Atmospheric scientists have long suspected that aerosol particles from industrial processes increase the brightness of clouds, resulting in greater reflection of sunlight and cooling of the Earth's climate. Now, using direct satellite observations and a computer-based atmospheric chemical transport model, Brookhaven Lab scientists and their university collaborators demonstrate that the brightening effect is real.

BY KAREN MCNULTY WALSH

Quantifying Cloud Brightness May Help Gauge the Magnitude of the Greenhouse Effect

Brookhaven chemical engineer Carmen Benkowitz and atmospheric chemist Stephen Schwartz, who co-developed a computer-based atmospheric chemical transport model to calculate the distribution of aerosol particles Earth's atmos

MINUTE PARTICLES SUSPENDED IN THE ATMOSPHERE, aerosols result from active volcanos, desert dust, and many human activities, including the ever-increasing burning of fossil fuels that began with the Industrial Revolution. Because clouds form when water vapor condenses on the ever-present aerosols, it has been long known that clouds owe their existence to these atmospheric particles.

By reflecting or absorbing sunlight, aerosols have long been thought to have an important direct and indirect effect on the Earth's climate, by influencing the amount of heat and light coming to the Earth from the Sun.

Now, scientists at Brookhaven Lab and their collaborators at Purdue University have determined that the brightness of clouds actually depends upon aerosol particles. This finding is important because the brighter the cloud, the more sunlight that is reflected away from the Earth, and the cooler the climate.

Using funding from the U.S. Department of Energy and the National Aeronautics and Space Administration, the Laboratory's Stephen Schwartz and his collaborators at Brookhaven and Purdue University used experimental data to demonstrate this cloud-brightening effect on a geographic scale the size of an ocean basin. An atmospheric chemist, Schwartz and his colleagues accomplished this by combining satellite measurements of cloud brightness, water content, and other variables with calculations of atmospheric aerosols.

Before, says Schwartz, it was only a supposition that aerosols had an impact on cloud brightness, and that supposition was based largely on computer-model calculations instead of on data from experimental observation.

This new understanding of the relationship between aerosols and cloud brightness, the researchers say, can now be used in assessing the magnitude of global climate change resulting from human activity since the Industrial Revolution.

"Our study provides a method of quantifying the cloud-brightness phenomenon globally over the past 15 years using archived satellite data," explains Schwartz. "Once this is done, we will have a much better idea of the true magnitude of the greenhouse effect."

The greenhouse effect is caused by carbon dioxide, methane, and other atmospheric gases, which trap heat from the Sun in the Earth's atmosphere, causing it to act like a greenhouse in keeping the world's climate warm. Because of the increase in the atmospheric concentration of these greenhouse gases, the greenhouse effect is thought to have been increasing since the Industrial Revolution and, therefore, affecting the global climate.

"We're not saying that, by increasing cloud reflectivity, aerosols can counteract the greenhouse effect," adds Schwartz, "but, rather, that we need to know how much of a cooling effect they do have so that we can have a clearer picture of the greenhouse effect. To whatever extent aerosols are offsetting greenhouse warming, then the offset is the unseen part of the greenhouse 'iceberg.' "

TWO WEEKS IN APRIL 1987

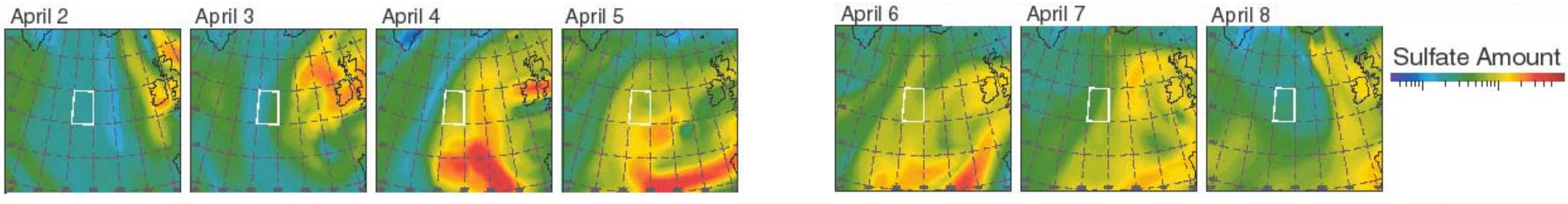
Typically, aerosols are present in the lowest 3 to 4 kilometers above Earth's surface, and they precipitate out of the atmosphere in about a week after their emission from either a natural or human-made source.

One difficulty of measuring the effect of aerosols is knowing their concentration. Explains Schwartz, "Because of their short residence time, aerosols are highly variable as a function of location and time, which makes it tough to measure their concentrations on a global scale."

Along with other collaborators, Schwartz and Brookhaven's Carmen Benkovitz, who is a chemical engineer, have been working for more than a decade to develop and refine a computer-based, atmospheric chemical transport model to calculate aerosol distribution. Their model uses archived data from weather prediction models to track the distribution of aerosols from industrial sources within various parts of the atmosphere.

"This model is the key to knowing where and when to look for the aerosol effect," comments Schwartz.

By analyzing data from their model, the Brookhaven-Purdue team identified two episodes during April 1987 when the modeled concentration



The images above show amounts of sulfate aerosol over the North Atlantic from April 2 to 8, 1987, as calculated by Brookhaven's computer-based, atmospheric chemical transport model. The aerosol amount in the indicated area peaked on April 5. Satellite measurements confirm theoretical predictions of enhanced cloud reflectivity for a given liquid water path in the clouds coinciding with increased amounts of aerosol. These observations point the way to measuring quantitatively cloud brightening by aerosols on global scales and, thus, determining the resultant cooling effect on climate.

"So that we can make sensible policy decisions about energy use, we must understand fully the greenhouse effect, which means understanding the influence of aerosols on atmospheric processes."

STEPHEN SCHWARTZ

Meet
Stephen Schwartz

Atmospheric chemist Stephen Schwartz has had his head in cloud chemistry since joining Brookhaven Lab's Atmospheric Sciences Division in 1975.

Schwartz's early days at the Laboratory were devoted to learning about how cloud chemistry might affect acid rain. "There wasn't much known at that time, so we pretty much had to invent the field," he explains. Schwartz divided his time among doing chemistry experiments in the lab, analyzing data collected in the field, and representing the data in models.

Now Schwartz focuses on clouds at both the microscopic level — how individual cloud droplets form around tiny particles — and the global level — how aerosol particles affect cloud brightness and, ultimately, Earth's climate. "It's very interesting science, and science that is relevant to our country and the world," he comments.

Schwartz earned a bachelor's degree in chemistry at Harvard University and a Ph.D. in physical chemistry from the University of California, Berkeley. Before coming to Brookhaven, he taught chemistry at Stony Brook University. Married to a retired school teacher with two grown children, he enjoys giving talks on atmospheric chemistry to students and other Laboratory visitors.

of sulfate aerosol over the North Atlantic Ocean — which is far from any local sources of aerosol emission — first increased significantly, and then decreased over the course of about a week. These large variations in aerosol concentration and the fact that there were no high-atmosphere clouds to obscure sunlight during these events made them ideal episodes for studying the effect of aerosols on cloud brightening.

The next challenge was to get the data on cloud brightness for that area over the same time period.

To do this, the scientists retrieved satellite measurements of radiance, which is how much light the clouds reflect, at two different wavelengths. They then used these measurements to derive important cloud properties, in particular the optical depth, which is a value related to how much light is transmitted through the cloud, and the liquid water path, which is the amount of liquid water in the cloud. The researchers were also able to analyze how these variables were related to one another, and how one variable changed as a function of the other.

The findings show that, for a given liquid water path, cloud reflectivity was indeed higher on the days with higher aerosol content than on the days with lower aerosol levels. "If the effect is as widespread as we think it is, then it would produce quite a substantial cooling effect on climate," states Schwartz.

AEROSOLS VERSUS GREENHOUSE GASES

Could aerosols be deliberately employed to offset the greenhouse effect?

"This is an attractive thought," comments Schwartz, "but it cannot work in the long run because aerosols are so short-lived in the atmosphere, whereas greenhouse gases accumulate over time. An ever-increasing amount of aerosols would be required. We'd never solve the long-term problem."

Also, says Schwartz, the aerosol effect may have a different geographical distribution from the greenhouse effect, and "the consequence of this mismatch is unknown." One key to assessing the overall impact of aerosols, concludes the Brookhaven atmospheric chemist, will be the further development of the satellite-based measurements.

MORE INFORMATION

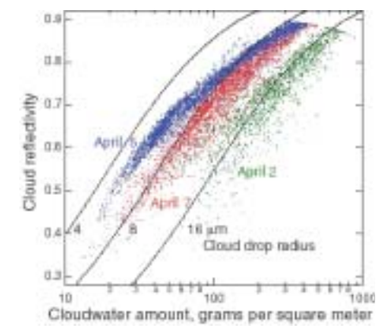
- *funding:* Office of Biological & Environmental Research, Office of Science, U.S. Department of Energy; National Aeronautics and Space Administration
- *paper:* "Aerosol enhancement of cloud albedo shown by satellite measurements and chemical transport modeling," Proceedings National Academy of Sciences, February 19, 2002, volume 99, issue 4, pp. 1784-1789
- *contact:* Stephen E. Schwartz, ses@bnl.gov or (631) 344-3100
- *Web:* www.bnl.gov/bnlweb/pubaf/pr/2002/bnlpr022802.htm and www.ecd.bnl.gov/steve/schwartz.html

Cloud Reflectivity Versus Cloud Water

The figure below shows cloud reflectivity for individual pixels in the study area, which is the region outlined on the map (see pages 14 and 15, bottom), plotted as a function of the amount of liquid water in the cloud in that pixel. The more cloud water, the brighter the clouds as seen by the satellite from above, which corresponds to darker clouds as seen from below.

The high variability in cloud water amount makes it difficult to discern the brightening influence of aerosols. However, the brightening effect is made evident by plotting the cloud reflectivity as a function of the amount of liquid water and comparing the data for days with different sulfate levels (April 5, blue = high sulfate; April 7, red = somewhat lower sulfate; and April 2 green = low sulfate). For a given amount of cloud water, clouds reflect more sunlight on days with more sulfate aerosol (April 5) than on the other two days. The more aerosol present on a given day, the more cloud droplets, and, hence, the smaller the drops are for a given amount of cloud water.

More, smaller drops have been hypothesized to lead to increased reflectivity. This hypothesis is represented by the black curves drawn for different cloud-drop radius values. The present study uses satellite data to confirm this hypothesis and to measure the increase in reflectivity quantitatively.



Brookhaven's Atmospheric Chemical Transport Computer Model

ONCE SCIENTISTS RECOGNIZED THE POTENTIAL for aerosols to influence cloud properties and the potential global magnitude of this influence, they needed a way to quantify the effect. So, Brookhaven researchers developed a computer-based, atmospheric chemical transport model to calculate sulfate concentrations as a function of location, date, and time, so they would know where to look for the aerosol effect.

The model divides the atmosphere into roughly 800,000 model grid cells, each of which is 1° latitude by 1° longitude from the equator to 82° north latitude over the Northern Hemisphere, with 27 layers of cells in the vertical direction from the surface up to an altitude of about 16 kilometers, or roughly 50,000 feet.

The sulfate concentration must be calculated in each grid cell, taking into account the many processes responsible for sulfate concentrations in the atmosphere, including:

- emissions of sulfates and precursor chemicals, principally sulfur dioxide (SO_2) from industrial sources such as power plants and natural sources such as volcanoes, and dimethylsulfide from marine organisms
- the location and intensity of these emissions
- weather data that account for how these chemicals are transported and influence the chemistry of these materials and their removal from the atmosphere
- the chemical reactions that transform SO_2 and other precursors into various sulfates in the clouds.

The program runs for six weeks at a time, allowing scientists to predict sulfate concentrations. The model has been extensively evaluated by comparison with measurements at air quality stations throughout the Northern Hemisphere.

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EDITOR: Marsha Belford

WRITERS: Patrice Pages, Mona S. Rowe, Karen McNulty Walsh

PHOTOGRAPHER: Roger Stoutenburgh

MARGE LYNCH, Assistant Laboratory Director for Community, Education, Government & Public Affairs

MONA S. ROWE, Manager, Media & Communications Office

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