MINISTÉRIO DA CIÊNCIA E TECNOLOGIA
INSTITUTO NACIONAL DE PESQUISAS ESPACIAIS

INPE-14052-NTE/371

INCORPORATION OF NEW SOLAR RADIATION SCHEME INTO CPTEC GCM

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INPE
São José dos Campos
2007

ABSTRACT

A sophisticated solar radiation scheme has been incorporated in the global model of CPTEC. The scheme considers fine effects of gaseous absorption and particle scattering which are not taken into account in the original scheme of the model. The new scheme demonstrates much higher accuracy in offline solar radiation calculations for the test cases. The two versions of the model, with the original and new radiation schemes, were integrated for time periods of 2.5 and 6 months with different initial conditions. The impact of the new solar radiation scheme on surface solar radiative fluxes and meteorological variables during astral summer over South America are analyzed here. The values of surface solar radiation provided by the model integrations with new radiation scheme are in a better agreement with satellite-derived data than those provided by the original model. The magnitude of precipitation is improved over equatorial Atlantic Ocean and over Southeastern Brazil, however there is not significant impact over Amazonia. Therefore, further improvement in the model performance requires changes in the convection scheme as well as in others physical parameterizations of the model.

INCORPORAÇÃO DE NOVO ESQUEMA DE RADIAÇÃO SOLAR NO MODELO DE CIRCULAÇÃO GERAL DO CPTEC

RESUMO

Um sofisticado esquema de radiação solar foi incorporado ao modelo global do CPTEC. O novo esquema leva em consideração detalhes da absorção gasosa e do espalhamento por partículas, que não eram considerados no esquema original. Em testes padrões realizados com os dois esquemas, fora do modelo global, o novo esquema apresentou maior acurácia. As duas versões do modelo global, com o esquema original e com o novo, foram integradas por períodos de 2.5 e 6 meses com diferentes condições iniciais. Os impactos do novo esquema de radiação solar nos fluxos radiativos e em variáveis meteorológicas, durante o verão austral, foram analisados sobre a América do Sul. Os valores da radiação solar à superfície obtidos com o novo esquema aproximam-se mais dos dados de satélite do que aqueles obtidos com o esquema original. Além disso, a precipitação sobre o oceano Atlântico equatorial e sobre a América do Sul, no centro da Zona de Convergência do Atlântico Sul, tornou-se mais próxima das observações. Entretando, não houve uma melhoria da precipitação sobre a Amazônia, região na qual o modelo falha em simular a forte atividade convectiva. Portanto, para conseguir uma melhor perfomance do modelo será necessário, além de um novo código de radiação, mudanças no esquema de convecção bem como em outras parametrizações físicas do modelo.

SUMMARY

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LIST OF ABBREVIATIONS

CPTEC - Centro de Previsao de Tempo e Estudos Climaticos

COLA - Center for Ocean, Land and Atmosphere Studies

GCM - General Circulation Model

GPCP - Global Precipitation Climatology Project

GOES 8 - Geostationary Operational Environmental Satellite number 8

HITRAN - HIgh-resolution TRANsmission molecular absorption database

ICRCCM - InterComparison of Radiation Codes in Climate Models

ITCZ - Inter Tropical Convergence Zone

LBL - Line-By-Line method of radiative transfer calculations

MLS - Mid Latitude Summer atmosphere

NCEP - National Center for Environmental Prediction

NOAA - National Oceanic and Atmospheric Administration

SAW - Sub Arctic Winter atmosphere

SRB - Surface Radiation Budget data sets

SACZ - South Atlantic Convergence Zone

SSiB - Simplified Simple Biosphere model

TRA - TRopical Atmosphere

WMO - World Meteorological Organization

CHAPTER 1

INTRODUCTION

The General Circulation Model (GCM) currently used for weather and seasonal climate forecast at the Centro de Previsão de Tempo e Estudos Climáticos (CPTEC) was initially derived from the National Center for Environmental Prediction (NCEP) and developed at the Center for Ocean, Land, and Atmosphere studies (COLA). The dynamical and physical processes introduced by COLA are described in Kinter et al.(1997). The main changes introduced by CPTEC in the COLA GCM were related to the kind of truncation (from rhomboidal to triangular), dissipation process, computational time performance, postprocessing scheme, and increase of the vertical levels (Cavalcanti et al., 2001). The model is referred hereafter as CPTEC GCM. This study is part of the further development of the CPTEC GCM related to the changes in physical parameterizations of the model, particularly, in its solar radiation scheme.

An accurate simulation of solar radiative fluxes incident at the Earth's surface is necessary for a good performance of a GCM. The incident solar radiative fluxes, simulated by the CPTEC GCM over South America for the period 1986-1988 (Tarasova and Cavalcanti, 2002), were compared with those derived from satellite irradiance measurements (Whitlock et al., 1993). The latter fluxes were obtained from the Surface Radiation Budget (SRB) project data sets. The comparison showed that the model systematically overestimates both all-sky and clear-sky SRB fluxes. The average difference in the zonally mean all-sky (clear-sky) fluxes is 43 (50) $\mathrm{W\,m^{-2}}$ in January and 21 (29) $\mathrm{W\,m^{-2}}$ in July. This is probably caused by the deficiencies in the shortwave radiation code of the model. The offline testing of the model original code with more comprehensive technique demonstrated that the code underestimates solar radiation absorption in the clear-sky atmosphere due to the trace gases and aerosols. Hence, the incorporation of more accurate shortwave radiation code will lead to the improvement in the surface fluxes representation in the model.

The original solar radiation scheme *SWRAD* of the CPTEC GCM follows the parameterizations of Lacis and Hansen (1974). The scheme accounts for the absorption lines of H_2O and O_3, as well as the reflection from the layers of molecular atmosphere and cloudiness. The solar radiation absorption by water vapor is computed with the broad-band absorption function of Yamamoto (1962) which underestimates the water vapor absorption as compared with the use of the HIgh-resolution TRANsmission molecular absorption database (HITRAN-96) of Rothman et al. (1998). The *SWRAD* scheme also does not account for the atmospheric absorption due to O_2, CO_2, aerosols, and water vapor continuum. The solar spectrum is divided in two regions: from 0.2 μm to 0.7 μm (ultraviolet and visible) and from 0.7 μm to 4 μm (near infrared).

We incorporated in the CPTEC GCM a sophisticated shortwave radiation scheme *CLIRAD-SW* developed by Chou ans Suarez (1999) and modified by Tarasova and Fomin (2000). The modified scheme is referred later as *CLIRAD-SW-M*. This scheme considers the fine effects of gaseous absorption and particle scattering which are not considered in the original scheme. It accounts in the parameterized form for the absorption lines of H_2O, O_3, O_2, and CO_2, as available in the HITRAN-96 database (Rothman et al., 1998) as well as considers the absorption and scattering properties of aerosol and cloud particles. The solar radiative transfer is calculated with the use of the delta-Eddington and two-stream adding approximations. The modified code *CLIRAD-SW-M* also takes into account the water vapor continuum absorption model proposed by Clough et al.(1989). The code has 8 spectral bands in the ultraviolet and visible regions of the solar spectrum and 3 bands in the near infrared region.

The only way of testing the accuracy of the above mentioned broad band schemes is to compare them with a Line-By-Line (LBL) method. For the offline validation of the schemes we used the results of radiative transfer calculations performed with the LBL method of Fomin and Gershanov (1996) for the test cases of Fouquart et al. (1991). The online comparison of the schemes is performed using outputs of the model integration with the original and new solar radiation schemes for summer 2003. The impact of the new scheme on the surface fluxes and meteorological variables provided by the model is analyzed.

1.1 Short Description

This manuscript is organized as follows:

- CHAPTER 2 - RADIATION SCHEMES OFFLINE VALIDATION: In this chapter the *SWRAD* and *CLIRAD-SW-M* shortwave radiation schemes are compared offline with the LBL method for the clear-sky and all-sky test cases.

- CHAPTER 3 - INCORPORATION OF NEW SCHEME IN THE MODEL: This chapter presents the description of the changes made in the Fortran subroutines of the model during incorporation of the new solar radiation scheme as well as the description of the new subroutines incorporated.

- CHAPTER 4 - MODEL AND EXPERIMENTAL DESIGN: This chapter, describes the CPTEC GCM physical parameterizations and the model integrations performed for the analysis of the impact of a new scheme on the surface fluxes and meteorological variables.
- CHAPTER 5 - CONCLUSIONS: The chapter contains a summary of the results, conclusions, and proposals about a further study.

CHAPTER 2

RADIATION SCHEMES OFFLINE VALIDATION

In order to estimate schemes' accuracy, we performed the offline validation of the *SWRAD* and *CLIRAD-SW-M* schemes with the LBL method of Fomin and Gershanov (1996). The LBL method accounts for the same absorption lines and water vapor continuum which are considered in the *CLIRAD-SW-M* scheme. Nevertheless, it has much higher accuracy due to the use of fine wavenumber grid of 1/256 cm^{-1} and of Monte-Carlo technique in the radiative transfer calculations. The grid is fine enough to resolve any spectral line. The water vapor absorption coefficients are precomputed using the HITRAN-96 spectroscopic database (Rothman et al., 1998).

In 1984 an international working group on the InterComparison of Radiation Codes in Climate Models (ICRCCM) was established. The group proposed a set of fixed atmospheric models, so-called "cases", for the intercomparison of the radiative transfer algorithms (Fouquart et al., 1991). For solar radiation calculations the group selected 57 test cases which cover a wide variety of atmospheric conditions. These cases are based on three standard atmospheric profiles, namely, TRopical Atmosphere (TRA), Mid-Latitude Summer atmosphere (MLS) and SubArctic Winter atmosphere (SAW) (WMO, 1986). The profiles define pressure, temperature, and density of water vapor and ozone at 33 levels from 0 km to 100 km. The concentration of CO_2 was determined as 300 ppmv and 600 ppmv. The first 30 cases account for absorption by H_2O, O_2, O_3, and CO_2 at the solar zenith angles of 30 and 75. Cases 31-42 account for the absorption by the same gases and molecular scattering. Cases 43-49 (50-57) also include scattering by cloud and aerosol particles. We used for the schemes intercomparison the clear-sky test cases 31, 33 (MLS atmosphere) and 35, 37 (TRA). For cloudy atmosphere we used the test cases 43 and 45. The values of the incident solar radiation at the surface and atmospheric absorption computed by different methods are compared for these cases.

For the clear-sky cases the results of the schemes intercomparison are presented in Table 2.1. The difference between the *SWRAD* and LBL schemes varies from +18

$W\,m^{-2}$ to +44 $W\,m^{-2}$ for incident solar radiation and from -15 $W\,m^{-2}$ to -45 $W\,m^{-2}$ for atmospheric absorption. This is largely related to the neglect of solar radiation absorption due to the weak water vapor lines, water vapor continuum, O_2, and CO_2 in the *SWRAD* scheme. The deviation of the *CLIRAD-SW-M* scheme from the LBL method is less then 2 $W\,m^{-2}$ for both incident solar radiation and atmospheric absorption. The last column of Table 2.1 shows that the *CLIRAD-SW-M* schemes calculates smaller incident solar radiation and larger atmospheric absorption than the *SWRAD* code for all clear-sky cases considered.

TABLE 2.1 - The bias between the clear-sky incident solar radiation at the surface Q ($W\,m^{-2}$) and atmospheric absorption A ($W\,m^{-2}$) values, as computed with the *SWRAD*, *CLIRAD-SW-M* (here *CLIRAD*) and LBL schemes; Case, ICRCCM test cases; ATM, standard atmospheres; SZA, solar zenith angle in degrees; surface albedo is 0.2.

			Q/A		
Case	ATM	SZA	*SWRAD*-LBL	*CLIRAD*-LBL	*CLIRAD*-*SWRAD*
31	MLS	30	+40/-41	0/0	-40/+41
33	MLS	75	+18/-15	0/0	-18/+15
35	TRA	30	+44/-45	+1/-1	-43/+44
37	TRA	75	+21/-18	+1/-2	-20/+16

The *CLIRAD-SW-M* scheme assumes that aerosol scattering and absorption can be taken into account. In the *SWRAD* scheme the incorporation of the aerosol effects is not assumed. In order to estimate the difference between the solar radiation fluxes calculated with the two schemes in an atmosphere with aerosol loading we incorporated in the *CLIRAD-SW-M* scheme the aerosol continental model with column aerosol optical depth of 0.22 (WMO, 1986). This aerosol model describes average aerosol loading over the continents far from strong sources of aerosol emission such as biomass burning. Table 2.2 shows the difference in the incident solar radiation and atmospheric absorption values calculated with the two schemes. Its magnitude is about 2 times larger as compared with that obtained for the cases prepared for gaseous atmosphere with molecular scattering only (Table 2.1). Note, the new radiation scheme is accurate for the calculations in the atmosphere with aerosol loading. The difference in the incident solar radiation between the new scheme and LBL method obtained for the MLS atmosphere and continental aerosol model is about 1-2 $W\,m^{-2}$.

TABLE 2.2 - The bias between the clear-sky incident solar radiation at the surface Q ($W\,m^{-2}$) and atmospheric absorption A ($W\,m^{-2}$) values, as computed with the *CLIRAD-SW-M* and *SWRAD* schemes; the former scheme accounts for the continental aerosol model; surface albedo is 0.2; MLS, midlatitude summer atmosphere; TRA, tropical atmosphere; SZA, solar zenith angle in degrees.

ATM	SZA	Q	A
MLS	30	-82	+72
MLS	75	-54	+30
TRA	30	-84	+74
TRA	75	-56	+31

The *CLIRAD-SW-M* scheme has also a higher accuracy when used for radiative transfer calculations in cloudy atmosphere. The parameters of clouds used in the test cases 43 and 45 of Fouquart et al. (1991) are shown in Table 2.3. The cases 43 and 45 describe clouds located at the altitude of 13 and 2 km, respectively, with the same optical depth of 2.8. Table 2.4 shows the bais between the incident solar radiation and atmospheric absorption values computed with the *SWRAD*, *CLIRAD-SW-M*, and LBL schemes. The difference between the *SWRAD* and LBL schemes is about +50 $W\,m^{-2}$ in incident solar radiation and about -40 $W\,m^{-2}$ in atmospheric absorption. The incident solar radiation values obtained from the calculations with the *CLIRAD-SW-M* and LBL methods differ by +6 $W\,m^{-2}$, in both cases. Therefore, in cloudy conditions the *CLIRAD-SW-M* scheme is more accurate than the *SWRAD* scheme and calculates smaller values of the incident solar radiation and larger values of atmospheric absorption (last column of Table 2.4).

TABLE 2.3 - Cloud parameters used in the test cases 43 and 45 for the radiation schemes intercomparison; CT, cloud type; COD, cloud optical depth; H(km), altitude of cloud top; $R_e(\mu$m), effective radius of cloud particles; CS, stratocumulus.

Case	CT	COD	H	R_e
43	CS	2.8	13	5.25
45	CS	2.8	2	5.25

TABLE 2.4 - The bias between the incident surface solar radiation Q ($\mathrm{W\,m^{-2}}$) and atmospheric absorption A ($\mathrm{W\,m^{-2}}$) values, as computed with the *SWRAD*, LBL, and *CLIRAD-SW-M* (here *CLIRAD*) schemes for the test cases 43 and 45 with clouds; surface albedo is 0.2; standard atmosphere is midlatitude summer; solar zenith angle is 30 degrees.

	Q/A		
Case	*SWRAD*-LBL	*CLIRAD*-LBL	*CLIRAD-SWRAD*
43	+57/-36	+6/-5	-51/+31
45	+54/-43	+6/-8	-48/+35

CHAPTER 3

INCORPORATION OF THE *CLIRAD-SW-M* SCHEME IN THE MODEL

The main subroutine used in CPTEC GCM for radiation computations (Chagas and Tarasova, 1996) is **spmrad**. Its input parameters are the model date, geographical coordinates of each model point, surface pressure, temperature, and albedo as well as air temperature, specific humidity, relative humidity, and vertical velocity at the middle of each vertical layer and pressure at bottom of each layer. The output parameters of **spmrad** are shortwave and longwave fluxes at the top of the atmosphere and at the surface in all-sky and clear-sky conditions as well as shortwave heating rate and longwave cooling rate in each vertical layer. The subroutine **spmrad** is called by **physcs** which is the main subroutine for turbulence closure.

The subroutine **spmrad** calls **radtim**, **getoz**, **cldgen**, **swrad** and **lwrad**. The subroutine **radtim** computes solar declination, eccentricity correction factor of the Earth's orbit and equation of time for the model date. These parameters are used later in **spmrad** for the calculations of solar zenith angle. The subroutine **getoz** interpolates ozone mixing ratio from climatological data into model date, given latitude, and each vertical layer. The subroutine **cldgen** calculates cloud amount of convective and large scale clouds in each vertical layer from the data of precipitation rate, relative humidity, vertical velocity, and lapse rate. The subroutines **swrad** and **lwrad** perform radiative transfer calculations in the shortwave and longwave intervals.

The main program for solar radiation computation is **swrad** which prepares input arrays for the calculations at the daytime latitude grid points, adds one layer at the top of the atmosphere in order to avoid extra heating in the stratosphere, and performs some preliminary calculations. The **swrad** subroutine calls **setsw** which calculates ozone amount and water vapor amount from ozone and water vapor mixing ratio, prepares input arrays at the cloudy daytime model grid points, and computes cloud optical depth in each vertical layer and layer's reflectivities. The **setsw** subroutine calls **clear** and **cloudy** which compute solar radiative fluxes at the top of the atmosphere and at the surface as well as the heating rate in each vertical layer in clear-sky and cloudy conditions, respectively. Hence, the shortwave radiative transfer calculations themselves are performed by the subroutines **clear** and **cloudy**. In order to incorporate another radiative transfer code we need to replace them by the subroutines of that code. Some changes have to be also done in the subroutines **swrad**, and **setsw** in order to suit the input parameters of the new code.

A complete computer code of the *CLIRAD-SW* scheme (Chou and Suarez, 1999) is available from ftp://climate.gsfc.nasa.gov/pub/chou/clirad_sw/. A special feature of this scheme is inclusion of the absorption due to the minor absorption bands of H_2O, O_2, and CO_2, The magnitude of absorption in those minor bands is small, but the total effect is large (about 10% of the column atmospheric heating). We also included the absorption due to the water vapor continuum changing the water vapor k-distribution functions in the 3 bands of the near-infrared region according to Tarasova and Fomin (2000). The magnitude of the continuum absorption is about 6% of the water vapor line absorption. Also the *CLIRAD-SW* scheme uses accurate methods for the radiative transfer calculations in the multi-layered scattering atmosphere (Delta-Eddington and two-stream approximations). Aerosol optical properties are specified as inputs to the scheme. All these improvements lead to much higher accuracy of the fluxes calculated by the *CLIRAD-SW-M* scheme than by the *SWRAD* scheme. On the other hand, the computing time for the flux calculations with the new scheme increases, but this can be overcome with the rapid development of computers capacity.

The main subroutine of the *CLIRAD-SW* radiation scheme is **sorad** with following input parameters: number of atmospheric layers, level pressure, layer temperature, layer specific humidity, layer ozone concentration and CO_2 mixing ratio as well as optical properties of clouds and aerosols and surface albedo. The output parameters are net solar radiative fluxes at the top of atmosphere and at the surface and heating rate vertical profiles. The subroutine **sorad** does preliminary calculations of ozone and water vapor amounts and calls **soluv** and **solir**. These subroutines calculates solar radiative fluxes in the ultraviolet plus visible and near infrared regions of solar spectrum, respectively. In order to perform radiative transfer calculations they call the following subroutines **deledd**, **cldflx**, **rflx**, and **cldscale**. The **deledd** subroutine uses the Delta-Eddington approximation for the computation of the bulk scattering properties of a single layer, **cldflx** computes upward and downward fluxes using a two-stream adding method, **rflx** computes the reduction of clear-sky downward solar flux due to CO_2 and O_2 absorption, and **cldscale** calculates the high, middle, and low cloud amounts and scales the cloud optical thickness.

In order to incorporate the new radiation scheme *CLIRAD-SW-M* into the CPTEC GCM, we changed some codes in the subroutines **swrad** and **setsw**, eliminated the subroutine **clear** and replaced the subroutine **cloudy**. In **swrad**, the top of atmosphere pressure level (pu) was changed from 0 to 0.05 because the new code does not function when the top pressure level is equal to 0. The calculations of solar heating rate in all-sky and clear-sky conditions (asl and $aslclr$) were removed. The new code computes solar heating rate in K/day as output parameter. Thus, only its transformation into K/sec is performed in **swrad**. In **setsw** all precalculations of ozone and water vapor amounts as well as of layer reflectivities were eliminated. The cloud optical depth and cloud amount arrays were separated. The subroutines **clear** and **cloudy** were replaced by the call of new subroutine **cloudy**. We wrote these subroutine as interfaces between the model parameters and inputs of the new code. The aerosol optical properties of continental aerosol model (WMO, 1986) were incorporated into the near surface layer of 2 km. The new **cloudy** subroutine call **soradcld** which is quasi identical to the original subroutine **sorad** of *CLIRAD-SW*. This subroutine calls **solircld** and **soluvcld** which are quasi identical to **solir** and **soluv** of *CLIRAD-SW*. In the subroutine **solircld** we replaced the water vapor k-distrubution functions in the 3 bands of the near infrared region by those proposed by Tarasova and Fomin (2000). The subroutines **solircld** and **soluvcld** call original subroutines **deledd**, **cldflx**, **rflx**, and **cldscale** of *CLIRAD-SW*. The new subroutines prepared for the incorporation of the *CLIRAD-SW-M* code into the CPTEC GCM are available from the authors.

CHAPTER 4

EXPERIMENTAL DESIGN AND MODEL INTEGRATION RESULTS

Physical parameterizations of the CPTEC GCM include the vegetation module Simplified Simple Biosphere model (SSiB; Xue et al., 1991), cloud cover scheme of Slingo (1987) and Hou (1990), longwave radiation scheme of Harshvardhan et al. (1987) and the convective scheme of Kuo (1974). For the climatological simulations we used the version of the model with the resolution T62L28 (triangular truncation of 62 waves in the horizontal coordinate and 28 vertical levels) which corresponds to the space resolution of about 200 km. The initial conditions are from National Center for Environmental Prediction (NCEP). Two sets of ensemble experiments with original and new solar radiation schemes were performed. The first set of model integration was started with initial conditions on 12,13,14,15,16,17,18,and 19 November 2002 and finished on 31 January 2003 (EXP-I). In this experiment we analyzed monthly mean fields of ground fluxes and meteorological variables for January 2003. The second set of model integrations was started with initial conditions on 1,2,3,4,and 5 September 2002 and terminated on 28 February 2003 (EXP-II). Monthly mean fields for December 2002, January 2003, and February 2003 were analyzed. The impact of the new radiation scheme on the simulation of the summer climate features with the CPTEC GCM was evaluated. In the following, the model integrations with the original radiation code are referenced as original model integrations. The integrations with the new radiation code are referenced as modified model integrations. As a forcing boundary conditions the model utilizes monthly fields of observed Sea Surface Temperature (SST) (Reynolds et al., 2002) of National Oceanic and Atmospheric Administration (NOAA) (OI version 2). Other boundary conditions, such as soil humidity and surface temperature, were introduced as initial climatological conditions adjusted during the integration. Albedo is predicted by the SSiB over the land and is a function of solar zenith angle over the ocean.

In this study the monthly mean fields of precipitation, incident solar radiation, and cloud amount in atmosphere column obtained from the model integrations EXP-I and

EXP-II are analyzed. The model integration results with a single initial conditions showed its strong impact on the monthly mean precipitation fields which justify performing of a set of ensemble experiments. The monthly mean precipitation fields averaged over 5 and 8 integrations started in November 2002 (EXP-I) are presented in Figures 4.1 and 4.2, respectively. One can see that the impact of inicial conditions is slightly pronounced in the average fields. The model integrations with both schemes reproduce increase of precipitation up to 8-12 $\mathrm{mm\,d^{-1}}$ in the South Atlantic Convergence Zone (SACZ). SACZ is responsible for the enhanced cloudiness and precipitation in the central and southeastern parts of Brazil during summer. Another summer climate feature is enhanced precipitation in the equatorial Atlantic Ocean related to the position of Inter Tropical Convection Zone (ITCZ). The difference between the average precipitation fields simulated with the modified and original models is shown in Figures 4.3a and 4.3b (for 5 and 8 integrations). Both Figures demonstrate similar impact of the new solar radiation scheme on the average precipitation fields. Thus, monthly mean precipitation increases by 2-4 $\mathrm{mm\,d^{-1}}$ in the southeastern parts of SACZ and decreases by 2-4 $\mathrm{mm\,d^{-1}}$ in the equatorial Atlantic Ocean.

For the validation of the model-simulated precipitation values we used the data available from the Global Precipitation Climatology Project (GPCP) (Huffman et al., 2000) with the space resolution of $1^\circ \times 1^\circ$. This is a combined observation-only gridded data set based on gauge measurements and satellite estimates of rainfall. Figure 4.4a shows the GPCP mean precipitation for January 2003. We also used for the validation the precipitation data obtained at the meteorological stations. Figure 4.4b presents mean precipitation values, obtained at the meteorological stations of Brazil and interpolated at the grid of $0.25^\circ \times 0.25^\circ$. (The description of the data are given at the web site http://cptec.inpe.br/.) One can see from Figures 4.2 and 4.4 that the modified model with the new radiation scheme simulates better the precipitation of 12 $\mathrm{mm\,d^{-1}}$ observed in the southeastern Brazil as well as the magnitude of precipitation in the equatorial Atlantic Ocean. Both model versions underestimate precipitation over Amazonia and Southern Brazil. The regions with the precipitation of 4 and 8 $\mathrm{mm\,d^{-1}}$ are smaller in both model simulations than in the observations. Note, that the difference between the observational data themselves (GPCP and meteorological stations) is noticeable. The mentioned change in convective precipitation values is related to the change in incident surface solar radiation provided by the new scheme. Figure 4.5a shows monthly mean values of incident surface solar radiation (averaged over 24 hours) for January 2003 provided by the original model over South America. For the comparison we used surface solar radiative fluxes derived from satellite radiance measurements and interpolated at the grid of 40 km (Figure 4.5b). The fluxes were obtained from Geostationary Operational Environmental Satellite number 8 (GOES 8) visible imagery using a simplified physical model developed at CPTEC (Ceballos et al., 2004). A comparison of Figures 4.5a and 4.5b reveals a systematic positive difference about 50 $\mathrm{W\,m^{-2}}$ between the model-simulated and the satellite-derived fluxes. Figure 4.6a shows that the fluxes obtained from the modified model simulation are smaller by 20-40 $\mathrm{W\,m^{-2}}$ than those provided by the original model over most part of South America. Hence, a systematic positive difference of about 10-30 $\mathrm{W\,m^{-2}}$ still exists between the modified model and satellite data. Error of satellite-derived fluxes themselves was estimated by the comparison with ground data (Tarasova et al., 2005). A careful analysis of satellite-derived and pyranometer daily irradiations suggests that satellite estimations presente a negative bias during January 2003, with daily averages over the network between -1 $\mathrm{W\,m^{-2}}$ and -18 $\mathrm{W\,m^{-2}}$, with monthly average of -11 $\mathrm{W\,m^{-2}}$ and standard deviation of 15 $\mathrm{W\,m^{-2}}$. Therefore, the difference between the fluxes provided by the modified model and satellite data is already comparable with the error of ground solar radiation measurements.

Figure 4.6b shows the difference of mean clear-sky incident solar radiation simulated with the modified and original models for January 2003. One can see that the modified model provides smaller values of clear-sky incident solar radiation over all domain. This is consistent with the offline comparison of the original and new solar radiation schemes for the clear-sky test cases performed in Chapter 2. In all cases the new scheme computes larger atmospheric absorption and smaller incident solar radiation at the surface due to the trace gases and the aerosol absorption considered. Therefore, zero and positive values of the all-sky flux difference shown in Figure 4.6a

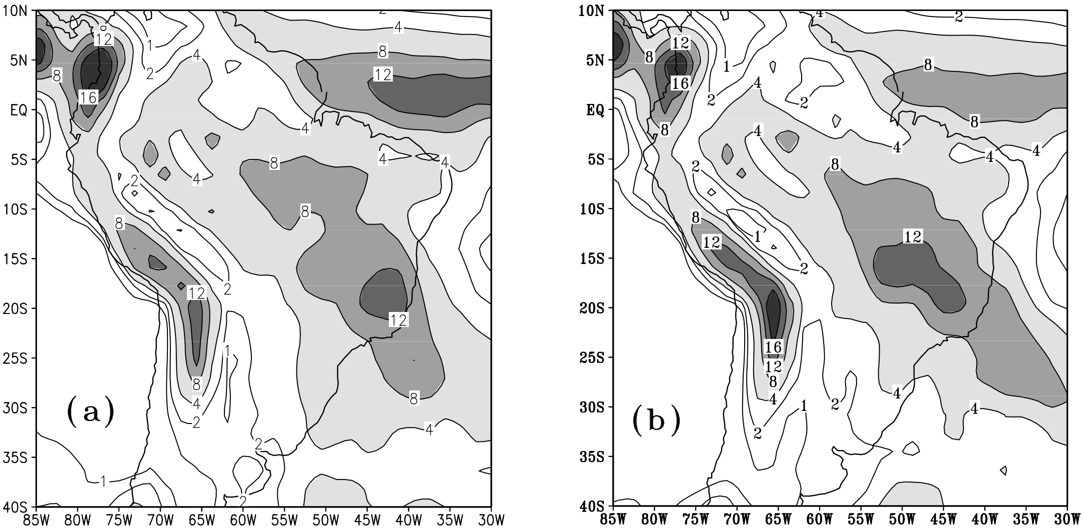

FIGURE 4.1 - January 2003 mean precipitation ($mm\,d^{-1}$) averaged over 5 integrations started on 12,13,14,15,16 November 2002 with (a) original and (b) modified models.

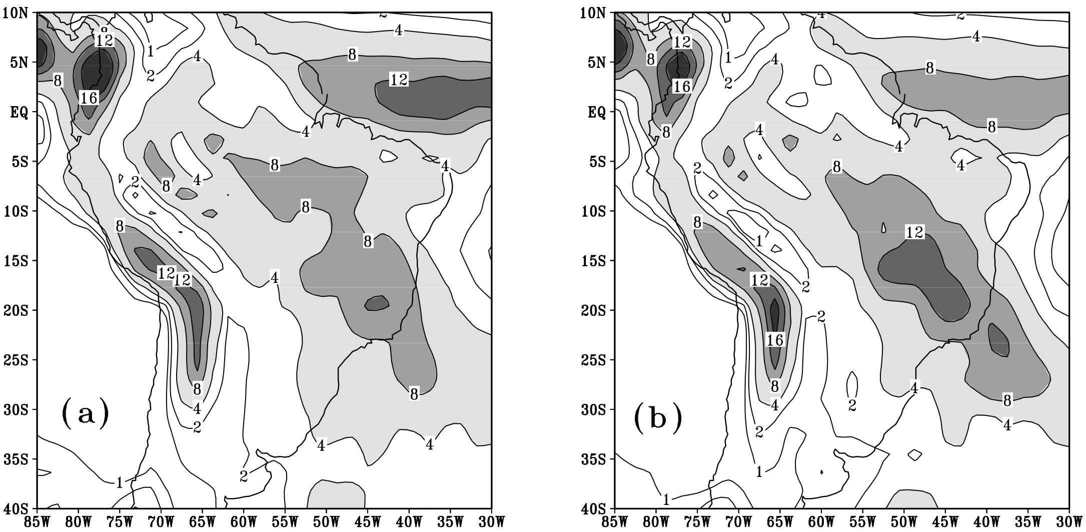

FIGURE 4.2 - The same as in Figure 4.4 but for 8 model integrations started on 12,13,14,15,16,17,18,19 November 2002.

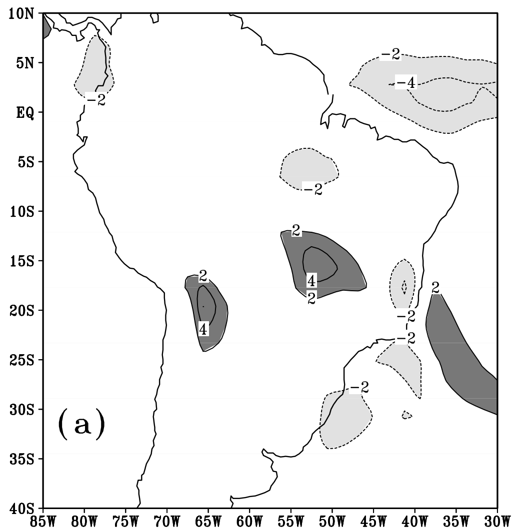

FIGURE 4.3 - Difference in January 2003 mean precipitation (mm d^{-1}) averaged over (a) 5 and (b) 8 integrations with modified and original models started in November 2002.

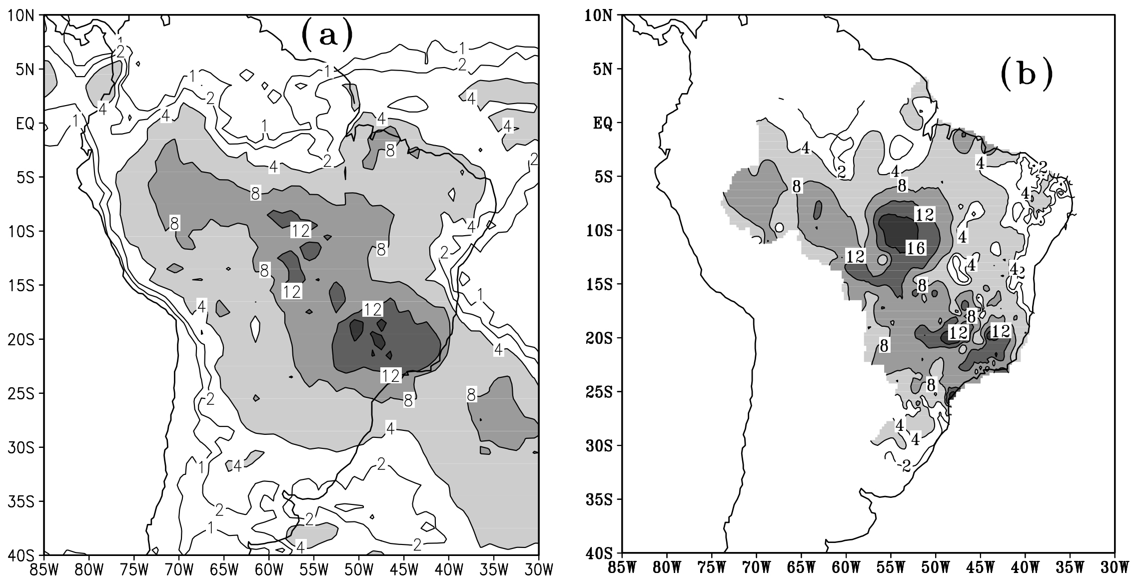

FIGURE 4.4 - January 2003 mean precipitation (mm d^{-1}) from (a) GPCP data sets and (b) observations at meteorological stations over Brazil.

are related to the presence of dense cloudiness. Figure 4.7a shows January 2003 mean cloud amount in % , averaged over 5 integrations with the original model. Due to the strong convective and cloud formation activities the highest values of cloud amount are presented in SACZ over the continent and in ITCZ over the ocean.

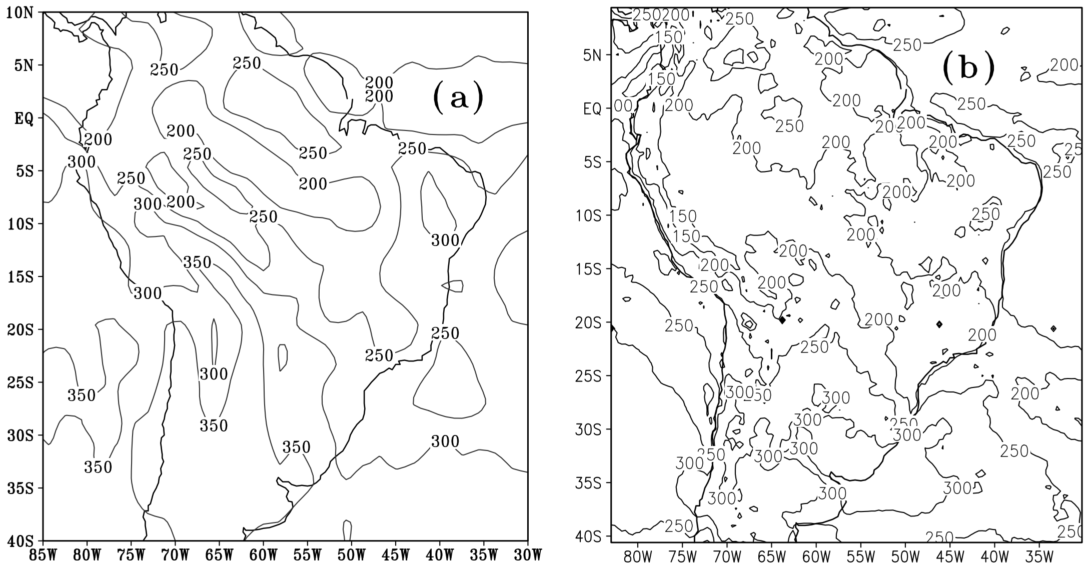

FIGURE 4.5 - January 2003 mean incident solar radiation, (a) averaged over 5 integrations with original model and (b) derived from satellite irradiance measurements.

The regions of highest values of cloud amount are related to the areas of zero and positive all-sky flux difference shown in Figure 4.6a. Figure 4.7b demonstrates cloud amount changes in the integration with the modified and original models. The modified model provides equal or smaller values of cloud amount in the regions of dense cloudiness and hence larger values of incident solar radiation at the surface. For the detailed analysis of cloud-radiation interaction we need not only cloud amount fields but cloud optical depth fields. For this, a new output has to be added to the model.

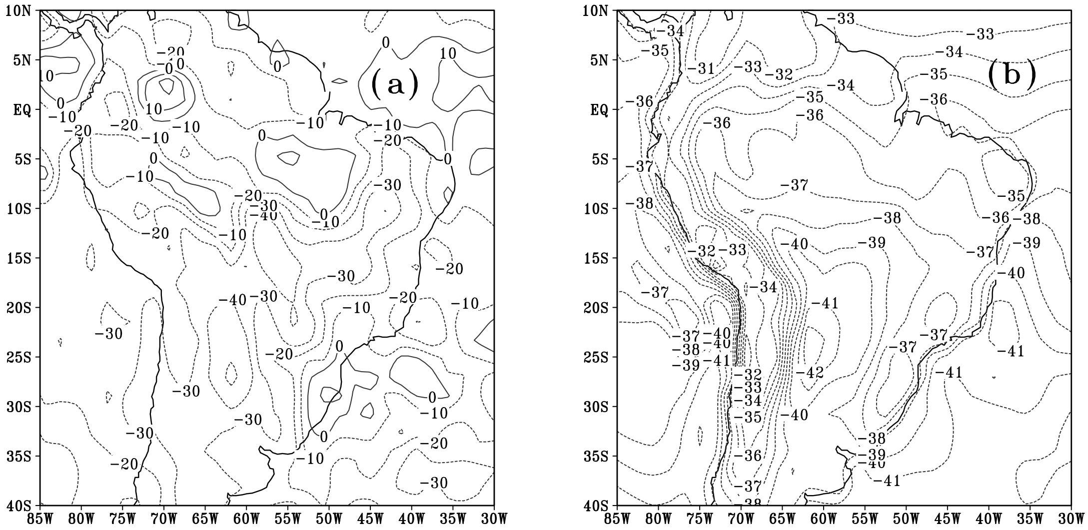

FIGURE 4.6 - Difference in January 2003 mean (a) all-sky and (b) clear-sky incident solar radiation, averaged over 5 integrations with modified and original models started in November 2002.

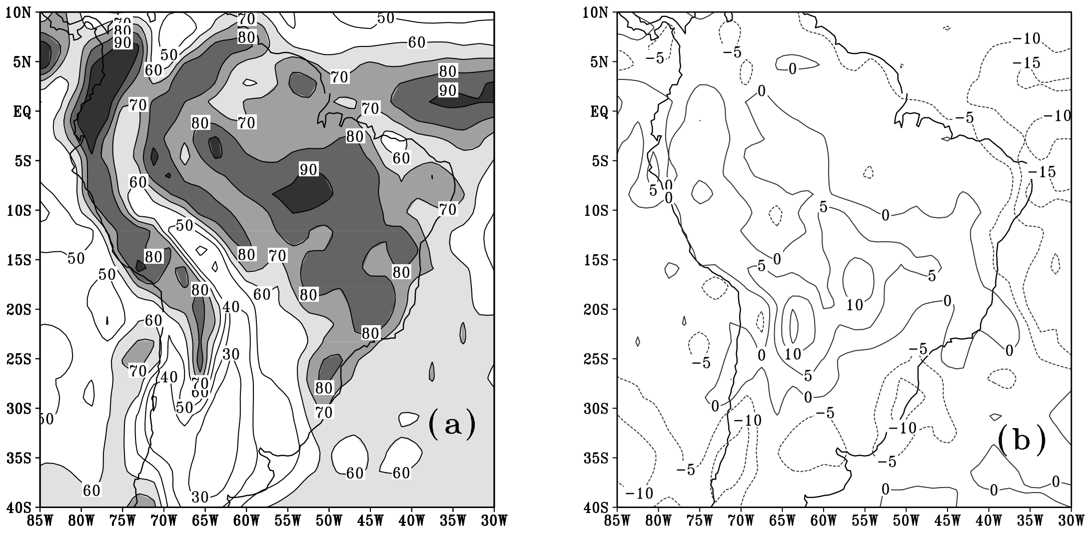

FIGURE 4.7 - (a) January 2003 mean cloud amount averaged over 5 integrations with the original model and (b) difference in January 2003 mean cloud amount between the modified and original models.

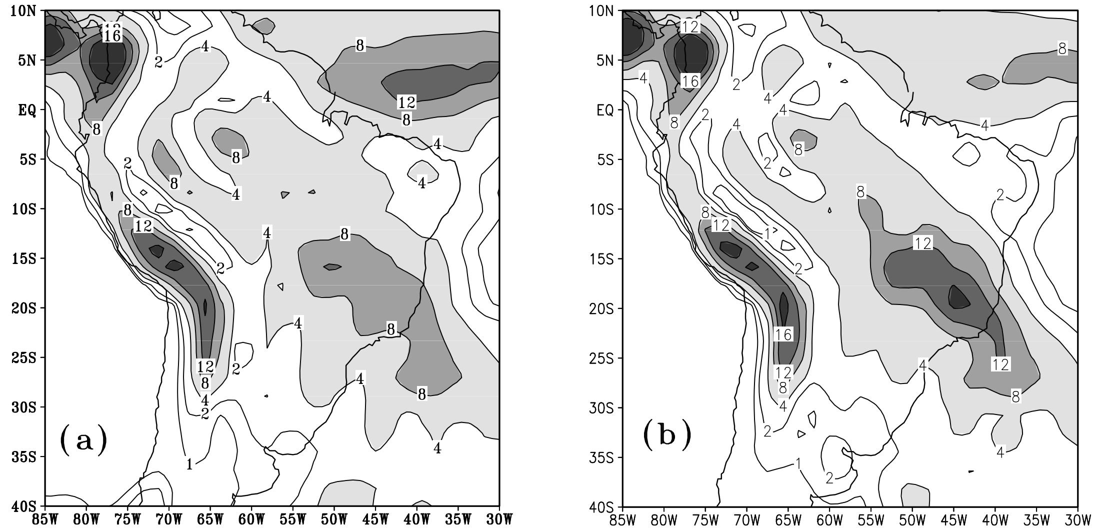

FIGURE 4.8 - December 2003 mean precipitation ($\mathrm{mm\,d^{-1}}$) averaged over 5 integrations with (a) original and (b) modified models.

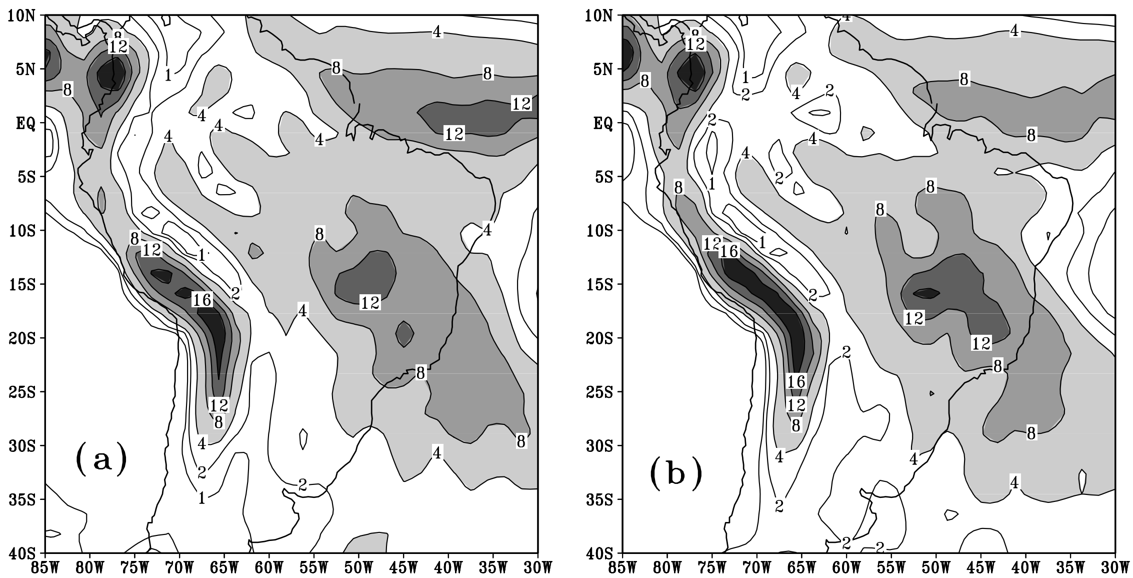

FIGURE 4.9 - January 2003 mean precipitation ($\mathrm{mm\,d^{-1}}$) averaged over 5 integrations with (a) original and (b) modified models.

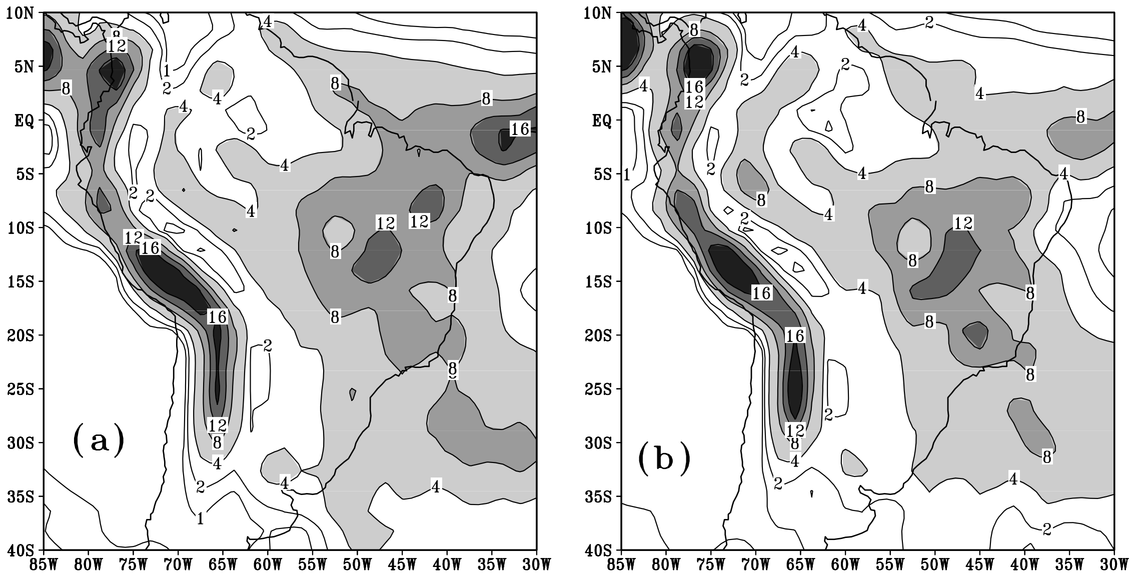

FIGURE 4.10 - February 2003 mean precipitation (mm d^{-1}) averaged over 5 integrations with (a) original and (b) modified models.

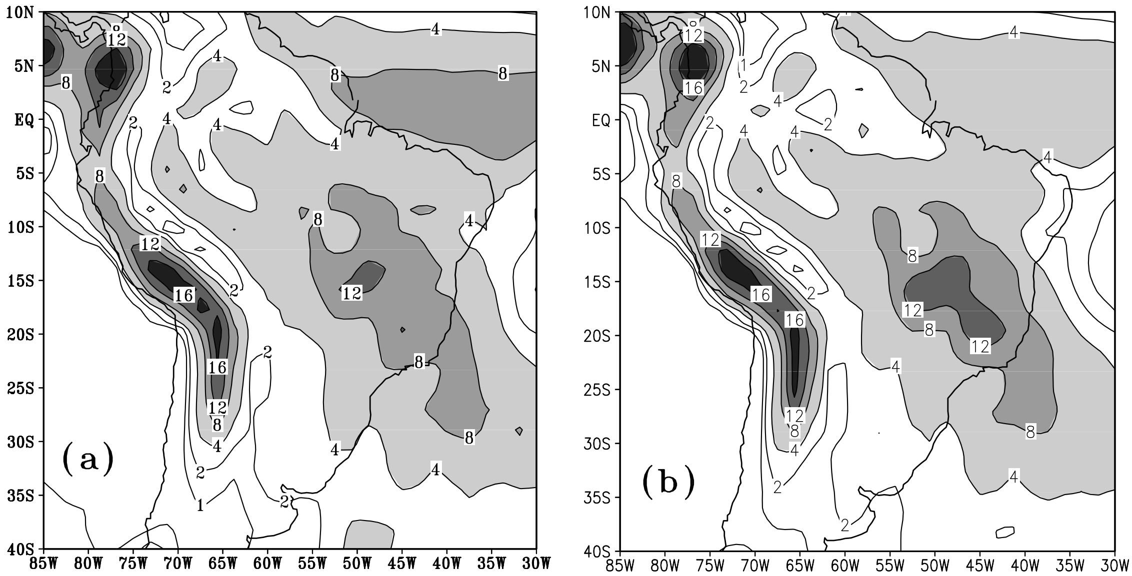

FIGURE 4.11 - Three months (December, January, February 2003) mean precipitation (mm d^{-1}) averaged over 5 integrations with (a) original and (b) modified models.

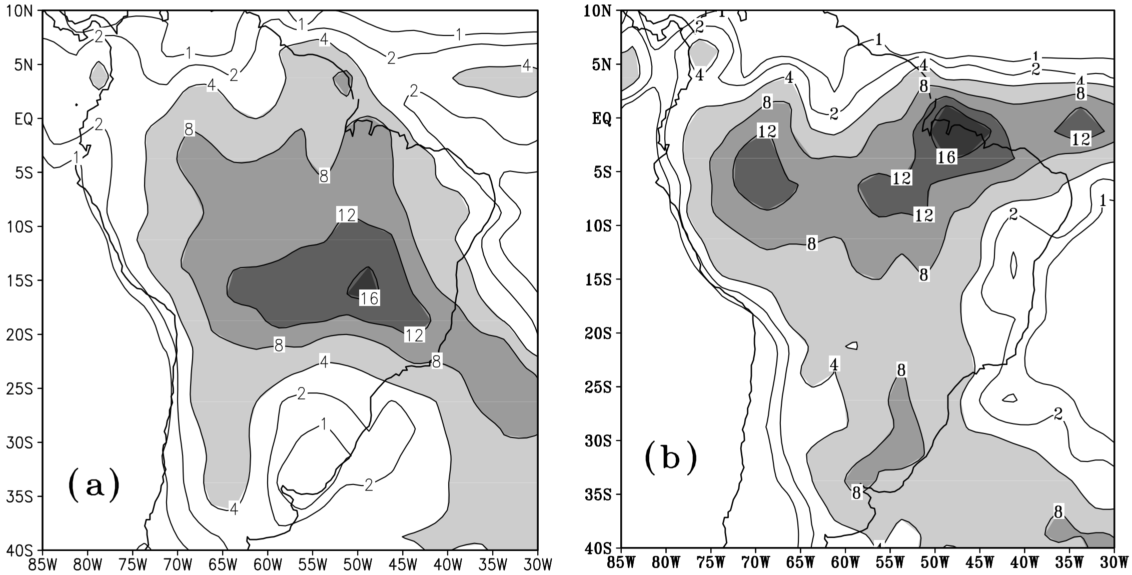

FIGURE 4.12 - GPCP (a) December 2002 and (b) February 2003 mean precipitation (mm d^{-1}).

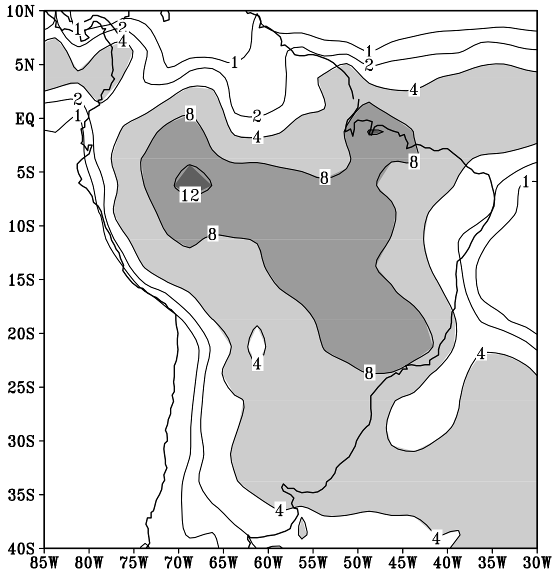

FIGURE 4.13 - GPCP three months (December, January, February 2003) mean precipitation (mm d^{-1}).

In order to analyze the impact of new radiation scheme on the model output for the austral summer months (December, January, February) we performed integrations with the original and modified models started on 1, 2, 3, 4, and 5 September 2002 and finished on 28 February 2003 (EXP-II). The monthly mean precipitation fields averaged over 5 simulations with the original and modified models are presented in Figure 4.8 for December 2002, in Figure 4.9 for January 2003, in Figure 4.10 for February 2003, and in Figure 4.11 for the three months average. All these figures reproduce the region of enhanced precipitation values in the central and southeastern Brazil in the SACZ and in the equatorial Atlantic Ocean in the ITCZ. The impact of the new solar radiation scheme is the same for each month and for the three months average: In the simulation with the new scheme the magnitude of precipitation increases in the SACZ over the continent and decrease in the ITCZ over the ocean. Figures 4.12 and 4.13 present the GPCP mean precipitation data for December 2002, February 2003, and three month averages (December, January, February). Comparison of these fields with the model-simulated precipitation fields (Figures 4.8, 4.10, and 4.11) demonstrates that both models, original and modified, have deficiencies in reproducing observed fields, particularly in February. High values of mean precipitation are not reproduced by the model in Amazonia where most of precipitation has convection origin in summer. Hence, the model needs modification of the convection scheme in conjunction with the solar radiation and cloudiness schemes. 2003, and three month averages (December, January, February). Comparison of these fields with the model-simulated precipitation fields (Figures 4.8, 4.10, and 4.11) demonstrates that both models, original and modified, have deficiencies in reproducing observed fields, particularly in February. High values of mean precipitation are not reproduced by the model in Amazonia where most of precipitation has convection origin in summer. Hence, the model needs modification of the convection scheme in conjunction with the solar radiation and cloudiness schemes.

CHAPTER 5

CONCLUSIONS

The new solar radiation scheme *CLIRAD-SW-M* has been incorporated into the CPTEC GCM in order to improve its surface flux representation. The new scheme demonstrates higher accuracy than the original scheme *SWRAD* in offline comparison with a detailed line-by-line method. In clear-sky atmosphere without aerosols loading, the difference between the original scheme and LBL method is about +30 $\mathrm{W\,m^{-2}}$ in incident solar radiation and from -10 $\mathrm{W\,m^{-2}}$ to -25 $\mathrm{W\,m^{-2}}$ in atmospheric absorption. Those differences estimated for the new radiation scheme and LBL method are about 1-2 $\mathrm{W\,m^{-2}}$. In cloudy conditions, the difference in incident solar radiation between the original scheme and LBL method is about +55 $\mathrm{W\,m^{-2}}$ and between the new scheme and LBL method is about 6 $\mathrm{W\,m^{-2}}$. The difference between the new and original schemes in clear-sky atmosphere with aerosol loading reaches about -80 $\mathrm{W\,m^{-2}}$ in incident solar radiation and +70 $\mathrm{W\,m^{-2}}$ in atmospheric absorption . This change in the surface radiation balance should lead to noticeable change in surface meteorological variables of the model such as temperature and precipitation.

A set of ensemble model integrations with the original and new radiation schemes were performed for the period from November 2002 to 31 January 2003 and from September 2002 to 28 February 2003. The impact of the new solar radiation scheme on meteorological variables during austral summer in South America was analyzed. The output fields were compared with each other and with observational data for December 2002, January 2003, February 2003, and three months average. The incident solar radiation values at the surface provided by the modified model are smaller than those simulated by the original model over main part of the continent. The decreased surface radiation values are in a better agreement with the satellite-derived data. The increase of monthly mean daily precipitation is obtained in the central and southeastern part of Brazil were dense cloudiness are formed in summer. In this region and in the equatorial Atlantic ocean the modified model reproduces monthly mean precipitation closer to the GPCP observational data. Both model versions have deficiencies in reproducing high precipitation values in Amazonia.

Comparison of the model-simulated solar radiation fluxes and meteorological variables with observations demonstrates that implementation of new radiation scheme improves surface flux representation over South America as compared with satellite-derived data. The magnitude of precipitation is improved over the equatorial Atlantic Ocean and Central and Southeastern Brazil but not improved over Amazonia. Therefore, change of solar radiation scheme in the model requires further changes in others physical parameterizations of the model aimed to improve the model performance.

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