AN INVESTIGATION OF CLOUD COVER CHANGE IN RESPONSE TO THERMAL FORCING

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Abstract. The role of cloud cover in determining the sensitivity of climate has been a source of great uncertainty. This article reviews the distributions of cloud cover change from several climate sensitivity experiments conducted at the Geophysical Fluid Dynamics Laboratory of NOAA (GFDL) and other institutions. Two of the sensitivity experiments conducted at GFDL used a general circulation model with a limited computational domain and idealized geography, whereas three other experiments were conducted by the use of a global model with realistic geography. A thermal forcing imposed was either a change of solar constant or that of the CO_2-concentration in the atmosphere. It was found that in all five cases, clouds were decreased in the moist, convectively active regions such as the tropical and middle latitude rainbelts, whereas they increased in the stable region near the model surface from middle to higher latitudes. In addition, cloud also increased in the lower model stratosphere and generally decreased in the middle and upper troposphere for practically all latitudes.

A comparison of the cloud changes obtained from investigations carried out at other institutions reveals certain qualitative (but not necessarily quantitative) similarities to the GFDL results. These similarities include a general reduction of tropospheric cloud cover especially in the vicinity of the rainbelts, a general increase of lower stratospheric cloud cover for almost all latitudes and an increase of low stratiform cloud in high latitudes.

1. Introduction

It is well known that cloud cover has a major effect on the radiative field of the atmosphere. In general, the increase of cloud amount exerts two opposing influences upon climate. (1) It increases the planetary albedo and cools the earth-atmosphere system. (2) It also reduces outgoing terrestrial radiation at the top of the atmosphere and warms the earth-atmosphere system. Therefore, the interaction among cloud cover and climate (i.e., the cloud feedback mechanism) has been the subject of many investigations (e.g. Manabe and Wetherald, 1967; Schneider, 1972; Cess, 1976; Schneider *et al.*, 1978; Roads, 1978; Ohring and Clapp, 1980; Hartmann and Short, 1980; Manabe and Wetherald, 1980; Wetherald and Manabe, 1980).

In the sensitivity studies of Manabe and Wetherald (1975) and Wetherald and Manabe (1975), the responses of a model climate to an increase of CO_2 and that of insolation were analyzed, respectively. Although these investigations were carried out using two types of forcing, the relative humidity was found to change in a similar manner in both studies. In particular, the relative humidity increased near the earth's surface and decreased in the middle and upper troposphere of the model in response to the forcing. In the Wetherald and Manabe (1975) study, it was speculated that the increase of low

Climatic Change 8 (1986) 5–23.

level relative humidity was caused by the enhancement of evaporation from the model surface, whereas the decrease of relative humidity at upper levels was attributed to the increase in the efficiency of water vapor removal by precipitation due to the intensification of vertical velocity.

Roads (1978) and Schneider *et al.* (1978) discussed the response of cloud cover to an increase of sea surface temperature based upon results from numerical experiments. According to Roads' analysis, warmer sea surface temperatures yield larger variances of vertical velocity and greater efficiency of moisture removal by precipitation. This, in turn, results in a lower relative humidity and cloudiness. In the Schneider *et al.* (1978) investigation, it was found that if the ocean surface temperature was increased in a zonal strip centered under the descending branch of the Hadley circulation, cloudiness increased over the strip and decreased in adjacent zones. If the positive ocean surface temperature anomaly was placed under the ascending branch of the Hadley cell, there was little change of cloudiness over the strip and again cloudiness decreased in adjacent regions. Finally, it was found that if the ocean surface temperature was increased uniformly over the entire global computational domain, cloudiness, in general, decreased.

In the later sensitivity studies of Manabe and Wetherald (1980) and Wetherald and Manabe (1980) (hereafter referred to as MW80 and WM80, respectively), it was found that both relative humidity and cloud amount decreased in the middle and upper troposphere, whereas both quantities increased in the stable layer near the model surface from middle to high latitudes. In addition, both relative humidity and cloud cover increased in the lower stratosphere for practically all latitudes.

Since the above studies were carried out with a model utilizing idealized geography, it was decided to repeat the MW80 experiment by integrating two versions of a global model with realistic geography. In these experiments, it was found that the distributions of cloud change in response to an increase of CO_2 were qualitatively similar to the distributions of cloud change obtained from the MW80 and WM80 experiments.

Comparisons are also made with the cloud changes obtained from the investigations by Washington and Meehl (1984) and Hansen *et al.* (1984). It is found that the patterns of cloud change obtained from these latter investigations qualitatively resemble those derived from the Geophysical Fluid Dynamics Laboratory (GFDL) studies in many respects. This paper, therefore, reviews the cloud changes computed from these various models and attempts to identify the common features which occur in all of them. The identification of the significant changes of cloud cover is an important step towards the exploration of the influence of the cloud feedback processes upon the sensitivity of climate. For the convenience of discussion, the cloud changes obtained from the GFDL studies will be discussed first followed by a comparison of the Washington and Meehl (1984) and Hansen *et al.* (1984) cloud changes.

2. Models With Idealized Geography

2.1. *Model Description*

A natural starting point for the comparison of cloud changes obtained by various GCM's is the WM80 study. Although this model was simplified in many respects, nevertheless it was quite useful for identifying general features of cloud change in response to a thermal forcing. Therefore, it is worthwhile to briefly outine the basic findings of this study.

The WM80 investigation utilizes an idealized, flat geography consisting of equal areas of continent and 'swamp ocean'. Cyclic continuity is assumed for the two meridional boundaries, 120° of longitude apart. The dynamical calculations are carried out on a horizontal network of gridpoints with 9 unequally spaced finite difference levels in the vertical direction. Insolation is prescribed as an annual mean distribution. In the computation of solar and terrestrial radiation, the mixing ratio of carbon dioxide is assumed constant everywhere; ozone is specified as a function of height and latitude; and the water vapor distribution is determined by prognostic equations.

Precipitation is predicted whenever supersaturation occurs. When the air temperature near the surface is below freezing, snowfall is forecast, otherwise rain is predicted. To incorporate moist convective processes a convective adjustment scheme is used (Manabe *et al.*, 1965).

In order to facilitate the analysis and interpretation of the results from the numerical experiment, the prognostic scheme of cloud cover is made as simple as possible. At each grid point, cloud is placed in the layer where the relative humidity exceeds a critical value. Otherwise no cloud is forecast. This value for the critical relative humidity is chosen so that the global integral of total cloud amount is approximately 50%. In the present scheme, cloud may occur at a single or at multiple contiguous finite difference levels. If the cloud is more than one level thick, it is regarded as a thick cloud.

The fractional absorption and reflection of solar radiation by various types of cloud cover are tabulated in Table I of WM80. For the computation of terrestrial radiation all clouds including 'cirrus' or high clouds are assumed to be completely black bodies.

It should be mentioned that the model does not compute cloud liquid water content and, therefore, the effect of varying optical depth of clouds is not taken into account in this study. For the sake of simplicity, it is assumed that all condensed water vapor immediately precipitates out of the model atmosphere despite the fact that cloud cover is placed whenever relative humidity exceeds the critical value.

For other details of the model such as the surface heat and water balance, the reader is referred to WM80.

2.2. *Zonal Mean Cloud Distribution*

Before passing on to the subject of cloud change, it is desirable to review the distribution of the cloud cover that is simulated by the WM80 model. Figure 1 shows the latitude-height distribution of the zonal mean cloud amount from the WM80 model. In this figure, one may note that the cloud amount is at a minimum in the subtropics. In addition, one may identify a layer of relatively large cloudiness in the upper model troposphere and a thin layer of large cloudiness near the Earth's surface in most latitudes.

In order to examine further the characteristics of the simulated cloud cover, it is desirable to classify the cloud into convective and nonconvective types. Figure 2 shows the simulated distributions of zonal mean amounts of convective and nonconvective clouds as a function of latitude and height.

According to Figure 2, the convective cloudiness of the annual model atmosphere is relatively large in the tropics and around 45 degrees latitude where the rainbelts of the tropics and middle latitudes are located. Out of these convective regions identified above, nonconvective cloud spreads upwards and laterally into the upper model troposphere. The nonconvective cloud also emerges in a similar fashion from the convective cloud in the rainbelt of middle latitudes. The heights of the nonconvective cloud layer in the upper model troposphere are ~12 km in the tropics, ~8 km in the middle latitudes and ~6 km in high latitudes. In view of the characteristics described above, it may be reasonable to regard these upper tropospheric clouds as cirrus clouds.

In the model subtropics, where the relative humidity is low because of the general subsidence of air, the amount of nonconvective cloud is significant only in the upper troposphere and planetary boundary layer of the model.

In high latitudes of the model, nonconvective cloud occupies a large fraction of area near the Earth's surface. In this latitude-region, moisture from the underlying surface is trapped in the planetary boundary layer because of the stable stratification. Furthermore,

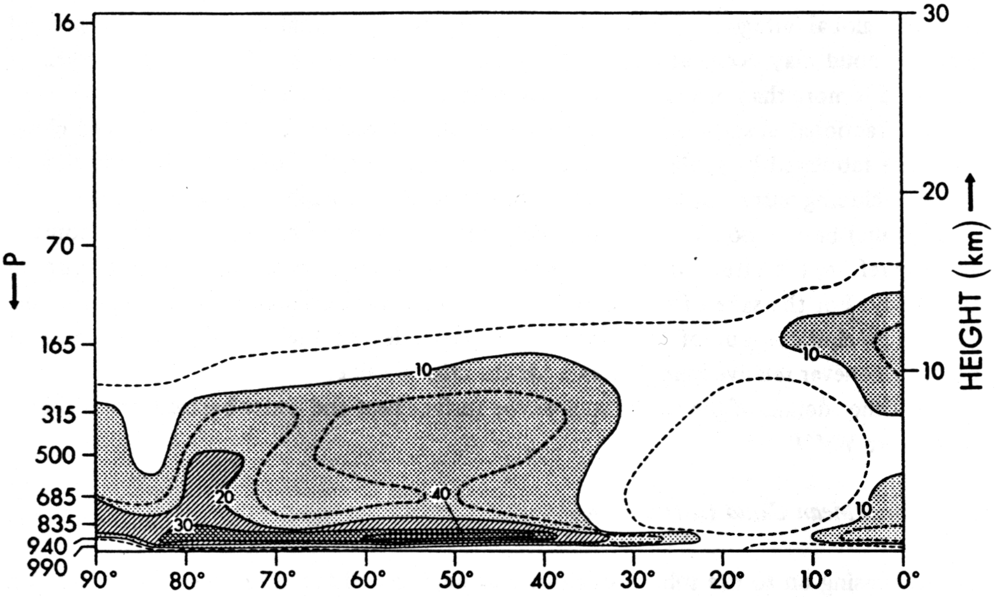

Fig. 1. Latitude-height distribution of zonal mean cloudiness in the standard experiment (taken from WM80). Units are in percent.

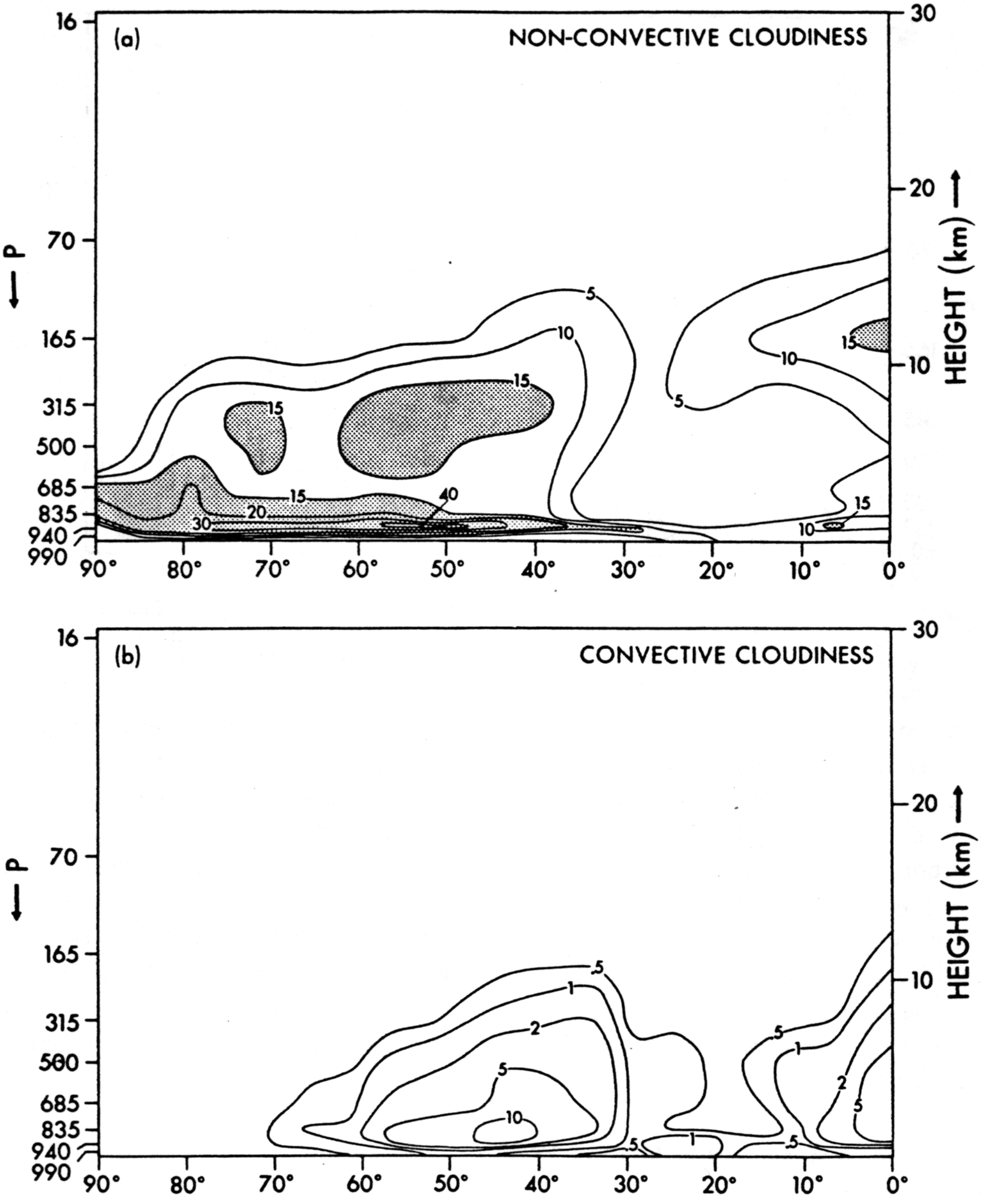

Fig. 2. Latitude-height distributions of zonal mean values of (a) non-convective cloudiness and (b) convective cloudiness (taken from WM80). Units are in percent.

the high relative humidity, caused by net radiative cooling of the cloud top and the trapping of water vapor near the Earth's surface, is responsible for sustaining an extensive cloud layer which may be regarded as a stratus cloud in high latitudes.

The distributions of convective and nonconvective cloud cover described above may be compared with the observed annual mean cloud distribution which is constructed from the seasonal data compiled by London (1957) and are shown in Figure 3. According to

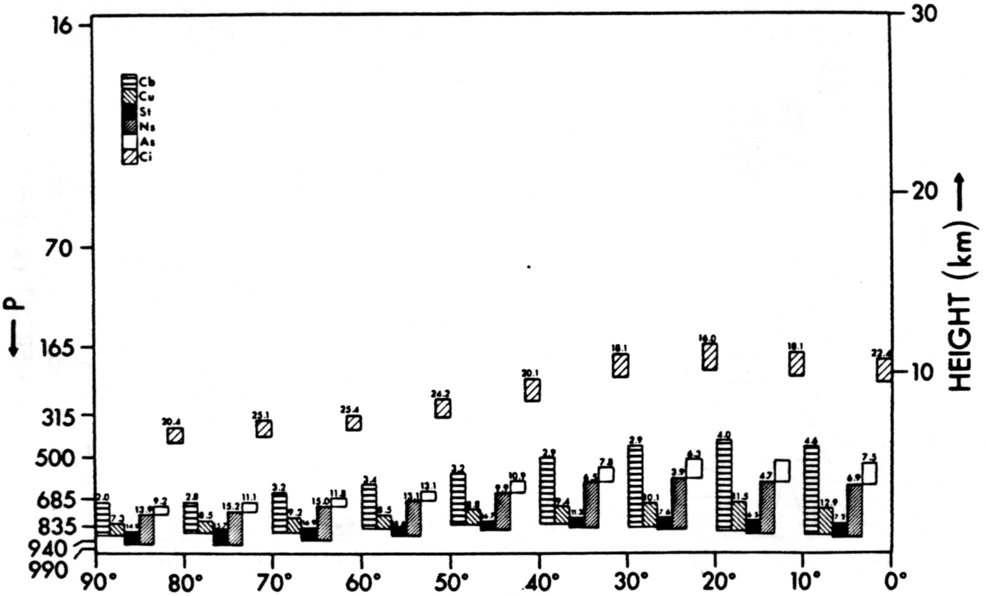

Fig. 3. Diagram depicting the annual-mean cloud distribution computed from the data compiled by London (1957). The different bars show vertical extents of various cloud types, whereas the numbers on top of each bar refer to the cloud amount in percent for that particular cloud type Cb; Cumulonimbus. Cu; Cumulus. St; Stratus. Ns; Nimbostratus. As; Altostratus. Ci; Cirrus.

this comparison, the latitudinal variation of the height in the non-convective cloud in the upper model troposphere corresponds reasonably well with the observed variation of the height of cirrus cloud as determined by London. Furthermore, the extensive layer of low cloud in high latitudes of Figure 1 resembles the stratus cloud contained in London's distribution, although the altitude of the simulated stratus is somewhat lower than that of observed stratus. In London's distribution, one can identify a cloudfree layer beneath the cirrus cloud. A similar feature is not evident in the simulated distribution. However, it is encouraging that the model atmosphere has a layer of minimum nonconvective cloudiness in the midtroposphere. In summary, the distribution of zonal mean cloud cover in the model atmosphere has some qualitative resemblance to the observed distribution compiled by London and his collaborators.

2.3. *Change of Zonal Mean Cloud Amount*

In the WM80 study, the model described above was integrated for separate values of the solar constant; a standard value and a 6% increase of this value. The change of cloud amount caused by a 6% increase of insolation was then investigated by comparing the statistically stationary cloud distributions obtained from these two separate integrations. In the companion MW80 study, the same model was used for the study of cloud cover change in response to a quadrupling of CO_2 concentration.

Figure 4a, b shows the latitude-height difference of both zonal mean cloud amount and relative humidity obtained from a 6% increase of the solar constant, respectively. Although one notes various quantitative differences between the changes of cloud amount and

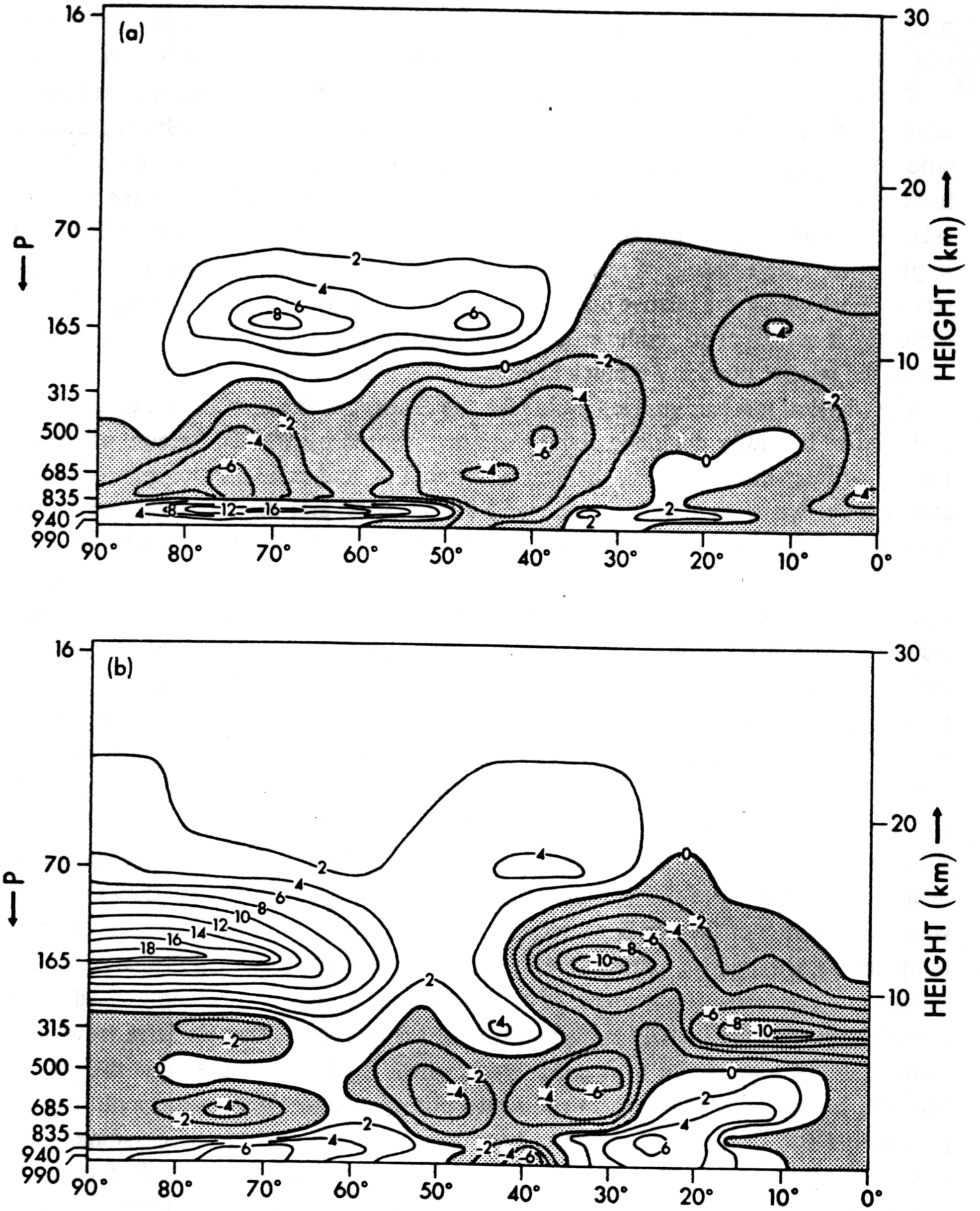

Fig. 4. Latitude-height distribution of the difference in zonal mean (a) cloud amount and (b) relative humidity obtained from a 6% increase of the solar constant (taken from WM80). Shaded areas indicate negative values. Units are in percent.

relative humidity, these two distributions are qualitatively similar to each other. Some common features are: (a) a decrease of both cloud amount and relative humidity in the moist, convectively active regions such as the tropical and middle latitude rainbelts, (b) an increase of cloud amount and relative humidity in the stable region near the model surface in high latitudes and the subtropics. In addition to the two main changes given above, one may also note an increase of cloud amount and relative humidity in the lower stratsphere and a general reduction of these quantities in the middle and upper troposphere.

The main difference between the distributions of cloud amount and relative humidity change concerns the magnitude of these changes as a function of altitude. In general, the ratio of the change of cloud amount to the change of relative humidity decreases with increasing altitude. It appears that this result is related to the fact that the area mean relative humidity from the standard experiment reduces with increasing altitude. This implies that a large change of relative humidity is required to alter cloudiness in the lower stratosphere where the relative humidity is quite low, whereas a smaller change of relative humidity is sufficient to produce the same change of cloudiness in the lower troposphere where the relative humidity is much higher.

The physical mechanisms responsible for the changes in the distribution of cloud cover and relative humidity described above were investigated by WM80. Because of the complexity of interaction between the general circulation and condensation processes in the atmosphere, we were unable to convincingly identify and explain these mechanisms. Nevertheless, we came up with tentative explanations which are reproduced below.

In the upper and middle troposphere of the model, both zonal mean relative humidity and cloudiness decrease because of the increase in the efficiency of moisture removal resulting from the increase in the variance of vertical velocity. Owing to the saturation and the condensation of water vapor, the moistening in the region of upward motion tends to be smaller than the drying in the region of subsidence. Thus, the reduction of area-mean relative humidity occurs in the layers of intensified vertical velocity. In high latitudes and the subtropics where the atmospheric static stability in the planetary boundary layer of the atmosphere is relatively stable, enhanced evaporation from the warmer surface contributes to the increases in both relative humidity and nonconvective cloudiness at the near-surface level where the warming due to increased insolation is less than the surface warming. Because of the non-linear reduction of saturation vapor pressure with decreasing temperature, the relative humidity reaches the critical value for cloud formation near the surface. In the lower stratosphere of the model, nonconvective cloudiness and relative humidity increase particularly in high latitudes. It is speculated that the large reduction of static stability around the tropopause level, which results from the large difference in warming between the troposphere and stratosphere, enhances the upward moisture transport across the tropopause and raises both the relative humidity and cloudiness in the lower stratosphere where the warming is relatively small. In summary, cloudiness decreases in the upper and middle troposphere of the model at most latitudes but increases near the Earth's surface and lower model stratosphere in high latitudes in response to an increase of the solar constant.

In WM80, a version of the model was integrated in which the cloudiness was prescribed rather than predicted. It is of interest to examine here the corresponding latitude-height difference distribution of zonal mean relative humidity computed from this model (Figure 5). In general, the same pattern of relative humidity difference appears to prevail for both the predicted cloud model (Figure 4b) and the prescribed cloud model (Figure 5), namely an increase of relative humidity in the upper and middle troposphere of the model and an

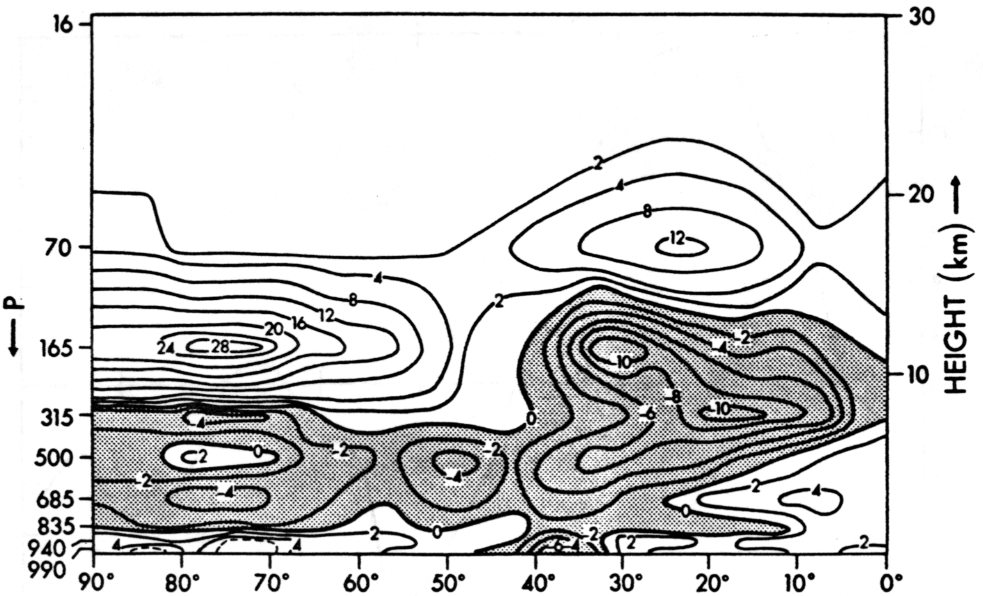

Fig. 5. Latitude-height distribution of the difference in zonal mean relative humidity obtained from a 6% increase of the solar constant in a version of the model in which clouds were prescribed (taken from WM80). Units are in percent.

increase of relative humidity in the lower model stratosphere. Qualitatively, similar changes in relative humidity were obtained in the earlier study by Wetherald and Manabe (1975) where a prescribed zonal mean cloud distribution was used. According to the above comparison, there is a considerably greater increase of relative humidity in the lower stratosphere for the prescribed cloud version of the model. However, the changes of relative humidity in the model troposphere of the two models are quantitatively similar. This suggests that the interactive radiation-cloud feedback processes have very little influence on the change of relative humidity in the model troposphere.

It is worthwhile to also note the difference of zonal mean total cloud amount obtained from WM80 (Figure 6). Qualitatively the WM80 model indicates a general reduction of total cloud amount from the equator to approximately 50° latitude and a large increase of total cloud amount poleward of this latitude. Also evident in Figure 6 is a relatively narrow region in the subtropics where very little total cloud change takes place in the model.

One can compare the changes of cloud cover induced by a 6% increase of insolation to the changes of cloud cover cuased by a quadrupling of CO_2 content as derived from MW80. Figure 7a, b shows the latitude-height difference of both zonal mean cloud amount and relative humidity obtained from a quadrupling of CO_2 (MW80), respectively. Qualitatively, the changes of cloud amount and relative humidity for this study are very similar to those obtained from the WM80 model. This suggests that the changes of cloud amount and relative humidity derived from these two studies are not dependent upon the details of the thermal forcing.

The qualitative similarity between the distributions of CO_2- and insolation-induced

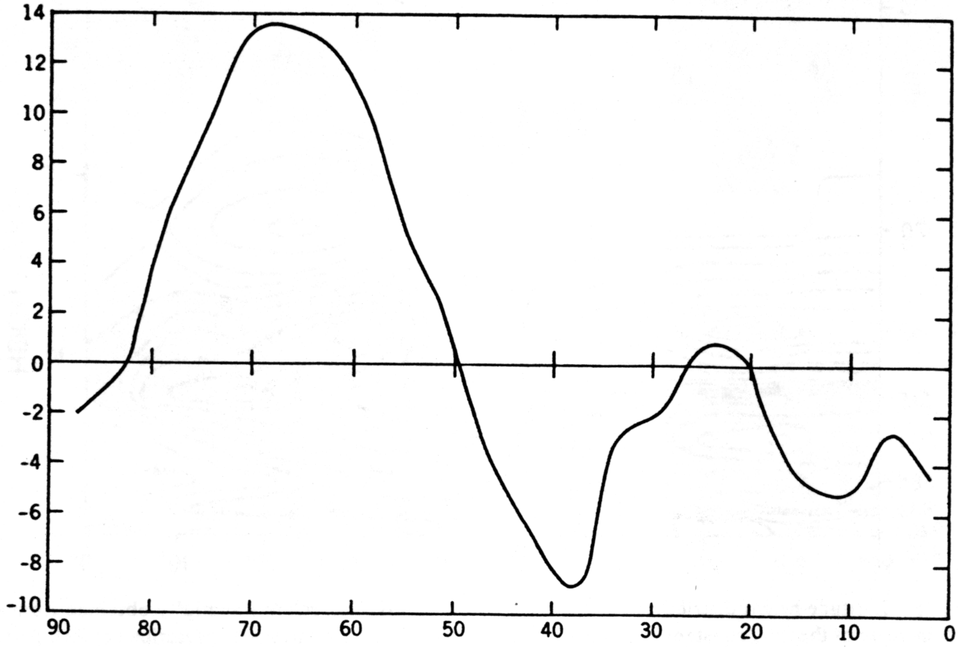

Fig. 6. Latitudinal distribution of zonal mean difference in total cloudiness obtained from a 6% increase of the solar constant (taken from WM80). Units are in percent.

changes of cloud cover may be understood by recalling the result from the MW80 study. It was shown that the latitudinal distribution of the change of zonal mean surface air temperature of the MW80 model due to the doubling of atmospheric CO_2 is very similar to the distribution of the corresponding change due to the 2% increase in solar constant.

3. Investigations with Global Models

3.1. *Geophysical Fluid Dynamics Laboratory Studies*

So far, the discussion has focused on the cloud changes obtained from models with idealized geography. Other investigations utilized a model with a global computational domain and realistic geography. The global model is similar to the Manabe and Stouffer (1980) model. It consists of an atmospheric general circulation model and a simple mixed layer ocean with a horizontally uniform heat capacity. The atmospheric GCM uses the spectral method in which the horizontal distributions of atmospheric variables are represented by a limited number of spherical harmonics. The horizontal resolution of the atmospheric GCM is determined by the degree of truncation of the spectral components. For this model, 15 components are retained in both the zonal and meridional directions, adopting the so-called rhomboidal truncation.

When the cloud prediction scheme which is essentially similar to the one used in WM80 and MW80 was incorporated into the global model, several unrealistic features were evident in the seasonal simulation of cloud cover. These features included an absence of

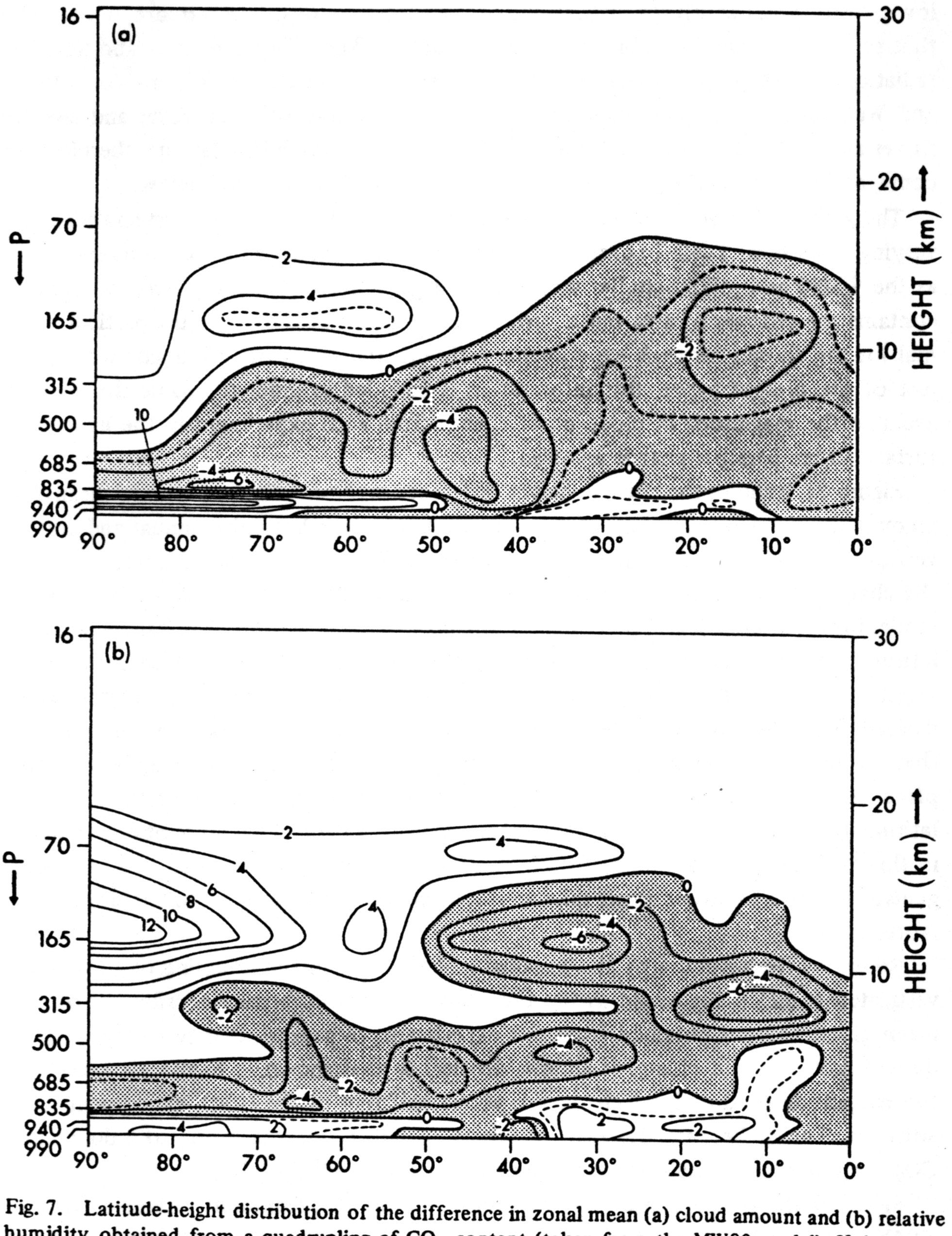

Fig. 7. Latitude-height distribution of the difference in zonal mean (a) cloud amount and (b) relative humidity obtained from a quadrupling of CO_2 content (taken from the MW80 model). Units are in percent.

low stratiform cloud off the west coasts of the major continents in subtropical latitudes and a general underestimation of low cloud amount in the oceanic regions of high latitudes during summer. Nevertheless, the global model successfully reproduces the areas of small cloud amount in the large deserts or dry regions of the world. Also simulated are the regions of relatively large cloudiness such as the tropical rainbelt and the semi-permanent low pressure areas which are present during the winter seasons. Furthermore, it was found that the seasonal and latitudinal distributions of zonal mean fluxes of solar and terrestrial radiation at the top of the model atmosphere compare favorably with observation. Manabe and Wetherald (1982) described in detail the distributions of cloud cover and radiative fluxes as simulated by the global model. The success in these simulations, therefore, encouraged them to use the global model for the pilot studies described below.

The global GCM was integrated under conditions of both annual mean and seasonally varying insolation. Table I contains the characteristics of these global experiments as well as the WM80 and MW80 studies with idealized geography. The last column of this table contains the changes of area mean surface air temperature caused by the particular thermal forcing chosen for each experiment. Although the sensitivity of climate is not a subject of the present paper, this information is included in order to enable the reader to evaluate the magnitude of cloud cover change from each experiment in the light of the surface air temperature change involved.

Figure 8a, b shows the latitude-height difference in the distribution of zonal mean cloud amount due to a quadrupling of CO_2 concentration for both the annual and seasonal versions of the global model. According to the comparison between Figures 8a and 8b, the change of cloudiness in the annual model is generally larger than that of the seasonal model for most latitudes. In particular, the increase of cloud in the near surface layer of high latitudes of the annual model is much larger than the corresponding increase in the seasonal model. Nevertheless, both distributions are qualitatively similar to the cloud changes derived from the earlier studies with idealized geography. For example, one may note that, again, the reduction of cloud amount in the upper and middle troposphere takes place mainly in the moist, convectively active regions such as the tropical and middle latitude rainbelts, whereas the increase of lower tropospheric cloud amount occurs mostly in the stable region near the surface from middle to high latitudes. Also, one may note a general increase of lower stratospheric cloud amount particularly from middle to high latitudes.

Recently, the response of the seasonal global model to the doubling of CO_2 was investigated (GS2X). Figure 8c shows the latitude-height difference distribution of zonal mean cloud amount obtained from this experiment. In general, it may be seen that the distribution of cloud change is almost identical to that shown in Figure 8b except that the magnitude of the cloud changes is about half that of the GS4X-experiment for all latitudes. This is because the zonal mean temperature difference due to a doubling of CO_2 is approximately half of the difference for a quadrupling of CO_2.

Figure 9 shows the annual mean change of total cloud amount obtained from the GS4X and GS2X experiments. According to this figure, there is a net decrease of total cloud cover in the tropical and subtropical regions for both hemispheres and a decrease of total cloud amount in middle latitudes for the Northern Hemisphere for both experiments. Poleward of about 45–50° latitude, there is a net increase of cloud cover in both hemispheres with the increase being much greater in the Northern Hemisphere than in the Southern Hemisphere. The narrow region of little cloud change in the subtropics which was evident in the models with idealized geography (WM80 and MW80) is not present in

TABLE I: Characteristics of general circulation models used for cloud studies.

Identification	Domain	Geography	Method	Insolation	Ocean	Forcing	ΔT_a	Reference
WM80	Sector	Idealized	Finite difference	Annual	Swamp	+6% SC	9.5 °C	Manabe and Wetherald (1980)
MW80	Sector	Idealized	Finite difference	Annual	Swamp	4 x CO_2	5.9 °C	Wetherald and Manabe (1980)
GA4X	Global	Realistic	Spectral	Annual	Swamp	4 x CO_2	9.2 °C	Current Work
GS4X	Global	Realistic	Spectral	Seasonal	Mixed Layer	4 x CO_2	7.2 °C	Current Work
GS2X	Global	Realistic	Spectral	Seasonal	Mixed Layer	2 x CO_2	4.0 °C	Current Work

SC-solar constant

ΔT_a : The change of area-mean surface air temperature caused by the forcing indicated in the neighboring column.

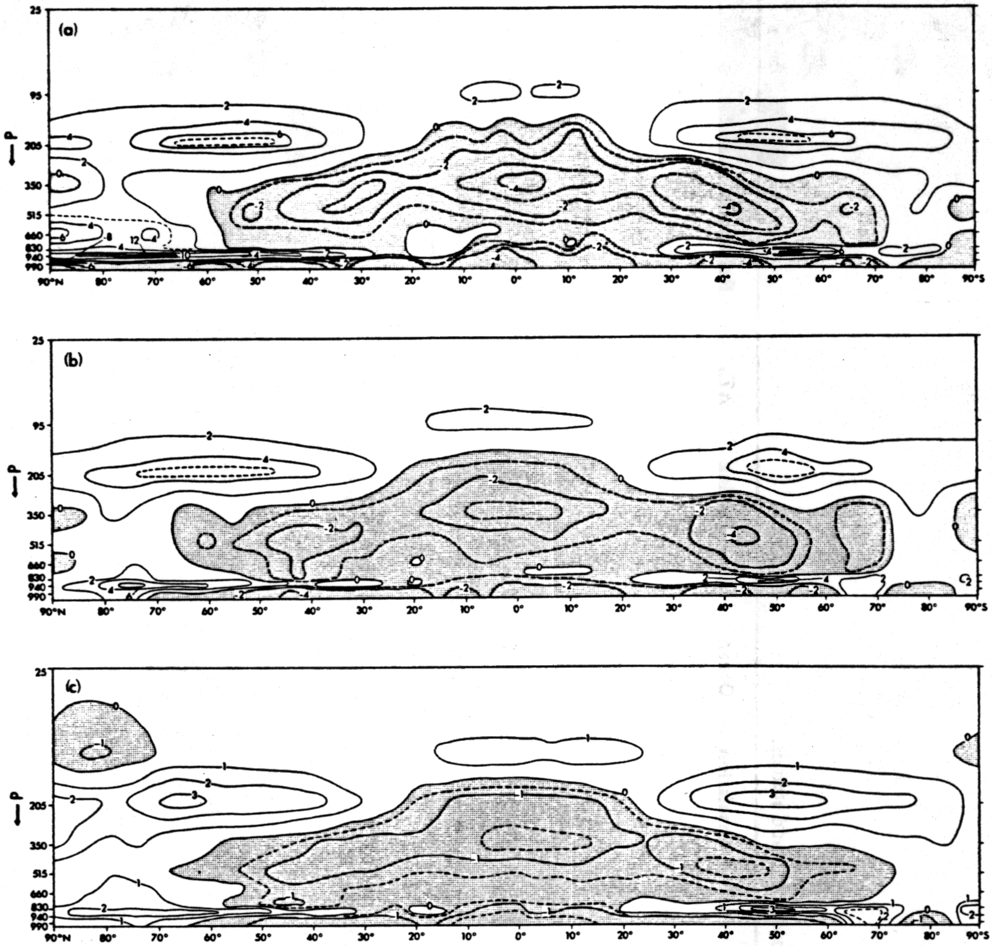

Fig. 8. Latitude-height distribution of the difference in zonal mean cloud amount computed from the (a) GA4X, (b) GS4X and (c) GS2X-experiments. The GA4X and GS4X results were obtained from a quadrupling of CO_2 whereas the GS2X-results were derived from a doubling of CO_2. The distributions for the GS4X and GS2X-experiments represent annual averages taken over 3 and 10 annual cycles, respectively. Units are in percent.

the global model. Also, it is of interest to note that the magnitude of the cloud change for the GS2X-experiment is approximately half that for the GS4X-experiment except for middle latitudes in the Southern Hemisphere and at the equator where they are quite similar.

3.2. *Comparisons with other Investigations*

In addition to the studies performed at the Geophysical Fluid Dynamics Laboratory (GFDL), other investigations have been conducted using global general circulation models incorporating methods of cloud prediction in which cloud amount is also related in some way to environmental relative humidity. These are, Washington and Meehl (1984) and

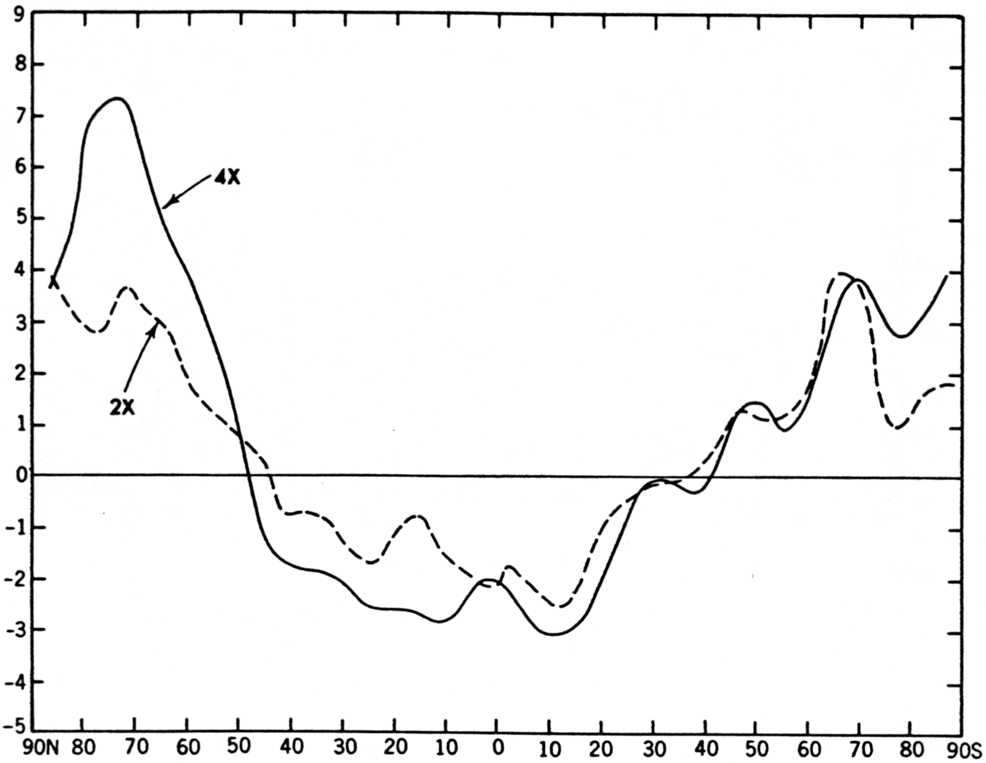

Fig. 9. Latitudinal distribution of zonal mean difference in total cloudiness obtained from the GS4X-experiment (solid line) and GS2X-experiment (dashed line). Averaging procedure is the same as in Figure 8. Units are in percent.

Hansen *et al.* (1984) which studied the change of climate due to a doubling of atmospheric CO_2. Since both of these investigations utilized global models with seasonal variation of insolation, it is worthwhile to compare the distributions of cloud change computed from these integrations with that of the GS2X-experiment. Figure 10a, b shows the latitude-height difference of zonal mean cloud amount obtained from the Washington and Meehl (1984) and Hansen *et al.* (1984) studies, respectively. In both cases, one may note the following features: (1) a general reduction of tropospheric cloud amount, particularly in the mean position of the middle latitude and tropical rainbelts, (2) an increase of cloud amount in the lower stratosphere for practically all latitudes, (3) an increase of low stratiform cloud near the model surface in high latitudes. These features are quite similar to the cloud changes obtained from the GS2X-experiment and also the other GFDL studies discussed previously (see Figures 4 and 8). However, the decrease of tropospheric cloud cover is considerably greater in the Hansen *et al.* (1984) model than in either the Washington and Meehl or GS2X models, particularly in low latitudes. This feature may be related to the fact that the difference in surface air temperature in low latitudes is much greater in the Hansen *et al.* (1984) model than in the other two models. Also, the increase of low stratiform cloud in high latitudes in the Southern Hemisphere which is evident in the GS2X-experiments is not as apparent in the results of Hansen *et al.* and Washington-

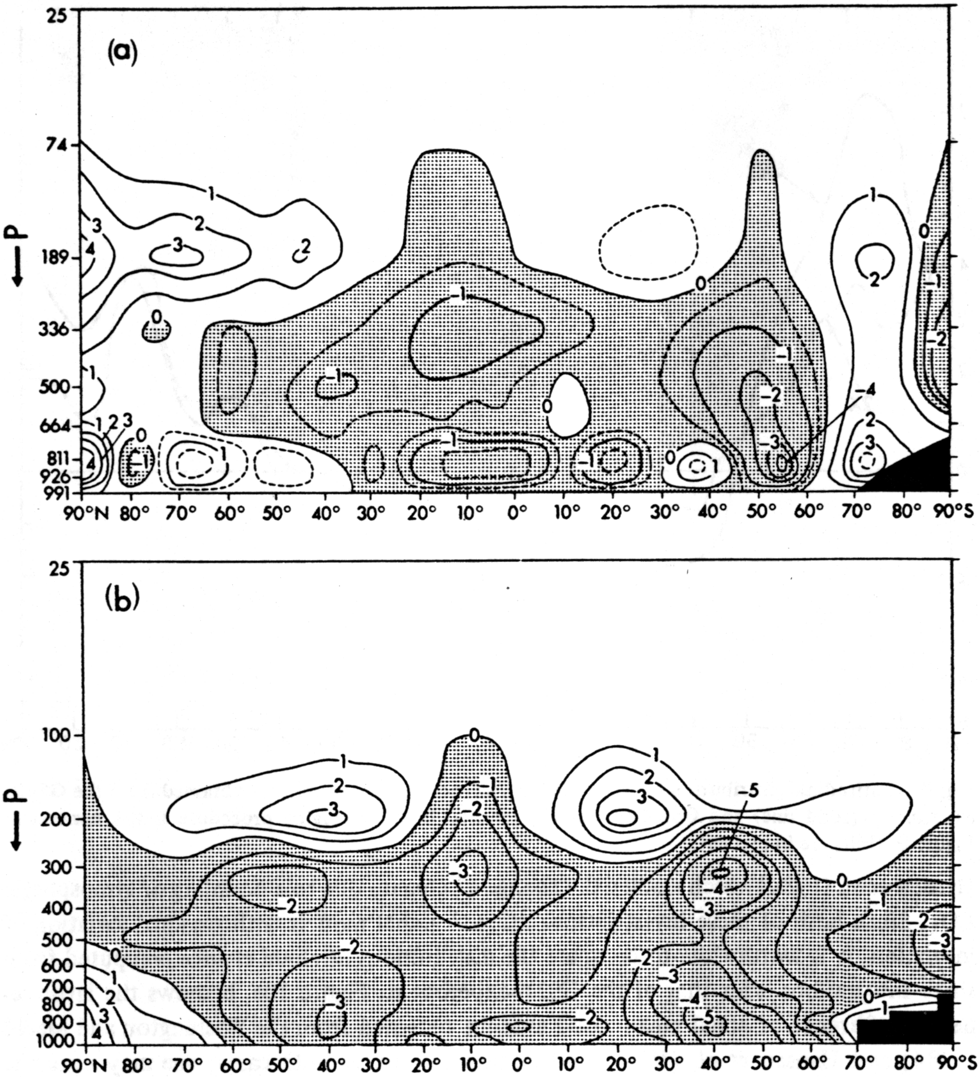

Fig. 10. Latitude-height distribution of the difference in zonal mean cloud amount due to a doubling of CO_2 obtained from the (a) Washington and Meehl (1984) model (published with permission of the authors), and (b) Hansen *et al.* (1984) model. Results represent annual mean cloud changes. Units are in percent.

Meehl. Although these and other quantitative differences exist among these investigations, the qualitative patterns of cloud change obtained from these three models are quite similar to one another.

5. Summary and Conclusions

In this paper, the cloud amount changes obtained from five separate experiments carried out at the Geophysical Fluid Dynamics Laboratory in response to a thermal forcing are compared with one another. It is found that the patterns of cloud change from all five experiments share two main features. These are: (a) a decrease of cloud amount in the moist, convectively active regions such as the tropical and middle latitude rainbelts, (b) an increase of cloud amount in the stable region near the model surface from middle to higher latitudes. In addition to these two main changes, there is also an increase of cloud amount from middle to higher latitudes in the lower stratosphere and a general reduction of cloud amount in the middle and upper troposphere for almost all latitudes. In general, it was found that clouds were reduced in the tropical and middle latitude rainbelt regions whereas they increased in the stable layer near the Earth's surface from middle to high latitudes.

Comparison of cloud changes obtained from other GCM studies reveals certain similarities to the GFDL results. For example, distributions of cloud change obtained from Washington and Meehl (1984) and Hansen *et al.* (1984) show a general reduction of tropospheric cloud cover particularly in the regions of the tropical and middle latitude rainbelts. Both cloud difference distributions also show a general increase of lower stratospheric cloud cover in most latitudes and an increase of low stratiform cloud in high latitudes.

It turned out that in WM80, the effects of cloud changes upon the global radiative heat budget of the earth-atmosphere system compensated each other to a large extent. Therefore, there was no appreciable difference in the sensitivity of surface temperature between the model with predicted cloud cover and another model with a prescribed cloud distribution. This compensation of cloud change was also present in MW80.

On the other hand, Hansen *et al.* (1984) found that the change of cloud cover enhances the CO_2-induced warming of the global atmosphere. The sensitivity of the present global model with seasons also increased by approximately 30% when the contribution of the cloud cover feedback process was incorporated. The reason why the cloud feedback process hardly changed the sensitivity of the MW80-experiment but altered that of the GS4X-experiment has not been determined. However, this difference in the behavior of the two models may be understood if one recalls that the CO_2-induced increase of cloud cover in the lower stratosphere at low latitudes for the GS4X-experiment is substantially larger than the corresponding increase in the MW80-experiment. Such a difference reduces the magnitude of outgoing terrestrial radiation and contributes to the enhancement of the CO_2-induced warming of the atmosphere in the GS4X-experiment as compared with the MW80-experiment. In addition, the CO_2-induced increase of low stratiform cloud in high latitudes for the GS4X-experiment is significantly less than the corresponding increase in the MW80-experiment particularly during the summer season when the insolation is at a maximum. The difference in the reflected solar radiation also contributes to the enhanced warming of the model climate in the GS4X-experiment. It has been speculated that these differences in the changes of cloud cover distributions may be responsible for the difference in the sensitivity between the GS4X model and the MW80 model.

Although the distributions of the CO_2-induced changes of cloud cover from various experiments resemble each other as discussed earlier, there are large quantitative differences among them. This is one of the important reasons why the influence of the cloud feedback process upon the sensitivity of a model climate varies substantially from one experiment to another as discussed in the preceding paragraph. Another reason is our ignorance of the optical properties of various types of cloud cover. In the numerical experiments reported in this review, the optical properties of clouds are specified in a highly casual manner. Furthermore, it is assumed that these properties are invariant despite the climate change caused by a thermal forcing. A recent study by Somerville and Remer (1984) on the possible influence of the change of liquid water content upon the sensitivity of climate underscores this difficulty. In view of the uncertainties identified above, it is decided to limit the scope of this paper to the identification of the features of cloud change which occur in response to a thermal forcing. The influence of cloud cover feedback upon the sensitivity of climate is the subject of current investigation at GFDL and will be discussed in a future publication. Nevertheless, it is hoped that the present article will constitute the first step in the study of this important feedback process.

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