Cloud and Radiation Processes Simulated by a Coupled Atmosphere-Ocean Model*

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ABSTRACT

Using NCC/IAP T63 coupled atmosphere-ocean general circulation model (AOGCM), two 20-yr integrations were processed, and their ability to simulate cloud and radiation was analysed in detail. The results show that the model can simulate the basic distribution of cloud cover, and however, obvious differences still exist compared with ISCCP satellite data and ERA reanalysis data. The simulated cloud cover is less in general, especially the abnormal low values in some regions of ocean. By improving the cloud cover scheme, simulated cloud cover in the eastern Pacific and Atlantic, summer hemisphere's oceans from subtropical to mid-latitude is considerably improved. But in the tropical Indian Ocean and West Pacific the cloud cover difference is still evident, mainly due to the deficiency of high cloud simulation in these regions resulting from deep cumulus convection. In terms of the analysis on radiation and cloud radiative forcing, we find that simulation on long wave radiation is better than short wave radiation. The simulation error of short wave radiation is caused mostly by the simulation difference in short wave radiative forcing, sea ice, and snow cover, and also by not involving aerosol's effect. The simulation error of long wave radiation is mainly resulting from deficiency in simulating cloud cover and underlying surface temperature. Corresponding to improvement of cloud cover, the simulated radiation (especially short wave radiation) in eastern oceans, summer hemisphere's oceans from subtropical to mid-latitude is remarkably improved. This also brings obvious improvement to net radiation in these regions.

Key words: AOGCM, cloud and radiation, cloud radiative forcing, cloud cover scheme

1. Introduction

Clouds cover about two thirds of the earth's surface. It plays an important role in radiation budget of the earth-atmosphere system. On the one hand, clouds can absorb and scatter short wave radiation (SWR), which cools the system; on the other hand, clouds can effectively absorb and reflect long wave radiation (LWR) emitted by the earth's surface and the underlying atmosphere, that is, the greenhouse effect. Their net effect plays a key role in climate change. However, due to our poor knowledge of clouds and radiative processes and the deficiency of their parameterization, great uncertainty exists in simulation of clouds and radiation by climate models, which directly affected the creditability of projection of future climate change. Some researches showed that there was a roughly threefold variation in global climate sensitivity among different models with different cloud and radiation parameterizations (Cess et al., 1990, 1996). IPCC (1990, 1996, 2001) also gave a climate sensitivity from 1.5 to 4.5°C, which shows great uncertainty, and most of them come from the simulation of cloud and its effect on radiation.

As an important radiative property, cloud cover can directly affect the distribution of radiation in the earth-atmosphere system, and its distribution and variation are very important to regulate the climate (Liu et al., 2003; Zeng and Zhang, 1996; Li et al., 2003; Yu et al., 2001, 2004). The deficiency in simulating cloud can impact the heat balance at the surface. It may affect the distribution of sea surface temperature, and then ocean circulation (Yu and Mechoso, 1999; Mechoso et al., 1995). The simulated deficiency of cloud may also impact the heat contrast between land and ocean, and further affect the simulation of monsoon circulation (Zhou and Li, 2002). Furthermore, cloud cover feedback has effect on climate sensitivity, which may strengthen the global warming due to doubling CO_2 (Wetherald and Manabe, 1988;

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Mitchell and Ingram, 1992).

Considering the significance of cloud cover and its effect on radiation, it is essential to validate them in climate models. In the past this work was mainly limited by cloud and radiation data. However, satellite detection technique has been developed greatly during the past several decades. Some well-known cloud and radiation projects have accumulated considerable cloud and radiation observations with longer time and better precision, such as International Satellite Cloud Climatology Project (ISCCP)(Rossow and Schiffer, 1999), Earth Radiation Budget Experiment (ERBE)(Ramanathan, Harrison et al., 1989), Atmospheric Radiation Measurement (ARM) (Ackerman and Stokes, 2003), etc. In addition, there are some reanalysis data as well, which integrated observations and results from advanced models, and can be used in the model's validation.

NCC/IAP T63 AOGCM was developed jointly by the National Climate Center (NCC) of China and Institute of Atmospheric Physics (IAP) of Chinese Academy of Sciences in the late 1990s. Since then it has been broadly used in short-term climate prediction, climate modelling, and projection of future climate change (Ding et al., 2000; Xu, 2002; Ding et al., 2004). In cloud and radiation aspects, Shen et al. (2000) have studied the effect of radiation parameterization on the model's forecast, however, the climatic characteristics of clouds and radiation processes in the model have not been studied systematically, which restricts our knowledge of the ability for the model to simulate clouds and radiation, and impacts its further development. Therefore, in this paper we took long-term integrations using NCC/IAP T63 AOGCM, analysed the simulated climatic characteristics of clouds and radiation, and modified the cloud cover scheme according to the deficiency in simulation of clouds and radiation.

2. Model and method

2.1 Model description

The NCC/IAP T63 AOGCM is a global spectral model. Both the atmosphere and ocean components are truncated at wavenumber 63 in horizontal direction, i.e., with a horizontal resolution of $1.875°\times1.875°$. In vertical direction the atmospheric the model uses hybrid $p-\sigma$ coordinates and has 16 vertical layers, while the oceanic model has 30 vertical layers. The used radiative parameterization scheme is Morcrette scheme; the modified Kuo scheme is used for deep cumulus convection calculation; Tiedtke scheme is used for shallow convection; a simple three-layer model is used to describe the land surface process; the topographic gravity wave drag scheme is modified following the scheme of Palmer et al.; a thermodynamical sea ice model is used to forecast sea ice. The atmospheric model calls the oceanic model once daily and exchanges the atmosphere-ocean fluxes. To restrain the climate drift, a daily flux anomaly (DFA) coupling method is adopted. For more details about atmospheric and oceanic models, you can see references (NMC, 1991; Dong et al., 1997; Dong. 2001; Jin et al., 1999). The following is mostly about cloud cover scheme.

2.2 Cloud cover parameterization and its modification

In the original cloud cover scheme, four cloud types are considered, i.e., convective cloud, high, middle and low stratus clouds (NMC, 1991). Stratus cloud is mainly expressed as the quadratic function of relative humidity (RH), which is almost the only factor in addition to the consideration of vertical velocity and inversion in the formation of low cloud. In fact the formation of cloud is affected jointly by RH, vertical velocity, atmospheric stability, convective mass flux, etc. In addition, the original scheme has not considered marine stratacumulus, resulting in the bad simulation on cloud cover over oceans. Considering these reasons, we refer to the parameterization of cloud cover in NCAR CAM2[‡], and modify the original scheme as follows:

(1) Parameterization of marine stratocumulus cloud is introduced, and its cloud fraction ($C_{\rm st}$) is expressed as

$$C_{\rm st}=\min\{1.0,\max[0,(\theta_{700}-\theta_{\rm s})\cdot 0.057-0.5573]\}, \tag{1}$$

[‡]Description of the NCAR Community Atmosphere Model (CAM2). <http://www.ccsm.ucar.edu/models/>.

where θ_{700} and θ_s are the potential temperatures at 700 hPa and the surface, respectively.

(2) Low cloud (below 750 hPa) is considered in the weak subsidence region, and its cloud fraction is diagnosed according to

$$C_l = \begin{cases} 0 & \omega > \omega_c \\ \left(\dfrac{\omega_c - \omega}{\omega_c}\right)\left(\dfrac{RH - RH_{\min}^{\text{low}}}{1 - RH_{\min}^{\text{low}}}\right)^2 & 0 \leqslant \omega \leqslant \omega_c \ , \\ \left(\dfrac{RH - RH_{\min}^{\text{low}}}{1 - RH_{\min}^{\text{low}}}\right)^2 & \omega < 0 \end{cases} \qquad (2)$$

where RH is the relative humidity, $RH_{\min}^{\text{low}}$ is the relative humidity threshold for low cloud formation, ω and ω_c are the vertical velocity and its threshold, respectively.

(3) Middle and upper level clouds are defined as

$$C_h = \left[\max\left(0, \frac{RH - RH_{\text{lim}}}{1 - RH_{\text{lim}}}\right)\right]^2, \qquad (3)$$

$$RH_{\text{lim}} = 0.999 - (1 - RH_{\min}^{\text{high}}) \cdot \left[1 - \min(1, \frac{N^2}{3.5 \times 10^{-4}})\right], \qquad (4)$$

where N^2 is the square of the Brunt-Väisälä frequency, $N^2 = -\dfrac{g^2\rho}{\theta}\dfrac{\partial\theta}{\partial p}$. $RH_{\min}^{\text{high}}$ is the relative humidity threshold for mid-level and high cloud fraction.

It is needed to point out that although the simulation on tropical convective cloud has large deficiency, we did not make corresponding modification. Because it is related to the modification of cumulus convective parameterization, which exceeds our research extent and will be considered in future study.

2.3 Data and experiment design

In this paper two sets of data are used. One is the ISCCP-D2 monthly mean data set (Rossow and Schiffer, 1999), which begins in July 1983 and ends in September 2001, including such items as cloud cover, cloud water content, cloud optical depth, etc. The other is recent 20-yr (1982-2001) monthly mean ECMWF 40-yr reanalysis data (ERA40)§, which includes the total cloud cover (TCC), high, middle and low clouds, LWR and SWR at the surface and top of atmosphere (TOA)(both for clear and full sky), etc. It is noted that there are some satellite and station-based observations for clouds or radiation. But considering the consistency between clouds, radiation and other atmospheric data, we still selected ERA data as the validation data. Therefore there are large uncertainties.

Two 20-yr integrations are processed with the original cloud cover scheme (ORIG, hereafter) and the modified cloud cover scheme (NEW, hereafter), respectively. In order to weaken the coupled shock, only the last 10-yr results are used for analysis, which are mainly analysed in terms of season, that is, spring (MAM), summer (JJA), autumn (SON), and winter (DJF).

3. Cloud cover

3.1 TCC

Table 1 gives the annual and seasonal mean total cloud cover (TCC) on global and regional scales. The TCC is close to each other between ISCCP and ERA data on global and regional scales, but for zonal mean the obvious differences exist in extratropical region, especially in polar regions. The introduction of NEW brings some improvements in the simulation of global and regional TCC, but the discrepancy is still obvious. The simulation is generally about 10% less than observations, and in tropical regions it even reaches 10%-20%. For zonal mean cloud cover, the

Table 1. Annual and seasonal mean TCC on global and regional scales (unit: %)

	ISCCP			ERA			ORIG			NEW		
	Annual	JJA	DJF	Annual	JJA	DJF	Annual	JJA	DJF	Annual	JJA	DJF
Globe	66.9	66.3	66.9	66.9	67.1	66.5	54.0	54.3	53.7	56.7	57.2	56.1
NH	67.8	65.6	70.2	68.8	66.8	70.7	56.8	55.5	58.8	58.8	59.4	58.1
SH	70.7	71.3	68.1	70.4	72.7	67.5	57.5	59.3	54.5	61.3	61.8	60.1
Tropics	60.1	60.2	60.4	59.3	59.4	59.3	45.1	45.3	45.2	47.4	47.5	47.6

Note: the regions are divided in terms of latitude. NH denotes the Northern Hemisphere from 90° to 20°N; SH denotes the Southern Hemisphere from 90° to 20°S; Tropics is between 20°N and 20°S.

§For more details refer to website <http://data.ecmwf.int/data/d/era40_moda/>.

remarkable improvement is mainly located in mid-latitude oceans of the Southern Hemisphere, subtropical region, and the Arctic region, where the cloud cover increases by more than 10% (Fig.1), but in tropical regions still exists remarkable difference.

3.2 Distribution of TCC

The simulated TCC has a similar distribution to ERA data, and both of them are higher in mid-high latitudes and tropics, and lower in subtropics, but the simulated TCC is generally smaller in quantity than the ERA. The ORIG has obvious deficiency in simulating the cloud cover over oceans, especially in the tropical Indian Ocean, the tropical mid-east Pacific, the subtropical Pacific close to North and South America, and the Southwest Atlantic adjacent to Africa, where the cloud cover is abnormally low. In addition, cloud cover is remarkably lower over the oceans in mid-high latitudes. The introduction of NEW scheme improves the simulation remarkably, especially in the eastern Pacific and Atlantic, summer hemispheric ocean from subtropical to mid-latitudes (between latitudes 30° and 60°), which can be clearly seen in Fig.2.

However, the modelling deficiency of TCC is still large in tropical regions, especially from the tropical Indian Ocean to the tropical West Pacific (figure omitted). That is likely attributed to the poor simulation of sea surface temperature (SST), deep cumulus

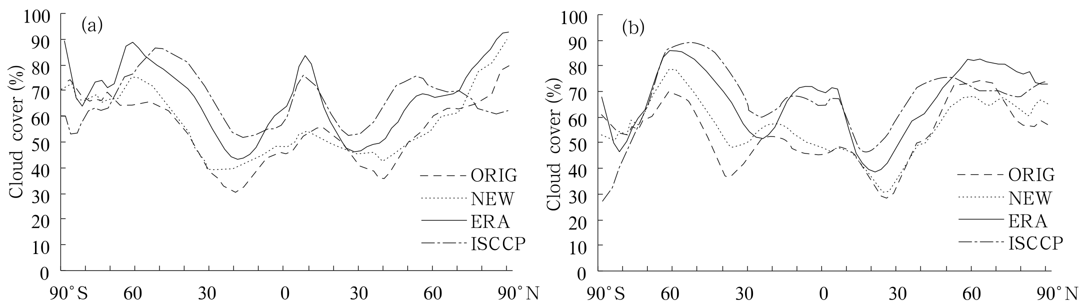

Fig.1. Zonal averaged total cloud cover (unit: %). (a) JJA and (b) DJF.

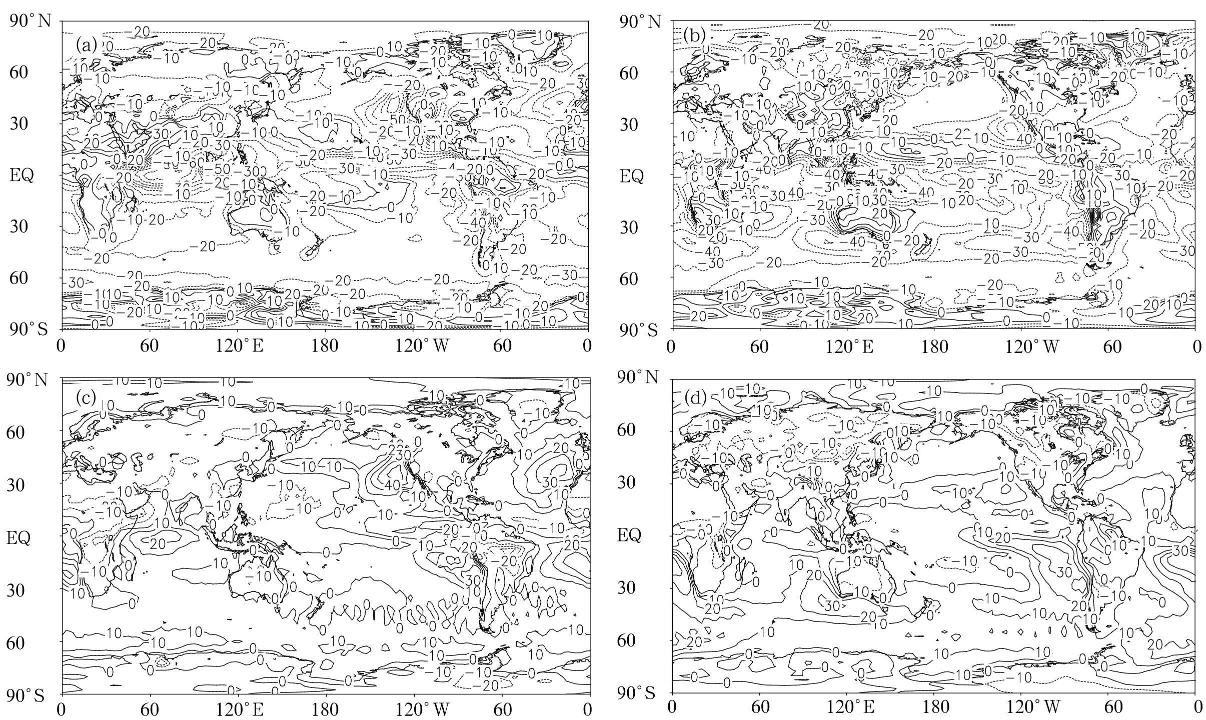

Fig.2. TCC differences (unit: %). (a) JJA, ORIG−ERA; (b) DJF, ORIG−ERA; (c) JJA, NEW−ORIG; and (d) DJF, NEW−ORIG.

convection and subsequent high cloud. It is notable that the simulation of cloud cover and precipitation by current models has common problems from the tropical Indian Ocean to the West Pacific, indicating the obvious deficiency in simulating the strong atmosphere-ocean coupled phenomenon there (Kang et al., 2002).

3.3 Vertical structure

The high, middle, and low clouds are defined in terms of their cloud top pressure, which are lower than 440 hPa, between 440 and 680 hPa, and higher than 680 hPa, respectively (Rossow and Schiffer, 1999). The simulation shows that the middle and low clouds change remarkably while high cloud does not show obvious change due to the modification of cloud cover scheme. Compared with the ERA, high cloud has the largest disparity in the NEW scheme, especially in areas from the tropical Indian Ocean to the tropical West Pacific, where the simulation is markedly less. This also gives an explanation that the simulated differences in these areas are mainly due to the simulated deficiency of high cloud.

The vertical distribution of zonal-averaged cloud cover is given in Fig.3, from which we can see that the ORIG scheme has a rough description of the vertical distribution, and cannot depict the low cloud center well in mid-high latitudes. In addition, obvious deficiency exists in simulation of high cloud cover in the upper troposphere of tropics. The introduction of NEW scheme improves the simulation of low cloud remarkably, which is the main reason for improvement of TCC simulation in the eastern Pacific and Atlantic, summer hemispheric ocean from subtropical to mid-latitudes.

4. Radiation

To better understand the role of two schemes in simulating radiation and cloud radiative effects, radiation is decomposed into two parts, clear-sky radiation and cloud radiative forcing (CRF). CRF is defined as the difference between radiative fluxes in cloudy and clear skies (Ramanathan, 1987).

4.1 CRF

In general, clouds are mostly to reflect SWR, therefore short wave cloud radiative forcing (SWCRF)

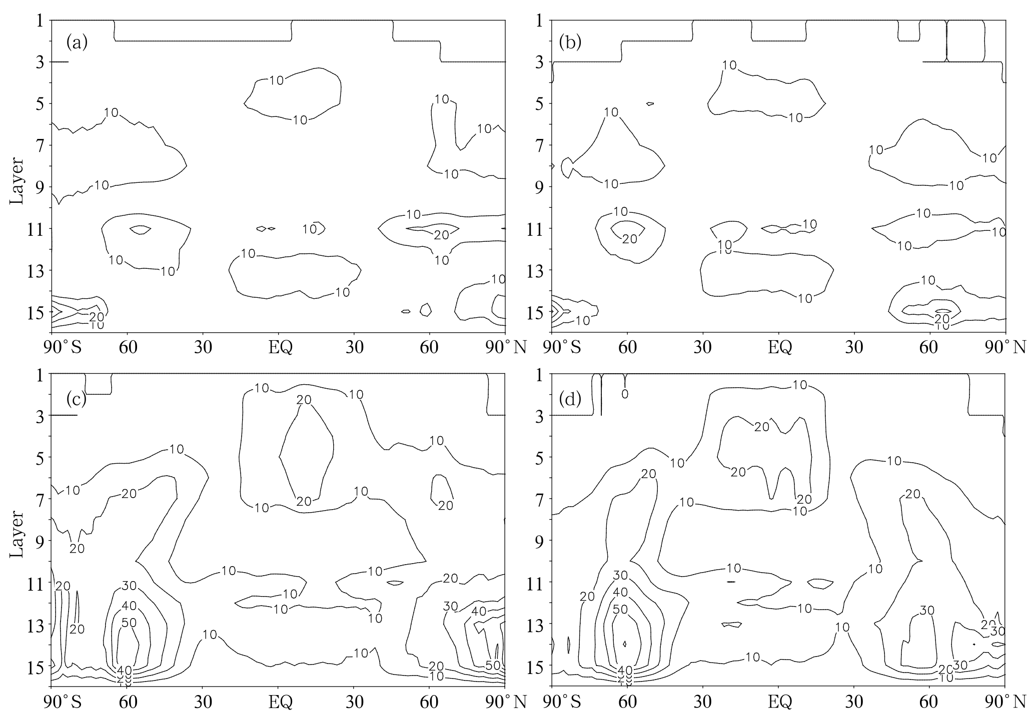

Fig.3. Latitude-height cross section of simulated cloud cover (unit: %). (a) Summer, ORIG; (b) winter, ORIG; (c) summer, NEW; and (d) winter, NEW.

is negative; while clouds can effectively absorb LWR and emit outgoing LWR with a lower cloud-top temperature, which makes the long wave cloud radiative forcing (LWCRF) positive. It is the net cloud radiative forcing (NCRF) to play a key role in climate change, whose sign is decided by the difference between SWCRF and LWCRF. ERA data show that the NCRF is mainly negative at TOA, with absolutely high values mostly in tropics and middle latitudes of summer hemisphere, which indicates that clouds are to cool the earth-atmosphere system generally. That is consistent with some researches (Ramanathan et al., 1989; Wang and Zhao, 1994). At the surface it is quite similar to the TOA except for the difference in middle latitudes of winter hemisphere, where the surface LWCRF is larger than SWCRF due to the low incident solar radiation, leading to the obviously positive NCRF.

4.2 SWR

Due to the variation of solar incidence angle with latitude, the SWR is higher in low and middle latitudes, and lower in polar regions, with high values in summer hemisphere. Compared with ERA data, the ORIG scheme simulated a higher SWR in general, with the highest values located in tropics and areas from subtropics to middle latitudes (especially over oceans) in summer hemisphere. Obviously, this is closely connected to the simulated deficiency of cloud cover there. Furthermore, it is simulated remarkably higher in the North Pole in the summer, which is partly due to the difference of cloud cover simulation, but is more likely owing to the simulated insufficiency of sea ice and snow cover in this region. The introduction of NEW scheme improved the simulation of SWR remarkably, especially in the eastern Pacific and Atlantic, and oceans from subtropics to middle latitudes, where the simulated SWCRF differences decrease obviously due to the improvement of simulation of low cloud cover (Fig.4). Low cloud is mainly to reflect solar radiation and cool the earth, and thus the increase of cloud cover can reduce the SWR reaching the surface and reflect more of them to outer space. It is noticeable that the improvement on simulation of low

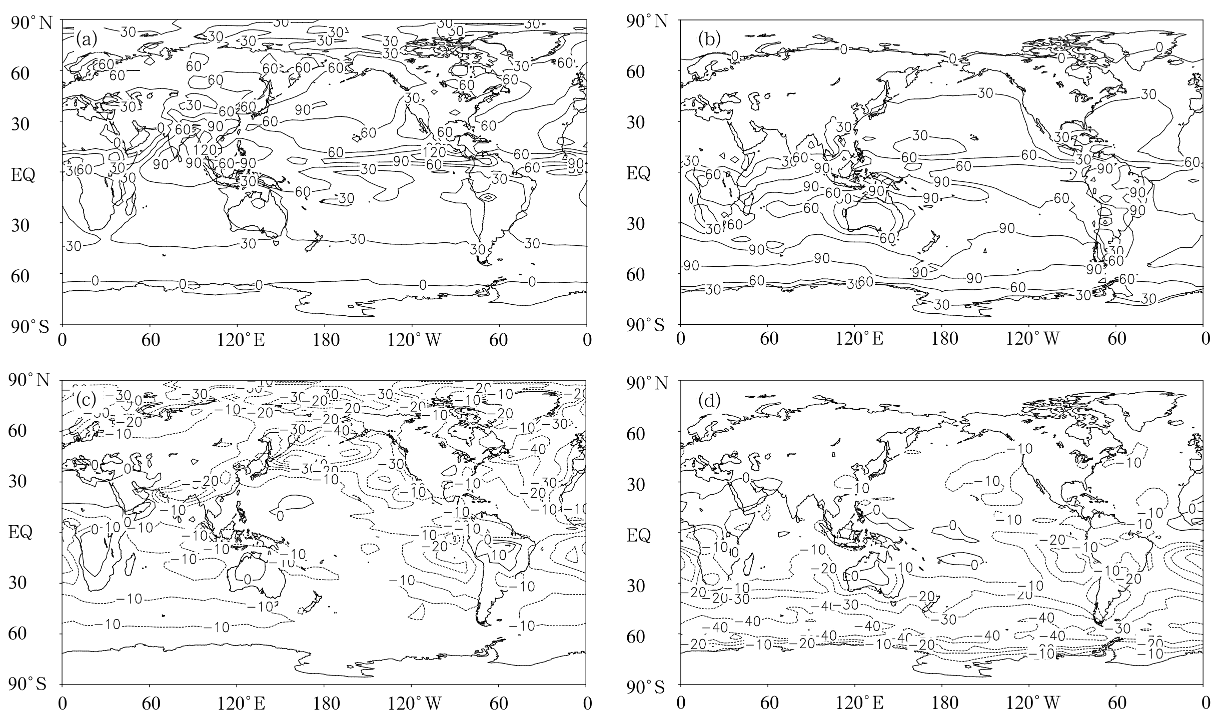

Fig.4. TOA short-wave cloud radiation forcing differences (unit: W m^{-2}). (a) JJA, ORIG−ERA; (b) DJF, ORIG−ERA; (c) JJA, NEW−ORIG; and (d) DJF, NEW−ORIG.

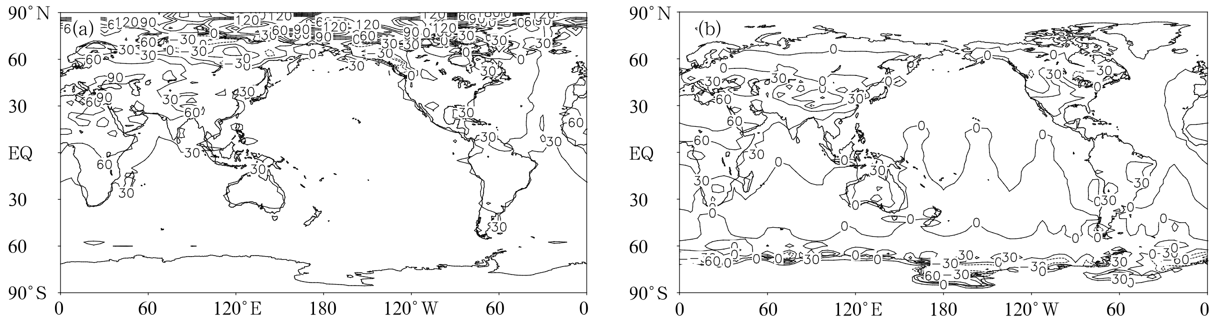

Fig.5. Surface clear-sky short-wave radiation differences (unit: W m^{-2}). (a) JJA, NEW$-$ERA; and (b) DJF, NEW$-$ERA.

cloud in the eastern Pacific and Atlantic may have impotant effect on ocean's simulation, because there exists obvious positive feedback between the local low stratus and SST, which may impact the simulation of climatic status of the ocean (Yu and Mechoso, 1999; Mechoso et al., 1995). This question will be discussed in other place.

The SWR in clear sky also has significant contributions to the simulated difference of SWR (Fig.5). Firstly, in summer's Arctic, Alaska, and north of Eurasian Continent, and in winter's ocean near the Antarctic, sea ice cannot be simulated well, resulting in the abnormal absorption of SWR by the surface, while too much snow cover is simulated in the land, causing the superfluous reflection of SWR there. Secondly, the SWR reaching the surface is higher obviously in Sahara and its surrounding regions, which is mainly due to neglecting the aerosol's (especially dust aerosols) effect on radiation in our model (Miller and Tegen, 1998). That leads to the obvious difference of SWR in these regions although SWCRF is rather small there.

4.3 LWR

Clouds can absorb LWR effectively, then there is a close connection between cloud cover and LWR. According to ERA data, the LWR is in inverse proportion to cloud cover at both TOA and surface, and the maximum LWR is mainly located in regions with little cloud cover in subtropics.

High cloud can trap surface LWR strongly and emit outgoing LWR with a lower cloud-top temperature, so modeling deficiency in LWR at TOA is mainly from the simulation of high cloud. The largest LWR difference from ERA simulated by ORIG scheme occurs in regions from the tropical Indian Ocean to the West Pacific, where high cloud is simulated less remarkably. However, NEW scheme did not improve LWR simulation, mainly due to the less change of high cloud there.

As for surface LWR, it is more affected by low cloud. The surface LWR is simulated obviously higher by ORIG scheme. After NEW scheme is introduced, modelling differences decrease remarkably, especially in the eastern Pacific and Atlantic, and summer hemispheric oceans from subtropical to mid-latitudes, where the simulation of low cloud improves greatly, leading to the increase of LWR reflected and emitted by low cloud above the surface (Fig.6). Furthermore, changes in LWR may partly reflect the feedback between cloud cover and SST, i. e., the increase of cloud cover would reflect more solar radiation and result in cooling of ocean due to the reduction of solar radiation absorption (Ramanathan and Collins, 1991), subsequently, LWR emission from the surface decreases, and then reduces the modeling difference of LWR. It should be noted that the surface LWR is still higher remarkably, mainly owing to the poor simulation of cloud cover.

Generally speaking, LWR is simulated much better than SWR. Therefore the modelling difference in LWR is far less than that of SWR, which may result in large modelling difference in net radiation (NR).

4.4 Net radiation

NR (net radiation) is more concerned than LWR

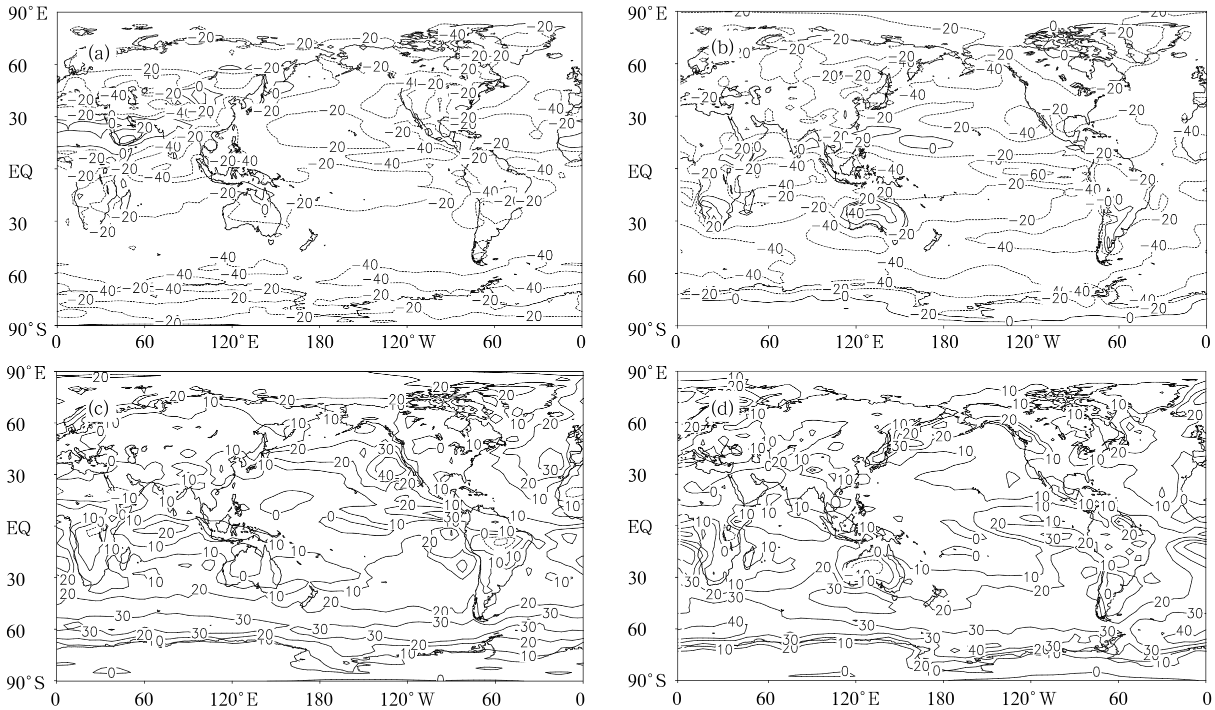

Fig.6. Surface long-wave radiation differences (unit: W m^{-2}). (a) JJA, ORIG−ERA; (b) DJF, ORIG−ERA; (c) JJA, NEW−ORIG; and (d) DJF, NEW−ORIG.

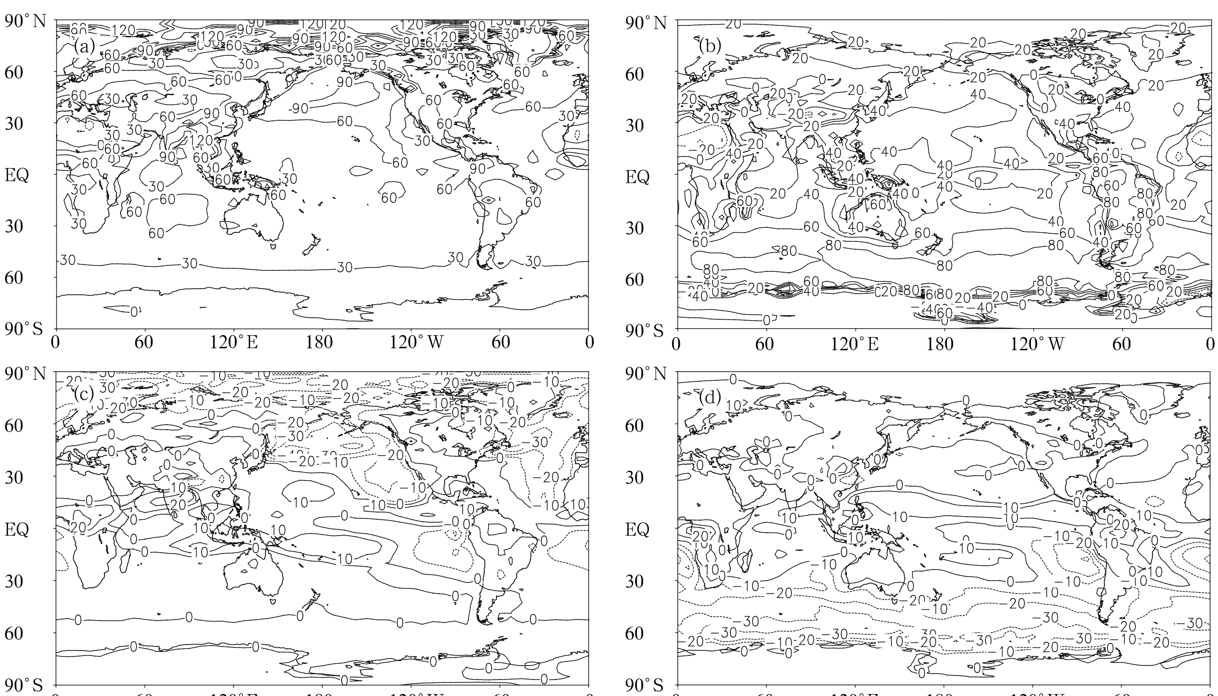

Fig.7. TOA net radiation differences (unit: W m^{-2}). (a) JJA, ORIG−ERA; (b) DJF, ORIG−ERA; (c) JJA, NEW−ORIG; and (d) DJF, NEW−ORIG.

and SWR, because it can directly impact the distribution of atmospheric diabatic heating, and further the atmospheric circulation. ERA data show that positive NR is mainly located in tropics and middle latitudes of summer hemisphere both for surface and TOA, but at the surface it is much higher (about twice) than TOA. Negative NR mainly occurs in mid-high latitudes of winter hemisphere for the surface, and almost all the winter hemisphere and the polar region of summer hemisphere for TOA.

At TOA, the NR is simulated obviously higher in ORIG scheme, especially in tropics and from subtropics to middle latitudes of summer hemisphere, which is mainly caused by the larger difference of SWR. The introduction of NEW scheme brings remarkable improvement to the simulation of NR in the eastern Pacific and Atlantic, and the ocean from subtropics to middle latitudes of summer hemisphere, mainly resulting from the SWCRF's improvement (caused by increase of low cloud cover) in these regions. The LWCRF at TOA mainly lies on the simulation of high cloud, hence it does not change much (Fig.7).

At the surface, the NR has a similar change to TOA except for the smaller quantity. That is because the surface LWR mainly depends on low cloud. when SWCRF changes, the LWCRF also varies remarkably. Moreover, LWCRF has an opposite sign to SWCRF, so it weakens the improvement of SWCRF to some degree. That is why the surface NR does not improve remarkably as TOA even in those regions with obvious change of low cloud cover.

5. Effect of cloud on radiative heating rate

Considering the vapour's effect on radiative heating rate, it can be expressed as

$$\left(\frac{\partial T}{\partial t}\right)_{\mathrm{rad}} = \frac{\mathrm{g}}{C_{\mathrm{p}}}\frac{\partial F}{\partial p}, \tag{5}$$

where F is the net radiative flux, $C_{\mathrm{p}} = C_{\mathrm{p_{dry}}}[1 + (C_{\mathrm{p_{vap}}} - C_{\mathrm{p_{dry}}})q/C_{\mathrm{p_{dry}}}]$, denoting the specific heat at constant pressure of moist air, therein $C_{\mathrm{p_{dry}}}$ and $C_{\mathrm{p_{vap}}}$ are the specific heat at constant pressure of dry air and vapour, respectively.

The simulated heating rate is given in Fig.8 (only results by NEW scheme), from which we can see that rate for LWR is larger than SWR. Maximum values are mainly located in the middle troposphere in mid-low latitudes for LW cooling rate, and in the stratosphere for SW heating rate (mainly due to the strong absorption by ozone). However, the net heating rate is negative for almost all model levels, which is unreasonable obviously (Yin, 1993). That also indicates that the model atmosphere is too transparent to SWR from one side.

In general, LWR warms the lower part of cloud and cools its upper part, and quite the reverse for SWR (Yin, 1993). After the introduction of NEW scheme, heating rate (especially for LWR cooling rate) changed remarkably corresponding to the change of cloud cover (Fig.9). Especially in the lower troposphere of mid-high latitudes, LWR caused obvious warming near the surface and obvious cooling in the upper part due to the large variation of cloud cover (which can be seen in Fig.3). As for SWR, its basic change can be simulated as well although the change is not remarkable due to the deficiency in simulating the scattering and absorption by cloud (figure omitted).

6. Conclusions

In this paper two 20-yr integrations were processed by use of ORIG and NEW cloud cover schemes to study their ability to simulate clouds and radiation. Results show that ORIG scheme has some ability to simulate the basic distribution of TCC, although great deficiency exists compared with ISCCP satellite data and ERA reanalysis data. The introduction of NEW scheme greatly improved the simulation of low cloud over the eastern Pacific and Atlantic, and the oceans from subtropics to middle latitudes of summer hemisphere. However, large differences still exist in tropical regions, especially from the tropical Indian Ocean to tropical West Pacific. That is mainly attributed to the poor simulation of local deep cumulus convection and subsequent high cloud.

In general, the model has a better simulation on LWR than SWR. Modelling difference of SWR is mainly from the poor simulation of SWCRF, and also caused by excluding the absorption of SWF by aerosol, and the albedo effect due to deficiency in simulating

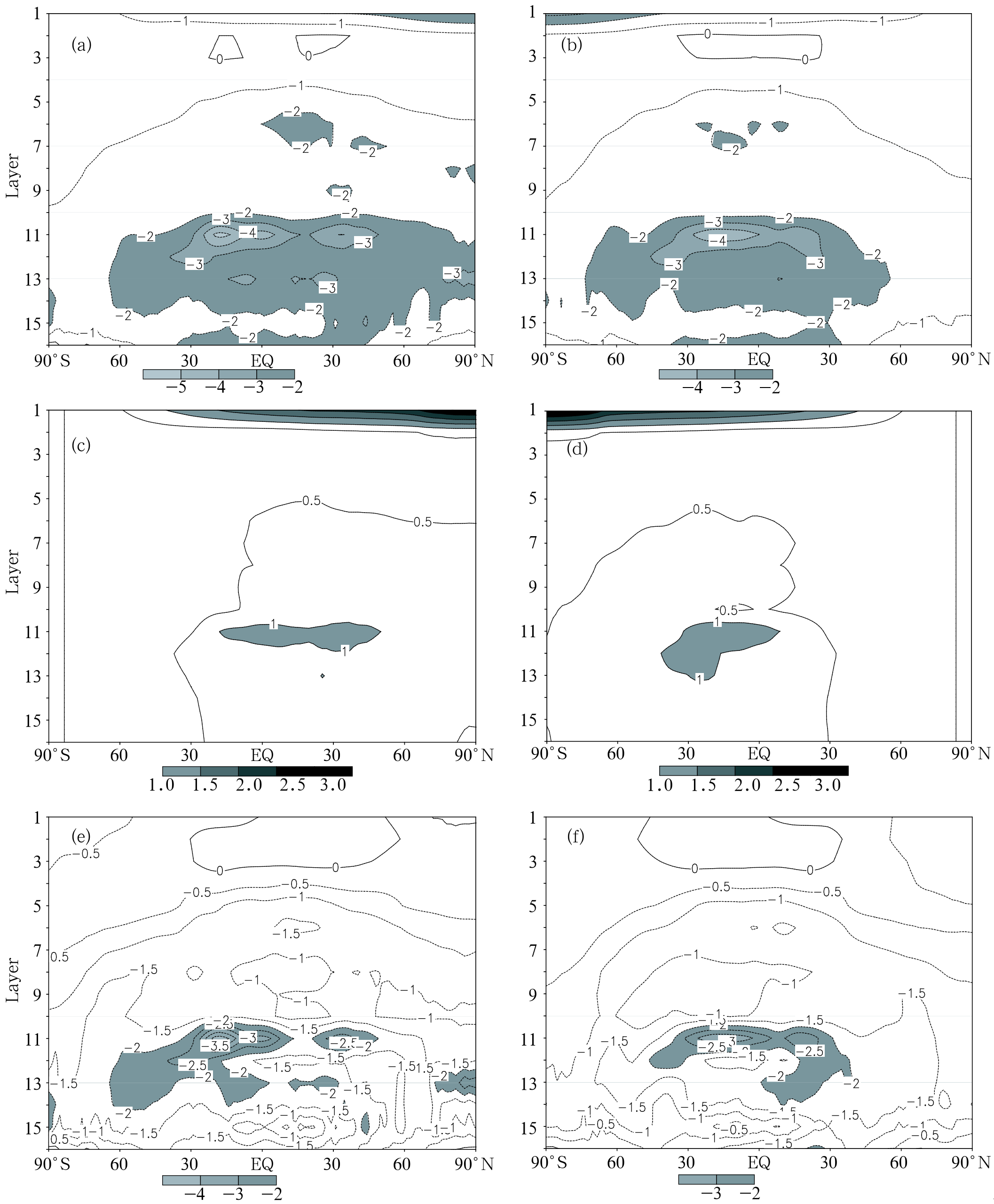

Fig.8. Latitude-height cross section of radiative heating rate simulated by NEW (unit: K day^{-1}). (a) Longwave for summer, (b) longwave for winter, (c) shortwave for summer, (d) shortwave for winter, (e) net radiation for summer, and (f) net radiation for winter.

sea ice and snow cover. Difference of LWR is mainly from the modelling deficiency in cloud cover and underlying surface temperature. Corresponding to the obvious improvement of low cloud cover simulation, the modelling CRF improves greatly in the eastern Pacific and Atlantic, and the oceans from subtropics to middle latitudes of summer hemisphere, resulting in the remarkable improvement on NR's simulation there.

Cloud also has great effect on radiative heating rate. The introduction of NEW scheme changed LWR cooling rate greatly, while SWR heating rate did not

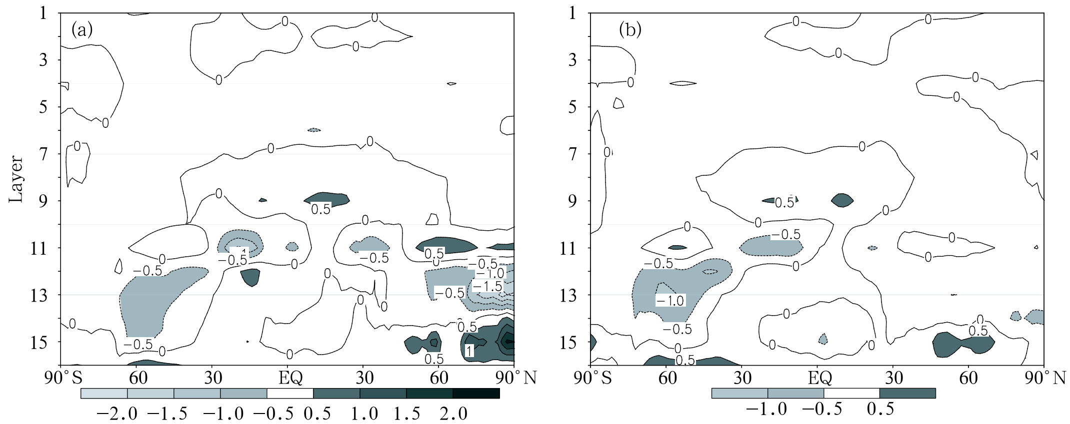

Fig.9. Latitude-height cross section of change in longwave cooling rate (NEW−ORIG)(unit: K day^{-1}). (a) Summer and (b) winter.

change much, mainly because the model atmosphere is too transparent to SWR.

It is noted that complicated feedbacks exist between cloud and radiation. Besides cloud cover, cloud can affect radiation through its micro-physical optical properties, such as cloud water content, optical depth, cloud droplet effective radius, etc. (Wang and Ding, 2005). In the current radiative parameterization scheme of this paper, these properties are still poorly treated, which is an important reason for obvious disparity in simulation of CRF. In addition, to improve the oceanic model, especially for simulation of SST and sea ice, is another significant approach to improve the simulation of cloud and radiation. Finally, due to the uncertainty of validating data (ERA-40), the results of this paper should be treated cautiously.

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