FORUM: Climate science

The aerosol effect

Anthropogenic aerosols in the atmosphere undoubtedly influence climate. But do the approaches taken in climate models to account for the effects of aerosols provide meaningful estimates of those effects? Two climate scientists offer their opinions.

THE TOPIC IN BRIEF

- Aerosol particles in the atmosphere influence clouds, and thereby climate, because they act as nuclei for cloud formation.
- Computational models of climate systems have sought to incorporate the effects of aerosols on clouds through parameterizations.
- However, the representation of aerosol–cloud interactions in climate models is based on simplifications that ignore the complexity of the small-scale physical processes governing such interactions in the real world.
- The value of studying the effects of aerosol–cloud interactions in climate models has therefore been questioned.

Grains of salt

BJORN STEVENS

There is something captivating about the idea that fine particulate matter, suspended almost invisibly in the atmosphere, holds the key to some of the greatest mysteries of climate science. Recent studies have reported that interactions of such aerosols with clouds may be hiding a large part of the sensitivity of global temperature to increasing levels of greenhouse gases[1]. It has also been claimed that aerosol–cloud interactions are reshaping patterns of rainfall[2] and even influencing the development of tornadoes[3]. But such interactions invariably turn out to be more nuanced than the simple ideas underpinning these and related studies would lead one to suspect. This explains why, despite decades of research, no consensus has emerged as to exactly what, other than perhaps a slight mitigation of twentieth-century global warming, is attributable to aerosol–cloud interactions[4].

To put matters into context, consider the analogous question of the effect of carbon dioxide on climate. Carbon dioxide always has the same composition, its lifetime is very much longer than that of atmospheric circulation systems, and it affects fluxes of radiant energy in ways that are well understood and are not particularly contingent on other factors. By contrast, aerosol particles can differ widely in composition, are ephemeral and affect clouds (and hence radiative fluxes) in ways that are poorly understood and depend on a long list of factors.

To determine the correct sign — let alone the magnitude — of the effect of some important aerosol–cloud interactions, one may, to borrow words from elsewhere, need a weatherman to know which way the wind blows[5]. Models can make good weathermen, and thus provide information about the wind, as well as about many of the other factors on which aerosol–cloud interactions depend. But for climate models, this is true only on scales that are so large (hundreds of kilometres) as to be almost irrelevant. On fine scales (tens of metres), at which there is some understanding of how aerosol particles influence cloud microstructure, climate modellers are groping in the dark.

Aerosol–cloud interactions are not only contingent on, but also compound, the 'cloud question'. It is one thing to ask, as the cloud question does, how the distribution of clouds responds to robust changes in the large-scale environment — for instance, changes that follow temperature. It is quite another to ask how indeterminate changes in clouds will be modified by uncertain interactions with aerosol particles whose properties are also not well understood. So, although some answers to the cloud question seem to be within reach, a quantitative understanding of the global effect of aerosols on clouds is definitely not. Fortunately, given that global aerosol burdens have remained more or less constant for a decade or longer[6], and that greenhouse-gas concentrations are increasing relentlessly, answering the cloud question might help to answer the more pressing questions related to Earth's changing climate.

Our poor understanding of the global effect of aerosols on clouds means that the incorporation of additional details into climate models does not make the models fundamentally better or more reliable, just more complex. Additional complexity can be great fun, but it should not disguise the fact that, at least for aerosol–cloud interactions, much is speculative, and the results of such complex models should be taken with a grain of salt.

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An essential pursuit

OLIVIER BOUCHER

Aerosols and clouds influence each other through multiple interactions at temporal and spatial scales that span many orders of magnitude. Increasingly detailed observations and modelling studies have revealed the complexity of aerosol–cloud interactions. Such complexity was certainly not recognized when the 'climate forcing' associated with these interactions — that is, their effects on the amount of energy entering and escaping from the atmosphere as radiation — was first estimated in an atmospheric general circulation model[7]. After almost two decades of research, parameterizations of these interactions in large-scale models remain simplistic in some respects, but they are neither worthless nor useless.

Estimates of anthropogenic climate forcing are essential for constraining climate sensitivity to such forcing in observations[8]. They are also important for understanding recent climate change[9] and to improve regional decadal climate prediction. Although small-scale observations and models are invaluable for investigating how man-made aerosols might affect cloud properties, they cannot easily be scaled up because of the large variability of aerosols, clouds (Fig. 1) and environmental conditions, and because they overlook the feedbacks on aerosols and clouds that act through large-scale atmospheric dynamics.

Satellite observations have been widely used to infer correlations between aerosols

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Figure 1 | Cloud diversity. Climate models must represent the net effect of clouds on solar and thermal irradiances over scales that often encompass a rich variety of cloud types, such as the diverse range in the cloud field pictured. Aerosol particles affect the microphysical structure of clouds, as well as irradiances in the cloud environment. The net effect of these interactions on the radiative properties of clouds is poorly understood, and incorporating them realistically into climate models is a challenge.

and cloud properties or precipitation. They can be combined with observations of Earth's radiative budget — the amount of energy that enters and leaves Earth's atmosphere as radiation — to estimate aerosol forcing on a global scale. The methodological challenges of such an approach, however, are increasingly being recognized, because both aerosols and cloud properties depend hugely on meteorological conditions. Climate models, although imperfect, are therefore indispensable for calculating climate forcing by anthropogenic aerosols. Such models are the only means of representing the feedbacks induced by aerosol–cloud interactions at the global scale. They can also be used to tease apart the interwoven effects of weather and aerosols on clouds, which currently impede observational studies[10].

Estimates of climate forcing from aerosol–cloud interactions have not varied much over time, even though research has moved from empirical to more mechanistic approaches for parameterizing these interactions. This does not mean, however, that such estimates are robust. They often lack a proper treatment of uncertainties, and there are indications from temperature observations that many climate-model simulations of such interactions imply too much cooling.

It is therefore vital to continue with efforts to parameterize aerosol–cloud interactions in climate models as a means of overcoming the present limitations. Indeed, some promising avenues of research are opening up. It is now possible to perform high-resolution simulations that incorporate complex microphysical representations of aerosol–cloud interactions over sufficiently large areas, and for long enough periods, to investigate the couplings between a cloud field and its environment, thus going some way towards bridging the gap between the cloud scale and the global scale. New methods for representing the statistics of cloud properties at scales below those resolved by climate models have also been developed[11,12]. Finally, cloud microphysics is now recognized as being important for numerical weather prediction; systematic verification of weather-model outputs against observations, and powerful data-assimilation techniques, may provide new insight into aerosol–cloud interactions. With so many encouraging developments, let's embrace the challenge! ■

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MUCOSAL IMMUNOLOGY

Infection induces friendly fire

Our immune system usually ignores 'friendly' gut bacteria. But when infection with a pathogen damages the intestine's mucosal lining, the resident microbes can invade the body, inducing immune responses directed at themselves.

DAVID MASOPUST & VAIVA VEZYS

The mammalian gastrointestinal tract harbours an extensive microbial community that is usually well tolerated by the immune system. Sometimes, however, inappropriate immune responses directed against these 'commensal' organisms arise, such as in inflammatory bowel disease. But how such responses are triggered is unclear. Writing in *Science*, Hand *et al.*[1] demonstrate that pathogenic infections that disrupt the integrity of the gut's mucosal barriers can precipitate the development of long-lived immunity directed against the host's resident microbes.

CD4$^+$ T cells are a class of immune cell that deploys potent effector functions to combat infections. During development, a repertoire of T cells is generated such that there will be low numbers of cells specific for any given antigen — a substance that stimulates responses from T and B cells of the immune system. 'Naive' T cells are those that have not yet encountered the antigen for which their own antigen receptor is specific. Infection with a pathogen stimulates proliferation of pathogen-specific T cells, which not only increases the number of these cells, but also causes their differentiation to effector cells. As the proliferative response is ending, a population of long-lived pathogen-specific 'memory' cells is established, which provides a heightened state