Studying Geoengineering with Natural and Anthropogenic Analogs

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Abstract

Solar radiation management (SRM) has been proposed as a possible option for offsetting some anthropogenic radiative forcing, with the goal of reducing some of the associated climatic changes. There are clearly significant uncertainties associated with SRM, and even small-scale experiments that might reduce uncertainty would carry some risk. However, there are also natural and anthropogenic analogs to SRM, such as volcanic eruptions in the case of stratospheric aerosol injection and ship tracks in the case of marine cloud albedo modification. It is essential to understand what we can learn from these analogs in order to validate models, particularly because of the problematic nature of outdoor experiments. It is also important to understand what we cannot learn, as this might better focus attention on what risks would need to be solely examined by numerical models. Stratospheric conditions following a major volcanic eruption, for example, are not the same as those to be expected from intentional geoengineering, both because of confounding effects of volcanic ash and the differences between continuous and impulsive injection of material into the stratosphere. Nonetheless, better data would help validate models; we thus recommend an appropriate plan be developed to better monitor the next large volcanic eruption. Similarly, more could be learned about cloud albedo modification from careful study not only of ship tracks, but of ship and other aerosol emission sources in cloud regimes beyond the narrow conditions under which ship tracks form; this would benefit from improved satellite observing capabilities.

Keywords: Geoengineering, Volcanic eruptions, Ship Tracks, Aerosols

1. Introduction

Geoengineering by means of solar radiation management (SRM) has been suggested as a potential approach (in concert with mitigation of greenhouse gas emissions) to manage climate change (Crutzen, 2006; Shepherd et al., 2009; GAO, 2011). We focus here on two SRM ideas in particular: the intentional introduction of stratospheric aerosols to scatter some incoming sunlight (e.g., Budyko, 1977), and altering the albedo of marine boundary layer clouds by injecting additional aerosols (Latham, 1990). Before decisions can be made about implementation, it is essential to improve our scientific understanding of likely positive and negative impacts, both intended and otherwise. Much of this understanding can come from numerical modeling (Bretherton and Rasch, 2013). Outdoor experiments might address some gaps in knowledge, but even small-scale experiments outside a laboratory environment could carry some risk (SRMGI, 2011). However, for both of the concepts considered here, there are natural or anthropogenic analogs: volcanic eruptions have provided the motivation for stratospheric aerosol SRM, while observations of ship tracks have provided the motivation behind marine cloud brightening. The processes related to these analogs are also important for understanding climate change itself. Here we discuss using analogs to study SRM.

While volcanic eruptions provide the evidence that increased stratospheric aerosols would indeed cool the planet, there are many reasons for concern about geoengineering with stratospheric aerosols (Robock, 2008), with many of these concerns yet to be quantified. Increasing marine boundary layer cloud albedo through injection of sea-salt aerosols to form additional cloud condensation nuclei (CCN) could have different undesired side-effects than stratospheric aerosols (e.g., Jones et al., 2009), and the effectiveness is more poorly understood.

For example, the conditions under which adding CCN would increase cloud albedo are not well known (Wang et al., 2011).

A long-term roadmap for geoengineering research (e.g., Caldeira and Keith, 2010) would clearly involve more modeling studies than have been done to date, possibly some limited small-scale but open-atmosphere experiments to resolve specific process questions (David Keith and James Anderson, personal communication, 2012), and only if implementation were planned, an initial subscale deployment phase to better understand the climate response (MacMynowski et al., 2011); progress would also be needed in governance appropriate to each stage. However, missing from this description is that much can be learned from a better understanding of natural and anthropogenic analogs, both to directly understand potential consequences, and to evaluate models. This knowledge could minimize or altogether avoid any risky experimentation with the planet. Here we discuss fundamental questions about SRM that can be studied using analogs.

2. Volcanic Analogs

The observation that large volcanic eruptions cool the planet was one of the original motivations for suggesting geoengineering (e.g., Budyko, 1977, Crutzen, 2006), with the eruption of Mount Pinatubo in 1991 for example cooling the planet by roughly 0.5°C by the injection of 20 Mt sulfuric acid into the stratosphere, producing more than 30 Mt of sulfate aerosols (Bluth et al., 1992; McCormick et al., 1995). However, while it is clear from these natural analogs of geoengineering that "mimicking" a volcanic eruption by producing sulfate or other aerosols in the stratosphere will result in cooling, there are many uncertainties regarding both the effectiveness and the side effects (i.e., the risks). One of the most valuable opportunities for reducing the uncertainties and risks of geoengineering with stratospheric aerosols thus comes from looking at past volcanic eruptions and from further study of the climate system response to volcanic eruptions.

One of the main differences between a somewhat permanent stratospheric aerosol cloud proposed for geoengineering and clouds produced by volcanic eruptions is the lifetime. The e-folding lifetime of stratospheric clouds from tropical volcanic eruption is about one year (Robock, 2000), while it is 2-4 months for those from high latitude eruptions (Kravitz and Robock, 2011). (By the way, this informs us about the frequency of stratospheric aerosol precursors that would be needed to maintain a cloud in the stratosphere.) The difference in lifetimes means that climate system responses with long time scales, such as oceanic responses, would be different between volcanic eruptions and geoengineering, but rapid responses, such as seasonal responses of monsoon circulations and precipitation would be quite similar, and the volcanic analog would be appropriate. For example, MacMynowski et al. (20111, 2011b) showed that precipitation response to stratospheric forcing had only a weak dependence on the frequency of the applied forcing, in contrast to the temperature response, which depends on the longer timescales imposed by ocean thermal inertia.

2.1. Lessons from past volcanic eruptions

Volcanic eruption analogs already tell us many things about the potential effects of stratospheric aerosol clouds. These were briefly discussed by Robock et al. (2008), but there are many more examples, discussed here, including additional things that could be learned from more studies. The beneficial impacts include:

Cool the surface, reducing ice melt and sea level rise. It is well-known that global average climate cools after large volcanic eruptions (Robock, 2000). After the 1991 Mt. Pinatubo eruption, global average temperature cooled for three years, with a maximum cooling of 0.7 K (Soden et al., 2002), after accounting for the effects of the simultaneous El Niño. Stenchikov et al. (2009) and Ottera et al. (2010) found long-term impacts on ocean heat content and sea level, and Zanchettin et al. (2010) all found an impact on North Atlantic Ocean circulation a decade later, so we might expect impacts from SRM also, but would need models and not observations to quantify them.

Pretty sunsets. The reflection of the setting Sun from the bottom of stratospheric aerosol clouds produces pretty yellow and red skies a half hour to an hour after sunset (Robock, 2000). The most famous paintings of volcanic sunsets are by Ascroft after the 1883 Krakatau eruption (Symons, 1888) and in "The Scream" by Edvard Munch, painted in 1893, but with the brilliant volcanic sunset based on his memory of the Krakatau eruption 10 years earlier (Olson et al., 2004), and Zerefos et al. (2007) have documented many volcanic sunsets in works of art. Certainly stratospheric SRM would produce such skies every night in most of the world.

Increase the CO_2 sink. Following volcanic eruptions, observations show an increase of the CO_2 sink from global vegetation. The main cause is a shift from direct to diffuse solar radiation (Robock, 2000), which enhances vegetation growth (Mercado et al., 2009). But net primary productivity also responds to temperature and precipitation changes, and vegetation adjusts to changing conditions, so the net effect from a continuous stratospheric aerosol cloud needs further study. Cao and Caldeira (2010) showed that even a massive one-time CO_2 removal would be balanced by outgassing from the land and ocean.

However, volcanic analogs also suggest a number of negative effects from a continuous stratospheric aerosol cloud. These include:

Reduced summer monsoon precipitation. The reduction in sunlight after large volcanic eruptions cools land more than oceans. In the summer, this reduces the temperature contrast between warm continents and cooler oceans, weakening the African and Asian summer monsoon circulation and its resultant precipitation. This has been observed after every major volcanic eruption, including 1783 Laki and 1912 Katmai (Oman et al., 2006), 1982 El Chichón (Robock and Liu, 1994), and 1991 Pinatubo (Trenberth and Dai, 2007). Anchukaitis et al. (2010) showed the average effect on the summer Asian monsoon using tree rings for many centuries, and Peng et al. (2010) showed the same thing with climate model simulations. Whether this effect is truly dangerous depends on the proposed SRM strategy, but it would be difficult to design an SRM strategy without negative impacts on precipitation (Ricke et al., 2010).

Destroy ozone, allowing more harmful UV at the surface. Observations following the 1982 El Chichón and 1991 Pinatubo eruptions showed additional ozone depletion because of heterogeneous chemistry on the additional stratospheric aerosols, in the same process that produces the spring ozone hole over Antarctica on polar stratospheric clouds (Solomon, 1999). This has also been simulated in response to SRM (e.g., Tilmes, et al., 2008).

Produce rapid warming when stopped. Observations show that once a volcanic cloud is removed from the atmosphere, the climate system rapidly warms. If global warming were balanced by a long-term stratospheric aerosol cloud, balancing a large positive radiative forcing, this warming rebound would produce a much more rapid climate change than the gradual climate change now happening because of increasing greenhouse gases.

Make the sky white. A volcanic aerosol cloud is actually a thin cloud, making the sky whiter, particularly near the Sun, where a large amount of the sunlight is forward scattered (e.g., Plate 3, Robock, 2000). Kravitz et al. (2012) showed that this would also be the case for stratospheric SRM.

Reduce solar power. The same process that increases diffuse sunlight reduces direct sunlight. For solar electricity generation that uses direct sunlight, there would be a large reduction in that generation. Murphy (2009) found that for 9 solar thermal power plants in California during the summer of 1992 after the 1991 Pinatubo eruption, that the summer on-peak capacity was reduced by 34% from pre-Pinatubo levels.

Perturb the ecology with more diffuse radiation. The same mechanisms that would increase the CO_2 sink would affect different plants differently, and the net effect on ecosystems and agriculture is not clear. Certainly there would be changes.

Damage airplanes flying in the stratosphere. Following the 1991 Pinatubo eruption, in addition to direct airplane damage from volcanic ash encounters immediately after the eruption, there was long-term damage to airplanes flying through a dilute sulfuric acid bath, particularly on polar routes where commercial aircraft entered the lower stratosphere. This required more frequent replacement of windows and other surfaces (Bernard and Rose, 1996).

Degrade astronomical observations. Any cloud that reflects some sunlight back to space will also reflect starlight. Furthermore, it will heat the stratosphere, producing enhanced downward longwave radiation, and could impact stratospheric water vapour content; these would affect IR astronomy. How important these effects would be for astronomical observations remains to be determined. It would be interesting to search for such effects after the 1991 Pinatubo eruption, and determine how such a cloud in the future would affect modern astronomical equipment.

Affect remote sensing. A stratospheric aerosol cloud would also affect shortwave and longwave radiation leaving Earth and observed by satellites. After the 1982 El Chichón eruption, the simultaneous development of a very large El Niño was not detected for months, since the enhanced longwave emissions from the warm ocean were masked by the stratospheric cloud (Strong, 1984). At the same time, famine warning systems were triggered by erroneous inputs to normalized difference vegetation index calculations.

Affect stargazing. In remote areas where it is possible to see the night sky without air or light pollution, certainly a perpetual stratospheric cloud would diminish the number of faint stars that would be visible. It would be interesting to search for such reports following the 1991 Pinatubo eruption.

2.2. What more can we learn from future eruptions?

While past volcanic eruptions inform us of some of the potential impacts of stratospheric aerosol clouds, there are several additional questions that can be addressed by planning for observations of the next large eruption, as well as additional study of past ones. These include:

What will be the size distribution of sulfate aerosol particles created by geoengineering? Will they remain at the typical effective radius of about 0.5 μm observed after Pinatubo, or will they grow as additional sulfate creates larger rather than more particles? Even though a typical large volcanic eruption is a one-time stratospheric injection, we can learn from the initial processes of conversion from SO_2 gas to sulfate particles and then to particle growth. The issue of how particle sizes evolve for geoengineering has been addressed through simulations (Heckendorn et al. 2009, Hommel and Graf, 2010, English et al. 2012a), but there are limited data to support analysis. It is also important to understand how particle size evolution depends on injection strategy, that is injecting SO_2 or H_2SO_4, and what the pattern of injection is (Pierce et al., 2010; English et al., 2012a). Such models can be tested by imposing the exact emissions from future volcanic eruptions, if the particle evolution from the eruptions is well monitored.

How will the aerosols be transported throughout the stratosphere? Under what conditions do tropical injections gradually spread globally? Do injections in the subtropics stay in one hemisphere? What are their lifetimes? How do high latitude injections behave? How does the phase of the Quasi-Biennial Oscillation affect the transport? Does the ENSO phase play a role through tropospheric impacts on atmospheric circulation? What is the dependence on the height of the injections?

How do temperatures change in the stratosphere as a result of the aerosol interactions with shortwave (particularly near IR) and longwave radiation? Is there a response in the circulation to these temperature and resulting geopotential height changes? This question is intimately related to the question above and the next two questions.

Are there large stratospheric water vapor changes associated with stratospheric aerosols? Is there an initial injection of water from the eruption? How do temperature and circulation changes in the stratosphere affect the tropical tropopause layer, and does heating this layer allow more water to enter the stratosphere? There were not robust observations of large impacts of the 1991 Pinatubo eruption on stratospheric water vapor, but was this a result of a poor observing system?

Is there ozone depletion from heterogeneous reactions on the stratospheric aerosols? How do changes in other species, such as H_2O, Br, and Cl, interact with the ozone chemistry, and what is the dependence on temperature changes and the location and time of year of the aerosols? Simulations of increased aerosol loading have also found changes in upper tropospheric chemistry (Hendricks et al., 1999).

As the aerosols leave the stratosphere, and as the aerosols affect the upper troposphere temperature and circulation, are there interactions with cirrus clouds? Do cirrus clouds increase or decrease, and how do these changes depend on the aerosol concentration and particular atmospheric conditions? How can observed cirrus changes be attributed to volcanic effects as compared to changes that would take place anyway in response to normal weather and climate variability? The connection between stratospheric sulfate aerosols and cirrus clouds in the upper troposphere has been studied in the context of volcanoes, with some studies indicating an effect from volcanic eruptions mixed with a signal from El Niño/Southern Oscillation (ENSO) (e.g., Wylie et al. 1994, Sassen et al. 1995, Song et al. 1996, Wang et al., 1995), but others finding no impact (Luo et al. 2003, Massie et al. 2003, Lohmann et al. 2003); the issue is important but not yet resolved.

How will tropospheric chemistry be affected by stratospheric geoengineering? What is the impact of the "rain-out" of stratospheric aerosols into the upper troposphere? Will the changing distribution of ultraviolet light caused by ozone depletion have subsequent impacts on the troposphere, particularly through OH and NOx chemistry?

2.3. Differences between volcanic eruptions and stratospheric geoengineering

Volcanic eruptions are clearly analogous to SRM using stratospheric aerosols in many ways, and thus serve as an important component of addressing the uncertainties listed above. However, there are also a few important differences:

Volcanic eruptions are into a clean stratosphere. The most significant difference is that injecting sulfate into a "clean" stratosphere results in a different coagulation problem from a continuous injection scenario. Theoretical studies show that massive volcanic eruptions (Timmreck et al., 2010) or continuous injection (Heckendorn et al., 2009) will result in larger particles than after a one-time injection such as from the 1991 Pinatubo eruption. The larger mean radii expected for geoengineering would result not only in higher concentrations being required to obtain the same radiative forcing, but also more rapid fallout into the troposphere, which would both increase the injection rate required to sustain the desired geoengineering effect and increase the potential for impacts on cirrus and upper tropospheric chemistry.

Volcanic eruptions also include significant ash. Therefore, it may be difficult to determine whether any initial effect observed (or not) on cirrus cloud formation, for example, is due to the ash rather than the sulfate. The lifetime of the ash is shorter than that of the aerosols, so this attribution question is primarily a challenge immediately after an eruption.

The time-scale of radiative forcing is different. This needs to be taken into account in extrapolating between the climate response observed after a volcanic eruption and what would be expected for continuous injection. For example, land-sea temperature contrast and precipitation respond to radiative forcing changes relatively rapidly (Dong et al., 2009), but global mean temperature changes more slowly, and hence the ratio of precipitation to temperature changes should be expected to be much more pronounced after a volcanic eruption than due to continuous SRM (MacMynowski et al, 2011b).

Because of the above differences, observations cannot be used as a direct estimate for conditions under continuous geoengineering. Regardless of the data available after an eruption, there will remain uncertainty in the factors listed above. These uncertainties can be limited by modeling or more representative outdoor direct testing, which for some uncertainties may require "tests" large enough to look more like deployment (Robock et al., 2010). Because of governance and other issues, such in situ testing may never take place (Robock, 2012).

2.4. Volcanic monitoring

The ability to successfully take observations after a volcanic eruption would be extremely valuable for validating models. However, previous large eruptions have not been sufficiently well monitored. More information is required, for example, regarding the initial aerosol concentrations in order to better validate particle formation, coagulation, and evolution models. Thus we make two recommendations.

First, more can be learned from further data mining from past eruptions; in addition to improving our knowledge, this will also clarify the observational gaps that need to be filled. The focus specifically on the uncertainties associated with geoengineering leads to a different perspective and hence possibly different questions from what might be asked if the goal were solely to understand volcanic eruptions. For example, it is insufficient to know whether a volcanic eruption does or does not have some impact on cirrus, without being able to separate out effects due to ash, or understand the dependence on the aerosol size distribution.

Second is to develop either a rapid response system or system for continuous observations so that we are ready for the next large volcanic eruption, and can gather the data needed to validate models. The evolution in stratospheric sulfate aerosol size distribution occurs over the first few months after an eruption (Stenchikov et al., 1998; English et al., 2011, English et al., 2012b), underscoring the need for a rapid response capability. Sustained observations would be required from less than roughly 3 months to 18 months following a massive eruption to capture the initial ramp-up, peak, and ramp-down of aerosol concentrations.

To provide data for validating the modeling of particle size distributions and their evolution, a volcanic monitoring system would need to obtain observations during the first few months after an eruption. This means that any rapid response system (e.g., using balloons) needs to be available for deployment at any time, with funding in place for the personnel and equipment. This rapid response capability needs to be in addition to sustained background observations (e.g., Deshler et al., 2003, Deshler, 2008).

To be of most use, a volcanic cloud monitoring system will need to measure the spatial peak (highest concentration) of the plume. Limb-scanning satellite measurements, such as SAGE-II, did not see the densest part after the 1991 Pinatubo eruption (Stenchikov et al., 1998). For balloon-based observing, this also requires a plume forecast capability (Vernier and Jumelet, 2011). Satellite observations will also need independent data on the aerosol size distribution if existing retrieval techniques depend on such assumptions. Stratospheric chemistry observations will require high resolution measurements with stratospheric balloons or high altitude aircraft. Cirrus is adequately observed with existing systems (Sassen et al, 2008; Vernier et al, 2009) uncertainties in cirrus impact are thus related to natural variability, and uncertainties in aerosol concentrations in the densest part of the volcanic plume.

3. Ship tracks and marine cloud brightening

Increasing the brightness of marine boundary layer clouds through the injection of aerosols such as sea salt (Latham, 1990) has also been proposed as a means of solar radiation management. This strategy derives from the observation of ship tracks, where, depending on conditions, there is a clear cloud signal resulting from the injection of aerosols from the ship exhaust (Christensen and Stephens, 2011, 2012). However, the complexity of cloud-aerosol interactions results in substantial uncertainties as to the effectiveness of this approach. As in the case of using volcanic eruptions as an analog to stratospheric aerosol geoengineering, there is much that can be learned from analogs. In this case, the principal analogs are anthropogenic, in the form of ship exhaust or emissions from coastal sites, although volcanic plumes in the boundary layer have also been explored (Yuan et al. 2011). A more thorough analysis of existing data would both improve our knowledge and clarify the observational gaps that need to be filled. There are also observational gaps that limit our current ability to assess this approach, such as the entrainment rate, or direct measurement of albedo at high spatial resolution.

The key concept is that increasing the number of cloud condensation nuclei (CCN) while keeping cloud liquid water constant results in more, smaller, droplets, and an increase in cloud albedo, the “Twomey” or “first indirect” effect (Twomey, 1974). However, liquid water path (LWP) rarely remains constant, and these changes can produce radiative impacts of the same order as those predicted from the Twomey hypothesis (e.g., Lohmann and Feichter, 2005, Isaksen et al. 2009). For example, precipitation and evaporation cause changes in LWP. Enhanced entrainment in polluted clouds not only affects LWP (Ackerman et al, 2004), but can also affect neighboring clouds where aerosols were not injected (Porch et al., 1990). A greater concentration of small drops has been hypothesized to suppress precipitation because the coalescence efficiency of cloud droplets increases strongly with droplet size (Albrecht, 1989), although robust relationships amongst changes in precipitation, cloud albedo, and cloud coverage have not yet been established from observations. The macrophysical response to aerosol injection depends on the environment; this is illustrated for example in large eddy simulations (Wang and Feingold 2009a, 2009b; Wang et al. 2010, 2011). Stratocumulus clouds also tend to naturally “buffer” against processes (such as changing aerosol) that change cloud albedo and precipitation (Stevens and Feingold, 2009), for example through changes in entrainment. Furthermore, we have inadequate observations to analyze the processes which influence these cloud properties. The challenges in understanding all of the feedbacks involved, and when the introduction of aerosols leads to greater albedo, and when it does not, points to the need both for careful data analysis, and for greater observational capability.

3.1 Key Uncertainties

There are several important uncertainties that would need to be resolved to understand the effectiveness and impact of marine cloud brightening for geoengineering. The first two we list here are closely related, and are also essential for understanding cloud-aerosol interactions for climate change modeling in general.

a) The sensitivities of marine cloud albedo to specific processes and parameters are poorly understood (e.g., entrainment, LWP, turbulent kinetic energy (TKE), number density, cloud fraction). An improved understanding of these sensitivities is required to determine under what conditions the net albedo increases with increased aerosols. In particular, no observational studies are able to measure the albedo sensitivity to entrainment and TKE.

b) Much of the data analysis to date has focused on ship tracks, as they represent the most visible change due to aerosols. However, focusing on ship tracks alone is insufficient as these are imperfect analogs. Exhaust plumes do not always produce ship tracks, and the clouds that are receptive to the plumes span a limited range of stratocumulus conditions (i.e., only in a shallow cloud, typically less than 1 km cloud top height in a relatively clean environment (Coakley et al., 2000)). It is also important to understand the aerosol indirect effect on clouds from other (non-ship track) emissions and pollution, including large smelters and volcanic plumes. Given the larger variability and range of environmental conditions, there could be greater uncertainty in the magnitude of the effect of additional aerosols on cloud albedo outside of the narrow range of conditions where ship tracks are visible.

c) Assessment of the predicted climate response to the spatially inhomogeneous radiative forcing introduced by selective brightening of marine boundary layer clouds. There have been many more simulations of the climate impacts from stratospheric aerosol injections or uniform reductions in sunlight than there have been for marine cloud brightening. To offset a significant fraction of anthropogenic radiative forcing using this approach, large changes in radiative forcing would be required over relatively small spatial extent, with unknown climate impact. For example, simulations by Jones et al. (2009) offset 35% of the radiative forcing due to current greenhouse gases with marine cloud brightening, but found detrimental effects on precipitation and net primary productivity in some regions, particularly for the Amazon rain forest. There could also be a large impact on drizzle and precipitations along coastlines; further assessments are clearly needed.

3.2 What have we learned, and what are the gaps?

There have been several comparative albedo studies for ship-tracks (e.g., Schreier et al., 2007; Christensen and Stephens, 2011, 2012; Peters et al., 2011; Chen et al, 2012), as well as other emission sources such as volcanic plumes in the boundary layer (Yuan et al 2011, Gasso et al 2008). Some of these uncertainties could also be addressed through experiments that intentionally introduce aerosols while monitoring cloud properties, such as the recent E-PEACE experiment (Eastern Pacific Emitted Aerosol Cloud Experiment; Chen et al. 2012). Whether the aerosols are introduced in a controlled experiment, or the effects of current aerosol emissions are monitored, there are gaps in our observational capabilities. Table 1 summarizes current capabilities and gaps in observations of key parameters for past field experiments as well as satellite observations.

Aerosol-cloud interactions are complex and cloud albedo (or surface cooling) is not always enhanced by increasing the aerosol concentration. The response depends on many factors: the cloud state, the emission source, the meteorology, the region, and the season, to name a few. Studies indicate that aerosol plumes containing abundant cloud condensation nuclei typically increase the number concentration and reduce the size of cloud droplets in warm clouds. They often, but not always, suppress warm rain precipitation; Christensen et al. (2012) found that precipitation was suppressed in 72% of observed ship tracks, however increases in cloud liquid water path and albedo rarely followed. In fact, cloud dimming occurred as frequently as cloud brightening when ship tracks were observed in precipitating closed cellular clouds. Cloud dimming primarily resulted from decreases in liquid water path caused, presumably, by the enhanced entrainment of the dry overlying air into the polluted clouds with smaller droplets. By contrast, ship tracks observed in open cells, where the free-troposphere is relatively moist by comparison, almost always exhibited cloud brightening compared to the surrounding unaffected clouds. The extent of LWP adjustments in response to changes in aerosol concentrations remains largely uncertain for low-level clouds as a whole, because these changes are linked to changes in entrainment and moisture in the free-troposphere, and these variables are either not measured at all from space (entrainment) or not measured with sufficient accuracy (moisture) to capture mixing at the entrainment interface. Additional studies, analyzing the aerosol effects on the mesoscale structure of warm low-level clouds (e.g., constructing a global database of open and closed cellular clouds), and atmospheric conditions that are receptive to cloud brightening/dimming on global and regional scales would provide insight into how effective SRM strategies would be for cooling the planet. For example, combining datasets from the multiple field campaigns (as listed in Table 1) could offer an opportunity to elucidate some of these processes in ship tracks that were overlooked in previous assessments.

Despite this progress on exploring the impact of aerosols on observed ship tracks, radiative forcing estimates of these “linear” ship tracks from satellite observations cast substantial doubt on the efficacy of using SRM strategies to brighten low-level clouds. Schreier et al. (2007) demonstrate that the radiative effect can be as large 100 W m^{-2} at the individual scale of the ship track, however, when integrated over the globe, the annual mean effect is negligible (-0.4 x 10^{-3} to -0.6 x 10^{-3} W m^{-2}). Similar results were identified by Peters et al. (2011), in which the properties of clouds were unchanged even near the world’s most densely populated shipping lanes. However, although the impact has been shown to be negligible on the global scale, ship tracks can still inform process understanding of aerosol-cloud interactions on the cloud and regional scale. The aerosol indirect forcing in an individual ship track is inferred from space using Moderate Resolution Imaging Spectroradiometer (MODIS)-derived optical cloud properties, which leads to significant uncertainty, since there is insufficient spatial resolution from current albedo measurements (e.g., Clouds and Earth’s Radiant Energy System (CERES) footprint is ~20 km). Higher resolution (~1 km) satellite-based albedo measurements would improve the assessment of aerosol indirect effects in “linear” ship track observational studies, and thus improve our understanding of aerosol indirect effects at the process level.

Aerosol plumes that do not produce ship tracks but nonetheless affect the properties of clouds after becoming widely dispersed are difficult, if not impossible to detect using current satellite technology. Goren and Rosenfeld (2012) describe a case study in which the emissions from ships affect the properties and increase the abundance of closed cellular stratocumulus for several days. It is anticipated that this may significantly contribute to the global aerosol indirect forcing because sulfur emissions from shipping largely outweigh the natural biogenic production in many oceanic regions, especially in the Northern Hemisphere (Capaldo et al., 1999). Presumably, a very small fraction of these emissions go into producing ship tracks, while the remaining aerosol affects the properties of stratocumulus to an unknown extent. General circulation model simulations performed by Capaldo et al. (1999) and Lauer et al. (2007) indicate that the radiative effect from shipping could be as large as 40% of the total aerosol indirect forcing due to all anthropogenic activities. Given the large discrepancies in the radiative forcing between satellite observations and climate model results, we present this as an outstanding problem that demands further investigation. Accurate assessments of the global aerosol indirect forcing could be made through better instrumentation that can measure aerosol activation, cloud top divergence, and cloud albedo through more advanced lidar, radar, and multi-angle passive sensor systems. In addition to improving our understanding of marine cloud geoengineering approaches, this would address a significant uncertainty in climate science writ large.

There may be additional opportunities to quantify the difference in the overall cloud albedo that results from changes in the global emissions from shipping using current satellite data in conjunction with global shipping emissions inventories. The recent global economic recession of 2008 could provide a test bed for analyzing low-cloud albedo responses to massive changes in shipping. From 2007 through 2009, the recession caused a significant plunge in international trade and shipping throughout many of the ports in the world (e.g., *Los Angeles Times*, 30 December 2010). An initial analysis has been conducted by Christensen (2012), but was unable to tease out the shipping response from the interannual variability in cloud albedo, possibly due to incomplete data. A longer time series of aerosol concentration, albedo, low-cloud fraction, and sea surface temperature would be needed to assess natural variability, to compare with the shipping response. In addition, there may be an upcoming opportunity to examine this effect due to the gradual phase-out of high sulfur content bunker fuel over the next few decades (International Maritime Organization, 1998). Radiative effects may also manifest in the Arctic ocean regions as ships will have the ability to travel in this area as sea ice progressively melts away in the future.

Finally, understanding the climate response to brightening marine boundary layer clouds would benefit from a new geoengineering modeling intercomparison project (GeoMIP) surrounding low cloud albedo enhancement. The current GeoMIP study (Kravitz et al., 2011, 2012) explores spatially uniform reductions in sunlight or stratospheric aerosols. Since not all models have clouds in the same locations, or clouds receptive to albedo modification, care must be taken as to whether a model intercomparison project is testing the robustness of the model-predicted response to spatially inhomogeneous radiative forcing perturbations, or testing differences between predicted cloud distributions, or testing differences between model parameterizations of cloud-aerosol interaction. The GeoMIP project is currently expanding to conduct such experiments.

4. Summary

Any long-term research strategy for evaluating geoengineering must include as an essential component the evaluation of natural and anthropogenic analogs, volcanic eruptions in the case of stratospheric aerosols and ship-tracks and other emission sources in the case of marine boundary layer cloud brightening. These are imperfect analogs, and will not provide all of the information required to assess effectiveness and risks. However, the ability of models to match observations of analogs would increase confidence in their predictions of geoengineering effects. Thus better evaluation of analogs could minimize or eliminate the need for open-atmosphere testing of geoengineering.

Current observational capabilities are insufficient to address geoengineering risks. It is particularly important to improve our observational capabilities prior to the next large volcanic eruption, so that our best opportunity to better understand stratospheric geoengineering is not missed. Similarly, improved instrumentation could improve our assessment of the global aerosol indirect effect, in order to understand the potential for marine cloud brightening beyond the narrow set of conditions in which ship tracks form. This is also timely, as changes in shipping fuel may soon provide an unintended experiment, but one where we have not yet adequately characterized the current baseline.

While the questions posed here are motivated by the need to better understand geoengineering, addressing these questions would have major co-benefits to climate science in general, by addressing key uncertainties in the models.

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Resource	N_d	Drizzle	CCN chemistry & microphysics	Turbulence	Entrainment Rate	LWC/LWP	Albedo	Cloud Thickness
MAST	✓	✓	some	✓	x	LWC	✓	✓
MACE-I & II	✓	✓	✓	✓	x	LWC	x	✓
E-PEACE	✓	✓	✓	✓	x	LWC	x	✓
VOCALS	✓	✓	✓	✓	x	✓	x	base
DYCOM-II	✓	✓	some	✓	✓	LWC	x	base
Satellite	x	✓	x	x	x	✓	✓	✓

Table 1. Cloud properties measured in different studies, or by satellite observations (bottom row). Studies include MAST (Ferek et al., 2000), MACE (Lu et al., 2009), E-PEACE (Chen et al., 2012), VOCALS (Wood et al., 2011), and DYCOM-II (Stevens et al, 2003). Measured properties listed here include cloud condensation nuclei (CCN) number density (N_d), cloud drizzle properties, CCN chemistry and microphysics, turbulence, entrainment rate, either liquid water content (LWC) or liquid water path (LWP), overall albedo changes, and cloud thickness measurements; measurements of entrainment and albedo are clear observational gaps in most of these experiments.

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