The Impact of Cloud Feedbacks on Arctic Climate under Greenhouse Forcing*

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ABSTRACT

The simulation of Arctic cloud cover and the sensitivity of Arctic climate to cloud changes are investigated using an atmosphere–mixed-layer ocean GCM (GENESIS2). The model is run with and without changes in three-dimensional cloud fraction under 2 × CO_2 radiative forcing. This model was chosen in part because of its relatively successful representation of modern Arctic cloud cover, a trait attributable to the parameterized treatment of mixed-phase microphysics. Simulated modern Arctic cloud fraction is insensitive to model biases in surface boundary conditions (SSTs and sea ice distribution), but the modeled Arctic climate is sensitive to high-frequency cloud variability. When forced with increased CO_2 the model generally simulates more (less) vertically integrated cloudiness in high (low) latitudes. In the simulation without cloud feedbacks, cloud fraction is fixed at its modern control value at all grid points and all levels while CO_2 is doubled. Compared with this fixed-cloud experiment, the simulated cloud changes enhance greenhouse warming at all latitudes, accounting for one-third of the global warming signal. This positive feedback is most pronounced in the Arctic, where approximately 40% of the warming is due to cloud changes. The strong cloud feedback in the Arctic is caused not only by local processes but also by cloud changes in lower latitudes, where positive top-of-the-atmosphere cloud radiative forcing anomalies are larger. The extra radiative energy gained in lower latitudes is transported dynamically to the Arctic via moist static energy flux convergence. The results presented here demonstrate the importance of remote impacts from low and midlatitudes for Arctic climate change.

1. Introduction

Arctic clouds exert a large influence on the surface radiation budget, reducing wintertime cooling of the surface by 40–50 W m^{-2} and summertime surface heating 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 and the melting of snow and ice in Arctic regions (Maykut and Untersteiner 1971; Curry and Ebert 1990). Satellite observations during the past two decades show significant trends (increases) in Arctic cloudiness, which have discernable effects on the surface energy budget (Wang and Key 2003).

Despite their importance, polar cloudiness is a variable that climate models generally simulate poorly (Randall et al. 1998). While the latest generation of GCMs shows some improvement over older simulations, state-of-the-art models still show considerable spread in the simulated climatological mean Arctic cloud coverage and its annual cycle (Walsh et al. 2002). The difficulties of models in reproducing Arctic clouds and other climatic fields prompted a recent international conference sponsored by the International Arctic Research Center, ''Simulating the Arctic in Large-Scale Models'' (Walsh et al. 2002, manuscript submitted to *Bull. Amer. Meteor. Soc.*). Problems in high-latitude cloud simulations were a common feature among the models presented, including those that have been recently upgraded. Many models fail to capture the correct phase of the annual cloud cycle in the Arctic, producing much more cloud cover during winter than summer.

The difficulty of climate models in reproducing modern Arctic cloud conditions is especially disturbing, given the nearly unanimous agreement among GCMs that polar regions are the most climatically sensitive regions on earth (Houghton et al. 2001). Although future Arctic cloud changes from rising greenhouse gas concentrations are uncertain, the importance of polar clouds in the present climate suggests that they may play an important role in shaping climatic conditions in coming decades. Credible predictions of polar and global climate trends require improvements in the models' treat-

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ment of high-latitude cloudiness and investigations into the processes governing cloud changes. Reliable projections of future Arctic climate are a central goal of the Arctic Climate Impact Assessment (ACIA; Källén et al. 2001).

While a study of future Arctic cloudiness may seem premature in light of difficulties modeling present cloud conditions, an alternative viewpoint is that projections can be assessed in terms of a model's ability to simulate clouds in the present climate. This tack has the advantage of potentially improving current cloud parameterizations, by identifying processes that either help or hinder simulations of modern polar cloudiness. For example, some studies have found that the modern annual cycle of Arctic cloud cover is better reproduced by models that explicitly include mixed-phase microphysics, because they account for the faster fallout rate of cloud ice crystals over liquid droplets (Beesley and Moritz 1999; Vavrus 2003). Predictions of Arctic clouds under altered climates may be more credible from this class of climate models. One such GCM is GENESIS2, a global climate model that has been used in studies of past, present, and future Arctic climates (Maslanik and Dunn 1997; Thompson and Pollard 1997; Levis et al. 1999; Vavrus 1999; Vavrus and Harrison 2003). Because this model simulates a more realistic annual cycle of modern Arctic cloud fraction than most GCMs, such as those included in the Atmospheric Model Intercomparison Project (AMIP; Walsh et al. 2002), a description of its cloud parameterization may prove beneficial to the modeling community. Furthermore, its projected changes in Arctic cloud properties under greenhouse warming should be more plausible than those simulated by models that fundamentally fail to reproduce primary Arctic cloud features in the present climate, such as cloud fraction and cloud radiative forcing (CRF).

The purpose of this paper is thus twofold: to describe and evaluate the present-day Arctic cloud simulation in GENESIS2 and to present the high-latitude impact of simulated cloud changes when the model is forced with a doubling of CO_2. It will be shown that the second goal requires a much broader perspective than merely considering the Arctic in isolation; much of the cloud feedback in the Arctic is caused by cloud changes occurring at lower latitudes. Quantifying the simulated cloud feedback is achieved by comparing the output from the standard $2 \times CO_2$ experiment with that from a parallel $2 \times CO_2$ simulation in which clouds are fixed at their modern control values. The author knows of no other study of this type with the current generation of GCMs, although Hansen et al. (1984) and Wetherald and Manabe (1988) suppressed cloud feedbacks under greenhouse forcing using much older models with less sophisticated cloud parameterizations and poorer representations of Arctic clouds. Thompson and Pollard (1995) ran a fixed-cloud simulation with $2 \times CO_2$ forcing with an older version of GENESIS that contained a very different cloud parameterization than the one described here. These GCM studies and those of Wilson and Mitchell (1987) and Li and Le Treut (1992) concluded that changes in cloud cover amplify greenhouse warming globally, but none of them focused on the Arctic. Targeting the Arctic with a one-dimensional column model, Curry et al. (1994) found that cloud-fraction changes constitute a positive feedback. The sensitivity of Arctic climate to cloud-cover variations was underscored by Curry et al. (1996): ''The largest uncertainty in assessing the cloud–climate feedback mechanism is the change in cloud cover in response to a change in atmospheric temperature.''

This prior work motivates the present investigation, which builds on previous studies by using a global model to quantify the total impact of cloud-cover changes on Arctic climate due to greenhouse forcing. The method used here thus goes beyond the traditional approach of calculating cloud feedback simply in terms of the local change in cloud radiative forcing. The paper is structured as follows. Section 2 describes GENESIS2 and its cloud parameterization, and section 3 follows up with a presentation of the model's simulated Arctic cloud characteristics for the present climate. Results from several sets of sensitivity tests are presented in section 4 to demonstrate the importance of cloud microphysical processes and changes in cloud cover. A discussion of the results is given in section 5, followed by conclusions in section 6.

2. Model description and simulations

GENESIS2 consists of an atmospheric model, a static mixed-layer ocean, and a land surface package that contains sea ice code and prescribed vegetation (Thompson and Pollard 1997). The atmospheric model uses T31 resolution (approximately $3.75° \times 3.75°$) and contains 18 vertical levels in a hybrid sigma-pressure coordinate system. 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 but does not allow interactive climate–vegetation feedbacks. The ocean component is a mixed layer of fixed 50-m depth with a prognostic meridional heat transport. Sea ice is represented by both thermodynamic and dynamic components, following Semtner (1976) and Flato and Hibler (1990).

Rather than being proportional to ambient relative humidity, cloud fraction at each level is predicted as a linear function of cloud water content for stratus, convective, and anvil cirrus types (Smith 1990; Senior and Mitchell 1993). Separate functions are used for each of the three cloud types, but there is no explicit dependence of cloud amount on temperature, latitude, height, or season. Thus, no tuning was performed to generate realistic regional cloud fields. 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 and are dependent on the phase of the cloud condensate (ice or liquid). Latent heat changes due to liquid versus ice clouds are neglected, although radiative properties and microphysical parameters take the temperature into account. Cloud phase is determined by the ambient temperature, such that condensate is entirely frozen at air temperatures below 258.16 K and entirely liquid above 268.16 K for all cloud types. Between these limits, the fraction of frozen cloud water varies linearly with temperature between 0 and 1.

In addition to describing the modern climate simulation, this paper focuses on the differences in simulated Arctic climate between the 2 × CO_2 simulations with and without changes in cloud fraction. The standard 2 × CO_2 simulation with prognostic cloud cover is denoted ''2CO2,'' while the corresponding simulation using fixed, monthly mean, three-dimensional cloud fractions from the modern 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°, denoted ''2CO2FHIGH''), and in lower latitudes only (equatorward of 60°, denoted ''2CO2FLOW''). All the results represent 10-yr-average conditions after the climate has equilibrated to the external forcing perturbations after approximately 20 yr.

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 slightly due to its partial dependence on cloud phase. The effects of fixing cloud fraction seem to dominate, however, such that the overall climatic response can be interpreted as being primarily forced by the changes in cloud concentration.

3. Modern simulation

The modern Arctic climate simulated by GENESIS2 has been described by Maslanik et al. (1996) and Vavrus (1999). Overall, this model reproduces observed fields of temperature, precipitation, sea level pressure, and sea ice distribution better than most GCMs, which traditionally have had difficulty simulating this region (Walsh and Crane 1992; Bromwich et al. 1994; Weatherly et al. 1998). For example, the simulated mean annual surface air temperature in the Arctic (70°–90°N) agrees to within 1 K of the observed value from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis (Kalnay et al. 1996), and the corresponding precipitation rate over the Arctic Ocean agrees to within 10% of estimates published in Walsh et al. (1998).

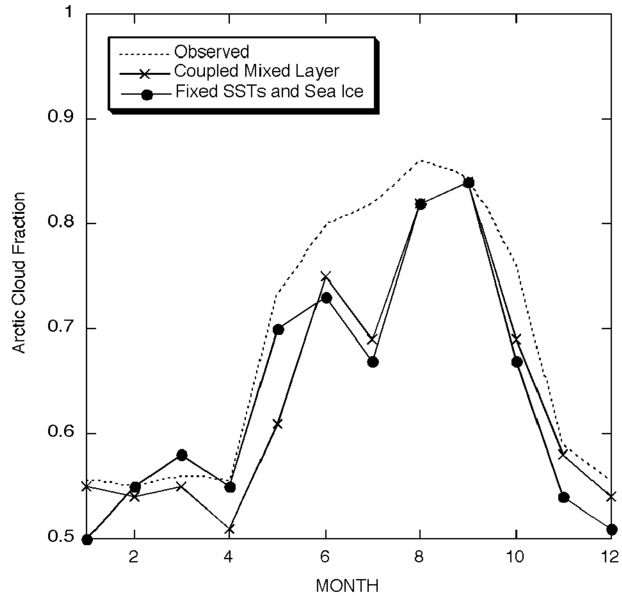

FIG. 1. Annual cycle of simulated (solid lines) and observed (dashed) total Arctic cloud fraction (70°–90°N). Values from the standard simulation using a coupled mixed-layer ocean are marked with ''×,'' and values from a simulation driven with observed SSTs and sea ice cover are shown in solid circles. Observations are from Hahn et al. (1995) and Makshtas et al. (1999).

GENESIS2 reproduces the observed annual 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; e.g., Fig. 16 of Walsh et al. 2002). Also apparent in Fig. 1 is that the simulated cloud coverage is dictated by the atmospheric model; the annual cycle of Arctic cloud fraction is virtually the same whether the AGCM is coupled to the mixed-layer ocean (and thus subjected to model biases) or is driven with observed SSTs and sea ice. This insensitivity to surface boundary conditions occurs despite known biases in the model's simulated sea ice, which is too thin and not extensive enough (Maslanik et al. 1996; Vavrus 1999). The model also successfully simulates cloud cover outside of the Arctic, matching the observed global mean annual cloud fraction (0.64) reported by Hahn et al. (1995).

The annual cycle of total cloud cover is largely dictated by low clouds (Fig. 2), which are the most prevalent Arctic cloud type in the model and in reality (Huschke 1969). GENESIS2 also captures the seasonal distribution of low, middle, and high clouds quite realistically. Both the model and Huschke (1969) show that low clouds are very common during summer but much less prevalent during winter, middle clouds are the second most common cloud type and show very little annual cycle, and high clouds are least common and exhibit a wintertime maximum and summertime minimum. The spatial distribution of simulated Arctic cloud amount (Fig. 3) is similar to data from coastal

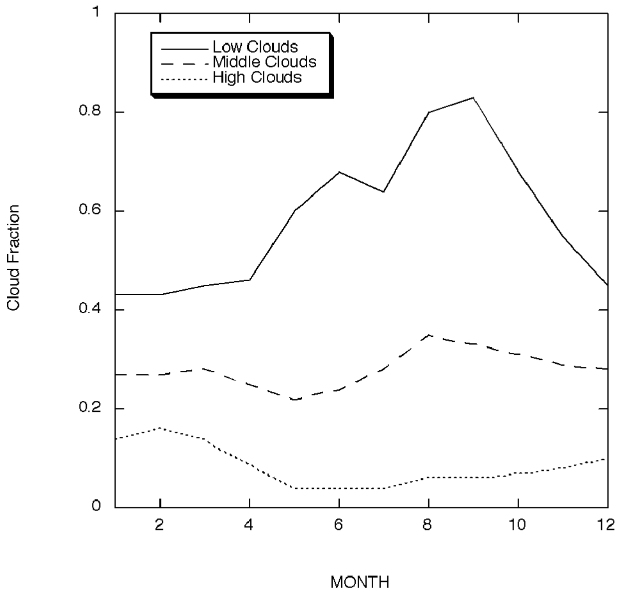

FIG. 2. Annual cycle of simulated Arctic low cloud amount (solid line), middle cloud amount (dashed), and high cloud amount (dotted) for the region 70°–90°N. These cloud fractions exceed the vertically integrated values shown in Fig. 1 because of cloud overlap.

and drifting ice stations, as compiled by Huschke (1969) and the European Working Group Atlas (Arctic Climatology Project 2000). The major features of the simulation and observations are the much greater cloud amount over the Nordic Seas than above the ice-covered Arctic Ocean and adjacent landmasses during winter and spring, greater cloud amount over the Arctic Ocean than above the landmasses during summer, and a fairly uniform spatial distribution of clouds across the Arctic during autumn.

The model's simulated CRF is another useful measure of its performance and is a valuable tool for diagnosing the impact of cloud changes under altered external forcing. CRF is defined as the impact of clouds on the radiative balance at either the top of the atmosphere (TOA) or at the surface. It is calculated as the difference between the fluxes of solar and longwave radiation under all-sky conditions from their values under clear skies (Ramanathan et al. 1989):

$$\mathrm{CRF} = (Q - Q_c) - (F - F_c), \tag{1}$$

where Q and F are the net downward solar and net outgoing longwave radiative fluxes at either the TOA or the surface, and the subscript "c" denotes the corresponding clear-sky flux. Positive (negative) values of CRF thus indicate that clouds are a warming (cooling) mechanism. The globally averaged cloud radiative forcing in GENESIS2 agrees well with observations from the Earth Radiation Budget Experiment (ERBE): the model's solar, longwave, and net CRF of −49, +34, and −15 W m^{-2}, respectively, are all within the ranges from satellite data reported by Ramanathan et al. (1989). CRF calculations have been made in various studies to identify Arctic clouds as a substantial surface warming mechanism, except for a period during summer (Curry et al. 1993; Schweiger and Key 1994; Walsh and Chapman 1998; Beesley 2000; Intrieri and Shupe 2002). Consistent with these results, GENESIS2 produces a mean annual surface CRF of +25 W m^{-2} for ocean areas poleward of 62°N, in agreement with the corresponding satellite-derived estimate of +26 W m^{-2} by Schweiger and Key (1994), and generates positive surface CRF values except from June to August. The impact of Arctic clouds at the TOA is less certain, however, owing to fewer datasets that cover the entire annual cycle. Both Schweiger and Key's satellite-derived estimate and Curry and Ebert's (1992) calculation from a one-dimensional column model indicate a substantially negative mean annual Arctic TOA CRF (∼−10 and −20 W m^{-2}, respectively). However, another one-dimensional column model of the central Arctic used by Beesley (2000) yields a near-neutral value (−2 W m^{-2}), as does the NCEP–NCAR reanalysis data averaged from 60° to 90°N (+3 W m^{-2}). The corresponding value in GENESIS2 (+2 W m^{-2}) agrees with the latter calculations, but the disagreement among the estimates makes it difficult to determine the precise thermodynamic role of Arctic clouds in affecting the TOA energy budget.

4. Sensitivity tests

a. *Modern radiative forcing*

The relatively successful GENESIS2 cloud simulation is attributed to its cloud parameterization (section 2), particularly the computation of cloud fraction as a function of prognostic cloud water content and the differential fallout rates of frozen and liquid condensate. Conversely, many GCMs calculate cloud fraction as a simple diagnostic function of relative humidity (e.g., Slingo 1987) without regard for important microphysical effects. The method used in GENESIS2 seems superior for simulating polar clouds, because it accounts for the Bergeron–Findeison process, which causes frozen cloud condensate to precipitate more rapidly than liquid condensate. This behavior is parameterized by prescribing vastly different time scales for the precipitation of liquid condensate (6.0 h) compared with ice condensate (0.4 h). The different fallout rates of frozen and liquid cloud particles cause a seasonal dependence of cloud condensate residence time that is consistent with more Arctic clouds during summer and is the most likely cause of the observed annual cloud-cover 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 to 6.0 h (Fig. 4). Without the faster ice-particle 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 dif-

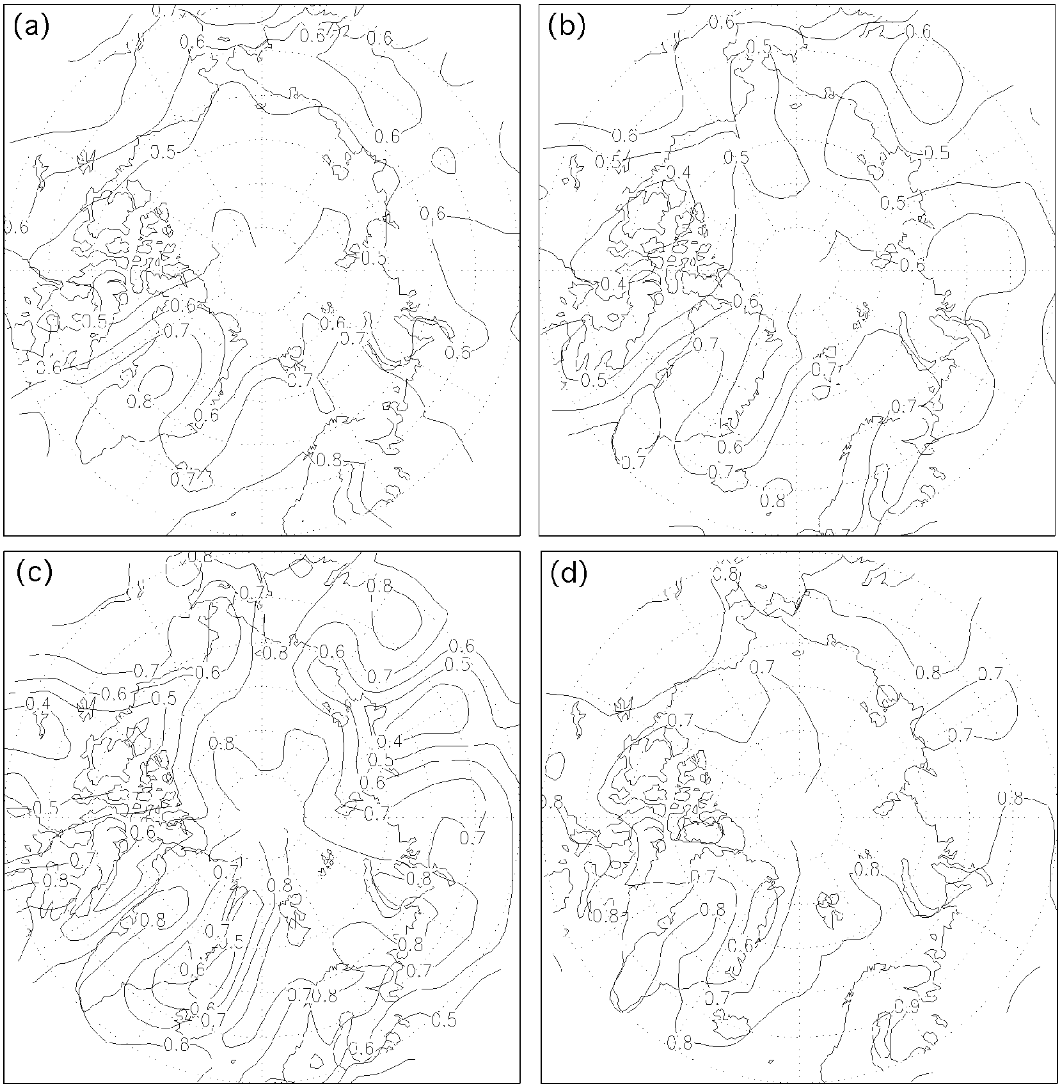

FIG. 3. Spatial and seasonal distribution of total Arctic cloud fraction during (a) DJF, (b) MAM, (c) JJA, and (d) SON.

ferential fallout rates are neglected. This simulation also highlights the importance of considering *global* impacts when modifying cloud parameterizations aimed at improving high-latitude climate: the longer residence time of ice condensate not only increases the prevalence of low clouds in polar regions but also sharply enhances heat-trapping high clouds in the Tropics, resulting in a global warming of over 10 K. A follow-up experiment with a more modest increase in ice-particle residence time (twice the control value applied globally and regionally) shows that the enhanced cloud cover in lower latitudes actually forces a larger polar warming than does the enhanced cloudiness in high latitudes, especially in the Arctic (Fig. 5). The greater impact of cloud changes outside the polar regions compared with local high-latitude cloud changes is largely due to the much greater surface area lying between 60°N and 60°S compared with 60°–90° (more than a 6 to 1 ratio). There is, however, a dynamical contribution as well: the poleward atmospheric energy flux convergence into the Arctic is approximately 10% greater when the persistence of ice clouds is enhanced in low latitudes rather than in high latitudes. Changes in the meridional energy transport to high latitudes will be shown to be very important in the $2 \times CO_2$ simulations as well (sections 4b and 4c).

b. $2 \times CO_2$ radiative forcing (prognostic clouds)

The thermodynamic and hydrologic response of GENESIS2 to greenhouse forcing is fairly typical of climate models. The mean annual global temperature rise in the $2 \times CO_2$ simulation with prognostic cloud changes (2CO2) is 2.5 K. This sensitivity falls within the range of 2.0–5.1 K produced by recent global sim-

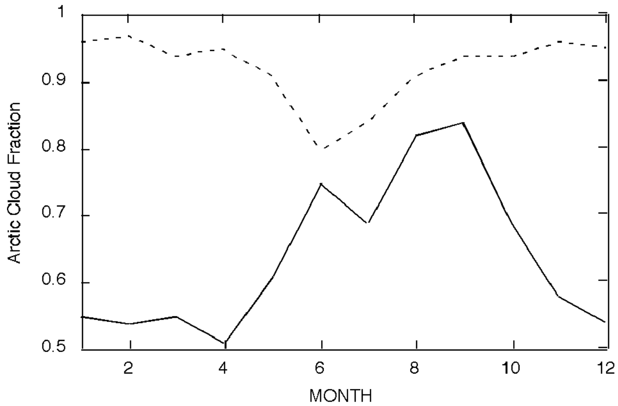

FIG. 4. Effect of varying the prescribed residence time of cloud ice condensate. The solid line shows the annual cycle of Arctic cloud fraction in the standard simulation, in which the fallout rate of frozen condensate is much faster than that of liquid condensate (same curve as in Fig. 1). The dashed line shows the Arctic cloud fraction when the fallout rate of ice condensate is set equal to the liquid fallout rate.

ulations with atmosphere/mixed-layer models reported by the Intergovernmental Panel on Climate Change (IPCC; Houghton et al. 2001). The globally averaged precipitation increase of 5% is also similar to the 7% average rise simulated by current models used in the IPCC assessment. GENESIS2 produces the typical polar amplification of even warmer and wetter conditions in high latitudes: a mean annual 3.9-K warming and a 23% increase in precipitation in the Arctic (60°–90°N). Also in line with other models is an enhanced wintertime warming, consisting of a 6.0-K Arctic temperature rise during December–January–February (DJF) compared with a 1.4-K increase during June–July–August (JJA).

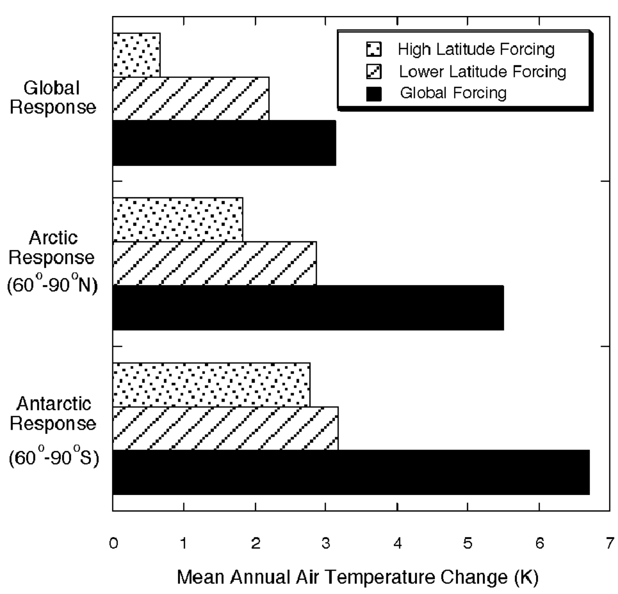

FIG. 5. Global, Arctic, and Antarctic response to a doubling of the simulated residence time of cloud ice particles applied globally (solid), only outside of polar regions (60°S–60°N; hatched), and only within polar regions (poleward of 60°; stippled).

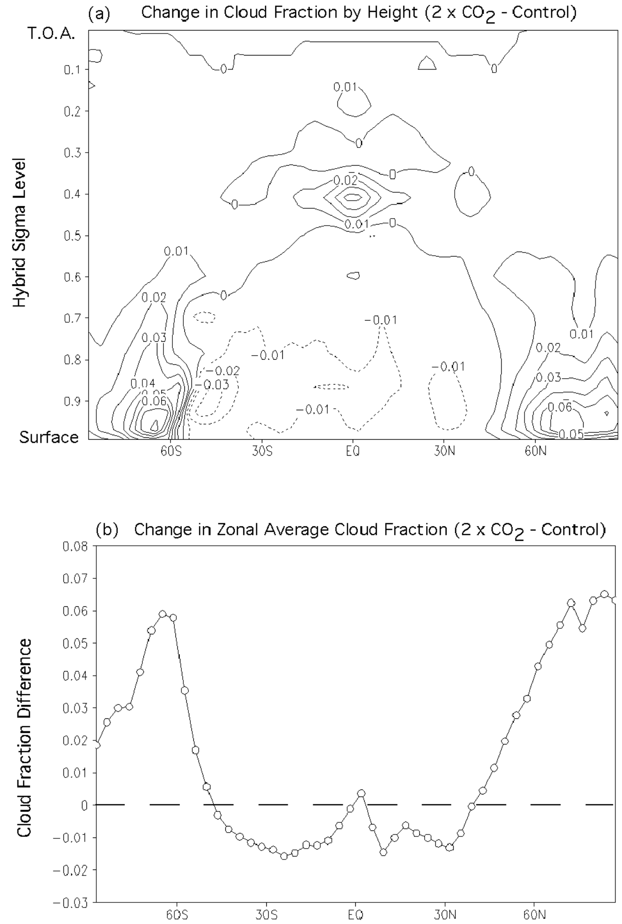

FIG. 6. (a) Vertical cross section of the change in mean annual cloud fraction under 2 × CO_2. (b) Change in zonally averaged, vertically integrated cloud fraction under 2 × CO_2.

The model produces changes in cloud cover that vary greatly by region and height. Under greenhouse forcing, cloud concentration increases in high latitudes but decreases elsewhere (Fig. 6). The greater cloud cover in the polar regions occurs predominantly at low levels with no corresponding decrease at mid–high levels, whereas elsewhere the general anomaly pattern consists of more mid–high cloudiness but less low cloud cover. This anomaly pattern is highly model dependent, however. The Climate System Model (CSM), for example, simulates nearly the opposite pattern under greenhouse forcing: decreased low cloud in both polar regions, increased low cloudiness in the Tropics, and decreased mid–high cloud cover in low and mid latitudes (Dai et al. 2001).

c. *Fixed cloud simulations*

As described in section 2, the simulations with fixed clouds use the mean monthly, three-dimensional cloud

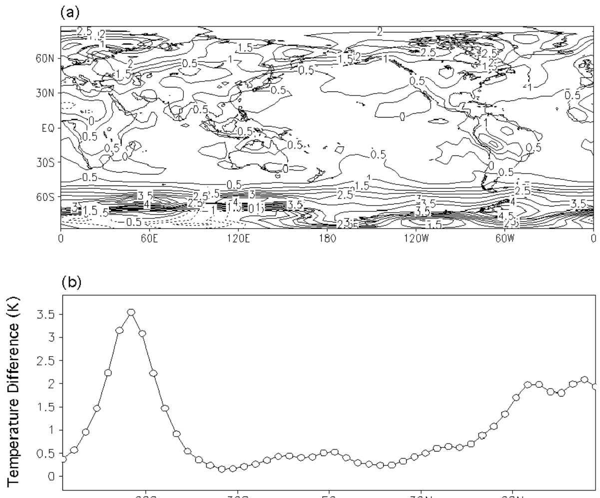

FIG. 7. (a) Global and (b) zonally averaged mean annual temperature differences between the modern control run using prescribed, mean monthly clouds minus the modern control using prognostic clouds. The temperature differences show the impact of suppressing high-frequency cloud-cover variability, since the *mean* three-dimensional cloud fractions are identical in both simulations.

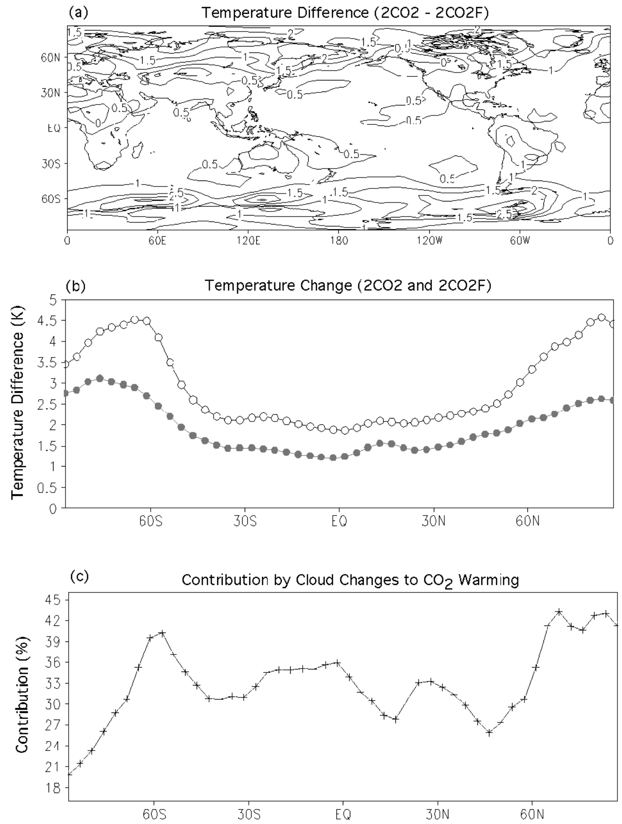

FIG. 8. (a) Difference in mean annual surface air temperature changes in 2CO2 minus 2CO2F. (b) Change in zonally averaged mean annual surface air temperature in 2CO2 (open circles) and 2CO2F (closed circles). (c) Percentage contribution by cloud-cover changes to the warming in 2CO2, calculated as the difference in warming between 2CO2 and 2CO2F divided by the temperature increase in 2CO2.

fractions generated in the prognostic-cloud control run. These monthly averaged fields are linearly interpolated in time to generate instantaneous values of cloud fraction at each grid point and each level. Although one might expect the control simulation with fixed clouds to be essentially the same as the one with prognostic clouds, because both have the same average cloud fraction, there are regions where temperature differences are surprisingly large. Zonally averaged temperatures are higher everywhere in the fixed-cloud control run, particularly in high latitudes, where the Arctic is nearly 2 K warmer and the Southern Ocean is more than 3 K warmer (Fig. 7). These differences capture the influence of high-frequency cloud variability, which is absent in the fixed-cloud simulations. Even though the monthly mean cloud cover at each atmospheric level is unchanged, the constant presence of partial cloudiness in the fixed-cloud simulations causes the vertically integrated cloud amount to be larger (17% greater annually over 70°–90°N). This difference stems from the nonlinear nature of the cloud overlap: a constant amount of partial cloudiness at each level will always result in a larger vertically integrated cloud fraction than if the same time-mean cloud amount at each level exhibits high temporal variability. As a result, the fixed-cloud simulations experience a greater insulating (warming) effect due to their effectively greater cloud amount. This radiative impact, in combination with strongly positive snow- and sea ice feedbacks, seems to account for the much warmer conditions throughout most of the polar regions in the fixed-cloud control simulation. To account for these differences in base states, the $2 \times CO_2$ simulations with fixed clouds and prognostic clouds are compared only with their respective control simulation in the results that follow.

The impact of cloud changes is large and widespread under $2 \times CO_2$ forcing, as evidenced by a comparison of temperature anomalies with interactive cloud changes (2CO2) and with fixed clouds (2CO2F; Fig. 8). Greater warming due to cloud cover changes occurs at all latitudes, ranging from 0.5 to 2.0 K zonally averaged, but is most pronounced in the Arctic. The contribution by cloud changes to greenhouse warming in 2CO2 can be calculated as

$$\frac{(\Delta T_{2CO2} - \Delta T_{2CO2F})}{\Delta T_{2CO2}}, \quad (2)$$

where ΔT is the change in mean annual temperature from the respective control run. This contribution, expressed in percentages in Fig. 8c, indicates that the changes in cloud fraction are responsible for approximately 40% of Arctic warming and one-third of global warming (1.7-K globally averaged warming in 2CO2F versus 2.5-K warming in 2CO2). In addition, the cloud changes generally cause greater precipitation under

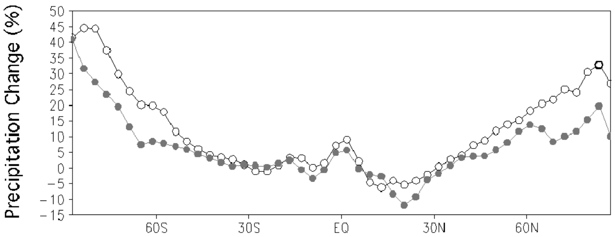

FIG. 9. Change in mean annual precipitation (%) in 2CO2 (open circles) and 2CO2F (closed circles).

greenhouse forcing (Fig. 9). This enhanced precipitation signal is amplified in the high latitudes of both hemispheres, where increases of 19% occur between 60° and 90°N and 23% between 60° and 90°S, compared with the globally averaged rise of 5%. This enhanced freshwater forcing due to cloud increases in the polar regions could have a significant effect on the ocean, including the thermohaline circulation, if this GCM contained a dynamical ocean model rather than its existing mixed-layer ocean.

The enhanced warming by cloud changes can be explained in part by differences in the CRF between 2CO2 and 2CO2F. As discussed in section 3, CRF can be calculated at either the surface or the TOA (1). The reference location affects the CRF differences between the two sets of experiments, which are shown in Fig. 10 and Table 1. The change in CRF in most regions is greater with cloud cover changes than without (2CO2 minus 2CO2F), resulting in global mean differences of +0.97 and +0.29 W m^{-2} at the TOA and surface, respectively. Notice, however, that the global mean change of CRF is negative in both sets of simulations, due mainly to the very large decreases in subpolar latitudes. These minima are caused primarily by the replacement of high-albedo ice and snow cover in the control runs with low-albedo seawater and bare ground in the greenhouse experiments (Fig. 11), thereby enhancing the negative shortwave radiative forcing by clouds. The change of CRF over the Arctic (60°–90°N) in 2CO2 versus 2CO2F is positive at the TOA and even more so at the surface (Table 1), indicative of enhanced warming due to cloud changes. The cause of differences in CRF anomalies between 2CO2 and 2CO2F can be diagnosed by decomposing the net change of CRF into its component parts: the changes in solar and longwave cloud radiative forcing (1). This breakdown shows that the gain in CRF in low latitudes (30°S–30°N) due to cloud changes is caused primarily by solar cloud forcing, whereas the corresponding CRF gain in high latitudes is caused mainly by the longwave cloud forcing term (Fig. 12). The decreased cloud cover in the Tropics therefore enhances greenhouse warming by allowing more solar radiation absorption, while the increased polar cloudiness accentuates the warming by trapping more longwave radiation.

The large tropical CRF increase at the TOA in 2CO2

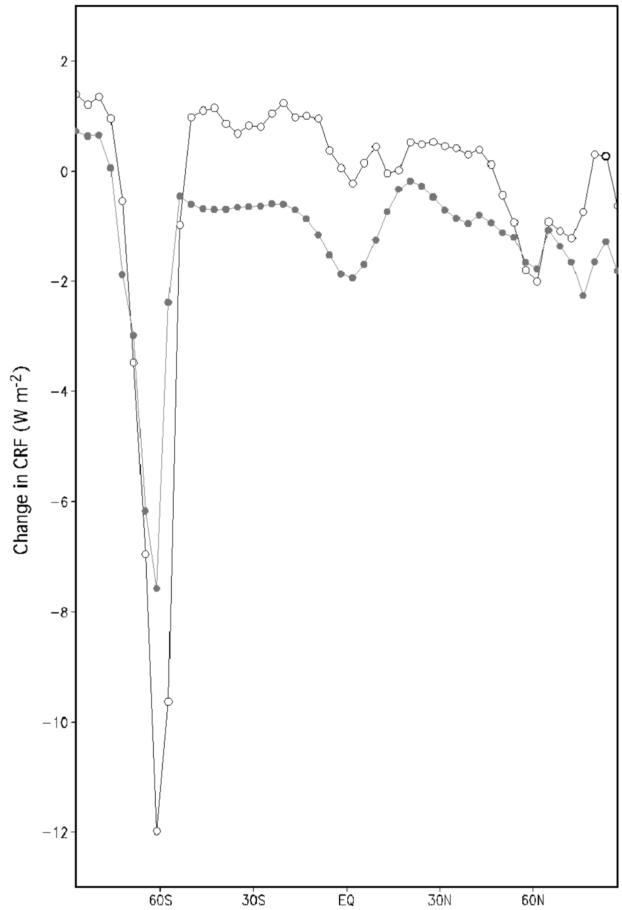

FIG. 10. Change in mean annual net CRF at the TOA in 2CO2 (open circles) and 2CO2F (closed circles).

TABLE 1. Change in net CRF (W m^{-2}) from the modern control simulations at the TOA and the surface in the 2CO2 and 2CO2F experiments.

Sector	2CO2	2CO2F	2CO2 − 2CO2F
	TOA		
60°–90°N	−1.00	−1.55	+0.55
30°–60°N	−0.11	−1.00	+0.89
0°–30°N	0.24	−0.87	+1.11
0°–30°S	0.81	−1.00	+1.81
30°–60°S	−0.47	−0.90	+0.43
60°–90°S	−4.08	−3.40	−0.68
Global	−0.18	−1.15	+0.97
	Surface		
60°–90°N	−0.35	−2.89	+2.54
30°–60°N	−1.88	−1.76	−0.12
0°–30°N	−0.89	−1.12	+0.23
0°–30°S	−0.97	−1.39	+0.42
30°–60°S	−3.29	−2.07	−1.22
60°–90°S	−2.37	−5.31	+2.94
Global	−1.59	−1.88	+0.29

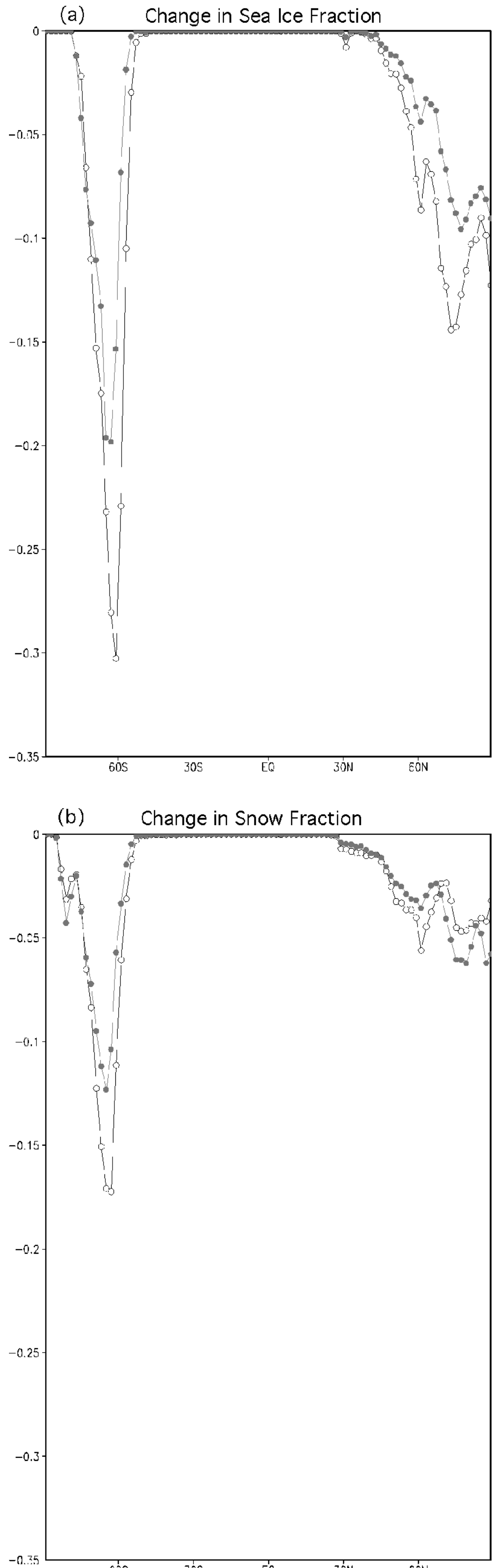

FIG. 11. Change in mean annual (a) sea ice fraction, and (b) snow fraction in 2CO2 (open circles) and 2CO2F (closed circles).

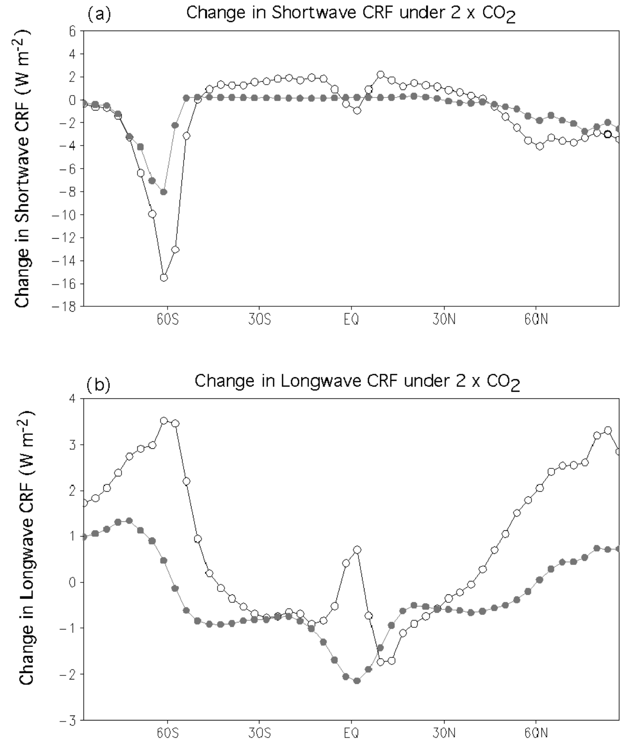

FIG. 12. As in Fig. 10, but for (a) shortwave CRF and (b) longwave CRF.

relative to 2CO2F represents a low-latitude energy source that could contribute to the cloud-induced enhancement of Arctic warming (Fig. 8) via meridional atmospheric energy transport. The potential for significant remote forcing from lower latitudes under 2 × CO_2 is suggested by the cloud microphysics sensitivity test under modern radiative forcing (section 4a; Fig. 5). To test this possibility, the two supplemental simulations described in section 2 (2CO2FHIGH and 2CO2FLOW) were used to compare the impact of remote versus local cloud forcing on Arctic climate change. These additional experiments resemble 2CO2F, except that in 2CO2FHIGH cloud fraction is fixed in high latitudes only (poleward of 60° in both hemispheres) and is prognostic elsewhere, while in 2CO2FLOW cloud cover is fixed only in low latitudes (equatorward of 60° globally). The change in mean annual Arctic air temperature is very similar whether clouds are fixed only in high latitudes (+3.2 K) or only in lower latitudes (+3.3 K; Fig. 13). This result implies that the remote impact of cloud 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 when tropical cloud changes (decreases) are allowed, 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 atmospheric moist static energy (MSE) flux into the Arctic between the two experiments confirms this ex-

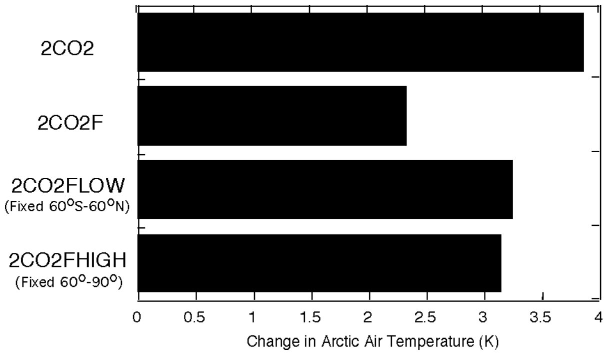

FIG. 13. Change in mean annual Arctic surface air temperature (60°–90°N) in 2CO2 and the 2 × CO_2 simulations with cloud fraction fixed globally (2CO2F), within low latitudes only (60°S–60°N; 2CO2FLOW), and within high latitudes only (poleward of 60°; 2CO2FHIGH).

planation: the MSE flux increases by 3.6 W m^{-2} when only low-latitude clouds change (2CO2FHIGH) but rises by only 0.8 W m^{-2} when the low-latitude cloud fraction is fixed (2CO2FLOW). Similarly, the MSE flux helps to explain the difference between the global fixed-cloud and interactive-cloud experiments, as the poleward atmospheric heat flux into the Arctic increases by 2.6 W m^{-2} in 2CO2 but by only 1.0 W m^{-2} in 2CO2F. Previous studies have also found that the MSE flux strongly influences Arctic climate directly (Bitz et al. 1996) and by affecting the dependence of sea ice thickness on cloudiness (Beesley 2000).

5. Discussion

The large influence of changes in sea ice and snow cover on the CRF in both sets of greenhouse experiments shows how strongly changes in surface conditions can affect CRF and, by extension, the interpretation of cloud feedback (Figs. 10 and 11). Using the traditional approach of equating cloud feedback with the change in CRF between a perturbed state and the modern control climate, the cloud feedback in the prognostic cloud experiment (2CO2) would be interpreted as negative both globally and within the Arctic (Table 1). An even more negative change of CRF occurs in 2CO2F, however, indicating that the cloud changes in 2CO2 actually serve as a warming mechanism both at the surface and aloft (a positive cloud feedback) relative to the greenhouse experiment that produces similar changes in surface conditions (2CO2F). This result suggests that if one uses a change in CRF to define cloud feedback, then the perturbed climate with no cloud changes represents a better reference state on which to base the CRF anomaly than does the modern control climate with its model-predicted cloudiness. A similar caveat about equating cloud feedback with CRF is given by Rossow and Zhang (1995), who stress that CRF can vary in the absence of cloud changes and that the fluxes constituting the cloud radiative ‘‘forcing’’ already include the partial effects of the climate system’s response to circulation feedbacks on the temperature field. Furthermore, even if changes in CRF could provide an unambiguous measure of cloud impacts alone, the resulting energy flux does not translate directly into a tangible climatic quantity, such as a temperature anomaly.

Another challenge in interpreting the modeling results stems from the difference in the modern reference states between the simulations with and without prognostic clouds (Fig. 7). On one hand, this difference serves as an interesting measure of the influence of high-frequency cloud variability, which is absent in the control run with prescribed cloud cover. However, the disagreement between the two control runs complicates the task of isolating the impact of cloud changes in the 2 × CO_2 experiments. Differences in base states can affect a model’s sensitivity to greenhouse forcing, due in part to differences in how much and how easily sea ice can melt off as the climate warms (Rind et al. 1995; Holland et al. 2001). Unfortunately, in this study the only way to prevent this base-state difference would be to save the cloud fractions at each time step in the prognostic-cloud control simulation for use at each time step in the fixed-cloud simulations. However, the limitations of disk storage and the extra computational time required for such high-frequency data input to the model make this kind of procedure unfeasible. Fortunately, in most regions of the world only small temperature differences occur between the two control runs ($<$0.5 K), and the changes in CRF expected from the simulated changes in cloud cover appear to dominate the climatic response over differences in the base-state climates.

6. Conclusions

Simulations using a coupled atmosphere–mixed-layer ocean GCM have yielded several important results that help to explain the behavior of modern Arctic clouds and that may be useful for anticipating how clouds could influence future climate change in the Arctic. In addition, understanding the relative success of GENESIS2 in simulating Arctic clouds could assist other modelers in the difficult task of simulating high-latitude cloudiness. The following are the primary conclusions of this study.

1) The inclusion of mixed-phase cloud microphysics in governing cloud fraction may be essential for realistically simulating the annual cycle of Arctic cloud cover. The shorter residence time of frozen condensate relative to liquid condensate (due to the Bergeron–Findeison process) seems to account for the smaller amount of Arctic cloudiness during winter compared with summer. This result supports the one-dimensional modeling results of Beesley and Moritz (1999), who also showed that GCMs that include

this process generally produce a more realistic annual cycle of Arctic cloud fraction. However, the model simulations described here do not invalidate alternative hypotheses to explain the annual cycle of Arctic cloudiness, such as the importance of evaporation at the surface of the ice pack or the difference in specific humidity between the pack ice and surrounding continents.

In many climate models the predicted cloud fraction is essentially a function of relative humidity, a parameterization that ignores the impact of differential fallout rates of frozen and liquid condensate on cloud concentration. Previous modeling studies have found that basing cloud fraction on cloud water content rather than on relative humidity can improve the simulation of present and past climates, while strongly influencing the climate sensitivity in future scenarios (Senior and Mitchell 1993; Liao et al. 1994). The cloud parameterization used in GENESIS2 produces reasonable cloud cover not only in the Arctic but globally as well.

2) The simulated Arctic cloud cover seems to be dictated by atmospheric physics, rather than being strongly dependent on coupling with the surface. GENESIS2 simulates nearly the same annual cycle of Arctic cloud cover regardless of whether the atmosphere is coupled to a mixed-layer ocean or driven by observed SSTs and sea ice (Fig. 1). This result is encouraging for coupled models, because it implies that (modest) errors in simulating the surface state in the polar regions (snow and ice extent and surface temperatures) need not contaminate the simulation of overlying clouds.
3) The simulated variability of cloud cover may significantly affect the mean climate in the polar regions. The control simulations with and without high-frequency cloud variations show large regional temperature differences (Fig. 7), despite identical mean monthly three-dimensional cloud fields. This finding suggests that errors in simulated cloud variability can affect mean climate in high latitudes and that models need to correctly reproduce not only time-averaged cloud cover but also its natural variability. The author knows of no published study that has evaluated this aspect of GCM performance, even though observations clearly show that wintertime Arctic cloud cover displays a bimodal frequency distribution consisting of a preponderance of nearly overcast and nearly clear conditions (Walsh and Chapman 1998; Makshtas et al. 1999).
4) Changes in cloud cover are a positive feedback in the $2 \times CO_2$ simulations, accounting for approximately one-third of the global warming and 40% of the Arctic warming (Fig. 8). This cloud feedback is similar to the global impact identified in previous studies (Weatherald and Manabe 1988; Thompson and Pollard 1995), but these earlier investigations used simpler cloud parameterizations and did not focus on regional effects. In this study the enhanced Arctic warming due to cloud feedback is caused nearly equally by changes (increases) in cloudiness within the Arctic and changes (less low cloud, more high cloud) in low and midlatitudes.
5) The importance of remote forcing on Arctic climate by cloud changes in lower latitudes is underscored both by a sensitivity test that suppresses the differential fallout rate between frozen and liquid condensate (Fig. 5) and by the calculated differences in MSE transport to the Arctic among the experiments. The former result demonstrates the difficulty in targeting regional cloud parameterizations in global models; modifying processes intended to affect one area can produce large and unanticipated responses elsewhere. Variations in the MSE flux into the Arctic appear to be the physical pathway through which changes in CRF in lower latitudes are expressed climatically in the polar regions. The strong influence of remote cloud forcing means that climate models must accurately simulate cloud changes outside the Arctic in order to realistically simulate climate sensitivity within the Arctic.
6) Quantifying cloud feedback is not straightforward. If one follows the traditional approach of equating it with a change in CRF, then care must be exercised in interpreting the cloud feedback, because changes in the surface state can dictate the change in CRF over changes in cloud characteristics. It is possible, however, to at least partially remove the influence of these competing surface effects (primarily albedo) by comparing the climate change *anomalies* between the fixed-cloud and prognostic-cloud simulations. In the cases considered here, this means that the relevant change in CRF is the difference between the CRF anomalies in the 2CO2 and 2CO2F simulations, rather than the CRF difference between 2CO2 and its modern control. Such a calculation better defines cloud feedback by targeting the portion of the CRF change that is actually caused by changes in cloud conditions, but even this method may still be biased by differences in climate sensitivity that stem from differences in the modern reference states.

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