NOTES AND CORRESPONDENCE

The Effect of Doubling the CO₂ Concentration on Convective and Non-convective Precipitation in a General Circulation Model Coupled with a Simple Mixed Layer Ocean Model

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1. Introduction

Vast differences exist in the treatment of clouds among the various GCMs that have been used for CO₂-sensitivity studies (see e.g., Rutledge and Schlesinger, 1985). However, a common feature has been found among several CO₂ sensitivity experiments (Hansen et al., 1984; Washington and Meehl, 1984; Wetherald and Manabe, 1986, 1988; Wilson and Mitchell, 1987; also see the review by Schlesinger and Mitchell, 1987). That is, when the CO₂ concentration in the model climate is doubled, the cloudiness decreases throughout most of the tropical and middle latitude tropospheres of both hemispheres, even though the tropics remains a moist and convectively active region with precipitation increasing in these regions. Based on this result, it is inferred that in the semi-arid tropical regions the increase in precipitation is expected to be in the form of convective rainfall, giving an increase in the intensity but not necessarily in the frequency of rainfall (Jaeger,1988). However, to date no study as yet has investigated the CO₂-induced changes in convective and non-convective types of precipitation and their frequency distributions on a global scale. This topic will be examined in the present note, based on a preliminary CO₂ sensitivity experiment, performed with the use of a general circulation model developed at the Meteorological Research Institute (MRI). Since cloudiness and area of precipitation are closely correlated, the CO₂-induced cloud feedback process will be discussed with respect to the response in the convective and non-convective areas of precipitation.

2. Brief description of the model

The model used in the present study is an atmospheric general circulation model coupled with a 50-m oceanic mixed layer, energy balance sea-ice model that follows the parameterization scheme employed in the zero layer model of Semtner (1976). The atmospheric model consists of a tropospheric version of the MRI-GCM-I described by Tokioka et al. (1984). A modified σ-coordinate with \( \sigma = (p - p_t)/(p_s - p_t) \) is used in the vertical, where \( p \) is the pressure, \( p_t \) the pressure at the top of the model (=100mb), while \( p_s \) represents the surface pressure. The model atmosphere is divided into five layers with interfaces located at 1/9, 3/9, 5/9 and 7/9 in \( \sigma \) as shown in Fig. 1. The Arakawa C grid scheme (Arakawa and Mintz,1974) is used, having a regular 4° x 5° latitude/longitude resolution.

The model determines three types of precipitation, which are denoted by LSPREC, MLPREC and CUPREC. The LSPREC is the precipitation due to saturation at a grid point. The MLPREC and CUPREC are the precipitation due to convection originating in the free atmosphere and in the planetary boundary layer, respectively.

The LSPREC occurs when the relative humidity at a grid point exceeds 100%. When condensation occurs in a layer, which is not the lowest layer of the model, the condensed water is transported down to the next lower layer, where it may evaporate. This process is repeated until the lowest layer is reached. When the lowest layer is saturated, the condensed water precipitates to the surface as rain or snow, depending on the surface air temperature.

Moist convective adjustment in the free atmosphere occurs whenever the saturation moist static energy \( h^*_s \) in a layer \( k \) becomes less than the moist...
static energy $h_{k+1}$ in the next lower layer $k+1$. That is, an air parcel rising from level $k+1$ experiences positive buoyancy at level $k$. If temperature and moisture in the levels $k$ and $k+1$ are modified in such a way as to reduce $h_{k+1} - h^*_{k}$ to zero and supersaturation occurs, the supersaturated water precipitates as the MLPREC (Arakawa, 1972).

The CUPREC is calculated through the cumulus parameterization developed by Arakawa and Schubert (1974). The Arakawa-Schubert parameterization takes into account the interaction of a cumulus cloud ensemble with the large-scale environment, which is divided into the subcloud mixed layer and the region above. For details, see Arakawa and Schubert (1974), Lord and Arakawa (1980), Lord (1982), Lord et al. (1982) and Tokioka et al. (1984).

Figure 1 shows the various types of clouds identified in the present GCM. However, not all of the clouds are considered in the radiation scheme. Since the cloudiness associated with shallow cumulus convection and moist convection in the free atmosphere is much smaller than 10/10, the clouds associated with shallow CUPREC (i.e., cumuli with tops below the 400 mb level and an air temperature of above $-40^\circ$C) and the MLPREC are not considered in the present radiation scheme. This is due to the fact that the shortwave radiation scheme developed by Katayama (1972) is valid for total cloudiness only. This restriction may possibly cause deterioration in the present simulation. For this reason, the authors are developing a new shortwave radiation scheme which permits partial cloudiness.

The diurnal and seasonal cycles are included. Shortwave fluxes are calculated every model hour while longwave fluxes are determined every three hours. Over snow-free land the surface albedo is specified, using values compiled by Matthews (1983) (see Kitoh et al. (1988) for details). The surface albedo over permanent land ice and snow is the minimum of $(0.85, 0.7 + 0.15z_s)$, where $z_s$ is the surface terrain height in km. For melting snow and for sea-ice without snow cover the albedo is 0.6. The ocean surface albedo is taken from Posey and Clapp (1963).

The horizontal oceanic heat transport is assumed to be zero for simplicity, although it is as important as the atmospheric heat transport. Therefore, the present model has the same bias as that of the Geophysical Fluid Dynamics Laboratory (GFDL; e.g., see Wetherald and Manabe, 1986) and National Center for Atmospheric Research (NCAR; see Washington and Meehl, 1984) models in the reproduction of observed values for the control simulation. That is, the simulated temperatures are higher than those observed in the low latitudes, while being lower than those observed in the high latitudes.

3. Experiments

The control (1$\times$CO$_2$) experiment (CO$_2$, 320 ppm) was initialized with model data for July 1 of another experiment, and integrated for 9 years. The doubled CO$_2$ experiment (2$\times$CO$_2$) started from July 1 data of the fifth year of the control experiment, and was also integrated for 9 years. The last 2 years of each experiment were used for time averaging of the results. In order to investigate the frequency distribution of various types of precipitation, a special sampling was made of the precipitation at every time step (one hour) for the calculation of diabatic heating. These sampling were made for 10 day periods at the beginning of January and July of the last year of each experiment.

The annual global mean surface air temperature for the 1$\times$CO$_2$ experiment was calculated as $14.8^\circ$C for year 9 and the difference between the 1$\times$CO$_2$ and 2$\times$CO$_2$ experiments (2$\times$CO$_2$ - 1$\times$CO$_2$) attained the value $4.3^\circ$C, which is within the range $2.8^\circ$C$\sim$5.2$^\circ$C obtained by other studies (see Cess and Potter, 1988). Neither $14.8^\circ$C nor $4.3^\circ$C is an equilibrium value since a period of 9 years is too short to reach final equilibrium. However, it can be expected from relaxation curves obtained by the NCAR and GFDL models, that by year 9 roughly 90% of the final equilibrium value has been attained. Therefore, the results given in the present note are only preliminary, and should be statistically confirmed by further experiments with longer integrations.

The deficiencies due to the zero oceanic heat transport were more pronounced for the present experiments than for the GFDL and NCAR experiments. Temperatures in the low latitudes and sea-
ice formed during winter were higher and more extensive, respectively, in the present control run than in the GFDL and NCAR control runs. The higher temperatures in low latitudes are partly attributable to the insufficient cloudiness for convective precipitation since, as noted in the previous section, clouds associated with shallow CUPREC and MLPREC were neglected in the radiation calculation of the present experiments, resulting in an overestimation of solar heating in low latitudes. In fact, the zonal and annual averaged total cloudiness in the control run was reduced throughout most of the troposphere except for the lower troposphere of the high latitudes. The explanation as to why the present model simulated more extensive sea ice than the NCAR model is not clear since the snow and ice albedos used in the NCAR model are 0.8 and 0.7, respectively, which are greater than those used in the present model, as shown in the previous section.

4. Results

The annual mean global average changes due to doubled CO$_2$, which were obtained from the means of the last two years of the 2 $\times$ CO$_2$ and 1 $\times$ CO$_2$ experiments, are as follows. The global surface temperature increased by 4.3°C. Evaporation and precipitation showed an increase of 7.4%, while relative humidity at the surface decreased by 2%.

4.1 Annual Mean Response

Figure 2 shows the latitudinal distribution of the annual mean rates of the various types of precipitation; CUPREC, LSPREC, MLPREC and total precipitation. The total precipitation increases over most latitudes in response to the doubling of CO$_2$. 
This is in agreement with the well-known scenario that CO$_2$ warming causes greater evaporation, increases the moisture content of the air and results in greater amounts of precipitation. However, Fig. 2 reveals that this scenario should not necessarily be applied to all the components of the total precipitation. The CUPREC increases over most latitudes in accordance with the above outline. In fact, it is found that the global mean increase in the total precipitation for the 2 x CO$_2$ model is 0.27 mm/day. This value is almost equal to the increase in CUPREC (=0.28 mm/day). On the other hand, the MLPREC exhibits a decrease over the ITCZ while in middle latitudes, its peak values increase and the latitudes of the maximum are shifted poleward. The LSPREC also shows a similar shift in location but its intensity is nearly conserved between the 1 x CO$_2$ and 2 x CO$_2$ experiments. The poleward shift of the rain belt has also been found by Manabe and Wetherald (1980) using a simplified sector general circulation model. It can be concluded from Fig. 3 that the increase in CUPREC and the decrease in LSPREC
in low and middle latitudes results in a decrease in cloudiness. A response similar to Fig. 3 is also found for the relative humidity field (not shown).

4.2 Seasonal Response

Latitude-time cross sections of the zonal mean precipitation for the 1 $\times$ CO$_2$ experiment and the differences between the 1 $\times$ CO$_2$ and 2 $\times$ CO$_2$ experiments are presented in Fig. 4. The effect of the poleward shift of the middle latitude rain belt (Manabe and Wetherald, 1987) is easily seen in the difference field of the LSPREC in Fig. 4. Here, a decrease in the LSPREC is found equatorward while an increase is seen poleward of the rain belt. As a result, precipitation is enhanced in the polar latitudes, in particular, in the Southern Hemisphere, suggesting that the Antarctic ice mass would exhibit an increase as opposed to melting in a warmer climate, therefore contributing to the sea level decrease. On the other hand, the decrease of LSPREC equatorward while an increase is seen poleward of the rain belt. As a result, precipitation is enhanced in the polar latitudes, in particular, in the Southern Hemisphere, suggesting that the Antarctic ice mass would exhibit an increase as opposed to melting in a warmer climate, therefore contributing to the sea level decrease. A reversed response in the total precipitation is found in the results of the NCAR model but not in the GFDL model (see Fig. 19 of Schlesinger and Mitchell, 1987).

4.3 Response in precipitation area

Figures 6 and 7 show scatter diagrams of the precipitation rate (mm/day) versus the ratio of the precipitation area to the global domain. In order to obtain a frequency distribution of precipitation, the data were sampled at every time step (one hour) from January 1 to 10 (Fig. 6) and July 1 to 10 (Fig. 7) of the final years of the 1 $\times$ CO$_2$ and 2 $\times$ CO$_2$ experiments. The mean scattering is approximated by ellipses in each panel of the figures, with a thick lined ellipse representing the 1 $\times$ CO$_2$ and the thin lined ellipse denoting the 2 $\times$ CO$_2$ experiment. It can be seen from Figs. 6 and 7 that the total precipitation increases but the precipitation area decreases in both months when the CO$_2$ concentration is doubled. The CUPREC rate increases as the area of precipitation increases. A clear reduction in the area of precipitation is found for the LSPREC, although little change can be seen in the precipitation rate. This feature is more significant during January than during July, reflecting a hemispherically different response. No definite changes are found for the MLPREC. Therefore, the reduction in the area and the increased rate of the total precipitation are attributable to the LSPREC and CUPREC responses, respectively. Similar scatter diagrams are illustrated in Figs. 8 (January) and 9 (July), representing three latitudi-
Fig. 6. Scatter diagrams of the precipitation rate (mm/day) versus the ratio (%) of the precipitation area to the global domain for January 1 to 10. Ellipses drawn with thick solid lines and thin solid lines denote the root mean square scattering for $1 \times$ CO$_2$ and $2 \times$ CO$_2$, respectively. Data points for $1 \times$ CO$_2$ and $2 \times$ CO$_2$ are denoted by crosses and dots, respectively.

Again, responses similar to the global domain can be seen in each zone except for the tropical zone during July, where convective precipitation (CUPREC and MLPREC) dominates the total precipitation. For responses in zones narrower than those shown in Figs. 8 and 9, similar scatter diagrams for smaller latitude bands were made (not shown). The diagrams reveal an increase in the LSPREC area in the high latitudes of the Northern Hemisphere. This is consistent with the increase in cloudiness found over this region in the present (Fig. 3) and other experiments (e.g., see Fig. 23 in Schlesinger and Mitchell, 1987).

Comparing Figs. 8 with 9, one can find a good qualitative agreement in the area response between summer minus winter and $2 \times$ CO$_2 - 1 \times$ CO$_2$. In addition to this, Hansen et al. (1984) and Wetherald and Manabe (1986) found good similarity between the latitude-height distribution of the difference in zonal mean cloud amount obtained from an increase of the solar constant and that obtained from an increase of CO$_2$ concentration. These facts suggest that the main factor that determines the cloud area response on global scales is temperature. Since the precipitation area and cloudiness are correlated, they also invoke the hypothesis that, on global scales, precipitation increases but cloudiness decreases as the temperature increases. There are some observations which support this hypothesis. Table 1 shows differences in total cloudiness and precipitation between summer and winter for three zones, $90^\circ$S-$30^\circ$S, $30^\circ$S-$30^\circ$N and $30^\circ$N-$90^\circ$N. These values were obtained by subtracting the monthly averaged cloudiness and precipitation in January from the corresponding values in July in the Northern Hemisphere, while subtracting the July from the January values for the South-
Fig. 7. As in Fig. 6 but for July 1 to 10.

Table 1. Differences in cloudiness and precipitation between summer and winter, obtained by subtracting the monthly averaged cloudiness and precipitation values for January (July) from the corresponding values for July (January) in the Northern (Southern) Hemisphere.

<table>
<thead>
<tr>
<th>cloudiness (%)</th>
<th>90°N~30°N</th>
<th>30°N~30°S</th>
<th>30°S~90°S</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dopplick (1979)</td>
<td>-5.5</td>
<td>2.2</td>
<td>-4.8</td>
<td>-1.5</td>
</tr>
<tr>
<td>Berlyand and</td>
<td>1.8</td>
<td>8.1</td>
<td>4.3</td>
<td>5.5</td>
</tr>
<tr>
<td>Strokina (1980)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISCCP (1983~1984)</td>
<td>-4.7</td>
<td>9.1</td>
<td>-3.6</td>
<td>2.4</td>
</tr>
<tr>
<td>precipitation (mm/day)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Jaeger (1976)</td>
<td>0.12</td>
<td>1.82</td>
<td>-0.21</td>
<td>0.89</td>
</tr>
</tbody>
</table>

erman Hemisphere. The cloudiness given by Dopplick (1979) and the International Satellite Cloud Climatology Project (ISCCP; July 1983 and January 1984) decreases during summer in the middle and high latitudes of both hemispheres, while the precipitation reported by Jaeger (1976) increases in these latitudes in the Northern Hemisphere. However, opposite responses are found in data of cloudiness given by Berlyand and Strokina (1980) and those of precipitation by Jaeger (1976) for the Southern Hemisphere. Moreover, all of the data shown in Table 1 indicate that both the cloudiness and precipitation are enhanced over the low latitudes during summer.
Fig. 8. As in Fig. 6 but for the latitudinal zones, 28°N~90°N (top), 28°S~28°N (middle) and 90°S~28°S (bottom). T denotes the total precipitation, C the CUPREC, M the MLPREC and L the LSPREC.

It should be noted that in the present, the NCAR and the Goddard Institute for Space Flight (GISS) models predicted decreases in cloudiness throughout the tropical troposphere when the CO2 concentration was doubled, which is not consistent with the observations of decreasing cloudiness as temperature increases. In this respect, Wetherald and Manabe (1988) stressed the importance of the vertical resolution of the tropopause and lower stratospheric clouds on simulating the response of cloud amount in the tropics. Actually, clouds were not permitted to form near the tropopause or lower stratosphere in the low latitudes of the NCAR, GISS and the tropospheric version of the MRI models. It is speculated that if clouds had been allowed to form at these higher levels, then these models might have obtained, at least qualitatively, similar results as the Wetherald and Manabe (1988) and Wilson and Mitchell (1987) studies. They found a general decrease of middle and upper tropospheric cloud
but a significant increase of high cloud cover around the tropopause in low latitudes, while both the NCAR and GISS models produced an increase of high clouds around the tropopause in the middle to higher latitudes. The discrepancy of the MRI model in this respect, along with others, may be attributable to the use of the tropospheric model. Indeed, it appears that GCMs which have been run more recently at the GFDL, without the above restriction on cloud formation, generally reproduce an increase of high clouds at all latitudes in response to a global warming (Wetherald, 1989; personal communication).

4.4 Response in the frequency distribution

Figures 10 and 11 show the cumulative frequency distribution of the precipitation for the same data used in Fig. 8. Plotted is the log-frequency of precipitation exceeding a given precipitation rate per one hour (Fig. 10) or per one consecutive precipitation (Fig. 11) at each grid point. It can be seen that the functional form of the cumulative frequency dis-
Fig. 10. Cumulative frequency distribution for precipitation rates of mm per hour for January 1 to 10. Plotted is the log-frequency of precipitation exceeding a given rate per one hour at each grid point. Data points for 1 × CO₂ and 2 × CO₂ are denoted by crosses and dots, respectively.
Fig. 11. As in Fig. 10 but for precipitation rates of mm per one consecutive precipitation event. Plotted is
the log-frequency of precipitation exceeding a given rate per one consecutive precipitation at each grid
point.
tribution depends on the type of precipitation, latitude and sampling (one hour or consecutive) but it is almost independent of the CO$_2$ concentration. In general, when the CO$_2$ concentration is doubled, convective precipitation (CUPREC and MLPREC) of high precipitation rates increase, but the reverse is true for non-convective precipitation (LSPREC). Most of the cumulative frequency distributions in the range for high precipitation rates decrease more rapidly than power law curves, i.e., $n^a(r)$, where $a$ is a constant and $n(r)$ is the cumulative frequency exceeding the precipitation $r$. The only distribution that obeys the power law is the consecutive MLPREC in low latitudes. It is of interest to investigate what processes determine the functional form of the distribution but this is beyond the scope of the present note.

5. Summary
The MRI-GCM-I coupled with a simple mixed ocean model has been used to investigate the effect of doubling the CO$_2$ concentration on convective and non-convective types of precipitation. The following changes in precipitation have been found when the CO$_2$ concentration was doubled.

1) The increase of the global mean total precipitation was attributed to the increase in the CUPREC (precipitation due to cumulus convection rooted in the planetary boundary layer).

2) In the ITCZ, the MLPREC (precipitation due to convective adjustment in the free atmosphere) decreased significantly at the latitudes adjacent to where the CUPREC showed an increase. In the mid-latitude rain belt, the increased rate of the CUPREC had a peak during early summer, but that of the MLPREC was minimized in the summer.

3) The decrease in the area of total precipitation was attributed to the reduction in the LSPREC (precipitation due to large-scale condensation) area. The area response obtained by increasing the CO$_2$ concentration is similar to that found between summer and winter, suggesting that the main factor that determines the response is temperature.

4) The frequency of intense convective rainfall increases but that of intense non-convective rainfall decreases.

The present model does not take into account the horizontal oceanic heat transport and also neglects cloudiness due to shallow cumulus convection and stratus in the planetary boundary layer. These restrictions may have affected the above results to some extent. A new experiment excluding the restrictions is now under way.

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