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Uncertainty in the sensitivity of Arctic sea ice to global warming in a perturbed parameter climate model ensemble

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[1] The retreat of Arctic sea ice is a very likely consequence of climate change and part of a key feedback process, which can accelerate global warming. The uncertainty in predictions in the rate of sea ice retreat requires quantification and ultimately reduction via observational constraints. Here we analyse a climate model ensemble with perturbations to parameters in the atmosphere model. We find a large range of the sensitivity of Arctic sea-ice retreat to global temperature change, from 11 to 18% per °C. This is placed in the context of the uncertainty obtained by alternative model ensembles. Reasons for the different sensitivities are explored and we find that differences in the amount of ocean and atmospheric heat transported from low to high latitudes dominates over local radiative contributions to the heat budget. Furthermore, we find no significant relationship between the uncertainty in sea ice response to climate change and climate sensitivity.

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1. Introduction

[2] Satellite records show a decreasing linear trend in Arctic sea ice extent since the late 1970s at a mean rate of about 0.3 × 10^6 km^2 per decade [*Cavalieri et al.*, 2003; *Stroeve et al.*, 2005]. This corresponds to a loss of 8% in the annual mean area covered between 1980 and 2005. Submarine observations and model derived sea ice analyses also indicate a thinning, by as much as 40%, of the Northern Hemisphere (NH) ice pack over the period 1966–1996 [*Rothrock et al.*, 2003]. Warmer atmospheric temperatures driven by anthropogenic greenhouse gas emissions are now considered the main contender to explain these recent changes [*Vinnikov et al.*, 1999; *Houghton et al.*, 2001; *Johannessen et al.*, 2004].

[3] Comparisons of observed and AOGCM (atmosphere-ocean coupled global climate model) simulated sea ice extent and thickness show a wide range of capability of these models [*Flato*, 2004; *Arzel et al.*, 2006]. The errors in the simulation of the recent past are found to be related to both the manner in which sea-ice processes are represented in the models (e.g. the inclusion or neglect of sea-ice motion) and to differences in the ocean and atmosphere components of the climate model, which determine the forcing that is locally applied to the ice components. There is also a large range in the simulated sea-ice response to future increases in atmospheric CO_2, again with no obvious stratification in terms of model attributes.

[4] It has been shown previously that the Arctic sea ice area in one of the AOGCMs, HadCM3, decreases linearly as global-average temperature rises [*Gregory et al.*, 2002]. Here, we extend previous work by examining the uncertainty in sea ice response using climate model ensembles. Here, the ‘Arctic’ is defined as the ocean region north of latitude 70°N, and the sea ice area is the integrated ice concentration across the Arctic region.

2. Method

[5] We consider a number of AOGCM simulations forced with the same scenario of increasing atmospheric greenhouse gas concentration. Atmospheric CO_2 concentrations increase at 1% per annum compounded until they reach four times pre-industrial levels (140 simulated years). Parallel control simulations with pre-industrial CO_2 concentrations are used to evaluate and remove linear climate drifts from the 1% per annum results. In all cases the drifts are found to be small. The fractional change in sea ice cover per degree rise in temperature, or “sea ice temperature sensitivity” (SITS), is evaluated for each climate change simulation by fitting linear trends to the drift corrected change in sea ice area with global temperature (Figure 1).

[6] The focus of our study is a 17-member “perturbed atmospheric physics” ensemble of the Hadley Centre climate model, HadCM3. For each ensemble member, multiple parameters in the atmospheric and surface components of the model are varied within specified ranges, and the atmosphere is coupled to the standard dynamical ocean component. Flux adjustments are employed, both to reduce regional sea surface temperature (SST) and salinity biases and also to allow the use of combinations of model parameter values which give non-zero values for the top of atmosphere radiation balance. This improves the extent to which the ensemble provides a credible basis for the quantification of uncertainties in climate change, especially at a regional level. Our implementation is a refined version of *Collins et al.* [2006]. Simulations are produced which are of comparable quality to the unperturbed and un-flux-adjusted version of HadCM3 [*Gordon et al.*, 2000]. This new ensemble perturbs different combinations of parameters in order to span a credible range of climate sensitivity. In what follows we refer to this as the “atmosphere ensemble”. One member of this ensemble has the same parameter settings as standard HadCM3 [*Gordon et al.*, 2000] and will be referred to as the “unperturbed member”.

[7] Our mechanistic results will focus on the “atmospheric ensemble” but to place the uncertainty ranges in SITS into context we will compare them with a limited set of

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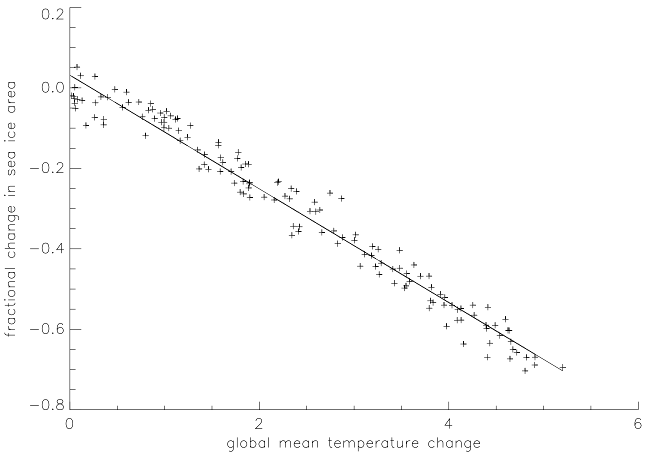

Figure 1. The straight line fits to the annual mean global temperature rise (°C), up to 4 × CO2, and change in Arctic sea ice area for the unperturbed HadCM3 simulation in the atmosphere ensemble. The baseline is a 100 year mean of the pre-industrial control. The gradient and error (2 standard deviations) is $-0.145 \pm 0.008°C^{-1}$.

results from two other climate model ensembles. The set of models with suitable diagnostics from the AR4 analysis provides an ensemble of opportunity comprising models of different structural design. Data and documentation for the 24 models of the AR4 are available through the Program for Climate Diagnosis and Intercomparison website (http://www-pcmdi.llnl.gov/). Only 8 models provide sea ice data among the 1% to 4 × CO2 simulations. A small (7 member) HadCM3 ensemble in which ocean parameters are perturbed provides a further ensemble. In this ensemble a handful of key ocean parameters are perturbed independently: the diffusivity of tracers along isopycnal surfaces, the calculation of the depth profile of wind-mixing energy in the ocean mixed-layer, and the vertical diffusivity of tracers. This ensemble also has an unperturbed member [*Collins et al.*, 2007].

3. Results

[8] The total spread in sea ice temperature sensitivities within the atmosphere ensemble members is from 11 to 18% per °C. In all cases the correlation coefficient for the linear fit between global temperature and sea ice area is greater than 0.96. In order to investigate whether these differences are outside the range due to natural variability, we examine multiple simulations of a single model version each with different (and largely independent) initial conditions obtained by starting the 1% per annum simulation from different times in the control simulation. The standard deviation of SITS from these simulations is quadratically combined with the uncertainty in the linear fit to give a total initial condition uncertainty of 0.33% per °C. Thus, the ensemble range in the SITS is primarily associated with the parameter changes rather than natural variability.

[9] The AR4 ensemble exhibits a SITS range from 4% per °C to 15% per °C whilst the ocean ensemble SITS cover a range from 15 to 22% per °C. Thus, while there is a significant degree of overlap, no ensemble alone can capture the full spread (Figure 2). The atmosphere and ocean ensembles both have members that are significantly more sensitive, measured in terms of SITS, than the AR4 ensemble. We do not establish here if one ensemble is more realistic than the others, except to note that in the ocean ensemble there tended to be less ice in the control simulation than in the atmosphere ensemble or in observations of pre industrial sea ice extent [*Rayner et al.*, 2003].

4. Discussion

[10] In addition to characterising the spread of the sensitivity in simulated sea ice to warming, the perturbed parameter atmospheric ensemble provides an opportunity to understand what controls this uncertainty. Combined with improved use of observational constraints this may eventually lead to the uncertainty in SITS being reduced. For pragmatic reasons, notably the availability of suitable model diagnostics and the size of the ensembles, our mechanistic study focuses on the atmospheric ensemble.

[11] Before proceeding we examine whether different experimental designs can alter SITS by comparing results from the unperturbed versions of the atmospheric and ocean ensembles with the HadCM3 result in the AR4 ensemble. The non-flux adjusted HadCM3, which forms part of the AR4 ensemble, has a SITS of 11.7% per °C rise in global mean temperature. The unperturbed member of the atmosphere ensemble, which differs from the AR4 ensemble member in terms of the interactive sulphur cycle and use of flux correction, has a larger SITS of 14.5% per °C. The equivalent unperturbed ocean ensemble member, which is not flux-adjusted but like the atmosphere ensemble does have an interactive sulphur cycle, has a SITS of 16.5% per °C. Clearly, these results differ by more than we would expect from natural variability alone, indicating that both structural uncertainties (in this case the presence or absence of a sulphur cycle model) and the use of flux corrections can both significantly affect the SITS values. The inclusion of the sulphur cycle creates a different top of the atmosphere balance to that when not present. This in turn means that the surface radiation is different and hence surface temperatures. The flux adjustments, which are applied only in ice free regions, are held constant throughout the 1% simulations. However, each ensemble member has a different flux adjustment which produces different initial conditions for the 1% simulations. The different initial conditions contribute to the spread in SITS in the atmo-

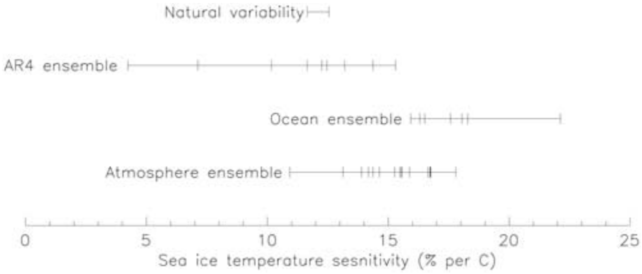

Figure 2. The spread of sea ice temperature sensitivity in each of the 3 AOGCM ensembles. Vertical dashes indicate the value for each ensemble member, with the natural variability estimate for a single member shown at the top.

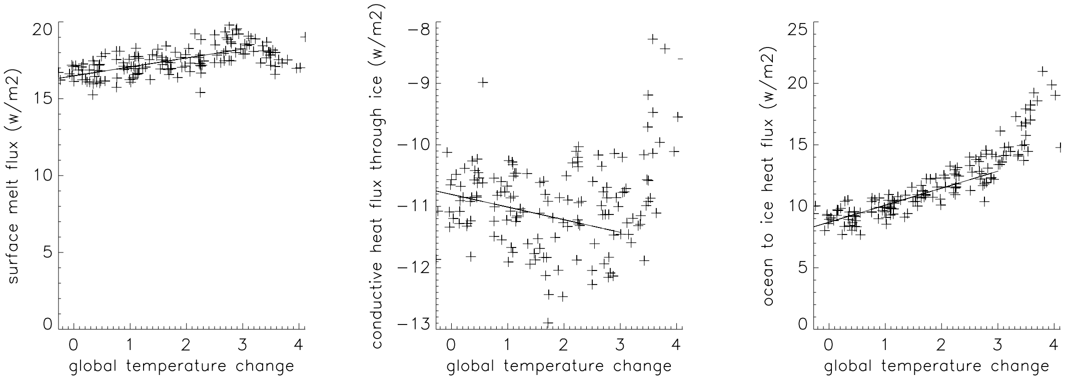

Figure 3. Example of the change in annual mean heat fluxes, averaged over the entire Arctic Ocean, influencing ice melt in one member of the HadCM3 atmosphere ensemble throughout the 1% scenario up to 4 × CO2. The baseline is a 100 year mean of the pre-industrial control. (left) The heat flux resulting in surface melt always causes a loss of ice. (middle) The conductive heat flux through the ice, from atmosphere to ocean, causes ice growth. (right) The turbulent heat from the ocean to the ice results in ice melt.

sphere and ocean ensembles. The correlation between the flux adjustments (both for the Arctic region and globally) and SITS is significant at the 20% level. This should be taken into account in designing future model intercomparisons.

[12] To understand what controls the spread of SITS in the atmospheric ensemble we first search for links between the perturbed parameters in the atmosphere ensemble and the magnitude of SITS, but no clear pattern is evident. This is not surprising since 29 parameters are varied simultaneously in the 17 ensemble members, making a direct mapping of parameters onto response difficult.

[13] Next we study the link between the value of SITS and the equilibrium climate sensitivity of the models (T_{2x}). Theoretically, a link might be expected because the climate sensitivity provides a global measure of the strength of climate feedbacks, including the ice-albedo feedback [*Hall*, 2004]. The correlation coefficient across the atmospheric ensemble of T_{2x} and SITS was found to be 0.44 which is not significant at the 20% confidence level. This finding is consistent with the ice –albedo feedback being weaker than the sum of the other temperature feedbacks [*Soden and Held*, 2006] and implying the combined uncertainties in global average water vapour, lapse rate and cloud feedbacks do not tend to greatly affect the spread in SITS.

[14] Finally, we examine the spread in local and regional heat budget changes across the atmospheric ensemble. Looking in detail at the local budget in a randomly chosen ensemble member we find that although the direct radiative terms (Figure 3) causing summer melting and winter freezing of the ice dominate the heat budget, they change slowly with warming compared with the flux of heat from the ocean to the ice. The larger rate of change in the ocean-to-ice heat flux suggests that the ocean plays the dominant role in sea ice decline, and the associated oceanic warming may be attributed to either an increase in ocean and atmospheric heat transport into the high latitude region or local radiative changes affecting the sea ice by first changing the water temperature. Figure 4 shows the spread across the ensemble in the three heat flux terms, normalised by the global mean surface warming, and the correlation coefficients between the normalised heat flux changes and SITS. This confirms our conclusion from the single member shown in Figure 3, that the ocean-to-ice heating term is locally most important. However in many cases the conductive heat through the ice is also significant. The spread in the change of the surface melting term is small and this remains the least important term across the ensemble.

[15] The large-scale heat budget is evaluated to indicate whether the local ocean heat content changes, which ultimately drives the sea ice changes, results from large-scale ocean and atmospheric transport from lower latitudes or whether it is due to local radiative changes warming the high latitude directly. The annual area mean oceanic ($\sim$10 W/m^2) and atmospheric ($\sim$110 W/m^2) heat convergence into the central Arctic are calculated along with the mean top of atmosphere net downward radiative flux. The

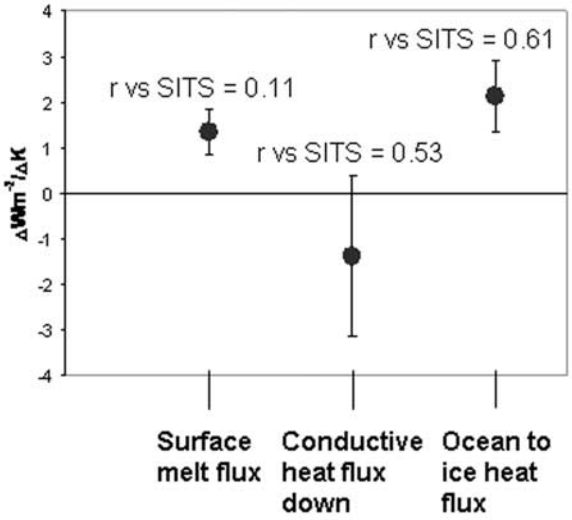

Figure 4. The change with global temperature of the annual mean heat fluxes contributing to the heat budget of the Arctic sea ice. The error bars mark the 2 sigma range across the ‘atmosphere ensemble’. The numbers are the cross-ensemble correlation coefficients of the heat fluxes with SITS.

atmospheric heat transport is inferred from the difference between top and bottom of atmosphere net downwards fluxes, a method that assumes that annual mean heat storage in the atmosphere is constant. The largest term in the atmospheric heat content is the thermal heat [*Peixoto and Oort*, 1992], and this shows an increase of 5% by the end of the simulations, equivalent to a heat flux into the atmosphere of only 0.03 W/m2, justifying our method. We correlate the total (ocean plus atmosphere) heat flux changes from lower latitudes with SITS across all members of the ensemble and find that the variance in the change in the total heat flux (normalised to temperature) can explain 76% of the variance in SITS across the atmosphere ensemble. The correlation is significant at 5% level. We do not correlate atmosphere or ocean separately with SITS because the changes in atmospheric and oceanic heat transport are not independent.

[16] An unexpected aspect of the sea ice behaviour is also highlighted by Figure 3, which shows the projected increase in surface melt with increasing temperature and an increase in basal freezing due to thinner ice conducting more oceanic heat to the atmosphere in winter. All three local fluxes change linearly up to a global temperature rise of ~3°C, at which point the Arctic first becomes ice free in summer, and behave non-linearly with further warming. What is notable is that the annual average ice area continues to change linearly (Figure 1) with temperature, with no sizable change in gradient after the loss of summer ice right through to the loss, in some ensemble members, of winter ice.

5. Conclusions

[17] We report on the spread in the sensitivity of Arctic sea ice area to increasing temperatures (SITS) across a "perturbed (atmospheric) parameter ensemble". The spread in this metric between model realisations of global climate change represents the uncertainty in the high latitude climate response and across the ensemble is much larger than expected from natural variability alone.

[18] A comparison of the atmospheric ensemble spread with that from other ensembles shows that although there is some overlap no single ensemble can explain the full uncertainty. Of the three ensembles analysed the largest spread is in the AR4 ensemble, indicating that model structural differences dominate the uncertainty budget. However, the perturbed parameter atmosphere and ocean ensembles both have members that are significantly more sensitive than any member of the AR4 ensemble.

[19] An analysis of the processes causing ice melt in the atmospheric ensemble reveals that the increase in local ocean temperature is the dominate component, with local longwave forcing being the second most important term. A study of the large-scale regional energy budget suggests that much of the extra heat associated with ice melting comes from heat transported into the region from mid-latitudes, rather than local radiative forcing. No strong relationship between SITS and climate sensitivity is evident in the results.

[20] This study suggests that reducing uncertainty in the high latitude sea ice response in climate models might benefit significantly from a narrowing of the uncertainty in the heat transport to high latitudes. However, since we also demonstrate the dependence of the results on the details of the experimental design this conclusion might not apply to other climate model ensembles. Future work will attempt to apply observational constraints to these model ensembles.

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