The role of sea ice in 2xCO2 climate model sensitivity: Part II: Hemispheric dependencies

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ABSTRACT. How sensitive are doubled CO_2 simulations to GCM control-run sea ice thickness and extent? This issue is examined in a series of 10 control-run simulations with different sea ice and corresponding doubled CO_2 simulations. Results show that with increased control-run sea ice coverage in the Southern Hemisphere, temperature sensitivity with climate change is enhanced, while there is little effect on temperature sensitivity of (reasonable) variations in control-run sea ice thickness. In the Northern Hemisphere the situation is reversed: sea ice thickness is the key parameter, while (reasonable) variations in control-run sea ice coverage are of less importance. In both cases, the quantity of sea ice that can be removed in the warmer climate is the determining factor. Overall, the Southern Hemisphere sea ice coverage change had a larger impact on global temperature, because Northern Hemisphere sea ice was sufficiently thick to limit its response to doubled CO_2, and sea ice changes generally occurred at higher latitudes, reducing the sea ice-albedo feedback. In both these experiments and earlier ones in which sea ice was not allowed to change, the model displayed a sensitivity of ~0.02°C global warming per percent change in Southern Hemisphere sea ice coverage.

Introduction

In a recent publication [*Rind et al.*, 1995] we explored the direct and indirect effects of sea ice in doubled CO_2 climate model sensitivity by running doubled CO_2 GCM simulations with and without sea ice change. The results showed that without a sea ice response, the temperature sensitivity of the model to a CO_2 doubling was reduced by 35-40%, indicating the importance of incorporating realistic sea ice formulations in climate models.

In that same publication, we utilized current climate control runs with thicker or more extensive sea ice. The results showed that the global average temperature response in an equilibrium doubled CO_2 simulation was greater if the control-run sea ice cover was either more extensive or thinner. In both cases, the sea ice - albedo feedback was enhanced in the corresponding doubled CO_2 simulations, as more sea ice was removed. With more extensive sea ice cover, there was a greater areal extent to remove as climate warmed, and with thinner sea ice, the ice was easier to remove.

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In an attempt to better understand how the distribution of sea ice in control run simulations affects the sensitivity of the modeled climate, a series of experiments was conducted with the Goddard Institute for Space Studies (GISS) General Circulation Model (GCM). The use of this model for doubled CO_2 experiments is described in detail in *Hansen et al.* [1984]; it includes a mixed layer ocean with specified heat transports and thermodynamic sea ice calculations. The results of the following sea ice sensitivity studies highlight some of the different sea ice characteristics which can influence global warming, including hemispheric differences; an additional characteristic, sea ice albedo, has been discussed by *Meehl and Washington* [1990].

Experiments

The characteristics of ten control and doubled CO_2 simulations are shown in Table 1. The runs were performed with a mixed layer "q-flux" ocean, in which ocean heat transports are prescribed so as to produce realistic modern day sea surface temperatures and sea ice. In these runs, the primary modification to the standard GISS model was to use remote sensing and in situ observations to better define proper sea ice coverage and sea ice thickness; as indicated in *Rind et al.* [1995, Figure 6], the specified heat transports were increased by ~10% globally to reduce control-run sea ice thicknesses in both hemispheres and produce more realistic distributions. It is this control run upon which the subsequent perturbations are performed.

Consistent with observations, the modeled sea ice now is thicker in the Northern Hemisphere, and relatively thin in the Southern Hemisphere. In the real world, sea ice in the two hemispheres has very different characteristics: Northern Hemisphere sea ice is often older (multiyear) and thicker, the result of minimal vertical ocean heat flux given strong ocean stability and continental influence. The Southern Ocean has marginal vertical stability, and as sea ice is formed, the

Table 1. Global Annual Average Results

Run	Current Climate			$2xCO_2$		Difference	
	Area (%)	Thick. (m)	Surf. Temp. (°C)	Area (%)	Thick. (m)	Area (%)	Surf. Temp. (°C)
1	2.5	0.44	13.55	0.60	0.24	-1.9	4.32
2	2.6	0.55	13.98	0.90	0.32	-1.7	4.21
3	2.6	0.78	13.94	1.20	0.56	-1.4	4.23
4	3.1	1.06	13.91	1.60	0.66	-1.5	4.32
5	3.1	1.21	13.60	1.60	0.79	-1.5	4.16
6	3.1	0.67	13.56	1.20	0.51	-1.9	4.38
7	3.2	1.03	13.87	1.60	0.62	-1.6	4.18
8	3.3	0.59	13.10	0.90	0.38	-2.4	4.52
9	3.6	1.75	13.37	2.10	0.97	-1.5	4.20
10	3.7	2.00	13.30	2.10	1.04	-1.6	4.51

Table 2. Global Average Relationships from the 10 Experiments

y	x	Linear Relationship	Correlation Coefficient
Control Sea Ice Coverage (%)	Control Surface Air Temp. (°C)	y=14.6 -0.85x	0.62*
Control Sea Ice Thickness (m)	Control Surface Air. Temp. (°C)	y=8.41 -0.54x	0.31
Control Sea Ice Thickness (m)	Control Sea Ice Coverage (%)	y=-2.19 +1.04x	0.82*
$2CO_2$ Surface Air Temp. (C)	Control Surface Air Temp. (°C)	y=8.33 -0.30x	0.67*
$\Delta 2CO_2$ Surface Air Temp. (°C)	Control Sea Ice Coverage (%)	y=3.94 +0.12x	0.36
$\Delta 2CO_2$ Surface Air Temp. (°C)	Control Sea Ice Thickness (m)	y=4.29 +0.01x	0.05
$\Delta 2CO_2$ Sea Ice Coverage (%)	Control Sea Ice Thickness (m)	y= -1.99 +0.29x	0.50**
$\Delta 2CO_2$ Sea Ice Coverage (%)	Control Sea Ice Coverage (%)	y= -1.74 +0x	0.00
$\Delta 2CO_2$ Sea Ice Coverage (%)	$\Delta 2CO_2$ Surface Air Temp. (°C)	y=4.62 -1.47x	0.65*
$\Delta 2CO_2$ Surface Air Temp. (°C)	$\Delta 2CO_2$ S.H. Sea Ice Coverage (%)	y=3.81 + 0.25x	0.68*
$\Delta 2CO_2$ Surface Air Temp. (°C)	$\Delta 2CO_2$ N.H. Sea Ice Coverage (%)	y=4.20 +0.07x	0.21
$\Delta 2CO_2$ Surface Air Temp. (°C)	$\Delta 2CO_2$ N.H. Surf. Air Temp. (°C)	y=0.75 +0.84x	0.75*
$\Delta 2CO_2$ Surface Air Temp. (°C)	$\Delta 2CO_2$ S.H. Surf. Air Temp. (°C)	y=1.42 +0.66x	0.93*
$\Delta 2CO_2$ Surface Air Temp. (°C)	S.H. Control Sea Ice Coverage (%)	y=0.48x +3.11	0.56**

*99% confidence level (F test)
**95% confidence level

extrusion of salt leads to entrainment of warmer thermohaline water, bringing up heat from below and hindering ice growth [*Martinson*, 1990]. This negative feedback, and the sea ice transport divergence away from the Antarctic continent and into warmer lower latitude waters, both contribute to a relatively thin Antarctic sea ice cover. A substantial seasonal ice cover nonetheless does grow each autumn/winter, assisted by the fresh water cap produced from sea ice melting, precipitation, and fresh water input from Antarctica. As a result sea ice in the Arctic tends to have longer lifetimes than sea ice in the Antarctic. In the model, these different hemispheric characteristics are preserved via the prescribed heat flux convergence in association with the modeled hemispheric difference in continentality.

To produce control runs with different sea ice characteristics, different heat transports were used. The altered transports were calculated by running preliminary simulations varying sea ice coverage by ±4% and ±8% relative to the concentrations in each hemisphere. When these transports were employed in their respective control runs, sea ice thicknesses varied by a factor of two. Between 60°N and Antarctica, the prescribed ocean heat flux convergences in the mixed layer at any latitude generally differed by ~$5 Wm^{-2}$ among the control runs (on the order of 20% of control run values); poleward of 60°N they differed by some 20 Wm^{-2} (100% variation). These are therefore the magnitude of poleward ocean heat flux changes which were required to produce the different sea ice distributions in the control runs.

Each experiment and doubled CO_2 simulation was run for 50 years; results shown are averaged over the last 10 years. As given in Table 1, the runs are numbered based on their global average sea ice coverage. The sea ice thickness variations in the control runs differ by a factor of five. Runs with colder temperatures tended to have greater sea ice coverage (correlation coefficient r=0.6) and thicker sea ice (r=0.3). Functional relationships and correlations between these and other variables are given in Table 2. The relatively low correlations result partly from the method of producing the sea ice differences. While reduced poleward ocean heat transports produced thicker and more extensive sea ice at high latitudes (correlation between sea ice thickness and extent of 0.8), tending to cool the climate, the extra heat available at low latitudes produced warmer sea surface temperatures, more evaporation and water vapor, with greater greenhouse capacity to warm the climate. Note that all the runs have a smaller doubled CO_2 temperature response than the "new sea ice run" in *Rind et al.* [1995] which closely matched the "best-guess" observed sea ice global coverage of 3.8% and 1.7m thickness, and produced a doubled CO_2 warming of 4.8°C.

Plots of zonally average control-run sea ice coverages and thicknesses (m) are shown in Figures 1a and 1b, respectively. Rainbow coloring is used to depict variations from the smallest sea ice coverage of run #1 (in red) to the largest sea ice coverage of run #10 (in blue). The five simulations with control-run average sea ice thickness less than 1.0 m are shown with dashed lines, and the runs of greater than 1.0 m thickness as solid lines. As appropriate, sea ice is much thicker in the Northern Hemisphere.

Doubled CO_2 Results

The doubled CO_2 results are included in Table 1. The global, annually averaged temperature sensitivity in the different experiments varied by up to 0.36°C, from a low of 4.16°C to a high of 4.52°C. Higher sensitivities generally occurred for runs with colder control-run temperatures (r=0.67; Table 2) and increased sea ice coverage (r=0.36). The global average relationship of doubled CO_2 temperature sensitivity with control-run sea ice thickness shows little correlation (r=0.05).

The latitudinal distributions of the surface air temperature change are shown in Figure 2a, using the same color/line coding as in Figure 1. In the Southern Hemisphere the surface air temperature increases are greatest for the control runs which had the largest sea ice coverage (blue lines). In the Northern Hemisphere the changes are greatest when the control run had thinner sea ice (dashed lines). To explain this result we show the sea ice changes in Figure 2b. In the Southern Hemisphere, all control-run simulations have (reasonable) thicknesses which are thin enough so that the controlling factor concerning how much sea ice could be removed is how much areal coverage there is initially. Therefore with more sea ice in the control run (blue lines), there is more lost in the doubled CO_2 run. In the Northern Hemisphere the (reasonable) ice concentrations in the ten control runs are all relatively similar, so the controlling factor in how much sea ice can be removed is how thick the ice is and therefore how easy it is to remove it. Hence more sea ice is lost when the control run sea ice is thinner (dashed lines). Overall, the global sea ice change is more related to the control-run sea ice thickness (r=0.50) than to the control-run sea ice coverage (r=0.00). .

The change in sea ice coverage is largely responsible for

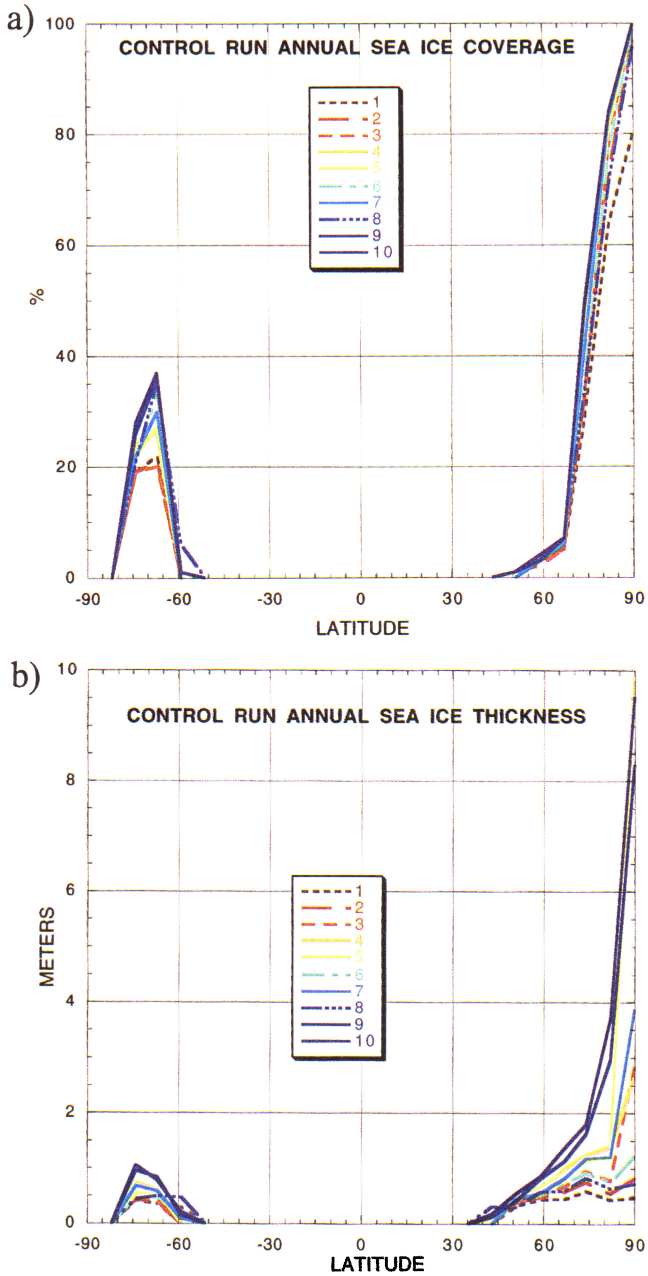

Figure 1. Control-run sea ice characteristics. Results are annual averages for the last 10 years of 50-year simulations: (a) percent (of land plus ocean area) sea ice coverage; (b) sea ice thickness.

determining the temperature sensitivity. In fact, the correlation of sea ice coverage decrease with temperature warming is 0.65, therefore representing 42% of the variance. This leads to an interesting combination in the global average results: as noted above, sea ice coverage change is primarily responsive to control-run sea ice *thickness*, and sea ice coverage change is a leading factor in determining the temperature change, yet the temperature change itself is much better related to control-run sea ice *coverage* (and not significantly to sea ice thickness). This apparent contradiction results from the respective parameter dependencies in the two hemispheres: in the model, global surface air temperature change is dominated by what happens in the Southern Hemisphere, while global sea ice coverage is equally influenced by both hemispheres. The global average surface air temperature change is more strongly influenced by changes in Southern Hemisphere sea ice, which shows larger decreases at lower latitudes, producing an enhanced albedo feedback; since Southern Hemisphere sea ice change depends primarily on the control-run sea ice coverage, so does the temperature response. Indicated in Table 2 is the relationship between the global temperature change and temperature changes in the two hemispheres; the Southern Hemisphere temperature change accounts for 86% of the variance in the global temperature change, while the Northern Hemisphere accounts for 56% (obviously the two hemispheric changes are also somewhat correlated: $r = 0.46$). The change in global sea

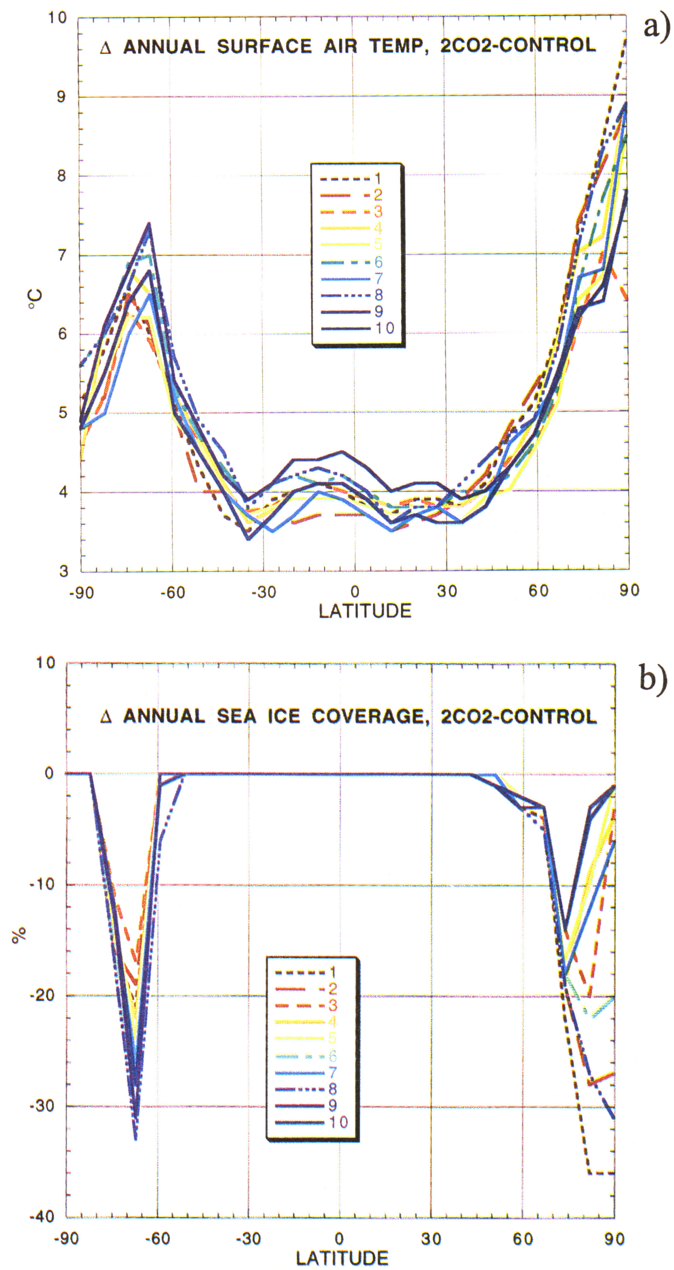

Figure 2. Annual changes due to doubled CO_2 with different control runs: (a) surface air temperature; (b) percent sea ice coverage.

ice coverage has nearly equal correlation with the change in each hemisphere (r= 0.72 with Northern Hemisphere sea ice change, r=0.77 with Southern Hemisphere sea ice change). These conflicting tendencies lower the correlations between global average changes and control-run parameters. A better correlation can be obtained between control-run sea ice coverage in the Southern Hemisphere and global temperature response (r=0.56, Table 2).

Since both control-run sea ice coverage and sea ice thickness can influence the subsequent surface air temperature change, a multivariate analysis can be used to investigate whether including both variables in any assessment significantly raises the percentage of explained variance. Using the results from Table 1, the following relationship arises: Δ global surface air temperature (°C) = 0.23 + 1.35 (control-run sea ice coverage in %) -0.06 (control-run sea ice thickness in meters). The linear multiple correlation, however, is not significantly changed (r=0.31) over the value for control-run sea ice coverage by itself. Again, the hemispheric differences prevent any stronger relationship between the global average changes.

Discussion and Conclusions

The results shown above suggest that given the current climate characteristics, temperature sensitivity to doubled CO_2 is affected more by sea ice coverage in the Southern Hemisphere and by sea ice thickness in the Northern Hemisphere. References discussing characteristics of climate model control runs, such as *IPCC* [1990], do not list the models' sea ice thickness in their validation review; yet ice thickness will obviously affect the climate sensitivity of the models. Future IPCC activities should include this parameter, for both "q-flux" and coupled atmosphere-ocean models.

Where sea ice is changed has a strong influence on the model sensitivity. In these experiments, the global surface air temperature change is more closely related to Southern Hemisphere sea ice coverage changes (r=0.68) than to Northern Hemisphere changes (r=0.21). Note in Figure 2b that the experiments differ in their sea ice coverage change primarily poleward of 75°N, where there is less sea ice-albedo influence. In addition, there was less change in Northern Hemisphere sea ice overall (1/3 of its ice, compared with 1/2 of the Southern Hemisphere ice). The Arctic ice is sufficiently thick that it can withstand significant warming without losing as much ice coverage. For these reasons, the sea ice differences in the Northern Hemisphere are less important for climate sensitivity in this model.

When sea ice was not allowed to change [*Rind et al.*, 1995], lower latitudes were affected, resulting in a greater impact on climate sensitivity, and reducing simulated global warming from 4.2°C to 2.8°C. This change of 1.4°C in warming was associated with a 60% change in Southern Hemisphere sea ice coverage, or ~0.02°C per percent Southern Hemisphere sea ice coverage loss. In the experiments discussed here, there was a 65±7% loss in Southern Hemisphere sea ice coverage, and a 4.3±0.13°C variation in global warming. Since the difference in Southern Hemisphere sea ice coverage loss among the experiments was relatively small, so was the range in warming; 0.13°C divided by 7% again equals ~0.02°C per percent Southern Hemisphere sea ice coverage loss. The results in this paper are thus perfectly consistent with the sensitivity derived previously.

Why was the percentage of Southern Hemisphere sea ice lost so similar with the different control runs? Is it a product of the altered q-fluxes which produced the differing control run concentrations, or is it some inherent stability of the system? This question can only be addressed in experiments using more complicated ocean and sea ice models, which will be performed as part of future papers in this series.

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