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# The effects of reduced land fraction and solar forcing on the general circulation: results from the NCAR CCM

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ABSTRACT

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Land fraction and the solar energy at the top of the atmosphere (solar constant) may have been significantly lower early in Earth's history. It is likely that both of these factors played some important role in the climate of the early earth. The climate changes associated with a global ocean(i.e. no continents) and reduced solar constant are examined with a general circulation model and compared with the present-day climate simulation. The general circulation model used in the study is the NCAR CCM with a swamp ocean surface First, all land points are removed in the model and then the solar constant is reduced by 10% for this global ocean case.

Results indicate that a 4 K increase in air temperature occurs with the global ocean simulation compared to the control. When solar constant is reduced by 10% under global ocean conditions a 23 K decrease in air temperature is noted. The global ocean warms much of the troposphere and stratosphere, while a reduction in the solar constant cools the troposphere and stratosphere. The largest cooling occurs near the surface with the lower solar constant.

Global mean values of evaporation, water vapor amounts, absorbed solar radiation and the downward longwave radiation are increased under global ocean conditions, while all are reduced when the solar constant is lowered. The global ocean simulation produces sea ice only in the highest latitudes. A frozen planet does not occur when the solar constant is reduced—rather, the ice line settles near 30° of latitude. It is near this latitude that transient eddies transport large amounts of sensible heat across the ice line acting as a negative feedback under lower solar constant conditions keeping sea ice from migrating to even lower latitudes.

Clouds, under lower solar forcing, also act as a negative feedback because they are reduced in higher latitudes with colder atmospheric temperatures allowing additional solar radiation to reach the surface. The overall effect of clouds in the global ocean is to act as a positive feedback because they are slightly reduced thereby allowing additional solar radiation to reach the surface and increase the warming caused by the removal of land. The relevance of the results to the "Faint-Young Sun Paradox" indicates that reduced land fraction and solar forcing affect dynamics, heat transport, and clouds. Therefore the associated feedbacks should be taken into account in order to understand their roles in resolving the "Faint-Young Sun Paradox".

## Introduction

The Sun's energy output received at the top of the Earth's atmosphere was significantly smaller early in Earth's history—perhaps 20–30% lower 3.8 Ga (Ga $= 1 \times 10^9$ yr) B.P. (Newman and Rood, 1977; Gough, 1977). Energy balance models (EBMs) predict that, if solar luminosity is reduced by a few percent, a frozen earth evolves (known as the ice-albedo catastrophe)(Sellers, 1969; Budyko, 1969). Contrary to model results, the geologic record shows that water was flowing at the Earth's surface 3.8 Ga (Walker, 1987). The discrepancy between model results and the geologic evidence of flowing water is commonly

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known as the "Faint-Young Sun Paradox". Moreover, there is no geologic evidence of glaciation until the late Archean (2.7 Ga) (Frakes, 1979).

Presently, the "Faint-Young Sun Paradox" can be resolved if the Earth's atmosphere contains large concentrations of carbon dioxide ($CO_2$) (Kasting, 1987; Kuhn et al., 1989). The absorption properties of $CO_2$ would have counterbalanced the lower energy output of the Sun by directing additional longwave radiation at the surface. The large concentrations of $CO_2$ for the Archean (2.5–3.8 Ga) are extrapolated from one-dimensional-radiative-convective (1DRC) models and EBMs. $CO_2$ is increased in these models until a balance is achieved between the lower solar luminosity and the warming effects of higher $CO_2$ concentrations. But, there is no direct evidence for very large amounts of atmospheric $CO_2$ in the early atmosphere (Walker, 1990). Cloud feedback (Rossow et al., 1982) and the possible role of oceanic transport (Henderson-Sellers and Henderson-Sellers, 1988) could be major factors to understanding Archean climate.

A general circulation model (GCM) is used to consider the effects of reduced solar forcing and land fraction on the climate system. The inclusion of interactive clouds and atmospheric dynamics could give some idea of how the climate of the early earth may have been different from the present. In essence, primary and secondary feedbacks are allowed because of the inclusion of atmospheric dynamics, interactive clouds, and the hydrologic cycle that have not been included in many of the earlier studies investigating the "Faint Young-Sun Paradox". As will be shown in section 3, dynamics, the hydrologic cycle and particularly clouds are affected by changes in land fraction and solar forcing.

Geologic evidence indicates that earth may have contained only small fractions of land in the early Archean (Hargraves, 1976). Continental cratons in the form of embryotic islands may have been the predominate land masses on this young planet with most of the present-day land forming after 3 Ga. Therefore a global ocean is simulated in this study to mimic the conditions of the early earth. The "swamp" ocean is described in section 2.

The second experiment in this paper investigates reduced solar forcing (the solar constant) at the top of the atmosphere. The solar constant is reduced by 10% under zero land fraction conditions with the National Center for Atmospheric Research (NCAR) Community Climate Model (CCM). While the solar forcing was likely 20–35% lower than present for the early earth, the purpose of this experiment is to determine if a frozen earth occurs as noted by Budyko(1969) and Sellers (1969) in their EBM studies. Recent EBM results (Gerald et al., 1992) show the solar constant can be reduced significantly under global ocean conditions before global glaciation occurs.

Second, there is a need to determine what changes in the climate system occurs with a 10% reduction in the solar forcing. Are there more clouds? Does the Hadley cell strengthen or weaken? Is the hydrologic cycle altered? These question can be answered with a GCM and could suggest important features of the climate that need to be investigated further. Wetherald and Manabe (1975) used a GCM to test the effects of the solar constant on atmospheric circulation and found sizable changes in precipitation, surface temperature, eddy kinetic energy, etc. But a completely frozen earth did not result from a 4% decrease in the solar constant. This simulation differs because interactive clouds are used compared to the fixed cloud experiments of Wetherald and Manabe (1975).

In summary, this study examines changes in the climate system under zero land fraction and also zero land fraction combined with a reduction in the solar forcing. Questions of how these changes affect dynamical features (transient eddies, Hadley circulation), surface energy balance, clouds, water vapor distribution, planetary albedo and sea ice equilibrium position will be addressed in this paper.

## Model description and experiments

The experiments for this study used the CCM0A version of the NCAR CCM. This version of the model has 9 vertical sigma levels (denoted $s$ in this paper) and a horizontal resolution of 4.5° of latitude by 7.5° of longitude (R15). The present-day climate simulation statistics for CCM0A is given by Washington and Meehl (1983). This version calculates the sea surface temperature from the surface energy balance for an ocean with no heat capacity. All simulations take place under mean annual forcing (ie. each latitude has a set zenith angle throughout the simulation). The swamp ocean takes approximately 200 days of simulation time to come to equilibrium. However, for statistical purposes (a large enough sample sized for analysis) this model should be run out considerably longer. I have run each experiment for approximately 300 days in order to keep computation cost at a minimum.

Two meters of sea ice forms in the model when the calculated sea surface temperatures are less than or equal to 271.2 K. The albedo scheme for snow and sea ice is (Washington and Meehl, 1986): If $T <= 263$K then sea ice albedo = 0.35; snow albedo = 0.4. If $T < 263$ K sea ice albedo = 0.7; snow albedo = 0.8. Snow is not permitted to accumulate over sea ice. There is interactive hydrology and clouds. Clouds form as a function of relative humidity and atmospheric stability (Ramanathan et al., 1983).

There are two types of clouds that can form in this version of the CCM, nonconvective and convective clouds. Nonconvective clouds form when the relative humidity is greater than 80% and have a fractional cloud coverage of 95%. Convective clouds form when the relative humidity is greater than 80% and there is atmospheric instability; the change of equivalent potential temperature with respect to height is less than zero. The fraction cloud coverage is a maximum of 30% percent for convective clouds. Clouds have albedos that vary as a function of the cosine of the zenith angle (Ramanathan et al., 1983). Low clouds (0.926*s* and 0.811*s*) have an albedo that vary from 0.3750 at the equator to 1 at the poles. Middle clouds (0.664*s*, 0.500*s*) have an albedo that vary from 0.31 at the equator to 1 at the pole while high clouds (above 0.500*s*) have an albedo that varies from 0.1304 at the equator up to 1 at the poles. If clouds are forming at two levels simultaneously, the cloud with the higher albedo is assumed for the total cloud albedo.

Three sets of experiments are performed (Table 1): a present-day simulation (CONTROL), a global ocean—zero land fraction (GLOCEAN), and a 10% reduction in the solar constant and zero land fraction (COLDO). The control experiment that represents the present-day climate is integrated for 300 days, the last 100 days used as the average. The global ocean experiment is integrated for approximately 450 days with the last 200 days as the time average. The initial boundary conditions for GLOCEAN was started from NH winter conditions and therefore took somewhat longer to equilibrium. COLDO is integrated for 300 days with the last 100 days used as the average.

TABLE 1

Summary of planned experiments

| Experiment | Land fraction (%) | Solar constant (W/m$^2$) |
|---|---|---|
| CONTROL | 100 | 1370 |
| GLOCEAN | 0 | 1370 |
| COLDO | 0 | 1233 |

## Responses to reduced land fraction and solar forcing

### *(a) Temperature*

When land is removed, considerable warming takes place at the surface and the equator-to-pole

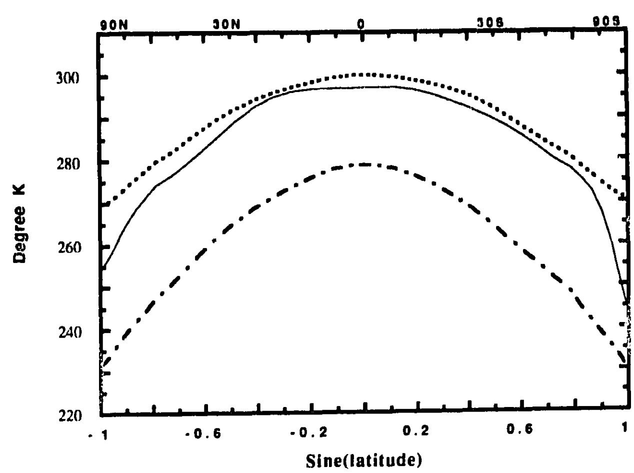


Fig. 1. Air temperatures (sigma = 0.991). Solid lines for the CONTROL, dotted lines for GLOCEAN and dash-dotted for COLDO. Units in degree K.

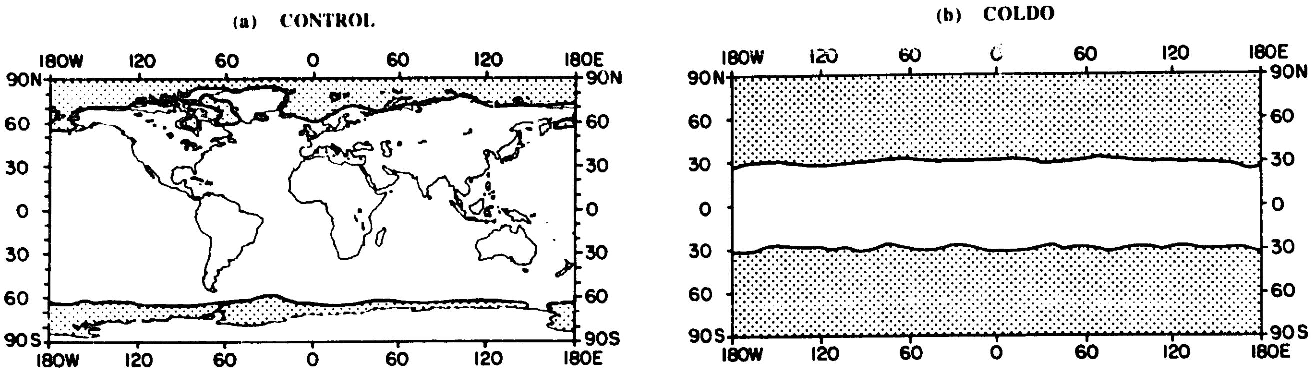


Fig. 2. Sea ice edge. (a) CONTROL. (b) COLDO. Sea ice exist in stippled areas.

temperature difference is the smaller than that of the control (Fig. 1). The polar temperatures in both hemispheres for experiment GLOCEAN are near the freezing point of sea ice (271.2 K), and equatorial temperatures are just above 300 K. On the other hand, a 10% reduction in the solar constant (experiment COLDO) causes much colder surface temperatures. The largest cooling occurs in high latitudes which increases the equator-to-pole temperature difference. The much cooler surface temperatures allows sea ice to migrate into subtropical regions. The sea-ice edge settles near 30° of latitude compared to the CONTROL sea-ice edge which is near 60° (Fig. 2).

Warmer tropospheric and stratospheric temperatures occur under global ocean conditions with the largest temperature increase occurring over Antarctica (Fig. 3a). The large increase is due to the removal of the Antarctic ice sheets. A similar warming occurs in the Northern Hemisphere polar regions but is smaller. The warming in the polar regions is related to the removal of sea ice. An area of heating occurs near 8 km in equatorial regions because of warmer sea surface temperatures (SSTs) which increases convection and allows for more latent heat release. In experiment COLDO, cooler temperatures result throughout the troposphere and stratosphere, with the largest cooling occurring very close to the surface and in the middle troposphere over the equator when compared to the present-day climate control (Fig. 3b). The reduced equatorial

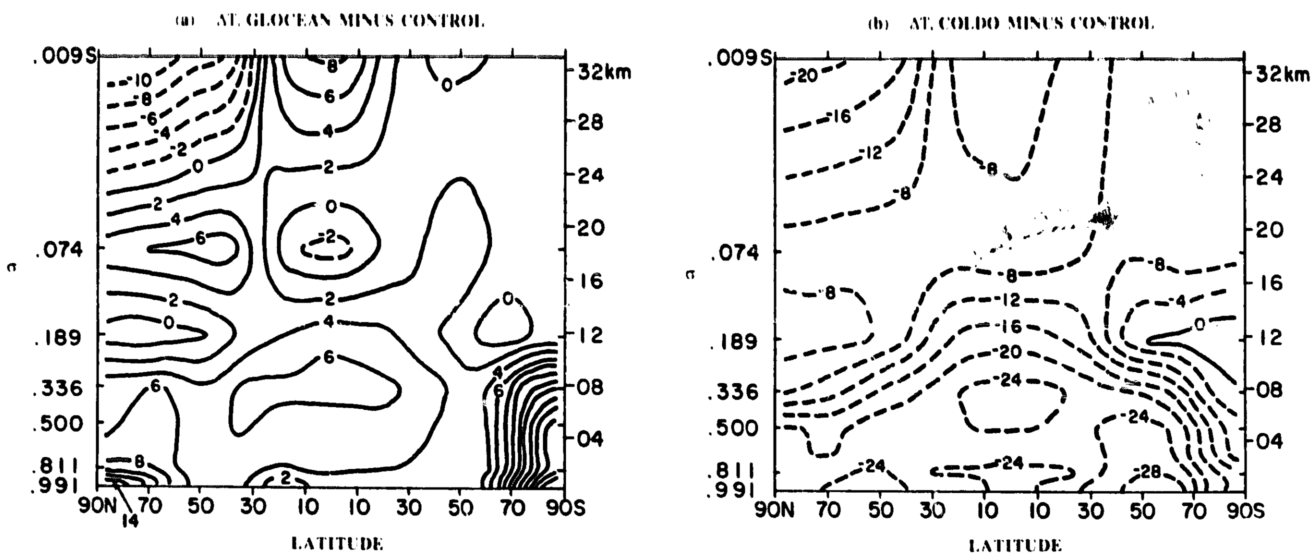


Fig. 3. Differences in atmospheric temperatures. (a) GLOCEAN minus CONTROL. (b) COLDO minus CONTROL. Units in degree K. Solid contours represent warmer temperatures, dashed cooler temperatures.

SSTs promote less convection reducing latent heating in the middle troposphere.

*(b) Dynamics*

The global swamp ocean allows for stronger westerly jets even though the surface equator-to-pole temperature difference is smaller compared to the control (Fig. 4a,b). However, the mean temperature for the layer between 200 and 500 mb displays a larger equator-to-pole difference in comparison to the control because of the warmer SSTs in equatorial regions which heat the middle troposphere. Thus, the thermal wind relationship is not violated. Experiment COLDO produces westerly jets with magnitudes similar (Fig. 4a,c) to the control but, they are shifted slightly equatorward and more narrow in latitudinal width than the control simulation.

Removal of land also brings about nearly symmetric Hadley and Ferrel cells. The Hadley cell in the control's Northern hemisphere is similar in magnitude to experiment GLOCEAN, while being somewhat stronger in the southern hemisphere (Fig. 5a,b). The Hadley and Ferrel cells are stronger in experiment COLDO than the present day control (Fig. 5a,c). There is more latent heat being released in the shallow air layers near the surface in equatorial regions of COLDO to drive the Hadley cell (Fig. 6). The stronger Ferrel suggest stronger baroclinic activity in middle latitudes of experiment COLDO.

In experiment COLDO, the transient eddies (traveling disturbances) behave somewhat differently as the ice-edge migrates into subtropical regions. The eddies in COLDO transport large amounts of sensible heat across the ice edge which is evident from the transport of dry static energy by transient eddies (Fig. 7). The sea-ice edge fluctuates in position with the development of traveling disturbances which can grow as a result of the large temperature gradient. The poleward transport of heat from low latitudes into mid-latitudes keeps sea ice from migrating into low latitudes. Analysis of the temperature tendency for dynamic terms indicate that the transients cool the subtropics much more than

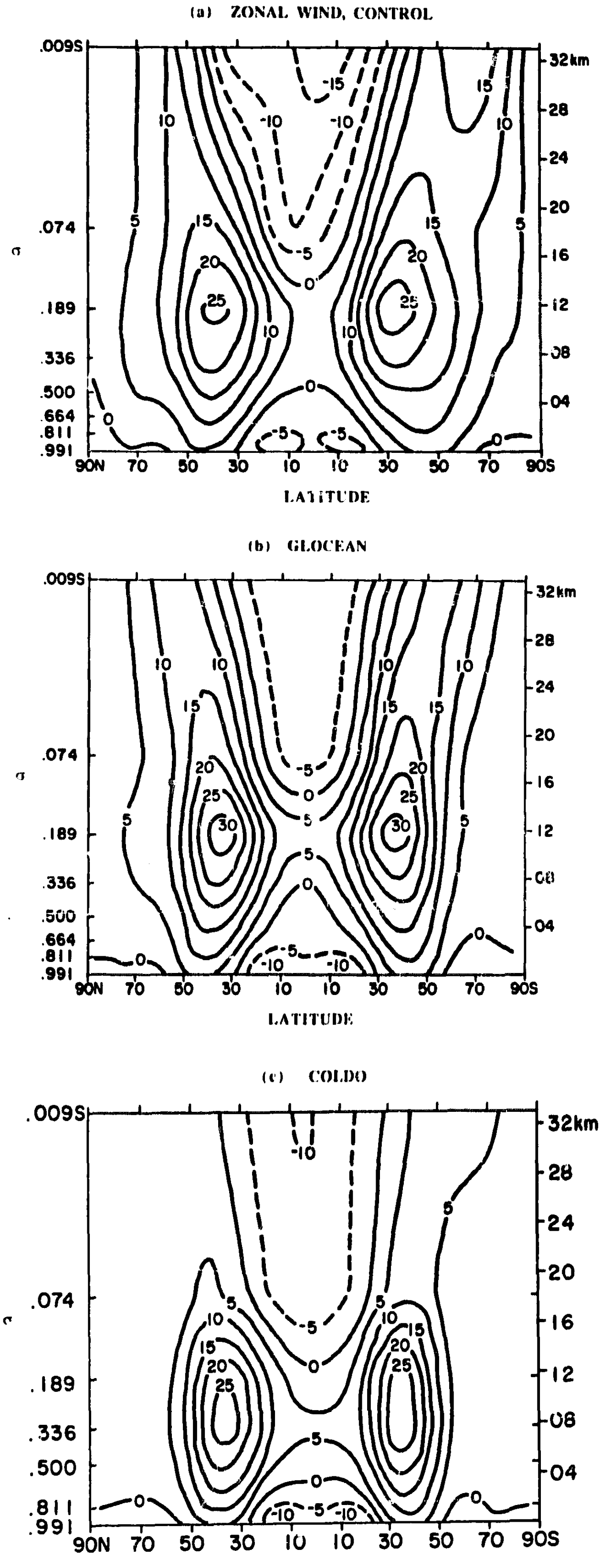


Fig. 4. Zonal winds for: (a) CONTROL, (b) GLOCEAN and (c) COLDO. Units in m s$^{-1}$.

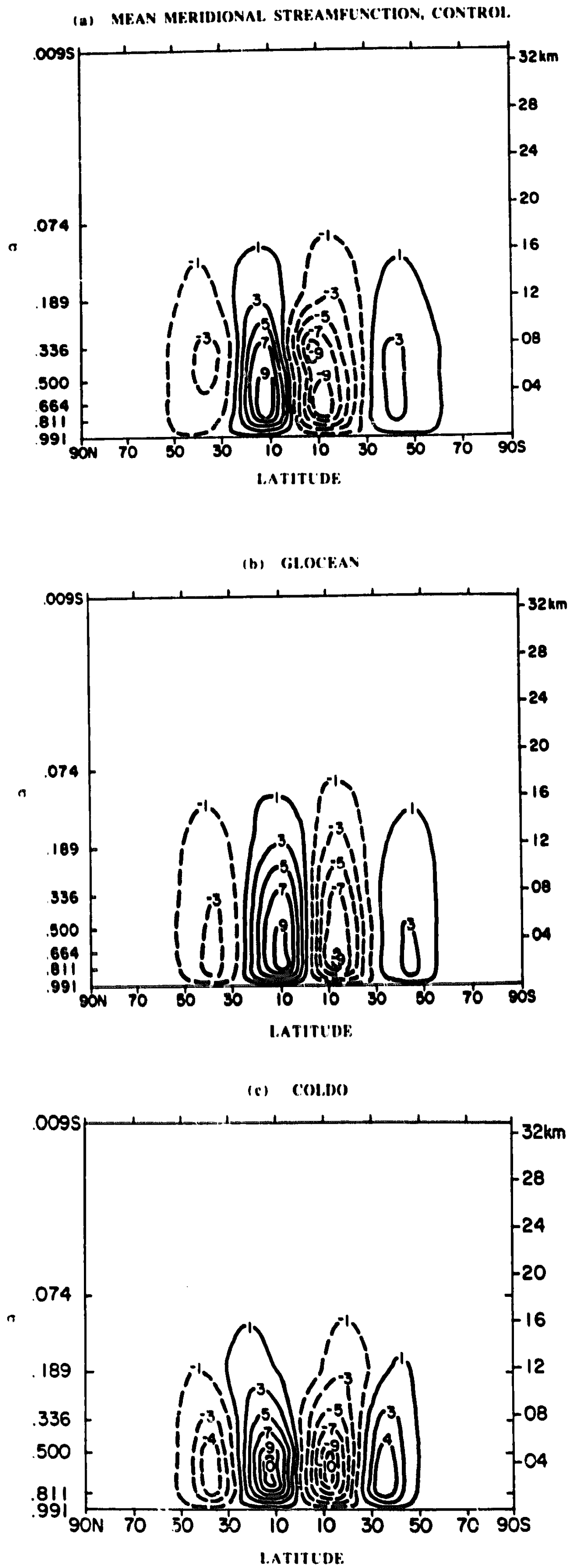


Fig. 5. Mean meridional streamfunction. (a) CONTROL. (b) GLOCEAN. (c) COLDO. Units in $10^{10}$ kg $s^{-1}$. Solid contours indicate counterclockwise flow, dashed contours indicate clockwise flow.

the present day climate control by transporting heat poleward (not shown).

### *(c) Surface energy balance*

The surface energy balance for experiment GLOCEAN shows that absorbed solar radiation and latent heat fluxes have increased, while sensible and net infrared radiative (net IR: $F\uparrow - F\downarrow$) fluxes have decreased (Fig. 8a–d). The increase in absorbed solar radiation is largest in high latitudes and is due to the smaller surface albedo of the global ocean and a slight reduction in clouds (Fig. 11a). The latent heat flux increases because of the additional water sources with the removal of continents. In addition to the larger ocean area with experiment GLOCEAN, the latent heat flux increases because of the warmer surface temperatures. The latent heat flux is proportional to the vertical gradient of water vapor and wind speed:

$$E \propto |V|(M_s(T(*)) - M_1) \qquad (1)$$

Here $E$ is the latent heat flux, $M_s$ is the saturation mixing ratio at the surface and is a function of $T(*)$, the surface temperature. $M_1$ is the mixing ratio at the lowest atmospheric layer and $V$ is the wind speed of the lowest atmospheric level. Thus, warmer surface temperatures increase the water vapor differences between the surface and the lowest atmospheric layer.

Atmospheric water vapor amounts also increase (Fig. 9a) which causes outgoing longwave radiation from the surface to be intercepted in the lower troposphere and emitted back towards the surface. Therefore $F\downarrow$ increases at the surface because of a strong water vapor feedback. But, because clouds decrease (Fig. 11a) in many regions which tends to reduce $F\downarrow$ and at the same time $F\uparrow$ increases because of higher surface temperatures everywhere, there is only a small decrease in global net IR for GLOCEAN (Table 2). Zonally, there is a decrease in the net IR in

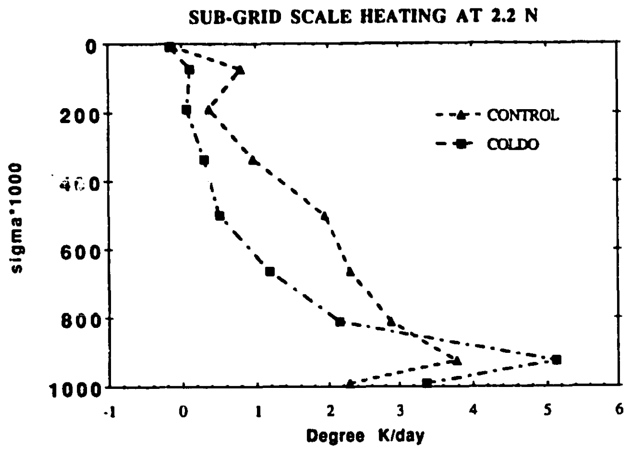


Fig. 6. Sub-grid scale heating at 2.2 N. Solid lines for CONTROL, dashed lines for COLDO. Units in degree K $day^{-1}$.

regions of cloud increases and a slight increase in Net IR in regions of cloud decreases (Fig. 8c). The sensible heat flux is smaller in GLOCEAN than the CONTROL experiment, indicating that the temperature differences between the surface and lowest atmospheric layer are smaller with a global ocean (Fig. 8d).

In experiment COLDO absorbed solar radiation and latent heat fluxes are smaller, while the sensible heat and net IR fluxes are larger than the control (Fig. 8a-d). In COLDO, the net IR at the surface primarily balances the heating from solar radiation. This is in contrast to the present-day climate control where evaporation largely balances the heating from solar radiation. One reason is that the absorbed solar radiation is smaller than the present-day control at all latitudes except the highest latitudes (Fig. 8a) The reduction in absorbed solar radiation cools surface temperatures, sea ice forms and the latent heat fluxes are driven down. However, in the highest latitudes the large reduction in clouds (fig. 11b) allows for more solar radiation to reach the surface than in the control experiment.

The latent heat flux of COLDO is smaller than the control because sea ice isolates the swamp ocean's water supply from the atmosphere. In addition, Eq. (1) shows that the cooler surfaces temperatures reduce the vertical water vapor gradient driving down the latent heat flux. The smaller latent heat fluxes are reflected in the amount of smaller atmospheric water vapor amounts in experiment COLDO when compared to the control (Fig. 9b). Smaller atmospheric water vapor amounts along with a reduction in clouds (Fig. 11b) is the reason that there is a decrease in the downward longwave radiation at the surface; the net IR increases. The larger sensible heat flux in experiment COLDO, especially in the low latitudes, indicates that a significant amount of heat is going from the open ocean to the atmosphere because of larger difference in surface and air temperatures (Fig. 8d).

### *(d) Responses of water vapor, relative humidity and clouds*

Atmospheric water vapor amounts are increased with the removal of land consistent with higher evaporation rates (Fig. 9a). However, this increase in water vapor is not totally reflected in the changes of relative humidity with a global ocean. The relative humidity decreases below the middle troposphere of low and mid-latitudes but increases throughout the rest of the troposphere (Fig. 10a). The relative humidity is computed in the CCM by two terms, the saturation vapor pressure and the mixing ratio. Therefore, relative humidity decreases are caused by warmer atmospheric temperatures (Fig. 3a) which increases the saturation vapor pressure. Increases in relative humidity are caused by increased atmospheric water vapor amounts as shown in Fig. 9a.

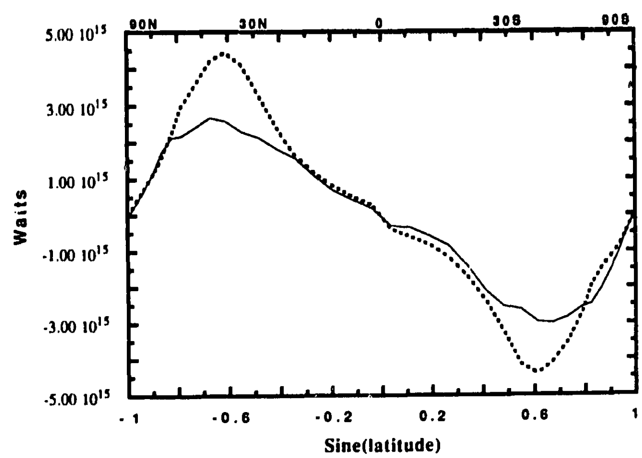


Fig. 7. Atmospheric poleward transport of dry static energy by transient eddies. Solid line for CONTROL, dashed lines for COLDO. Units in Watts.

Because clouds are produced as a function of relative humidity, the distribution of clouds increases and decreases are similar to the changes in relative humidity. Cloud amounts decrease below the middle troposphere in low and mid-latitudes and increase elsewhere (Fig. 11a). This amounts to an increase in total clouds in high latitudes and a slight decrease in middle and low latitudes (Fig. 12). Equatorward of 50° warmer SSTs lead to convective instability increasing convective clouds (not shown) and decreasing nonconvective clouds which have a smaller cloud fraction than convective clouds. Therefore the total cloud fractions slightly decrease. The Southern Hemisphere shows a decrease in clouds between 60°S and 70°S (circumpolar current) due to a decrease in nonconvective clouds caused by the removal of land masses. This region of open waters in the control is associated with storm tracks and high cloud amounts.

Reduced solar forcing (exp. COLDO) has smaller atmospheric water vapor amounts associated with smaller evaporation rates (Figs. 9b and 8b). The reduction in the water vapor amounts is reflected in the relative humidity which decreases throughout much of the troposphere and stratosphere (Fig. 10). An increase in relative humidity occurs in low latitudes of the lower troposphere because of a slight equatorial shift of the Hadley cells. Near 30° of latitude there is rising motions for

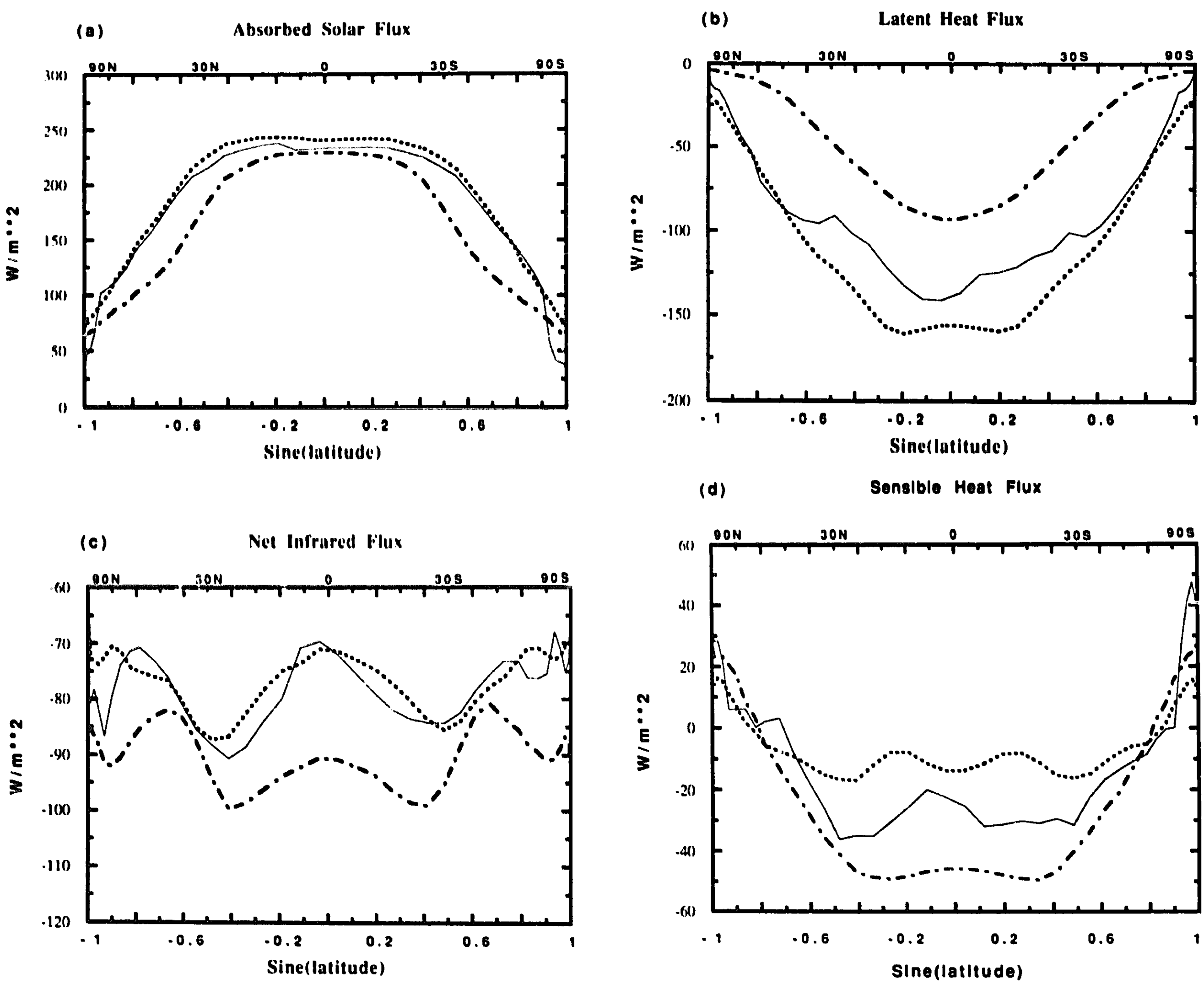


Fig. 8. Surface energy balance. (a) Absorbed solar radiation at the surface. (b) Latent heat fluxes. (c) Net longwave fluxes. (d) Sensible heat fluxes. Solid lines for CONTROL, dotted lines for GLOCEAN and dash-dotted for COLDO. Units in W $m^2$. Positive values represent fluxes into the surface, negative values are fluxes to the atmosphere from the surface.

TABLE 2

Global mean values for CONTROL, GLOCEAN, COLDO

| Variable | CONTROL | GLOCEAN | COLDO |
|---|---|---|---|
| $T_{air}$ (K) | 284.96 | 289.10 | 261.28 |
| Total cloud fraction | 0.423 | 0.407 | 0.409 |
| Sensible Heat ($W/m^2$) | 16.364 | 7.718 | 27.298 |
| Latent heat ($W/m^2$) | 93.139 | 110.910 | 47.164 |
| Net IR ($W/m^2$) | 78.173 | 77.173 | 96.789 |
| $F_{solar}$ at surface ($W/m^2$) | 188.09 | 197.75 | 165.15 |
| Planetary albedo | 0.292 | 0.255 | 0.361 |

COLDO in contrast to sinking motions in the control at the poleward edge of the Hadley cell. Whereas, near 40° of latitudes, a stronger eddies associated with a stronger Ferrel cell allows for greater vertical motions (Fig. 4).

Changes in clouds in COLDO follow the trend of the changes in the relative humidity field. In general, clouds increase in the middle troposphere equatorward of 50°, but decrease elsewhere (Fig. 11b). The decrease in high latitude

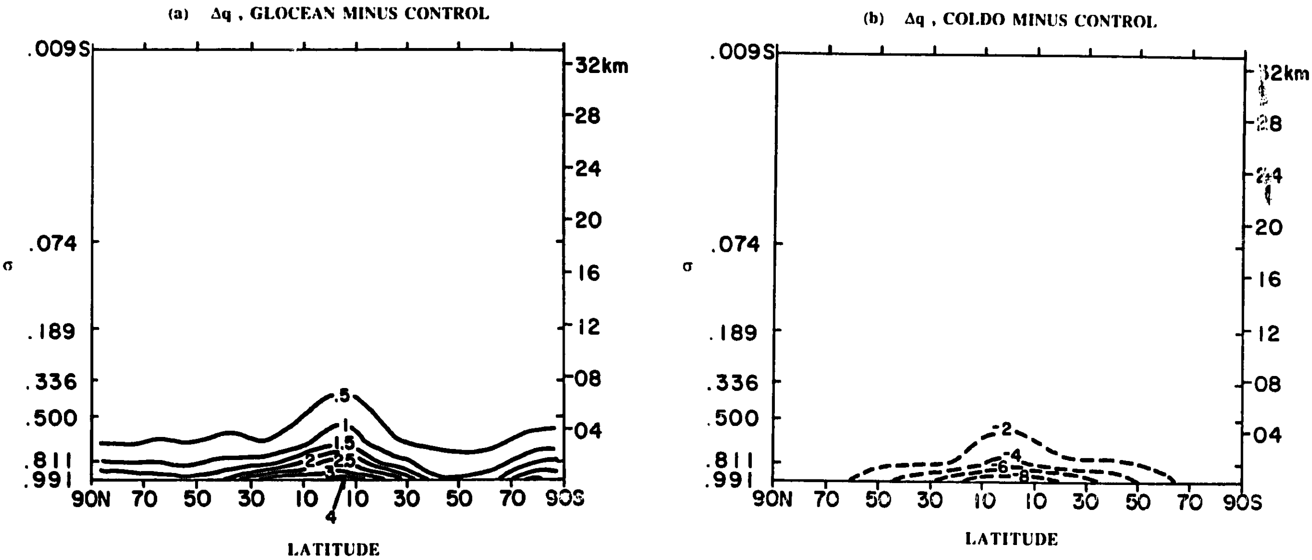


Fig. 9. Differences in mixing ratio. (a) GLOCEAN minus CONTROL. (b) COLDO minus CONTROL. Units in g $kg^{-1}$. Solid contours represent higher atmospheric water vapor amounts, dashed contours represent lower water vapor amounts.

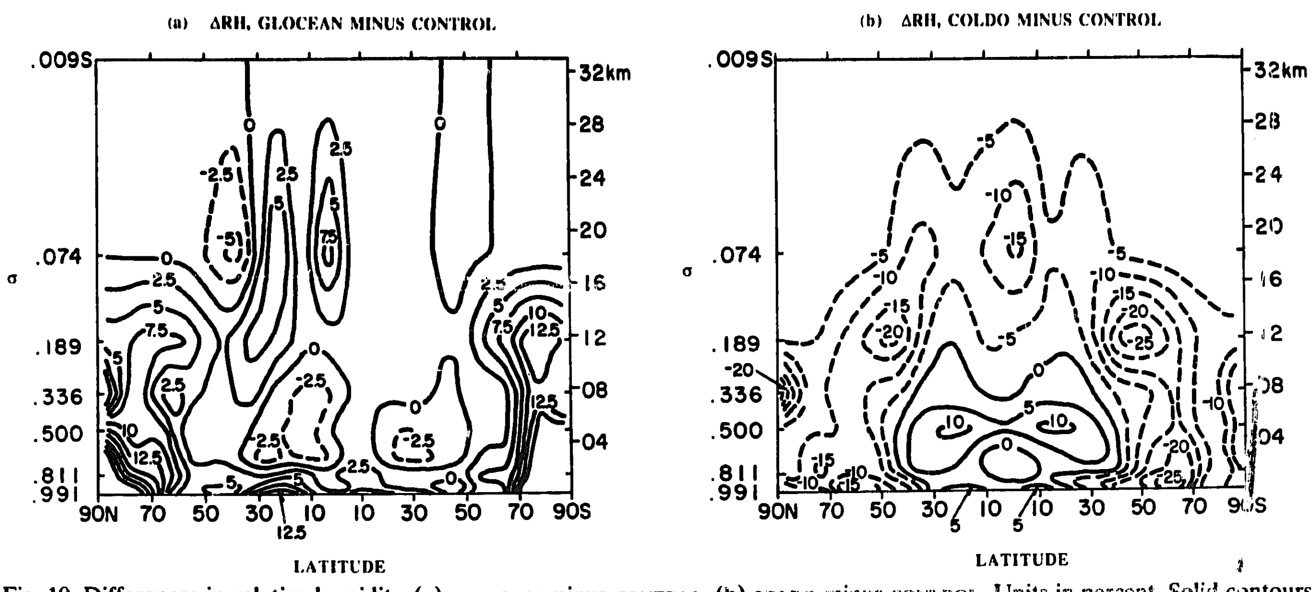


Fig. 10. Differences in relative humidity. (a) GLOCEAN minus CONTROL. (b) COLDO minus CONTROL. Units in percent. Solid contours represent increases in relative humidity, dashed contours represent decreases in relative humidity.

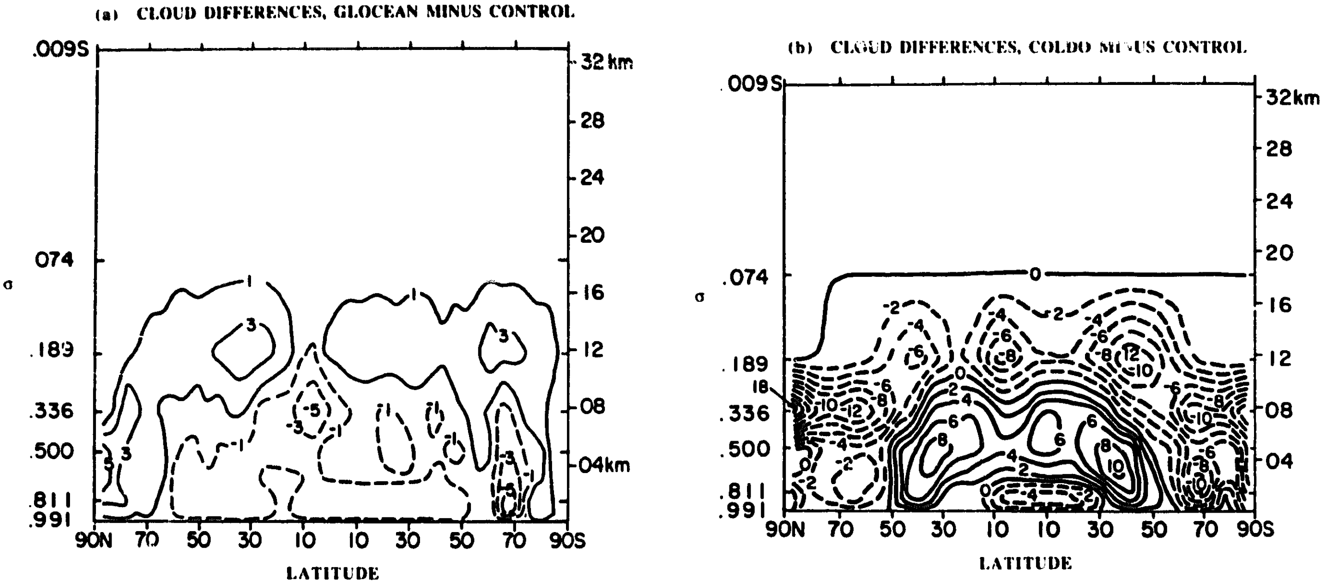


Fig. 11. Differences in clouds. (a) GLOCEAN minus CONTROL. (b) COLDO minus CONTROL. Units in percent.

clouds following the trend of relative humidity and water vapor, while the increase in cloud are primarily caused by changes in Hadley cell position. The zonal mean total cloud fractions decrease in the highest and lowest latitudes but increase elsewhere. Even with lower equatorial SSTs, an increase in convective clouds (not shown) in the lowest layers occurs in response to a stronger Hadley cell (Fig. 4c). Convective clouds form at the expense of the nonconvective clouds, thereby driving down the total cloud fraction in these regions.

## *(e) Planetary albedo*

The planetary albedo is reduced with the removal of land because of the lower surface albedos (Fig. 13). GLOCEAN shows that what should amount to an increase in planetary albedo due to an increase in middle and high clouds (Fig. 11a)

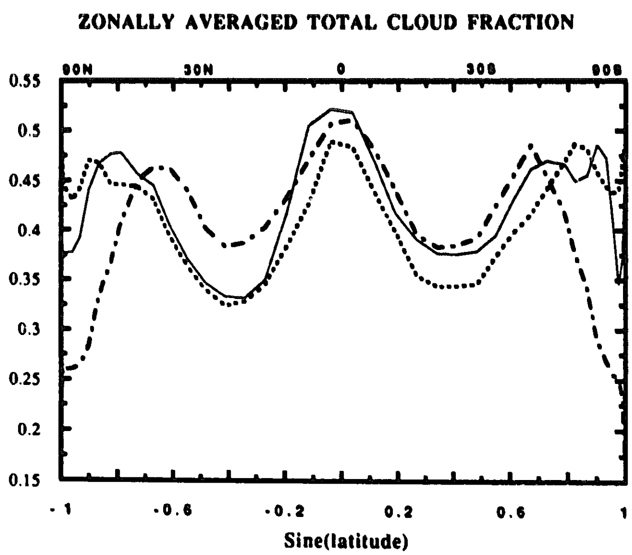


Fig. 12. Total cloud fraction. Solid lines for the CONTROL, dotted lines for GLOCEAN and dash-dotted for COLDO. Units in percent.

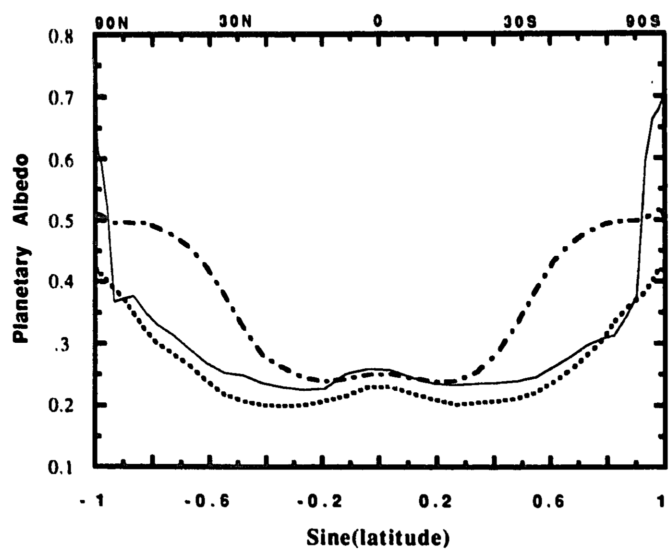


Fig. 13. Planetary albedo. Solid lines for the CONTROL, dotted lines for GLOCEAN and dash-dotted for COLDO. Units in percent.

is counterbalanced by the lower surface albedos under near ice-free conditions.

The planetary albedo increases at all latitudes except the highest latitudes with a reduction in solar forcing (Fig. 13). In experiment COLDO extreme high latitudes undergo a large reduction in clouds (Fig. 12) and hence the planetary albedo is reduced. In addition, because snow is not allowed to form on sea ice a slightly smaller surface albedo occurs in COLDO. The Global mean planetary albedos for GLOCEAN and COLDO is given in Table 2.

## Conclusions

This study was undertaken to gain insight to climate changes caused by reduced land fraction and solar forcing with the NCAR CCM. This paper is part of a larger study (Jenkins, 1991) in which the effects rotation rate, solar forcing, land fraction and higher $CO_2$ concentrations on climate were investigated with the NCAR CCM. A swamp ocean was used in this coupled atmosphere–ocean model to mimic global ocean conditions. In the next paper (in progress) the role of carbon dioxide and rotation rate under lower solar constant conditions will be explored.

In summary, a global ocean simulation had warmer surface, tropospheric and stratospheric temperatures compared to the present-day climate control. The cloud fraction was somewhat smaller than the control because of a switch from nonconvective to convective clouds and reduced relative humidity in a few regions. The evaporation and water vapor amounts were larger than the control. Finally, mean meridional motions were more symmetric in general. A summary of changes under land-less conditions is noted in Table 2.

When the solar constant was reduced by 10% under zero land fraction condition, much colder surface, tropospheric and stratospheric temperatures resulted. Atmospheric water vapor, relative humidity and clouds were lower except in regions of the Hadley cell where an increase associated with a slight shift in the Hadley cell occurred. Both the Hadley and Ferrel cells were stronger than the present-day climate control. The transient eddies responded in such a way as to transport greater amounts of sensible heat across the sea ice edge which was centered near 30° of latitude. A summary of changes associated with lower solar forcing is given in Table 2.

Because an ice covered earth did not evolve means that other factors responded in such a way as to counter the effects of ice-albedo feedback. The two factors that appear to have the most impact were clouds and the heat transporting properties of transient eddies. As the atmospheric temperatures cooled, water vapor amounts were reduced and clouds dissipated, ultimately allowing more solar radiation to reach the surface in polar and equatorial regions, thus acting as a negative feedback in response to the lower solar forcing. Rossow et al. (1982) showed a reduction in global clouds at most atmospheric levels for a lower solar constant with their (1DRC) model. Their results are similar to the resultant changes in high latitude clouds under lower solar forcing in the NCAR CCM (Fig. 11b). The increase in clouds with the CCM under lower solar forcing was associated with changes in the mean meridional circulations.

The transient eddies responded by transporting more heat from low latitudes into mid-latitudes as the sea-ice edge approached subtropical regions, acting as a negative feedback in response to the approaching sea ice. It is possible that if ice were extended into even lower latitudes the transient eddies could have a smaller effect. The Hadley cell would then be responsible for diffusing heat from low into higher latitudes, otherwise the sea ice would advance. The diffusion properties of the low latitudes has been considered a possible mechanism for keeping an ice-free planet under lower solar forcing conditions (Lindzen and Farrell, 1977).

Results of Gerard et al., (1992) with their $1\frac{1}{2}$ dimensional (EBM), showed that a global ocean can have reduced solar forcing of 16.8% before the ice-covered planet results. This result is consistent with results from this paper which suggest that the solar constant would need to be reduced further to create a frozen planet. Gerald et al. (1992) further shows that the $CO_2$ amounts would still need to be increased by 2000 times the present with a global ocean with a 30% decrease in the solar constant. But they needed only 6 times the present atmospheric levels (PAL) with a reduction of 20% in the solar constant in order to avoid planetary glaciation under reduced continental area.

Results from simulations with the NCAR CCM (Jenkins, 1991) show that with 8 times the present $CO_2$ concentrations and a 20% reduction in the solar forcing does not lead to complete glaciation although ice does exist in low latitudes. From these calculations it is likely that the amount of $CO_2$ necessary for surface temperatures above freezing under a solar forcing similar to that of the early Archean (20–30% lower) is probably on the order of 10–100 times the present amount. Rossow et al. (1982) show in their results that an increase of 5 times the present $CO_2$ amounts would be enough to keep global average temperatures above the freezing point of sea water with a 30% reduction in the solar forcing.

In view of the results of this paper, the simplicity of the swamp ocean surface which contains no oceanic heat storage or transporting properties warrents future investigation. For example, it may be plausible to suggest that the poleward transport of heat by oceans would tend to inhibit sea ice migration into low latitudes. Furthermore, because the simulation takes place under mean annual conditions and seasonality is neglected the roles of heat storage might be important. Future work is intended to investigate the storage properties of the ocean using a mixed layer ocean coupled to the atmospheric model. The ocean heat transport issue will be investigated using implied oceanic heat transport (see Covey and Thompson, 1989).

Current research (Jenkins et al., 1993) shows that a faster rotation rate significantly reduces the total cloud fraction leading to warmer surface temperatures under present day conditions. Rossow et al. (1982) have suggested from their results that clouds may be a key factor to understanding the climate of the early earth. While the cloud schemes of GCMs vary from model to model, they do lend understanding to processes which influence clouds in the GCM, such as a shift in the Hadley cell. Therefore, special attentions should be given to clouds in both simple and complex climate models. From the results of this paper and current research, it is possible that reduced land fraction and solar forcing in combination with faster rotation rate and higher carbon dioxide concentrations may provide the key to understanding the climatic conditions of the early earth.

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