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Could geoengineering research help answer one of the biggest questions in climate science?

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Key Points:
- Anthropogenic aerosol impacts on clouds constitute the largest source of uncertainty in quantifying radiative forcing of climate
- A lack of control conditions for anthropogenically perturbed clouds has led to an impasse in separating aerosol from meteorological impacts
- Controlled aerosol perturbation experiments would overcome an impasse in constraining aerosol–cloud interactions using observations

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Abstract Anthropogenic aerosol impacts on clouds constitute the largest source of uncertainty in quantifying the radiative forcing of climate, and hinders our ability to determine Earth's climate sensitivity to greenhouse gas increases. Representation of aerosol–cloud interactions in global models is particularly challenging because these interactions occur on typically unresolved scales. Observational studies show influences of aerosol on clouds, but correlations between aerosol and clouds are insufficient to constrain aerosol forcing because of the difficulty in separating aerosol and meteorological impacts. In this commentary, we argue that this current impasse may be overcome with the development of approaches to conduct control experiments whereby aerosol particle perturbations can be introduced into patches of marine low clouds in a systematic manner. Such cloud perturbation experiments constitute a fresh approach to climate science and would provide unprecedented data to untangle the effects of aerosol particles on cloud microphysics and the resulting reflection of solar radiation by clouds. The control experiments would provide a critical test of high-resolution models that are used to develop an improved representation aerosol–cloud interactions needed to better constrain aerosol forcing in global climate models.

Introduction

Anthropogenic aerosol impacts on clouds constitute the largest source of uncertainty in quantifying the radiative forcing of climate [*Myhre et al*., 2013]. Pollution particles generated by industrial processes, biomass burning, and other human activities mix with low-lying clouds, increasing the number and reducing the size of water droplets within the clouds, and often increasing the amount of sunlight they reflect. Uncertainty in this aerosol forcing of climate impedes our ability to determine accurately the Earth's climate sensitivity to increasing greenhouse gases [*Andreae et al*., 2005] and therefore thwarts accurate projections of greenhouse warming. Currently, the uncertainty in overall aerosol forcing since 1750 is estimated to be between −0.1 and −1.9 W m^{-2} [*Myhre et al*., 2013]. To put this in context, the radiative forcing from anthropogenic greenhouse emissions ranges from 2.2 to 3.8 W m^{-2} [*Myhre et al*., 2013]. Without greenhouse gas increases, aerosol emissions would have led to considerable global cooling over the 20th century. Because anthropogenic aerosol loading is expected to decrease over the 21st century for air quality improvement and greenhouse gas reduction, reduced aerosol cooling will unmask the effects of existing greenhouse gases, resulting in additional warming to an extent that is poorly known [*Myhre et al*., 2013].

Representing aerosol impacts on clouds in climate models is particularly challenging because aerosol–cloud interactions depend on complex fluid dynamical and microphysical processes occurring on spatial scales much smaller than the resolution of the models [*Stevens and Feingold*, 2009]. Consequently, the modeling community has been searching for ways to represent these complex interactions using parametric equations that, based on high-resolution model studies, are strongly scale-dependent [*McComiskey and Feingold*, 2012] and nonlinear [*Carslaw et al*., 2013]. As an illustration of the challenges, a single climate model can be tuned to produce either warming or cooling over the 20th century simply by making small changes in the threshold cloud droplet size required to produce rain [*Golaz and Levy*, 2013]. Uncertainties in aerosol–cloud interactions also drive major uncertainties in our ability to quantify regional climate change [*Booth et al*., 2012] and forecast weather accurately [*Mulcahy et al*., 2014].

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Barriers in Understanding Cloud–Aerosol Effects

A large body of observational research [e.g., *Martin et al.*, 1994; *Ramanathan*, 2001; *Lohmann and Feichter*, 2005; *Isaksen et al*., 2009] has shown positive correlations between aerosol concentrations and the number and concentration of cloud droplets, a relationship first postulated by *Twomey* [1974]. Observations show that an increase in aerosol number produces more numerous cloud droplets, which are then smaller in size, which, in the absence of other changes, results in brighter clouds. Observations also find correlations between aerosol concentrations and reduced precipitation, especially in shallow marine clouds [*Sorooshian et al*., 2009; *Terai et al*., 2012]. Climate models with their parameterized aerosol–cloud interactions tend to agree that aerosol-suppressed precipitation leads to a retention of cloud water, which further increases the brightness of clouds. However, small-scale process models that are able to resolve turbulent and microphysical processes do not universally agree on these effects, and instead find that the responses of cloud condensate to aerosol increases can work in both directions depending upon meteorological conditions. Cloud and turbulence resolving models are able to represent aspects of the turbulent mixing of clouds with the overlying and surrounding clear air [*Ackerman et al*., 2004] that are very difficult to represent parametrically. However, even high-resolution models struggle to accurately represent the effects of mixing across sharp boundaries such as those commonly found at the top of the marine boundary layer [*Stevens et al*., 2003].

Researchers have sought to address these model limitations with observations, but a major problem with the use of correlative observational studies to quantify the impacts of aerosol changes on clouds is that both aerosols and meteorological changes directly influence cloud radiative properties. Winds transport aerosol particles from land over the ocean where they affect clouds. But we know that even without aerosol changes, cloud properties depend upon winds and meteorological state [e.g., *Wood*, 2012]. It is therefore no great surprise that changes in aerosol properties at any given location depend upon meteorological conditions, and that these too will impact cloud properties. Small changes in meteorology can have major impacts on cloud thickness and cover, making it difficult to isolate the impacts of aerosol from those due to correlated meteorological drivers [e.g., *Stevens and Feingold*, 2009].

Yet there are some circumstances where clouds are unequivocally impacted by aerosols. Ship tracks produced by container vessels [*Durkee et al*., 2000] and wakes of fumarolic volcanoes [*McCoy and Hartmann*, 2015] are two such examples. These are situations where aerosol sources are very strong but, even in these circumstances, it can be difficult to quantify aerosol source strengths, particle size distributions, and composition, and arrive at accurate conclusions about their impacts. When source strengths are weaker [e.g., for broad shipping lanes rather than individual ships], the aerosol effects on cloud thickness and coverage are typically swamped by meteorologically driven cloud variability "noise" [*Peters et al*., 2011]. Even in regions where clouds are exposed regularly to strong aerosol perturbations, they are often influenced differently from one day to the next because of meteorological variability in aerosol sources. For example, ship emissions are affected by differing schedules, fuels, cargo loads, engine emission controls, age and condition; volcano emissions differ from one day to the next due to variations in eruption strength [e.g., *Businger et al*., 2015]. Further, variations in wind speed not only produce variations in the strength of the surface submicron aerosol concentrations, but also produce variations in the concentration of giant sea salt particles that can produce different cloud responses from those expected from smaller aerosol. For example, giant particles can promote precipitation formation that may oppose the impacts of increasing submicron aerosol concentration [*Dadashazar et al*., 2017].

Controlled Experiments May Offer a Breakthrough

To overcome these challenges, it would be extremely valuable to explore aerosol influences on clouds in situations where meteorological and source variability do not introduce confusion, and aerosol sources are carefully designed to control composition, size, shape, amount, and altitude of injection. This would allow exploration of cloud responses under more controlled conditions, eliminating many of the factors that inhibit accurate interpretation of cloud responses to aerosols.

Climate model simulations indicate that regions of extensive marine low clouds account for a large portion of the global aerosol indirect forcing [*Kooperman et al*., 2012; *Carslaw et al*., 2013]. This may seem counter-intuitive, but marine clouds in these pristine areas are very susceptible to small changes in aerosol.

Hence, small changes in aerosol sources in these regions such as ocean biological activity or volcanic emissions can lead to significant changes in cloud properties. Controlled experiments in these areas, well away from populated regions, could therefore yield critical information for testing our representations of aerosol–cloud interactions in both process and climate models.

In this context, "controlled experiments" entail a means of generating and delivering a controlled input of aerosols with the desired characteristics (e.g., particle size distribution and number) for inducing and examining these effects. Such experiments would allow scientific investigations to be performed in a manner much closer to that in a laboratory setting, facilitate the use of models to predict cloud responses in advance, and validate or disprove model findings about the resulting cloud–aerosol interactions. We may then be able, for the first time, to substantially improve climate model representations of cloud–aerosol effects, narrow the uncertainty in aerosol forcing globally, and improve climate forecasts and projections of future warming.

A Proposal for High-Value, Low-Impact Experiments

It is possible to perform such experiments in ways that will not have a discernable impact on weather or climate, or on local ecosystems [*Wood and Ackerman*, 2013]. Using well-characterized aerosol from a natural source (as opposed to pollution aerosol from ship engines) protects pristine oceanic environments and supports maximum control of inputs. The injected aerosol particles will alter cloud microphysical properties in a measurable way, similar to observed changes in ship tracks. However, the measured effects on clouds will (1) disappear within 1 or 2 days at most; (2) have little if any impact on sea surface temperatures (certainly less than the range of typical natural variations); and (3) have no discernable impact on local ecosystems. *Morgan and Ricke* [2010] suggest that such experiments be evaluated though the use of "allowable zones," which are defined in terms of perturbations to existing environmental quantities such as sea surface temperature, cloud reflectivity, etc. These proposed experiments can be evaluated quite easily within such a framework to allow the science community to define the extent of the allowable zone for aerosol injections. Furthermore, creating aerosol particles by spraying ocean salt water will produce effective sea-salt cloud condensation nuclei, which avoids the introduction of pollutants, or any type of new material, into the ecosystem.

These types of perturbation experiments are extremely valuable because they can be conducted with very precise specification of the aerosol source properties, and with well-defined spatial and temporal extent. Turning the aerosol source on and off with some predetermined temporal signal will produce temporally varying responses that can be measured and used to evaluate aerosol efficacy. In addition, regions of clouds adjacent to perturbed regions with similar characteristics can be monitored to serve as an experimental "control."

Controlled experiments to test the effects of sea-salt aerosols on clouds have been proposed in the context of research on a potential approach to reducing climate warming by increasing the reflectivity of marine clouds [e.g., *Latham et al.*, 2012; *Wood and Ackerman*, 2013; *Keith et al.*, 2014]. The effect is similar to that observed when emissions from ships create bright streaks in marine clouds [*Durkee et al.*, 2000]. Early studies suggest that it might be possible to offset a doubling of CO_2 globally by brightening 10%–30% of marine clouds. Some studies suggest it may also be possible to brighten clouds in localized regions to reduce coral bleaching, relieve heat stress on coastal redwood forests, reduce the severity of storms, and increase arctic ice cover [*Latham et al.*, 2014]. But to date, practically all research has been limited to a small number of modeling studies, where models also contain the aforementioned gaps in representations of cloud–aerosol processes. Much remains unknown.

The single exception to model studies is the 2011 Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE), which conducted a limited controlled aerosol perturbation experiment off the California coast [*Russell et al.*, 2013]. Lessons were learned during E-PEACE that should inform the design of future field studies, including difficulty producing a sufficient number of particles to brighten clouds with currently available technology, difficulty lofting emitted particles without sufficient buoyancy, an absence of suitable clouds and scattered clouds on many days, multiple cloud layers, and thermodynamic and dynamic conditions near cloud top impacting cloud top entrainment of dry air.

With knowledge of these challenges, controlled experiments to study cloud aerosol effects and improve our knowledge of aerosol–cloud interactions appear to be feasible. They require investment to develop the technology to produce controlled outputs of salt aerosol particles of optimum size and sufficient quantity (e.g., 100 nm in size delivered at a rate of 10^{15} particles per second from point sources). Promising new technology currently exists at the laboratory scale, [*Cooper et al.*, 2014] but requires significant upscaling, testing, and hardening for deployment on ocean platforms or aircraft.

Controlled cloud perturbation experiments constitute a fresh approach to climate science. They will provide unprecedented data to untangle the effects of aerosol particles on cloud microphysics and the resulting reflection of solar radiation by clouds. Modeling these observed processes with high-resolution models will allow scientists to improve the physics in these models and increase confidence in their output. The output of these validated models will then serve as the basis for better and more constrained parameterizations for use in lower-resolution global climate models. The anticipated outcome of this process is a substantial reduction in the current uncertainty associated with the effect of aerosol on marine clouds. This will improve our simulation of climate over the past century and narrow ranges of predicted climate change for the current century. At the same time, these controlled experiments will provide useful new information about the feasibility and risks of proposals to use similar techniques as one means of reducing greenhouse warming, perhaps replacing the effects produced by less benign aerosol emissions today.

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