



On the wings of an instrument-laden research aircraft (above) and through the beam of a LIDAR (light detection and ranging) instrument (opposite) the Cloud Indirect Effects Experiment (CIFEX) reached out to touch air pollution to trace the effects of particulate matter from the other side of the world on West Coast rainfall.

**Opposite page,** CIFEX Chief Scientist Veerabhadran Ramanathan (inset).



# CLIMATE CHANGE TAKES FLIGHT

BY ROBERT MONROE



**Y**OU COULD SAY that Greg Roberts and his ingenious particulate-measurement device had a dark cloud hanging over them.

The very first commercial version of the cloud condensation nuclei (CCN) counter invented by Roberts, a project scientist at Scripps Institution of Oceanography, almost didn't get to assume its starring role in April's Cloud Indirect Effects Experiment (CIFEX). First, the laser that helps it count and size cloud droplets went haywire just days before it was to be mounted onto a research airplane. Then, on the way back to the manufacturer for repair, the courier company's parcel deliverer dropped the laser, breaking it into pieces.

So on April 15, the cheers and backslaps in the hangar at Arcata Airport north of San Francisco culminated a comeback story worthy of an Olympics telecast. The CCN counter returned in time to join a suite of instruments mounted on the plane that corkscrewed through clouds over the Pacific Ocean to witness a transcontinental phenomenon affecting Pacific Northwest climate.

The counter performed flawlessly on its maiden voyage, reported Carl Schmitt, the flight scientist. An atmospheric physicist at the National



Center for Atmospheric Research, Schmitt had driven from Colorado to participate in CIFEX, taking his turn in the navigator's seat on the morning flight. As the congratulatory handshakes for Roberts subsided, the experiment's chief scientist turned the impromptu meeting back to the business at hand.

"O.K. Carl," said Scripps scientist Veerabhadran Ramanathan. "Now tell me, what did you see?"

The long answer to that question will come after months of data analysis that could cast the dynamics of cloud formation—and how people are changing them—in a new light. CIFEX is the first study to determine how aerosols like dust and soot from exhaust emissions transported over thousands of miles interact with and affect clouds in places like North America. The particulate pollution caused by human activities could be stifling rainfall in many areas of the world and cooling the atmosphere.

## DISCOVERING THE PARTICULARS OF PARTICULATES

For decades, the influence of greenhouse gases such as carbon dioxide has dominated climate change research and policy. Ramanathan, director of the Center for Clouds, Chemistry and Climate at Scripps,





*The smog generated in cities like Singapore finds its way to North America, whose member countries in turn pass their air pollution on to Europe in a conveyor belt of high-altitude atmospheric circulation.*

helped shape that discussion with discoveries he made starting in the 1970s. A string of conclusions led him to CIFEX.

In the mid-1970s, Ramanathan found that chlorofluorocarbons (CFCs) were an important greenhouse gas, about 10,000 times more effective than carbon dioxide in trapping solar radiation in the lower atmosphere. At about the same time, a group of researchers discov-

ered the damaging effects of CFCs on the ozone layer. The work would eventually win them a Nobel Prize.

Ramanathan later recruited two of those Nobel laureates, Paul Crutzen and Mario Molina, to join him at Scripps, bringing together three of the first atmospheric chemistry researchers to recognize the importance of aerosols in affecting events like cloud forma-

tion, precipitation, and other climatic functions.

Ramanathan's attention turned to aerosols during his 1993 Central Equatorial Pacific Experiment (CEPEX). CEPEX began as a study of how clouds influence sea-surface



*Veerabhadran Ramanathan talks preflight strategy with NCAR researcher Carl Schmitt. Instruments at work during sorties included wing-mounted aerosol probes.*





temperatures in the oceans around Fiji. By the end of the experiment, he concluded that aerosols were the major factor governing how clouds absorb solar heat.

The quest to understand the influence of aerosols led to the Indian Ocean Experiment (INDOEX) in the 1990s, one of the most sweeping studies of its kind ever conducted. Over the course of six years, a team of 200 researchers led by Ramanathan and Crutzen documented that the haze produced by South Asian pollution dramatically affects climate not only in that region of the world but also in places as far away as the United States through long-range transport. Recently, Ramanathan and Crutzen began conducting Project Atmospheric Brown Cloud (ABC), a look at the various environmental impacts of particulate pollution.

Now Ramanathan's interest is turning closer to home. He is exploring how long-range transport of pollution from Asia could be impacting the West Coast of North America. As a result, Ramanathan designed CIFEX, which is helping shape an emerging portrait of climate that suggests we are interfering with the mix of atmospheric aerosols at our own peril.

#### WE REALLY DON'T KNOW CLOUDS AT ALL

In nature, only some clouds develop enough critical mass to drop rain, snow, and hail. Others serve only to



*Bulky measurement devices aboard the plane left room only for University of Wyoming pilot Kevin Fagerstrom and one flight scientist, Veerabhadran Ramanathan on the April 15 afternoon flight.*

act as bright reflective shields that bounce solar radiation back up to space, cooling Earth's surface.

At the outset of cloud formation, aerosols form the scaffolding on which water molecules collect. The aerosol particles can be dust or sea salt kicked high into the atmosphere by wind or even microorganisms lifted from the ocean. When they attract water in clouds, they form cloud condensation nuclei.

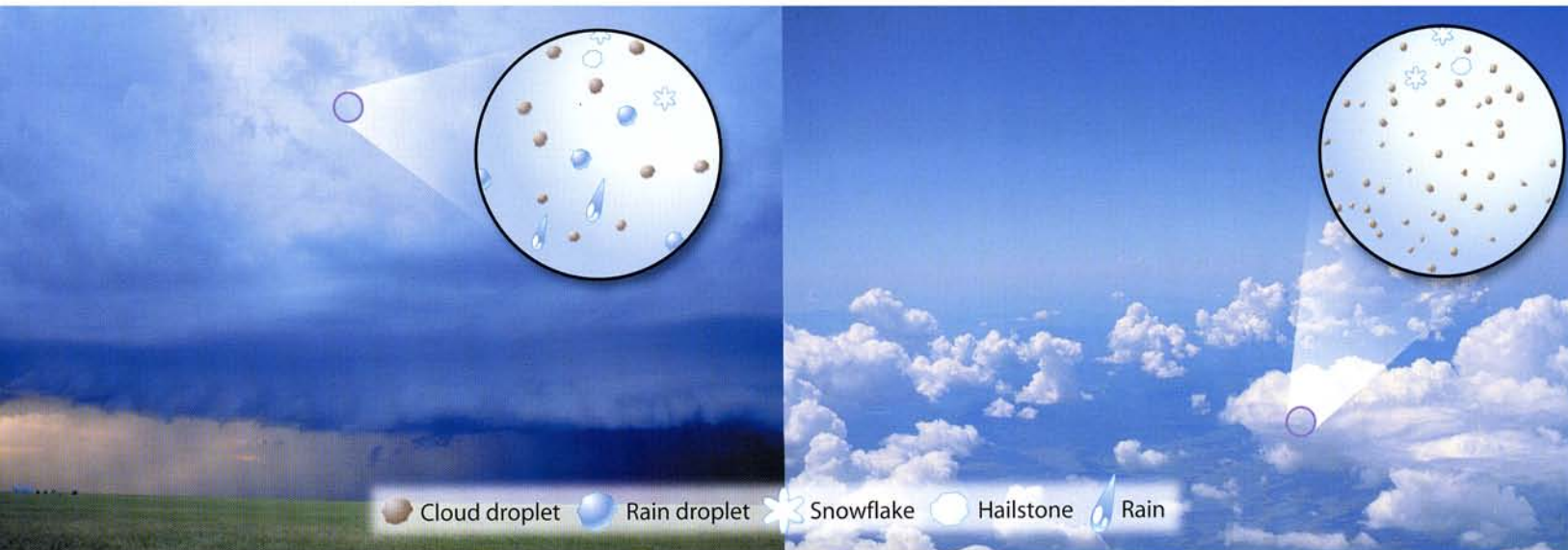
The particles range in size. Larger particles have more surface space to accommodate water molecules to collect and gather enough mass to fall as precipitation. For

smaller particles, it is more difficult to achieve this state, known as supersaturation; there is too much tension on their small surfaces for water to take liquid form. Instead it tends to remain a vapor.

Because little is known about the behavior of these smaller particles, Roberts's CCN counter was an especially important instrument during the April experiment. The device can detect these particles and track their growth more accurately than older models, collecting and processing them as the aircraft flies through clouds. It can also take a measurement every second rather



## GOOD CLOUD, BAD CLOUD



Typically, cloud droplets can achieve sufficient mass to become precipitation in the form of ice, hail, or rain (left). When pollutant aerosols are in abundance and contribute to cloud formation, moisture can become diffuse and render clouds less likely to produce precipitation (right).

EXPLORATIONS  
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than every 20 seconds, meaning it can analyze materials that a slower counterpart could miss altogether during a cloud flyby.

The premise behind CIFEX and Project ABC is that human activities, whether they be driving cars or farming practices that turn fertile land into desert, are adding more aerosols to the atmosphere than would get there naturally. In doing so, humans are creating clouds that are brighter and drier.

“You add aerosol particles to a cloud, you’re distributing the same amount of water vapor over more drops,” Roberts said. “If you have more drops but the same amount of water vapor, each particle on average is going to be smaller.”

That means more solar energy gets reflected into space—the so-called indirect effect of aerosols—and that fewer clouds make rain.

CIFEX gathered evidence to test this hypothesis by making observations of clouds off the California coast



Project Scientist Greg Roberts checks his invention, a cloud condensation nuclei (CCN) counter, prior to takeoff.





that were interacting with brown bands of haze transported at high altitude from Asia during spring months. The King Air 200T, a University of Wyoming aircraft used in CIFEX, was outfitted with an array of instruments ranging from radar to measure cloud thickness to probes that could identify the shapes of ice crystals in the atmosphere. The aircraft made several flights during a two-week period in April, when the haze peaked off the California coast. Scripps graduate students Odelle Lariviere and Guillaume Mauger pored over forecast models of haze movement to help coordinate the flights, timing them to catch contrasts between “clean” clouds and “dirty” ones that had interacted with the pollution.

At the same time, the CIFEX science camp in the coastal town of Trinidad conducted complementary ground measurements, including an analysis of airborne particles (see “The Dust Collector,” Summer 2004 *Explorations*) and readings of airborne aerosol layers using LIDAR, an imaging technology similar to radar.

The Asian particles are but one link in a worldwide chain of pollution transfer. A few months after CIFEX, an international collaboration of scientists, the International Consortium for Atmospheric Research on Transport and Transformation (ICARTT), studied the effects on the Atlantic Ocean



of the air pollution that is channeled through northeastern states—the country’s so-called “tailpipe.” The cause is global; the effects are local.

“Every nation is polluting the backyard of a neighboring nation,” Ramanathan said. “It is through international collaborative studies such as ABC and ICARTT that we are going to get a better handle on the problem of pollution and its impact on the health of humans and that of the planet.”

#### AIR POLLUTION AND A CHANGING CLIMATE

Some researchers have been tempted to see an ironic silver lining in the brighter cooling clouds, noting that they mitigate greenhouse-gas warming significantly. To Ramanathan, such thinking mischaracterizes the climate change that we are witnessing.

**Top left,** At the CIFEX base in Trinidad, California, members of the research team (from left), Veerabhadran Ramanathan, Guillaume Mauger, Eric Wilcox, Carl Schmitt, and Greg Roberts analyze cloud forecast data to determine ideal flight times. Roberts also set up a CCN counter at a research station on the coast.





Prototypes of the unmanned aircraft Veerabhadran Ramanathan hopes to fly en masse to create large-scale measurements of planetary albedo.



## MISSION: ALBEDO

**A FLEET OF DOZENS OF UNMANNED** drone aircraft patrols the skies, covering thousands of miles over the course of a year. At the end of that year, scientists will gain for the first time detailed knowledge of how clouds affect the amount of solar heat reaching Earth.

Think of it as the ultimate reconnaissance mission.


"At least that's my dream," said Veerabhadran Ramanathan, director of the Center for Clouds, Chemistry and Climate at Scripps Institution of Oceanography.

At the moment, it's a dream with a little seed money behind it. The Global Albedo Project (GAP) so far exists only as a National Science Foundation pilot project to develop prototypes of the low-cost aircraft needed for the job. Ramanathan said that more support is crucial for measuring Earth's albedo, a key component of the planet's energy budget that has been ignored until now.

"We know how greenhouse gases have changed things, but we don't know about the other major thing, which is albedo," he said. "By changing aerosol concentrations in clouds, we are changing albedo patterns, and there's no concerted effort to measure that."

About 30 percent of the solar radiation that reaches Earth is reflected back into space at the top of the atmosphere. That percentage represents the planet's albedo, or reflectivity. Even slight fluctuations of albedo level could be enough to cool or warm the planet enough to seriously disrupt everyday life.

Ramanathan believes that the only way to effectively study albedo is to create a comprehensive set of data, which can only be obtained using several aircraft that take measurements over long periods of time. The fleet he envisions would be the atmospheric equivalent of the internationally operated Argo array of floats, some 1,300 of which are currently recording basic temperature and salinity data in the world's oceans. His research group has developed a pair of autonomous airplanes and conducted the first successful test flight in summer 2004.

"I am hoping that if we can make them inexpensively, they will revolutionize atmospheric observations," Ramanathan said. 

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"It's possible that we have not seen most of the effect of global warming, that the effect is much larger than what we think it is," he said. "If the net cooling effect suddenly disappears, global warming could accelerate rapidly."

The results of ABC suggest that global efforts to reduce aerosol emissions need to be made with care, but do need to be made. Ramanathan points out that the carbon from industrial emissions and dust created by desertification cause their own set of public health and environmental problems that range from asthma to stunted agricultural production.

One of Ramanathan's follow-ups to CIFEX will include a look at how the black carbon particles coming from Asia affect California's snowpack. In the meantime, CIFEX promises to help scientists understand the coupled effect of aerosols suppressing northern California rainfall and the washing of aerosols out of the atmosphere by precipitation.

Some early results have yielded surprises about the nature of itinerant pollution. In August, Ramanathan and Lariviere, using a transport model created by researchers at the University of Iowa, reported that during certain spring months, just as much of the particulate pollution in northern California is coming from Asia as from local sources.

"Data from INDOEX and other field studies are suggesting that climate change from air pollution can be just as large as that due to greenhouse gases," Ramanathan said, "and we may be in for a major climate surprise in the coming decades." 🍷



Graduate students Odelle Lariviere (left) and Guillaume Mauger briefed Veerabhadran Ramanathan on LIDAR's performance.



Top to Bottom, Carl Schmitt describes results of a morning research flight to other CIFEX participants. Ground-based measurements from the Trinidad Head station and from LIDAR, which measured the height and thickness of pollution layers, supported in-flight readings.

