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Defining success and limits of field experiments to test geoengineering by marine cloud brightening

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Abstract Marine cloud brightening (MCB) has been suggested as a possible solar radiation management approach to geoengineering the Earth's climate in order to offset anthropogenic global warming. We discuss the utility of field experiments to test MCB. These experiments, if appropriately designed, would provide an unprecedented controlled environment to not only test MCB, but to understand aerosol impacts on climate. We discuss the science of MCB and review a set of field experiments that has been proposed as de minimis first steps to field test the concept. Our focus is upon issues of success determination, international oversight and/or governance, and outcomes if initial tests are deemed successful.

1 Introduction

Marine cloud brightening (MCB) has been suggested as a possible solar radiation management (SRM) approach for geoengineering the Earth's climate to offset anthropogenic global warming (Latham 1990; Shepherd et al. 2009; Latham et al. 2012). The fraction of incoming solar radiation reflected back to space (the albedo) by marine stratocumulus clouds is sensitive to the concentration of droplets they contain (Twomey 1974, 1977), which in turn is sensitive to the concentration of cloud-forming aerosol particles (termed cloud condensation nuclei, CCN) ingested into them. Geoengineering by MCB seeks to increase cloud droplet concentrations in marine stratocumulus by augmenting the existing CCN population with salt particles created from seawater. The intent is to generate these particles using yet-to-be developed spray technology on seagoing vessels (Latham et al. 2012) and disperse them into the marine boundary layer where they would be lofted by turbulent mixing into low clouds.

MCB raises a series of scientific, ethical and legal questions. Of these, the scientific questions are perhaps the best posed because the scientific community has already invested considerable effort in studying marine stratocumulus systems. However, approaching the study of marine stratocumulus from the viewpoint of MCB raises science issues that have not yet been addressed. The ethical and legal questions surrounding MCB specifically are

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only now being raised (Asilomar 2010). These questions become increasing complex and intertwined as one contemplates moving from small MCB experiments through short-term, regional experiments to long-term, global experiments. This article is primarily concerned with the transition from small experiments to short-term regional experiments. The issues that we address are (1) is it possible to field test MCB and how will we know if experiments actually produce a desired effect; (2) is it necessary and/or possible to determine if there are unexpected consequences from small to medium size experiments; and (3) is it necessary or desirable to engage international oversight at the level of regional experiments and what would that supervision need to look like.

In the next section we provide a brief summary of the current science of MCB. We then address the subject of experimental controls, followed by a section on measuring experimental effects. We then address the subjects of governance and ethics and present our conclusions.

2 The science of marine cloud brightening

Anthropogenic aerosol particles are already enhancing the albedo of clouds to an extent that offsets perhaps 20–40 % of the radiative forcing due to increasing greenhouse gases (Isaksen et al. 2009). Termed "aerosol indirect forcing" (AIF) because the aerosol forcing is indirectly mediated through clouds rather than via direct aerosol-sunlight interaction, AIF includes not only increased cloud droplet concentration and reduced size, but also changes to cloud dynamics that can influence the amount of condensate and the area covered by clouds (IPCC 2007). Aerosol particles are very small, typically on the order of a few tenths of a micrometer. Their efficacy as nuclei for cloud droplets is a function of size and solubility. Cloud droplet growth depends on meteorological factors such as temperature, humidity, and local turbulent circulations, and is also controlled by the availability of CCN. Because droplet size impacts precipitation and radiative heating, both of which impact turbulence, CCN particles are intimately connected to atmospheric motions.

Uncertainty in AIF is largely caused by complexities in aerosol-cloud interactions, our limited knowledge of some aspects of the physics of these interactions, and their rudimentary treatment in climate models. Uncertainty in AIF thus limits our knowledge of climate sensitivity (Kiehl 2007) and limits the accuracy with which the prediction of responses to increasing greenhouse gases over the coming century can be made, even if global aerosol forcing becomes smaller due to cleanup motivated by air quality considerations.

Despite large uncertainties in the AIF, there is preponderance of evidence that aerosol increases can enhance the albedo of marine stratocumulus. Locally-brightened regions seen in cloud fields on visible satellite images form in response to aerosol injections from commercial shipping (Durkee et al. 2000a, b) and provide a striking example of local albedo enhancement. Although the overall impact of ship tracks is climatologically negligible (Schreier et al. 2007), each ship track represents strong (tens of W m^{-2}) local enhancement (e.g., Fig. 1) of albedo. Ship tracks thus present a useful analog for testing the possible efficacy of MCB geoengineering (Robock et al. 2013) and can help to critically test our understanding of aerosol-cloud interactions (e.g., Wang et al. 2011).

Climate model simulations of MCB have to date focused primarily upon the large scale climate impacts driven by increases in cloud droplet concentrations (Latham et al. 2008; Bala et al. 2010; Baughman et al. 2012). In these simulations, seeded cloud microphysical properties are prescribed, either by fixing cloud droplet concentration (Rasch et al. 2009; Jones et al. 2009) or cloud droplet size (Bala et al. 2010). Climate models can represent changes in clouds on scales of the climate model grid scale (~100 km) but do not permit the types of complex mesoscale interactions that cloud resolving models indicate are important for understanding cloud responses (Wang et al. 2010). Climate models show that macroscale cloud changes induce further brightening by increasing cloud cover and condensate (Lohmann and Feichter 2005). In contrast, observations and cloud-resolving models show reduced condensate under some common meteorological environments (e.g., Ackerman et al. 2004), suggesting that radiative responses to aerosol perturbations are more strongly buffered in reality than they are in climate models (Stevens and Feingold 2009). Precipitation, a critical mediator of cloud responses to aerosols, appears to be less sensitive to aerosols than most climate models indicate (Wang et al. 2012). Any future deployment of MCB would rely heavily upon knowledge gained from large scale model predictions of the climate responses of seeding strategies. It is therefore imperative that we improve the representation of the model physics if such predictions are to be trustworthy.

Much can be learned from cloud resolving models about the potential efficacy of MCB, but few studies yet exist. Wang et al. (2011) used a cloud-resolving model (CRM) to study responses to seeding within a limited domain. Their model includes explicit treatments of particle dispersion and cloud dynamics and they find a strong sensitivity of cloud response to both the seeding strategy (whether the seeding is applied uniformly through the domain as opposed to from one or more point sources) and the properties of the unperturbed clouds. Despite the process realism that CRMs offer, these models are not without their own set of problems, some of which may critically limit their skill at predicting cloud responses to aerosols. In particular, the way in which CRMs simulate small scale mixing processes, particularly those associated with cloud top entrainment, remains problematic. However, a number of studies point to cloud top entrainment as a critical component of low cloud responses to aerosol perturbations (Ackerman et al. 2004; Wood 2007); thus, CRMs need improvement before they are completely reliable for predicting the outcome of MCB experiments.

Field observations have proven to be an essential link in the model improvement chain (Randall et al. 2003). Detailed observational case studies have been a key vehicle for identifying and reducing process and large-scale model errors. The GEWEX[1] Cloud System Study (GCSS) has been the primary organ for organized activities in this area, but there are also numerous collaborative efforts between the modeling centers and data providers/interpreters (e.g., US Climate Process Teams) that are confronting models with observational datasets.

Observational case studies can be extremely useful for understanding cloud system physics, but they do not provide a direct means to determine the *sensitivity* of cloud systems to aerosol perturbations. Understanding this sensitivity and its controlling processes is necessary for the ultimate goals of predicting AIF and the effects of MCB geoengineering. Using observations, we can quantify cloud systems perturbed by anthropogenic aerosol and contrast them with cloud systems without such perturbations. It is often incorrectly assumed in such studies that observed differences are caused solely by the aerosol differences themselves. Because major anthropogenic aerosol sources are more or less temporally continuous, aerosol variability at a given location is determined by meteorological variability. Since meteorological variability is the primary driver of cloud variability, it is difficult to separate the component of the cloud variability controlled by aerosols from that driven by meteorological factors (Stevens and Brenguier 2008). In essence, we lack adequate unperturbed control cases against which to contrast perturbed clouds to identify aerosol impacts.

[1] Global Energy and Water Cycle Experiment, a subprogram of the World Climate Research Program

3 Obtaining adequate controls

Control of experimental conditions is a fundamental component of the scientific method, and the lack of adequate controls besets many scientific disciplines. A fundamental paradigm of scientific research is to perform an experiment repeatedly under conditions that are as identical as possible. Unfortunately, this paradigm is inappropriate for scientists studying cloud processes because the environmental conditions are beyond their control. Thus, the best that scientists can do is to (1) select locations and times where meteorological conditions are least variable and (2) monitor them as well as possible.

We note that there are occasional events that allow scientists to study aerosol impacts. For several days following the 9/11 attacks, commercial air traffic was stopped, allowing study of the impacts of aircraft on cirrus clouds (Travis et al. 2001). Efforts to reduce emissions during the Beijing Olympics permitted studies that contrasted cleaner air quality conditions with those before and after (Wang et al. 2010). Some power plant shutdowns have permitted assessments of local impacts. These studies, while interesting, are limited and generally occur by omission—the effects are caused by reducing aerosol loading below typical levels. A much better analogue for our consideration is cloud seeding.

In the second half of the twentieth century, scientists conducted many cloud seeding studies that aimed to enhance precipitation or suppress hail by seeding selected clouds with ice-forming particles. Statistically significant precipitation enhancement in 'rainmaking' studies has never been successfully proven despite numerous programs extending over several decades (Fleming 2006).

Rainmaking studies should serve as an important reminder of the difficulty identifying adequate control populations, but it is important to point out the differences between the cloud systems targeted for rainmaking and those that are the focus of MCB. A major difference is one of spatial homogeneity. Rainmaking typically focuses upon relatively deep, convectively unstable cloud systems that are intermittent and statistically heterogeneous. Marine stratocumulus clouds over the oceans are far more spatially homogeneous. Proof of this is evident in Fig. 1, which shows ship tracks embedded in marine stratocumulus off the Californian coast. The tracks are readily observed because of the homogeneity of the background cloud on the scale of the tracks (10–500 km). Indeed, the very fact that one can observe ship tracks at all provides a qualitative sense that the concept of a control cloud and a perturbed cloud is a viable one in marine stratocumulus. No analogous demonstration is available for rainmaking endeavors. Other important differences between rainmaking and marine cloud brightening are highlighted in Table 1.

The key measurable needed to demonstrate rainmaking is also fundamentally different from that needed to demonstrate MCB. Precipitation is a highly intermittent and localized phenomenon. Only a small portion of any given cloud system is precipitating and precipitation rates are highly variable in space and time. The albedo of a stratocumulus field is a much more evenly distributed property in space and is temporally coherent. Thus the acquisition of statistics on precipitating systems is a more challenging prospect than determining the statistics of stratocumulus albedo.

4 The field testability of geoengineering

Robock et al. (2010) argues that it is impossible to field-test stratospheric sulfur injection (SSI) geoengineering technology without significant modification to the climate system and that it is impossible to separate field study from actual deployment of SSI geoengineering.

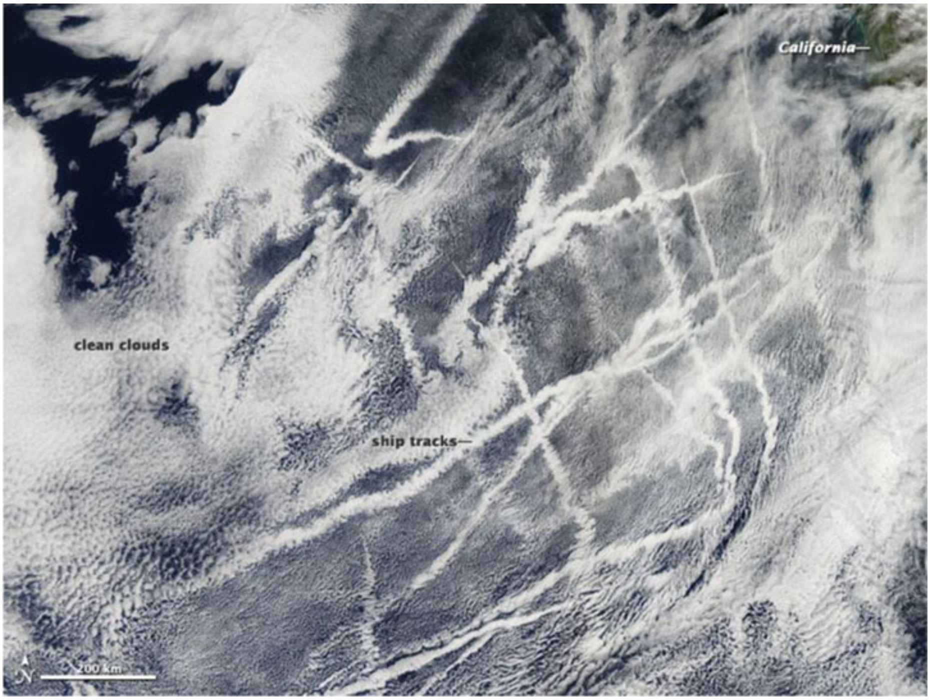

Fig. 1 Ship tracks off the California coast acquired on March 8th 2012 with the NASA MODIS satellite. The scene is a true color image approximately 1,400 km across. Image available from the NASA Earth Observatory archive: http://earthobservatory.nasa.gov/IOTD/view.php?id=77345)

This argument is specific to SSI, which is currently considered to be one of the most feasible schemes (Crutzen 2006; Royal Society 2009; BPC 2011). The climatic response to SSI is obtained from the slow growth and spreading of particles for weeks to months over a large fraction of the globe; thus, the climate response of injection at a given location is highly non-

Table 1 Key differences between aspects of cloud systems perturbed for the purposes of rainmaking and for marine cloud brightening

Aspect	Rainmaking	Marine cloud brightening	Implications
System horizontal heterogeneity	Highly heterogeneous	Relatively homogeneous	Relatively simple to distinguish perturbed clouds from control clouds (e.g., ship tracks)
System vertical heterogeneity	Convective cloud environment only intermittently coupled with surface	Marine boundary layer is coupled to ocean surface and relatively well-mixed	Rainmaking seeding generally applied to individual clouds from aircraft whereas MCB seeding agent can be released continuously from the surface
Cloud condensate	Clouds contain both ice and liquid	Liquid clouds only	The basic physics of liquid drop interactions is well understood, whereas this is not true for the ice phase where basic understanding of ice formation is lacking

localized. Many thousands of injections of the particle precursor gas sulfur dioxide (SO_2) are necessary to produce a measurable, inherently global climate response. So Robock is correct that it would be extremely difficult to measure an effect on the albedo from a field test consisting of only a small number of injections. Judged by the criterion of needing to measure a radiative response, we agree that SSI geoengineering cannot be reasonably field tested without inducing a globally-significant radiative signal.

The argument of non-testability does not apply, however, to MCB. Because aerosol particles in the marine boundary layer have short lifetimes (few days) compared with their stratospheric counterparts (1–2 years), perturbations to the radiative budget from MCB are inherently localized in space and time.[2] Thus, both the aerosol injections and the radiative responses associated with MCB occur over relatively small spatial scales. Geoengineering by MCB on a global scale can be construed as an upscaling of many localized perturbations to the Earth's radiative budget. We argue that this key distinction makes field testing of MCB potentially feasible without inducing a significant climate response.

5 Field experiments to test marine cloud brightening

A series of small-scale[3] field tests to critically examine the efficacy of MCB has been proposed by Latham et al. (2012; L12 hereafter). Here, we summarize the proposed studies, comment on some of their key aspects, and discuss the need for modeling studies to inform experimental design. We then extend the discussion about field testing of MCB geoengineering to discuss what large-scale field tests might then be conducted should the small-scale tests deliver results that suggest a potential efficacy for MCB.

The field tests proposed by L12 comprise three sequential phases:

1. Environmental testing of salt spray technologies in a marine environment to examine the dispersion and evolution of injected aerosol particles.
2. Experiments to create ship tracks in marine stratocumulus using the salt particle injection strategies tested in phase 1 and examine their microphysical and radiative signatures in contrast with the surrounding unperturbed cloud.
3. Experiments to create multiple overlapping ship tracks over an area of ~100×100 km^2 for a period of about a month and examine the microphysical, macrophysical and radiative responses of perturbed clouds by contrasting them with unperturbed clouds.

Latham et al. (2012) argue that even phase 3 of these experiments may induce negligible climate and weather responses compared with natural variability. This conclusion is reached based upon the potential impact that a 2 month experiment with 20 seeding periods of 12 h each would have on the sea-surface temperature (SST) by blocking sunlight to the surface. Because the expected reduction in SST is small and no greater than the typical month to month variability driven by random ocean—atmosphere processes, and because the spatial

[2] The spatial scale of the perturbations is determined by the injected aerosol lifetime and the typical wind speed. For a typical lifetime of 2 days for near-surface aerosols, and a typical wind speed of 10 m s^{-1}, the spatial scale is limited to within 1,700 km of the injection site. While there could be teleconnected responses outside this region, this is fundamentally different from the geographical distribution of SSI responses.

[3] The term 'small-scale' is here used to distinguish field tests with de minimis climate impacts from larger-scale field tests with detectable climatic impacts. In this context, "de minimis climate responses" means that the field experiments have no detectable climatic signal beyond the experimental region, and that any climatic changes resulting from radiative perturbations *within* the experimental region that are detectable immediately following the cessation of the experiment decay to the background with a period of days to a week or two.

scale of the perturbed SST is a small fraction of the ocean basin, the authors conclude that any climatic responses would be negligible. We believe this to be a reasonable assessment. But given a phase 3 experiment with a significantly longer duration or with seeding that was more continuous throughout the 2 month period, the assumption of de minimis climate/weather responses may not hold, an issue we return to when we discuss governance/oversight below.

5.1 Single shiptrack experiments

The proposed MCB experiments are designed to intentionally add particles to the marine atmosphere and then determine how those particles impact cloud properties, including specifically the ability of the clouds to reflect incident sunlight. Our first question is whether it is possible to field test MCB and how would we know if experiments actually produce a desired effect. In short we want to know whether we can demonstrate that aerosol injection modifies cloud processes. In addition, we need to know if we can model the effects of this injection sufficiently well to make confident predictions of the effects when upscaled to larger spatial and temporal scales.

Marine stratocumulus experiments to date have focused on understanding the natural processes that control stratocumulus and on anthropogenic emissions that may be influencing stratocumulus properties. For the latter, there has been an emphasis on acquiring data on aerosol properties (such as number density, size and chemical composition) and interpreting how these aerosol particles may be influencing cloud properties. The second phase of the experiments proposed in L12 is a new step in stratocumulus field experiments because the proposed experiments are moving towards deliberate modification of clouds for experimental purposes. There have been a number of studies of inadvertently-created ship tracks[4] and much has been learned from such studies about how clouds are likely to respond to deliberate seeding (Robock et al. 2013). There has also been a very limited amount of recent pilot testing to explore the use of seeding to explore stratocumulus responses to aerosol. For example, Ghate et al. (2007) seeded marine stratocumulus with aerosol from an aircraft and successfully tracked cloud microphysical responses. In 2011, scientists attempted to seed marine stratocumulus with particles from a military smoke generator on a ship (Russell et al. 2013). Prior to these recent deliberate modification efforts, field experiments were deemed successful if an adequate dataset on environmental and cloud properties was collected for analysis and modeling; we are now required, however, to define success in more specific terms. Achieving success in a Phase 2 experiment requires that the scientific team measures aerosol properties and cloud properties in perturbed and unperturbed regions of the same stratocumulus area. Because one wants adequate control on environmental conditions, these measurements in the perturbed and unperturbed areas must be made nearly simultaneously. Given adequate support for aircraft and ship-based measurements, we see no problem with doing these measurements and establishing (presumably) that adding aerosol particles increases CCN concentrations and modifies cloud and precipitation properties. This is analogous to past observations of ship tracks of opportunity (Robock et al. 2013), with the only change being one of deliberately creating a ship track.

Establishing a radiative forcing due to these injections may be more difficult because radiative flux measurements of line sources like ship tracks is challenging as the measurement includes contributions from the seeded track and unseeded areas to the sides. The

[4] The largest such field study thus far has been the Monterey Area Ship Tracks (MAST) Experiment that was conducted in 1994 and studied numerous ship tracks with a variety of platfoms (Durkee et al. 2000a).

problem is exacerbated by the fact that enhanced cloud droplet concentrations are not uniform across the ship track (Durkee et al. 2000c). Further, secondary circulations may result in modification of the cloud surrounding the directly seeded area (Wang et al. 2011) making it difficult to objectively separate modified and unmodified cloud.

Experimental success in the case of a single ship track experiment is determined by a statistical comparison of data collected in the perturbed and unperturbed regions. Given adequate sampling, we think this analysis is possible and likely to produce a positive outcome.[5] Dealing with a negative answer is considerably more challenging because we are then faced with deciding if the negative outcome occurred because our physical understanding is wrong and/or if the sampling was inadequate. This is the conundrum that plagued rainmaking experiments discussed earlier. Given the potential sampling problems and statistical uncertainties, one may well be faced with ambiguous or statistically null results.

As we noted earlier, it is imperative that these experiments include a modeling component that can be used to decide if the theory of cloud formation and the environmental controls are adequate to understand the problem. Adding a requirement that we be able to successfully simulate the results of a ship track experiment in order to declare overall experiment success raises the bar. We consider that this is a logical requirement since the intent is that we learn enough in these progressive steps to be able to predict the outcome of global MCB.

Thus far we have not discussed a temporal component to this experiment, but it is clearly necessary to define a timescale. Ship tracks typically last less than a day, but some persist for longer (Durkee et al. 2000b). The fact that these tracks can persist means that an observational program would need to plan for longer term observations that provide data on track persistence and cloud property evolution. We think this is an expansion of resource usage and, presumably, cost, but not a particularly technical challenge.

5.2 Multiple shiptrack experiments

Assuming that single ship track experiments provide positive results, subsequent proposed experiments would involve somewhat larger experiments of multiple ship tracks on spatial scales of about 100 km by 100 km to better assess the effects that, if upscaled globally, could generate sufficient radiative forcing to offset that of anthropogenic greenhouse gases. This type of experiment provides a more challenging set of questions than the single track experiment.

Establishing success in terms of aerosol and cloud microphysics measurements becomes more difficult for two reasons. The first is that determining the control situation is likely to be harder. Instead of sampling a line source through a cloud deck with samples in unperturbed areas to either side, sampling unperturbed areas must be done more than 100 km from the perturbed area. This introduces questions about the consistency of large scale environmental factors across such a large domain and what impact these factors may be exerting on the cloud properties. Secondly, the hypothesis of the experiment is that changes occur *on average* over the large domain. This requires sampling of a large spatial domain, which means either a multiple aircraft or a combined satellite-aircraft sampling strategy. The latter has certain attractions given the size of the area to be sampled but is limited by satellite overpasses. The best platforms for sampling cloud properties are polar orbiters, which

[5] Definitive in this context simply means that the experiment (adding aerosol particles) results in an expected outcome (an increase in cloud droplet number) consistent with theoretical scientific understanding. Negative means that the expected outcome cannot be demonstrated. The terms "positive" or "negative" are not used here to imply anything about ethical choices or outcomes.

transect any given area only once per day (when the sun is up). Geostationary satellites offer more frequent views but with less capable and lower resolution sensors. One other possibility is the use of unmanned aerial vehicles (UAVs), which can stay aloft for longer than a day.

Determining the cloud albedo response is also complicated due to dependency on solar zenith angle and other factors. Measuring fluxes simultaneously in perturbed and unperturbed conditions requires multiple aircraft each outfitted with radiometers mounted on stabilized platforms. It makes more sense to use satellite observations for this purpose, which again raises issues of sampling. Other complications include the possibility that the cloud responses systematically change (and may even change sign) as a function of distance downstream of the seeding locations as indications from models suggest (Wood 2007). Because cloud-controlling processes occur on multiple timescales from hours to several days, this may necessitate monitoring of the plume and the unperturbed environment for many hundreds of kilometers downwind of the seeding site.

We think it likely that these multiple shiptrack experiments would have to be carried out over a period of weeks to a month or more to determine impacts. Given natural variability, it would take some time to acquire sufficient cases to demonstrate statistically that the effect actually occurs. Finally, there is an issue of large scale cloud feedbacks whereby clouds modify the large scale environment by changing radiative forcing, boundary layer structure, and sea-surface temperature. Even if one could show that cloud impacts occur for a single day or a few days of aerosol generation, one would need to carry out longer timescale experiments to ensure that such effects do not disappear on timescales of weeks due to adjustments at the large scale.

To assess the potential for feedbacks on longer timescales and the possibility that such experiments may induce non-negligible climate/weather responses, numerical modeling studies are a critical element of the entire design of multiple shiptrack field studies. Models are required to predict the optimal seeding strategy, ship separation, particle sizes and production rates for the experiment and, of course, the cloud radiative responses to the seeding. Such design work must take place during the experimental planning stage, in contrast to the conventional paradigm of post-hoc modeling, placing a significant responsibility upon the modeling community.

Carrying out these longer term experiments would increase the possibility of unintended consequences or the perception of such. Simply as a matter of speculation, consider the following. One global climate model investigation has suggested that MCB-induced changes over the southeastern Atlantic stratocumulus would change rainfall in the Amazon basin (Jones et al. 2009). Now suppose that a 2 month MCB experiment is carried out and there is a simultaneous increase in Amazon thunderstorms and rainfall that leads to excessive flooding with associated loss of life and property damage in Brazil. The Brazilian government may blame the stratocumulus experiment and could take legal action against the experiment organizers in international court.

One might be inclined to think that this hypothetical case is exaggerated and unlikely to occur. We point out, however, that this situation is analogous to events that resulted in the banning of cloud seeding in southern Pennsylvania and the arrest of a young man for trying to change the weather. Farmers blamed cloud seeding intended to suppress hail for enhancing a regional drought. Meteorologists testified at the time that cloud seeding was ineffective and could not possibly have caused the effect but their testimony was not believed. The fact that meteorologists undertook seeding was taken as *prima facie* evidence that the meteorologists thought they actually were modifying rainstorms (see Steinberg 1995 for an extended discussion).

The inherent problem posed by the coincidence of harmful weather events that occur contemporaneously with an MCB experiment would be proving that the experiment had no connection with the harmful events. The very arguments that we are testing, namely, that MCB is designed to modify climate, would then be used to argue that the experiments did in fact modify climate, but in undesirable ways. It is not clear how to deal with this conundrum. Modeling studies to establish the likelihood of inadvertent events occurring in response to the experiments would help, but may not convince. In order to understand the consequences of MCB, the community must carry out the regional experiment(s), but the community is unsure of the outcomes and is thus exposed to potential charges of producing unwanted effects.

6 International governance

Scientists are in general ill disposed towards governing bodies for experiments, although those who use human or animal subjects in their research presumably have become used to the process. Geoscientists have largely been excluded from this process because their experiments do not use or directly affect humans or animals. Thus the starting point for this discussion is that international governance is not required for experiments of the type that we have outlined. But such a starting point leaves us with questions; here we address two of those questions. The first concerns the grounds for the statement that the experiments outlined above require no international governance. The second is under what conditions we might expect that assessment to change.

In recent writing on the subject, Morgan and Ricke (2010) argued that there is some "allowed zone" in which experiments may take place without international governance. The definition of this allowed zone is not well quantified at this point and they argue that defining it should be one of the immediate tasks of the scientific community. We strongly support that statement, although we are not going to attempt quantification here.

The allowed zone has the general property that those conducting experiments within its perimeter must demonstrate that the experiments do not have lasting impacts on regional or global climate and weather. As one might expect, there is considerable ambiguity in such a definition. Furthermore, impacts may occur in more than one geophysical variable and thus the allowed zone has multiple dimensions. In the case of MCB, the principal dimension (or axis) is radiative forcing, but one can separate that into two components, one being magnitude and one being duration. The likely demonstrable effects are cooling of the regional climate and/or regional teleconnections. Another dimension to consider might be sea surface temperature effects on local marine ecosystems (since increasing cloud reflectivity over time would reduce sea surface temperatures and perhaps affect local biology). The demonstrable effect here is definitely more difficult to quantify but is presumably related to ecosystem balance.

Our position is that the experimental team must determine in advance what the allowed zone is for the experiment in question, and provide quantitative estimates of where the proposed experiment fits within that allowed zone. In addition, the experimental team must provide measurements and analysis within the context of the experiment to demonstrate that the experiment did in fact fit within the allowed zone and the experimental estimate.

There is little doubt that single ship track experiments would fit into any reasonable allowed zone. It is considerably more difficult to assess the multiple ship track experiment. Consider a series of regional experiments that proceed from short (a few days) to medium timescale (a week or two) to long timescales (2 to 3 months). Suppose the model simulations of these experiments are ambiguous about the regional impacts. The decision is made to carry out the short experiment, which produces an effect that is larger than anticipated, but still in the allowed zone. Now suppose the medium timescale experiment produces some quite significant impacts that are at the margin of the allowed zone. What do we do now about the long timescale experiment? Does pushing towards the somewhat ambiguous edge of the allowed zone warrant involvement of governance at the international level? Although the team might not think so, sponsoring agencies might very well disagree. One can easily imagine, at least in the United States, that the science agencies would demand oversight of the next phase of the experiment.

This simple example begins to reveal some of the complex issues associated with MCB experiments. In order to proceed with regional scale experiments, especially those lasting longer than a few days, we think that the scientific community must:

1. Develop models that can be used to simulate expected experimental results;
2. Develop an understanding of the perimeter of an "allowed zone" for this class of experiments;
3. Carry out regional experiments in a stepwise fashion over increasing area and longer times;
4. Evaluate model simulations carefully against experimental results to develop confidence in the quality of the simulations and their use as a predictive tool for the next experiment.

We realize that this approach would lengthen the time required to carry out experiments and raise the cost, but we think that care and due diligence is essential to protect the environment and maintain public confidence in the management of the experiments.

At some point, as we suggested, national or international oversight of these experiments is almost assured. We are not sure what that oversight will or should look like. Other papers in this special issue address this issue, one which we are sure will be difficult and contentious.

7 Ethical considerations

We close with a brief discussion about the ethical considerations associated with MCB field experiments. It is not our purpose to discuss this subject at length, but we would be remiss to ignore it completely.

Ethical questions raised by geoengineering are new and challenging. There is an extensive literature on biomedical ethics dealing both with experiments and patient treatment. In these cases, a great deal of weight is given to prior information and informed consent of those involved. Little of this is applicable to MCB testing because of the intent to carry out experiments over the ocean far removed from human population and the large spatial area being modified is embedded in the global atmosphere, making informed consent a logical and logistical impossibility.

The literature on geoengineering ethics is rapidly expanding. Recently, Preston (2013) provided an overview of ethical issues that attempts to consider the issue in three time spaces: (1) contemplating geoengineering, (2) research and development, and (3) implementation. In his second category, which is our primary concern, he focuses primarily on governance issues (e. g., the Oxford Principles, Rayner et al. 2013) and the need to foster participation of the vulnerable. Interestingly, he largely ignores the precautionary principle (PP), which we think may well be our strongest ethical defense for conducting MBL experiments.

We realize that we are entering murky waters when invoking an argument based on the PP because there is substantive disagreement in the literature on environmental ethics about exactly what the PP means and how it should be stated. The objection is that simple statements of the PP (e.g., "do no harm") are too vague to be useful and that attempts to formulate more specific statements run into difficulties of establishing valid boundaries. Gardiner (2006) describes versions of the PP as existing between weak principles that provide little decisional guidance for environmental problems and strong principles that make environmental considerations the highest, and perhaps only, consideration. He suggests that one can define a core PP that lies between these extremes and can be usefully used to address environmental problems. Sunstein (2006) makes the interesting point that a statement of the PP depends on societal heuristics and, therefore, will vary depending on the values and mores of a society. This perspective is troubling in the sense that it implies great difficulty in achieving international agreements on PP arguments. Hartzell-Nichols (2012) argues for scrapping the concept of a single PP in favor of more specific statements relevant to a particular situation that may help clarify the utility of the precautionary principle. Our discussion here borrows from several of these studies but is most heavily influence by Hartzell-Nichols.

Much of our discussion thus far has implicitly assumed a PP. Experiments can only be carried out if careful assessments of risks are carried out and risks are deemed acceptable. In this case, a precautionary principle does not preclude action; it demands that action be consistent with an understanding of the risk involved.[6] We think our approach achieves this. From an opposing perspective, one might argue that the greater risk is imposed by doing nothing in the face of impending climate change. Thus, a PP may be used to argue that the experiments must be done in order to prepare for the eventuality of severe impacts of climate change. We also advocate MCB experiments because they have the co-benefit of enhancing our understanding of climate change. Following the arguments of Hartzell-Nichols (2012), we do not think the experiments pose risk of catastrophe and, therefore, are a reasonable component of a research strategy designed to take precautionary measures against potentially devastating consequences of climate change.

It is always difficult to deal with the issue of unintended consequences. By definition, we do not know what they are, so we cannot assess their importance. The best that we can do is to think carefully about possible consequences and to simulate experimental conditions as completely as possible. Physical systems operate under well-understood principles (such as conservation of energy and laws of motion and thermodynamics) even though we may not have completely accurate mathematical representation of those principles in atmospheric models. Thus, we argue that unintended consequences are less likely than in biological systems whose complexity is inadequately understood. We realize that this is not a very satisfactory answer but are not convinced that a better one currently exists.

We close by stating that we are not advocates of the implementation of MCB and this article should not be construed as arguing for implementation. We have been led to discuss MCB experimentation because we are convinced that the scientific community and society in general needs to understand the potential of MCB. We cannot do this without

[6] In reading through the ethics literature on this subject, one is struck by the struggle to define the concept of environmental risk and the attempt to find relationships between risk and cost-benefit analysis. To some extent, environmental scientists are responsible for this difficulty because we find it difficult to provide rigorous definitions of risk for problems like climate change. Furthermore, the cost-benefit tradeoffs are not well understood and often contain value judgments that may themselves be difficult to defend. Reaching acceptable definitions of risk and costs for climate change and geoengineering must necessarily involve at a minimum environmental scientists, ethicists, and economists.

experimentation, but experiments must be carried out thoughtfully and cautiously. We hope that our comments will contribute to and further encourage an open and vigorous discussion of these issues by scientists, ethicists, legal scholars, and the general public.

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