IOP Publishing Environmental Research Letters

Environ. Res. Lett. **4** (2009) 045112 (8pp) doi:10.1088/1748-9326/4/4/045112

Geoengineering by cloud seeding: influence on sea ice and climate system

Philip J Rasch[1], **John Latham**[2,3] **and Chih-Chieh (Jack) Chen**[2]

[1] Pacific Northwest National Laboratory, 902 Battelle Boulevard, PO Box 999, MSIN K9-34,
Richland, WA 99352, USA
[2] National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80303, USA
[3] SEAES, University of Manchester, PO Box 88, Manchester, M60 1QD, UK

Received 10 August 2009
Accepted for publication 20 November 2009
Published 18 December 2009
Online at stacks.iop.org/ERL/4/045112

Abstract

General circulation model computations using a fully coupled ocean–atmosphere model indicate that increasing cloud reflectivity by seeding maritime boundary layer clouds with particles made from seawater may compensate for some of the effects on climate of increasing greenhouse gas concentrations. The chosen seeding strategy (one of many possible scenarios) can restore global averages of temperature, precipitation and sea ice to present day values, but not simultaneously. The response varies nonlinearly with the extent of seeding, and geoengineering generates local changes to important climatic features. The global tradeoffs of restoring ice cover, and cooling the planet, must be assessed alongside the local changes to climate features.

Keywords: geo-engineering, climate change, global warming, cloud seeding, aerosol indirect effect

S Supplementary data are available from stacks.iop.org/ERL/4/045112/mmedia

1. Introduction

There is increasing concern today that the emissions of radiatively important greenhouse gases (GHGs) are changing our climate [1], and that the formidable energy system transformation needed to avoid the risk of dangerous climate change is proceeding very slowly. A variety of ideas have been proposed to compensate for the effects of increasing greenhouse gases on our planet under the theme of ‘geoengineering’ or ‘climate intervention’. One class of these ideas is based upon methods designed to slightly reduce the amount of sunlight reaching the Earth’s surface, thereby cooling the planet to compensate for the warming from increased concentration of GHGs. The increase in planetary albedo will not compensate for all the consequences of increasing GHGs (e.g. ocean acidification), so geoengineering can thus be viewed as a means to provide some additional time while society finds the means to stabilize CO_2 concentrations through other mitigation activities [2].

Latham [3, 4] suggested that the planetary albedo might be increased by changing the albedo of maritime boundary layer clouds by seeding them with aerosol produced from seawater. The aerosol particles would have a size designed to make them very efficient cloud condensation nuclei (CCN). These CCN are activated on entry to clouds, thereby increasing the cloud drop number concentration (henceforth CDNC), with a corresponding reduction in mean droplet size, thus increasing the albedo [6] and possibly the longevity and areal extent [7] of the clouds.

Studies cited here, and in [4], indicate that increasing the reflectivity of clouds is in principle capable of producing short-wave negative forcing of up to about -4 W m^{-2}, a value roughly adequate to balance the positive forcing associated with a doubling of present atmospheric CO_2 concentrations. There are a number of technological [5] and scientific questions [4] that have to be resolved before it is clear whether significant negative forcing is achievable. Recent independent field studies involving satellite measurements [8–10] and instrumented aircraft [11] suggest that increasing CDNC in boundary layer maritime clouds produces an increase of cloud albedo reasonably consistent with our computations. While it is implicitly assumed in our model that adding CCN to the clouds will always brighten them according to the Twomey equation, the changes predicted in albedo and lifetime may be modified by other processes that counteract the influence of increases to CCN [12–19]. These numerical simulations of marine stratocumulus and trade wind cumulus clouds revealed some situations where nonlinear dynamical responses to increasing CCN actually decreased cloud liquid water content and either decreased or did not change the albedo. It is clearly critical to our geoengineering strategy that these nonlinear interactions be understood, quantified, and verified and their relative importance compared to the Twomey effect be assessed. A better understanding of cloud microphysics and dynamics is required before we will know under what circumstances increasing the CCN number will indeed increase the planetary albedo. This understanding will be achieved eventually through a combination of fieldwork and improvements to our theoretical understanding and modelling of clouds.

In spite of these uncertainties, it is of interest to explore the response of the climate system to deliberate changes in the CDNC. The climate system is expected to cool locally, and this will induce changes in circulation features, and through feedbacks, in many other components of the climate system. Our earlier general circulation model (GCM) computations characterized the forcing associated with changing the clouds using models with fixed sea surface temperatures that strongly constrained responses in the climate system. Fully coupled ocean–atmosphere models are required to explore responses in sea ice extent and thickness, and in ocean circulation, and also in circulation features where feedbacks are important. To our knowledge, only one other study [20] has explored the climate response to cloud seeding geoengineering in a fully coupled model. It used a different seeding strategy and scenarios producing much weaker forcings that are insufficient to compensate for the warming associated with a doubling of CO_2, focusing primarily on the precipitation response. The focus here is principally on the influence that much stronger forcings produce on sea ice extent, although we also discuss other circulation features and precipitation. The geoengineering forcing, which is primarily local to areas where seeding takes place (midlatitudes and equatorial regions), can also produce a strong mitigation of Arctic warming through non-local effects (see also [21–23]).

2. Model description

We use a modified version of the Community Climate System Model (CCSM, [24] that includes a prognostic cloud water parameterization [25, 26] predicting condensate mass and number for ice and liquid species, and revisions to the convection scheme [27, 28]). The atmospheric model uses a finite volume numerical technique and is run at 1.9° × 2.5° horizontal resolution with 26 layers extending from the surface to 35 km. We chose this version over standard releases in order to allow a more reasonable and internally consistent characterization of 'aerosol indirect effects' (that is, how the cloud microphysical, precipitation and radiative properties change with changes in cloud drop number due to the geoengineering) than the standard CCSM3 configuration. The ocean model is quite similar to CCSM3 [24], except: (1) the shear dependent (Smagorinsky) horizontal viscosity terms have been eliminated, leading to improvements in, e.g. reduced sea ice cover in the Labrador and Bering Seas, and stronger tropical instability wave activity, both in better agreement with observations [29]; and (2) the near-surface eddy flux parameterization has been modified by eliminating the tapering of the mixing coefficients near the surface [30], removing a spurious near-surface eddy-induced circulation and improving heat transport. This version of the CCSM uses the CICE model as described in [33].

The control climate is quite similar to that described in the citations of the previous paragraph. The model has quite a strong El Niño/Southern oscillation (ENSO) signature, with signals much as described in [28]. It has a lower sensitivity in sea ice response to climate change than CCSM3, which was among the more sensitive of the IPCC AR4 models to anthropogenic forcing, and among the more realistic of all the IPCC models in simulating the recent changes in sea ice extent, as indicated in [31]. The experimental model has a smaller sea ice response to CO_2 warming than CCSM3—more like the 50% of the models in IPCC AR4 that do not reach ice free summer conditions after CO_2 concentrations double [32]. This version of the coupled model is very new, with much less analysis and tuning employed than the production versions of CCSM, but the model climate is quite reasonable, and we believe the signals revealed in this study will be robust across model versions. To highlight these signals we have chosen a somewhat easier path than used with models trying to reproduce historical changes in climate through anthropogenic forcings by changes in aerosol emissions, greenhouse gases, and land use over the anthropocene era. Instead, we explore the model response to forcing changes by comparing simulations begun from a set of initial conditions nearly at equilibrium for a fixed (present day) CO_2 concentration (defined to be 355 ppmv) but run with forcing changes from doubling concentrations (to 710 ppmv) compared to our control, in combination with various amounts of cloud seeding using a strategy discussed below. We have analysed at least two independent realizations of each model configuration to confirm that the features that we discuss below are robust, and compare the cases by averaging fields between years 81 and 100 of each simulation. The changed forcing operates over a sufficiently long period (80 years) that significant changes have occurred to mean fields, and averaging over a 20 year time period reduces much of the variability associated with higher frequency natural events such as ENSO.

Our CONTROL simulation is run from the spun up initial conditions for 100 years, with the cloud drop number freely calculated using the algorithms described in the references above. Case $2 \times CO_2$ doubles the CO_2 mixing ratio. The geoengineering cases also assume a $2 \times CO_2$ gas concentration and perfect control of the CDNC for all clouds within a prescribed fraction of the open ocean and pressures between 850 and 1000 hPa (CDNC is set at 1000 cm^{-3} for all seeding simulations).

We use a seeding strategy defined in [4]. The susceptibility to cloud seeding is first determined for each ocean grid point for each month by comparing two 20 year model runs driven with prescribed, time varying ocean surface temperatures. The susceptibility for each ocean location is defined by how strongly the seeding at that location increases the amplitude of the short-wave cloud forcing (SWCF) at that location. The ‘seeding mask’ is defined as the model locations ranked most susceptible to a change in CDNC up to a fixed areal extent of the open ocean. For a given seeding scenario, identified by the total areal extent, the seeding mask varies monthly, but the extent is constant in time, and the seeded areas repeat annually. Coupled runs use the mask to define the regions to seed. We label our four geoengineering cases 20PCT, 30PCT, 40PCT, and 70PCT by the areal extent of the ocean surface that was seeded (20, 30, 40, and 70% respectively). Much of the higher latitude seeded areas occur in the summer hemisphere when the seeding mask is small, but with larger seeded extents many locations are seeded most of the year (see supplementary material (available at stacks.iop.org/ERL/4/045112/mmedia)). Other seeding strategies are possible (see, e.g. [20] and the discussion below), and different seeding strategies are likely to produce different model responses.

All model experiments use prescribed, seasonally varying distributions of sulfate, black and organic carbon and dust that do not change with case, so we do not account for changing emissions of anthropogenic aerosols and precursors on the climate. We have also ignored the direct aerosol forcing associated with the emission of the geoengineered particles. Our simulations thus attempt to compensate for the $2 \times CO_2$ forcing only with the geoengineered aerosol acting on clouds that are influenced by present day aerosol concentrations.

3. Computational results

While geoengineering has consequences to many components of the climate system, for brevity we restrict the discussion to the consequences of the seeding on polar ice cover (northern and southern), surface temperature and precipitation rate. Figures 1–3 display the response of the model system to combinations of doubled CO_2 forcing and geoengineering compared to present day (i.e. control) for cases $2\times CO_2$, 20PCT and 70PCT.

3.1. Global surface temperature (T_s)

Figure 1(a) displays the high latitude amplification of warming seen in most IPCC models from a doubling of CO_2. The globally averaged T_s is 1.8 K warmer than the control at this point in the simulation (the model would continue to warm for thousands of years if the simulations were extended). Cloud seeding produces significant cooling: case 20PCT (figure 1(b)) reduces the warming to 0.8 K, more than halving the temperature rise associated with the GHG forcing. Case 70PCT (figure 1(c)) overcools the planet. It is 0.4 K cooler than the control and 2.2 K cooler than the $2 \times CO_2$ model run at this point in the simulation. Both seeding schemes generate pronounced cooling along the central and eastern Pacific in regions where the seeding strategy operates full time, and where the surface temperature would be cooler than present day. The cooler waters follow primary ocean circulation features and suggest that attention must also be paid to the impact of geoengineering on the ocean. The cloud seeding increases the amplitude of the globally averaged SWCF by about -2.5 W m^{-2} and -3.9 W m^{-2} for the 20PCT and 70PCT cases respectively.

3.2. Polar sea ice cover

Our model shows (figure 2) a substantial decrease in minimum sea ice extent associated with the increased CO_2 forcing (by 20% compared to the control in the Northern Hemisphere (NH) during September and 36% in the Southern Hemisphere (SH) during March over years 81–100). Case 40PCT changes the sea ice areal extent so that it is 9% smaller than the control in the NH and 8% smaller in the SH. The higher seeding level (Case 70PCT) has actually returned the minimal sea ice coverage to within 2% of its present day level in the NH and overcompensated for sea ice reductions produced by CO_2-doubling in the SH, where the ice occupies a larger areal extent (+20%) compared to the present day. Seeding is more effective in the southern hemisphere because those clouds are more susceptible to brightening [4]. It is very important to note, however, that the sea ice distributions for each of the geoengineering simulations differ in spatial distributions from the control, even though the geoengineering has strongly influenced the total sea ice extent.

3.3. Global precipitation rate (p)

Figure 3 shows the change in annually averaged precipitation rate for the three seeding scenarios. This particular geoengineering strategy results in reductions in precipitation along the equator between the eastern Pacific and the maritime subcontinent. This change is consistent with the precipitation reduction resulting from increasing aerosols reported in [34]. There is an enhancement in precipitation for all cases in the South Pacific convergence zone (SPCZ). We note that [20] showed a strong decrease in annual precipitation over north-eastern South America. Our results do not show a similar signature. In fact the precipitation increases by 0–1 mm day^{-1} in this region, which has an annually averaged precipitation rate of 2–6 mm day^{-1}, highlighting the uncertainties in predicting regional climate features, or the sensitivity of the conclusions to particular seeding strategies.

3.4. Compensation for changes caused by CO_2-doubling

Figure 4 shows changes in globally averaged surface temperature, precipitation rate and polar ice cover resulting from seeding in the presence of a $2 \times CO_2$ forcing compared to the present day climate. The figure normalizes the difference between a geoengineering experiment and the control run by the difference between cases $2 \times CO_2$ and control to portray the impact as the fraction of the change introduced by the greenhouse gas forcing (when the geoengineering strategy is completely ineffective the measure will be ‘1’; if it operates to return the mean climate to present day values it will be ‘0’). The precipitation responds most strongly to the geoengineering using this seeding strategy, of the fields examined here, and NH sea ice responds least strongly to the geoengineering. An approximately 20% seeding mask

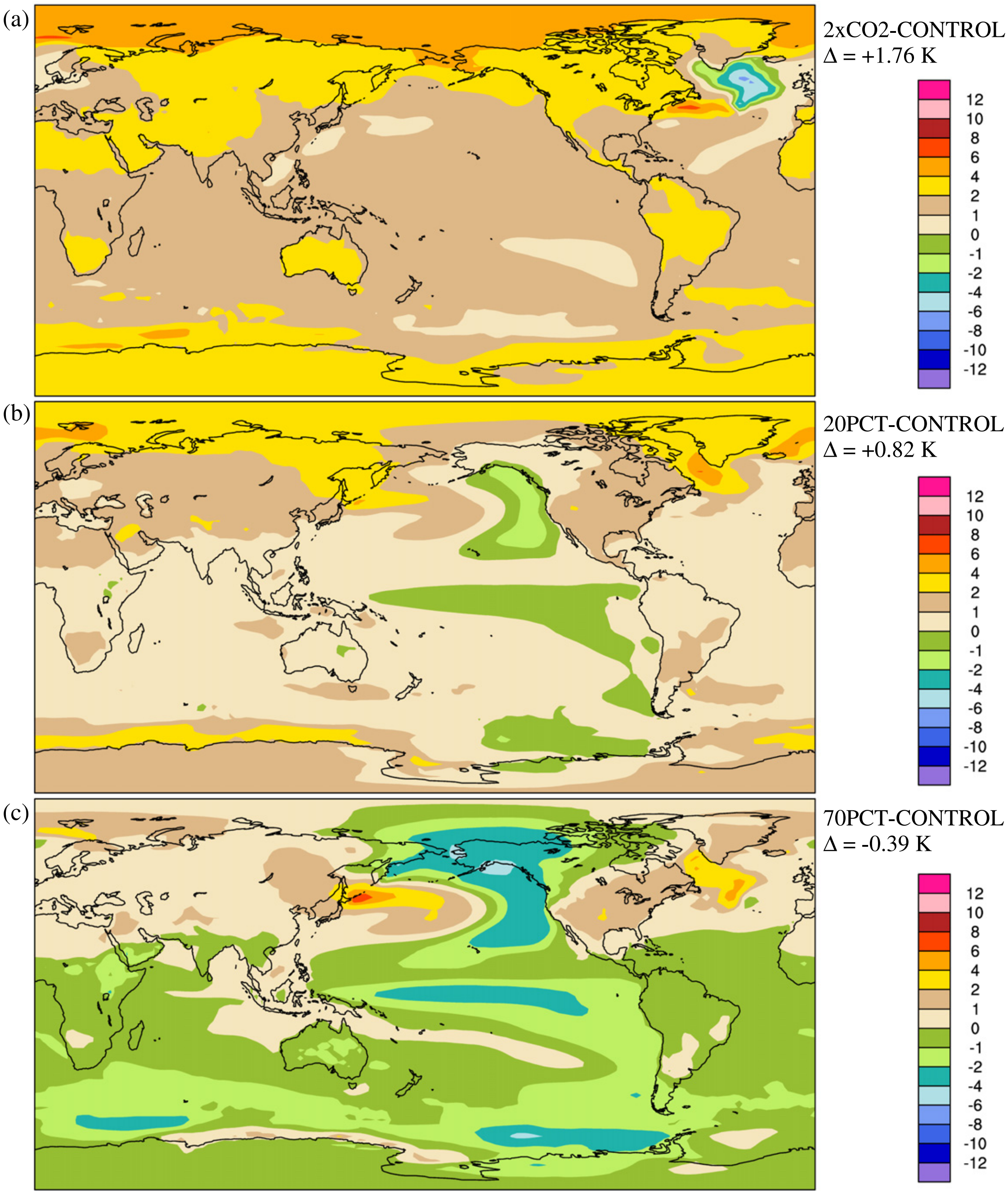

Figure 1. Global surface temperature (K) distributions showing departures from the current condition (CONTROL): (a) case 2 × CO_2, (b) case 20PCT, and (c) case 70PCT.

is required to restore the annual precipitation to its current condition. A much larger areal extent must be seeded to maintain polar sea ice (more than 60% for NH and 40% for SH) at its present state. The surface temperature response is intermediate to the other fields. Our seeding strategy is unable to compensate uniformly for the effect of CO_2 doubling in terms of correcting surface temperature, precipitation, and sea ice coverage simultaneously.

4. Discussion

Our computations suggest that this geoengineering method could help in compensating for some consequences of global warming (presuming that the outstanding technological and scientific issues outlined earlier, and discussed more fully in [4], are satisfactorily resolved and provide consistent support for the results presented here) by stabilizing the Earth's average temperature and polar ice coverage for some considerable time.

Our study highlights the difficulty in compensating uniformly for all the changes resulting from increasing greenhouse gas concentrations. Returning the planet to approximately the present day global average surface temperature using this geoengineering method, and this particular seeding strategy, would not result in a simultaneous return to present day global average precipitation, or sea ice

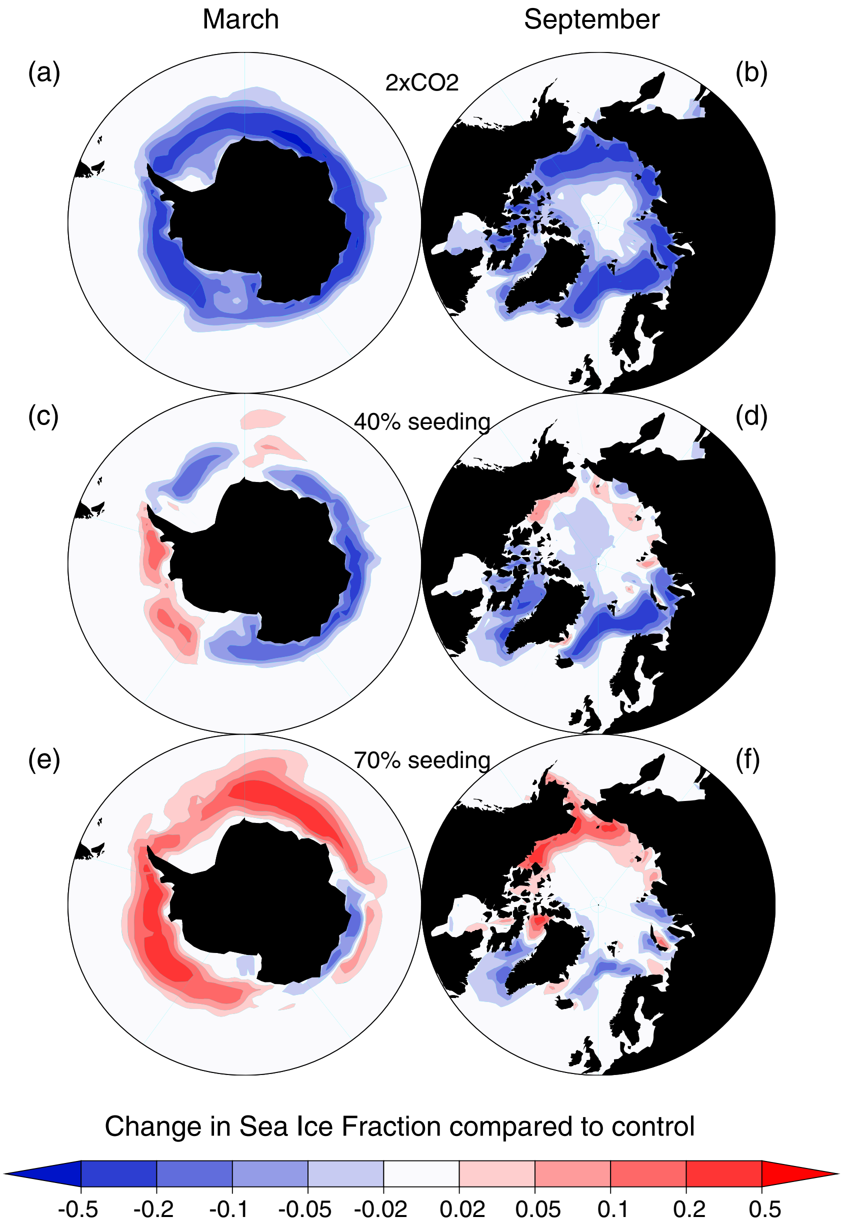

Figure 2. Polar sea ice coverage distribution showing departures from the current condition (CONTROL): (a) case 2 × CO_2 (SH in March), (b) case 2 × CO_2 (NH in September), (c) case 40PCT (SH in March), (d) case 40PCT (NH in September), (e) case 70PCT (SH in March), and (f) case 70PCT (NH in September).

extent in our model—or potentially for other fields important to climate and society. In addition, of course, maintaining the globally averaged value of a field-fixed value does not prevent the occurrence of significant local departures. (e.g. the precipitation departures seen above).

Other seeding strategies are possible that may produce other responses. Jones *et al* [20] used a related, but different strategy for seeding boundary layer clouds and reported significantly different results from those presented here, particularly with respect to changes in precipitation amounts and geographical distribution. That study seeded areal extents ranging between 1 and 4% of the ocean surface whereas ours ranged between 20 and 70%. Additionally, in our geoengineering simulations the concentration of CO_2 was doubled and a solution in equilibrium was sought, whereas in their study a transient solution was presented since the CO_2 concentration followed the A1B scenario from [36]. They found a very strong response to their seeding strategy in Amazon precipitation and our study showed almost no sensitivity in that region (indeed the change in precipitation there had the opposite sign and was much weaker). The differences highlight the need for a more systematic exploration of seeding strategies, and an assessment of models to identify differences in forcing and response, and the reasons for those differences.

The final design of a geoengineering strategy should be dictated by cost, and consequence (physical and societal) to the planet. It is therefore of crucial importance to examine, as rigorously and comprehensively as possible, all the possible ramifications of the possible adoption of the technique.

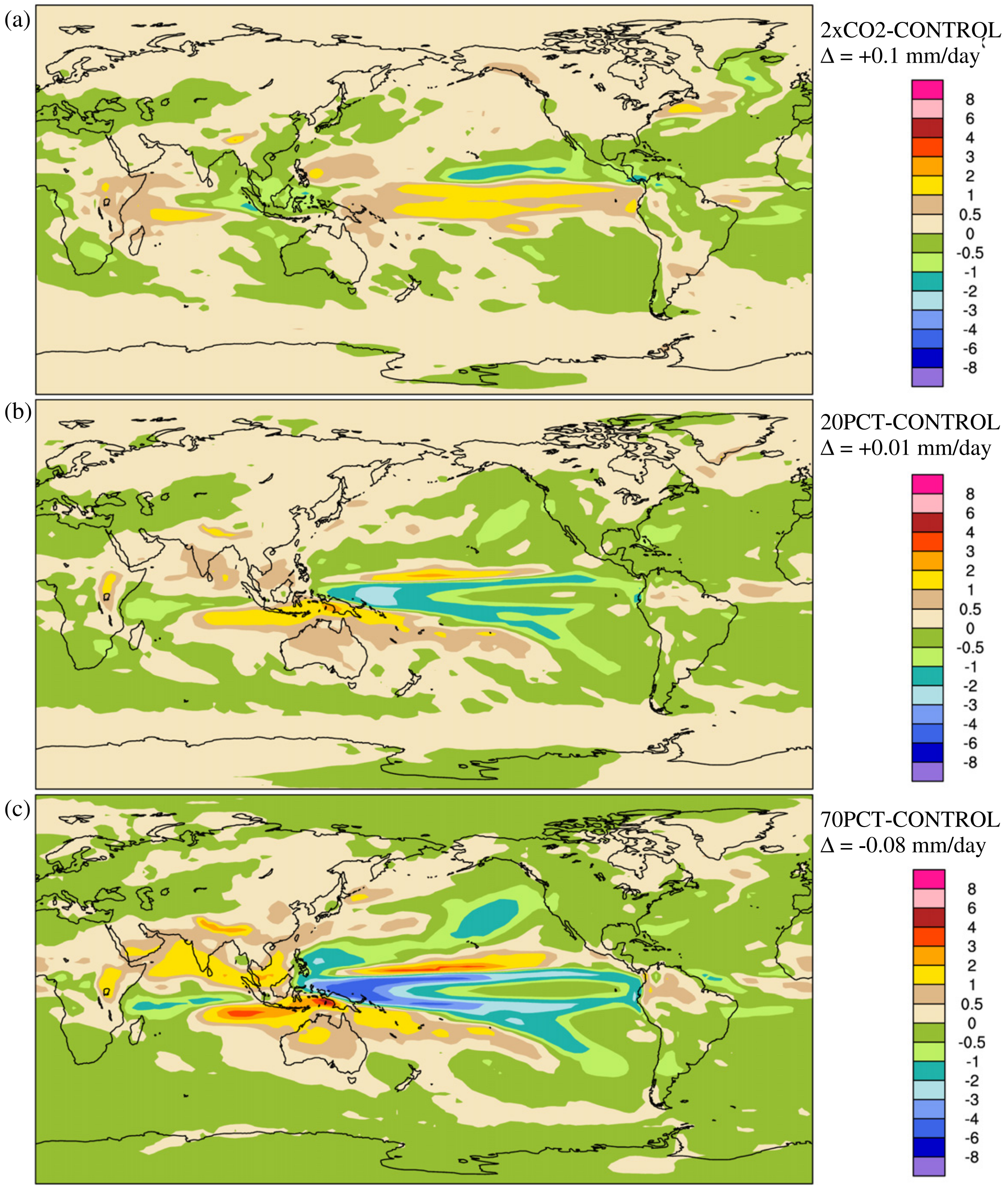

Figure 3. Global annual precipitation rate (mm day^{-1}) distributions showing departures from the current condition (CONTROL): (a) case $2 \times CO_2$, (b) case 20PCT, and (c) case 70PCT.

Some useful flexibility exists which might prove helpful in reducing adverse changes from existing patterns to acceptable levels. As this study demonstrates, it is not necessary to seed all suitable clouds in order to have a very significant impact in compensating for impacts from CO_2 forcing. Assuming sufficient understanding, it is feasible, in principle, to modify the selection of regions, time of year, and amount of seeding to change the geographical and temporal distribution of negative forcing. In some circumstances, it may also prove possible to obtain beneficial results from much more limited-area seeding e.g. it may help with coral reef preservation, hurricane emasculation or restoration or maintenance of polar ice cover. It may also prove desirable to deploy it in conjunction with other techniques, such as stratospheric aerosol geoengineering [35]. One might envisage the latter as contributing the primary global cooling and the former providing localized, and hopefully quantitatively controlled, cooling to optimize or rectify the conditions obtaining in small and important regions. This idea requires much more examination.

The computations presented in this paper are principally focused on trying to establish the extent to which our cloud albedo enhancement scheme could compensate for the effects of doubling the atmospheric CO_2 concentration from present day values. It may take several decades to achieve this $2 \times CO_2$ situation. Prior to that point, the amount of seeding required

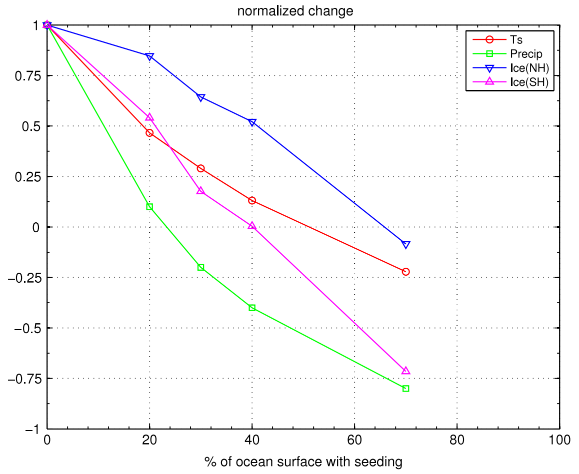

Figure 4. Globally averaged annual response in surface temperature, precipitation rate, and sea ice coverage for years 81–100 resulting from different seeding schemes normalized by the change associated with 2 × CO_2.

for global temperature stabilization would be less, and one element of our seeding strategy would be to optimize the geoengineering to balance the GHG forcing. In the early part of this period it seems likely that the much reduced level of seeding—compared with that at $2 \times CO_2$—would yield smaller departures from existing global distributions.

Particular objectives for our GCM work in the near future are to: (1) conduct more comprehensive studies of the issues examined herein; (2) study the effects of seeding on the values and distributions of other fields; (3) examine the sensitivity of our results to changing seeding strategies, as discussed earlier; (4) make particularly detailed studies of the ramifications (especially adverse ones) of the possible adoption of this geoengineering strategy. In parallel with these endeavours we will engage in LES modelling studies of marine stratocumulus clouds, in an effort to derive further understanding of the conditions under which they will and will not experience significant albedo increase when seeded with seawater CCN. At the same time, we will conduct studies of CCN concentration/cloud droplet number/cloud albedo relationships, based on examination of data from the recent international VOCALS experiment: and commence planning and preparation for a limited-area field experiment in which we will seek to determine the extent to which cloud-albedo-enhancement of natural marine boundary layer clouds can result from seeding with seawater aerosol.

Acknowledgments

PJR was supported by NCAR/NSF and PNNL for this work. JL was supported by NCAR/NSF. C-CC and JL were supported by grants from the U Calgary. Simulations were performed at NCAR and on the NSF Teragrid computing system via grant TG-ATM090009. We thank Cecilia Bitz for her comments on the manuscript, and advice/insight into the sea ice and ocean component of the simulations.

Author contributions. All authors contributed equally to this work. PJR designed the model simulations and much of the analysis strategy, and wrote a first draft of the manuscript. JL asked hard questions, analysed model output, and contributed to the manuscript. C-CC designed the 'cloud mask strategy' outlined in the model description section, made all model simulations and figures, and contributed to the manuscript.

References

[1] Solomon S, Qin D, Manning M, Chen Z, Marquis M, Avery K, Tignor M and Miller H (ed) 2007 Summary for policymakers *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the 4th Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press) pp 1–18

[2] Wigley T M L 2006 A combined mitigation/geoengineering approach to climate stabilization *Science* **314** 452–4

[3] Latham J 1990 Control of global warming? *Nature* **347** 339–40

[4] Latham J, Rasch P J, Chen C-C, Kettles L, Gadian A, Gettelman A, Morrison H, Bower K and Choularton T W 2008 Global temperature stabilization via controlled albedo enhancement of low-level maritime clouds *Phil. Trans. R. Soc.* A **366** 3969–87

[5] Salter S, Sortino G and Latham J 2008 Sea-going hardware for the cloud albedo method of reversing global warming *Phil. Trans. R. Soc.* A **366** 2989–4006

[6] Twomey S 1977 Influence of pollution on the short-wave albedo of clouds *J. Atmos. Sci.* **34** 1149–52

[7] Albrecht B A 1989 Aerosols, cloud microphysics and fractional cloudiness *Science* **245** 1227–30

[8] Platnick S and Oreopoulos L 2008 Radiative susceptibility of cloudy atmospheres to droplet number perturbations: 1. Theoretical analysis and examples from MODIS *J. Geophys. Res.* **113** D14S20

[9] Oreopoulos L and Platnick S 2008 Radiative susceptibility of cloudy atmospheres to droplet number perturbations: 2. Global analysis from MODIS *J. Geophys. Res.* **113** D14S21

[10] Quaas J and Feichter J 2008 Climate change mitigation by seeding marine boundary layer clouds *Consequences of Geo-Engineering and Mitigation as Strategies for Responding to Anthropogenic Greenhouse Gas Emissions at the EGU General Assembly (Vienna, April 2008)* Poster paper

[11] Ramanathan V, Cess R, Harrison E, Minnis P, Barkstrom B, Ahmad E and Hartmann D 1989 Cloud-radiative forcing and climate: results from the earth radiation budget experiment *Science* **243** 57–63

[12] Ackerman A S, Toon O B and Hobbs P V 1993 Dissipation of marine stratiform clouds and collapse of the marine boundary layer due to the depletion of cloud condensation nuclei by clouds *Science* **262** 226–9

[13] Ackerman A S, Kirkpatrick M P, Stevens D E and Toon O B 2004 The impact of humidity above stratiform clouds on indirect aerosol climate forcing *Nature* **432** 1014–7

[14] Wang S, Wang Q and Feingold G 2003 Turbulence, condensation, and liquid water transport in numerically simulated nonprecipitating stratocumulus clouds *J. Atmos. Sci.* **60** 262–78

[15] Xue H and Feingold G 2006 Large-eddy simulations of trade wind cumuli: investigation of aerosol indirect effects *J. Atmos. Sci.* **63** 1605–22

[16] Jiang H, Xue H, Teller A, Feingold G and Levin Z 2006 Aerosol effects on the lifetime of shallow cumulus *Geophys. Res. Lett.* **33** L14806

[17] Wood R 2007 Cancellation of aerosol indirect effects in marine stratocumulus through cloud thinning *J. Atmos. Sci.* **64** 2657–69

[18] Guo H J, Penner E, Herzon M and Pawlowska H 2007 Examination of the aerosol indirect effect under contrasting

environments during the ACE-2 experiment *Atmos. Chem. Phys.* **7** 535–48
[19] Zuidema P, Xue H and Feingold G 2008 Shortwave radiative impacts from aerosol effects on marine shallow cumuli *J. Atmos. Sci.* **65** 1979–90
[20] Jones A, Haywood J and Boucher O 2009 Climate impacts of geoengineering marine stratocumulus clouds *J. Geophys. Res.* **114** D10106
[21] Shindell D 2007 Local and remote contributions to arctic warming *Geophys. Res. Lett.* **34** L14704
[22] Levy H II, Schwarzkopf M D, Horowitz L, Ramaswamy V and Findell K L 2008 Strong sensitivity of late 21st century climate to projected changes in short-lived air pollutants *J. Geophys. Res.* **113** D06102
[23] Koch D, Menon S, Del Genio A, Ruedy R, Aleinov I and Schmidt G A 2009 Distinguishing aerosol impacts on climate over the past century *J. Clim.* **22** 2659–77
[24] Collins W D *et al* 2006 The community climate system model version 3 (CCSM3) *J. Clim.* **19** 2122–43
[25] Morrison H and Gettelman A 2008 A new two-moment bulk stratiform cloud microphysics scheme in the community atmosphere model, version 3 (CAM3). Part I: description and numerical tests *J. Clim.* **21** 3642–59
[26] Gettelman A, Morrison H and Ghan S J 2008 A new two-moment bulk stratiform cloud microphysics scheme in the community atmospheric model (CAM3), Part II: single-column and global results *J. Clim.* **21** 3660–79
[27] Richter J H and Rasch P J 2008 Effects of convective momentum transport on the atmospheric circulation in the community atmosphere model, version 3 *J. Clim.* **21** 1487–99
[28] Neale R B, Richter J H and Jochum M 2008 The impact of convection on ENSO: from a delayed oscillator to a series of events *J. Clim.* **21** 5904–24
[29] Jochum M, Danabasoglu G, Holland M, Kwon Y-O and Large W G 2008 Ocean viscosity and climate *J. Geophys. Res* **113** C06017
[30] Danabasoglu G, Ferrari R and McWilliams J C 2008 Sensitivity of an ocean general circulation model to a parameterization of near-surface eddy fluxes *J. Clim.* **21** 1192–208
[31] Holland M M, Bitz C M and Tremblay B 2006 Future abrupt reductions in the Summer Arctic sea ice *Geophys. Res. Lett.* **33** L23503
[32] Serreze M C, Holland M M and Stroeve J 2007 Perspectives on the Arctic's shrinking sea-ice cover *Science* **315** 1533–6
[33] Hunke E C and Lipscomb W H 2008 CICE: the Los Alamos sea ice model *Documentation and Software User's Manual Version 4.0* LoLA-CC-06-012 T-3 Fluid Dynamics Group, Los Alamos National Laboratory, Los Alamos, NM 87545
[34] Liepert B G, Feichter J, Lohmann U and Roeckner E 2004 Can aerosols spin down the water cycle in a warmer and moister world? *Geophys. Res. Lett.* **31** L06207
[35] Rasch P J, Tilmes S, Turco R, Robock A, Oman L, Chen C C and Stenchikov G 2008 A review of stratospheric sulfate aerosols for geoengineering *Phil. Trans. R. Soc.* **366** 4007–37
[36] Nakicenovic N *et al* 2000 *IPCC Special Report on Emission Scenarios* (Cambridge: Cambridge University Press)