Cloudy Concerns

Will clouds prevent or promote a drastic global warming?

By RICHARD MONASTERSKY

Picnic planners hope for sunshine; despondent farmers pray for rain. But if Earth's climate warms as atmospheric scientists predict, we may all beg for stratocumulus clouds.

Some studies suggest that if the number of these low clouds over the ocean grows by 4 percent, the increase could compensate for a doubling in atmospheric carbon dioxide – saving the planet from a potentially disastrous temperature hike of 1.5°C to 5.5°C over the next half-century.

On the other hand, an increase in another cloud type – the high, ice-filled cirrus clouds – would add to the greenhouse effect.

Stratocumulus and cirrus clouds do not spawn thunderstorms, tornadoes or other severe weather, so they haven't attracted as much attention from researchers as more menacing cloud forms. But these two types play a most important role in setting Earth's temperature – a role that scientists have recently come to appreciate amid growing concern over the greenhouse gases accumulating in the atmosphere.

A team of more than 150 researchers is conducting a decade-long experiment called FIRE to study the climatic role of clouds – particularly cirrus and marine stratocumulus. The first phase of FIRE, launched in 1986, gathered information that has forced several changes in cloud theories. During the next few years, investigators will prepare for a second phase, set for the early 1990s.

Climate experts often call clouds the wild card in the game of global change. (Oceans may be a second wild card in the deck, because they could drastically affect the pace of a greenhouse warming.) At present, neither theorists nor large-scale computer climate models can predict with accuracy whether cloud systems will help or hurt a warming globe.

"Potentially they can have a fantastic effect," says Anthony Slingo, who works on one of the large climate models, called general circulation models, at the National Center for Atmospheric Research in Boulder, Colo. Such computer models are a key tool for predicting climate change.

"I think the trouble is the lack of a very firm theoretical foundation for the way we treat clouds in a general circulation model. When we get a result on climate change, we really don't know what confidence to give it."

FIRE will provide some of the needed confidence. Owing its name to the bureaucratic propensity for acronyms, FIRE stands for First ISCCP Regional Experiment. ISCCP, or the International Satellite Cloud Climatology Project, is an effort to monitor clouds around the globe using sensors on several satellites.

According to Stephen K. Cox, chairman of the FIRE science experiment team and an atmospheric scientist at Colorado State University in Fort Collins, this project has two basic goals: to improve satellite monitoring of clouds and to generate better cloud modeling. The NASA-run program involves field experiments, long-term observations and theoretical modeling.

All clouds have a split personality: They feature some characteristics that cool the Earth and others that warm it.

Because clouds are white, they reflect light from the sun and cool the world's surface. But they also trap infrared radiation, much as greenhouse gases do. For some clouds, the opposing forces counterbalance each other and the cloud exerts little net effect on the Earth's temperature. Other clouds, however, have properties skewed in one direction.

In cirrus clouds, the greenhouse personality dominates. Even a casual observer can tell these clouds lack significant cooling power because they tend not to hide the sun completely. While some cloud types often blot the sun from view, cirrus clouds let through much of the sun's visible and ultraviolet light.

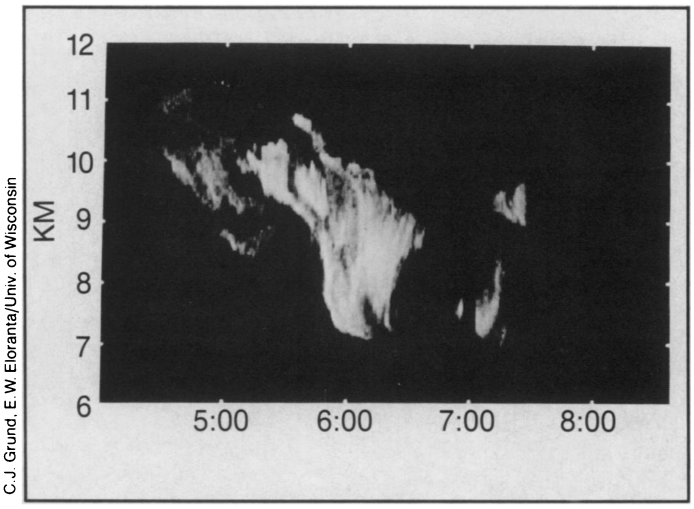
With radiation from the longer end of the spectrum, cirrus clouds are more opaque. Infrared radiation headed away from Earth cannot pass easily through these clouds, says David O'C. Starr, a cirrus specialist at NASA's Goddard Space Flight Center in Greenbelt, Md.

Cirrus clouds warm the atmosphere because they function like a greenhouse gas, absorbing more infrared energy than they emit. All objects, from a human body to a coal stove, emit infrared radiation, but cool objects radiate less than warm ones. Because cirrus clouds form in the upper, colder levels of the troposphere, they cannot radiate away much of the infrared energy they absorb. The surplus stays in the cloud and excites its molecules, generating heat that warms the air.

According to observation tables, cirrus clouds cover some 16 percent of the globe at any given time. Thus they weave a critical greenhouse layer with a substantial effect upon Earth. Yet scientists have only a rudimentary understanding of these clouds, partially because their high altitude sets them beyond the reach of all but a few research aircraft, says Starr.

In October 1986, FIRE investigators staged a large experiment in central Wisconsin to gather important data on cirrus clouds. The field campaign involved a corps of observing instruments, including NASA's high-flying ER-2, eight different satellites, research balloons and laser radars called lidars.

Starr says this experiment nearly doubled the available *in situ* measurements, those taken inside cirrus clouds. By comparing the *in situ* observations with infor-

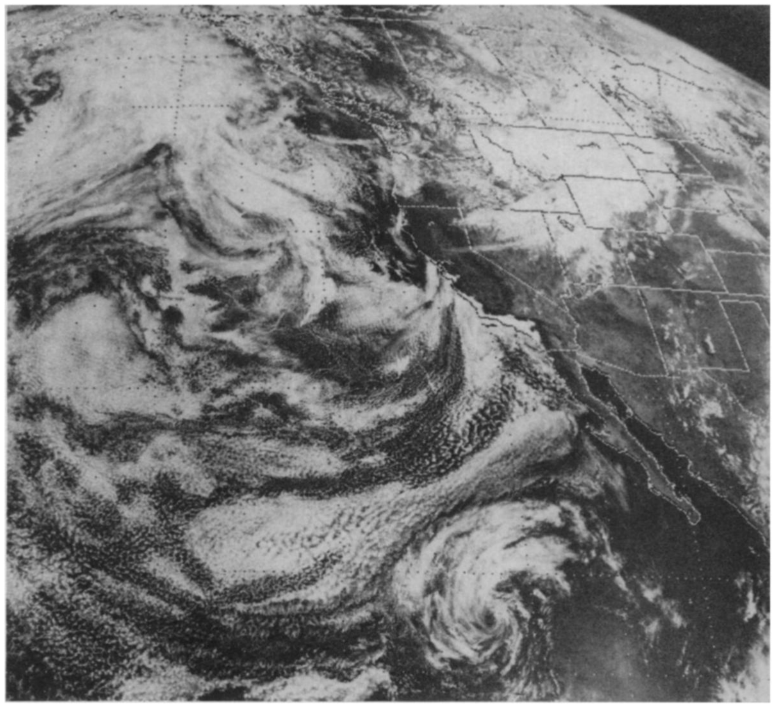


Clouds through the eyes of a laser: FIRE scientists have studied cloud properties with lidars, which shoot laser pulses upward and measure the light bouncing off cloud particles and other objects. These vertical "slices" show how a cirrus cloud changes over several hours. Scale at left indicates altitude in kilometers.

mation gathered by satellite and by plane, researchers are beginning to answer basic questions such as why these clouds develop and how they influence the climate.

"We went in here not blind, but pretty childlike in the questions we were asking," Starr says. "Now we are getting a heck of a lot more refined."

In particular, FIRE measurements are leading researchers to revise their ideas about the size of ice particles in cirrus clouds. Measurements from satellites and aircraft indicate the clouds may contain more tiny ice particles than expected. Though the small bits may account for only a small portion of the cloud mass itself, they could overshadow weightier particles in determining these clouds' greenhouse power, says Bruce A. Wielicki at NASA's Langley Research Center in Hampton, Va. The next cirrus phase of FIRE, scheduled for Kansas in 1990, will include instruments specially designed to measure such small ice particles.



A cool blanket on the world: Marine stratocumulus and other low clouds cover about a third of the ocean area and keep Earth's surface cool by reflecting away sunlight. This satellite image from July 10, 1987, made with visible light, reveals a large deck of marine stratocumulus off the coast of California and Baja. Clouds to the north are part of a storm system, and most are not stratocumulus.

Albrecht

While cirrus clouds warm the atmosphere, marine stratocumulus clouds cool it. Though thin – perhaps only a few hundred meters from top to bottom – these clouds are filled with water droplets that reflect much of the sun's shortwave radiation back toward space. Moreover, they don't trap much of the infrared radiation coming off Earth's surface because they are low, warm clouds that can radiate away much of their absorbed energy, says atmospheric scientist Bruce A. Albrecht of Pennsylvania State University in University Park. Marine stratocumulus clouds sit only 500 to 1,000 meters above the sea.

These and other low clouds exert such a strong cooling influence on the planet that they overpower the warming effect from their high-altitude cousins. A recent satellite study, conducted as part of the Earth Radiation Budget Experiment, indicates that clouds in general cool the Earth – at least for the present (SN: 1/7/89, p.6).

Marine stratocumulus clouds, says Albrecht, "are probably the most important low-level clouds in a climatological sense because of their large aerial extent and their persistent nature." Floating above the ocean surface, they often form sheet-like "decks" spreading over large areas. Studies show that stratocumulus and other low clouds cover 34 percent of the world's oceans at any given time.

To investigate them, FIRE researchers in July 1987 gathered their forces around San Nicolas Island, off the California coast near Los Angeles.

This experiment revealed that air currents flow in a complex pattern both above and below marine stratocumulus clouds. Scientists had assumed that air usually moved freely from the ocean surface up through the cloud to the top, notes atmospheric scientist David A. Randall of Colorado State University, co-chairman of the FIRE science team. The 1987 measurements, however, show that a thermal barrier frequently develops at the cloud base and inhibits air circulation. Called a temperature inversion – where cold air gets trapped under warm air – this barrier is the same kind that holds smog over Los Angeles and Denver. Researchers had seen the effect in marine stratocumulus before, "but we didn't realize it was so widespread," Randall says.

The stable temperature inversion tends to cut off the cloud from the ocean, which supplies its moisture. Lacking a moisture source, such a cloud will disappear during daytime hours as the sun evaporates its water droplets.

In the next stage of its stratocumulus investigation, FIRE will address exactly how these clouds break apart and how that process affects their ability to absorb and reflect light. The experiment, planned for 1992, will focus on the Northeast Atlantic Ocean around the Azores.

Like the cirrus experiment, the 1987 stratocumulus experiment uncovered important details about cloud microphysics – the complex world of tiny particles. Flying their planes through the exhaust trails of ships, investigators made the first direct measurements of the effect of ship exhaust on cloud droplets.

Researchers had theorized that certain types of pollution would make clouds more reflective by supplying an artificial source of cloud-condensation nuclei. These particles serve as surfaces upon which supercooled water vapor can condense. Theoretically, if extra nuclei entered a cloud, the available water would spread itself among old and new cloud-condensation nuclei – an effect that should increase droplet number while making each drop smaller. Because cloud particles reflect light, the bloom of additional drops would brighten a cloud.

Two years ago, researchers reported that ship exhaust tracks do indeed show up as bright streaks on satellite images (SN: 9/12/87, p.168). The FIRE flight, though, was the first to actually pierce a ship track and measure the air inside, notes meteorologist Lawrence F. Radke of the University of Washington in Seattle, who took part in the flight. Radke says the researchers tried to intercept tracks several times while returning to base after completing missions. But success came only when they crossed some tracks unintentionally.

As expected, the number of cloud droplets soared and the droplet size shrank inside the tracks. In fact, Radke and his cohorts didn't know they had passed through ship trails until they noticed the dramatic particle changes appearing on the monitors.

While confirming certain suspicions, the trail crossings also held some surprises. Measurements indicate the trails contained more liquid water than did surrounding clouds. Investigators now believe they can explain this initially puzzling observation. Radke and Albrecht suggest ship pollution inhibits a stratocumulus cloud's ability to drizzle by keeping drops small, allowing the cloud to retain water.

Drizzle helps control a cloud's life span. Falling water droplets not only pull moisture from the cloud but also can

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bond to each other and to a small cast of other atoms such as hydrogen, oxygen and nitrogen.

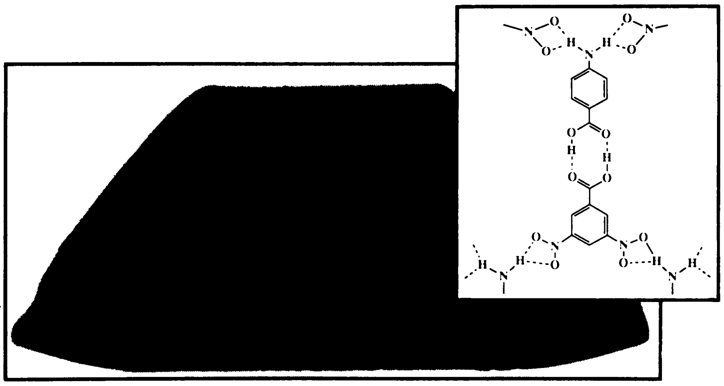
Chemist Margaret C. Etter of the University of Minnesota at Minneapolis describes traditional organic chemistry as the science of *intra*molecular bonds. "What we're doing is trying to unravel how to do synthetic chemistry of *inter*molecular bonds," she says. "If you could learn to put [collections of] molecules together in a preferred way, the potential is equally broad and promising as has been conventional synthetic chemistry," which has produced Saran Wrap, nylon and numerous pharmaceuticals, among other innovations.

"We're looking at how hydrogen bonds can be used to hold molecules together," Etter says. Chemists have not traditionally viewed hydrogen bonds – which are weaker than the covalent bonds linking atoms in typical molecules such as ethanol – as a chemical glue for assembling molecules into materials. "Here's where organic chemists' minds have been poisoned," Etter says. "In fact hydrogen bonds are weaker, but that doesn't mean they aren't good for doing syntheses."

"We now have a new synthetic method for designing materials" such as nonlinear optical crystals, she says. Normally, crystals are made up of identical atomic or molecular units. "But if I can take a single organic molecule and learn

A 1:1 ratio of p-aminobenzoic acid and 3,5 dinitrobenzoic acid yields the designed co-crystal shown at right. Inset shows how the constituents assemble via hydrogen bonds, depicted here as series of dashes.

Etter et al./Univ. of Minnesota



how it hydrogen-bonds to different kinds of molecules, I then can put it into a solid and surround it with molecules different from itself." In one example, Etter and her co-workers start with the molecule para-nitroaniline – used for making dyes – and assemble it with other molecules into 25 different crystals, or solid states, each with unique optical and electronic properties.

"Until now, we have had to simply take Mother Nature's products – whatever grew out of solution, whatever crystallizes," Etter notes. And these natural crystals have unvarying microstructural features such as the interatomic or intermolecular distances. But by using hydrogen bonds to construct new crystal structures, she says she can gain control over these "invariables," thus loosening the strictures of nature. Scientists at the Du Pont Co. in Wilmington, Del., are learning to harness other intermolecular forces, such as electrostatic interactions, to control how different molecular building blocks assemble. Like Etter, they seek to develop new materials for optical communications technologies. They are also aiming to make molecule-scale versions of electronic components like transistors and wires (SN: 3/18/89, p.166).

"On a millennium time scale, we have had an explosion of activity in what materials are available and what we know we can do with them," says Carr. As scientists get a better feel for how a material's bulk properties stem from its microstructure at atomic, molecular, cluster and higher levels, they will improve their ability to custom-design materials for specific applications. "In the 1990s," Carr predicts, "we're going to be deft enough with our understanding to really chain it all together." □

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form a temperature inversion at its base. Both effects hasten cloud breakup.

Flight results show that changes in the cloud-condensation nuclei can influence climate in several ways, Radke says. An increase in the number of particles makes stratocumulus clouds brighter, and it also makes them last longer – two forces that cool the Earth's surface.

Climatologists need to understand how global warming might affect the number of condensation nuclei in these clouds, Radke says. Some scientists have suggested tiny ocean organisms called plankton may provide an important climatic feedback loop because they produce sulfur compounds that become cloud-condensation nuclei. Theoretically, if these plankton fared poorly in a future climate warming, the number of cloud particles would drop, intensifying the warming (SN: 12/5/87, p.362).

An individual water droplet in a cloud can measure as little as 10 microns across. At the opposite end of the size scale, a cloud system can span 1,000 kilometers.

"That's 100 billion orders of magnitude. It's no wonder we have problems," says atmospheric modeler Slingo.

The most advanced climate models – the general circulation models – break the atmosphere and oceans into thousands of boxes, their sides typically measuring a few hundred kilometers each. Within such a large grid, individual clouds fall through the cracks. Modelers therefore account for clouds through a process called parameterization.

"When I first came into large-scale modeling," says Slingo, "I thought [parameterization] was one of the most evil words I had ever come across. It's a little like an admission of failure."

To parameterize, modelers draw up equations that represent a general "cloudiness" factor based on physical principles and empirical observations. The equations might, for example, indicate that when relative humidity reaches a certain level in a box, the box begins to reflect sunlight and to rain.

As one of FIRE's main goals, researchers hope to develop better parameterizations by gathering detailed data on real clouds and testing the basic assumptions within their models.

In the future, as computing power grows and box size shrinks, computer experts will steadily improve the way they handle clouds, Slingo says. But the results of FIRE's cirrus and stratocumulus experiments may be opening a whole new dimension of problems for programmers. Those who work with general circulation models say they had hoped to avoid specifically including the complexities of microphysics. Yet the properties of minute drops strongly influence the entire cloud, and modelers can no longer overlook microphysics in an effort to keep things simple.

At present, clouds represent the weakest atmospheric link in climate models – a point illustrated by a study of 14 atmospheric general circulation models reported in the Aug. 4 SCIENCE. When researchers compared climate forecasts for a world with double its present amount of carbon dioxide, they found the 14 models agreed quite well if clouds were not included. But when the investigators incorporated clouds, the models failed to agree and produced forecasts ranging over a wide spectrum.

With such discrepancies plaguing the current generation of models, scientists find it difficult to predict how quickly the world's climate will change; nor can they tell which regions will face dustier droughts or deadlier monsoons.

Says Randall, a computer modeler himself, "If we can better include cloud effects in the climate models, those forecasts will become more reliable. The more reliable they are, the better we'll be able to plan for the future." □