The Use of New Parameterizations for Gaseous Absorption in the CLIRAD-SW Solar Radiation Code for Models

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ABSTRACT

The new gaseous absorption parameterizations are incorporated in the CLIRAD-SW solar radiation code for models, openly distributed for the scientific community. In the new parameterizations, the magnitude of absorption coefficients in each homogeneous layer depends on both species concentrations in the layer and species amounts accumulated along the direct solar radiation path from the top of the atmosphere (TOA). The number of the k-distribution terms varies from 1 to 4 in each of the eight bands. The total number of pseudomonochromatic intervals in the new version of the code is 15, compared with 38 currently in CLIRAD-SW. This reduces computational time of the code by approximately 2 times and facilitates its using in the numerical models. The error of the new version of CLIRAD-SW is determined here as the difference between the flux or heating rate values calculated with the code and line-by-line model. The surface and top-of-the-atmosphere flux difference is less than 1.5 W m^{-2} in calculations for the standard gaseous atmospheres and less than 7 W m^{-2} in calculations for the standard gaseous atmosphere with aerosol or cloud scattering and absorption incorporated. The relative flux error is less than 1% for all cases of gaseous atmosphere with and without molecular scattering and aerosol extinction. This error is less than 1.5% for the cases with cloudiness. The errors of heating rate calculations in the clear-sky atmospheres are less than 6% up to the height of 70 km, while these errors in cloudy layers reach values of about 30%, which is typical for current broadband parameterizations. The method to reduce these errors is suggested.

1. Introduction

Early solar radiation codes for numerical models based on the parameterizations of Lacis and Hansen (1974) demonstrate surface flux and atmospheric absorption errors up to 30 W m^{-2} as compared with current line-by-line (LBL) calculations made for clear-sky gaseous and molecular atmospheres (Tarasova et al. 2006). The errors increase up to 50–70 W m^{-2} when the comparisons are made for aerosol or cloudy atmospheres. The recently developed codes declare smaller differences from the LBL benchmarks that are less than 1–3 W m^{-2} in clear-sky solar radiation incident at the surface and atmospheric absorption as well as less than 5% in clear-sky heating rate values (Chou and Suarez 1999; Clough et al. 2005; Freidenreich and Ramaswamy 1999). The declared errors agree with a recent independent intercomparison of shortwave codes performed by Halthore et al. (2005).

Since the work of Lacis and Hansen (1974) the improvement of the code accuracy was related to an increase in the number of its spectral bands and k-distribution terms, jointly named as pseudomonochromatic intervals (PMIs). Unfortunately, this led to an increase of the codes' computational time because of the need to repeat radiative transfer calculations for

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each PMI. Note that due to the computational cost of the current radiation codes, the radiation forcing in GCMs is computed less frequently than dynamics or other physical processes. The negative effect of such economies on the model results has already been demonstrated (Morcrette 2000). Therefore, further development of the codes should be related to the improvement of their computational efficiency without the loss of the code accuracy.

One of the solar radiation codes for models characterized by a relatively small number of PMIs (38) and high accuracy is CLIRAD-SW developed by Chou and Suarez (1999) at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and applied to various atmospheric models at GSFC. The code is openly distributed to the scientific community. This facilitates its further development and application to numerical models. The improvement of the surface flux representation in the Eta Model with the CLIRAD-SW code incorporated is shown by Tarasova et al. (2006). The water vapor absorption parameterizations of Chou and Lee (1996) used in the CLIRAD-SW were advanced by Tarasova and Fomin (2000) by including the water vapor continuum of Clough et al. (1989).

The CLIRAD-SW code includes solar radiation absorption due to water vapor, O_3, O_2, CO_2, clouds, and aerosols, as well as interaction among absorption and scattering by molecules, cloud drops, and aerosol particles. The solar spectrum is divided into the eight bands in the ultraviolet (UV) and visible (VIS) regions and three bands in the near-infrared region (NIR) where the k-distribution method is applied. The radiative transfer calculations have to be performed for 10 k-distribution terms in each of three NIR bands. Chou and Lee (1996) demonstrate that when an insufficient number of k terms is used, the heating profile exhibits strong oscillation. It is found that at least 10 k terms are required to obtain a good agreement between the parameterizations and line-by-line model. Thus, the code performs radiative transfer calculations in 38 PMIs and does not allow considerable reducing of the PMI number without decreasing the code accuracy.

New parameterizations of gaseous absorption developed by Fomin and Correa (2005) overcome the above-mentioned restriction on the number of k terms. The formulas for volume absorption coefficients are given for three bands in the UV and VIS regions and for the five bands in the NIR. The magnitude of absorption coefficients in each homogeneous layer depends on both species concentrations in the layer and species amounts accumulated along the direct solar radiation path from the top of the atmosphere. The number of the k-distribution terms varies from 1 to 4 in each of the NIR bands. Thus, the total number of PMI in the new code is 15 as compared with 38 in CLIRAD-SW, and the computational time is proportionately reduced by a factor of 2.5. Some additional time is needed to calculate absorption coefficients, but this time should not be long as compared with the time reduction due to the smaller number of radiative transfer calculations in the atmospheric column.

TABLE 1. Spectral bands and number of k-distribution terms of CLIRAD(FC05)-SW in the UV + VIS region (bands 1–3) and the NIR region (bands 4–8).

Band	Limits (μm)	No. of k terms
1	0.2–0.303	1
2	0.303–0.323	1
3	0.323–0.7	1
4	0.323–1.22	1
5	0.7–1.22	3
6	1.22–10.0	1
7	1.22–2.27	4
8	2.27–10.0	3

In this note, we describe the incorporation of the new parameterizations in the CLIRAD-SW code (section 2) and perform comparison between the new version of the code and line-by-line model (section 3). It should be mentioned that this model has been independently tested and briefly described in the paper of Halthore et al. (2005). Concluding remarks are given in section 4.

2. Incorporation of new gaseous absorption parameterizations in the CLIRAD-SW code

The spectral bands and number of k-distribution terms used in the parameterizations of gaseous absorption of Fomin and Correa (2005, hereafter FC05) are shown in Table 1. There are three bands in the UV + VIS region and five bands in the NIR region of solar spectrum. Bands 4 (0.323–1.22 μm) and 6 (1.22–10.0 μm) are not continuous but consist of a set of subintervals accounted for O_3 and CO_2 absorption, respectively. The NIR bands 5, 7, and 8 have the same spectral limits as those selected by Chou and Suarez (1999). Similar bands were selected to make it possible to use their parameterizations of cloud optical properties. The total number of pseudomonochromatic intervals is 15. In addition to the original subroutines of CLIRAD-SW we wrote two new subroutines calculating the volume absorption coefficient in each atmospheric layer and each of 15 PMIs in visible and near-infrared spectrums. These subroutines use formulas from Tables 1 and 2 given in FC05. The represented molecular species are H_2O, O_3, O_2, and CO_2. Their broadband absorption

TABLE 2. Difference (W m^{-2}) between CLIRAD(FC05)-SW and FLBLM in incident surface solar flux F_d, upward flux F_{up} at TOA, atmospheric absorption Abs for the standard atmospheres and solar zenith angle of 30° (gaseous absorption only).

Flux	TRP	MLS	SAW	MLW	SAS	USA
Fd	−1.0	−1.3	1.2	0.2	−1.4	−0.7
Fup	−0.3	−0.3	−1.0	−0.9	−0.6	−0.7
Abs	1.1	1.3	0.0	0.7	1.7	1.2

coefficients were obtained from the spectroscopic high-resolution transmission molecular absorption database (HITRAN-11v) of Rothman et al. (2003) by means of a new *k*-distribution technique of Fomin (2004), which is based on a fast line-by-line model (FLBLM) of Fomin and Mazin (1998). The total amount of the solar radiation at the top of the atmosphere is 1372.4 W m^{-2}.

The main subroutine of CLIRAD-SW prepares input optical parameters for two subroutines calculating solar fluxes in the UV + VIS and NIR regions. We incorporated into them the recalculations of gaseous concentration values in each layer from g g^{-1} in molecules cm^{-2} km^{-1} and the calculation of gaseous amounts at the direct solar beam in molecules cm^{-2}. These concentrations are used in the new subroutines that calculate volume absorption coefficients. The CLIRAD-SW code calculates radiative transfer in eight bands in the UV + VIS region. In the new version of the code the total number of bands are decreased from eight to three with a following change of band mean Rayleigh scattering coefficients as well as mean scattering and absorption coefficients of aerosol and cloud particles. The total optical depth and other optical parameters in each layer are prepared for use in the original radiative transfer solver of CLIRAD-SW. The solver uses the delta-Eddington approach for radiative transfer calculations in each homogeneous layer (Joseph et al. 1976). Then the two-stream adding method is used for the radiative transfer calculations in a multilayered atmosphere (Lacis and Hansen 1974; Chou and Suarez 1999).

The original subroutine of CLIRAD-SW, which calculates radiative transfer in the NIR region, calls for a radiative transfer solver for 10 *k* terms in each of the three bands in NIR. In the parameterizations of FC05 as compared with CLIRAD-SW, the number of bands is increased from three to five, but the number of *k* terms is reduced from 30 to 12 (Table 1).

In the parameterizations of FC05, the solar radiation absorption due to O_2 and CO_2 is included in the bands 1, 4, 5, and 6. Hence, we removed the lines from the original main subroutine of CLIRAD-SW related to the flux reduction due to O_2 and CO_2 absorption. The cloud overlapping scheme used in the CLIRAD-SW code is not changed. The new code is referenced hereafter as CLIRAD(FC05)-SW; that is, the CLIRAD-SW code that uses the gaseous absorption parameterizations of Fomin and Correa (2005). The revised version of the CLIRAD(FC05)-SW code is available from the authors.

3. Comparison between the new version of the code and line-by-line model

The error of the CLIRAD(FC05)-SW code is determined here as the difference between the flux or heating rate values calculated with the new code and FLBLM, which uses the Monte Carlo technique to treat the scattering by the molecules and aerosol or cloud particles. The calculations were made for a set of fixed atmospheric models, so-called test cases, similar to those proposed by Fouquart et al. (1991) for radiation algorithms intercomparison. The cases use standard atmospheric profiles, such as tropical (TRP), midlatitude summer (MLS), midlatitude winter (MLW), subarctic summer (SAS), subarctic winter (SAW), and U.S. standard atmospheres (USA; WMO 1986). The profiles define pressure, temperature, and density of water vapor and ozone at 101 levels from 0 to 100 km. The concentrations of CO_2 and O_2 are determined as 360 ppmv and 23.14%, respectively. There are cases for gaseous absorption only, for gaseous absorption with Rayleigh scattering, and with scattering and absorption by aerosol and cloud particles.

During the integration, atmospheric numerical models use the variables provided by the solar radiation scheme such as solar radiative fluxes at the surface and at the top of the atmosphere (TOA) as well as heating rate profiles in the atmosphere. Here, we perform the comparison of these variables. Table 2 shows the difference between solar radiative fluxes calculated with CLIRAD(FC05)-SW and FLBLM at the surface and at the TOA for standard gaseous atmospheres at solar zenith angle (SZA) of 30°. One can see that magnitude of the difference is less than 1.5 W m^{-2} for all cases. The comparison performed for the solar zenith angle of 75° demonstrates the same magnitude of the flux difference.

For the test cases accounted for the scattering by molecular or aerosol (cloud) particles, the difference between CLIRAD(FC05)-SW and FLBLM depends not only on the accuracy of the gaseous absorption parameterizations but on the method used for radiative transfer calculations as well as on the spectral resolution for cloud and aerosol scattering properties. We

TABLE 3. The same flux difference (W m^{-2}) as in Table 2 for the test cases accounted for gaseous absorption with Rayleigh scattering (R. scat.), aerosol profiles Mar-I and Cont-I, and one cloud layer (CS2, CS13, CS2–28) in MLS atmosphere.

Flux	R. scat.	Mar-I	Cont-I	CS2	CS13	CS2–28
Fd	−1.8	−0.4	0.9	7.1	3.9	3.8
Fup	1.3	1.0	3.0	−4.2	−3.7	−6.4
Abs	0.2	−0.5	−3.7	−1.4	0.7	3.4

remind readers once more that both versions of CLIRAD-SW use approximate delta-Eddington and two-stream adding methods and FLBLM uses the much more accurate Monte Carlo technique. Nevertheless, the difference, shown in Table 3, between the fluxes calculated with CLIRAD(FC05)-SW and FLBLM, increases a little as compared with clear-sky cases. Its magnitude is less than 4 W m^{-2} for the cases considered gaseous absorption in conjunction with Rayleigh scattering and aerosol extinction. The difference is less than 7 W m^{-2} for the cases with one cloud layer incorporated. In the calculations we used MLS atmosphere, SZA = 30°, Rayleigh scattering coefficients given in FC05, Mar-I and Cont-I profiles of aerosol optical parameters from WMO (1986), and three cloudy atmospheres with one cloud layer incorporated. In cloudy cases CS2 and CS13, cloud optical depth (COD) is equal to 2.8, the cloud layer is located at the height from 1 to 2 km (CS2) and from 12 to 13 km (CS13). The new cloudy case (CS2–28) considers a cloud layer of COD = 28 located at the height from 1 to 2 km. Effective radius of cloud drops in all cases is equal to 5.25 μm.

The heating rate profile is an important variable used by atmospheric models during the integration. The model integration results are strongly sensitive to the simulated heating rate values in the atmosphere. Hence, high accuracy of the heating rate calculations in the models is an important issue of the radiation code development. We compared the heating rate profiles calculated by CLIRAD(FC05)-SW and FLBLM for the test cases shown in Tables 2 and 3. For the cases that considered gaseous absorption only, the difference between the heating rate values at the same level is less than 0.1 K day^{-1} from 0 to 40 km and less than 1 K day^{-1} from 40 to 65–70 km (pressure level of 0.1 mb). The relative error is less than 6%. The same errors are for the cases that considered gaseous absorption with Rayleigh scattering, two aerosol profiles, and cloud layer located at the height from 1 to 2 km. For the case that considered cloud layer located at the 12-km height, the heating rate error is 30% in the cloud layer and 10%–20% in some layers below the cloud. The original version of CLIRAD-SW has the same difficulties in heating rate calculations in cloud layers.

As it was shown by Espinoza and Harshvardhan (1996) and Fomin and Correa (2005) the heating rate errors in cloudy atmosphere are related to the use of three broad bands in the NIR region. These bands have approximately the same spectral limits in all current parameterizations because the limits of the bands are selected in accordance with spectral variations of optical parameters of water drops. Hence, the cloud heating rate errors should have a similar magnitude in all broadband codes. One possibility to reduce these errors is to take into account a correlation between water vapor and cloud water absorptions. The Fomin and Correa technique can reduce errors because it does not use the "sorting procedure," in contrast with the correlated-*k* method. In the new technique, it is known to which *k* term each wavenumber point (with its gas or particulate scattering and absorption properties) belongs. So, it is easy to separate wavenumber points corresponding to a given *k* term, and after that to apply the usual procedure of averaging with the solar spectrum as the weight function in order to get any individual cloud (aerosol) properties.

With the use of individual treatment of cloud optical properties in each *k* term the method of Fomin and Correa (2005) gives a possibility of halving the errors in cloud layers. To confirm this statement we performed the calculations for the atmosphere with one cloud layer using the same Monte Carlo program in both FLBLM and fast *k*-distribution model (FKDM). The cloud layer is characterized by liquid water path of 200 g m^{2}, effective radius of cloud particles R_{eff} = 31 μm, and COD = 48.5 (Fouquart et al. 1991). It is located at the height between 300 and 500 m in the first case shown in Fig. 1 and between 12.3 and 12.5 km in the second case shown in Fig. 2. The solar zenith angle is equal 30°. Figures 1 and 2 show the results of triple calculations performed by FLBLM (referenced) and FKDM with and without the above-mentioned correlation treatment. One can see that using FKDM with the correlation treatment leads to better agreement between FLBLM and FKDM.

It should be mentioned that a mix of linear and logarithmic wavenumber averaging of cloud optical parameters over NIR bands is used in order to reduce such errors in current parameterizations. However "no optimal method has been found for deriving mean single-scattering co-albedo over a broad band" (Chou and Suarez 1999). It is evident that such a "perfect" method cannot be found because the errors depend also on the water vapor amount above the cloud layer as shown in Figs. 1 and 2. The problem can be only solved by taking

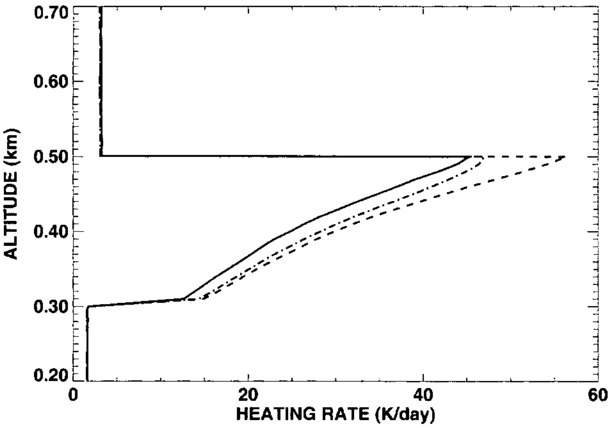

FIG. 1. Heating rates inside low cloud layer at the height from 300 to 500 m (R_{eff} = 31 μm, COD = 48.5, SZA = 30°, MLS atmosphere) calculated by FLBLM (solid), MKD (dashed), and MKD with the correlation treatment (dot–dash).

into account the individual optical properties of clouds in each k term (see also Espinoza and Harshvardhan 1996).

4. Concluding remarks

We incorporated the gaseous absorption parameterizations of Fomin and Correa (2005) in the CLIRAD-SW solar radiation code for models. The accuracy of the code with new parameterizations is similar to that of CLIRAD-SW of Chou and Suarez (1999), but its computational time is 2 times smaller. This facilitates using the new code in atmospheric models. Note that the gaseous absorption parameterizations of CLIRAD(FC05)-SW and CLIRAD-SW are based on the different versions of the HITRAN spectroscopic database, particularly HITRAN-2001 and HITRAN-1996 (Rothman et al. 1998). The impact of different spectroscopic databases on the calculated solar radiative fluxes is discussed by Fomin et al. (2004). We estimated the flux difference due to the use of the HITRAN-96 and HITRAN-2001 databases in line-by-line calculations as 1–3 W m^{-2}. Each of the parameterizations has an accuracy of 1–2 W m^{-2} for the clear-sky atmosphere. Thus, the surface flux difference between the CLIRAD-SW and CLIRAD(FC05)-SW codes can be up to 7 W m^{-2} in clear-sky conditions and about 10–15 W m^{-2} in cloudy conditions. Such difference can affect model output meteorological fields including surface temperature and precipitation. The use of the new code in each model has to be verified by comparing model-simulated fluxes with those observed on the ground.

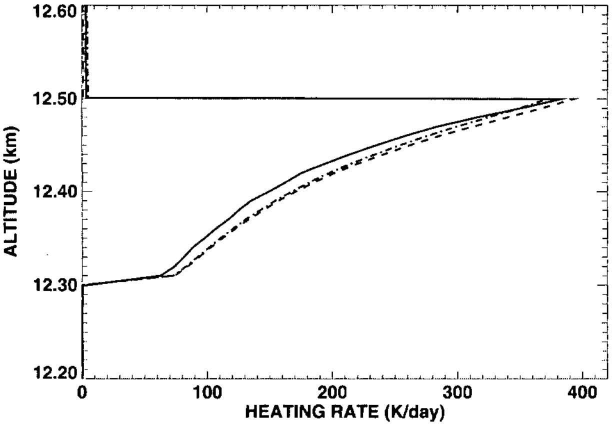

FIG. 2. Same as in Fig. 1, but for high cloud layer at the height from 12.3 to 12.5 km.

We are planning to continue further development of the subroutines in CLIRAD(FC05)-SW in order to decrease its computational time. We also intend to halve the errors (to less than 10%) in the heating rate calculations inside cloud layers by taking into account individual optical parameters of clouds in each k term. Moreover, we are planning fundamentally to increase the accuracy of the parameterizations by adjusting the limits of the spectral bands in NIR.

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