5.9 THE IMPACT OF CLOUD FEEDBACKS ON ARCTIC CLIMATE CHANGE FORCED BY INCREASED CO_2

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1. INTRODUCTION

Arctic clouds strongly influence the surface radiation budget, reducing wintertime cooling of the surface by 40-50 W m^{-2} and summertime heating of the surface by 20-30 W m^{-2} (Curry et al., 1996). The net effect of Arctic clouds during the course of the year is a warming of the surface, except for a period during summer, but the precise nature of the cloud radiative forcing is a complicated function of cloud fraction, height, thickness, and water content (Curry and Ebert, 1990; Walsh and Chapman, 1998). The presence or absence of clouds has a large impact on sea ice growth, as well as on the surface melting of snow and ice in Arctic regions (Maykut and Untersteiner, 1971; Curry and Ebert, 1990). Thus, it is reasonable to expect that changes in cloudiness could be important drivers of future greenhouse-forced climate change in the Arctic.

The regional impact of cloud changes caused by a 2 x CO_2 radiative perturbation is calculated using a global climate model. Similar studies have generally *inferred* the climatic impact of cloud changes by computing the difference in cloud radiative forcing (CRF), rather than by comparing the simulated 2 x CO_2 climate with and without prognostic cloud changes. Here the total climatic impact is determined by running two 2 x CO_2 experiments, one of which uses model-predicted cloud fraction and the other uses the three-dimensional cloud fraction from the control simulation.

2. DESCRIPTION OF MODELS AND SIMULATIONS

The climate model used in this study, GENESIS2, is a coupled atmosphere/mixed-layer GCM (Thompson and Pollard, 1997). The model consists of an atmospheric model, a mixed-layer ocean, and a land-surface package containing the sea ice code and prescribed vegetation. The atmospheric model uses T31 resolution (approximately 3.75^o x 3.75^o) and contains 18 levels. The physical effects of vegetation are accounted for by the land-surface transfer model (LSX), which exchanges energy, mass and momentum between the atmosphere and vegetation. The GCM's ocean component is a mixed-layer of fixed 50 m depth with a prognostic meridional heat transport. The sea ice component uses a modified version of Semtner's three-layer thermodynamic treatment (Semtner, 1976) and the Flato-Hibler ice dynamics parameterization (Flato and Hibler, 1990).

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Clouds are predicted using prognostic water contents for three separate cloud types: stratus, convective, and anvil cirrus (Smith, 1990). Clouds are advected by semi-Lagrangian transport and mixed vertically by convective plumes and background diffusion. Cloud evaporation, conversion to precipitation, aggregation by falling precipitation, reevaporation of falling precipitation, and turbulent deposition of lowest-layer cloud particles onto the surface are all included. Latent heat changes due to liquid versus ice clouds are neglected, although the determination of cloud fraction, radiative properties, and microphysical parameters take the temperature into account. Cloud fractions for each type are proportional to the grid-box average cloud amounts.

This paper focuses on the differences in simulated Arctic climate between the 2 x CO_2 simulations with and without changes in cloud fraction. The standard 2 x CO_2 simulation with prognostic cloud cover is denoted “2CO2”, while the corresponding simulation using fixed, monthly-mean cloud cover from the control run is labeled “2CO2F”. To further evaluate the effect of cloud changes, two supplemental experiments consist of cloud cover fixed in high latitudes only (poleward of 60^o, denoted “2CO2FHIGH”), and in lower latitudes only (equatorward of 60^o, denoted “2CO2FLOW”). All the results represent 10-year average conditions after the climate has equilibrated to the external forcing perturbations after approximately 20 years.

In the fixed-cloud simulations, most of the other cloud variables besides cloud fraction also remain at their values from the control simulation. Particle size, optical depth, liquid water path, and cloud albedo remain unchanged. Cloud phase (liquid or ice) does change as a function of temperature, and cloud emissivity changes somewhat due to its partial dependence on cloud phase. The effects of fixing cloud fraction seem to dominate the influence of cloud phase and emissivity changes, such that the overall climatic response can be interpreted as being forced by the changes in cloud concentration.

3. RESULTS

3.1 Modern Cloud Simulation

GENESIS reproduces the observed seasonal cycle and mean annual value of Arctic cloud concentration (Fig. 1) much better than most GCMs, some of which fail to match the correct phase of minimum (maximum) cloud fraction during winter (summer) (Walsh et al., 2002). The more successful GENESIS simulation is attributed to its cloud parameterization, which computes cloud fraction as a function of prognostic cloud water content instead of relative humidity, as GCMs commonly do (e. g., Slingo, 1987). The former approach seems superior for simulating Arctic clouds, because it accounts for the mixed-phase microphysical processes that cause frozen cloud condensate to fall out more rapidly than liquid condensate. This differential fallout rate causes a seasonal dependence of cloud condensate residence time that is consistent with greater Arctic cloud cover during summer and is the most likely cause of the observed seasonal cycle (Beesley and Moritz, 1999). This hypothesis is supported by a sensitivity test in which the residence times of frozen and liquid cloud condensate were set equal (Fig. 2). Without the faster ice-crystal fallout, the wintertime cloud fraction increases dramatically to the point of reversing the seasonal cycle: more Arctic cloud cover occurs during winter than summer when the differential fallout rates are neglected.

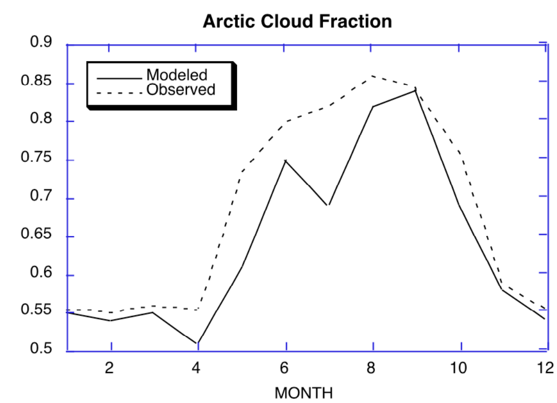

Fig. 1. Annual cycle of simulated (solid) and observed (dashed) Arctic cloud fraction (70°-90°N). Observations are from Hahn et al. (1995) and Makshtas et al. (1999).

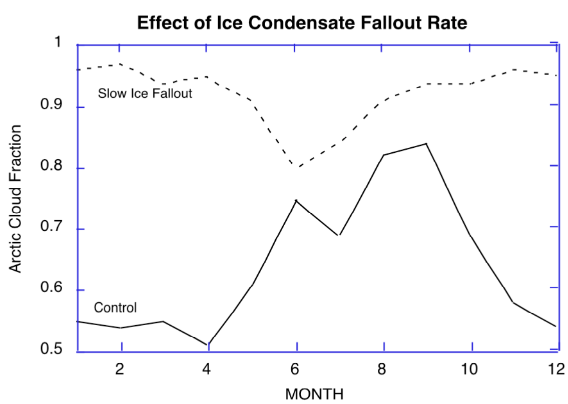

Fig. 2. Arctic cloud cover sensitivity to the prescribed residence time of cloud ice condensate. When the fallout rate of ice crystals slows to that of liquid cloud droplets, the annual cycle of Arctic cloud cover changes dramatically: cloudiness becomes more prevalent during winter than summer.

3.2 Simulations with 2 x CO_2

Under greenhouse forcing, the model simulates a pronounced increase of vertically integrated annual cloud fraction in both polar regions, while producing decreased total cloudiness elsewhere (Fig. 3). The greater cloud cover in high latitudes occurs predominantly at low levels with no corresponding decrease at mid-high levels, whereas elsewhere the general anomaly pattern consists of increased mid-high cloudiness but decreased low cloud cover. These simulated changes in cloud distribution cause enhanced warming in the 2CO2 experiment compared with the fixed-cloud simulation, 2CO2F (Fig. 4). Temperature increases are greater at all latitudes with the interactive clouds, particularly in the Arctic, where approximately 40% of the annual warming is due to cloud changes (the cloud changes account for one-third of the globally averaged warming). The uniformity of the positive cloud feedback globally is consistent with changes in the pattern of cloud radiative forcing (CRF) (Fig. 5), in that nearly every latitude shows a gain in radiative energy in 2CO2 relative to 2CO2F. Despite its high climate sensitivity to the cloud cover changes, the Arctic is not the region with the largest difference in CRF between 2CO2 and 2CO2F. Interactive clouds force the greatest radiative gain in the tropics (30°N-30°S), which absorb 1.5 W m^{-2} more radiation in 2CO2 than in 2CO2F, compared with 0.6 W m^{-2} more in the Arctic. This extra energy is primarily in the form of solar radiation in the tropics and longwave radiation in polar regions (not shown).

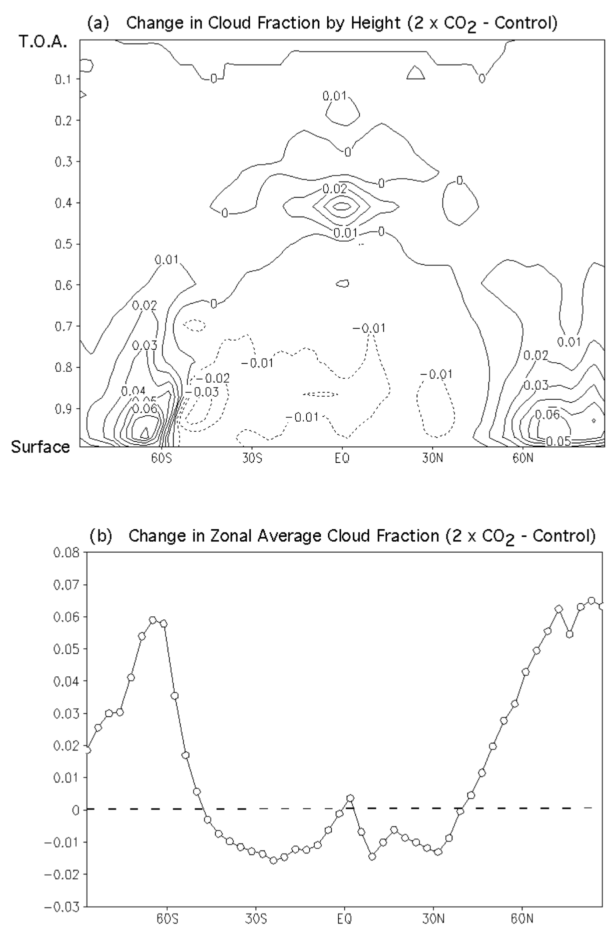

Fig. 3. (a) Vertical cross section of the change in mean annual cloud fraction under 2 x CO_2, (b) Change in zonally averaged, vertically integrated cloud fraction under 2 x CO_2.

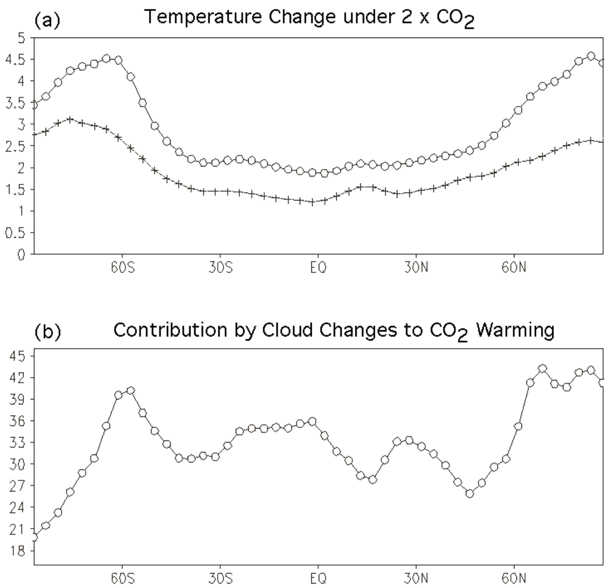

Fig. 4. (a) Change in mean annual surface air temperature in 2CO2 (circles) and 2CO2F (crosses), and (b) Percentage contribution by cloud cover changes to the warming in 2CO2, calculated as the difference in warming between 2CO2 and 2CO2F divided by the temperature increase in 2CO2.

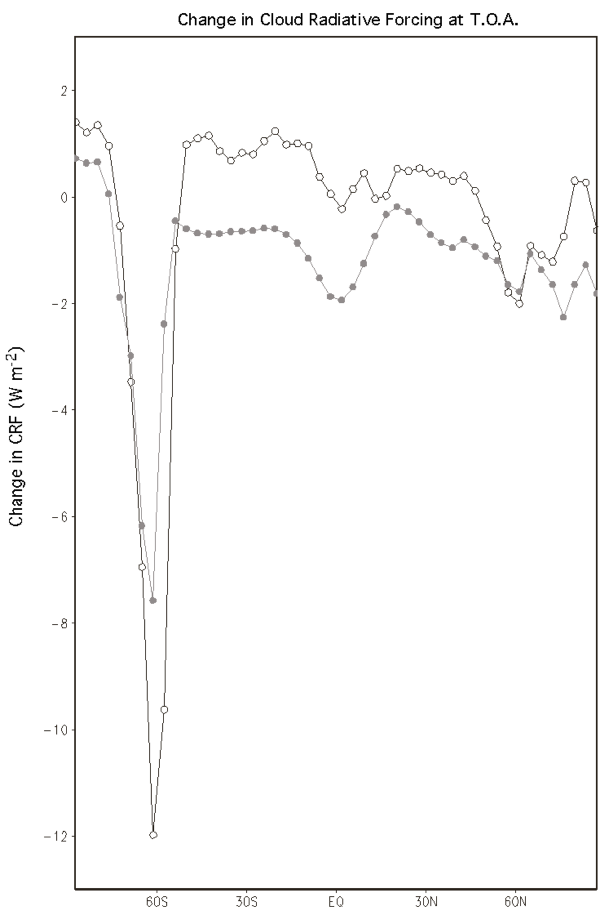

Fig. 5. Change in mean annual cloud radiative forcing (CRF) at top of atmosphere in 2CO2 (open circles) and 2CO2F (closed circles)

To determine the climatic significance of these regional differences in CRF anomalies due to interactive clouds, a pair of supplemental simulations helped quantify the remote and local impact of cloud changes on Arctic climate. These additional experiments resemble 2CO2F, except that in one simulation clouds are fixed in high latitudes only (poleward of 60° in both hemispheres) and are interactive elsewhere (2CO2FHIGH), while in the other simulation clouds are fixed only in low latitudes (equatorward of 60° globally) (2CO2FLOW). A comparison of the change in mean annual Arctic air temperature among the four simulations (Fig.6) shows a very similar warming in the northern polar region whether clouds are fixed only in high latitudes (+3.3 K) or only in lower latitudes (+3.2 K). This result implies that the remote impact of cloud cover feedbacks on the Arctic is approximately equal to the local impact within the Arctic. This similarity can be explained by the much larger low-latitude radiative energy gain (mostly solar) in 2CO2FHIGH, compared with 2CO2FLOW, which results in more poleward heat transport to the Arctic offsetting the smaller radiative energy gain within the Arctic in 2CO2FHIGH. A comparison of the moist static energy (MSE) flux into the Arctic between the two experiments confirms this explanation: the MSE flux increases by 3.6 W m^{-2} when low-latitude clouds change but rises by only 0.8 W m^{-2} when the low-latitude cloud fraction is fixed. Similarly, the MSE flux helps to explain the difference between the global fixed-cloud and interactive-cloud experiments, as the poleward atmospheric heat transport into the Arctic increases by 2.6 W m^{-2} in 2CO2 but by only 1.0 W m^{-2} in 2CO2F.

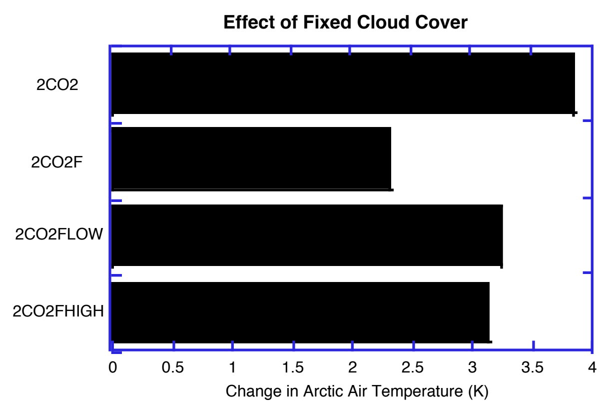

Fig. 6. Change in mean annual Arctic surface air temperature in the standard 2 x CO_2 simulation with interactive clouds (2CO2) and the 2 x CO_2 simulations with cloud fraction fixed globally (2CO2F), outside of polar regions only (2CO2FLOW), and within high latitudes only (2CO2FHIGH).

4. CONCLUSIONS

The results of this study have several implications for our understanding of Arctic clouds. First, because the difference in fallout rates between frozen and liquid cloud condensate seems to explain the observed seasonal cycle of Arctic cloud cover, climate models may need to account for this effect. Second, although the simulated greenhouse-forced cloud responses described here are model-dependent, they suggest that cloud feedbacks in low- and mid-latitudes may be as important for affecting Arctic climate as are local cloud feedbacks in high latitudes. Third, cloud changes may be accompanied by changes in atmospheric poleward heat transport that can act as a powerful remote forcing mechanism for Arctic climate change.

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