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Analysis of errors in solar heating rate calculations with broadband radiation codes in cloud layers

T.A. Tarasova[a,b] and B.A. Fomin[c]

[a]*National Institute of Space Research/Center for Earth System Science (INPE/CST), Cachoeira Paulista, SP, Brazil*
[b]*Obukhov Institute of Atmospheric Physics, Russian Academy of Science, Moscow, Russia*
[c]*Central Aerological Observatory, Moscow, Russia*

Abstract. The accuracy of broadband radiation codes for models is less studied for cloudy atmosphere than for cloud-free atmosphere. In this study, various test cases are proposed for atmosphere with clouds. The calculations of the heating rate (HR) profiles were made for 15 cloudy test cases with vertical resolution of 1 km by using the two broadband shortwave radiation codes (CLIRAD-SW-M and CLIRAD(FC05)-SW) characterized by different parameterizations of gaseous absorption and one line-by-line radiative transfer model (FLBLM). The calculation results show that the HR error of both broadband codes is about 20% in cloud layers, while it is less than 5-10% in cloud-free layers. The mean absolute HR value in cloud layers of 1 km thickness is about 10-15 K/day as compared with 1-3 K/day in cloud-free low atmosphere. These errors are not high and can be accepted by current atmospheric models. But further improvement of models' performance will require improvement of accuracy of radiation calculations in cloud layers.

Keywords: Radiation transfer, cloudy atmosphere, radiation codes for models
PACS: 92.60.Vb

INTRODUCTION

The improvement of accuracy of heating rate (HR) calculations in atmospheric models is important issue of model development. All shortwave broadband codes for models demonstrate larger HR errors in cloudy atmosphere than in cloud-free atmosphere as compared with the line-by-line calculations [e.g.,1,2,3]. The accuracy of HR calculations is better than 5-10% in clear-sky atmosphere but the uncertainty can reach 20-30% in cloudy layers and adjacent layers. The errors in cloudy layers are mainly related to the difficulties to take into account the correlation between the water vapor absorption and absorption by cloud particles in broad bands in the near infrared solar spectrum [1,2]. For more detailed analysis of HR errors we prepared new test cases that consider cloud layers located at various levels in the atmosphere. The magnitude of cloud optical depth in cloud layers varies with the height of layer and type of cloud. For these test cases, the comparison of mean HR profiles in the layers of 1 km thickness is performed between the two broadband codes (CLIRAD-SW-M, CLIRAD(FC05)-SW) and the line-by-line model (FLBLM). The errors of broadband calculations are estimated as a difference between the broadband and line-by-line heating rate values.

RADIATION CODES

In this comparison, the two broadband solar radiation codes (CLIRAD-SW-M, CLIRAD(FC05)-SW) and one line-by-line radiation model (FLBLM) are used. The CLIRAD-SW-M code is the modified version of the CLIRAD-SW code [4]. The water vapor absorption parameterizations of the code were advanced in [5] taking into account the H_2O continuum absorption. The CLIRAD-SW code accounts for the solar radiation absorption due to H_2O, O_3,

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CO_2, clouds, and aerosols. The solar spectrum is divided into eight pseudo monochromatic intervals (PMI) in the ultraviolet and visible regions and in three intervals in the near-infrared (NIR) region where the k-distribution method is applied in 30 sub intervals. The solar radiation absorption by water cloud particles is taken into account in the 3 NIR bands: 0.7-1.22 μm, 1.22-2.27 μm, and 2.27-10 μm. For the particles of effective radius of 10 μm, the mean single scattering albedo in these bands is equal to 0.999, 0.992, 0.846, respectively. Thus, the largest relative solar radiation absorption by cloud particle is in the third band. But its absolute value is also determined by the relative amount of solar radiation incident at the top of the atmosphere in each band that is equal to 0.32, 0.17, 0.04, respectively. The CLIRAD(FC05)-SW [3] includes new parameterizations of gaseous absorption [2]. This allows to decrease the total number of PMI to 15 and to halve the code computational time without decreasing the code accuracy. Both codes were compared for various clear-sky test cases and for the two cloudy test cases in [3]. This comparison showed that the CLIRAD-SW-M and CLIRAD(FC05)-SW codes have similar accuracies as compared with the line-by-line calculations.

The benchmark calculations were made using the fast line-by-line model (FLBLM) [6]. The model uses HITRAN-12v spectral database [7] and recent (MTCKD-2.1) water vapor continuum model [8] (http://rtweb.aer.com). A solar spectrum at the atmosphere top is from MODTRAN. The total amount of solar radiation at the atmosphere top is 1372.4 W/m^2. The scattering and absorption is treated by Monte-Carlo technique. Notice that the FLBLM code has been validated during recent intercomparison efforts [9].

CLOUDY TEST CASES

In the comparison of heating rate calculations in cloudy atmosphere [3], only two cloudy test cases were used (for low and high clouds). Here, we propose 15 test cases for radiative transfer calculations in the atmosphere with low, middle, mixed, and extending clouds that include following cloud types: Cu, St, Sc, Ac, As, Ns. The calculations were made for the midlatitude summer standard atmospheric profile [10] which defines pressure, temperature, and density of H_2O and O_3 at 33 levels from 0 to 100 km. The concentration of CO_2 is 360 ppmv. The solar zenith angle is equal to 30 degrees. The integral surface albedo is equal to 0.2. The values of cloud optical depth were obtained during long-term radiation measurements in Meteorological Observatory of Moscow State

TABLE 1. The cloudy atmosphere test cases: H, height of cloud layer in km; COD, cloud optical depth. The heating rate profiles for the cases 2, 8, 12, 14 are shown in Fig.1.

Case	H (km)	COD	H (km)	COD	H (km)	COD
1	1-2	10				
2	1-2	30				
3	1-2	70				
4	1-2	140				
5			3-4	2.5		
6			3-4	10		
7					5-6	2.5
8					5-6	10
9	1-2	10	3-4	5		
10	1-2	70	3-4	5		
11	1-2	10	3-4	5	5-6	5
12	1-2	70	3-4	5	5-6	5
13	1-11	30				
14	1-11	50				
15	1-11	70				

University [11] with the method [12]. In this study, we assume that cloud optical depth varies from 10 to 140 for low clouds and from 2.5 to 10 for middle clouds, mean effective radius of cloud particles is equal to 10 μm. Low clouds are located from 1 to 2 km, middle clouds are located from 2 to 7 km (cloud height equals to 1 km). Extending clouds are located in the layer from 1 to 11 km. The proposed cloudy atmosphere test cases are shown in Table 1.

HEATING RATE PROFILES

For the test cases shown in Table 1, we made radiative transfer calculations with the CLIRAD-SW-M, CLIRAD(FC05)-SW, and FLBLM codes. The resulted heating rate profiles obtained with FLBLM are presented in the left column of Fig. 1. The relative error between the broadband codes and FLBLM profiles is given in its right column.

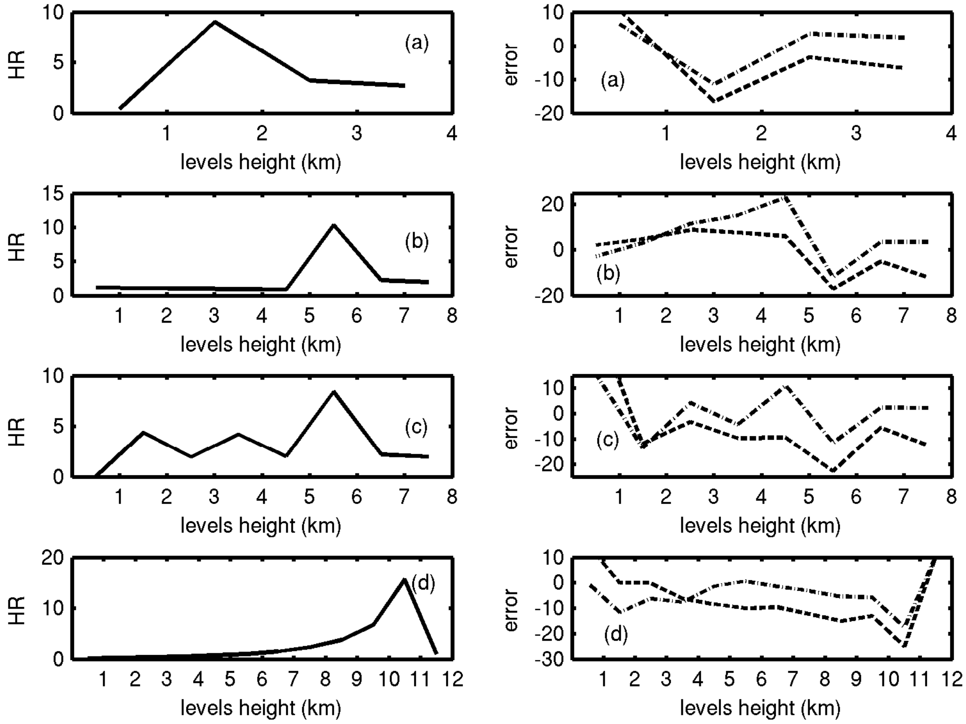

FIGURE 1. Heating rate (HR) (K/day) calculated by FLBLM (left) and relative error (%) of HR profiles (right) calculated by CLIRAD-SW-M (dashed) and CLIRAD(FC05)-SW (dot-dashed) in cloudy atmosphere: (a) case 2, (b) case 8, (c) case 12, (d) case 14.

In the left column of Fig 1a, one can see that the heating rate value calculated with FLBLM in the cloud of COD=30 located at the height from 1 to 2 km is about 10 K/day. This value is four times larger than the HR value in cloud-free atmosphere at the same height (2.5 K/day). The relative error of HR value calculated by CLIRAD(FC05)-SW is about 10% and that of CLIRAD-SW-M is about 16%. Both codes underestimate HR value in the cloud layer. The better performance of CLIRAD(FC05)-SW is probably associated with the fact that the same line-by-line model was used for the development of gaseous absorption parameterizations for this code and for the code validation. Further increase of cloud optical depth to 70 and 140 in the layer from 1 to 2 km demonstrates smaller impact of cloud on the HR value (not shown). The HR value in the cloud layer of COD=70 and 140 is also about 10 K/day.

The cloud located at the higher altitude produces larger impact on heating rate profile. Figure 1b shows that the heating rate values in the cloud of COD=5 located at the height from 5 to 6 km is about the 10 K/day that is five times larger that the HR value in cloud-free atmosphere at this height (2 K/day). The error also increases in the layer below the cloud layer, but it is less important due to the small HR value below the cloud. Figure 1c presents the heating rate profile in the atmosphere with 3 cloud layers: 1-2 km, 3-4 km, 5-6 km. The cloud optical depth in these layers are 70, 5, 5, respectively. Notice that the strongest impact is produced by the high cloud of COD=5 located from 5 to 6 km and not by the low cloud of COD=70. The error of HR broadband calculations is also largest in the high cloud layer. The heating rate profile calculated by FLBLM for extending Cu cloud of COD=30 located in the layer from 1 to 11 km is shown in Fig. 1d. The largest HR value of 15 K/day is seen in the top cloud layer from 10 to 11 km, then the HR magnitude decreases rapidly to the surface. The error of HR calculations with both broadband codes is about 20-25%.

The estimated errors of the HR calculation with broadband codes in cloud layers are not high and can be accepted by current numerical atmospherical models. But further development of GCM and climate models requires further improvement of accuracy of radiation calculations. For example, the technique proposed in [2] is able to reduce errors in cloudy atmosphere by taking into account a correlation between water vapor and cloud water absorption. Applying of this technique to broadband codes is one of possibility to increase accuracy of shortwave HR calculations in numerical models.

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