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A break in the clouds

Clouds and aerosol particles have bedevilled climate modellers for decades. Now researchers are starting to gain the upper hand.

BY JEFF TOLLEFSON

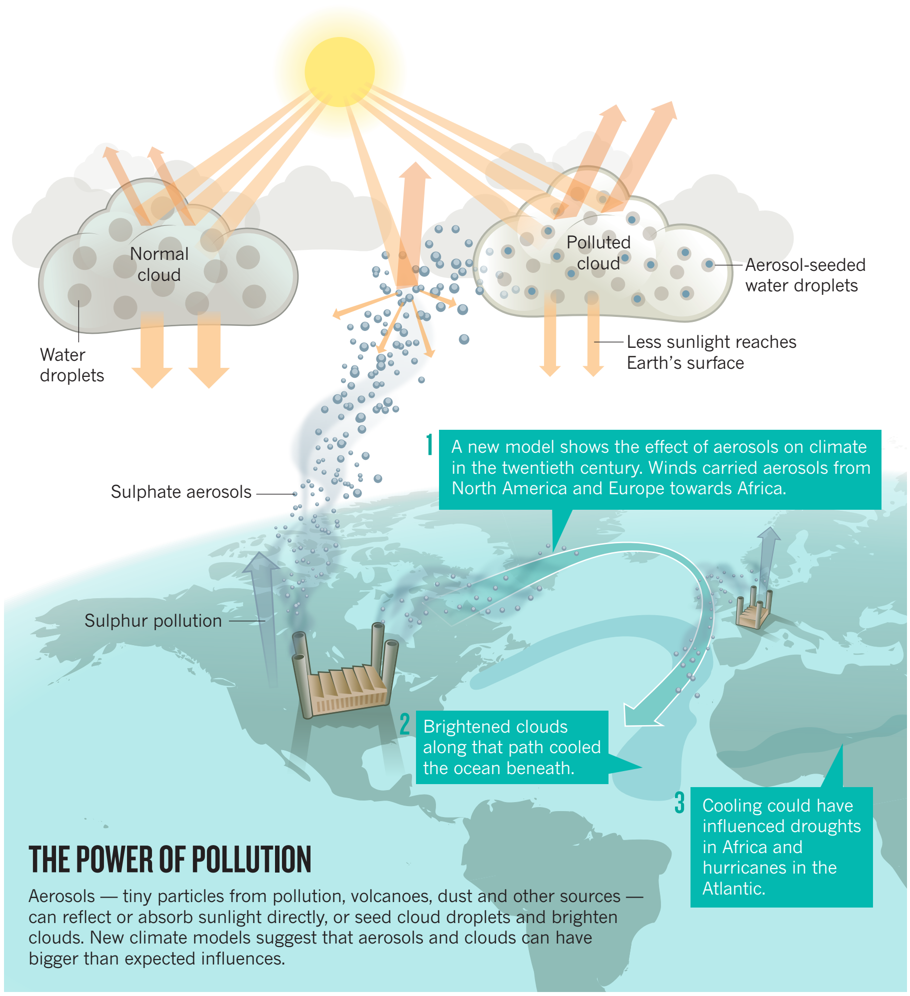
Seen from space, Earth can look dressed up or downright dowdy, depending on the location. In some spots, swathes of cloud cloak the dark ocean, offering a stunning contrast of hues. In others, power plants spew out plumes of grey haze and desert storms cover vast regions in palls of dust.

Together, those clouds and the fine particles, which are known as aerosols, do more than just obscure the planet's surface. By reflecting, absorbing and emitting radiation, they have a major role in setting Earth's temperature and have proved maddeningly difficult to simulate in atmospheric models. For decades, they have been the biggest sources of uncertainty in forecasts of future climate.

But researchers say they are beginning to turn a corner in simulating clouds and aerosols. In recent months, climate scientists have started rolling out initial results from the newest generation of models, which represent atmospheric chemistry and microphysics in much more sophisticated ways than previous incarnations. These models allow clouds and aerosols to evolve as they interact with each other and respond to factors such as temperature, relative humidity and air currents. And early results suggest that such processes have a much greater impact on regional climate than scientists had realized. Recent studies have shed light on the roles that clouds and aerosols might have in triggering major African droughts, altering Arctic climate and weakening the monsoon in southern Asia.

"This is fundamentally new science," says Ben Booth, a climate modeller at the UK Met Office Hadley Centre in Exeter, who is investigating how aerosols influence surface temperatures in the North Atlantic Ocean and affect the weather on the surrounding continents. "The new generation of models is changing the kinds of questions we face as scientists."

And more science is coming soon. Leading climate-modelling groups around the world are racing to work up their latest results for the Intergovernmental Panel on Climate Change (IPCC), which is due to release its fifth report section by section in 2013 and 2014. It is already clear that the issue of aerosols and clouds will provide some of the biggest surprises. "This is the real wild card,"



THE POWER OF POLLUTION

Aerosols — tiny particles from pollution, volcanoes, dust and other sources — can reflect or absorb sunlight directly, or seed cloud droplets and brighten clouds. New climate models suggest that aerosols and clouds can have bigger than expected influences.

says Ron Stouffer, a climate researcher at the National Oceanic and Atmospheric Administration's Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, New Jersey.

THE DROUGHT-MAKERS

Each day, the winds that sweep east across North America stir up a witch's brew of atmospheric refuse. Power plants belch out sulphur dioxide gas, which evolves into sulphate particles that reflect sunlight and serve as seeds for clouds. Microscopic specks of carbon rise from vehicles, steel smelters, agricultural fires and other sources. The brighter carbon particles scatter the Sun's rays and dark ones absorb them, processes known as the direct aerosol effect. As the particles ride the air currents eastward, they collide with each other and mix with natural dust and ocean spray to form the load of atmospheric aerosols. Over time, they can build up chemical coatings or merge to form new particles with different properties.

The prevailing winds carry this aerosol stew on a long horseshoe-shaped route around the Atlantic basin (see graphic). The particles are first transported eastward across the ocean, then take a right turn down the coast of France, gathering up more pollution from Europe. The aerosol-laden air curves towards the west coast of North Africa before veering westward and riding tropical air currents back towards America.

Scientists have proposed that this arc of aerosols could block enough sunlight to cool sea surface temperatures in the Atlantic Ocean and alter the regional climate. So Booth and fellow researchers at the Hadley Centre tested the idea with their newest model, which simulates not only the direct aerosol effect but also many of the indirect effects that aerosols have on cloud properties. These interactions take place on too fine a scale to simulate in a global model, so they are represented by statistical equations derived from even more detailed models.

The Hadley Centre team reported last month that, in the model, the aerosols had an exceptionally large effect on North Atlantic sea surface temperatures[1]. And it was an indirect aerosol effect that made the bulk of the difference. The sulphate particles attracted water vapour to create a vast supply of tiny droplets within clouds, brightening them and reducing the amount of sunlight reaching the sea surface.

Overall, North Atlantic sea surface temperatures climbed throughout the simulation, from 1860 to 2005. But an increase in aerosols slowed the ocean warming during the mid-twentieth century, when rapid industrialization caused extreme levels of air pollution. After restrictions on sulphur emissions in the United States and Europe started to kick in the 1970s, the skies grew clearer and sea surface temperatures increased.

In the end, Booth says, the changing output of industrial aerosols explains two-thirds of the long-term swings observed in sea surface temperatures in the North Atlantic. "It's only in the current generation of models that we can see that relationship physically," says Booth.

The Hadley Centre's results seem to overturn the prevailing wisdom in climate circles, which holds that the ups and downs in sea surface temperatures result from a natural ocean cycle dubbed the Atlantic multidecadal oscillation (AMO). Earlier research suggested that the cooler Atlantic temperatures associated with the AMO could have contributed to droughts over the Sahel in Africa during the latter half of the twentieth century; the same cooling effect may have led to a reduction in the force of tropical storms and hurricanes steaming towards America[2]. But on the basis of the new picture, human pollution could be causing these climate disruptions instead.

The question now is whether the results will hold up. Researchers at the National Center for Atmospheric Research (NCAR) in Boulder, Colorado, say that they see hints of similar effects in their new simulations. But not everybody is convinced that aerosol pollution could have such a profound effect on ocean temperatures — and consequently on climate. NCAR climate scientist Kevin Trenberth says that the results depend on uncertain estimates of aerosol pollution and cloud distributions around the Atlantic. At the same time, satellite observations do not find the indirect aerosol effect to be as strong as the models seem to suggest, he says. "It would be surprising to me if the ocean is not playing a substantial role" through natural cycles.

ARCTIC WARMERS

Researchers are also struggling to tease apart the roles of natural cycles and human-caused changes in the melting Arctic. The sea ice there has taken a beating during the past few decades and coverage reached a near-record low of 4.33 million square kilometres last September. Because the speed of the ice loss has outstripped all but the most dire model predictions, researchers have wondered what might be missing from their simulations.

Early results from the new models suggest that the addition of the more complex clouds and aerosols to simulations could help to provide an explanation. NCAR's new atmospheric model produced more warming and sea-ice loss than the previous iteration[3], and the culprit seems to be clouds — a result that caught researchers by surprise. "I'm a cloud girl, but I didn't go into this thinking that clouds were going to play the lead role," says Jennifer Kay, an atmospheric scientist at NCAR.

To figure out what was happening, the team built new diagnostic tools into the model that effectively tell scientists what they would see if they were observing the planet from a pair of US satellites, CloudSat and Calipso. The model's output is translated into a signal that can be compared directly with radar and laser instruments aboard the satellites, Kay explains. "You basically fly a little satellite around inside the model," she says, "and what it shows is that the clouds are remarkably improved in the new version." They tend to be thinner and more transparent — more like their physical counterparts in the Arctic skies — although why remains unclear.

The gauzy clouds allow more sunlight through in the summer, which melts more ice and exposes more sea and land surfaces; these effects are enhanced by deposition of dark aerosol particles on the snow. It all adds up to a shift towards darker surfaces that absorb more sunlight and amplify warming. Although the model still tends to underestimate sea-ice loss on average, Kay says, some simulations lined up with satellite observations reasonably well.

Researchers at the GFDL are also seeing greater sea-ice declines with their new climate model. Michael Winton, a modeller at the GFDL, says this is likely to be a theme in the IPCC's fifth assessment, but he warns against premature celebration. The addition of enhanced clouds and aerosols to the simulations is driving the extra warming, but the exact details remain unclear[4].

In the end, the climate community must confront a basic question about models. "If you made a model and it matched the observations perfectly, would you claim success?" Winton asks. Although the new GFDL model has an enhanced representation of the atmosphere and does a better job of matching satellite observations, Winton warns that modellers could get the right answer for the wrong reasons. There is some evidence, for example, that natural variability in ocean circulation has caused some of the sea-ice loss during the past two decades. "The Arctic has to be understood in the context of the overall climate," he says.

TAMING THE MONSOON

In satellite images, southeast Asia is often covered by a giant blemish — a brown cloud fed by black carbon emissions from millions of primitive cooking stoves and open fires throughout rural India and neighbouring countries. In the atmosphere, those dark particles absorb sunlight and heat the surrounding air while cooling the land below, effectively stabilizing the atmosphere and slowing the regional circulation that draws moisture inland from the northern Indian Ocean. Researchers proposed seven years ago that this mechanism could explain why the south Asian summer monsoon has grown weaker over the past half-century[5].

However, simulations with one of the new models at the GFDL suggest that the situation might be more complicated, with aerosols and clouds disturbing a much larger hemispheric energy exchange[6].

The overall system is driven by the summer Sun, which delivers more heat north of the equator than south. In what amounts to a massive heat engine that redistributes energy between the hemispheres, hot air rises in the north and carries heat at altitude to the south, where the air descends and picks up moisture from the Indian Ocean on its return north. It is this last step that brings the summer monsoons, which provide up to 80% of the precipitation to most of India. But the GFDL results, reported in *Science* last October, showed that aerosols are creating a major disruption[6].

"Aerosol emissions are like putting up a sunscreen over the Northern Hemisphere, and that reduces the solar imbalance that drives the system," says Yi Ming, a GFDL climate modeller and an author of the study. "We're trying to argue this from a larger spatial scale."

Their model also shifts the blame away from the black-carbon emissions of cooking stoves and agricultural fires, and towards sulphur pollution from coal-fired power plants throughout the region. The sulphate particles that develop from such pollution serve as the seeds for water droplets and brighten clouds, cooling the land below. In addition to capturing the 4–5% overall decline in summer rainfall over India since 1950, the model reproduces regional variations in precipitation — more drying over north-central India versus a slight increase in rainfall over southern India and northwestern India and Pakistan. Ming says the indirect aerosol effect included in the new study shows "a different part of the puzzle".

Surabi Menon, a climate modeller and an affiliate scientist at the Lawrence Berkeley National Laboratory in California, cautions that the simulations rely on relatively incomplete estimates of emissions. Menon has been exploring aerosols and the monsoon with the latest model from the NASA Goddard Institute for Space Studies in New York, and says that modellers can at least check their data against measurements of pollution, which were not available even a few years ago. "We are getting there," she says. "Slowly."

> "What we need now is to really understand what the models are doing, and why they differ."

THE GLOBAL PUZZLE

As climate researchers test drive the new generation of models, they are particularly keen to measure the models' overall sensitivity: how strongly they warm up in response to increasing concentrations of greenhouse gases. The addition of indirect aerosol effects makes the new model at NCAR more sensitive to greenhouse gases, says NCAR researcher Andrew Gettelman. Simulations show that the additional cooling from aerosol pollution, as well as the direct effect of haze, masked some of the warming from greenhouse gases during the twentieth century; but the model shows enhanced warming in the twenty-first century as curbs on pollution expose the full power of greenhouse gases. In simplified runs that double greenhouse-gas concentrations — which could happen by the end of this century — the new atmospheric model projects a 4 °C rise in global temperatures, whereas the previous model showed a 3.1 °C increase.

The Hadley Centre model is moving in the same direction, but this is not the rule. A model at the Pierre Simon Laplace Institute near Paris produces less warming in response to greenhouse gases than did the previous generation, says Sandrine Bony, a climate modeller there. The improved treatment of clouds may help explain that change, but the researchers have yet to fully analyse the new results.

These are just the first wave of a deluge in modelling data. Scientists in the IPCC's physical science working group have until 31 July 2012 to submit papers for the IPCC process, so the literature will explode with results from climate simulations over the coming year.

Then the real hard work will begin — working out what to believe. Scientists must tease apart the subtle causes and effects in their models and, where possible, test their results against other models and observations. "What we need now is to really understand what the models are doing, and why they differ," Bony says. "It's really by comparing the results from a spectrum of models that we can assess which results are robust." ■

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