizations participating in the project.

For further information about the model, contact Klemp at 303-497-8902 or klemp@ucar.edu. ✱

Update
CSM sees a wet, hot 21st century

by Anatta

The NCAR climate system model (CSM) has completed two simulations of climate change through the 21st century; results were released on 12 April. The Climate of the 21st Century Project was first reported in the *UCAR Quarterly* Summer 1998 issue (http://www.ucar.edu/quarterly/summer98/history.html.)

If future carbon dioxide emissions continue to grow at their current rate, wintertime precipitation over the U.S. Southwest and Great Plains could increase by 40% as global average temperature rises 2°C (3°F). Reducing the buildup of CO_2 concentrations by one-half over the next century largely dries up the extra rain and snow and slows the global temperature rise to 1.5°C. Globally, CO_2 stabilization has more effect on temperatures in Europe and Asia than in North America.

The CSM simulated the earth's climate from 1870 to 1990 and then continued the simulation to 2100 under two different scenarios. The first was a "business-as-usual" increase in greenhouse gases in which atmospheric CO_2 doubles over the next century. In the second scenario, CO_2 increases are stabilized at 50% above today's concentrations.

"These values are three to four times as large as the warming that has occurred over the 20th century," says Tom Wigley, director of ACACIA (A Consortium for Application of Climate Impact Assessments), the joint NCAR-industry program that sponsored the computer runs. The results are especially noteworthy because the CSM is less sensitive to anthropogenic greenhouse-gas forcing than are most other models, Wigley notes.

In the business-as-usual projection, changes in precipitation vary markedly by region and by season. Within the

(continued on p. 14)

United States, the greatest increases occur in the Southwest and Great Plains in winter and substantially exceed the range of natural variability. Limiting CO_2 emissions reduced the precipitation changes.

The model shows no clear separation between the business-as-usual and the stabilization cases until around 2060, even though the CO_2 concentrations begin to diverge in 2010. The half-century lag is the result of thermal inertia in the earth's climate system, especially in the oceans.

The CSM is one of only a handful of models in the world capable of realistically simulating the chemistry and transport of individual greenhouse gases and sulfur compounds. The model employs a scenario for future emissions of sulfur dioxide, which cools the climate, that the researchers believe is more realistic than those used by the Intergovernmental Panel on Climate Change, which do not take possible policy changes into consideration. The ACACIA scenario assumes that societies will take steps to reduce sulfur dioxide emissions over the next century as the public-health consequences of the emissions increase. In the ACACIA scenario, the sulfur dioxide cooling effect gradually diminishes, allowing the simultaneous greenhouse warming to emerge more clearly.

Wigley says, "These results show that we will experience not only future climate change, but also the results of policies to reduce these changes, in ways that are not simply related to changes in the global mean temperature. Policy decisions about reducing greenhouse emissions should not, therefore, be dictated by projected changes in global mean temperature alone."

Data from these NCAR climate system model runs are available to scientists studying the effects of climate change on human health, water resources, agriculture, natural ecosystems, and the economy. Besides the NCAR group, scientists from NOAA also worked on the study, which was funded by NSF and ACACIA. The simulations were run on supercomputers at NCAR and in Japan.

For more information, see Wigley's background paper at http://www.cgd.ucar.edu/cas/ACACIA/index.html. For model data, see the U.S. National Assessment site at http://www.nacc.usgcrp.gov. ✱

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