NOTES AND CORRESPONDENCE

Solar Radiation Absorption due to Water Vapor: Advanced Broadband Parameterizations

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ABSTRACT

Accurate parameterizations for calculating solar radiation absorption in the atmospheric column due to water vapor lines and continuum are proposed for use in broadband shortwave radiative transfer codes. The error in the absorption values is less than 1.5 W m^{-2} as compared with the values obtained by the line-by-line method for the three standard atmospheres and solar zenith angles of 30° and 75°. The error in the heating rates is less than 0.1 K day^{-1} at most of the atmospheric levels.

The additional absorption of solar radiation due to the water vapor continuum was also estimated. Its magnitude in the total near-infrared region of the solar spectrum is noticeable and reaches 13.0 W m^{-2} (6.4% from the water vapor absorption in lines) for the tropical atmosphere and solar zenith angle of 30°. Therefore, using of the proposed parameterizations can help to obtain better agreements between the solar radiative fluxes calculated and measured at the earth's surface.

1. Introduction

Recent comparisons of model calculations with measurements show that broadband radiative transfer models overestimate the magnitude of the total solar irradiance incoming at the surface in clear-sky conditions by the value up to 10% or 40–50 W m^{-2} at high solar angles (Kato et al. 1997; Kinne et al. 1998; Tarasova et al. 1999). More than one-half of this difference can be attributed to the underestimation of absorption in the near-infrared region of the solar spectrum. Better agreement in this region can be achieved by taking into account the water vapor continuum model extended to the above region. Thus additional absorption of about 10 W m^{-2} has been obtained by Fomin and Gershanov (1996, 1997) at the solar zenith angle of 30° for the midlatitude summer atmosphere (McClatchey et al. 1972) by incorporating the continuum model of Clough et al. (1989) into their line-by-line radiative transfer model.

In this study, we estimate the magnitude of water vapor absorption in broad intervals of solar spectrum by means of the line-by-line radiative transfer method as well as parameterized technique. Note that the issue about the validity of the spectroscopic data is not discussing here. The parameterizations for the absorption proposed by Chou and Lee (1996) were advanced by using the more complicated HITRAN-96 spectroscopic database (Rothman et al. 1998) and the above continuum model in the benchmark line-by-line calculations. The line-by-line technique and method to derive parameterizations are described in section 2. Section 3 presents the values of the absorption in the atmospheric column and heating rate profiles computed for tropical, midlatitude summer, and subarctic winter atmospheres (McClatchey et al. 1972) as well as for the two solar zenith angles of 30° and 75°. Concluding remarks about the need to improve parameterizations for computing

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the solar radiation absorption in the earth's atmosphere are given in section 4.

2. Calculation technique

First, we performed the line-by-line (LBL) radiative transfer calculations of the solar radiation absorption due to the water vapor with a method developed by Fomin et al. (1994). The method incorporates main features of the LBL techniques described in the earlier studies, (e.g., Ramaswamy and Freidenreich 1991), with some improvements aimed to increase the calculation speed. The water vapor absorption coefficients k_ν ($p_{\rm ref}$, $T_{\rm ref}$) have been precomputed using the HITRAN-96 spectroscopic database and the effective interpolation technique by Fomin (1995) at the points of the uniform wavenumber grid for the conditions suggested by Chou and Arking (1981), namely, $p_{\rm ref}$ = 300 hPa and temperature $T_{\rm ref}$ = 240 K. The grid was fine enough (1/256 $\rm cm^{-1}$) to resolve any spectral line.

To obtain the parameterizations for the absorption we follow the approach proposed by Chou and Lee (1996). It should be stressed once more, that as opposed to the above work the water vapor continuum model (Clough et al. 1989) has been also taken into account. In accordance with the above paper, have been considered the mean transmittances of narrow spectral intervals ($\Delta\nu_i$ = 40 $\rm cm^{-1}$), where the extraterrestrial solar irradiance can be used as a constant. As it is well known the mean transmittance $\tau_i(w)$ of ith interval for some water vapor amount w is given by

$$\tau_i(w) = \frac{1}{\Delta\nu}\int_{\Delta\nu} e^{-k_\nu w}\, d\nu, \tag{1}$$

and can be calculated numerically using precomputed k_ν. However, this integral can be replaced using k-distribution method by the sum

$$\tau_i(w) \sim \overline{\tau_i(w)} = \sum_{n=1}^{N} f_i(k_n) e^{-k_n w} \tag{2}$$

where $f_i(k_n)$ are the weights $[0 < f_i(k_n) < 1]$:

$$\sum_{n=1}^{N} f_i(k_n) = 1, \tag{3}$$

and k_n are the effective absorption coefficients. It should be mentioned that $f_i(k_n)$ need to be defined for each ith interval, but coefficients k_n are the same for the whole spectral region considered. We shall use the set of the 10 coefficients suggested by Chou and Lee (1996), which are shown in Table 1.

The weights $f_i(k_n)$ should be suited so that the integral (1) and the sum (2) give as close results as it possible for any water vapor amount w. The weights given in Chou and Lee (1996) were derived from the line-by-line method of Chou (1992) by using HITRAN-92 spectroscopic database (Rothman et al. 1992) without taking into account the water vapor continuum model. For the

TABLE 1. The flux-weighted k-distribution function Δg in one visible range and five spectral intervals in the near-infrared and infrared regions. Absorption coefficient k: $\rm g^{-1}\,cm^2$.

		Δg					
n	k	0.55–0.7 μm	0.7–1.22 μm	1.22–2.27 μm	2.27–2.8 μm	2.27–5 μm	2.27–10 μm
0	0.0000	$0.733\,200 \times 10^{00}$	—	—	—	—	—
1	0.0010	$0.219\,966 \times 10^{00}$	$0.602\,392 \times 10^{00}$	$0.418\,720 \times 10^{00}$	$0.000\,000 \times 10^{00}$	$0.100\,184 \times 10^{00}$	$0.715\,997 \times 10^{-01}$
2	0.0133	$0.246\,110 \times 10^{-01}$	$0.178\,305 \times 10^{00}$	$0.118\,546 \times 10^{00}$	$0.174\,405 \times 10^{00}$	$0.158\,381 \times 10^{00}$	$0.147\,046 \times 10^{00}$
3	0.0422	$0.138\,910 \times 10^{-01}$	$0.651\,370 \times 10^{-01}$	$0.480\,756 \times 10^{-01}$	$0.694\,499 \times 10^{-01}$	$0.130\,600 \times 10^{00}$	$0.121\,332 \times 10^{00}$
4	0.1334	$0.690\,802 \times 10^{-02}$	$0.750\,770 \times 10^{-01}$	$0.103\,762 \times 10^{00}$	$0.160\,730 \times 10^{00}$	$0.149\,868 \times 10^{00}$	$0.147\,772 \times 10^{00}$
5	0.4217	$0.796\,458 \times 10^{-03}$	$0.437\,527 \times 10^{-01}$	$0.676\,036 \times 10^{-01}$	$0.894\,841 \times 10^{-01}$	$0.120\,244 \times 10^{00}$	$0.125\,041 \times 10^{00}$
6	1.3340	$0.208\,745 \times 10^{-03}$	$0.181\,407 \times 10^{-01}$	$0.832\,642 \times 10^{-01}$	$0.502\,853 \times 10^{-01}$	$0.657\,255 \times 10^{-01}$	$0.719\,108 \times 10^{-01}$
7	5.6230	$0.175\,978 \times 10^{-03}$	$0.768\,065 \times 10^{-02}$	$0.121\,417 \times 10^{00}$	$0.834\,195 \times 10^{-01}$	$0.733\,715 \times 10^{-01}$	$0.847\,805 \times 10^{-01}$
8	31.6200	$0.157\,633 \times 10^{-03}$	$0.508\,430 \times 10^{-02}$	$0.160\,241 \times 10^{-01}$	$0.103\,011 \times 10^{00}$	$0.692\,753 \times 10^{-01}$	$0.797\,552 \times 10^{-01}$
9	177.8000	$0.854\,838 \times 10^{-04}$	$0.314\,907 \times 10^{-02}$	$0.170\,456 \times 10^{-01}$	$0.234\,939 \times 10^{00}$	$0.113\,355 \times 10^{00}$	$0.128\,086 \times 10^{00}$
10	1000.0000	—	$0.128\,161 \times 10^{-02}$	$0.554\,177 \times 10^{-02}$	$0.342\,773 \times 10^{-01}$	$0.189\,953 \times 10^{-01}$	$0.226\,772 \times 10^{-01}$

TABLE 2. Solar radiation absorption due to the water vapor lines and continuum (ABS) and due to the continuum only (CONT) both computed with the line-by-line method; PAR − LBL is the difference between the absorption values (ABS) computed with the parameterizations (PAR) and line-by-line method (LBL); surface albedo is set to 0.2; TA, MLS, and SAW are tropical, midlatitude summer, and subarctic winter atmospheres, respectively; solar zenith angle is set to $\theta = 30°$, ESI is extraterrestrial solar irradiance ($\theta = 0°$), units: W m^{-2}.

		TA			MLS			SAW		
Intervals, μm	ESI	ABS	CONT	PAR − LBL	ABS	CONT	PAR − LBL	ABS	CONT	PAR − LBL
0.55–0.7	251.7	4.5	0.1	+0.1	3.4	0.1	+0.3	0.6	0.0	+0.2
0.7–1.22	441.7	82.8	4.3	−1.4	71.3	3.0	−0.5	26.1	1.3	+1.4
1.22–2.27	228.0	89.1	5.9	−0.4	83.3	4.6	+0.4	54.7	3.4	+1.0
2.27–2.8	24.5	17.5	1.0	−0.3	16.7	0.9	−0.2	11.9	0.5	+0.5
2.27–5	51.0	30.5	2.5	+0.1	28.6	2.1	+0.2	19.4	1.0	−0.5
2.27–10	56.5	35.0	2.7	+0.1	33.0	2.3	+0.2	23.2	1.2	−0.5
0.55–10	977.9	211.4	13.0	−1.6	191.0	10.0	+0.4	104.6	5.9	+2.1

calculations of the weights we used the HITRAN-96 database in conjunction with the above water vapor continuum model (Clough et al. 1989). Its lookup table is available from the well-known LOWTRAN-7 program (Kneizys et al. 1988). This semiempirical continuum model is the most widely distributed now and gives a possibility to take into account the water vapor continuum absorption up to 0.5 μcm. The absorption consists of the far wings of collisionally broadened spectral lines. Both water–water molecular broadening (self broadening) and water–air molecular broadening (foreign broadening) is included. It should be stressed that neglecting of the continuum is not physically correct and means the nonphysical spectral line cut off.

We have used the least squares fit method to derive the k-distribution weights. The comparison with the weights derived directly from the line-by-line calculations showed that the fit can give us better approximation of the heating rates. This fact is in agreement with the results from Cusack et al. (1999). Note that in this work the same shortwave water vapor continuum model is considered. Unfortunately, the k-distribution parameters are not available from the paper, and the effect of the water vapor continuum absorption is not estimated in it.

Thus a set of amounts w_n was considered:

$$w_1 = w_{\max}/N_{\max}, \quad w_2 = 2w_{\max}/N_{\max}, \quad \ldots, \quad w_{\max} = N_{\max}w_{\max}/N_{\max}, \tag{4}$$

where $N_{\max} \sim 3N = 30$ and $w_{\max} = 10$ g cm^{-2} that is approximately upper limit of the water vapor amount in the atmosphere. For these amounts in each ith interval the mean transmittances (1) have been calculated. After that, using the Monte Carlo method we suited the weights so that the functional

$$Q_i[f_i(k_1), f_i(k_2), \ldots, f_i(k_{10})] = \sum_{n=1}^{N_{\max}} [\tau_i(w_n) - \overline{\tau_i(w_n)}]^2 \tag{5}$$

was minimal.

During the calculations the value was evaluated for the control

$$\sqrt{Q_{\min}/N_{\max}}. \tag{6}$$

This procedure is the same that a random search of the minimum of the Q_i function, which is dependent on $f_i(k_1)$, $f_i(k_2)$, . . . , $f_i(k_{10})$, satisfying (3).

Last, follow Chou and Lee (1996), for wide spectral interval j the needed flux-weighted k-distribution function is given by

$$\Delta g_j(k_n) = \frac{1}{S_j}\sum_i S_i f_i(k_n), \tag{7}$$

where S_j is extraterrestrial solar flux in broad spectral interval j, and S_i is the extraterrestrial solar flux in the ith spectral interval 40 cm^{-1}.

Table 1 gives the values of $\Delta g_j(k_n)$ for the small band 0.55–0.7 μm in the visible spectrum where the water vapor absorption is also noticeable. Some modern radiative transfer codes for models already take this absorption into account (e.g., Chou and Suarez 1999). Table 1 also presents the k-distribution functions for the broad spectral intervals in the near-infrared and infrared regions. Different parameterizations for the intervals 0.7–1.22, 1.22–2.27, and 2.27–5 μm are required by broadband radiative transfer codes because of the need to implement later the cloud droplet absorption properties (Slingo 1989). The 2.27–2.8-μm band is chosen to perform comparisons with pyranometer measurements. Using the values of $\Delta g_j(k_n)$ from Table 1, the downward solar flux over the spectral broad band j can be computed from

$$F_j(p) = S_j\mu_0 \sum_{n=1}^{10} \Delta g_j(k_n)e^{-k_n w(p)/\mu_0}, \tag{8}$$

where μ_0 is the solar zenith angle, the values of S_j for various spectral ranges are shown in Table 2. The scaled water vapor amount w is given by

$$w(p) = \int_0^p (p'/p_{\mathrm{ref}})^m H(T', T_{\mathrm{ref}})q(p')\frac{dp'}{g}, \tag{9}$$

where q is the specific humidity, g is the gravitational acceleration, $H(T, T_{\mathrm{ref}}) = \exp[0.001\,35(T - T_{\mathrm{ref}})]$, and $m = 0.8$ (Chou and Arking 1981).

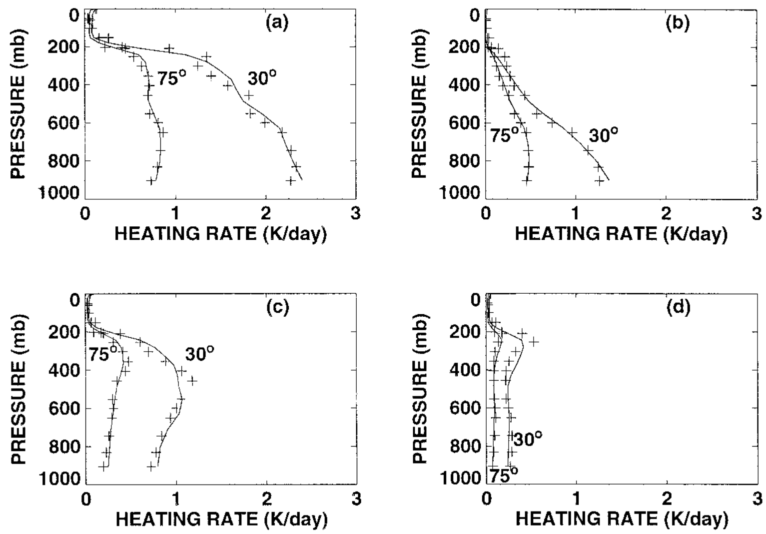

FIG. 1. Comparisons of the heating rate profiles computed with the LBL method (solid) and *k*-distribution functions from Table 1 (pluses) taking into account the solar radiation absorption due to the water vapor lines and continuum. Calculations were performed for the midlatitude summer atmosphere and for the two solar zenith angles 30° and 75° in the spectral intervals (a) from 0.7 to 5 μm, (b) from 0.7 to 1.22 μm, (c) from 1.22 to 2.27 μm, and (d) from 2.27 to 5 μm.

3. Magnitude of absorption

Using the line-by-line method described in section 2, we calculated the magnitude of solar radiation absorption due to the water vapor lines and continuum for the tropical, subarctic winter and midlatitude summer atmospheres and for the two solar zenith angles of 30° and 75°. Surface albedo was set to 0.2. Calculation results obtained for the solar zenith angles of 30° are given in Table 2 for the above mentioned spectral intervals. The values of the absorption computed without continuum agree well with the line-by-line calculation results reported by other authors. For example, the value of the absorption computed for the midlatitude summer atmosphere at the 30° solar zenith angle in the spectral range from 0.7 to 10 μm is equal 176.7 W m^{-2}, while Chou and Lee (1996) give 174.0 W m^{-2} in that case. The difference of 2.7 W m^{-2} probably is related to the use of different versions of the HITRAN database and the line shape model [we have used the sub-Lorentz profile and the line cut off at 25 cm^{-1} from the line center in accordance with the above paper (Clough et al. 1989)]. Note once more that the magnitude of the absorption in the visible spectral interval from 0.55 to 0.7 μm is not negligible and reaches the value 4.4 W m^{-2} for the tropical atmosphere at the solar zenith angle of 30°.

To assess the magnitude of additional solar radiation absorption due to the water vapor continuum, we performed the line-by-line calculations with and without continuum model incorporated. The difference of the absorption values is shown in Table 2. One can see that the water vapor continuum absorption is small in the visible region of the solar spectrum and increases in the intervals 0.7–1.22 and 1.22–2.27 μm. The total effect in the near-infrared region is 13.0 W m^{-2}, determined for the tropical atmosphere at the solar zenith angle of 30°.

Then we made calculations of the solar radiation absorption and heating rate profiles due to water vapor lines and continuum for the same spectral intervals by using the *k*-distribution functions from Table 1 and formulas 8 and 9. Table 2 presents the difference between the absorption values computed with the *k*-distribution functions and by the line-by-line method for the tropical, midlatitude summer, and subarctic winter atmospheres at the solar zenith angle of 30°. One can see that the error of the parameterized technique is small. Generally it is less than 2.0 W m^{-2} for all atmospheres and for the two solar zenith angles 30° and 75°.

Figure 1 presents the comparison of the heating rate profiles due to water vapor lines and continuum calculated for four spectral intervals: 0.7–5, 0.7–1.22, 1.22–2.27, and 2.27–5 μm by using the line-by-line method as well as *k*-distribution functions from Table 1. The difference obtained is less than 0.1 K day^{-1} at most of the levels. Maximum error is about 0.2 K day^{-1}. Note that using in the calculations only the first nine terms of the *k*-distribution functions from Table 1 does not lead to the larger errors in the absorption values and heating rates.

4. Conclusions

The efficient parameterizations for the absorption of solar radiation by water vapor proposed by Chou and

Lee (1996) were advanced by using the more complicated version of the HITRAN spectroscopic database (Rothman et al. 1998) and shortwave water vapor continuum model of Clough et al. (1989). The parameterizations were determined for a set of broad spectral intervals in the visible and near-infrared solar regions consistent with those usually assumed in broadband radiative transfer codes. Use of these parameterizations in the radiative transfer codes employed in general circulation and climate models allow one to obtain better agreement between simulated and measured shortwave radiative fluxes at the earth's surface. An analysis of the satellite and ground-based radiation measurements also requires precise parameterizations for water vapor absorption in order to improve the accuracy of the aerosol parameter derivation. Note that the water vapor spectral line data and the continuum model should be more thoroughly tested themselves. Nevertheless, the same results obtained by different authors in the independent model-to-measurement comparisons indicate that absorptive properties of the earth's atmosphere are stronger than those currently assumed in most radiative transfer codes for models.

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