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2009 Environ. Res. Lett. 4 045102

(http://iopscience.iop.org/1748-9326/4/4/045102)

IOP Publishing Environmental Research Letters

Environ. Res. Lett. **4** (2009) 045102 (8pp) doi:10.1088/1748-9326/4/4/045102

Modification of cirrus clouds to reduce global warming

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Received 1 April 2009
Accepted for publication 12 August 2009
Published 30 October 2009
Online at stacks.iop.org/ERL/4/045102

Abstract

Greenhouse gases and cirrus clouds regulate outgoing longwave radiation (OLR) and cirrus cloud coverage is predicted to be sensitive to the ice fall speed which depends on ice crystal size. The higher the cirrus, the greater their impact is on OLR. Thus by changing ice crystal size in the coldest cirrus, OLR and climate might be modified. Fortunately the coldest cirrus have the highest ice supersaturation due to the dominance of homogeneous freezing nucleation. Seeding such cirrus with very efficient heterogeneous ice nuclei should produce larger ice crystals due to vapor competition effects, thus increasing OLR and surface cooling. Preliminary estimates of this global net cloud forcing are more negative than -2.8 W m^{-2} and could neutralize the radiative forcing due to a CO_2 doubling (3.7 W m^{-2}). A potential delivery mechanism for the seeding material is already in place: the airline industry. Since seeding aerosol residence times in the troposphere are relatively short, the climate might return to its normal state within months after stopping the geoengineering experiment. The main known drawback to this approach is that it would not stop ocean acidification. It does not have many of the drawbacks that stratospheric injection of sulfur species has.

Keywords: geoengineering, cirrus clouds, climate modeling

1. Introduction

Geoengineering ideas have been classified into two categories (Lenton and Vaughan 2009): (1) those increasing reflectance of solar radiation and (2) those increasing outgoing longwave radiation (OLR) by removing greenhouse gases like carbon dioxide. The geoengineering idea proposed in this letter fits in neither of these categories, although it would if category 2 were broadened by removing the restriction of greenhouse gas removal. The idea proposed is to cool surface temperatures by reducing the coverage of high cirrus clouds to increase OLR.

Since greenhouse gases warm the planet by trapping OLR, and clouds have the greatest impact on the earth radiation budget, it may make sense to target clouds that most strongly regulate OLR for climate engineering purposes. Of the nine cloud types considered in Chen *et al* (2000), cirrus clouds (visible optical depth <3.6, cloud top pressure <440 mb) had the greatest impact on top-of-atmosphere (TOA) longwave fluxes and had a global annual mean net warming of $+1.3$ W m^{-2}. A similar study (Hartmann *et al* 1992) found a TOA global annual net cloud forcing for cirrus (optical depth <9.4) of $+2.4$ W m^{-2}. Thus cirrus tend to trap more outgoing thermal radiation than they reflect incoming solar radiation and have an overall warming effect on the climate system. Conversely, liquid water clouds have a net cooling effect, reflecting more solar radiation than retention of longwave radiation. This difference is primarily due to the relatively cold temperatures of cirrus clouds, causing the earth to radiate at an effectively colder temperature (i.e. nearer the cirrus cloud temperature), thus trapping thermal radiation below cirrus altitudes that would otherwise escape to space. This is why the higher (i.e. colder) the cirrus clouds are, the greater is their OLR impact. Both liquid water and cirrus clouds effectively absorb and emit longwave radiation, but the low water clouds are emitting this thermal radiation at temperatures only slightly cooler than the surface. Thus it makes sense to target the colder cirrus clouds for geoengineering due to their greater impact on OLR.

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One approach for selecting a geoengineering strategy is to target a component of the climate system that the climate system is sensitive to and can be intentionally modified. Recent research indicates that cirrus microphysics has a strong impact on climate sensitivity, S (i.e. the equilibrium response of global mean surface temperature to CO_2 doubling). In the recent study by Sanderson *et al* (2008), an ensemble of thousands of 'perturbed physics' global climate model (GCM) simulations was provided through the distributed computing project, climate*prediction*.net. A principle component analysis was applied to identify the dominant physical processes responsible for variation in S across the ensemble. The two leading EOFs accounted for 70% of the ensemble variance in λ—the global feedback parameter, where $\lambda = 1/S$. Both EOFs were dominated strongly by one physical parameter; the entrainment coefficient for the first EOF and the ice fall speed for the second EOF. The entrainment coefficient controls the amount of moisture laden boundary layer air that is vertically advected into the upper troposphere in thunderstorms (i.e. a coefficient of zero means no dilution of boundary layer air upon ascent). The ice fall speed controls ice removal rates from cirrus, thus affecting the cirrus ice water path (IWP), life cycle and coverage. Both parameters govern λ by affecting (1) the cirrus coverage and IWP and (2) the upper troposphere relative humidity. The main impact of reducing the entrainment coefficient was an enhanced clear-sky greenhouse effect, while the main impact of reducing the ice fall speed was an increase in longwave cloud forcing. In regards to cloud forcing, this study indicates that climate sensitivity depends more on changes in cirrus clouds than on low-level boundary layer clouds.

Another GCM study by Mitchell *et al* (2008) relates the findings in Sanderson *et al* (2008) more intimately to cirrus microphysics by relating the ice particle mass, area, and ice particle size distribution (PSD) to the ice fall speed and optical properties. It was shown that changing the concentrations of small ice crystals (i.e. the degree of bimodality) of the PSD strongly affects the representative PSD ice fall speed, V_t. By increasing V_t, the cirrus IWP decreased by 12% and cirrus coverage decreased by 5.5% globally. This substantially affected annual global means of cloud forcing, heating rates and temperatures in the upper troposphere.

The Sanderson *et al* and Mitchell *et al* studies combined indicate that climate sensitivity depends substantially on the ice fall speed and that the ice fall speed depends on ice nucleation rates (i.e. the concentrations of small ice crystals). Therefore a successful geoengineering strategy might be to modify the ice fall speed by modifying ice nucleation rates.

2. Geoengineering idea

The essence of this idea was described under conclusions in Mitchell *et al* (2008). The idea relates to the interaction between homogeneous and heterogeneous ice nucleation in cirrus clouds, which has been recently the focus of much research. The main distinction here is the linking of this topic to the ice fall speed (which was also done by Lohmann *et al* 2008) and the application to the field of geoengineering.

An important process for ice crystal production in cirrus clouds is homogeneous freezing nucleation, which seems fairly well understood (Sassen and Dodd 1988, Heymsfield and Sabin 1989, Koop *et al* 2000, DeMott 2002, Lin *et al* 2002, Möhler *et al* 2003, Haag *et al* 2003a, Koop 2004). At temperatures below −37 °C, homogeneous freezing nucleation on haze droplets often prevails and ice supersaturations (S_i) are relatively high (e.g. ∼45–60%) in cirrus clouds. Heterogeneous ice nucleation generally occurs at lower S_i and insoluble aerosol particles that nucleate ice crystals in this way can out-compete the homogeneous freezing ice nuclei for water vapor. Heterogeneous ice nuclei include crystal or mineral particles (e.g. Zuberi *et al* 2002, DeMott *et al* 2003a, Richardson *et al* 2007) and some types of soot (e.g. Kärcher 1996, Jensen and Toon 1997, DeMott *et al* 1997, Kärcher *et al* 2007). Homogeneous freezing nucleation is thought to dominate ice crystal production at temperatures less than −40 °C (Kärcher and Spichtinger 2009), consistent with the higher S_i observed in this temperature regime (e.g. Ström *et al* 2003). If so, then the introduction of very efficient heterogeneous ice nuclei at these cold temperatures in the right concentration may result in larger ice crystals as the heterogeneous ice nuclei would out-compete the homogeneous freezing nuclei. This process has been coined as the negative Twomey effect (Kärcher and Lohmann 2003) in association with the traditional Twomey effect in liquid water clouds, where increases in cloud condensation nuclei produce higher cloud droplet concentrations and cloud albedo. The negative Twomey effect can lead to reductions in ice particle concentration by up to a factor of 10 under natural conditions and to decreased cirrus cloud albedo (Haag and Kärcher 2004). Indirect observational evidence for a negative Twomey effect is described in a satellite study of ice cloud–aerosol interactions over the Indian Ocean (Chylek *et al* 2006) while *in situ* measurements have provided direct evidence (Haag *et al* 2003b, DeMott *et al* 2003b).

Substances exist that nucleate ice crystals as effectively as silver iodide (AgI, the best ice nucleant known) at cirrus cloud temperatures, and some are relatively inexpensive and non-toxic (see section 2.1). If significantly larger, these artificially seeded ice crystals would fall faster, and their higher fall velocities may lead to reduced cirrus cloud coverage as predicted in GCM simulations (Mitchell *et al* 2008, Sanderson *et al* 2008). The lower cirrus cloud coverage would result in greater OLR and cooler surface temperatures, thus reducing the impact of global warming. It is important to note that the decrease in cirrus coverage would occur where the cirrus greenhouse effect is strongest (i.e. temperatures <−40 °C). This is a key principle for this geoengineering idea.

Soot particles emitted from aircraft jet engines may possibly nucleate ice through heterogeneous nucleation (e.g. Möhler *et al* 2005b), but soot particles may also become coated with soluble species that make them act more like homogeneous freezing nuclei (Möhler *et al* 2005b, 2005a, DeMott *et al* 1999). Other studies have found that jet fuel exhaust particles fail to nucleate ice below water saturation (DeMott *et al* 2002), and that fresh biomass combustion particles act as homogeneous freezing ice nuclei (DeMott *et al* 2009).

Thus many have argued that the evidence implicating soot particles as heterogeneous ice nuclei in the upper troposphere is rather poor. Moreover, even when considered as a heterogeneous ice nucleus, an ice supersaturation threshold of ∼30% is often assumed for soot (e.g. Kärcher *et al* 2007). In this case one would expect efficient ice crystal seeding material introduced into the upper troposphere to generally out-compete soot particles for water vapor.

A modeling study by Kärcher *et al* (2007) describes the vapor competition between crustal aerosol, soot and homogeneous freezing ice nuclei, where the latter were sulfuric acid particles at 500 cm^{-3}. We first consider the case when soot is ignored and vapor competition is only between homogeneous freezing nuclei and crustal aerosol (i.e. dust), with a critical S_i for dust nucleation of 10% and 55% for homogeneous freezing. Mineral dust particles can be viewed as a surrogate here for the geoengineered seeding material. For cloud updrafts of 5 and 25 cm s^{-1} with dust concentrations of 2 and 20 l^{-1}, respectively, ice crystal number concentrations were reduced by a factor of 5 by the introduction of the dust aerosol. If we assume an ice particle mass–dimension relationship of the form $m = \alpha D^\beta$, where $\beta = 2.8$ for dimension $D < 240\ \mu\text{m}$ (Mitchell *et al* 2009), then it can be shown that a five-fold reduction in ice crystal concentration results in an increase in D by a factor of 1.8. If we assume that the ice fall speed (representing the PSD downward mass flux) lies in the range 15–50 cm s^{-1} for $T < -40\,^\circ\text{C}$, an 80% increase in ice crystal length would increase the fall velocity by ∼70–130% (Mitchell and Heymsfield 2005). Such an increase would significantly change cirrus cloud coverage. Introducing soot with a S_i threshold between 30% and 50% does not seriously change these results until the soot concentration exceeds ∼2 l^{-1} for the 5 cm s^{-1} updraft and 20 l^{-1} for the 25 cm s^{-1} updraft. Higher soot concentrations increase ice crystal concentrations, which then become less sensitive to nuclei type. Thus, if ambient soot particles do serve as ice nuclei and their concentrations are sufficiently high, it is possible that they would inhibit or prevent the seeded ice crystals from growing large enough to have sufficiently high fall velocities needed to significantly reduce cirrus cloud cover.

2.1. Potential seeding material

An ideal ice nucleating agent for cirrus geoengineering would be one having a high effectivity (for ice nucleation) at temperatures colder than ∼−20 °C, but a very low effectivity at warmer temperatures. Bismuth tri-iodide (BiI_3) had been investigated as an ice nucleant for weather modification programs but was unsuitable because its effectivity threshold was below −10 °C. However, this makes it a suitable ice nucleant for geoengineering, targeting primarily cirrus clouds and not the clouds normally targeted in cloud seeding experiments. In addition, BiI_3 is non-toxic and reagent grade bismuth metal is about 1/12th the cost of silver, suggesting BiI_3 would be about 1/12th the cost of AgI.

Bismuth tri-iodide can be generated in aerosol form by combustion of an alcohol solution of BiI_3 (solubility, 3.5 g/100 ml). A better aerosol generating system for this nucleant is pyrotechnic combustion. For this, a modest program of research and development would be required. A pressed composite mixture of BiI_3, potassium perchlorate (KClO_4), aluminum and gilsonite (a natural hydrocarbon) would be appropriate.

2.2. Delivery mechanism

Since commercial airliners routinely fly in the region where cold cirrus clouds exist, it is hoped that the seeding material could either be (1) dissolved or suspended in their jet fuel and later burned with the fuel to create seeding aerosol, or (2) injected into the hot engine exhaust, which should vaporize the seeding material, allowing it to condense as aerosol in the jet contrail. The objective would not be to seed specific cloud systems but rather to build up a background concentration of aerosol seeding material so that the air masses that cirrus will form in will contain the appropriate amount of seeding material to produce larger ice crystals. Since the residence time of seeding material might be on the order of 1–2 weeks, release rates of seeding material would need to account for this. With the delivery process already existing, this geoengineering approach may be less expensive than other proposed approaches.

2.3. Production of new cirrus

Aircraft (Helten *et al* 1998, Spichtinger *et al* 2004) and microwave limb sounder (MLS) satellite measurements (Read *et al* 2001, Spichtinger *et al* 2003) show that large portions of the clear-sky upper troposphere are supersaturated with respect to ice. While natural cirrus may or may not form in these regions over time, the global, quasi-uniform distribution and continuous introduction of efficient heterogeneous ice nuclei might produce more cirrus clouds in these regions than would otherwise occur. Over time, the relatively large ice crystals would sediment to lower levels and warmer temperatures where the cirrus greenhouse effect is less. Water vapor concentrations in the upper troposphere should decrease with this export of moisture to lower levels, and the water vapor greenhouse effect in the upper troposphere should decrease. In fact, the upper troposphere water vapor content in GCMs (affecting the clear-sky OLR) is sometimes 'tuned' by changing the ice fall speed.

The impact of the ice fall speed on global relative humidity (RH) is shown in figure 1, based on the GCM study described in Mitchell *et al* (2008). By increasing the ice fall speed primarily for cold ($T < -40\,^\circ\text{C}$) cirrus, RH is significantly decreased, which increases the clear-sky OLR.

Therefore the equilibrium response to the global introduction of sufficient concentrations of efficient ice nuclei may be a drier upper troposphere having less cirrus coverage. This could substantially increase the amount of outgoing longwave radiation (OLR) and thus have a substantial cooling effect on surface temperatures.

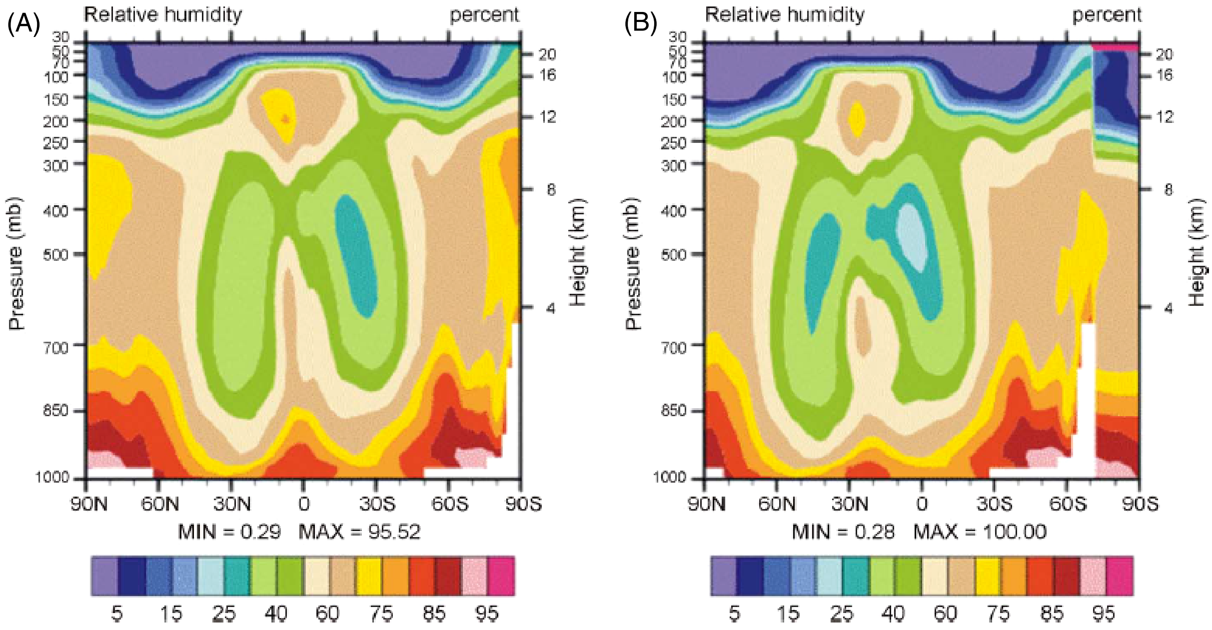

Figure 1. (A) Lower ice fall speed simulation in Mitchell *et al* (2008), showing relatively higher RH in the upper and middle troposphere. (B) Corresponding higher ice fall speed simulation from Mitchell *et al* (2008). A plotting offset error occurred (∼18°) in extreme right side of image.

3. Evidence from GCM studies

Some insight into the theoretical plausibility of this geoengineering idea can be obtained from GCM studies investigating the influence of homogeneous and heterogeneous ice nucleation on climate. Such a study was conducted by Lohmann *et al* (2008) using the ECHAM5 GCM, which contains a two-moment cloud microphysics and two-moment aerosol microphysics scheme, and thus can form cirrus either by homogeneous or heterogeneous freezing. Homogeneous freezing was permitted on soluble/mixed Aitken, accumulation and coarse mode aerosol, while heterogeneous freezing nuclei were comprised of immersed mineral dust that froze at 30% S_i. A number of simulations were performed, including (1) homogeneous freezing only, where solution droplets (that limit homogeneous freezing) often exceeded 100 cm^{-3} at cirrus levels; (2) heterogeneous freezing of mineral dust (∼0.02–0.2 cm^{-3} at cirrus levels) when S_i exceeds 30%; (3) both homogeneous and heterogeneous freezing are allowed such that only heterogeneous freezing occurs when the immersion dust nuclei concentration exceeds 1 l^{-1}, and homogeneous freezing occurs otherwise. This was justified since both nucleation mechanisms seldom occur simultaneously. Henceforth these three simulations will be referred to as E5-homo, E5-het and E5-homhet, respectively.

This version of ECHAM5 included improved ice microphysics, with a more realistic treatment of ice particle fall velocities that depend on ice crystal shape and mass, with quasi-spherical 'droxtals' assumed at small sizes and columnar crystals otherwise. Relating the ice particle size and mass to the fall velocity, as done here, is critical for exploring this geoengineering idea.

Some results from this study are shown above in figure 2, showing annual zonal means for the cirrus PSD effective radius r_e, cirrus cloud coverage, and shortwave and longwave cloud forcing for each of the ECHAM5 simulations mentioned above along with observational data. Ice crystal concentrations (not shown) in E5-homo were 50% greater on average relative to E5-het and E5-homhet, resulting in a global annual mean r_e of 29.7 μm for E5-homo and a corresponding r_e of 32.7 and 33.0 μm for E5-het and E5-homhet, respectively. As expected, the heterogeneous ice nuclei in simulations E5-het and E5-homhet, activating at lower S_i, produce larger ice crystals with higher fall velocities, resulting in less cloud coverage. The shortwave cloud forcing for E5-homo is only slightly stronger than E5-het and E5-homhet, while the longwave cloud forcing is significantly greater for E5-homo than E5-het or E5-homhet. This derives from the fact that cirrus coverage and IWP were decreased for the coldest cirrus in E5-het and E5-homhet. The global annual means for shortwave and longwave cloud forcing were reduced in E5-het and E5-homhet by 2.7 W m^{-2} and 4.7 W m^{-2}, respectively, relative to E5-homo, giving a net global cirrus cloud forcing of 2.0 W m^{-2}, with the OLR increase exceeding the cloud reflectance decrease by 2.0 W m^{-2}. While not reported in Lohmann *et al* (2008), the global mean change in net TOA radiation for the het–homo and homhet–homo comparisons was −2.8 W m^{-2} and −2.5 W m^{-2}, respectively, with the additional cooling due to a change in the clear-sky fluxes (resulting from a decrease in RH in the het and homhet simulations) (Lohmann 2009). These results suggest that the above geoengineering strategy could be effective for slowing the rate of global warming since the forcing due to a doubling of atmospheric $\mathrm{CO_2}$ is estimated to be 3.71 W m^{-2} (Lenton and Vaughan 2009).

If the Lohmann *et al* (2008) study predicts a net global cooling of ∼2.7 W m^{-2} from increasing ice particle sizes by only 11%, where S_i for heterogeneous freezing is 30%, it would be interesting to determine what change in ice crystal

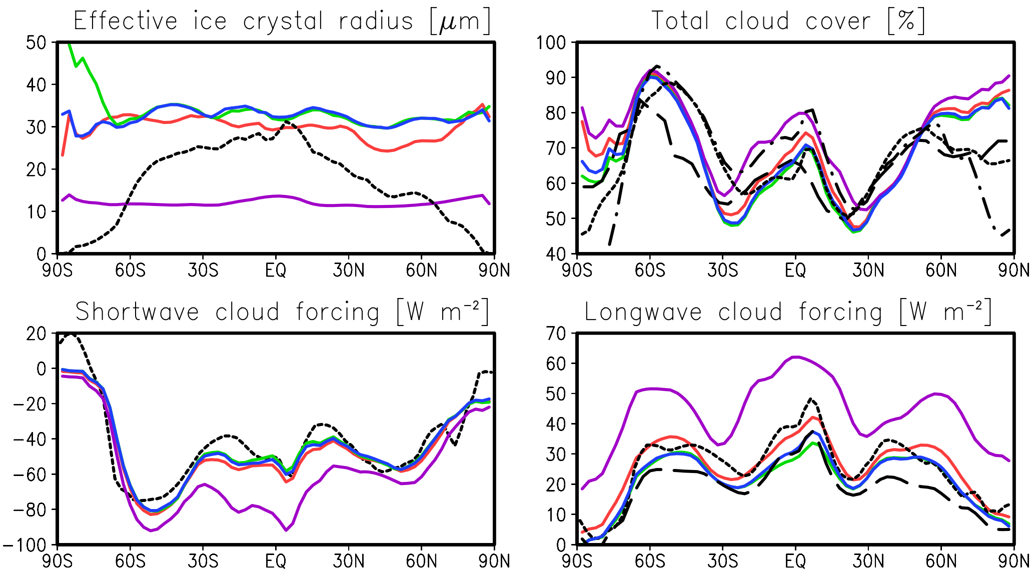

Figure 2. Annual zonal means for ECHAM5 simulations E5-homo (red), E5-het (green), E5-homhet (blue), and for water vapor accommodation coefficient = 0.006 (purple). Black dashed curves show observational data. As indicated, the zonal means show the cirrus PSD effective radius (μm), total cirrus cloud cover (%), and shortwave and longwave cloud forcing (W m^{-2}). From Lohmann *et al* (2008).

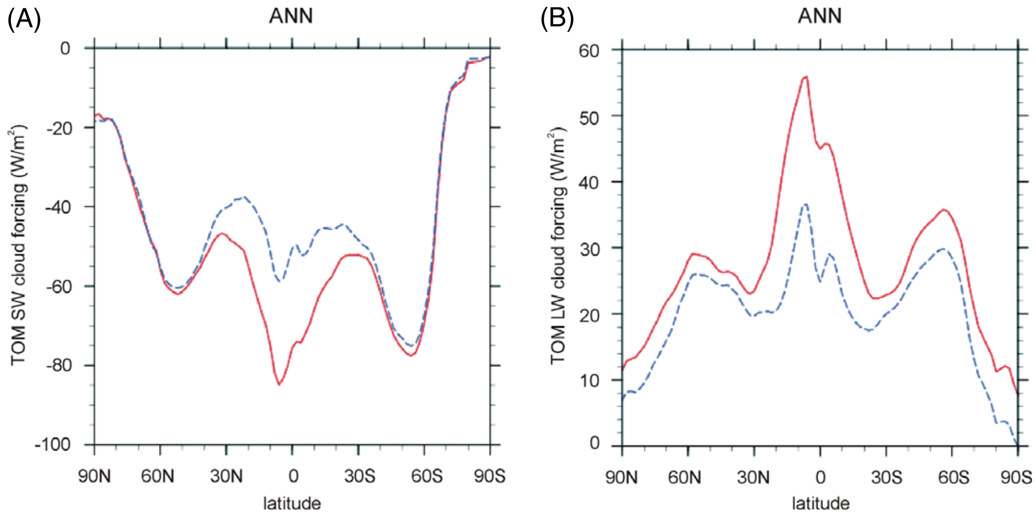

Figure 3. (A) Annual zonal mean shortwave cloud forcing in the higher ice fall speed (blue dashed) and lower ice fall speed (red solid) CAM3 simulations. (B) Same but for longwave cloud forcing. From Mitchell *et al* (2008). TOM = top of model atmosphere.

size is likely for very efficient heterogeneous ice nuclei, where $S_i \approx 1$–5%. Clearly a larger size increase should produce a larger increase in fall velocity and a larger decrease in cloud cover and a larger net cooling.

Supporting results were obtained in Mitchell *et al* (2008), where the ice particle mass, area, and the PSD were related to the ice fall speed and optical properties in the Community Atmosphere Model version 3 (CAM3). The fall speed representing the PSD mass flux was altered by changing the relative concentrations of small ice crystals, with one CAM3 simulation having lower fall speeds than the other simulation. The higher fall speed simulation had 5.5% less cirrus cloud coverage. As shown in figure 3, the shortwave cloud forcing in the midlatitude and polar regions was almost unchanged since low clouds dominate shortwave cloud forcing there, but the longwave cloud forcing difference was appreciable since it depends mostly on high clouds. These simulations suggest cirrus seeding may be most effective in the polar and midlatitude regions where global warming is more severe.

It should be noted that for the two simulations in Mitchell *et al* (2008), the difference in the ice fall speed is manifested primarily for temperatures <−45 °C. This is the region most targeted in this geoengineering scheme, and is the region where the greenhouse effect of cirrus clouds is most powerful.

4. Advantages and drawbacks

A review of possible geoengineering approaches is given in Lenton and Vaughan (2009), and of the many listed, only two, stratospheric injection of sulfate aerosols and mechanical seeding of marine stratus clouds, seemed capable of fully neutralizing the radiative forcing due to a doubling of CO_2. The exploratory investigation described here indicates that cirrus cloud seeding is also having the potential to fully neutralize the radiative forcing from a CO_2 doubling. In addition, this approach could be relatively inexpensive if a method were developed to disperse the seeding material from commercial aircraft and the commercial airline industries were willing partners. The details of what would be the ideal ambient concentration of seeding material and how much seeding material would be needed to realize this concentration have not yet been worked out.

As described under section 1, recent GCM studies suggest that cirrus clouds and upper tropospheric water vapor represent the component of the climate system that most strongly affects the prediction of climate sensitivity. Thus it seems logical to target this component in a geoengineering strategy. Moreover, greenhouse gases trap OLR, and cirrus affect OLR more than all other cloud types (Chen *et al* 2000, Hartmann *et al* 1992). In this way this strategy directly addresses the radiation imbalance due to greenhouse gases.

The most studied geoengineering option, stratospheric injection of sulfate aerosols, has some drawbacks, such as (1) increasing the rates of stratospheric ozone destruction, (2) higher costs of injecting sulfur compounds into the stratosphere, (3) decreased solar radiation possibly altering the hydrological cycle with more frequent droughts (Trenberth and Dai 2007), (4) change in sky color from blue to white and (5) less solar power. In addition, modeling studies indicate it would take at least 3 years for the climate system to return to 'normal' upon termination of this geoengineering. The cirrus seeding option does not appear to suffer from these drawbacks, although slightly more solar radiation would reach the surface with less cirrus cloud coverage. Less cirrus coverage would also lower atmospheric heating rates at temperatures $<-40\,^\circ$C, which could increase deep convection and precipitation. Since the residence time of cloud seeding aerosols is on the order of 1–2 weeks, the cirrus seeding option could easily be terminated if unanticipated environmental problems arose from this practice. None of the 'albedo' geoengineering options address the problem of ocean acidification due to elevated CO_2 concentrations, and this is true for the cirrus seeding option as well.

Instead of seeding cirrus throughout the world, an alternate option is to seed cirrus mostly over the polar regions and midlatitudes, since these are the regions most affected by global warming. The density of airline flight corridors is highest over these regions and least dense over the tropics, so a seeding strategy based on commercial airline flights might naturally favor this prioritization. Such a strategy might affect OLR in these regions by a greater percentage than the tropics. One potential drawback or advantage to this approach, depending on how you look at it, would be a possible increase in the temperature gradient between the polar and tropical air masses. This intensification of the global temperature gradients should lead to stronger jet streams with greater baroclinicity, with stronger and more frequent storms along the storm track (Wallace and Hobbs 1977). In a warmer climate, the jet streams might shift polewards and midlatitude weather systems might become weaker (Yin 2005, Bengtsson *et al* 2006). If correct, this geoengineering strategy might counteract this to some degree and alleviate global warming induced drought in some regions. On the other hand, an intensified storm track could increase cloud cover at all levels, and the complex implications of such a proposal would need to be investigated through GCM studies.

One potential drawback is the seeding material itself; it must be non-toxic and not too expensive. As noted, there do appear to be substances available that meet these criteria. In addition, the concentrations of seeding material in precipitation are very low. Cloud seeding studies using AgI show that the levels of AgI in seeded snowfall are generally less than 10 ppt, which does not pose any risk to human health (Super 1986, Warburton *et al* 1995).

Another geoengineering idea targeting cirrus clouds has been proposed by Cotton (2009). That idea suggests increasing the amount of soot in the upper troposphere to increase temperatures there to reduce cirrus coverage through sublimation. The solar radiation absorbed by soot would decrease temperatures at the surface, and the reduced cirrus coverage would allow more OLR to escape. However, the higher temperatures produced by soot may not change the RH (Held and Soden 2000), making the fate of cirrus less certain. Details describing the efficacy of this approach have not yet been released.

Perhaps the greatest drawback to this and any other geoengineering option is that it may divert political will and resources away from mitigation strategies designed to reduce the levels of greenhouse gases. It is argued that it would be a mistake to view geoengineering as a remedy for global warming since if the level of greenhouse gases are not reduced, the non-engineered climate will become increasingly hostile to human life on Earth. Mankind would become increasingly dependent on geoengineering, which can only neutralize greenhouse gas warming for a limited amount of time before increasing greenhouse gas levels overwhelm the radiative forcing due to geoengineering. At that 'moment of truth' a planetary climate holocaust would result. Therefore, geoengineering should be viewed as a means to 'buy time' for the implementation of 'green' energy technologies and to allow greenhouse gas mitigation strategies time to work. At the same time, climate catastrophes that might otherwise occur might be avoided.

5. Next steps?

More detailed modeling studies of cirrus microphysics, testing some of the physical principles and assumptions used here, as well as related laboratory studies, should be carried out. For example, in cirrus generated from mesoscale motions, their microphysical properties appear to be governed by the dynamics (Kärcher and Ström 2003). Modeling studies could be conducted to examine how significant the negative Twomey effect is in these cirrus. Another uncertainty is the ice sedimentation rate, a key factor determining how strong an effect this climate engineering approach is likely to have. The rate of increase in the ice particle fall velocity with respect to particle size, $\mathrm{d}V/\mathrm{d}D$ where D = ice particle maximum dimension, decreases with increasing D. Hence this approach will be most effective for narrow PSD where the relative change in size after seeding is large. *In situ* measurements indicate such PSD are common when $T < -40\,^{\circ}\mathrm{C}$, but these measurements may be contaminated by larger ice particles shattering at the inlet of the measurement probe, producing many small artifact ice fragments that are counted as natural ice crystals. This problem of ice particle shattering has cast a cloud of uncertainty over *in situ* PSD measurements and needs to be resolved to obtain reliable estimates of ice sedimentation rates, which depend strongly on the concentrations of small ice crystals (Mitchell *et al* 2008).

Drawing from these process-oriented studies, GCM experiments could be designed to test this hypothesis. Since the parameterized physics differs considerably between GCMs, climate predictions differ as well, making it important to test this hypothesis in more than one GCM. In all GCM experiments, ice particle size, mass and projected area must be represented as accurately as possible for reliable fall speed estimates, and the cirrus microphysics should be coupled with the cirrus optical properties (Mitchell *et al* 2008, Baran 2009).

Field experiments could also be designed to test certain aspects of the hypothesis, such as the impact of efficient ice nuclei on the microphysics of cold cirrus wave clouds (i.e. upwind seeding of only one section of cloud and comparing the microphysics of seeded and unseeded sections). Such field studies could benefit from complementary satellite and ground based remote sensing studies, as considerable microphysical information can now be obtained through remote sensing. If such studies supported the hypothesis, the idea could be implemented by injecting cloud seeding material into the exhaust of commercial airliners that normally fly in this temperature regime (without involving the jet engines themselves).

6. Recapitulation

Recent GCM studies (Sanderson *et al* 2008, Mitchell *et al* 2008) suggest that climate sensitivity is very sensitive to upper tropospheric cloud cover and humidity, making cirrus clouds a logical candidate for climate modification efforts. Cirrus clouds also affect OLR more than other cloud types, with their modification directly addressing the radiation imbalance imposed by greenhouse gases. Due to the expected dominance of homogeneous freezing nucleation at temperatures below $-40\,^{\circ}\mathrm{C}$, it may be possible to decrease cirrus cloud coverage by introducing efficient heterogeneous ice nuclei at these temperatures where the cirrus greenhouse effect is strongest. Due to vapor competition effects, this may result in larger ice crystals with higher fall velocities, which should decrease cirrus coverage and increase OLR, thus cooling surface temperatures. While there may be an initial increase in cirrus coverage due to ice supersaturation in clear skies, over time the increase in net downward transport of water substance (due to higher ice fall speeds) should reduce the relative humidity and cirrus coverage of the upper troposphere. Based on one GCM study, it appears that seeding cirrus clouds on a global scale could cool the planet by well more than 2.8 W m^{-2}, perhaps enough to cancel the radiative forcing due to a doubling of CO_2 (3.7 W m^{-2}). The distribution of seeding material could be done relatively inexpensively through the airline industry. Seeding along conventional flight corridors should increase OLR preferentially over the northern high latitudes where global warming is most severe. But this may also slightly intensify the global temperature gradients, the jet streams and the frequency and strength of frontal systems. Studies employing a variety of GCMs might be needed to understand the feedbacks involved. On the other hand, this geoengineering option does not have many of the drawbacks that the most studied geoengineering option has, that option being the stratospheric injection of sulfur compounds.

Acknowledgments

This research was sponsored by the Office of Science (BER), US Dept of Energy, Grant No. DE-FG02-06ER64201. We are grateful to Ulrike Lohmann for granting us permission to use figures from her 2008 ERL letter. Comments from Ulrike Lohmann, Peter Spichtinger and the other reviewer are much appreciated, as well as comments from Alan Robock and Phil Rasch. Credit for this work rightfully belongs to the community of investigators that developed the science on which this stands; the authors merely ‘connected the dots’.

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