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High resolution modeling of the Far-infrared Spectra of the Earth's Atmosphere

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1. INTRODUCTION

Recent studies [e.g., Kratz, 2001] have used monochromatic calculations to demonstrate that over 40% of the thermal energy escaping from the Earth's atmosphere-surface system is emitted to space within the spectral range known as the far-infrared. Extending from 100 to 650 cm^{-1} (100 to 15.4 µm), this portion of the spectrum is dominated by the line and continuum spectral features of the pure rotation band of water vapor. In addition to being the principal infrared-active molecule in the Earth's atmosphere, water vapor is also one of the most spatially and temporally variable of the atmospheric trace species. Sensitivity studies comparing the water vapor absorption and emission in the far-infrared to other spectral ranges have revealed that the radiative impact of water vapor in the far-infrared provides the greatest sensitivity of the outgoing thermal radiation to perturbations in upper tropospheric humidity, and plays a prominent role in determining the rate of cooling throughout the free troposphere [Clough et al, 1992]. Indeed, the distribution of water vapor throughout the atmosphere along with the associated far-infrared radiative forcings and feedbacks are well recognized as significant uncertainties in the forecasting of the Earth's future climate state. Despite the magnitude of the calculated far-infrared contribution, however, very few spectrally-resolved measurements of the Earth's atmosphere-surface system have been taken from space-based instruments. As part of the National Aeronautics and Space Administration (NASA) Instrument Incubator Program (IIP), the Far-Infrared Spectroscopy of the Troposphere (FIRST) project developed an instrument capable of measuring the spectrum over the range from 100 to 1000 cm^{-1} (100 to 10 µm). With a highly successful balloon flight launch from Ft. Sumner, NM on 7 June 2005 [Mlynczak et al, 2006], FIRST has opened a new window on the spectrum for studying atmospheric radiation and climate, cirrus, and water vapor for the upper troposphere. This talk reviews the high resolution modeling effort being done in support of the far-infrared studies at Langley Research Center.

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2. THE FIRST PROJECT

The FIRST project was conceived with the intent to design, develop, and field demonstrate a nadir-viewing instrument capable of measuring the Earth's thermal emission over the spectral range from 100 to 1000 cm^{-1} with an unapodized spectral resolution of order 0.6 cm^{-1} and a NEΔT of 0.2 K [Mlynczak et al, 2001]. The goals of the FIRST project require a nadir viewing IFOV with a 10 km spatial footprint and a cross-track capability to provide daily global coverage. The spectral coverage and spectral resolution are necessary to measure the unobserved far-infrared thermal emission while simultaneously measuring the 15 µm band of CO_2 and a parts of the infrared window region. Such measurements will enable temperature retrievals and validation against mid-infrared sensors. The NEΔT sensitivity of 0.2 K is necessary for temperature profiling that can resolve changes to the climate state. The IFOV is necessary to resolve clear from cloudy fields of view, while the daily global coverage is necessary to provide global observations of water vapor that reflect the spatial variability in the observed radiation and cloud fields.

3. INTERCOMPARISON OF MODELS

Properly analyzing the data taken by the FIRST instrument requires the availability of accurate far-infrared radiative transfer models. To establish the mutual reliability of the available high-resolution algorithms, an inter-comparison was undertaken among several of the far-infrared radiative transfer models. To facilitate this inter-comparison, the results from each model were subtracted from the results of a single reference model, here taken to be the Monochromatic Radiative Transfer Algorithm (MRTA) [Kratz et al, 2005]. Figure 1 illustrates the results derived from an inter-comparison of the TOA (upper plot) and surface (lower plot) radiance calculations from the various radiative transfer algorithms for the sub-artic winter atmosphere. In both the TOA and surface cases, the differences among the models were found to be quite small, with the normalized radiance defined by the equation:

$$R_\omega = \frac{I_\omega(Model) - I_\omega(MRTA)}{I_\omega(MRTA)}, \qquad (1)$$

having means which were less than 0.36% and standard deviations which were less than 0.83%. The results shown in Figure 1 for the sub-arctic winter atmosphere are fairly representative of results obtained from other atmospheric profiles. For instance, calculations based upon the tropical atmosphere produced means and standard deviations within 0.40%.

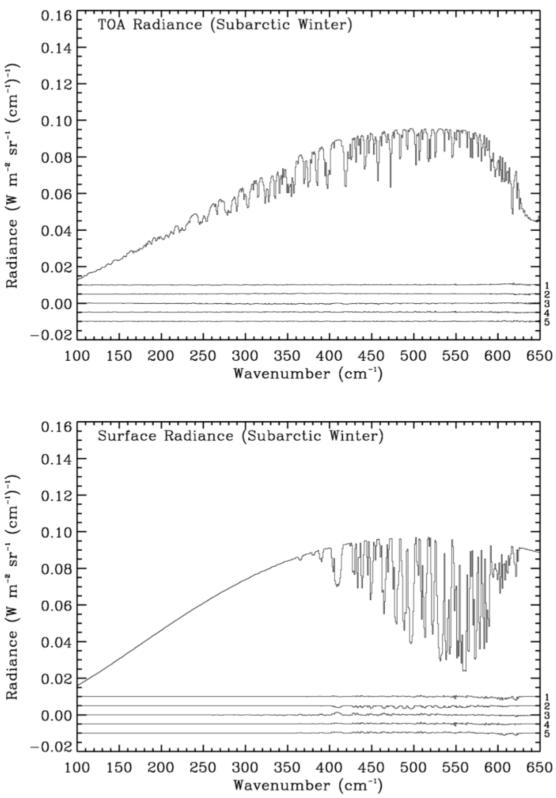

Figure 1. *A comparison of TOA and surface radiance calculations at a resolution of 1.0 cm^{-1} for the sub-arctic winter atmosphere for the spectral range from 100 to 650 cm^{-1}. The uppermost curve represents the radiances calculated with the MRTA using the HITRAN 2000 database for H2O, CO2 and O3, and version 2.4 of the CKD continuum. The numbered curves represent: (1) LBLRTM – MRTA, (2) LINEPAK – MRTA, (3) HARTCODE – MRTA, (4) FUTBOLIN – MRTA, and (5) GENLN2 – MRTA, with the results being vertically offset from one another for clarity.*

To obtain a better perspective on the relative sizes of the differences observed in the model inter-comparison, additional calculations were performed to examine the impact of changing model inputs. While a considerable number of test cases could be run, the present study was focused upon such items as the neglect of CO_2 line mixing, neglect of all the infrared-active species, different continuum formulations and different versions of the HITRAN database. Figure 2 illustrates the resulting impact to the sub-arctic winter atmosphere calculations caused by changes in these model inputs. As can be observed, changes to the spectral line parameterization, continuum algorithm, choice of included trace species, and other model inputs frequently produce significantly greater impacts than the differences found among the radiative transfer models. This emphasizes the relative accuracies of the radiative transfer models as compared to the inputs into those models.

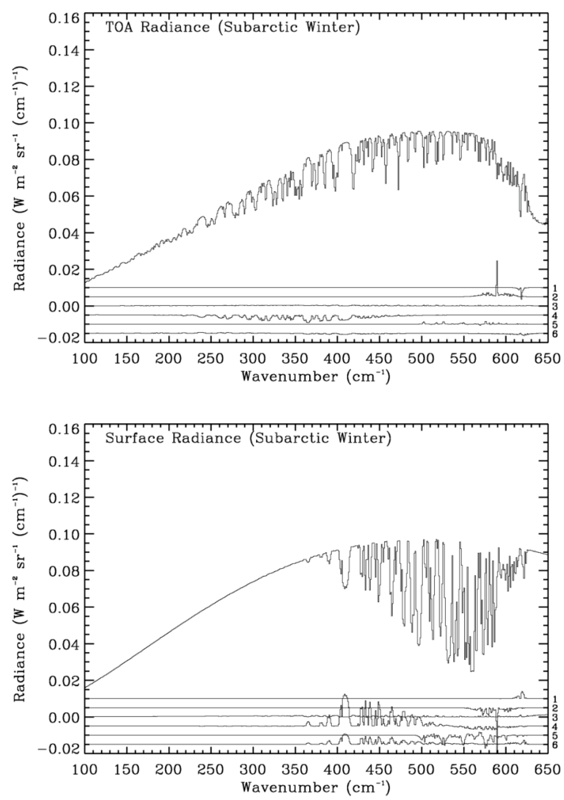

Figure 2. *A comparison of TOA and surface radiance calculations that are analogous to those presented in Figure 1 except that the numbered curves represent (1) without line mixing – with line mixing, (2) without N_2O – with N_2O, (3) the mean-layer temperature approximation – linear in tau approximation, (4) CKD 2.1 – CKD 2.4, (5) HITRAN 1996 – HITRAN 2000, and (6) MT_CKD 1.0 – CKD 2.4.*

In contrast to the results provided by the inter-comparison of radiative transfer codes studies (see Figure 1), the results obtained from model input sensitivity studies (see Figure 2) frequently produce noticeably different sensitivities for the various atmospheric profiles. Indeed, as shown in Table 1, warm, moist atmospheric profiles tend to have surface radiances which are relatively insensitive to changes in the model inputs, whereas cold, dry atmospheric profiles tend toward surface radiances that are quite sensitive to model inputs. These sensitivity studies strongly suggest that cooler, dryer atmospheres, such as the sub-arctic winter atmosphere, provide more critical test conditions for downward radiances than the warm, moist atmospheres. The reason for this enhanced sensitivity is linked to the greater transparency of cooler, drier atmospheres. Our present results in conjunction with the previously reported field measurements provided by Tobin et al [1999] strongly suggest that future inter-comparison studies of the far-infrared should include the very cold, dry Artic/Antarctic profiles.

Case	Profile	I_{up}(TOA)	I_{dn}(Surf)
1	Tropical	-0.377	0.003
1	SAW	-0.307	0.473
1	Isothermal	-0.216	0.600
2	Tropical	-0.085	0.018
2	SAW	-0.031	0.210
2	Isothermal	-0.075	0.195
3	Tropical	0.063	-0.010
3	SAW	0.020	-0.141
3	Isothermal	0.061	-0.132
4	Tropical	-0.063	0.006
4	SAW	-0.033	0.106
4	Isothermal	-0.044	0.093

Table 1. *Differences in the integrated radiances in $Wm^{-2}sr^{-1}$ as calculated for the spectral range from 100 to 650 cm^{-1}, where the numbered curves represent: (1) CKD2.1–CKD2.4, (2) MT_CKD–CKD2.4, (3) HITRAN '96–2k, and (4) HITRAN '04–2k.*

The sensitivity of our results to the selection of line parameter database and continuum formulation further emphasizes the need to use the most current, validated versions of these resources. The lack of measurements for very cold, dry conditions of the far-infrared spectra, especially in the 100 and 400 cm^{-1} range, however, means that considerable uncertainties may remain in the water vapor line intensities and half widths, as well as the continuum formulations. This, in turn, leads to uncertainties in the model calculated radiance values that may well be comparable to the impact of doubling CO_2 [Turner and Mlawer, private communication]. This observation provides further evidence of the critical need to obtain far-infrared measurements such as those proposed by the FIRST project.

4. FIRST LIGHT SPECTRA

The FIRST instrument was carried aloft by a 310 thousand cubic meter helium-filled balloon on June 7, 2005 to a nominal flight altitude of approximately 27 km. During the 5.5 hours of flight operations, nearly 15,000 interferograms were recorded by the FIRST instrument. By successfully measuring the spectrum from 50 to 2000 cm^{-1}, the FIRST instrument demonstrated the capability to observe the entire energetically significant portion of the infrared. The FIRST instrument further demonstrated the ability to provide the optical throughput necessary to achieve daily global coverage from low earth orbit [Mlynczak et al, 2006].

At approximately 2:25 pm local time, NASA's Aqua spacecraft flew over the flight-track of the FIRST instrument. This overpass facilitated a comparison of the FIRST measurements within the mid-infrared window region to data provided by AIRS, CERES and MODIS. For the 800 to 950 cm^{-1} spectral range, the spectral features and integrated radiances measured by FIRST were found to be in remarkable agreement with the corresponding AIRS results [Mlynczak et al, 2006]. In addition, the surface skin temperatures retrieved from the FIRST data agreed well with the MODIS observations, and were consistent with CERES window channel radiances. Such results have verified the calibration accuracy of the FIRST instrument.

Since the primary focus of the FIRST project is concentrated toward the far-infrared, there is a need to validate the FIRST spectrum for the spectral region between 50 and 600 cm^{-1}. Unlike the mid-infrared window region, however, no spectral measurements are available for the far-infrared. Thus, a theoretical radiative transfer model has been substituted for this comparison. Shown in Figure 3 is a single spectrum recorded by the FIRST interferometer between the limits of 20 and 600 cm^{-1}. The very rich structure of the far-infrared is readily evident from this FIRST spectrum. Figure 3 also illustrates the difference between the measured FIRST spectrum and a line-by-line (LbL) derived spectrum computed using the AIRS temperature and moisture profile derived from measurements taken during the Aqua overflight of June 7, 2005. The difference spectrum shown in Figure 3 emphasizes the excellent agreement between the observed and computed spectra from this "first light" stage of the instrument analysis. These results provide confidence in both the proper functioning of the FIRST instrument and the radiative transfer models used in the analysis of the FIRST measurements.

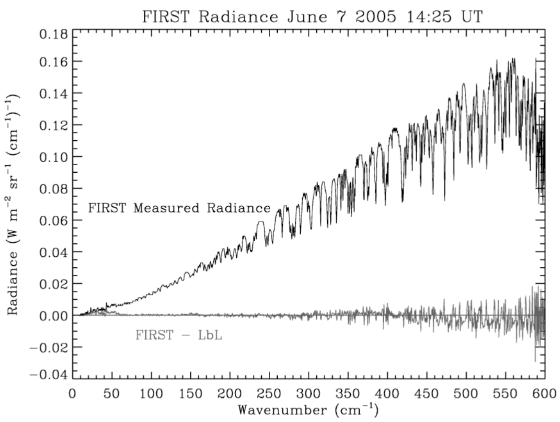

Figure 3. *Far-infrared spectrum (0 to 600 cm^{-1}) measured by FIRST with a realized unapodized resolution of 0.643 cm^{-1} and the difference between that spectrum and one computed with a line-by-line (LbL) radiative transfer code using an AIRS temperature and moisture profiles.*

5. CONCLUSIONS

The monochromatic calculations considered in this study have demonstrated remarkable agreement for a wide range of atmospheric profiles. Our results provide a high degree of confidence in our ability to analyze the FIRST radiance measurements and are consistent with the conclusions of the ISSWG line-by-line inter-comparison [Tjemkes et al, 2003] for the mid-infrared spectral range from 590 to 2700 cm^{-1}. This confidence in our models was further justified when the model calculated radiance spectra were found to be in excellent agreement with the observed FIRST data.

Our results also confirm previously reported conclusions that the low absolute humidity conditions prevalent for high latitude and altitude cases can allow for the appearance of semi-transparent micro-windows in the far-infrared [see e,g., Tobin et al, 1999]. Such micro-windows serve as spectral regions of heightened sensitivity that can be used to uncover differences in model formulations. This strongly suggests that future far-infrared studies should include Arctic/Antarctic atmospheric profiles as well as cases which are representative of high-altitude mountain regions.

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