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Short communication

Atmospheric radiative transfer modeling: a summary of the AER codes

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Abstract

The radiative transfer models developed at AER are being used extensively for a wide range of applications in the atmospheric sciences. This communication is intended to provide a coherent summary of the various radiative transfer models and associated databases publicly available from AER (http://www.rtweb.aer.com). Among the communities using the models are the remote sensing community (e.g. TES, IASI), the numerical weather prediction community (e.g. ECMWF, NCEP GFS, WRF, MM5), and the climate community (e.g. ECHAM5). Included in this communication is a description of the central features and recent updates for the following models: the line-by-line radiative transfer model (LBLRTM); the line file creation program (LNFL); the longwave and shortwave rapid radiative transfer models, RRTM_LW and RRTM_SW; the Monochromatic Radiative Transfer Model (MonoRTM); the MT_CKD Continuum; and the Kurucz Solar Source Function. LBLRTM and the associated line parameter database (e.g. HITRAN 2000 with 2001 updates) play a central role in the suite of models. The physics adopted for LBLRTM has been extensively analyzed in the context of closure experiments involving the evaluation of the model inputs (e.g. atmospheric state), spectral radiative measurements and the spectral model output. The rapid radiative transfer models are then developed and evaluated using the validated LBLRTM model.

Keywords: AER radiative transfer models; Line-by-line radiative transfer model (LBLRTM); LNFL; RRTM; Monochromatic radiative transfer model (MonoRTM); Continuum (MT_CKD); Kurucz solar source function

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1. Introduction

The purpose of this communication, which is a commission from The Editor of this journal, is to provide the radiative transfer community summaries of the publicly available radiative transfer models and databases that have been developed and applied to atmospheric problems at AER (http://www.rtweb.aer.com). We include summaries and recent updates of the following models: line-by-line radiative transfer model (LBLRTM); the associated line file creation code (LNFL); the longwave and shortwave rapid radiative transfer models, RRTM_LW and RRTM_SW; monochromatic radiative transfer model (MonoRTM); the MT_CKD continuum; and the Kurucz solar source function [1]. It should be noted that there are also other accurate radiative transfer models used by the radiative community.

The accuracy that the AER models currently demonstrate has been attained as a consequence of two important initiatives: (1) the continuing improvement in the quality of the line parameter database and (2) the spectral radiometric measurements obtained by the University of Wisconsin group [2] using interferometers with high photometric accuracy. The HITRAN database provides the basis for the line parameters used in our models. The improvements in this database have been significant; perhaps the most notable example for atmospheric radiative transfer has been the recent improvement in the water vapor lines in the infrared [3]. The role of medium-resolution spectral radiance measurements of high radiometric accuracy obtained from the surface (e.g. atmospheric emitted radiance interferometer (AERI)) and from medium and high altitude interferometers (e.g. high resolution interferometric sounder (HIS)) cannot be overemphasized. These measurements in conjunction with the accurate specification of atmospheric state, such as profiles obtained at the Atmospheric Radiation Measurement program (ARM) Southern Great Plains (SGP) site, have had an important influence on the development of model parameterizations including the water vapor continuum and the line shape and continuum associated with carbon dioxide.

Finally, the current models have a strong and valued heritage in the research program on atmospheric radiation conducted at the Air Force Geophysics Laboratory, now known as Air Force Research Laboratory, over an extended period. Important contributors to that program whose work has had a strong influence on the current models include Frank Kneizys, Eric Shettle, John Selby, Gail Anderson, Bill Gallery, Larry Rothman, Jim Chetwynd, and Richard Davies.

2. Description of AER radiative transfer models and updates

2.1. LBLRTM (v8.1)

LBLRTM [4] is an accurate and efficient line-by-line radiative transfer model derived from the Fast Atmospheric Signature Code (FASCODE) [4,5]. LBLRTM has been and continues to be extensively validated against atmospheric radiance spectra from the ultraviolet to the sub-millimeter (e.g. [6]). It has a key role in ARM and the forward model used in the retrieval of atmospheric constituents from space with the NASA tropospheric emission spectrometer (TES) [7] is based on LBLRTM.

The following summarizes the important LBLRTM_v8.1 attributes: the Voigt line shape is used at all atmospheric levels with an algorithm based on a linear combination of approximating functions; LBLRTM incorporates the continuum model MT_CKD, which includes self- and foreign-broadened water vapor as well as continua for carbon dioxide, oxygen, nitrogen, ozone and extinction due to Rayleigh scattering; all parameters on the HITRAN line database [8] are used including the pressure shift coefficient, the halfwidth temperature dependence and the coefficient for the self-broadening of water vapor; a new version of the Total Internal Partition Function (TIPS) program is used for the temperature-dependence of the line intensities [9,10]; the effects of CO_2 line coupling are treated to second order (refer to Section 2.2); temperature dependent cross section data such as those available with the HITRAN database may be used to treat the absorption due to heavy molecules, e.g. the halocarbons; an algorithm is implemented for the treatment of the variation of the Planck function within a vertically inhomogeneous layer as discussed in Clough et al. [5]; Fast Fourier Transform (FFT) instrument function is included [11].

These attributes provide spectral radiance calculations with accuracies consistent with the measurements against which they are validated and with computational times that greatly facilitate the application of the line-by-line approach to current radiative transfer applications. Algorithmic accuracy of LBLRTM is approximately 0.5% and the errors associated with the computational procedures are of the order of five times less than those associated with the line parameters so that the limiting errors in the general case are attributable to the line parameters and the line shape.

Since there have been a number of important updates and improvements to LBLRTM, we are outlining the important changes contained in recent releases: a new water vapor continuum model, MT_CKD_1.0 (0–$20,000\,\mathrm{cm}^{-1}$), has been implemented (refer to Section 2.5); important changes made to the O_2 and CO_2 continua are also included in MT_CKD_1.0 (refer to Section 2.5); LBLRTM has added the flexibility of inputting atmospheric profiles on either altitude or pressure grid; LBLRTM has the capability to compute quantities for atmospheric layers that are not in local thermodynamic equilibrium (non-LTE option); the capability to perform the radiative transfer for downlooking scenes with a Lambertian surface has been added; the interface between LBLRTM and LOWTRAN7 has been updated to facilitate the inclusion of aerosol and cloud models in the calculation; the portability of LBLRTM has been extended, in particular, to improve compatibility with LINUX, IBM (AIX), and Apple (OS X) systems. Makefiles for creating both single and double precision executables for a number of platforms have been included (Table 1).

LBLRTM line parameter inputs are obtained by running the LNFL program (see Section 2.2) on the spectroscopic line file database for the spectral lines. The model utilizes temperature dependent cross sections for the heavy molecules: the pressure dependence is treated by performing a convolution of the cross section spectrum with an appropriate Lorentz function effectively increasing the broadening width to the proper value. LBLRTM also utilizes the Kurucz [1] solar source function.

Fluxes and heating rates can be calculated from LBLRTM radiances for user-specified spectral intervals using a separate program called RADSUM, which is also available to the research community through the AER radiative transfer working group web site.

Table 1
Current LBLRTM platforms

System	Manufacturer	Compiler	Single	Double
IRIX	SGI		F90, f77	F90, f77
SOLARIS	SUN		F90, f77	F90, f77
AIX	IBM		F90	F90
LINUX		PGI	F90	F90
LINUX	INTEL			F90
OS X	APPLE	ABSOFT	F90	F90
OS X	APPLE	GNU	G77	G77

LBLRTM has previously been run on DEC alpha, Cray, MS-DOS, and HP platforms.

2.2. LNFL (v1.14)

LNFL is utilized to obtain binary line parameter files from the HITRAN line parameter and similar line databases. LNFL also adds line coupling/mixing parameters to the line parameter database used as input into LBLRTM. LNFL v1.14 includes line coupling parameters for CO_2 Q-branches in the $v2$ region (600–800 cm^{-1}) that have been updated to be consistent with the HITRAN 2000 line parameters, including Hoke et al. [12] first and second order coupling parameters. First order line coupling parameters for CO_2 at the 1932, 2076, 2093, 2193 cm^{-1} Q-branches have also been included following Strow et al. [13]. LNFL and LBLRTM currently handle the isotopic variants associated with molecular species through molecular number 38, consistent with the HITRAN database.

2.3. RRTM

The accurate and rapid radiative transfer model RRTM calculates shortwave fluxes, longwave fluxes and cooling rates for application to general studies of atmospheric radiative transfer and for implementation into general circulation models [14–16]. The correlated-k method utilized by RRTM has been selected for its computational efficiency with accuracy consistent with line-by-line radiative transfer models, and its direct adaptability to multiple-scattering calculations. The absorption coefficients used to build the relevant k-distributions were obtained from LBLRTM (which included the CKD_2.4 continuum model and the HITRAN database). The accuracy of the absorption coefficients has been established by numerous high-resolution validations with measurements, particularly those performed as part of the ARM Program [6,15].

RRTM is divided into sixteen contiguous bands in the longwave (hereinafter referred to as RRTM_LW) from 10 to 3250 cm^{-1} and fourteen bands in the shortwave (hereinafter referred to as RRTM_SW) from 820–50,000 cm^{-1}. Spectral bands were chosen based on the major absorption features of the active gaseous species. In addition to clear sky radiative transfer, parameterizations of the radiative effects of water clouds [17] and ice clouds [18,19] are available in RRTM.

The RRTM package has been extensively validated against LBLRTM as well as against measurements. On the basis of such validations, an accelerated version of RRTM_LW (also publicly available) has been implemented as the operational longwave code at the European Center for Medium-Range Weather Forecasts (ECMWF) [20] and in the Global Forecast System (GFS) of the National Centers for Environmental Prediction (NCEP). It is also being tested for application in the National Center for Atmospheric Research (NCAR) Community Climate Model [16,21] and the more recent NCAR Community Atmosphere Model (CAM). RRTM_LW has been implemented in a number of other dynamical models including the PSU/NCAR mesoscale model (MM5), the (NCEP/NCAR) Weather Research and Forecasting (WRF) model, the Arctic Regional Climate System Model (ARCSyM) [22], and it has provided the k-distributions for the Spherical Harmonic Discrete Ordinate Method SHDOM [23]. In addition, the accuracy of RRTM_SW has allowed it to serve as a reference model in the development of other shortwave rapid radiative transfer models. An important feature of RRTM_SW is that it produces significantly greater absorption in the clear sky than most current shortwave codes in climate models.

2.3.1. RRTM_LW (v3.0)

RRTM_LW calculates fluxes and heating rates for the longwave spectral regime. Modeled molecular absorbers are water vapor, carbon dioxide, ozone, nitrous oxide, methane, oxygen, nitrogen, and the common halocarbons. In September 2002, RRTM_LW version 3.0 was released. Validations of the RRTM_LW v3.0 against LBLRTM have been performed for a wide variety of atmospheric conditions. From these validations the clear-sky longwave accuracy of RRTM_LW has been established as follows: 1.0 $W\,m^{-2}$ (relative to LBLRTM) for the net flux at any altitude; 0.1 $K\,day^{-1}$ for the total cooling rate error in the troposphere and lower stratosphere, and 0.3 $K\,day^{-1}$ in the upper stratosphere and above. RRTM_LW v3.0 includes a number of substantial updates from the previous release of version 2.3: new k-distributions compiled from HITRAN96 line parameter database, except for water vapor, which are based on a pre-release version of the HITRAN 2000 database [3]; reduced errors in fluxes and cooling rates computed in RRTM_LW v3.0 for atmospheres having abundances of trace gases (e.g. carbon dioxide, methane) substantially different from current abundances; and reduced errors in computed stratospheric cooling rates. In RRTM_LW v3.0 the average maximum stratospheric cooling rate error (for a representative set of 43 atmospheric profiles) is 0.27 $K\,day^{-1}$, compared with an average error of 0.53 $K\,day^{-1}$ for RRTM_LW v2.3.

2.3.2. RRTM_SW (v2.4)

RRTM_SW [24] calculates fluxes and heating rates for the shortwave spectral regime. Modeled sources of extinction include water vapor, carbon dioxide, ozone, methane, oxygen, aerosols, and Rayleigh scattering. The discrete-ordinate-method radiative transfer algorithm DISORT [25] is used to perform the radiative transfer calculations for multiple scattering. For the total flux (direct plus diffuse) at the surface, RRTM_SW and the multiple-scattering LBLRTM/CHARTS [26] agree to within 1.5 $W\,m^{-2}$, with good agreement for each RRTM_SW spectral band.

RRTM_SW is suitable for use as a reference to improve the performance of GCM shortwave codes. The critical feature justifying the utilization of RRTM_SW in the context of GCM performance is its traceability to ARM measurements provided through comparisons to the high resolution, data-validated models LBLRTM/CHARTS [15,26]. It is only through such a connection to measurements at the highest spectral resolution available that a rapid radiation model can be assured of accurately incorporating the relevant physics. An accelerated version of RRTM_SW, which will be applicable for GCM implementation and will utilize a 2-stream method for radiative transfer, is nearing completion.

2.4. MonoRTM (v 2.11)

MonoRTM is a radiative transfer model that utilizes the same physics as LBLRTM but is designed to process a limited number of monochromatic spectral output values [27]. In its current configuration MonoRTM (v2.11) is fully functional for the microwave region and has limited capability for laser propagation studies in other spectral domains. The code has been developed to perform radiative transfer calculations for frequencies specified in the input stream. Since the number of output frequencies is typically limited, the computational cost of the calculations while important, is not the dominant consideration. The Humlicek Voigt line shape [28] is used for all pressure regimes and all relevant spectroscopic lines are used in the general case.

MonoRTM includes the capability of calculating cloud liquid water absorption in the microwave using the model developed by Liebe et al. [29]. The version of the continuum currently implemented in MonoRTM is CKD_2.4; however, in the microwave region MT_CKD [30] virtually is identical with CKD_2.4. A special line file derived from updated HITRAN 2000 is utilized. The line strengths for the 22 and 183 GHz water vapor transitions are from Clough et al. [31]; the other parameters are from updated HITRAN_2000. Line-coupling parameters for oxygen in the microwave region [12] are included. For the spectral region up to 300 GHz, an optimal subset of spectral lines that includes 41 lines of oxygen, 40 lines of water vapor, 32 lines of ozone and 4 lines of N_2O, is available. The magnitude of the brightness temperature differences for uplooking and downlooking configurations is less than 0.1 K compared with results using the full set.

2.5. Continuum (MT_CKD)

The water vapor continuum model, MT_CKD_1.0 [30], has recently been released and represents the first re-computation of the entire self and foreign broadened continuum since the original CKD model was developed in 1980 [32]. This version of the continuum is included in the line-by-line model LBLRTM v7.01 (and subsequent releases) and will ultimately be utilized in all related AER radiative transfer models. The MT_CKD continuum is based on a new formulation: the self and foreign continuum models are each based on the contributions from two components, a collision-induced component and a line shape component. This change in perspective has resulted from the difficulty in developing a line shape model based on sound physics that explains the magnitude of the increased absorption in the intermediate wing over that provided by the impact approximation. The data used to develop the new continuum model have come predominantly from spectral atmospheric measurements. Only cases for which the characterization of the atmospheric state has been highly scrutinized have been used. This new model has been developed by Mlawer, Tobin and Clough building on the original CKD formulation; hence the name MT_CKD.

In addition to the water vapor continuum there have been important changes made to the O_2 and CO_2 continua. The collision-induced O_2 continuum from 15,000 to 29,870 cm^{-1} [33], first implemented in CKD 2.4.1, is included in MT_CKD_1.0. CO_2 continuum improvements were implemented for the calculation of the optical depth for the carbon dioxide bands in the 500–900 cm^{-1} region. The lineshape and the continuum for carbon dioxide have been modified in this region resulting in an overall increase in absorption. These changes were principally based on validations with the U. Wisconsin interferometric measurements: High resolution interferometric sounder (HIS) Convection and moisture experiment (CAMEX), scanning-HIS (SHIS) ARM/FIRE water vapor experiment (AFWEX) and atmospheric emitted radiance interferometer (AERI) at the ARM North Slope of Alaska site [34]. These changes to the continuum model for CO_2 were first introduced into CKD 2.4.2 and are also included in the MT_CKD_1.0 continuum.

Users should note that a stand-alone program, cntnm_progr.f, is available for this initial release of MT_CKD_1.0. The driver for this program has been changed slightly so that pressure, temperature, and path length may be entered as input.

2.6. Solar source function

The solar source function is used in shortwave radiation calculations and is based on theoretical radiative transfer calculations for the solar atmosphere. We have used the Kurucz [1] solar source function in our research in shortwave radiation [15]. The solar source function is available at a high spectral resolution (i.e., for monochromatic calculations) and at 1 cm^{-1} resolution.

3. Validation examples

3.1. LBLRTM validation example

AER's radiative transfer models are well validated against atmospheric observations. A validation example of LBLRTM calculations against HIS during CAMEX is provided in Fig. 1. The HIS observations from this CAMEX case from 09/29/1993 have been used extensively in validation studies for a number of forward models [35,36]. For this case, the HIS sensor had a spectral resolution of 0.32 cm^{-1} and flew over the ocean on an aircraft at 20 km, which was above the tropopause.

The original radiosonde temperature profile used in the LBLRTM calculations was modified using a least-squares retrieval. The Masuda sea surface spectral emissivity model was utilized in the calculation [37,38]. The residuals between the HIS spectral radiance and a reference LBLRTM calculation, performed using LBLRTM_v6.01 with spectral lines from HITRAN96 [39], are shown in Fig. 1a. A second calculation was performed using LBLRTM_v8.1 with improved line parameters built from HITRAN2000 including HITRAN updates through 09/2001 and with ozone parameters based on Wagner et al. [40]. This ozone line parameter set is currently being used for MIPAS retrievals. The initial characterization of the atmosphere was obtained from a radiosonde. The temperature profile was refined by performing a physical retrieval utilizing the ν_2 CO_2 spectral region. Comparing the residuals in Fig.1a with Fig.1c, one sees a significant reduction in their magnitude resulting from the combined improvements of LBLRTM_v8.1 and

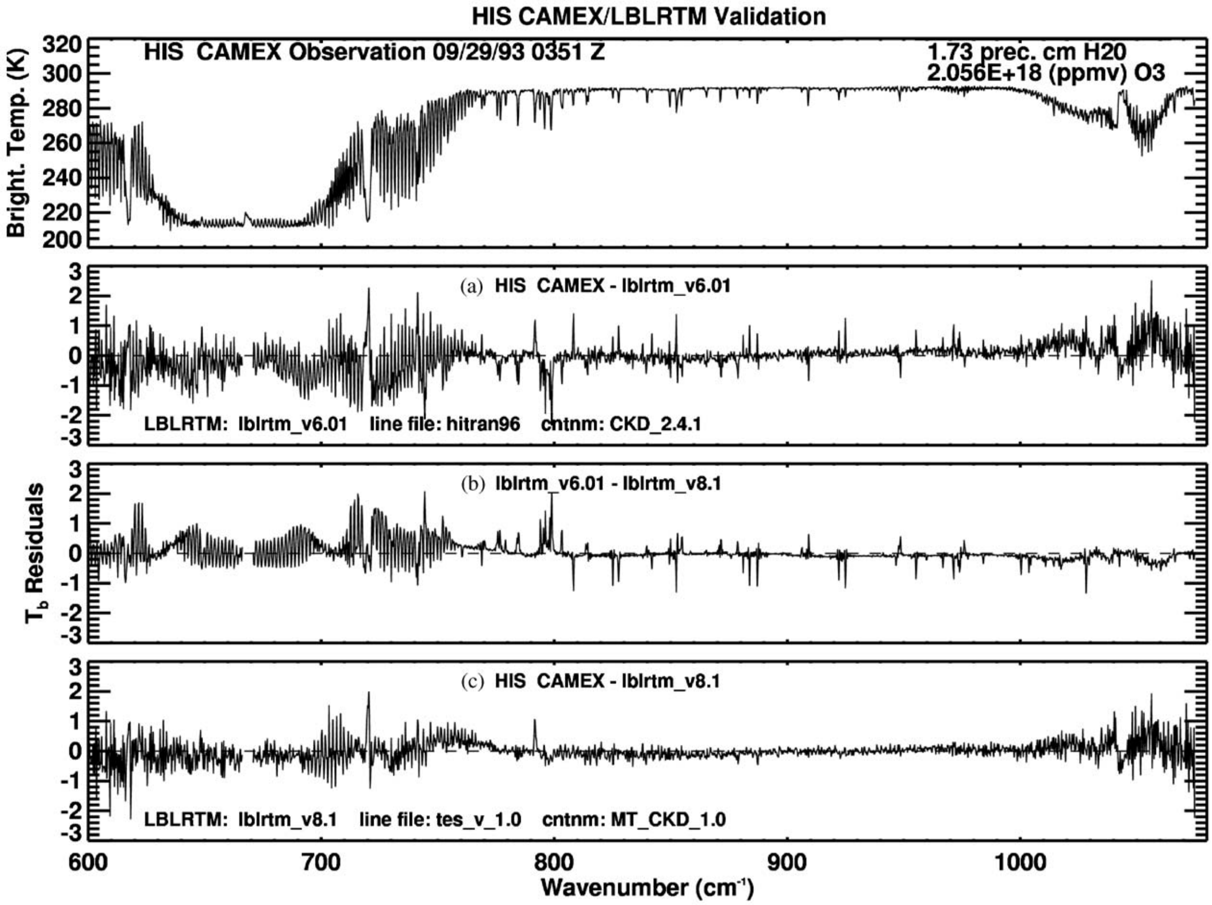

Fig. 1. The top panel is the observed HIS CAMEX spectral radiance provided by the U. of. Wisconsin–Madison. The bottom panels are residual plots of (a) HIS CAMEX–LBLRTM_v6.01 with HITRAN96 spectral line parameters and CKD 2.4.1 continuum, (b) the difference between the two LBLRTM_6.01 with HITRAN96 and LBLRTM_v8.1 with tes_v_1.0 spectral line parameters calculations, and (c) HIS CAMEX–LBLRTM_v8.1 with tes_v_1.0 spectral line parameters and MT_CKD_1.0 continuum.

the new spectroscopic line parameters used. The reduced residuals in the ν_2 CO_2 region (700–780 cm^{-1}) in Fig. 1c are due to the overall increased absorption associated with improvements made to the CO_2 lineshape and continuum [34]. In the window region from 780–980 cm^{-1}, Toth's [3] improved water vapor line parameters in HITRAN2000 significantly reduce the large residual peaks associated with the water lines. Even though there is a slight improvement in the O_3 region from 980 to 1080 cm^{-1} significant residuals remain. Inaccuracy in the representation of the atmospheric state (ozone and temperature) is the most likely explanation for the residuals in this region, with an additional contribution from the ozone line parameters. The original ozone sonde profile in the altitude regime near the aircraft was scaled to increase the ozone amounts and reduce the residuals between the observations and the calculations [35]; however, a full least-squares retrieval needs to be performed in order to better characterize the ozone profile.

In addition to the extensive validations with measurements that LBLRTM has undergone in the longwave regime, the calculations of the model have also been compared to spectral measurements at solar frequencies. In the spectral range 2000–10,000 cm^{-1}, radiance calculations by LBLRTM were compared to measurements [41] of direct-beam spectral (resolution 0.6 cm^{-1}) radiance taken by the absolute solar transmittance interferometer (ASTI) [42]. These comparisons showed good agreement and helped determine the strength of collision-induced oxygen absorption bands in this spectral domain. Additional comparisons in the solar regime have been performed using measurements of direct and diffuse irradiance [15] taken by the rotating shadowband spectroradiometer (RSS) in the spectral range 10,000–28,500 cm^{-1} [43]. These measurements agreed well with the calculations of LBLRTM used in conjunction with CHARTS, an adding-doubling code developed at AER, indicating that there were no significant unknown sources of molecular absorption in this spectral range. Of particular interest is the validation that has been done with LBLRTM/CHARTS in the shortwave and longwave for an atmosphere with a reported homogeneous cloud [26].

3.2. MonoRTM validation example

MonoRTM has been run over a large number of profiles from the ARM SGP site, and the results evaluated against MWR (MicroWave Radiometer by Radiometrics) measurements of the downwelling radiance at 23.8 and 31.4 GHz. These two frequencies are used for the simultaneous retrieval of precipitable water vapor (PWV) and cloud liquid water (CLW). CLW is a critically important element in our understanding of cloud microphysics and the radiative properties of the atmosphere. In order to achieve accurate retrievals of CLW, it is critical that the brightness temperatures associated with the vapor be consistent at the two frequencies. The spectral radiance in brightness temperature for an atmosphere with 3 precipitable cm of water vapor is given in Fig. 2a. For 2258 clear sky cases spanning a three-year period, the column water vapor has been retrieved from the MWR measurements at 23.8 GHz. Using the associated sonde profiles scaled to attain agreement with the retrieved column values, the brightness temperatures at 31.4 GHz have been calculated with MonoRTM and compared with the MWR measurements at that frequency.

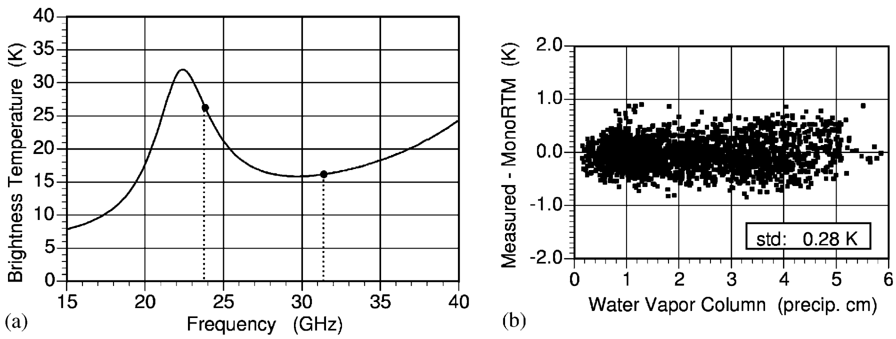

Fig. 2. (a) The microwave spectrum of the atmospheric downwelling radiation at the surface in the vicinity of 22.24 GHz water vapor line for 3 precip. cm of water vapor. The two radiometrics MWR frequencies at 23.8 and 31.4 GHz are indicated by •. (b) The residuals between MWR measurements and model calculations at 31.4 GHz based on the PWV values retrieved at 23.8 GHz as a function of column water vapor (2258 clear sky cases).

The residuals are shown in Fig. 2b. The standard deviation is 0.28 K, which includes error contributions from the forward model and from measurement errors at the two frequencies. This remarkable agreement demonstrates the high level of consistency in the model between the two frequencies and provides support for the halfwidth, foreign-continuum and self-continuum used in the model, as well as for the quality of the MWR measurements over an extended period. The application of MonoRTM to the physical retrieval of PWV and CLW with this demonstrated MWR performance is expected to provide retrieval accuracies approaching 1% for PWV (above 1 precipitable cm) and 0.01 mm for CLW for clouds whose distribution of water in the atmosphere is accurately represented.

4. Remarks

A brief description of the publicly available AER models and their recent updates has been provided. These models are well validated against atmospheric observations and are used in the radiative transfer calculations of such models as the TES retrieval algorithm, the ECMWF weather forecast model, NCEP GFS, WRF and MM5. In order to provide easier access to these models for the research community, AER's Radiative Transfer Working Group has developed a web site (http://www.rtweb.aer.com) where the radiative transfer models and databases described in this article can be obtained as well as further description and validations.

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