Fighting Climate Change by Engineering Air Pollution to Brighten Clouds

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Abstract

Natural, industrial, and residential combustion produces both aerosols that cool the Earth as well as CO_2 that warms, and the amount of combustion worldwide has increased substantially since the invention of the steam engine as well as with the increase in populations relying on wood and char burning. In fact, natural and early man-made combustion processes emitted aerosols and CO_2 roughly proportionally, although the ratios of emission types were dependent on burning conditions. In the wake of the 1952 London smog-induced respiratory-health-related deaths and the ensuing legislation in favor of limiting emissions in the United States and Europe, "air quality engineering" began reducing emissions of aerosols in the emissions of combustion processes. This reduction in emissions aerosols (without reductions in CO_2 emissions) led to more warming per combustion-generated energy (with some offset for reductions in absorbing aerosol emissions). One approach to "climate engineering" is to intentionally undo the recent reductions in aerosol emissions in a way that avoids the health and visibility impacts of pollution but still allows for particles to cool the Earth both by reflecting sunlight directly and by brightening clouds (which magnify the scattering of light with water). The engineering challenge with this approach is that clouds are the least understood component of the climate system, and current models are unable to reliably predict their formation and properties. Recent research in the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) 2011 illustrates that judicious selection of the meteorological regime and the size and composition of particle emissions can achieve substantial cooling effects. Nonetheless, socio-economic questions about climate engineering remain, such as the possibility that, if implemented, sudden cessation of enhanced particle emissions could exacerbate the climate effects on ecosystems and might interfere with oceanic and terrestrial ecosystem processes, thus requiring cautious and comprehensive research.

Introduction

The fundamental physics that control the global mean surface temperature are well understood: about one-third of the incoming solar radiation is reflected back to space by the Earth's albedo and the remaining two-thirds is absorbed at the surface, then emitted as longwave energy following the T^4 dependence of the Stefan-Boltzmann equation, so that the incoming and outgoing energy at the top of the atmosphere largely balances the energy leaving (by the first law of themodynamics), after partially trapping some of the energy by the greenhouse effect of atmospheric water vapor and clouds as well as greenhouse gases [*IPCC*, 2007a]. Consequently that increased albedo can offset warming by increasing shortwave reflection of clouds by adding additional aerosol is equally straightforward, keeping in mind that maintaining global mean surface temperature does not imply maintaining regional temperature nor precipitation. The challenge in engineering aerosol particles to "fight" climate change by brightening clouds is predicting how the physics of clouds affect the albedo response to increased particles.

Recent Model Simulations of Cloud Brightening

Recent model simulations have established the plausibility of producing enough particles to modify enough clouds to offset sufficient global warming to delay or lessen some of the effects expected in our changing climate [*Latham*, 1990; 2002; *Latham et al.*, 2008]. Some schemes focus on a perceived need for engineering and development of new technology, such as Flettner rotors and high efficiency seawater atomization [*Salter et al.*, 2008]. Other studies employ detailed global modeling investigations to show that the details of both how many clouds are brightened, with more aggressive increases in brightening resulting in exacerbation of climate in some regions even though others are improved [*Rasch et al.*, 2009]. In addition, global simulations have shown that which clouds are targeted is also important, with some choices resulting in exacerbation of drought conditions in some regions [*Korhonen et al.*, 2010; *Rasch et al.*, 2009].

However, aerosol-cloud-radiation interactions are widely held to be the largest single source of uncertainty in climate model projections of future climate change due to increasing anthropogenic emissions. The underlying causes of this uncertainty among modeled predictions of climate are the gaps in our fundamental understanding of cloud processes [*IPCC*, 2007a]. There has been significant progress with both observations and models on these important questions. However, while the qualitative aspects of the indirect effects of aerosols on clouds are well known, the quantitative representation of these processes is nontrivial and limits our ability to represent them in global climate models. To date, global models lack (i) accurate aerosol particle activation, with the resulting implications for the profiles of supersaturation, vertical velocity, liquid water content, and drop distribution; (ii) realistic microphysical growth and precipitation processes that control the formation and impacts of drizzle on cloud structure, lifetime, and particle concentration; and (iii) eddy-based transport processes that control the effects of entrainment on cloud thickness and lifetime as well as the dispersion of aerosol plumes. These are basic scientific issues that have not been addressed by climate models or by climate engineering proposals that involve perturbing marine stratocumulus.

New Experimental Evidence of Cloud Brightening

To learn more about the uncertainties in the cloud physical processes that affect the uncertainty in aerosol-cloud-radiation interactions, we designed the Eastern Pacific Emitted Aerosol Cloud Experiment (E-PEACE) 2011 as a targeted aircraft campaign with embedded modeling studies, using the Center for Interdisciplinary Remotely-Piloted Aircraft Studies (CIRPAS) Twin Otter aircraft and the R/V *Point Sur* in July 2011 off the coast of Monterey, California, with a full payload of instruments to measure particle and cloud number, mass, composition, and water uptake distributions [*Russell et al.*, in review 2012; *Shingler et al.*, 2012]. Three central aspects of the collaborative E-PEACE design and the resulting highlights are:

1. Controlled particle sources were used to separate particle-induced feedbacks from natural variability. We have investigated and developed three types of sources that provide three different sizes and compositions of particles to target specific aspects of aerosol-cloud

interactions: (a) Ship-emitted particles at rates of 10^{16} - 10^{18} s^{-1} with dry diameters between 50 and 100 nm [*Coggon et al.*, 2012], (b) Ship-board smoke generator particles at rates of 10^{11} - 10^{13} s^{-1} with dry diameters between 100 nm and 1 μm, and (c) Aircraft-based milled, coated salt particles at rates of 10^{9} s^{-1} with dry diameters between 3 and 5 μm.

2. Large Eddy Simulations and Aerosol-Cloud Parcel modeling studies specifically address the open questions outlined above which describe the dynamical response to microphysical changes. These models provide insight on the limitations in plume dispersion and cloud interactions that were observed with shipboard and aircraft observations.

3. Satellite observations showed a range of impacts on cloud albedo from ship tracks [*Chen et al.*, 2012], but the controlled emission of smoke generated particles demonstrated efficient cooling of clouds at very low warming cost, using existing technology and minimal resources. From this result we see that cooling outweighs warming by a factor of 50 on days that tracks were made [*Russell et al.*, in review 2012]. This cooling effect exceeds that of commercial shipping, for which track-making ships make twice as much cooling as warming.

Implications

The E-PEACE results provide proof of concept that cloud brightening to reduce global mean warming is possible, with existing, decades-old technology, for some cloud conditions (but it will not reduce drought or ocean acidification). However, while technology for particle emission and distribution exists, the engineering required for cloud brightening is hardly trivial. The issues that are most critical to engineering the design of cloud brightening on the large scale are (1) cloud feedback responses to aerosol enhancements that reduce the expected brightening through turbulence or precipitation, (2) multilayered clouds that mask any changes in underlying clouds, and (3) ecosystem impacts of particle deposition [*Russell et al.*, 2012]. These issues require region-specific observations and small-scale, short-duration testing to acquire realistic constraints for modeling.

While cloud brightening will target atmospheric emissions outside of national boundaries (since offshore marine stratocumulus have some of the largest impact on albedo) in areas that are largely unregulated, any large-scale implementation should involve multinational agreement and cooperation, as well as compensation for unexpected and harmful consequences. Furthermore, as with any solar reflection method that does not also reduce greenhouse gases, once initiated the cessation of cooling would likely cause accelerated warming as the system returns to the non-masked warming [*Russell et al.*, 2012]. Given this, while cloud brightening could be appropriate to prevent tipping points (such as massive sea ice loss), implementation of cloud brightening to offset climate warming should only be considered as an option after sufficient research is devoted to better constraining aerosol-cloud-radiation interactions.

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