Trouble in the greenhouse

Tiny airborne particles affect the Earth's climate, in part by influencing the formation of clouds. But modelling the effects of these aerosols is proving to be one of the thorniest problems in climatology, says Mark Schrope.

“If I wake up with a nightmare, it is the indirect aerosol effect,” says Veerabhadran Ramanathan of the Scripps Institution of Oceanography in La Jolla, California. Ramanathan studies how the Earth's climate is influenced by atmospheric aerosols — dust, soot and other tiny particles. His research has helped reveal just how poorly their effects — in particular the ‘indirect’ effects mediated by cloud formation — are understood. As the world struggles to predict and control the extent of global warming, and to mitigate its effects, Ramanathan's nightmares could come to haunt us all.

Aerosols enter the atmosphere from a variety of natural and anthropogenic sources. Factories and diesel engines can pump out soot and sulphates; volcanoes and wildfires, such as those that have scorched the United States this summer, add to the haze. Meanwhile, winds whip up dust from deserts, and salt from sea spray. When they are carried into the atmosphere, these aerosols exert a direct cooling effect, reflecting sunlight back into space. But they also exert an indirect effect, influencing the formation and lifetime of clouds — and it is this that represents the biggest question mark in climate modelling. Most climatologists believe the overall influence of these indirect effects will be cooling, but that is about as far as they are prepared to go. “I don't think we have error bars yet,” says Yoram Kaufman, an atmospheric scientist at NASA's Goddard Space Flight Center in Greenbelt, Maryland.

Removing these uncertainties will mean collecting extensive data to fill the vast gaps in current knowledge of the composition and global distribution of aerosols. To that end, a number of major satellite and ground-based projects are already underway or in the works. On the modelling side, all agree that a daunting task lies ahead, but the mood is one of cautious optimism. For the first time, researchers are expressing some confidence that they have identified the major components that must be included in models assessing the overall effects of aerosols. “I think we're at a crossroads,” says Joyce Penner, a modeller at the University of Michigan in Ann Arbor. “Now the challenge is to figure out how to really parameterize these things correctly.”

One of the main complicating factors in modelling the effect of aerosols is their short residence times in the atmosphere. Typically, particles remain aloft for a week or less, being either dragged down by their weight or removed by rain. In contrast, molecules of carbon dioxide persist for about a century, and other greenhouse gases also have long residence times. So although greenhouse gases become well mixed on a global scale, levels of aerosols can vary widely on scales of less than one kilometre. And because concentrations at a given spot are highly influenced by winds, air masses loaded with aerosols can be carried a long way from the sources of the particles.

> Indirect cooling effects of aerosols could be similar in size to the warming effects of greenhouse gases.

A question of balance: anthropogenic aerosols might be counteracting greenhouse warming.

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Up in the air

The chemistry of aerosols adds to the complexity. Many aerosol particles begin as gases. For example, sulphur dioxide coughed out of a volcano or smokestack can be oxidized to form particles of sulphate salts. But the formation of these sulphates is influenced by ozone — and so is affected by the presence of photochemical smogs. As a result, changes in atmospheric chemistry arising from pollution controls could influence the effects of aerosols on climate in ways that are difficult to predict. “It's a complicated system,” says John Seinfeld, an atmospheric scientist at the California Institute of Technology in Pasadena.

Direct aerosol effects are relatively straightforward to calculate because the ways in which various particles scatter and reflect sunlight are well known. Even so, there are complicating factors — one of which was recently documented by the Indian Ocean Experiment (INDOEX), an international study of aerosols and atmospheric chemistry conducted in 1998 and 1999 that integrated ground-, ship- and aircraft-based measurements with satellite data. INDOEX revealed that dark particles such as soot can have a warming effect by absorbing solar energy[1,2]. “We just made the problem a lot more complex,” says Ramanathan, who was co-chief scientist for the project with Nobel laureate Paul Crutzen of the Max-Planck Institute for Chemistry in Mainz, Germany.

Calculations of direct aerosol effects can be checked by correlating data on aerosol concentrations with satellite measurements of reflected solar radiation. Model-derived estimates of direct effects of aerosols being considered by the Intergovernmental Panel on Climate Change (IPCC) are still in error by as much as 50% when compared with these data. But the models can predict general patterns of highs and lows in direct aerosol-induced cooling, says Penner, who is lead author of a chapter on aerosols for the next IPCC report, due to be approved at a meeting in Shanghai in

January 2001. "I wouldn't say we're doing perfectly," she says, "but it's very encouraging."

Integrating indirect aerosol effects into global climate models is still in its infancy. The modellers did not begin including these effects until after the last IPCC report in 1995, and their results so far have led to a dramatic decline in the certainty with which the overall effects of aerosols can be predicted. "Indirect forcing is potentially a pretty important thing, and we really do need to learn how to model it," says Penner.

Blowing hot and cold

The indirect effects fall into two main categories. First, aerosols can act as cloud condensation nuclei, spurring the formation of more water droplets in a cloud than would normally be present. This increases the reflectance of clouds, causing more solar radiation to bounce back into space — and so should exert a cooling influence. This concept was first put forward by Sean Twomey of the University of Arizona in the 1970s[3], but received little attention until 1987, when the effect was observed for aerosols in emissions from ships[4]. The Twomey effect has since been included in some climate models, but with little reliability.

The second category is rain suppression. When more droplets form within a given cloud, the available water is spread more sparsely, making each droplet smaller. This can prevent the droplets from growing large enough to fall as rain, increasing the cloud's lifetime and potentially prolonging its cooling effects. Bruce Albrecht of the University of Miami suggested in 1989 that aerosols could suppress rain[5]. Recently, Daniel Rosenfeld of the Hebrew University of Jerusalem showed this to be true for aerosols from burning vegetation[6] and industrial pollution[7], using data from the Tropical Rainfall Measuring Mission satellite. Researchers led by Maria Cristina Facchini of the Institute of Atmospheric and Oceanic Science in Bologna, Italy, have also shown that organic aerosols dissolving in water droplets reduce the surface tension, which in clouds would inhibit droplet growth, preventing rain[8].

But as with direct aerosol effects, INDOEX revealed an indirect effect that would cause warming: the absorption of heat by soot can 'burn' away cumulus clouds[9].

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Unknown quantity: volcanoes, sea spray and wildfires all add aerosols to the atmosphere, but predicting their effects is proving to be difficult.

Numerous other studies have added to the uncertainty. For instance, Qingyuan Han and co-workers at the University of Alabama in Huntsville have found that in certain types of clouds, decreasing droplet size decreases the clouds' reflectance[10]. Aircraft emissions of aerosols also complicate the picture when they trigger the formation of ice clouds high in the atmosphere. These clouds reflect less solar radiation than those containing water droplets and can also absorb heat, making their overall influence one of warming[11]. Integrating these effects into current climate models will be difficult. The problem is that the models divide the atmosphere into 'cells' with a scale of around 100 kilometres, whereas modelling clouds would ideally use scales closer to one kilometre.

Although the uncertainties remain large, some modellers predict that indirect cooling effects could be similar in size to the warming effects of greenhouse gases[12,13]. If so, that raises the troubling possibility that aerosols

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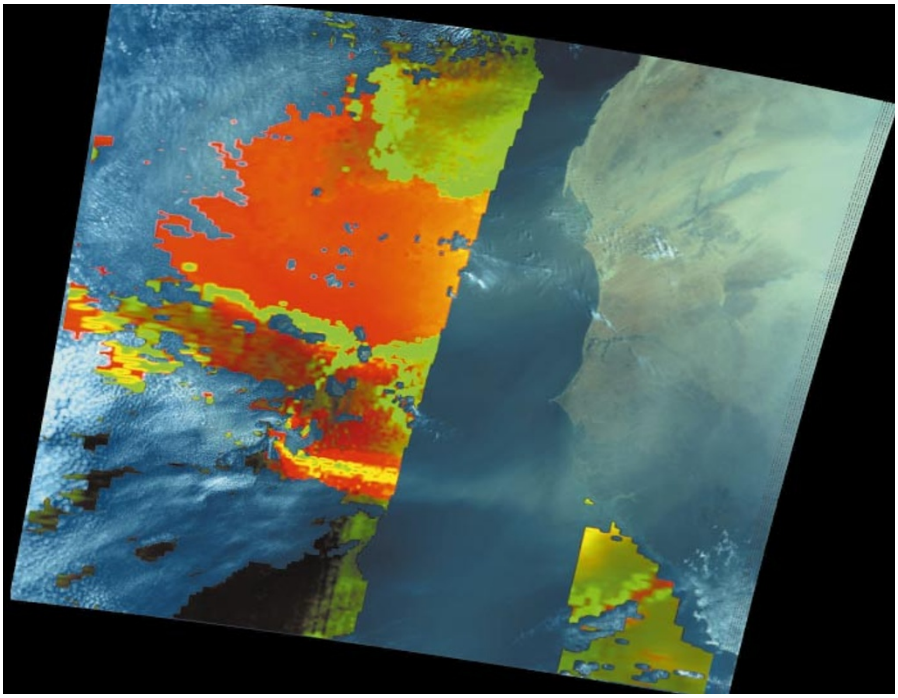
could be counteracting the full effect of greenhouse warming. This could mean that the coming decades will see even more calamitous climate change than current models suggest — particularly if clean-air controls result in a reduction in anthropogenic aerosols. Whatever the truth, the uncertainty over aerosol effects makes it difficult to determine how, exactly, humans have altered the climate. "It means that we should be cautious in interpreting the past 100 years of climate change," says Penner.

In the past, opponents of stringent action to combat global warming have seized on such scientific uncertainties. But most experts say that delaying measures to reduce greenhouse emissions until the indirect aerosol effect is better understood would be a grave mistake. "That debate should proceed independently of any consideration of particles," says Seinfeld, "because those greenhouse gases are with us for a long time."


Y. KAUFMAN/NASA

Homing in: an image of dust blowing from the Sahara to the Atlantic Ocean taken by NASA's Terra satellite. Analysis of the data reveals mineral dust (red) and aerosol particles (green).

Terra's firmer data

Nevertheless, answering the questions surrounding the indirect aerosol effect remains a top priority for climatologists. "I think we've got our work laid out for us, but even the next five years could see some much better answers," says Penner. That prediction is based in large part on the anticipation of new data that should soon begin pouring in from satellites. The chief source will be the international satellite Terra, launched in December 1999, which is the flagship of NASA's Earth Observing System.

Three of Terra's five instruments will provide an unprecedented global view of aerosols. The Moderate-Resolution Imaging Spectroradiometer, or MODIS, measures reflected solar radiation at 36 different wavelengths across a 2,000 kilometre-wide swath, giving near-full global coverage once a day. This is providing the first global view of particle size distributions, because larger particles, such as mineral dust and salt, reflect more radiation at longer wavelengths. An instrument called MISR, the Multi-Angle Imaging Spectroradiometer, takes radiative measurements at four wavelengths and nine different angles giving a three-dimensional view of the atmosphere. Near major sources of aerosols, such as plumes of smoke, it will show the vertical distribution of particles in the atmosphere.

To round out the picture, CERES, or the Clouds and the Earth's Radiant Energy System, will measure reflected sunlight and thermal radiation to determine the overall effect on climate of the aerosols present. Direct aerosol effects will be easier to study than indirect ones, as there is still no way to profile aerosols within clouds. But Kaufman, who is the project scientist for Terra, says that in some cases aerosols within clouds can be inferred from measurements of the clear air at the same altitude. He also hopes that it will prove possible to devise ways of using Terra's data to determine the proportion of atmospheric aerosols that are anthropogenic. "That's something for the future," he says.

Terra will be followed into orbit in December by a satellite called Aqua, which has similar capabilities but will fly in a 'later' orbit. This will, for example, give it an afternoon view of the tropics, compared with Terra's morning flyover. This is important as factors such as cloud cover vary with the time of day. In 2003, NASA and CNES, the French space agency, intend to launch PICASSO-CENA (Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations-Climatologie Etendue des Nuages et des Aerosols). Flying in formation with Aqua, this will use lidar — the laser equivalent of radar — to study the vertical distribution of aerosols and clouds.

Satellite measurements will be coordinated with those from a network of about 100 automated ground-stations known as the Aerosol Robotic Network, or AERONET, run by NASA, CNES and CNRS, France's national research agency. AERONET will provide better data on the size distribution of particles — a key factor in modelling cloud condensation nuclei. Terra and the other satellites also perform best over water where background reflection from the Earth is relatively constant. AERONET will do a better job of measuring aerosols over land. It will also be used to validate satellite measurements.

The Asian-Pacific Regional Aerosol Characterization Experiment (ACE-Asia), which will combine satellite, aircraft and surface-based measurements in a similar manner to INDOEX, should also be in full swing by next year. Pollution from Asia is a major source of aerosols, and prevailing winds carry much of them over the Pacific Ocean. ACE-Asia will provide the first full characterization of these aerosols. "They have the most complicated soup that you could imagine coming off Asia," says Seinfeld, who is involved with the project.

When data from these projects are placed in the modellers' hands, climatologists are optimistic that indirect aerosol effects will no longer seem such an intractable problem. "Some of the best minds in the business are working on this," says Seinfeld. "It's going to be a while, but I think that we're going to understand it sooner or later." ■

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Web links

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IPCC ▸ **http://www.ipcc.ch**
Terra ▸ **http://terra.nasa.gov**
Aqua ▸ **http://eos-pm.gsfc.nasa.gov**
PICASSO-CENA ▸ **http://www-picassocena.larc.nasa.gov/picasso.html**
AERONET ▸ **http://aeronet.gsfc.nasa.gov:8080**
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