On Sensitivity of Spectral Radiative Fluxes to Atmospheric Water Vapor in the 940 nm Region (Numerical Simulation)

T.B. Zhuravleva and K.M. Firsov
Institute of Atmospheric Optics
Tomsk, Russia

Introduction

It is well known that water vapor is a critical component in many aspects of atmospheric research, such as radiative transfer and cloud and aerosol processes. This requires both improved measurements of the columnar water vapor and its profiles in the atmosphere in a wide range of conditions (Revercomb et al. 2003), and adjustment of water vapor parameterizations in radiation codes including the perfection of spectroscopic parameters (Ellingson et al. 1991; Fouquart et al. 1991).

The intercomparison of modern radiation codes performed by Barker et al. (2003) has shown that most one-dimensional (1D) codes used for research and by the weather and climate models underestimate atmospheric absorption of solar radiation relative to the benchmark Code for High-Resolution Accelerated Radiative Transfer (CHARTS). In our opinion, in most cases this bias results from the lack of water vapor continuum absorption and because many 1D models are based on the old spectroscopic databases LOWTRAN7 and HITRAN92. The estimates presented by Barker et al. (2003) also show that 1D codes inadequately describe the radiative properties of realistic three-dimensional (3D) cloud fields because of inappropriate cloud overlap assumptions and neglect of horizontal variability of clouds. This stimulates the development of 3D radiative codes, usable for testing new methodologies invented for computing heating rates in large-scale models, and for obtaining accurate estimates of spectral fluxes and brightness fields in retrieval of atmospheric characteristics from satellite and ground-based radiation measurements.

Presently, there are a few radiation codes that make it possible to calculate radiative characteristics with moderate spectral resolution based on newer database HITRAN96, taking into account 3D cloud effects (O'Hirok and Gautier 1998; Benner and Evans 2001). Earlier, we presented the effective statistical algorithms for calculating the spectral solar radiative fluxes in clear-sky and cloudy atmosphere including broken clouds, which use the k-distribution method for description of the molecular absorption and take into account the instrumental functions of real devices (Zhuravleva and Firsov 2004).

In this paper, we present the results of the comparison of our calculations and downward solar fluxes measured by the Rotating Shadowband Spectroradiometer (RSS; Harrison et al. 1999) under conditions of horizontally homogeneous clouds. We also will discuss the sensitivity of atmospheric radiation characteristics to variations of water vapor in the band 940 nm; these results may be useful for the development of new methods of retrieval of the total column water vapor content (WVC) in the atmosphere from data of radiation observations (e.g., Kiedron et al. 2001).

Comparison of Simulated and Measured Downward Spectral Fluxes

To calculate spectral solar fluxes, we used algorithms we developed earlier (Zhuravleva and Firsov 2004). The effective molecular absorption coefficients were calculated for simplified (Gaussian) instrumentation functions of the RSS (512 channels) (ftp://oink.asrc.cestm.albany.edu/pub/RSS102) and spectral solar constant of Kurutz (1992) using the database of spectral lines HITRAN-2004 (http://www.hitran.com) and modern models of the continuum absorption (http://rtweb.aer.com/continuum_code.html). The concentrations of absorbing gases (except for H_2O) were chosen in accordance with the Air Force Geophysics Laboratory (AFGL) model (Anderson et al. 1986). The vertical stratification of the aerosol optical properties corresponded to the WCP aerosol model (WCP 1986). In calculations of extinction coefficient and single-scattering albedo of clouds, we used the cloud microstructure model corresponding to the "wide particle size distribution" (Feigelson 1981).

The simulated spectral fluxes of solar radiation were compared with observations obtained for cases of single-layer low-level overcast cloudiness during Atmospheric Radiation Measurement (ARM) campaign of 1997-1998 at the Southern Great Plains (SGP) site (Li et al. 2000). The data from the spectral fluxes were obtained using the RSS, which measures the direct, diffuse, and total radiation in 512/1024 channels within spectral region 350-1075 nm (Harrison et al. 1999). The vertical profiles of pressure, temperature, and water vapor were retrieved from radiosonde data, while the liquid water path of clouds was retrieved from microwave sensing. The information about total ozone content was taken from the Total Ozone Mapping Spectrometer (TOMS) archive. The top and bottom boundaries of the cloud layer were determined with the aid of ground-based radars. The calculations accounted for the spectral behavior of the surface albedo as derived from mutifilter rotating shadowband radiometer (MFRSR) (Li et al. 2001). The cloud extinction coefficient was chosen so that the calculated and measured spectral fluxes coincided in the 500-550 nm band.

Comparisons show that the results of numerical modeling and spectral irradiance measurements are in good agreement with each other (Figure 1), and, hence, the algorithms we proposed can be used for description of the solar radiation transfer in the real atmosphere. Here, also, we present spectral flux calculations, performed using MODTRAN4 (Li et al. 2000).

The Effect of Variations of Column Water Vapor Content on Radiative Characteristics

Water vapor measurements. To estimate the variations of the spectral radiative characteristics when water vapor changes in the atmosphere, we used the radiosonde measurements obtained in summer in Novosibirsk, Russia (54°N, 83°E) in 1961–1970: profiles of temperature extend up to 30 km, and humidity profiles up to 7 km. As a rule, radiosonde measurements were performed twice a day

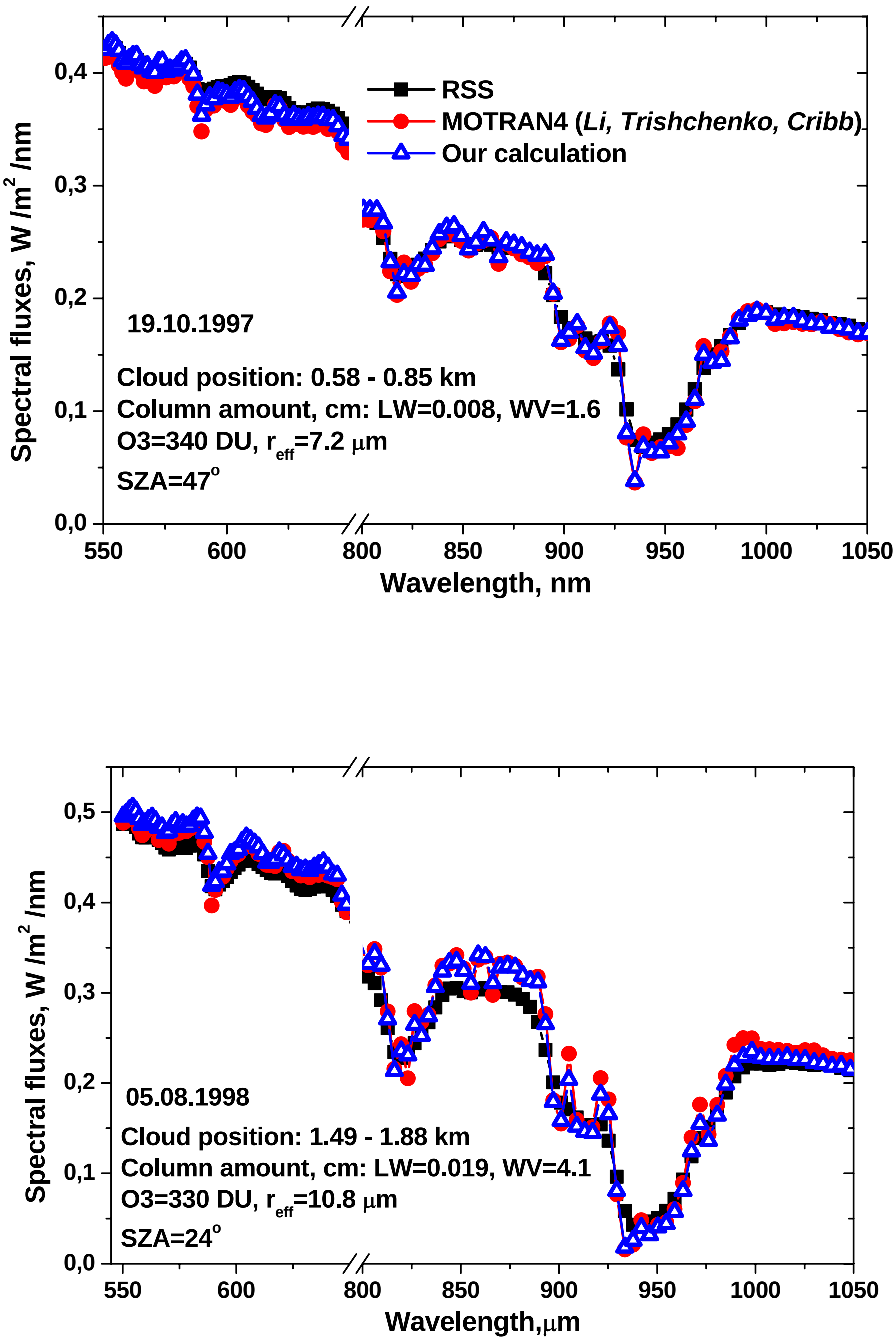

Figure 1. Downward fluxes at the surface level at ARM SGP site: RSS 512 channels measurements and model calculation (rural aerosol, visibility range 23 km).

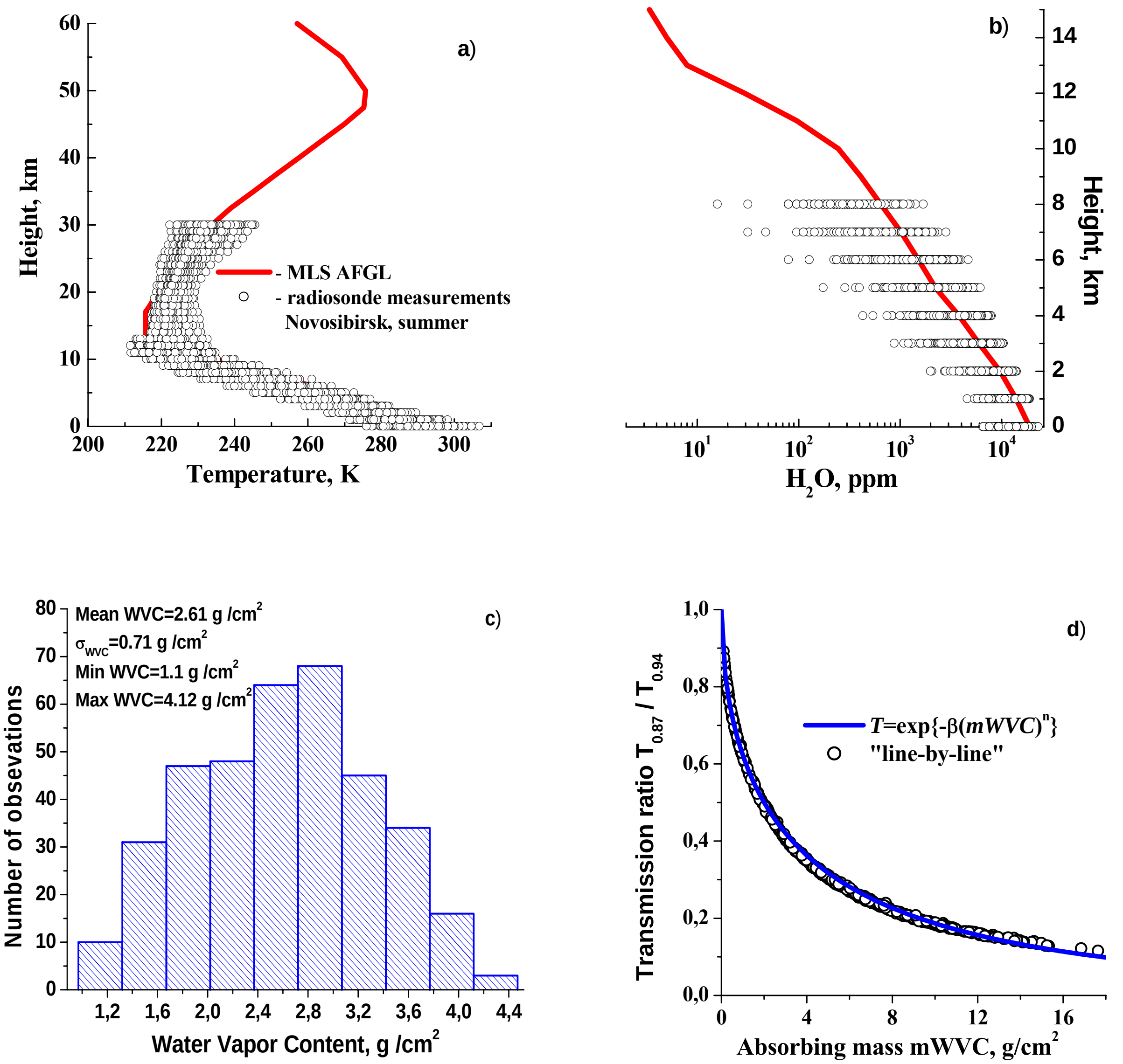

Figure 2. Vertical profiles of (a) temperature, (b) water vapor concentration, and (c) distributions of WVC in Novosibirsk (54°N, 83°E), summer. Atmospheric transmittance ratio T as a function of the absorbing mass of water vapor in two channels (870 and 940 nm) of the photometer SP-6 (d).

(00:00 and 1600 Local Time [LT]), with the total number of profiles being 360. Profiles of temperature and humidity outside the aforementioned height ranges were added according to the data of meteorological AFGL model (Anderson et al. 1986). Variations of temperature and concentration of water vapor, as well as distribution of WVC over Novosibirsk in summer are shown in Figure 2a-c.

Average value $\overline{WVC} = 2.6$ g/cm^2 is close to the mean WVC in AFGL model (2.98 g/cm^2), root-mean-square deviation $\sigma_{WVC} = 0.71$ g/cm^2, and the minimum and maximum values are 1.1 and 4.1 g/cm^2.

The dependence of the atmospheric transmittance ratio T in two spectral channels 870 and 940 nm of the photometer SP-6 (Sakerin et al. 2004) on the absorbing mass of water vapor mWVC, (m is the atmospheric mass) calculated by the "line-by-line" method and by the two-parameter approximation formula (Chesnokova et al 2004), is shown in Figure 2d. It follows from the simulation results that, under clear-sky conditions, the atmospheric transmittance in the band 940 nm is a function of mWVC and depends weakly on temperature variations and air pressure. In this regard, we restrict ourselves to consideration of five vertical H_2O profiles corresponding to the $\overline{WVC}$, $\overline{WVC} \pm \sigma_{WVC}$, as well as minimum and maximum WVC values. These same profiles will also be used in radiation flux calculations for broken clouds.

Radiance properties. Variability of the fluxes when WVC varies with respect to $\overline{WVC}$ is characterized by the quantity

$$\Delta Q_s(\lambda) = 100\% \times \left(Q_s(WVC, \lambda) - Q_s(\overline{WVC}, \lambda)\right) / Q_s(\overline{WVC}, \lambda).$$

Examples of calculations of the spectral diffuse radiation fluxes $Q_s(\lambda)$ at the underlying surface under clear-sky conditions and conditions of broken clouds at different values of WVC are shown in Figure 3. The value $|\Delta Q_s(\lambda)|$ is asymmetric with respect to the deviations of WVC from the mean value, and $\max|\Delta Q_s(\lambda)|$ is observed for minimum WVC values. As solar zenith angle (SZA) increases, $|\Delta Q_s(\lambda)|$ grows for the other input model parameters kept fixed.

The dependence of the total absorption A and absorptance Abs (%) in the wavelength range 870-1030 nm in absence of clouds and in presence of broken clouds is shown in Table 1. Atmospheric absorption is the sum of absorption in above-cloud (A^{up}) and below-cloud (A^{down}) atmosphere, as well as within the cloud layer (A^{cl}). For fixed solar angle and a given H_2O profile, an increase of cloud fraction N leads to increase of albedo of the cloud layer and, hence, to the growth of absorption of the above-cloud atmosphere. The larger N, the greater the number of photon collisions with cloud matter, favoring growth of A^{cl}. At the same time, the fractions of radiation coming to the cloud layer and above-cloud atmosphere accordingly decrease. This leads to the fact that A^{cl} and A^{down} (for moderate surface albedos) have a tendency to decrease.

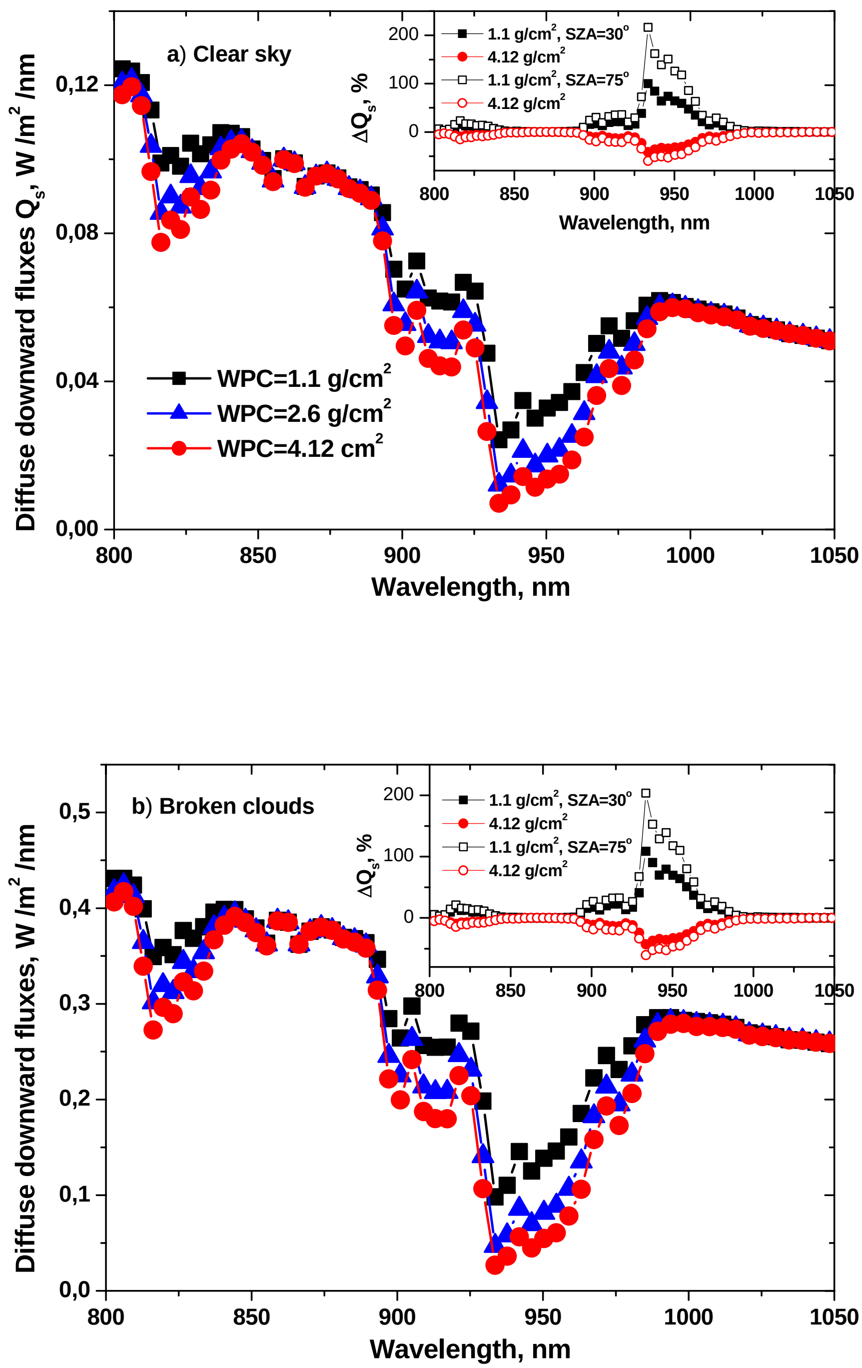

Figure 3. Diffuse downward radiance Q_s and variability ΔQs as functions of WVC in (a) clear sky and (b) broken clouds: cloud fraction N=0.5, cloud height=1-2 km, cloud extinction σ_{cl} (0.55 μm)=10 km^{-1}. SZA=30°, A_s=0.2.

Table 1. Atmospheric absorption A (W/m^2) (absorptance Abs, %) in the range 870–1030 nm in clear sky and broken clouds. Cloud optical depth τ=10, As=0.2.

	Clear sky		Broken clouds			
			N=0.3		N=0.5	
WVC, g/cm^2	$SZA = 30^\circ$	$SZA = 75^\circ$	$SZA = 30^\circ$	$SZA = 75^\circ$	$SZA = 30^\circ$	$SZA = 75^\circ$
1.1	22.3 (19.8)	11.1 (32.8)	22.4 (19.8)	9.3 (27.7)	23.1 (20.5)	8.9 (26.5)
2.6	31.3 (27.8)	14.0 (41.4)	31.6 (28.0)	12.4 (36.7)	32.4 (28.7)	12.0 (35.6)
4.1	36.7 (32.5)	15.6 (46.3)	37.1 (32.9)	14.2 (42.0)	37.9 (33.6)	13.8 (40.9)

Depending on cloud properties (height of cloud top boundary, cloud optical depth, and cloud fraction N), amount of water vapor in the atmosphere, and observation conditions (A_s and *SZA*), each of the above-mentioned factors influences the atmospheric absorption A to a larger or smaller degree. When SZA changes in the wide range SZA ≤ 60°, occurrence of low-level clouds leads, as a rule, to increase of the total absorption: $A_{clr} \leq A_{low}$. Difference between A_{clr} and A_{low} increases with growing N and WVC in the atmosphere. As solar zenith angle further increases (SZA=75°), the albedo of clouds increases and, hence, absorption within the cloud layer can decrease. The difference between A_{clr} and A_{low} is reduced, and situations are possible when occurrence of low-level clouds leads to decrease of absorption in the atmosphere.

Contribution of water vapor continuum. To get closer agreement between simulated and measured shortwave radiative fluxes at the earth's surface, radiation codes must account for continuum absorption by water vapor. For instance, Tarasova and Fomin (2000) showed that the water vapor continuum absorption in the intervals 700-1220 nm and 1220-2270 nm is 3 W/m^2 and 4.6 W/m^2, and that the total effect in near-infrared region is 10 W/m^2 (midlatitude summer atmosphere, SZA=30°).

From our calculations it follows that the value of continuum absorption in the interval 870-1030 nm at SZA=30° varies approximately from 0.8 to 1.5 W/m^2 as WVC increases from minimum to maximum value (1.1-4.1 g/cm^2). For SZA=75°, the continuum absorption amounts to ~0.3-0.5 W/m^2. The presented estimates are valid both under clear-sky conditions and in presence of stochastic clouds (cloud fraction $N \leq 0.5$). We note that the neglect of continuum absorption in the band 940 nm influences more significantly the atmospheric absorption in comparison with the effects of random cloud geometry which do not exceed 0.3-0.4 W/m^2 for the input parameters indicated above.

Sensitivity of Radiative Characteristics to the Accuracy of Water Vapor Content Specification

The radiation measurements used for comparison with model calculations have temporal resolutions of a few minutes at most. WVC can vary greatly during the day (Figure 4), while sometimes there is no possibility to obtain regular data on the state of H_2O in the atmosphere. For example, the rate of radiosonde launches can vary from 3 hours during an intensive operational period to 6-12 hours during routine operations. In this connection, the question arises: to what errors in calculation of radiative characteristics the deficiency of the data on WVC can lead?

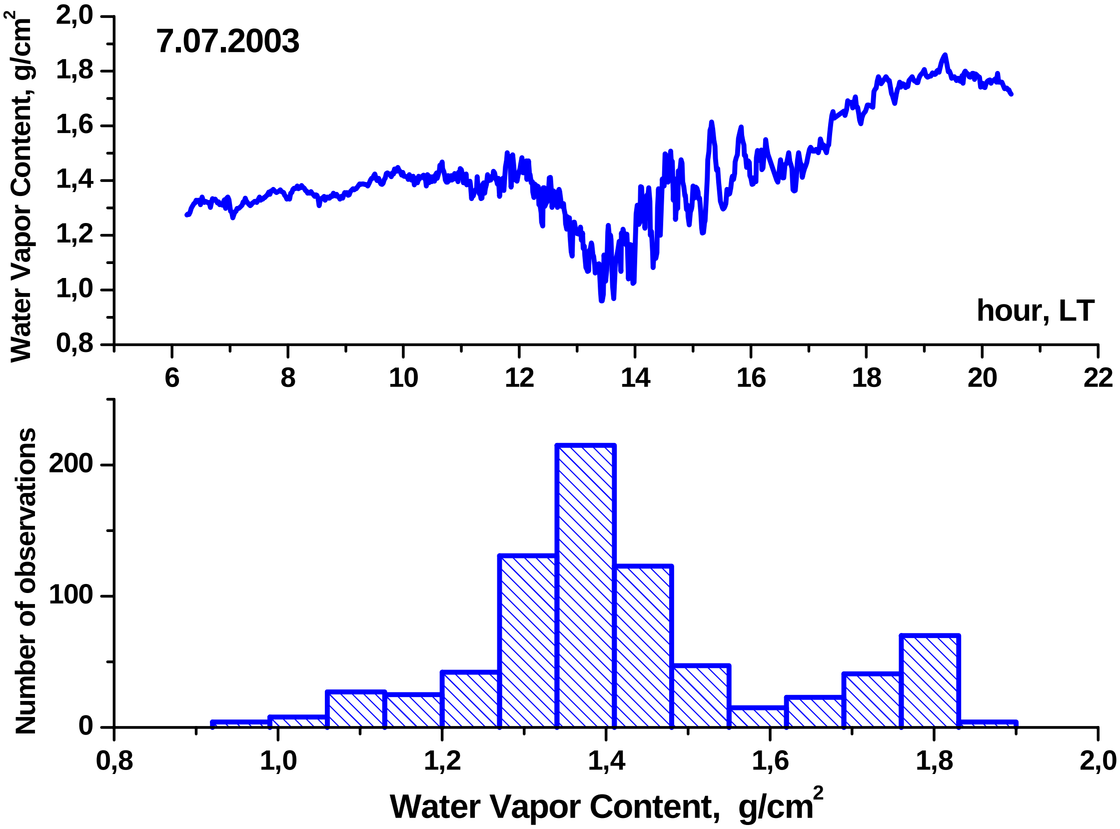

Figure 4. Diurnal variability of *WVC*. The data were obtained on the basis of an original technique for retrieving *WVC* from the data of measurements by sun-photometer SP4, IAO SB RAS, Tomsk, Russia, and HITRAN04.

Let us assume that all atmospheric parameters with the exception of water vapor are accurately specified, and instead of "true" values $WVC^* = \overline{WVC} \mp \sigma_{WVC}$ we will use average value $\overline{WVC}$ in the calculation. Simulation results show that the relative errors in determination of upward and downward fluxes reach 40% near the band's centre under clear-sky conditions at SZA=30°, increasing to 40-80% at N=0.5 and SZA=75°. Besides, errors in albedo determination are almost twice as large as the diffuse transmittance's errors in broken clouds, if the underestimated values of WVC have been used.

Acknowledgements

This work was partially supported by the Department of Energy (under contract No 5012) as part of ARM Program and Russian Fund for Basic Research (under the grants 03-05-64655, 04-07-90123). We also thank L. Harrison, P. Keidron, A, Trishchenko, and M. Cribb who kindly provided us with information about the RSS necessary for our work.

Corresponding Author

Tatiana Zhuravleva, ztb@iao.ru

References

A preliminary cloudless standard atmosphere for radiation computation. World Meteorological Organization. 1986.

Anderson, G, S Clough, F Kneizys, J Chetwynd, and E Shettle. 1986. AFGL Atmospheric Constituent Profiles (0 - 120 km). Air Force Geophysics Laboratory. AFGL-TR-86-0110. Environmental Research Paper No. 954. 1986.

Barker, H, GL Stephens, PT Partain, JW Bergman, B Bonnel, K Kampana, EE Clothiaux, S Clough, S Cusack, J Delamere, J Edwards, KF Evans, Y Fouquart, S Freidenreich, V Galin, Y Hou, S Kato, J Li, E Mlawer, J-J Morcrette, W O'Hirok, P Raisanen, V Ramaswamy, B Ritter, E Rozanov, M Schlesinger, K Shibata, P Sporyshev, Z Sun, M Wendisch, N Wood, and F Yang. 2003. "Assessing 1D atmospheric solar radiative transfer models: Interpretation and handling of unresolved clouds." *Journal of Climate* 16, 2676-2699.

Benner, TC, and KF Evans. 2001. "Three-dimensional solar radiative transfer in small tropical cumulus fields derived from high-resolution imagery." *Journal of Geophysical Research* 106, 14975-14984.

Chesnokova, TYu, KM Firsov, DM Kabanov, SM Sakerin. 2004. "Spectroscopic software for an SP-6 sun photometer." *Atmospheric Oceanic and Optics* 17, 807-810.

Ellingson, R, J Ellis, and S Fels. 1991. "The intercomparison of radiation codes used in climate models: Longwave results." *Journal of Geophysical Research* 96, 8929-8954.

Feigelson, EM. 1981. "Radiation in Cloudy Atmosphere." Leningrad: Gigrometeoizdat. 280 p.

Fouquart, Y, B Bonnel, and V Ramaswamy. 1991. "Intercomparing shortwave radiation codes for climate studies." *Journal of Geophysical Research* 96, 8955-8968.

Harrison, L, J Berndt, P Kiedron, J Michalsky, Q Min, and J Schlemmer. 1999. "Rotating Shadowband Spectroradiometers (RSS) in the ARM Program." In *Proceedings of the Ninth Atmospheric Radiation Measurement (ARM) Science Team Meeting*. Available URL: http://www.arm.gov/docs/documents/technical/conf_9903/harrison-99.pdf

Kiedron, P, J Berndt, L Harrison, J Michalsky, and Q Min. 2001. "Column water vapor from diffuse irradiance." In *Proceedings of the Eleventh Atmospheric Radiation Measurement (ARM) Science Team Meeting*: http://www.arm.gov/publications/proceedings/conf11/abstracts /kiedron1-pw.pdf

Kurucz, TL. 1992. "Synthetic infrared spectra." In Infrared Solar Physics. In *Proceedings of the 154th Symposium of the International Astronomical Union*. Edited by DM Rabin and JT Jefferies, Kluwer, Academy, Boston, Massachusetts.

Li, Z, A Trishchenko, and M Cribb. 2000. "Analysis of cloud spectral radiance/irradiance at the surface and top-of the atmosphere from modeling and observations." In *Proceedings of the Tenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*. Available URL: http://www.arm.gov/publications/proceedings/conf10/abstracts/li-z.pdf

Li, Z, M Cribb, and A Trishchenko. 2001. "A new method and results of estimating area-mean spectral surface albedo from downwelling irradiance measurements." In *Proceedings of the Eleventh Atmospheric Radiation Measurement (ARM) Science Team Meeting*. Available URL: http://www.arm.gov/publications/proceedings/conf11/abstracts/li-z.pdf

O'Hirok, W, and C Gautier. 1998. "A three-dimensional radiative transfer model to investigate the solar radiation within a cloudy atmosphere. Part I: Spatial effects." *Journal of Atmospheric Science* 55, 2162-2179.

Revercomb, HE, DD Turner, DC Tobin, RO Knuteson, WF Feltz, J Barnard, J Bosenberg, S Clough, D Cook, R Ferrare, J Goldsmith, S Gutman, R Halthore, B Lesht, J Liljegren, H Linne, J Michalsky, V Morris, W Porch, S Richardson, B Schmid, M Splitt, T Van Hove, E Wesrwater, and D Whitemam. 2003. "The ARM Program's water vapor intensive observation periods." *Bulletin of the American Meteorological Society* 84, 217-236.

Sakerin, SM, DM Kabanov, AP Rostov, SA Turchinovich, and YuS Turchinovich. 2004. "System for the network monitoring of the atmospheric constituents active in radiative processes. Part 1. Sun photometers." *Atmospheric and Oceanic Optics* 17, 314-320.

Tarasova, T, and B Fomin. 2000. "Solar radiation absorption due to water vapor: Advanced broadband parameterizations." *Journal of Applied Meteorology* 39, 1947-1951.

Zhuravleva, TB, and KM Firsov. 2004. "Spectral fluxes of solar radiation in broken clouds: Algorithms for calculation." In *Proceedings of the Fourteenth Atmospheric Radiation Measurement (ARM) Science Team Meeting*: http://www.arm.gov/publications/proceedings/conf14/extended_abs/zhuravleva2-tb.pdf