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High-latitude climate change in a global coupled ocean-atmosphere-sea ice model with increased atmospheric CO_2

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Abstract. A global atmospheric general circulation model (GCM) coupled to a global 1-degree, 20-level ocean GCM with dynamic and thermodynamic sea ice is integrated with CO_2 increasing at 1% per year compounded for 75 years (CO_2 doubles at about year 70). Flux correction is not used in the experiment. The increase of globally averaged surface air temperature at the time of CO_2 doubling is 3.8°C. The warm subsurface Atlantic layer at intermediate depths in the Arctic is maintained mainly by the sinking and intrusion of water from the West Spitsbergen Current in the model and the observations. With increased CO_2 in the model, the warmer surface waters are intruded into the upper portion of the Atlantic layer producing an anomalous warming in the model at depths between 200 and 400 m. This resembles an anomalous warm layer near those depths recently observed in the Arctic. As the climate warms and sea ice retreats, low clouds increase over the newly exposed water. Yet the consequent increase of cloud albedo over these regions is more than compensated for by the decrease of surface albedo due to the melting of sea ice. This produces a net decrease of planetary albedo in the Arctic that contributes to a strong ice-albedo feedback and the comparatively high sensitivity of the model.

Introduction

In the global coupled model described here, we use a somewhat improved atmospheric model compared to our first version [*Washington and Meehl*, 1989]. It is still rhomboidal 15 (R15 or approximately 4.5° latitude by 7.5° longitude) and nine levels, but it now includes a mass-flux convective scheme and parameterized cloud-albedo feedback. The inclusion of the processes represented by these formulations provides the ability to simulate some aspects of climate sensitivity involved with the balance between cloud albedo feedback and the super greenhouse effect [*Meehl and Washington*, 1995]. A significant upgrade to the model involves the inclusion of a 1 × 1 degree, 20-level ocean general circulation model [*Washington et al.*, 1994] and dynamic [*Flato and Hibler*, 1990] as well as a three-layer thermodynamic [*Semtner*, 1976] sea ice formulation. We have examined the aspects of the ocean circulation in this ocean model and found them to be superior to the previous 5° degree ocean model [*Washington et al.*, 1994]. Additionally, the 1-degree version is able to simulate many features of ocean temperature, salinity, and circulation seen in a higher-resolution version (0.5-degree by 0.5-degree) of this ocean model [*Semtner and Chervin*, 1992; *Washington et al.*, 1994]. Consequently, the upgrades to the components have contributed to an improved simulation of present-day climate in the coupled model compared to the earlier version (both run without flux adjustment, for example, comparing *Washington and Meehl* [1989] with *Meehl and Washington* [1995].

The purpose of this paper is threefold. First, we provide an initial description of a 1% per year transient CO_2 increase experiment we have performed with this coupled model. Second, we note the mechanism in the model for maintaining the warm subsurface Atlantic layer in the Arctic and relate the warming of the upper part of this layer in the increased CO_2 experiment to recent observations of subsurface warming in the Arctic. Third, we provide evidence for why the ice albedo feedback in this model is strong with consequent contributions to comparatively high climate sensitivity.

We are presently conducting a set of sulfate aerosol experiments with the present global coupled model (refer to *Taylor and Penner* [1994], *Mitchell et al.* [1995], and *Hasselman et al.* [1995]. The high-latitude effects in our sulfate experiments are qualitatively similar to the present experiment where we include CO_2 increase only but with less warming. We will use the analyses here as a baseline with which to compare high-latitude effects in the sulfate aerosol experiments as well as in experiments with ozone changes and alterations to other forcings.

Sensitivity Experiment

The ocean model was spun up as described by *Washington et al.* [1994]. Briefly, the ocean model was initialized by first running for 14 years with robust diagnostic forcing from the three-dimensional observed temperature and salinity values of *Levitus* [1982], along with the "early winter" sea surface temperatures (SSTs) in the area near Greenland described by *Washington et al.* [1994] that produce a meridional overturning initial state in the Atlantic of about 20 sverdrup (Sv). The subsurface forcing was turned off after 14 years, and the ocean model was run only with the observed surface forcing for 100 years. As described by *Washington et al.* [1994], the largest drifts by the end of the 100-year integration were a few tenths of a degree in the vicinity of the thermocline, and the surface layers were relatively stable. As noted in the earlier *Washington and Meehl* [1989] coarse-grid model, most of this drift is due to anomalously high vertical heat diffusion.

The coupled model was run with present amounts of CO_2 in a control run for 130 years. A transient CO_2 increase experi-

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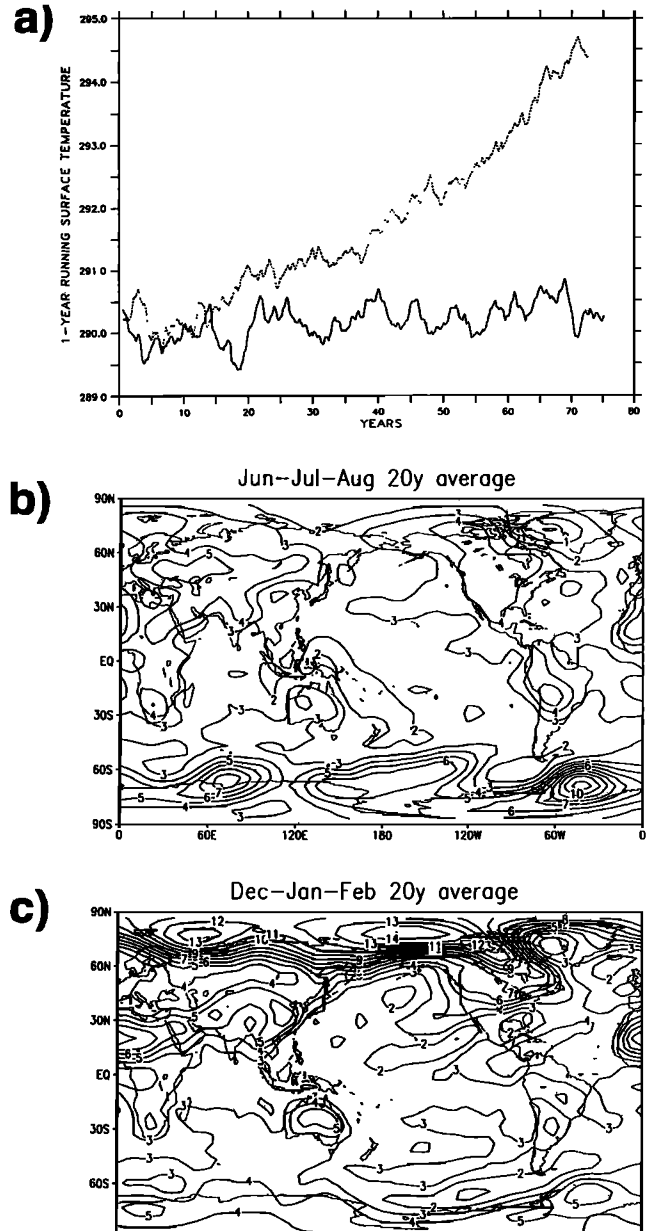


Figure 1. (a) Time series of globally averaged surface temperature for the control case with present-day amounts of CO_2 (solid line) and for the transient CO_2 increase experiment with CO_2 increasing 1% per year compounded; CO_2 doubles at about year 70 (dashed line). (b) Seasonal average, June-July-August, for temperature differences, transient CO_2 increase experiment minus control, averaged over the last 20 years of the experiment (years 56–75); (c) same as Figure 1b except for December-January-February.

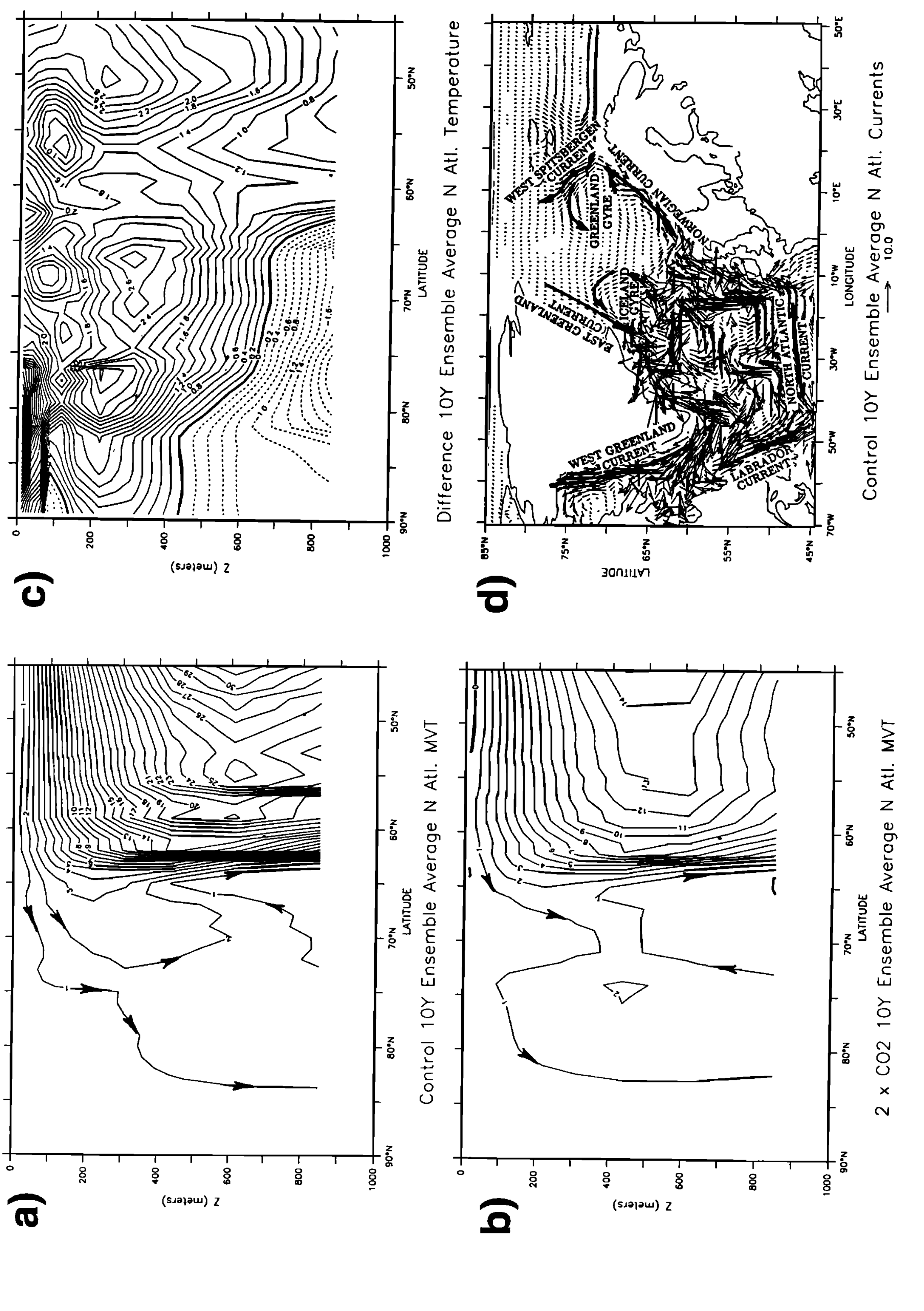
ment (CO_2 increasing at 1% per year compounded) was run for 75 years with CO_2 doubling at about year 70. Here we compare the first 75 years from the control run with the transient CO_2 increase experiment. The time evolution of surface temperature is shown in Figure 1a. The globally averaged surface air temperature difference for the 10 years around the time of CO_2 doubling (years 65–74) is 3.8°C. This is higher than other coupled models [*International Panel on Climate Change* e.g., (*IPCC*), 1992] and could be expected to produce larger-amplitude climate change signals than in other models with lower sensitivity. The higher-amplitude response in this coupled model to increased CO_2 was not entirely unexpected for two reasons. First, the addition of the mass flux convective scheme increased overall sensitivity from 4.0°C to 4.6°C in an equilibrium integration of this model with a nondynamic slab (50 m deep) ocean [*Washington and Meehl*, 1993]. Second, this model exhibits a strong ice-albedo feedback that contributes to fairly large high-latitude warming (e.g., Figures 1b and 1c). We will explore the reasons for the strong ice-albedo feedback in this paper.

The geographical pattern of surface air temperature change in Figures 1b and 1c is characterized by features seen in earlier coupled model experiments [*IPCC*, 1992]. These include greater high-latitude warming in the winter hemispheres, most continental regions warming faster than the oceans, and a minimum of warming near 50°S in the circumpolar southern oceans as well as in the western North Atlantic. The warming at high northern latitudes in some sectors is consistent with recent observed temperature trends in that region [*Chapman and Walsh*, 1993]. However, as noted by *Chapman and Walsh* [1993], the relationship between sea ice distribution and surface temperature change is a complicated one and appears to depend on the region being considered. Another interesting feature is the greater warming east of the date line in the tropical Pacific compared to the tropical western Pacific with increased CO_2 in the model. This feature is even more evident in the SST differences (G. A. Meehl and W. M. Washington, El Nino-like Pacific climate change in a model with elevated atmospheric CO_2 concentrations, submitted to *Nature*, 1996) (hereinafter referred to as Meehl and Washington, submitted manuscript, 1996) and is thought to occur in part due to cloud albedo feedback and other processes in the tropical western Pacific that inhibit warming there compared to the tropical eastern Pacific (Meehl and Washington, submitted manuscript, 1996). This slackening of the east-west SST gradient across the tropical Pacific has also been noted during the recent decadal timescale climate fluctuation that occurred during the 1980s [*Bottomly et al.*, 1990].

High-Latitude Climate Change in the Northern Hemisphere

A well-known feature of the Arctic Ocean is a warm layer at intermediate levels referred to variously as the Atlantic layer [*Aagaard et al.*, 1985] or Atlantic intermediate water [*Mikhalevsky et al.*, 1995]. This layer, extending from about 200 m to

Figure 2. (opposite) (a) Meridional overturning stream function (sverdrups) in the Atlantic sector for the control case for the years 65–74 showing annual mean, arrows on streamlines indicating flow; (b) same as Figure 2a except for the transient CO_2 increase experiment, showing a 10-year annual average near the time of CO_2 doubling (years 65–74). (c) Zonally averaged ocean temperature differences are shown, transient CO_2 increase experiment minus control; annual averages are as in Figures 2a and 2b for the North Atlantic sector. (d) Annual average surface current vectors for years 64–75 in the control case are shown; units of the scaling vector at bottom are in centimeters per second. Note that Iceland and Spitsbergen are represented by the ocean bottom topography but are submerged in the top three model layers (see *Washington et al.* [1994] for details).


a)
Control 10Y Ensemble Average N Atl. MVT
b)
2 x CO2 10Y Ensemble Average N Atl. MVT
c)
Difference 10Y Ensemble Average N Atl. Temperature
d)
Control 10Y Ensemble Average N Atl. Currents
WEST SPITSBERGEN CURRENT
NORWEGIAN CURRENT
GREENLAND GYRE
ICELAND GYRE
EAST GREENLAND CURRENT
WEST GREENLAND CURRENT
LABRADOR CURRENT
NORTH ATLANTIC CURRENT
Z (meters)
LATITUDE
LONGITUDE

about 700 m northward of about 70°N, is thought to originate with the sinking and spreading of warm water carried northward by the West Spitsbergen Current [*Aagaard et al.*, 1985]. The Atlantic layer is represented in the coupled model with relatively warm water at intermediate depths north of about 70°N, extending from about 200 m to 800 m (similar to that shown by *Washington et al.* [1994] in their Figure 3a). Owing to systematic errors noted by *Washington et al.* [1994] and also since the coupled model does not use flux correction, this layer is several degrees warmer than observed. Almost all of this drift occurs in the first 50 years of the ocean spin-up integration, with drifts in the remaining 50 years of less than 0.1°C per century [*Washington et al.*, 1994]. The subsurface salinities in the model are also greater than observed thus maintaining the density structure required for the existence of the Atlantic layer. Consequently, the pattern is qualitatively similar to observations with salinity minima near the surface north of about 70°N and increasing with depth in the Arctic. There are also maximum values near the surface near 65°N [*Washington et al.*, 1994] in the areas of active convection north of the Denmark Strait as observed [*Aagaard et al.*, 1985].

The associated circulation from the coupled model is represented by a plot of meridional overturning stream function for the high latitudes of the Atlantic sector (Figure 2a). A consequence of the lack of flux adjustment in this coupled model is an intensification of the meridional overturning in the North Atlantic from near 20 Sv in the initial ocean state [*Washington et al.*, 1994, Figure 12b] to maximum values greater than 30 Sv in the coupled model (Figure 2a). In spite of the stronger overturning in the coupled model, the general pattern of temperature and salinity is similar to the initial ocean state as noted above. Most of the major circulation features in the North Atlantic region (refer to *Aagaard et al.* [1985] are represented in the coupled model (Figure 2d). For the Arctic, warm water carried northward by the West Spitsbergen Current (Figure 2d) sinks to intermediate levels (Figure 2a) thus maintaining the Atlantic layer at a relatively warmer temperature between about 200 m and 800 m. The colder saline water from below 800 m is then transported southward up and over the Greenland-Scotland Ridge near 65°N (see *Washington et al.* [1994] for ocean bottom topography) to join the sinking waters south of 65°N (Figure 2b). Thus without flux adjustment and in spite of systematic errors that include a warmer and more saline-than-observed Atlantic layer and meridional overturning that is probably somewhat too strong (and sea ice that is somewhat over-extensive, e.g., Figure 3), the coupled model appears to represent the fundamental processes and circulation features involved with the formation and maintenance of the warm Atlantic layer in the Arctic.

A feature of CO_2 climate change experiments noted previously has been the weakening of the meridional overturning in the Atlantic [*IPCC*, 1992]. This is also the case in the present coupled model experiment where the meridional overturning is reduced by about half at the time of CO_2 doubling (Figure 2b). As in other climate change experiments, this is associated with a general warming and freshening of the North Atlantic with increased CO_2. The temperature change for the Atlantic sector from the coupled model near the time of CO_2 doubling is shown in Figure 2c. Consistent with the surface air temperature changes in Figures 1b and 1c, there is warming near the surface in the upper 80 m, with a minimum of warming near 100 m. At intermediate levels from about 200 to 400 m extending from about 70°N to the pole there is a second maximum of warming. Since the warm Atlantic layer extends from about 200 to 800 m in the coupled model, the upper part of this layer has warmed with increased CO_2 in the model. The minimum of warming near 100-m depth suggests that simple diffusive processes are not the main cause of the warming at intermediate depths.

An indication of how the Atlantic layer warms is shown in Figure 2b. With increased CO_2 the intrusion of surface water from the south continues to occur (as indicated by the meridional overturning stream function) but is weakened along with the general reduction of the overturning in the North Atlantic. However, the warmer surface waters (associated with the warming caused by increased CO_2) to the south in Figure 2c are now being intruded into the subsurface Arctic thus causing a general warming of the upper part of the Atlantic layer from about 200 to 400 m in the model. Meanwhile, since the strength of the flow being intruded is reduced (comparing Figures 2a and 2b northward of about 70°N and below about 500 m, roughly 2 Sv in the control case and about 1 Sv in the increased CO_2 case), proportionately less warm water is transported to the lower part of the Atlantic layer thus resulting in a relative cooling below about 600 m. Since these features were not indicated in our earlier 5-degree, four-layer ocean model version that was coupled to a similar atmospheric model [*Washington and Meehl*, 1989], it is likely that the higher ocean resolution in the present 1 degree, 20-layer ocean is necessary to represent this type of CO_2 climate change signal.

Recent observations from the Arctic have shown an anomalous warming at intermediate depths [*Travis*, 1994; *Mikhalevsky et al.*, 1995]. A hypothesized model of the Atlantic layer discussed by *Mikhalevsky et al.* [1995] addresses the scenario of intrusion of warmer Atlantic water via the West Spitsbergen Current. The results show that acoustic mode 2 is most sensitive to such an intrusion. They also note that mode 2 responds strongly to temperature changes between depths of about 200 and 700 m thus suggesting that the Atlantic layer has warmed at those levels by about 0.2°C to 0.4°C since the mid-1980s.

Examination of the time evolution in the model shows that the maximum warming rate of the Atlantic layer occurs at about 0.45°C per decade. The standard deviation of annual mean temperature in this layer is about 0.1°C. Therefore the signal of warming emerges from the noise (as measured by one standard deviation) in the first decade. The rate of warming in the model with CO_2 increase is somewhat larger than the rate of hypothesized warming in the observations noted above of about 0.2°C–0.4°C per decade (assuming the warming has occurred over the past 10 years from the mid-1980s to the mid-1990s). Our larger number is consistent with the relatively high sensitivity of the model to increased CO_2 as noted above. However, preliminary results from a sensitivity experiment run with our model including the effects of the direct effect of sulfate aerosols reduces the overall sensitivity of the model by roughly 40%, with a proportionately smaller rate of warming of the Atlantic layer of about 0.3°C per decade. This latter number is closer to the hypothesized warming in the observations.

The intriguing suggestion, of course, is that the anomalously warm Atlantic layer noted in the recent observations may have something to do with CO_2 warming in the climate system. Even though some areas of the surface western North Atlantic have cooled in recent years, there are indications that the presumed source region for the Atlantic layer (the West Spitsbergen Current) warmed during the 1980s [*IPCC*, 1990]. Thus it is possible that warmer surface water has been intruded into the

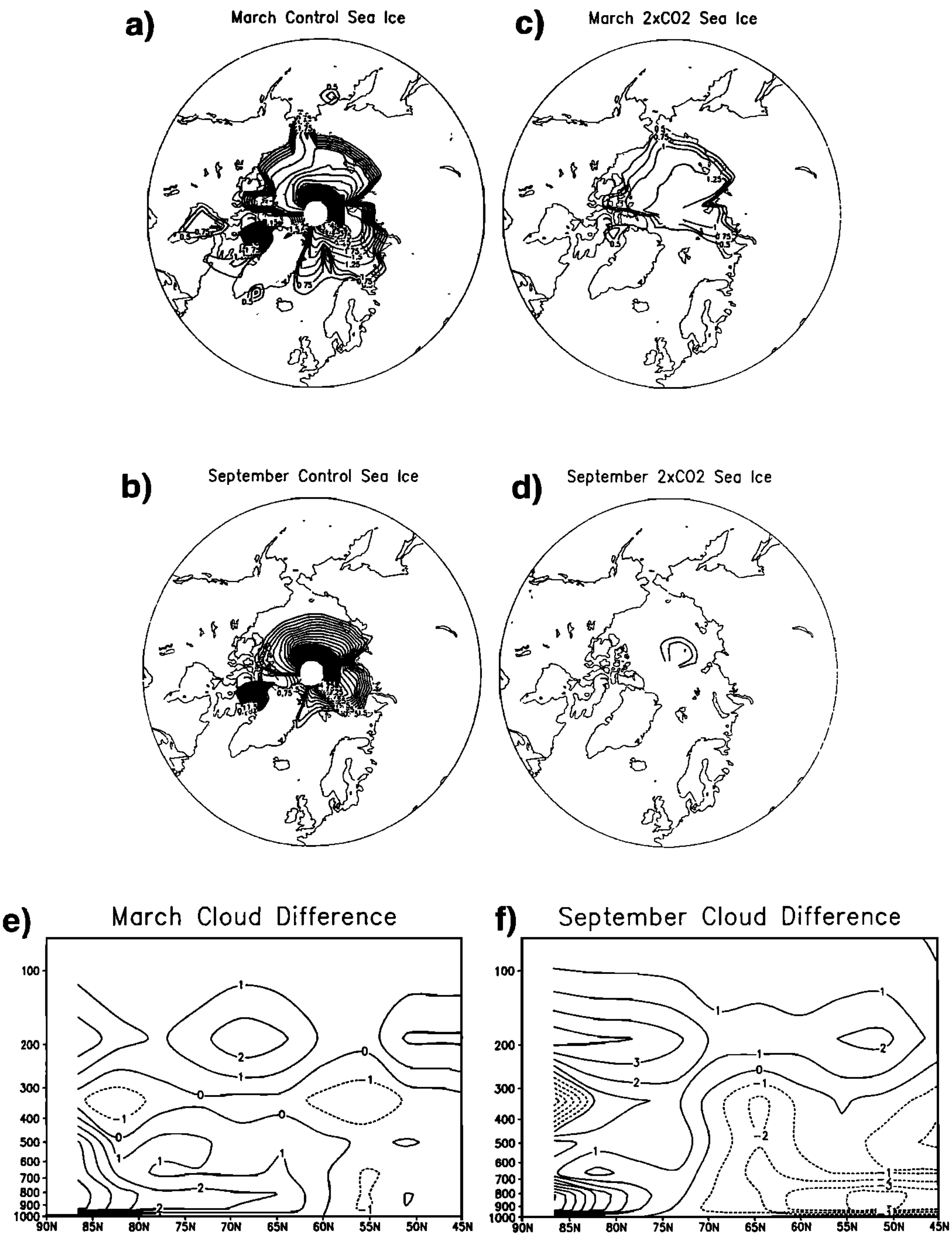


Figure 3. (a) Mean sea ice thickness (in meters, values greater than 0.5 m are plotted) for 20-year averages for the years 55–74 for March from the control integration; (b) as in Figure 3a except for September averages from the control integration; (c) same as Figure 3a except for the transient CO_2 increase integration; and (d) same as Figure 3b except for the transient CO_2 increase integration. The sea ice formulation predicts both ice thickness and concentration. Average ice thickness is shown here. Generally, a definition of ice boundary involving some combination of ice thickness and fraction is less extensive than the simple average ice thicknesses shown here. (e) Zonally averaged March cloud differences north of 45°N for 20-year averages for years 55–74 with transient CO_2 increase experiment minus control are shown; solid lines indicate positive values or increased cloud amount in the increased CO_2 experiment. (f) A plot of the same quantity as in Figure 3e is shown, except zonally averaged cloud differences are for September.

subsurface Arctic region resulting in the anomalously warm Atlantic layer. This appears to be the case for the coupled model with increased CO_2, since the warming of the upper portion of the Atlantic layer is a persistent feature (it is seen in different time periods of the increased CO_2 integration and is not a product of inherent variability in the model). A qualitatively similar signal has also appeared in other coupled models [*Manabe et al.*, 1991; *Cubasch et al.*, 1992; *Murphy and Mitchell*, 1995]. However, we cannot make any definitive statements concerning attribution since a number of signals in the climate

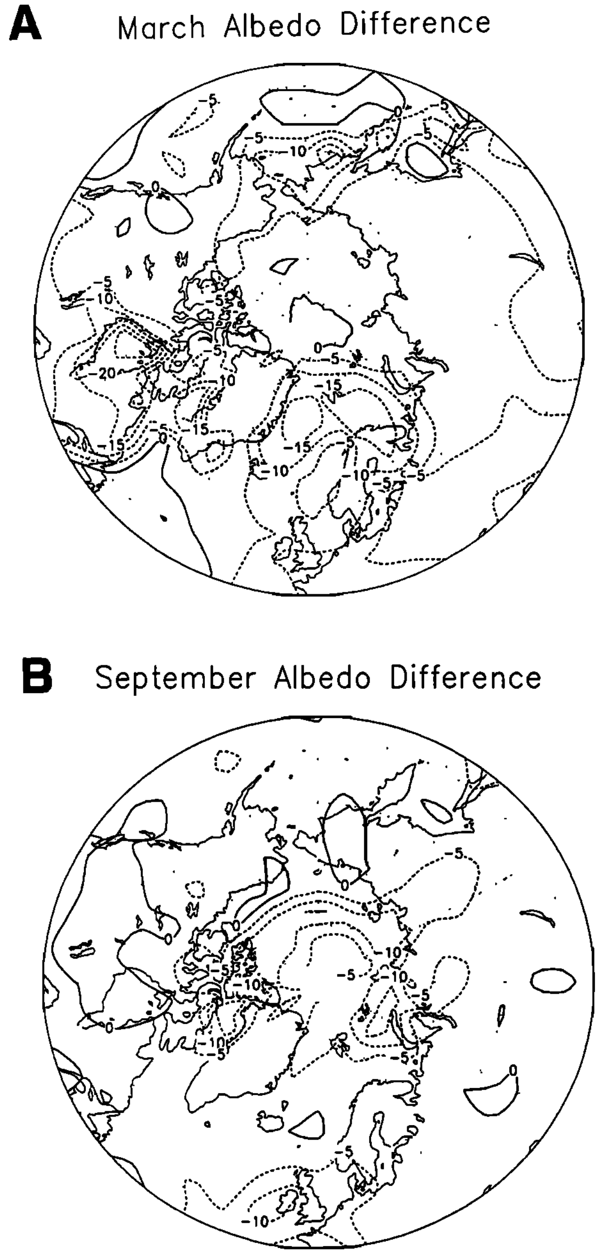


Figure 4. Planetary albedo differences for the transient CO_2 increase experiment minus control, in tenths, for 20 year averages as in Figure 3, for (a) March and (b) September.

system may arise from either "inherent" low frequency variability or from other causes. Yet the coincidence of the recent observations with the model results suggests that this region should be monitored with more fidelity to verify these climate change signals.

Ice Albedo Feedback in the Coupled Model

Associated with the warming of the surface temperatures, we also note a rapid retreat of sea ice in the increased CO_2 experiment (Figures 3a–3d). (Note that these are average ice thicknesses, not average ice extent; average ice extent is dependent on definitions of threshold ice thickness and/or fraction; typical definitions for average ice extent show demarcations less extensive than those suggested by average ice thickness in Figure 3.) This extensive retreat is indicative of an active ice-albedo feedback in the model. This also suggests a similarity to a recent documentation of Arctic sea ice diminishing at a rate of 3%–4% per decade [*Johannessen et al.*, 1995]. As discussed above, this does not allow us to attribute the recent observed trends to increasing CO_2 in the climate system, but the model results do indicate a qualitative consistency with the observations even though there is large decadal timescale variability associated with sea ice extent [e.g., *Barry et al.*, 1993].

We observe that when sea ice melts in the spring and summer in the Arctic with the seasonal cycle, there is a preponderance of low stratus cloud that decreases incoming solar radiation to contribute to moderating the albedo effects of the diminished seasonal sea ice [e.g., *Curry and Herman*, 1985]. To examine changes of cloud in the coupled model, Figures 3e and 3f show that indeed with the retreat of sea ice with increased CO_2 there is an increase of low cloud at both times of year that is especially pronounced during March (Figure 3e). These features have also been noted in other coupled model studies. Thus one could expect that the decrease of surface albedo from the melting sea ice would be compensated to a certain extent by the increase of albedo from the greater amounts of low stratus cloud. Since low cloud does increase over the Arctic in the simulation with increasing CO_2, there is a contribution to increased planetary albedo from this source. However, this does not totally compensate for the lower surface albedo as certain regions in the Arctic make the transition from ice-covered in the control case to ice-free in the increased CO_2 case. Figure 4 shows that planetary albedo decreases over most regions of the Arctic in the simulation with increased CO_2 leading to an enhanced ice-albedo feedback (since the surface absorbs more incoming solar radiation in summer, not shown).

Discussion and Conclusions

A global coupled ocean-atmosphere-sea ice climate model is run with CO_2 increasing at 1% per year compounded without flux correction. In this paper we have addressed three topics. First, we have provided an initial description of the results from this experiment involving global patterns of surface air temperature change and globally averaged temperature increase. Second, we have noted the mechanism in the model that contributes to the maintenance of the Atlantic layer in the subsurface Arctic and that intrusion of warmer surface water in the increased CO_2 experiment warms the upper portion of the Atlantic layer in the model. This is also qualitatively similar to recent observations of warming of the Atlantic layer in the Arctic. Third, we have presented evidence that coupled cloud feedbacks involving sea ice retreat in the model does not moderate the ice-albedo feedback, and this contributes to the high sensitivity of this model.

One major question that remains is how realistically the coupled model simulates ocean-ice-low cloud feedbacks. With an improved boundary layer formulation, it is possible that there would be even more enhancement of low cloud over ice-free regions in the increased CO_2 case that would moderate the strong ice-albedo feedback in this and other coupled models. Another major question is whether the warm layer recently observed at intermediate depths in the Arctic is due to climate changes associated with increased CO_2 or whether it is associated with some kind of inherent decadal timescale fluctuation. Answers to the first question will involve improved coupled models, and answers to the second question will require enhanced observations in the Arctic over a longer time period.

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