Monitoring of geoengineering effects and their natural and anthropogenic analogues

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1. Executive Summary

A number of climate intervention concepts, referred to as "geoengineering," are being considered as a potential additional approach (beyond mitigation of greenhouse gas emissions) to manage climate change. However, before governments go down the path of attempting deliberate climate intervention including precursor field-experiments, it is essential that the scientific community take the necessary steps to validate our understanding that underpins any of the proposed intervention concepts in order to understand all likely consequences and put in place the necessary strategies for monitoring the expected and unintended consequences of such intervention. The Keck Institute for Space Studies (KISS) has sponsored a project to identify specific priorities for improved scientific understanding and focused efforts to address selected priorities. This project does not advocate the deployment of geoengineering, outdoor geoengineering experiments, or monitoring systems for such proposed geoengineering field experiments, but is rather a precautionary study with the following goals:

- enumeration of where major gaps in our understanding exist in solar radiation management (SRM) approaches,
- identification of the research that would be required to improve understanding of such impacts including modeling and observation of natural and anthropogenic analogues to geoengineering, and

- a preliminary assessment of where gaps exist in observations of relevance to SRM and what is needed to fill such gaps.

This project focuses primarily on SRM rather than other proposed geoengineering techniques such as carbon dioxide removal from the atmosphere because there exist a number of analogues to the SRM methods that currently operate on Earth that provide a unique opportunity to assess our understanding of the response of the climate system to associated changes in solar radiation. Additionally, the processes related to these analogues are also fundamental to understanding climate change itself being of central relevance to how climate is forced by aerosol and respond through clouds, among other influences. In other words, this research has likely powerful co-benefits for climate science writ large.

The study phase of the project was executed in 2011 and consisted of two workshops at Caltech (May 23-26 and November 15-18) as well as several smaller meetings and telecons. Participants in the study included individuals with an established track record of geoengineering research (primarily modeling studies), experts in the theory and observation of related physical processes, as well as engineers with expertise in risk management and systems analysis. Graduate students and post-doctoral fellows were active participants in the study.

Four major topics that were identified during the workshops as priorities for subsequent research and development, particularly in regards to addressing related observational gaps:

1. Volcanoes as analogues of geoengineering with stratospheric aerosols
2. Ship tracks and cloud/aerosol interactions in general as analogues of geoengineering with marine-cloud brightening
3. Studying more targeted geoengineering interventions to counteract specific consequences of climate change, and
4. Identifying the satellite-based albedo monitoring needs that would be required for monitoring either a geoengineering test or its natural and anthropogenic analogues.

Major volcanic eruptions that inject sulfate aerosol into the stratosphere cool the planet and are one of the motivating examples behind geoengineering. Much more could be learned about the intentional introduction of stratospheric aerosols through a combination of more thorough analysis of existing data, and development of a rapid-response observing strategy to maximize what we can learn from a future large eruption. Gaps in our knowledge include the evolution of aerosol size, the interaction with cirrus, water vapor, and ozone, and tropospheric chemistry more broadly. There are also attribution challenges that need to be understood, as the conditions following volcanic eruptions are not the same as those due to SRM (e.g. the presence of ash, or the discrete vs continual injection).

The second main concept put forth for geoengineering is to introduce aerosols (e.g. salt) to change the optical depth of marine clouds; the current analog for this effect is ship tracks and other cloud/aerosol interactions. There is potential for further analysis of existing data to better understand these interactions and assess the science behind this SRM approach. The sensitivities of cloud albedo to specific processes and parameters are poorly understood. There are also observational gaps, such as the entrainment rate, or direct measurement of albedo, that limit our current ability to assess this approach.

Third, it is important to understand what the actual goals for a possible eventual implementation of SRM might be, since SRM would quite possibly be deployed in response to a particular concern, rather than a generic desire to restore the overall climate. The highest priority identified during the study program was to focus on the high risk, high impact potential for a “tipping point” associated with Arctic permafrost melt, and the potential for geoengineering to reverse this. Other tipping points involving Arctic sea-ice and the Greenland and Antarctic ice-sheets may also warrant targeted intervention studies.

Finally, one of the specific gaps in our observational capability is the ability to monitor albedo accurately enough to measure and attribute changes, with sufficient spatial, spectral, and temporal resolution. This capability is needed for all of first three SRM topics.

These findings and action items for future efforts are addressed in more detail in sections 3 through 6 of this report.

2. Study scope and objectives

Climate change is happening and its full consequences are not yet understood. A prevailing view contends that any warming above about 2 Celsius degrees from pre-industrial times will be dangerous, producing serious negative consequences for humans and natural systems. The safest and most obvious method of moderating against such climate change is to take early and effective action to reduce emissions of greenhouse gases, the principal cause of the climate change being experienced. However, global efforts to reduce these emissions have not yet been successful and there is no evidence that the proposed reductions required to avoid reaching the potentially dangerous climate change will be achieved in the near or medium term future.

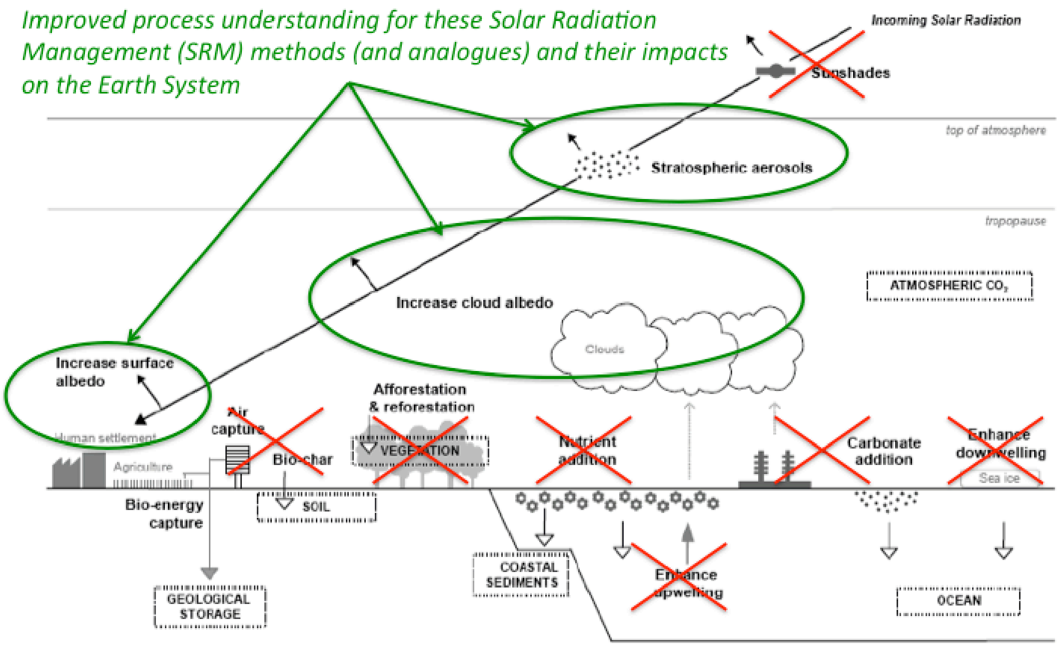
Because of our inability to reach agreements to reduce emissions to thus mitigate climate change, and given the long term consequences of adding greenhouse gases into our atmosphere today, a number of climate intervention concepts have been proposed. These concepts, referred to as “geoengineering”, are reviewed in a number of reports (e.g., Shepherd et al., 2009 (Royal Society report), GAO, 2010) and broadly divide into two classes: 1) Solar Radiation Management (SRM) techniques that seek to increase the amount of the solar radiation reflected back into space, thus increasing Earth’s albedo by a small percentage to offset the effects of increased greenhouse gases, and 2) Carbon Dioxide Removal (CDR) techniques which aim to remove CO_2 from the atmosphere. This project focused on SRM rather than CDR geoengineering techniques because there exist a number of analogues to the SRM methods that currently operate on Earth that provide a unique opportunity to assess our understanding of the response of the climate system to associated changes in solar radiation and because the observational needs for CO_2 and carbon management are relatively well understood and being addressed by other efforts.

The objective of this study has been to investigate the scientific basis of prevailing SRM concepts, in particular emphasizing those that artificially propose to mimic the effect of volcanic eruptions, using stratospheric aerosols, or enhance marine cloud albedo. It is essential that we validate our understanding of the science that underpins these SRM concepts. The strategy proposed here is to examine both the natural and serendipitous anthropogenic analogs to each of these methods. These analogs provide a framework for testing our understanding of the processes as they occur in the natural system. Furthermore, these analogs also provide an opportunity to examine how changes to one component of the energy balance of the planet (such as albedo) couple to and alter other components of the climate system (such as the water cycle). The reduction of surface snow albedo by dust, the addition of stratospheric aerosol by volcanoes and the effects of ship effluents on marine clouds (ship-tracks) are examples of such analogs. Other SRM methods such as reflectors in space were not included in this study since such an approach does not study Earth system processes and is more of an exercise in engineering and economics.

The goals of the study, as described in the proposal, were to:

(i) determine the degree to which we understand the factors that determine the planet's albedo and the impact of changes to albedo from factors that are analogs of SRM,
(ii) review the broader consequences of possible changes to the albedo on the entire Earth system as a necessary step to understanding the risks, the likelihood of success and the likelihood of significant unintended consequences of SRM climate adaptation,
(iii) determine whether we can adequately validate this understanding with current observational resources as a precursor to developing a monitoring strategy for the outcomes of SRM climate adaptation, and
(iv) develop a strategy for monitoring the consequences of in situ experiments of marine cloud brightening or stratospheric aerosol creation.

The workshops in this study helped to clarify the range of research methods relevant to geoengineering studies: 1) observational and process-model study of natural and anthropogenic geoengineering analogues, 2) simulation of responses and consequences to geoengineering using climate models, 3) sub-scale field experiments and demonstrations of geoengineering technology, and 4) study of the related socio-political issues including governance, law, economics and ethics. Given the focus of KISS and resource constraints the team agreed that future attention would focus on topics 1 and 2. Topics 3 (geoengineering field studies) and 4 (governance and socio-political) are being addressed by other activities in the US and abroad.



after Lenton & Vaughan, ACP, 2009

Figure 1. The project scope is limited to the indicated Solar Radiation Management (SRM) methods with direct relevance and co-benefits to other climate processes. Other methods relevant to carbon management are not addressed by this project given that they are already covered by existing programs (e.g., US Carbon Cycle Science Program).

In particular, four major topics were identified during the workshops as priorities for subsequent research and development, particularly in regards to addressing related observational gaps:

1. Volcanoes as analogues of geoengineering with stratospheric aerosols
2. Ship tracks and cloud/aerosol interactions in general as analogues of geoengineering with marine-cloud brightening
3. Studying more targeted geoengineering interventions to counteract specific consequences of climate change, and
4. Identifying the satellite-based albedo monitoring needs that would be required for monitoring either a geoengineering test or its natural analogues.

These are elaborated in the following sections.

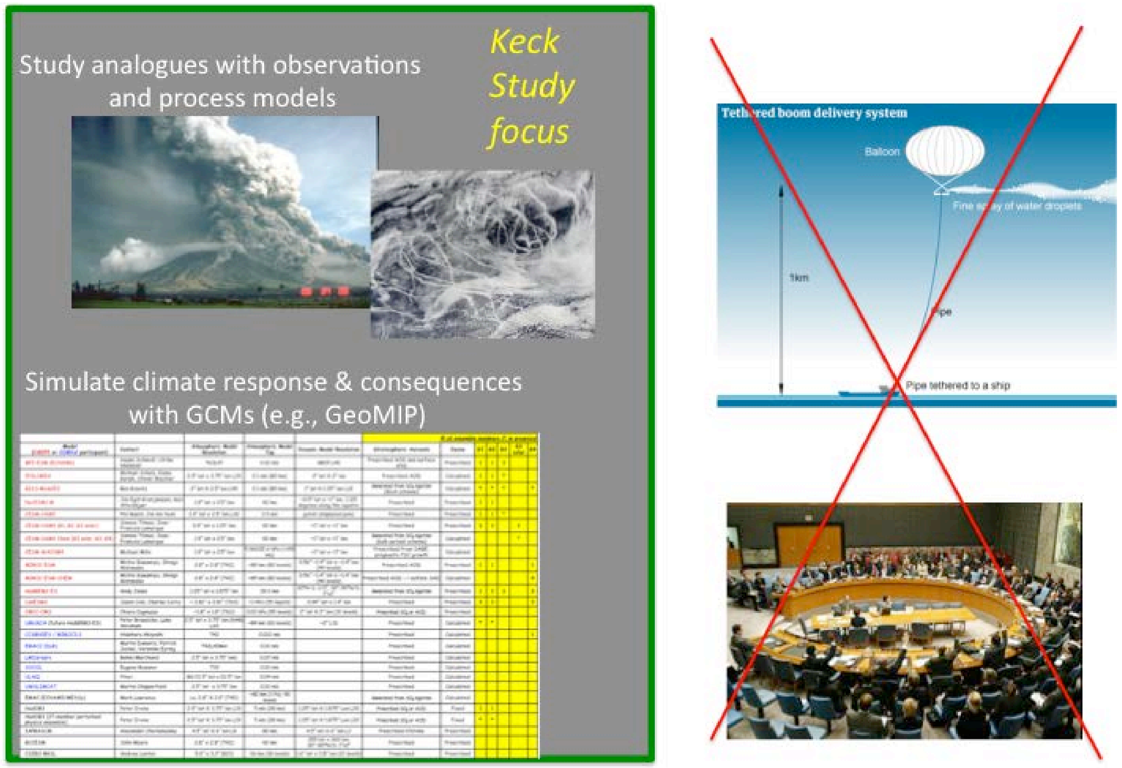


Figure 2. This project is focused on observational and process-model study of geoengineering analogues and climate-model study of impacts and consequences rather than geoengineering field experiments or socio-political/governance studies.

3. Volcanoes as analogs of stratospheric aerosol geoengineering

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 about 36 Mt of sulfate aerosols. However, while it is clear from these natural analogues 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 further study of volcanic eruptions.

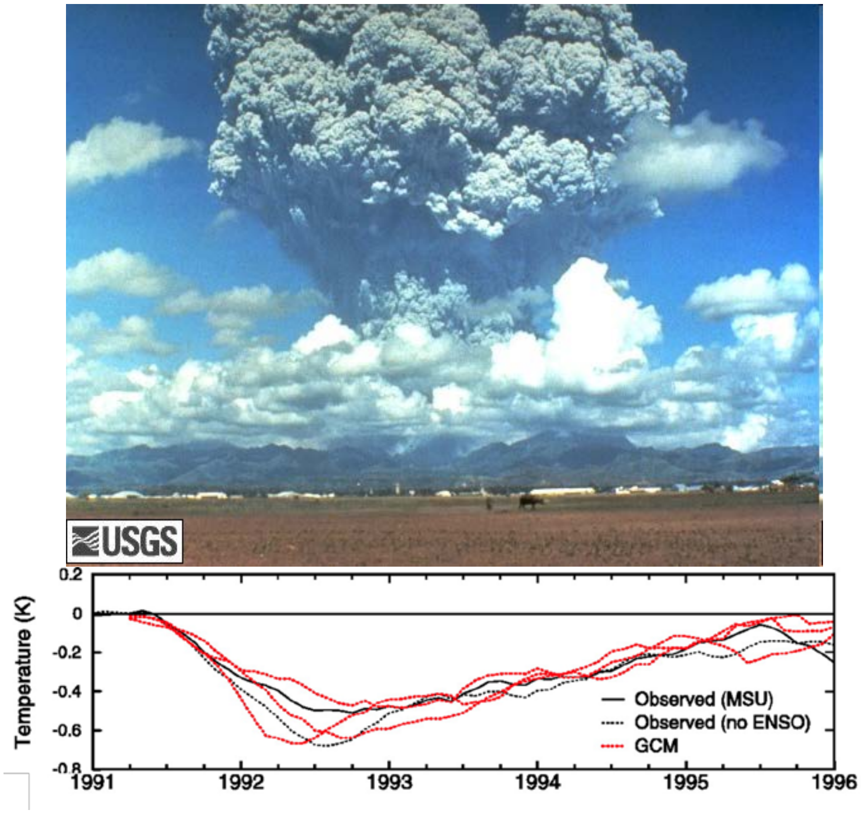


Figure 3. Mount Pinatubo volcanic eruption, and the resulting global mean temperature from observations and models (from Soden et al, 2002).

A critical thrust here is to develop either a rapid response system or continuous observations so that we are ready for the next large eruption, and can gather more data than is currently available for use in validating models. Note that the evolution in stratospheric sulfate aerosol size distribution occurs over the first few months after an eruption (English et al, 2011), underscoring the need for a rapid response capability.

There is also still much that 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 different questions: there are clearly substantial co-benefits to this work in terms of better understanding how the climate responds to natural sources of aerosol.

Finally, it is important to also recognize not just what can be learned from volcanic eruptions, but what can't be. Two key differences between a volcanic eruption and geoengineering with stratospheric aerosols are that (i) volcanoes also inject substantial ash, and (ii) that the volcanic eruption is an impulsive injection into a relatively clean stratosphere, rather than a continuous injection. Modeling will thus remain critical; validating models against data from volcanic eruptions will improve confidence in the model predictions of geoengineering.

Major findings: The following key uncertainties need to be addressed:

a) The connection between the injection and evolution of stratospheric sulfate aerosols and cirrus cloud formation in the troposphere is poorly understood– and hence the significance of any warming effect/offset associated with large eruptions or geoengineering.

b) The connection between stratospheric sulfate aerosol injection and water vapor is poorly understood; particularly in the tropics, where impacts on tropopause transition layer (TTL) heating and H_2O transfer lead to changes in stratospheric water vapor.

c) The impacts of stratospheric sulfate injection impact on ozone, including the convolved effects from other species, H_2O, Br, Cl, and also from climatic factors such as ENSO or QBO, are not well understood for geoengineering scenarios. There are significant limitations in relevant models and observations. Impacts on surface UV (and impacts to human health) from volcanic eruptions have already been studied to some extent.

d) Impacts on tropospheric chemistry (including NOx, OH, etc.) in response to stratospheric geoengineering have not yet been assessed.

e) The relative sensitivity of sulfate particle size distribution and its evolution to microphysics vs stratospheric aerosol dynamics and transport is poorly understood, in part because there are only sparse observations for the tropics.

f) There remain major observational gaps for studying volcanic eruptions as a geoengineering analogue; see Section 3.2 below for a detailed list.

g) Attribution challenges – how representative are volcanic eruptions as analogues, given the presence of confounding effects such as ash, and the difference between one-time vs continual aerosol injection?

There have been efforts to explore these issues. Ozone is clearly affected by stratospheric aerosols (e.g., Tilmes et al., 2008, 2009). Simulations of increased aerosol loading have also found changes in upper tropospheric chemistry (Hendricks et al., 1999). 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 and/or ENSO (e.g., Wylie et al. 1994, Sassen et al. 1995, Song et al. 1996, Wang et al., 1995) and others finding no impact (Luo et al. 2003, Massie et al. 2003, Lohmann et al. 2003); the issue is important but not yet resolved. Finally, the issue of how particle sizes evolve has been addressed through simulations for geoengineering (Heckendorn et al. 2009, Hommel and Graf, 2010, English et al. 2012), but there are limited data to support analysis. Injecting sulfate into a "clean" stratosphere results in a different coagulation problem from a continuous injection scenario, where larger particles are likely to form – this results in more rapid fallout into the troposphere, both increasing the injection rate required to sustain the desired geoengineering effect, and raising concern over the amplification of unwanted impacts on cirrus and upper tropospheric chemistry. Data collected after the Pinatubo eruption are insufficient to resolve all of these questions, although there is additional analysis that could be done with existing data. It is essential that we are prepared for the next large volcanic eruption with sufficient data collection to be able to validate models and inform geoengineering studies while minimizing the need for any intentional tests.

3.1 Identified action items

A number of specific action items were identified during the workshop. Several specific hypotheses, and the action items that could help resolve them are:

1) Volcanic eruptions do or do not cause a change in cirrus sufficient to produce a significant heating offset. (This does not directly mean that geoengineering with sulfate aerosols would or would not, as the distribution of aerosol sizes would be different, leading to more fallout into the upper troposphere; volcanic eruptions also have a confounding effect from ash.)
    a) Continue to look for a cirrus signal in CALIPSO data and to examine whether improvements can be made using OSIRIS. Need to look at statistics both outside of the plume and inside of the plume.
    b) Design a model-data intercomparison exercise. Based on an initial intercomparison, we could propose expanding the next GeoMIP exercise (Kravitz et al., 2011).
    c) Consider applying mesoscale cloud models vs larger scale. (E.g., the cirrus component of the GEWEX Cloud System Study (GCSS).)
    d) Complete the definition of rapid response observational needs (see section 3.2 for a first cut).
2) Volcanic eruptions of magnitude X don't impact stratospheric water vapor beyond threshold Y. (Again, geoengineering with sulfate aerosols is potentially distinct, although improved knowledge of volcanic effects will improve model validation necessary for predicting geoengineering effects.)
    a) Look at Pinatubo reconstructions in model simulations, and for multiple models (e.g. the NASA GSFC GEOS5 simulations are looking at water vapor in particular.)
    b) Assess current capability of satellite observations (e.g. Microwave Limb Sounder (MLS) or Atmospheric Infrared Sounder (AIRS)), including the potential for a unified observing approach that covers both climate variability (e.g. ENSO/QBO) and eruptions.
3) Volcanic eruptions (and again sulfate geoengineering efforts as a separate case?) of magnitude X don't cause damage to the ozone layer beyond threshold Y.
    a) Need to define what is an "acceptable" threshold for O_3 impacts from geoengineering? (Including consideration of human health and ecosystem impacts.) Note that the impact depends on when geoengineering is implemented, compared to ambient Cl, Br, CFCs, etc.
    b) Further analysis of the impact of recent volcanic eruptions.
    c) Use further modeling with densities derived from CARMA/WACCM (Whole Atmosphere Community Climate Model) to simulate the impact on O_3 over the last 10 years of minor eruptions, for example, and/or to reproduce Pinatubo conditions.
    d) Produce a forecast WACCM/CARMA with aerosols, chemistry, and stratospheric circulation (e.g. build on Haywood et al. (2010) that tracks aerosols including data assimilation).

3.2 Gaps in observations of volcanic plumes

The following observational gaps have been identified. This is a starting point for future efforts that would further refine this list, ultimately leading to a plan to address these gaps. One cross-cutting question that needs to be addressed is, what is the appropriate threshold for initiating an intensive observing campaign? For example, we should deploy a rapid response system if the eruption is sufficient to produce at least 2 Tg of SO_2 injection into the stratosphere.

1) Particle size distributions in the stratosphere, and their evolution:
    a) Conduct an OSSE (Observational System Simulation Experiment) run to study optimal observing scenario.
    b) Consider rapid response capability in concert with sustained background observations (e.g., balloon measurements conducted in Laramie, WY (see Deshler et al. 2003, Deshler, 2008)
    c) Need to have at least one balloon site in tropics.
    d) Try to measure high concentration part of the plume (spatial peak); current satellite measurements do not see the densest part of the plume (potentially use direct plume measurement, e.g. via aerostat?)
    e) Need to observe during the first 3 months after the eruption in order to understand the initial conditions and initial evolution (English et al., 2011)
    f) Need a plume forecast capability (including CALIPSO reanalysis) for the above, so that balloon launch, for example, can be directed to the correct location.
    g) Compare with SEAC4RS campaign (Southeast Asia Composition, Cloud, Climate Coupling Regional Study).
    h) What is the optimal data fusion of CALIPSO, OSIRIS, GOMOS, and other satellite observations both for re-analysis and for future eruptions?
    i) Improved calibration and validation for satellite observations (for aerosol size distribution in particular).
    j) Re-consider cloud chambers as alternative to waiting for volcanic eruptions?
2) Cirrus uncertainty
    a) We do not need new observational capability, but we do need to study existing data.
3) Stratospheric chemistry observations
    a) High resolution ozone and precursors (1-2km vertical resolution)
    b) O_3 sondes (status of Canadian effort)
    c) Stratospheric balloons & high altitude aircraft (e.g., NASA ER-2 asset is going away; explore options with GlobalHawk + ATTREX?)
4) Tropopause heating & stratospheric H_2O
    a) Use COSMIC-GPS for vertical temperature profiles
    b) Water vapor at tropopause is a challenge

4. Ship tracks as analogs of marine cloud brightening

The second major strategy that has been proposed for geoengineering (SRM) is to brighten marine boundary layer clouds through the injection of aerosols, such as salt (e.g. Latham, 1990). 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 (see Figure 4). 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 analogue to stratospheric aerosol geoengineering, there is much that can be learned from analogues. In this case the principal analogues are anthropogenic, in the form of ship exhaust or emissions from coastal sites, although volcanic plumes in the boundary layer can also be explored. Again, there are significant observational gaps, as well as opportunity for further mining of existing data – a more thorough analysis of existing data both improves our knowledge and helps clarify the observational gaps that need to be filled.

The key concept is that increasing the number of cloud condensation nuclei while keeping everything else constant results in smaller droplets, and an increase in cloud albedo (Twomey, or first indirect effect). However, everything else does not remain constant; changes in macrophysical cloud properties produce radiative impacts of the same order as those from Twomey (e.g., Lohmann and Feichter, 2005, Isaksen et al. 2009). For example, precipitation and evaporation cause changes in liquid water path (LWP), changes in entrainment not only affect LWP, but can also affect neighboring regions where aerosols weren't injected, etc. 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 data is inconsistent. The macrophysical response to aerosol injection depends on the environment; this is illustrated for example in LES simulations (Wang and Feingold 2009, Wang et al. 2010, 2011). The challenges in understanding all of the feedbacks involved, and when the introduction of aerosols leads to greater albedo, and when it doesn't, points to the need for careful data analysis. A summary of the existing literature, provided by Matt Christensen, is given below in section 4.1. (See the top panel of Figure 5 for an illustration of the difference in ship tracks for different cloud conditions; here for open- and closed-cell regimes.)

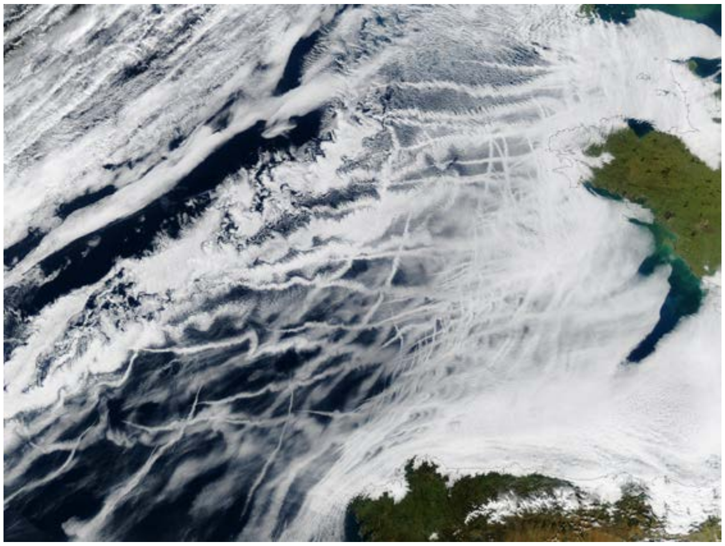
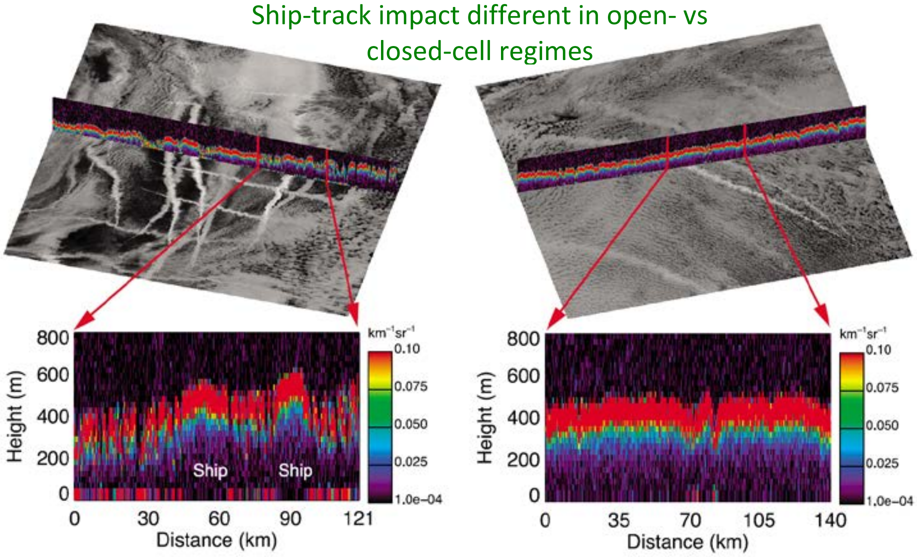


Figure 4. Example of ship tracks observed in the Atlantic Ocean.


Ship-track impact different in open- vs closed-cell regimes

Resource	N_d	Drizzle	CCN chem & micro	Turbu-lence	Entrain-ment	LWC/LWP	Albedo	Cloud thick-ness
MAST	✔	✔	some	✔	X	LWC	✔	X
MACE-I & -II	✔	✔	✔	✔	X	LWC	X	X
E-PEACE	✔	✔	✔	✔	X	LWC	X	X
VOCALS	✔	✔	✔	✔	X	✔	X	base
DYCOM-II	✔	✔	some	✔	✔	LWC	X	base
Satellite	X	✔	X	X	X	✔	✔	tops

Figure 5. (top) Example of remote-sensing (Cloudsat) study of the impact of ship-tracks on clouds in different regimes; (middle) assessment of observational gaps relevant to marine cloud-seeding efficacy, comparing data available in various studies (see text); (bottom) coastal pollution source, indicative of the need to address non-ship track emission sources.

Major findings: The following uncertainties need to be addressed.

a) The sensitivities of marine cloud albedo to specific processes and parameters are poorly understood (e.g. entrainment (We), liquid water path (LWP), turbulent kinetic energy (TKE), number density (N_d), cloud fraction, etc).
b) The two major observational gaps for ship-track and low cloud studies are entrainment rate and albedo (on the space-time scales relevant to geoengineering).
c) Focusing on ship tracks alone is insufficient (i.e., these are imperfect analogues). We don't understand the impact on clouds from other (non-ship track) emissions. Need broader area study of aerosol indirect effect from emissions/pollution (including large smelters and volcanic plumes).
d) Assessment of the predicted climate response to the spatially inhomogeneous radiative forcing introduced by selective brightening of marine boundary layer clouds.

There have been some comparative albedo studies for ship-tracks (e.g. Schreier et al., 2007, Christensen and Stephens, 2011, 2012, Peters et al., 2011), as well as other emission sources such as volcanic plumes in the boundary layer, as noted in section 4.1. 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). Whether the aerosols are introduced in a controlled experiment, or the effects of current aerosols emissions are monitored, there are observational gaps in our capabilities. See, for example the middle panel of Figure 5, illustrating what variables were measured (droplet number density, drizzle, CCN chemistry, turbulence, entrainment rate, liquid water content or path (LWC/LWP), albedo, and cloud thickness) during various experiments, and for satellite observations (bottom row of table).

Additionally, 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) explores spatially uniform reductions in sunlight or stratospheric aerosols. Some initial ideas have been sketched for a low cloud GeoMIP, but need further refinement; since not all models have clouds in the same locations, or clouds receptive to albedo modification, care must be taken as to whether the model intercomparison 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.

4.1 Literature Review: Emissions affecting the albedo of low-clouds

(Courtesy of Matt Christensen)

This literature review discusses the aerosol indirect effect of near surface emitted aerosol plumes on the albedo of low-clouds. A variety of emissions sources (ship tracks, volcano tracks, and smelters) and their interactions with cloud systems over water (stratocumulus, tradewind cumulus, and Arctic clouds) are discussed using results from in situ and satellite observational studies.

1. Ship Tracks and Marine Boundary Layer Clouds

Ship tracks are an example of the direct mixing of an aerosol plume, laden with cloud condensation nuclei (CCN), with an elevated cloud layer. These features are commonly observed in stratocumulus where the cloud tops are low (less than 2 km), capped by a strong temperature inversion, and coupled to the surface moisture. This enables the aerosol plume to reach cloud base before being overly dispersed in the sub-cloud boundary layer. Ship tracks demonstrate the complicated nature of cloud brightening because the response depends largely on the thermodynamics of the atmosphere and the state of the clouds (whether they are closed, open, etc…).

Increases in cloud albedo, found in a variety of studies, are often observed in ship tracks due to the Twomey effect (an increase in CCN promotes more numerous and smaller droplets which increases the albedo of the clouds). However, the extent of this increase is often muted through adjustments made by reductions in liquid water content caused by the enhanced entrainment (brought about by the smaller droplets) of the overlying free-tropospheric air (Ackerman et al., 2004). Occasionally, (when the boundary layer is decoupled from the surface) the liquid water path reductions are so large that ship tracks undergo a dimming effect. This phenomenon is commonly associated with drizzling closed cellular clouds. In contrast, ship tracks observed in open cellular clouds exhibit significant increases in cloud albedo. Overall, the net effect in both regimes is negative, but is significantly stronger in the open cell regime.

Ship Track Cloud Radiative Forcing (W m^{-2})

	Twomey	Adjusted	Net
Open Cell Clouds:	-13.3	-24.2	-37.5
Closed Cell Clouds:	-10.7	+4.5	-6.2

*Results from Christensen and Stephens (2012).

Outstanding Question: How frequently do ship tracks occur?

The above table shows the sensitivity of the cloud radiative forcing by a ship plume. However, the frequency in which ship tracks are forming in these regimes remains unknown. Knowing how often an aerosol plume emitted by a ship produces a ship track would lend insight into how receptive these clouds regimes are to cloud brightening.

In Christensen and Stephens (2011), higher numbers of ship tracks were observed in the closed cell regime, however due to the extraordinarily difficult task of constructing a climatology of cloud types by hand, this step was not performed. Findings from such a study would have implications for attempts to deliberately brighten low-clouds through geoengineering strategies involving solar radiation management. A possible outcome being that aerosol exerts a small or even possible cancellation of the aerosol indirect forcing by competing cloud regimes.

2. Volcanic Plumes

a. Trade wind cumulus Regime and plumes downwind from Hawaii

Yuan et al. (2011) demonstrates the first observational evidence of large-scale increase of cloud amount due to aerosols in a trade cumulus regime. Here they found that the aerosol plume from Hawaii decreases droplet size, decreases precipitation efficiency, increases cloud amount, and increases cloud top heights. Here, the adjusted forcing would contribute to the Twomey effect, leading to a significantly large cloud radiative forcing. They estimated the total aerosol forcing (direct + indirect) to be 20 W m^{-2} from to the volcanic plume with the majority of the response being caused due to the changes in the cloud properties (indirect effect).

b. Stratocumulus regime

Gasso et al. (2008) show that “volcano tracks” in mid-latitudes (the Aleutian Islands in the North Pacific and the South Sandwich Islands in the South Atlantic) resemble the effect of anthropogenic ship tracks on marine boundary layer clouds. Here, using a combination of MODIS, AMSR-E, and GOES observations they demonstrate an immediate increase in cloud brightness and decreases in both cloud effective radius and liquid water downwind of the volcanoes. Like ship tracks the volcano cloud can extend for hundreds of kilometers. Also, like many ship tracks, negative adjustments to cloud albedo (dimming) arise from decreases in liquid water paths.

Comment: It would be interesting to revisit this study and analyze these volcano tracks by the marine stratocumulus convective regimes. If they do indeed resemble ship tracks then one might expect to see differences in the indirect effect responses between cloud regimes.

3. Impacts from Smelters

a. Chilean Smelters (VOCALS)

The effect of anthropogenic sources of aerosol particles such as power plants, urban pollution and smelters on the stratocumulus deck was investigated during the VOCALS field experiment. Many flights focused on the gradient in cloud properties along an East-West track from near the Chilean coast to remote areas offshore. Cloud droplet effective radii were typically small off the coast of Chile and Peru and increased rapidly away from land. The consequence of which was deduced from enhanced cloud droplet concentration, particularly downwind of the major copper smelters whose combined sulfur emissions total 1.5 Tg S yr^{-1}, comparable to the entire sulfur emissions from large industrialized nations such as Mexico and Germany (Source: GEIA). However, cloud thickness and liquid water path are also smaller near shore. This also results in smaller droplet sizes overall. The net effect is that cloud albedo is not significantly higher near shore relative to offshore in this region, despite the aerosol effects on clouds.

b. Norilsk Ni-Cu Smelter complex in Siberia

The Norilsk Ni-Cu smelter is responsible for nearly 2 percent of the entire global emissions of sulfur dioxide. This complex produces abundant cloud and ice condensation nuclei that are transported over long distances (more than 2000 km). Because the Arctic front typically remains south of Norilsk (latitude 70°N), haze generated by the complex of smelters is often transported over the Arctic Ocean. The aerosol indirect effect on clouds typically causes a cooling of the Earth's surface by increasing the reflection of visible solar radiation. However, most of the clouds residing over the Arctic Ocean only receive sunlight for half of the year. In addition, a strong surface temperature inversion in the Arctic persists throughout the diurnal cycle, producing a unique situation for cloud radiative effects. Low-clouds that are thus warmer than the surface exert a warming influence through infrared radiation. Clouds in the springtime are often optically thin and susceptible to the effects of particle pollution. As a consequence, aerosol indirect effects increase the emissivity of the clouds and warm the surface during winter and early spring. It's noteworthy that cooling effects have also been observed, aerosol containing abundant ice nuclei stimulate precipitation in these clouds and reduce cloudiness. During summer, when the sun rises, the aerosol indirect effect reverts back to a surface cooling due, assuming aerosol does not reduce cloudiness.

Lubin and Vogelmann, (2010) used six years of ARM data to demonstrate that the total (short-wave and long-wave) first indirect effect in the high Arctic is found to yield a transition from surface warming of +3 W m^{-2} during March to a cooling of –11 W m^{-2} during May. Thus, the sign and magnitude of the aerosol indirect effect depends on the season and size distribution and chemical composition of the aerosol affecting the clouds.

Additional Comments:

I could not find a single study using in situ or satellite observations involving the direct impact of these smelter plants on the clouds. Most of the results were focused on the impacts of acid rain generated by these plants. An aerosol indirect effects study could be achieved using observations from the A-train as it frequently orbits over this region (multiple times a day).

4. Conclusions

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. Thus, this literature review is by no means entirely comprehensive. However, a common theme does emerge from the studies mentioned above: aerosol plumes containing abundant cloud condensation nuclei, quite frequently, increase the number concentration and reduce the size of cloud droplets in warm clouds. They often, but not always, suppress warm rain precipitation. This generally leads to higher cloud coverage. Reductions in liquid water content and changes in cloud depth are common amongst these studies. The extent of liquid water path adjustments to the microphysical cloud brightening effects remains largely uncertain for low-level clouds. Additional studies, analyzing the low-cloud regimes 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.

5. Targeted interventions: Arctic

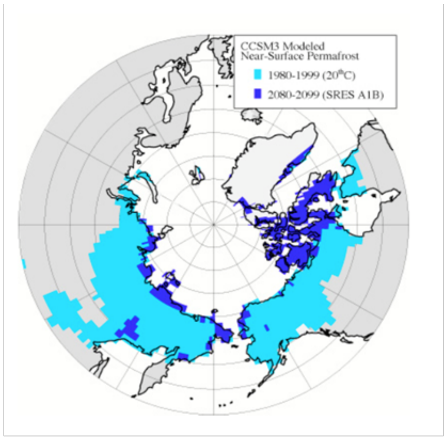
It is essential to consider what the goals of implementing geoengineering might be, as this influences what type of intervention would be required, and where and when it might be deployed. It is plausible that any eventual implementation would be to target some specific consequence of climate change, rather than restoring the entire climate to a baseline state. It also may be technically more straightforward to intervene for a specific goal in a specific region, rather than address the full climate system. Of course, all aspects of the climate are interconnected, and thus it is not possible to intervene only in one region without impacts elsewhere (e.g., Robock et al., 2008), but the adverse consequences of deploying geoengineering might be reduced if the target for intervention was more narrowly defined.

There are a number of plausible targets for intervention (MacCracken 2009), from reducing regional drought, to mitigating hurricane intensity and it could be worthwhile to identify specific strategies for each of these. Rather than explore every possible option, we have identified the highest priority, and chosen to focus on the Arctic region, and permafrost melting in particular.

A tipping point event associated with permafrost melting carries high risk and merits top priority for a “targeted intervention” study. The likelihood is unknown (there is very limited observational data to date, but there are upcoming in-situ and airborne campaigns planned by DOE and NASA). However, the potential impact is extreme.

The goals of future study would need to include a concise definition of “tipping point” (including consideration of irreversibility), an analysis of the controlling processes, and focused modeling and observations relevant to potential geoengineering actions ranging from stratospheric aerosols, low clouds, and surface albedo modification.

Other tipping points involving arctic sea-ice and the Greenland and Antarctic ice-sheets may also warrant targeted intervention studies. Some initial analysis may be warranted (e.g., the impact of damming GIS fjords to reduce dynamical ice loss) to assess the merits of such an effort.



High risk of permafrost thaw,
Schuur et al., *Nature* (Dec. 2011)

"Carbon released into the atmosphere from permafrost soils will accelerate climate change, but the magnitude of this effect remains highly uncertain. Our collective estimate is that carbon will be released more quickly than models suggest, and at levels that are cause for serious concern."

~1700 GtC stored
In permafrost
(19,000,000 km^2)

Potential for tipping-point prior to 2030?

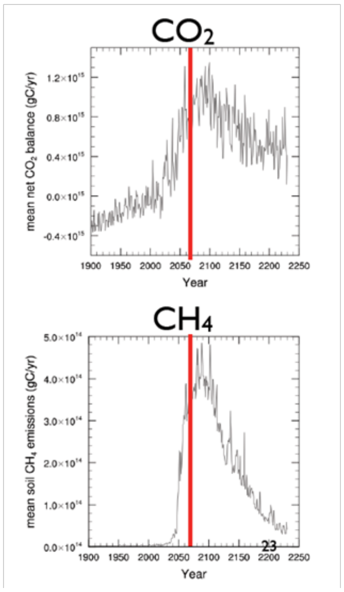


Figure 6. Summary of the magnitude of carbon sequestered in arctic permafrost at risk of rapid and irreversible (on 100 year time-scale) release and corresponding uncertainty on impact as an example of potential need to improve monitoring of arctic tipping points, relevant to potential "targeted interventions" (e.g., regional scale geoengineering efforts such as Arctic surface albedo modification) focused on managing specific impacts.

Major Findings: The key questions that need to be answered are:

1. What constitutes a climate tipping point for permafrost melt? Is it possible/likely (i.e. understand dependence on parameter space). Is it reversible, and when might it occur?
2. How far in advance of the tipping point is intervention required?
3. Specifically what intervention is required (how much and where)?
4. How much of permafrost melt is driven by summer short-wave vs other forcings?
5. What are the options for optimal intervention (tropospheric or stratospheric sulfate, cloud seeding, surface albedo (e.g. vegetation change), etc)?
6. What are the global impacts, risks, and co-benefits of interventions targeted on avoiding a permafrost tipping point?
7. What observations are required, both to answer the above questions as best as possible in the short term, and ongoing to monitor conditions to detect a tipping point as early as possible?

The goal of a future study would be to answer these questions, both to address the risk of a tipping point, and assess whether there are specific geoengineering actions that could prevent or delay an irreversible, high impact transition in the earth system. There are relevant tasks involving both modeling and observational assessment. The former includes model intercomparison (e.g. GeoMIP) and dynamic analysis (e.g. to define "tipping point" more precisely, and to explicitly incorporate parameterized methane feedback into a climate model to assess questions 1-3 above in particular.)

There is considerable uncertainty in permafrost melt models due in part to the lack of relevant observations; an important first task is to clearly articulate what observations would be required to help close the knowledge gap. Because of the significant role that the positive feedback from Arctic methane release could play in motivating geoengineering, it is essential that we work to further understand this source of climate risk.

5.1 Permafrost: what is known

The current permafrost carbon pool (an area of roughly 10^7 km^2 above 50 degrees north) is estimated to contain more than 1000 GtC in the top 3 meters, with half of that in the top meter (Tarnocai et al., 2009). The area of permafrost could shrink to 10^6 km^2 by 2100 in the IPCC A2 (business as usual) scenario (Ciais et al., 2012). Estimated emissions are predicted to be primarily CO_2 for a warmer/dry future whereas warmer/wet conditions should produce more CH4 with a multiplier for global warming potential (GWP) relative to CO_2 of 22 – 75 for 100 and 20 year time-scales respectively. The fraction released as methane is thus a key uncertainty. Some model studies suggest a "tipping point" event as early as 2020 – 2030 (Schaefer et al., 2011), defining this as when the Arctic shifts from being a net sink of carbon to a net source. The carbon released by melting permafrost is an irreversible change in the climate system, and provides a positive feedback on the climate (Koven et al., 2011, Khvorostyanov et al., 2006). This could result in some threshold, beyond which there is a significant increase in the incremental climate response to an incremental radiative forcing perturbation (a more conventional definition of tipping point); whether this could occur, and if so, when this could occur, is unknown. There are also other high-latitude reservoirs of methane that could be destabilized by warming.

6. Albedo monitoring

The Sun provides the energy that fuels the dynamical, chemical, and biological processes of the Earth system. It has long been speculated that the quasi-cyclic variations in this solar energy reaching the Earth influences the climate system. However, the variations in incoming solar energy are an order of magnitude less than the other major forms of climate forcing (Haywood et al., 1999; Forster et al., 2007). By contrast the solar energy leaving Earth varies significantly in space and over time, and the processes responsible for determining how much solar energy is reflected back to space establish important climate feedbacks. Techniques to modulate this reflected solar energy form the basis of the Solar Radiation Management (SRM) approach to geo-engineering. This management strategy hinges on increasing the amount of solar radiation reflected back to space, thus increasing the Earth's albedo by a small percentage as a way of offsetting the effects of increased greenhouse gases. These SRM methods were studied in phase I of this KISS study.

The reflected sunlight from Earth, expressed as albedo, is a fundamental component of the planet's energy balance and thus the climate system. There is still much that we do not fully understand about this energy flow. Two pressing questions are:

- By how much does this energy flow vary and what are the important processes that establish this variability?
- Can spectral information provide a more precise way of detecting change and fingerprint the mechanisms of change?

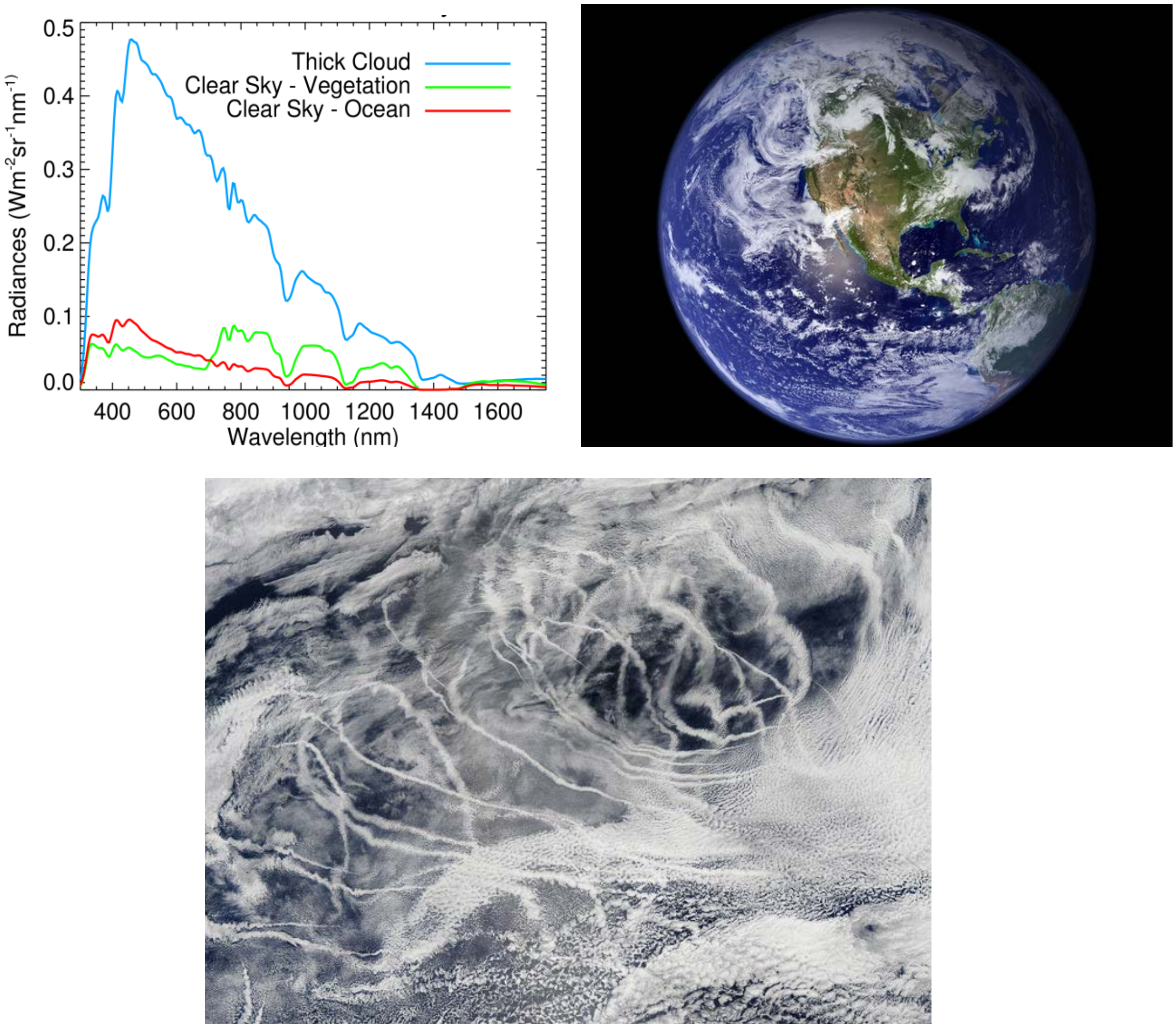


Figure 7. Illustration of the importance and relevance of monitoring reflected sunlight (spectral albedo) from space. Different surfaces have different spectral albedo characteristics; understanding what has changed requires high temporal, spatial, and spectral resolution.

The importance and relevance of monitoring reflected sunlight from space is widely recognized across multiple disciplines. Monitoring reflected sunlight should also be an essential aspect of any SRM strategy and it will be necessary to establish an observational strategy to determine the extent to which any changes to the albedo of the system can be attributed to SRM activities. Thus a proposed technical follow-up study will be directed towards defining the appropriate observing strategy for detecting both changes in albedo and the mechanisms of such change.

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Appendix: Workshop Agendas and participants

The following pages provide the agendas from the two workshops, and the list of participants for each workshop, along with their research areas.

Monitoring of Geoengineering Effects and
their Natural and Anthropogenic Analogues
May 23-26, 2011
Overview Schedule

Monday, May 23, 2011 in Salvatori Seminar Room, 365 South Mudd

Short Course on Climate Physics and Geoengineering*

Time	Event	Speakers
8:30 - 9:00	Coffee and refreshments	
9:00 - 10:30	Motivations for considering geoengineering (including "climate emergencies"), overview of key physical processes and geoengineering	MacCracken
10:30-11:00	Break	
11:00-12:30	Stratospheric aerosols, their effects on radiative forcing, analogues (volcanoes) & risks	Robock
12:30 - 2:00	Lunch	
2:00 - 3:30 pm	Cloud-aerosol microphysics, effects of marine and high clouds on albedo & climate, analogoues (ship tracks), and risks	Feingold
3:30 - 4:00	Break	
4:00-5:00	Surface cover effects on albedo & climate, analogues (dust on snow), and risks	Painter
5:00-6:00	Modeling Climate Physics: challenges & climate sensivity studies	Rasch
6:00 - 8:00	KISS Welcome Dinner at the Athenaeum (Workshop Particpants only)	

Tuesday, May 24, 2011 in Millikan Library - 6th Floor

Stratospheric Aerosols & Radiative Forcing

Time	Event	Speaker
8:30 - 9:00	Coffee and refreshments	
9:00 - 9:30	KISS Logistics and Overview	Michele Judd/Tom Prince
9:30 - 9:45	Introductions	ALL
9:45 - 10:15	Goals of Workshop	Team Leads
10:15 - 10:45	Break	
10:45 - 11:45	What do we need to know about stratospheric aerosols, their radiative forcing, analogues, and geoengineering risks?	Robock Toon Keith
11:45 - 12:45	Current & planned observational capabilities: strato aerosols and radiative forcing	Vernier
12:45 - 2:15	Buffet lunch at the Athenaeum provided by KISS	
2:15-3:15	Student/Post doc presentations (three 20 min)	Students and Postdocs
3:15 - 3:45	Break	
3:45-5:15	Breakout discussions - enumerate gaps between knowledge needs and current/planned capabilities for stratospheric aerosols, radiation, earth system consequences	
5:15-6:00	Plenary Discussion	
6:00 - 8:00	Offsite dinner in Pasadena (KISS will pay for grad students and postdocs who attend)	

Wednesday, May 25, 2011 in Millikan Library - 6th Floor

Aerosols & Cloud Albedo

Time	Event	Speaker
8:30 - 9:00	Coffee and refreshments	
9:00-10:30	What do we need to know about cloud-aerosol microphysics, marine and high cloud albedo, effects of sulphates on cloud albedo, analogues, and geoengineering risks?	Feingold Rasch
10:30 - 11:00	Break	
11:00-12:00	Current & planned observational capabilities: clouds and albedo	TBD (passive methods) Stephens (active methods)
12:00 - 2:00	Lunch on your own	
2:00-3:00	Student/Post doc presentations (three 20 min each)	Students and Postdocs
2:45-4:15	Break-out discussions - enumerate gaps between knowledge needs and	
4:15-4:45	Break	
4:45-5:30	Plenary Discussion	
6:00 - 8:00	KISS Dinner at the Athenaeum (everyone expected to attend)	

Thursday, May 26, 2011 in Millikan Library - 6th Floor

Time	Event	Speaker
8:30 - 9:00	Coffee and refreshments	
9:00-11:00	Writing time (breakout groups): summarize knowledge needs, capabilities, and gaps per topic area	TBD
11:00-12:00	Plenary synthesis	
12:00 - 2:00	Buffet lunch at the Athenaeum provided by KISS	

Monitoring of Geoengineering Effects and their Natural and Anthropogenic Analogues 2

November 15-18, 2011
Overview Schedule

Tuesday, November 15, 2011, Keith Spalding, Third Floor

Monitoring volcanic eruptions (as geoengineering analogues)

Time	Event	Speaker
8:00 - 8:30	Coffee and refreshments	
8:30 - 8:45	KISS Logistics and Overview	Michele Judd/Tom Prince
8:45 - 9:15	Introductions and Goals of Workshop	Riley Duren
9:15 - 10:15	Stratospheric geoengineering and the volcano analog	
	Volcano analog, GeoMIP	Alan Robock
	Aerosol evolution	Jason English
	WACCM and ozone	Simone Tilmes [via Webex]
	WACCM and ozone	Mike Mills
10:15 - 10:30	Break	
10:30 - 11:30	Stratospheric geoengineering and the volcano analog (continued)	
	Regional geoengineering	Mike MacCracken
	Chinese research, ice cores	John Moore
	Volcanic eruptions and cirrus clouds	Ken Sassen
	Agricultural responses	Lili Xia
11:30 - 12:00	Discussion	
12:00 - 1:30	Lunch at the Athenaeum	
1:30 - 3:30	Existing monitoring capability for volcanic eruptions	
	Balloons	Terry Deshler
	Lidar	Jean-Paul Vernier
	Limb-scanning satellites	Adam Bourassa
	Constellation of small satellites proposal	Brian Toon [via Webex}
3:30 - 4:00	Break	
4:00 - 5:00	Discussion	
5:00 - 7:00	KISS Dinner at the Athenaeum	

Wednesday, November 16, 2011, Hameetman Auditorium, Cahill Building

Ship Track/Cloud Studies (as geoengineering analogues)

Time	Event	Speaker
8:00 - 8:30	Coffee and refreshments	
8:30 - 9:00	Welcome	Joyce Penner
9:00 - 10:15	Expectations for response of clouds to aerosols	Robert Wood
	How good are satellite data (or issues with satellite data) for determining response of clouds to aerosols?	Jay Mace
	The potential use of CALIPSO to study the possible impact of volcanic plumes on cirrus clouds microphysics	Jean-Paul Vernier
	Global modeling of Cirrus clouds	Xiaohong Liu
10:15-10:30	Break	
10:30 - 12:00	Recent studies off the coast of Monterrey	Armin Sorooshian John Seinfeld
	Ship Effects	Veronika Ehring [Webex]
	Process-modeling study of ship tracks and marine cloud brightening	Hailong Wang
	Can ship track data be used to evaluate geo-engineering schemes?	Phil Durkee
	Use of Satellite data to determine indirect effects	Kari Alterskjær
	Modeling data: Is it possible to use satellite data in combination with models to determine response?	Joyce Penner
12:00 - 1:00	Lunch on your own	

Wednesday, November 16, 2011, Hameetman Auditorium, Cahill Building (continued)

Ship Track/Cloud Studies (as geoengineering analogues)

1:30 - 2:00	High resolution global modeling of response of models to geo-engineering injections	Minghuai Wang
2:00 - 3:00	Discussion	
3:00 - 5:00	**Placeholder** for splinter discusssions (location: Keith Spalding, Third Floor)	
5:30 - 7:00	Dinner Buffet at the Athenaeum (spouses and significant others welcome to attend)	

Thursday, November 17, 2011, Keith Spalding, Third Floor

KISS Geoengineering Project (core team meeting)

Time	Event	Speaker
8:00 - 8:30	Coffee and refreshments	
8:45- 9:00	Objectives: planning for Development Phase of project (and other opportunities)	Riley Duren
9:00-10:00	Summary/Discussion of Task 1 (Volcano monitoring) findings and recommendations	Alan Robock
10:00-10:15	Break	
10:15 - 11:15	Summary/Discussion of Task 2 (Ship track studies) findings & recommendations	Joyce Penner
11:15 - 12:45	Summary/Discussion of Task 3 (Reflected solar energy monitoring) findings & recommendati	Graeme Stephens
12:45 - 2:00	Lunch on your own	
2:00 - 3:30	Summary/Discussion of Task 4 (Targeted Interventions) findings & recommendations	Jane Long
3:30 - 4:00	Discussion of relative priority of tasks	All
5:00 - 7:00	Offsite no-host dinner in Pasadena (but KISS will pay for grad students and postdocs who attend)	

Friday, November 18, 2011, Keith Spalding, Third Floor

KISS Geoengineering Project (core team meeting)

Time	Event	Speaker
8:00 - 8:30	Coffee and refreshments	
8:30 - 10:00	Continued discussion: priorities and ranking of tasks for development phase	All
10:00 - 10:30	Outline for development phase proposal	Riley Duren
10:30 - 12:00	Breakout writing: summarize key points for proposal	
12:00 - 1:30	Lunch	
1:30 - 2:00	Review proposal outline with key points	
2:00 - 3:00	Timeline and next steps	
3:00	End of Workshop	

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Research: My research primarily focuses on the aerosol indirect effects of warm low-level maritime clouds deduced from the observations of ship tracks. Multiple instruments in the afternoon train of satellites, with the recent addition of the radar on CloudSat, are used to diagnose the microphysical and macrophysical properties of the clouds. Several hundred-ship tracks identified in MODIS imagery coincident with the observations from CloudSat and Calipso have been used to examine the precipitation and cloud dynamic responses associated with ship tracks.

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Research: Systems engineering of monitoring systems and decision support services for climate change mitigation, adaptation, and geoengineering.

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Research: I am using the WACCM whole atmosphere climate model with MOZART full chemistry and CARMA sectional aerosol microphysics to conduct detailed study of aerosols in the upper troposphere and stratosphere. I have applied this model to nucleation schemes and stratospheric sulfur geoengineering and am continuing to use it for further science questions.

Dr. Graham Feingold
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http://www.esrl.noaa.gov/csd/staff/graham.feingold/

Research: Aerosol-cloud interactions in warm boundary layer clouds using fine-scale models, in-situ observations and surface-based remote sensing.

Dr. Brian Kahn
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http://science.jpl.nasa.gov/people/BKahn/

Research: Brian Kahn is a Staff Scientist working most closely with the Atmospheric Infrared Sounder (AIRS) group. His research interests are in the remote sensing of clouds, aerosols, temperature, water vapor, and minor gases, their synthesis using multiple instrument platforms, and their application to scientific problems regarding observing and modeling present and future climate.

Dr. Benjamin Kravitz
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Research: I conduct climate model simulations of various aspects of geoengineering, primarily focusing on the climate effects of using stratospheric aerosols. My thesis work involved using black carbon aerosols. I am also a coordinator of the Geoengineering Model Intercomparison Project (GeoMIP), which prescribes standardized geoengineering scenarios to be simulated by many different climate modeling groups. My future work will also involve simpler, more idealized studies of geoengineering using single column and radiative transfer models to evaluate individual processes and concerns highlighted by the general circulation models.

Dr. Jane C.S. Long
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Research: A hydrogeologist and geotechnical engineer with more than 34 years of national laboratory and academic experience has been selected as Lawrence Livermore National Laboratory's Associate Director for Energy and Environment.

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Research: My research relating to climate engineering focuses mainly on the potential for applying solar radiation management in selective ways to alleviate changes of particular types in particular regions, or even globally. For example, I am interested in determining if limiting SRM to polar latitudes can limit climate change in the Arctic and possibly elsewhere, if modification of clouds in particular areas can be used to push storm tracks back to traditional paths, and if tropospheric sulfate injections in remote areas can be used to preserve the present sulfate offset as emissions from use of coal are reduced.

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Research: Applying tools from engineering control and dynamics to help understand geoengineering (e.g. test limitations, or optimization), and climate variability

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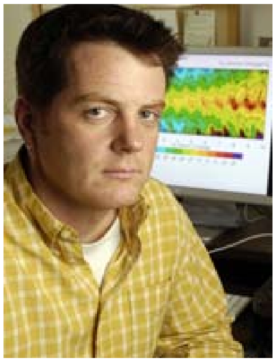

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Research: My research has focused on modeling the chemistry and microphysics of the middle atmosphere, which affect the ozone layer and our climate. I have been collaborating on CESM-WACCMâ€™s participation in the Climate Model Intercomparison Project 5, and am leading WACCMâ€™s participation in GeoMIP. I have developed a version of WACCM/CARMA for studying stratospheric sulfate microphysics in a chemistry-climate model context. I have also used WACCM/CARMA in published studies of the impacts on climate and ozone of black carbon in nuclear winter and space tourism scenarios.

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Research: Past sea level change and prediction; natural and anthropogenic climate forcing; impacts of extreme events, and geoengineering scenarios. Development of advanced statistical methods for time series analysis, with the aim of a mechanistic understanding of the climate system. Network analysis of climate system. Ice sheet and glacier flow modelling using sophisticated models. Socio-economic adaptation strategies to climate change in the Arctic. Extraction of paleoclimate information from physical and chemical analysis of Arctic and Antarctic ice cores.

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Research: His areas of interest are snow hydrology, radiative impacts of light-absorbing impurities on snow and glacier melt, water resources from mountain snow and ice, multispectral remote sensing and imaging spectroscopy, and solar system astrobiology. Dr. Painter has pioneered our understanding of the impacts of dust emission from land use change on snow and ice cover in mountain systems and the hydrologic response. He has also developed cutting edge retrievals of snow and ice properties from imaging spectrometer and multispectral optical data and field technologies for characterization of cryospheric optical properties.

Professor Joyce E Penner

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Research: Global modeling of aerosols and aerosol/cloud interactions

---

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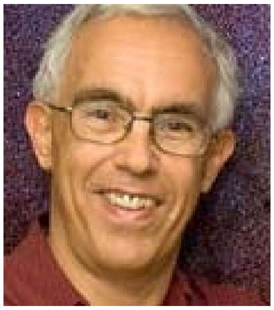
Research: Research interests include quantifying the Earth-atmosphere radiative energy budget; satellite, airborne, and surface remote sensing of clouds and aerosols; solar spectral variability and its effects on terrestrial climate; and theoretical atmospheric radiative transfer. Principal Investigator for the NOAA & NASA Joint Polar Satellite System Total and Spectral Solar Irradiance Sensor and a co-Investigator on the NASA Solar Radiation and Climate Experiment.



Professor Thomas Prince

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Research: I am interested in learning more about the processes that influence earth albedo and what measurements might be needed to better estimate both natural- and human-induced changes to albedo.

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Research: My personal research is focused on two areas: General circulation modeling and chemistry/climate interactions: I am particularly interested in the role of clouds in controlling climate and trace species distributions, and in numerical methods for the solution of differential equations in climate models.

Ms. Kate Ricke
Graduate Research Assistant
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Research: I model stratospheric SRM with HadCM3L, using large ensembles to explore parametric uncertainty

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Research: My research involves many aspects of climate change. I conduct both observational analyses and climate model simulations. My current research focuses on geoengineering, regional atmosphere-hydrology modeling, climatic effects of nuclear weapons, soil moisture variations, the effects of volcanic eruptions on climate, detection and attribution of human effects on the climate system, and the impacts of climate change on human activities.

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Research: Large-scale atmosphere dynamics

Professor Graeme L Stephens
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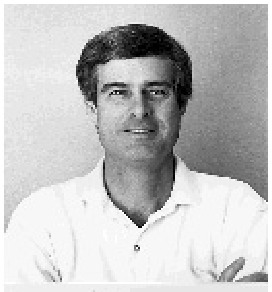
Research: His work has dealt with the remote sensing of cloud properties from both space-borne and aircraft measurements and the application of this information to problems of better understanding the physical processes that define the Earth's atmosphere. Other activities include the fundamental advances in atmospheric radiative transfer and the role of clouds in climate. His current research focus is on understanding the hydrological cycle in the climate system.



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Research: Atmospheric aerosols/atmospheric chemistry/climate

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Research: My research work mainly focuses on stratospheric aerosol by: - Using CALIPSO to study aerosol sources and sinks in the Upper troposphere and Lower stratosphere with a special interest for the tropics - Building a stratospheric aerosol record with space borne instruments including SAGEII/GOMOS/CALIOP for climate science community - Studying how CALIPSO can be used to improve the forecast of volcanic plume dispersion.

Dr. Duane Waliser
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Research: Climate dynamics, tropical variability, prediction and predictability, model-data diagnostics studies.

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Research: I am working on stratospheric geoengineering impacts on agriculture. Since stratospheric geoengineering would change summer monsoon pattern and affect hydrologic cycle, the reduction of precipitation might decrease agricultural productivity in East Asia and India where the population density is the highest. Therefore, it is important to quantify the sensitivity of major crop yields regarding to climate changes and possible improvements of agriculture practice. Our preliminary result show that yields of rice and maize in major production provinces in China will reduce ~6% and ~3% respectively due to stratospheric geoengineering, and ~10% increasing of fertilizer can approximately compensate this negative effect.

Professor Yuk L Yung

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Research: Planetary atmospheres; planetary evolution; atmospheric chemistry; atmospheric radiation; astrobiology; global change; synergistic interactions between modeling, laboratory experiments and field observations.

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Research: Clouds; radiation; remote sensing; aerosols, global climate change

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Research: I do research on cloud aerosol interactions in general, using the Norwegian Earth System Model. More specifically, I am part of the a European project on geo-engineering (IMPLICC) and do research on cloud seeding. As part of this we have developed a tool based on satellite observations to find suited sites for further research on cloud seeding.

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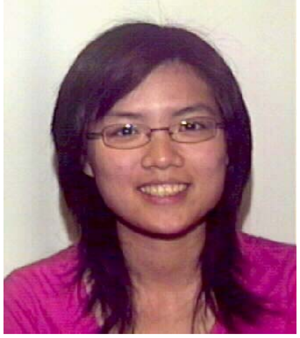
Research: I work on radiative transfer modelling and retrieval algorithms for optical satellite measurements of cloud, aerosol and trace gases. I am particularly interested in retrievals of stratospheric aerosol properties from spectral measurements of limb scattered sunlight, which can be made with relatively high spatial and temporal resolution.



Yi-Chun Chen
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Research: aerosol-cloud-precipitation interactions in marine stratocumulus cloud (both modeling and experiment studies).

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Research: My research primarily focuses on the aerosol indirect effects of warm low-level maritime clouds deduced from the observations of ship tracks. Multiple instruments in the afternoon train of satellites, with the recent addition of the radar on CloudSat, are used to diagnose the microphysical and macrophysical properties of the clouds. Several hundred-ship tracks identified in MODIS imagery coincident with the observations from CloudSat and Calipso have been used to examine the precipitation and cloud dynamic responses associated with ship tracks.

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Research: In general, I work with the aerosol mass spectrometer (AMS) to study the chemical and physical nature of aerosols. My current research is to understand how organic aerosols from ship emissions impact marine stratocumulus. Based on AMS measurements of controlled emissions made during a recent aircraft-based field mission, I aim to understand how highly organic aerosols age downwind of a point source. Ultimately, I seek to determine the extent of water uptake by these particles and if these particles can serve as cloud condensation nuclei.

Terry Deshler
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http://www-das.uwyo.edu/~deshler/

Research: Making in situ measurements of stratospheric aerosol size distributions. Using those measurements to address our understanding of stratospheric ozone in the polar and mid latitude stratosphere, the evolution of stratospheric aerosol following volcanic eruptions, and the non-volcanic fraction of stratospheric aerosol. Making a full suite of in situ aerosol measurements at the surface, and using those measurements to address our understanding of the direct and indirect of affect of aerosol on the Earth's radiation

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Research: Systems engineering of monitoring systems and decision support services for climate change mitigation, adaptation, and geoengineering.

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Research: Satellite observations of atmospheric constituents

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Mobile: 920-915-6255
Fax: 303-492-6946

Research: I am using the WACCM whole atmosphere climate model with MOZART full chemistry and CARMA sectional aerosol microphysics to conduct detailed study of aerosols in the upper troposphere and stratosphere. I have applied this model to nucleation schemes and stratospheric sulfur geoengineering and am continuing to use it for further science questions.

Brian Kahn
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http://science.jpl.nasa.gov/people/BKahn/

Research: Brian Kahn is a Staff Scientist working most closely with the Atmospheric Infrared Sounder (AIRS) group. His research interests are in the remote sensing of clouds, aerosols, temperature, water vapor, and minor gases, their synthesis using multiple instrument platforms, and their application to scientific problems regarding observing and modeling present and future climate.

Zachary Lebo
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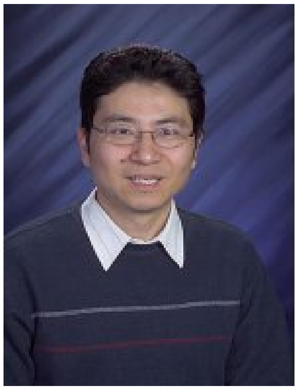
Research: Modeling the effects of aerosol and cloud properties



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Atmospheric Science and Global Change Division
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Research: Global modeling study of aerosol life cycle in the atmosphere and impacts on climate; Development and evaluation of aerosol and cloud microphysics schemes for climate models; Aerosol-cloud-precipitation-climate interactions; Aerosol direct and indirect effects on climate.

Jane C.S. Long
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Research: A hydrogeologist and geotechnical engineer with more than 34 years of national laboratory and academic experience has been selected as Lawrence Livermore National Laboratory's Associate Director for Energy and Environment.

Michael C. MacCracken
Chief Scientist for Climate Change Programs
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Research: My research relating to climate engineering focuses mainly on the potential for applying solar radiation management in selective ways to alleviate changes of particular types in particular regions, or even globally. For example, I am interested in determining if limiting SRM to polar latitudes can limit climate change in the Arctic and possibly elsewhere, if modification of clouds in particular areas can be used to push storm tracks back to traditional paths, and if tropospheric sulfate injections in remote areas can be used to preserve the present sulfate offset as emissions from use of coal are reduced.

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Research: Clouds, Remote Sensing

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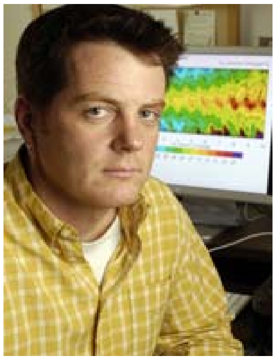
Research: Applying tools from engineering control and dynamics to help understand geoengineering (e.g. test limitations, or optimization), and climate variability



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http://acd.ucar.edu/~mmills/

Research: My research has focused on modeling the chemistry and microphysics of the middle atmosphere, which affect the ozone layer and our climate. I have been collaborating on CESM-WACCM's participation in the Climate Model Intercomparison Project 5, and am leading WACCM's participation in GeoMIP. I have developed a version of WACCM/CARMA for studying stratospheric sulfate microphysics in a chemistry-climate model context. I have also used WACCM/CARMA in published studies of the impacts on climate and ozone of black carbon in nuclear winter and space tourism scenarios.

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Research: Past sea level change and prediction; natural and anthropogenic climate forcing; impacts of extreme events, and geoengineering scenarios. Development of advanced statistical methods for time series analysis, with the aim of a mechanistic understanding of the climate system. Network analysis of climate system. Ice sheet and glacier flow modelling using sophisticated models. Socio-economic adaptation strategies to climate change in the Arctic. Extraction of paleoclimate information from physical and chemical analysis of Arctic and Antarctic ice cores.

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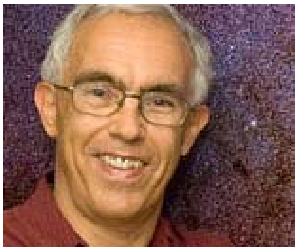
Research: Global modeling of aerosols and aerosol/cloud interactions.



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Research: Gravitational wave detection and gravitational wave astrophysics.

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Research: My research involves many aspects of climate change. I conduct both observational analyses and climate model simulations. My current research focuses on geoengineering, regional atmosphere-hydrology modeling, climatic effects of nuclear weapons, soil moisture variations, the effects of volcanic eruptions on climate, detection and attribution of human effects on the climate system, and the impacts of climate change on human activities.

Kenneth Sassen
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Research: Cloud physicist who specializes in remote sensing cloud and aerosol studies using polarization lidar and W-band radar.

Mathias Schreier
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JIFRESSE
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Research: Observation of the indirect aerosol effect from ship emissions. Combining satellite instruments for cloud/atmosphere observations.

John H. Seinfeld
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Research: Atmospheric chemistry and physics, Aerosols

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Engineering/Atmospheric
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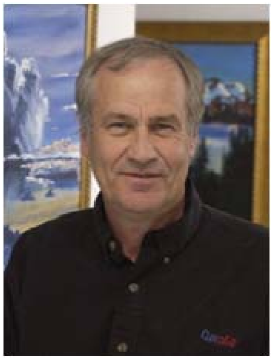
Research: Studying effects of atmospheric aerosol particles on climate change, public health, and the hydrologic cycle. My research includes instrument development, field measurements, model data analysis, and use of remote sensing observational data.



Graeme L Stephens
Director of the Center for Climate Sciences
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http://science.jpl.nasa.gov/people/Stephens/

Research: His work has dealt with the remote sensing of cloud properties from both space-borne and aircraft measurements and the application of this information to problems of better understanding the physical processes that define the Earth's atmosphere. Other activities include the fundamental advances in atmospheric radiative transfer and the role of clouds in climate. His current research focus is on understanding the hydrological cycle in the climate system.

Joao Teixeira
Deputy Director, JPL Center for Climate Science
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Jet Propulsion Laboratory
Climate Physics Group
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Phone: 818-354-2762

Research: Turbulence, clouds and climate: Using a variety of models and observations to better understand the interactions between the Earth's climate system and small-scale processes, such as turbulence, convection and clouds.

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Project Scientist
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Atmospheric Research
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Research: My scientific focus covers the evaluation of chemistry climate models with regard to chemical and dynamical processes in the atmosphere, using remote and in-situ observations. I have investigated past, present and future evolution of the ozone hole in both hemispheres, using both models and observations, and the impact of Geo-engineering on the Earth's system and the stratosphere. In recent years I extended my research towards the UTLS and the troposphere, with focus on long-range transport of pollutants as well as the evolution of tropospheric ozone. As the Chemistry-Climate Liaison, I work with the Community Earth System Model (CESM1) model at NCAR.

Jean-Paul Vernier
Postdoc
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NASA Langley
Atmospheric Science
21 Langley Boulevard
Hampton, VA 23665

Phone: 757-864-9021

Research: My research work mainly focuses on stratospheric aerosol by: - Using CALIPSO to study aerosol sources and sinks in the Upper troposphere and Lower stratosphere with a special interest for the tropics - Building a stratospheric aerosol record with space borne instruments including SAGEII/GOMOS/CALIOP for climate science community - Studying how CALIPSO can be used to improve the forecast of volcanic plume dispersion.

Duane Waliser
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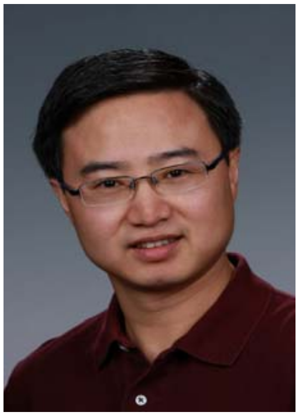
Research: Climate dynamics, tropical variability, prediction and predictability, model-data diagnostics studies.



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http://www.pnl.gov/science/staff/staff_info.asp?staff_num=7432

Research: I use the high-resolution Weather Research and Forecasting (WRF) model with explicit treatment of aerosol-cloud-precipitation interactions to perform cloud-system-resolving simulations of shiptracks and marine cloud brightening by injecting sea-salt particles. I also do climate modeling of aerosols and clouds.

Dr. Minghuai Wang
Scientist
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Research: My research focus is about modeling aerosol-cloud interactions in global climate models. I have examined how different aerosol nucleation mechanisms affect CCN concentrations and further affect the estimate of the first aerosol indirect effects. I have recently developed a Multi-scale aerosol-climate model that uses a cloud -resolving model to replace the conventional cloud parameteization. I am working on using this model to examine aerosol-cloud-precipitation interactions

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Research: Cloud-climate interactions, particularly focused on low clouds. I use data from field programs, satellites and models to study factors (thermodynamics, dynamics, and aerosols) that control clouds in the current and future climates.

Lili Xia
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Environmental Sciences
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Research: I am working on stratospheric geoengineering impacts on agriculture. Since stratospheric geoengineering would change summer monsoon pattern and affect hydrologic cycle, the reduction of precipitation might decrease agricultural productivity in East Asia and India where the population density is the highest. Therefore, it is important to quantify the sensitivity of major crop yields regarding to climate changes and possible improvements of agriculture practice. Our preliminary result show that yields of rice and maize in major production provinces in China will reduce ~6% and ~3% respectively due to stratospheric geoengineering, and ~10% increasing of fertilizer can approximately compensate this negative effect.

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Research: Planetary atmospheres; planetary evolution; atmospheric chemistry; atmospheric radiation; astrobiology; global change; synergistic interactions between modeling, laboratory experiments and field observations.
