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Infrared spectral radiance measurements in the tropical Pacific atmosphere

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Abstract. Downwelling thermal infrared emission from the tropical atmosphere is affected strongly by the typically large amounts of water vapor. In two experiments within the last 2 years we have used a Fourier transform spectroradiometer to measure tropical atmospheric emission, concentrating on the "window" region between about 800 and 1200 cm^{-1}. Shortly after the first of these experiments, substantial differences between measured and calculated radiances led to the development of a new water vapor continuum model. This model subsequently has been incorporated into several widely distributed radiative transfer codes (LBLRTM, MODTRAN, FASCODE). Measurements from the second tropical experiment, which occurred during March and April 1996, validate this new continuum model. This is an important comparison because the new measurements were taken with an improved instrument under better defined clear-sky conditions than the original tropical data on which the continuum correction was based. Model residuals are of the order of the uncertainty in measurements, especially of the atmospheric water vapor and temperature profiles:

Introduction

Radiation fluxes in the tropics play a major role in the planetary climate. The incoming solar radiation absorbed at the surface is large because of the near-normal incidence angle. At the same time, much of the infrared radiation from the surface is trapped by water vapor absorption in the atmosphere. The water vapor absorption is attributed to discrete molecular transitions and to a broad continuum of underlying absorption between these lines. The ability to model both of these processes accurately for tropical atmospheres is essential to climate studies and to retrievals of atmospheric constituents and sea surface temperature.

In 1993 the National Oceanic and Atmospheric Administration/Environmental Technology Laboratory (NOAA/ETL) participated in the Pilot Radiation Observation Experiment (PROBE) in Kavieng, Papua New Guinea. During that experiment, we measured infrared spectral radiances during clear and cloudy conditions, with only a small number of clear-sky spectra for a single location [*Westwater et al.,* 1994, 1995]. Significant spectral differences were observed between those measurements and the CKD_1 continuum model [*Clough et al.,* 1989] used in the LBLRTM radiative transfer program [*Clough,* 1995]. As a consequence of these measurements, a new continuum model was developed. Here we show that new data from the tropical Pacific validate the new CKD_2.2 water vapor continuum model. Residuals are of the order of the uncertainty of the measurements, especially of the atmospheric water vapor and temperature profiles.

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Radiance Measurements

We deployed a Fourier transform infrared (FTIR) spectroradiometer on the NOAA R/V *Discoverer* in the tropical Pacific during early 1996. The experiment objectives included testing the CKD_2.2 water vapor continuum model with an improved instrument and over an extended region of the tropical Pacific. As indicated in Figure 1, the ship left Pago Pago, American Samoa, on March 15, 1996, and sailed northwest to 2° south latitude, continuing west until arriving at the island of Manus, Papua New Guinea, on March 23, where it remained until April 2 (solid line, Figure 1). The ship then sailed back along the 2°S transect (dashed line, Figure l), eventually turning northeast and arriving in Honolulu, Hawaii, on April 13. During this time, the FTIR system operated continuously, except during brief periods of rain.

The instrument is based on a Bomem Michelson interferometer with 1 cm^{-1} spectral resolution over a range of 500 to 2000 cm^{-1} [*Shaw et al.,* 1995]. The instrument is operated with a l-cm optical path difference and a Hanning window apodization function. When viewing the atmosphere, it looks vertically with a field of view of 35 mrad. It is calibrated with a linear extrapolation of two commercial blackbody-simulation targets. For this cruise the calibration target temperatures were 28°C and 55°C. The typical measurement sequence is to view one calibration target for 32 scans of the interferometer (about 3 min), view the atmosphere for 32 scans, and then view the

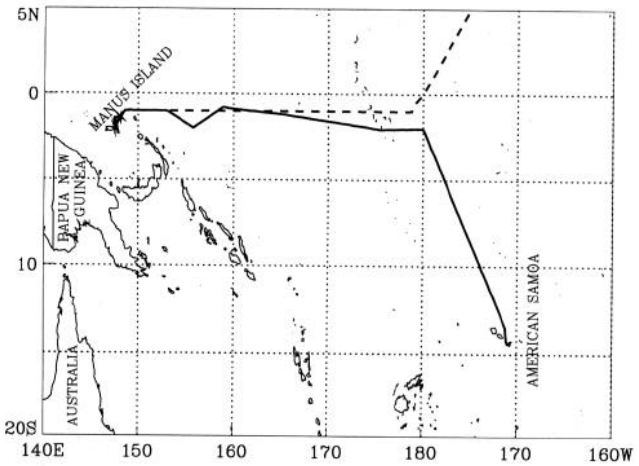

Figure 1. Route taken by the National Oceanic and Atmospheric Administration *(NOAA)* R/V *Discoverer* during the CSP cruise in March and April 1996. The solid line shows the route from American Samoa to Papua New Guinea, while the dashed line indicates the route taken from Papua New Guinea to Honolulu, Hawaii, the cruise ending point.

other calibration target for 32 scans, then back to the atmosphere, and so on. Calibration spectra from just before and just after each atmospheric observation are used to calibrate the atmospheric emission spectra. The FTIR is mounted inside an environmentally controlled container, looking through an infrared window at the calibration and beam-steering optics. The optics and calibration sources are mounted in an external container that is protected from the weather and carefully monitored but not environmentally controlled, other than having dry air fed into it continually to reduce the adverse effects of high humidity and sea salt on the optics. The data set we collected during this cruise contains more than 400 clear-sky spectra, with integrated water vapor contents ranging from nearly 3 to greater than 6 cm.

We estimate the accuracy of the FTIR radiance measurements to be within 1% of the background blackbody radiance. Simultaneous measurements from our FTIR and a similar FTIR operated on the *Discoverer* by the University of Wisconsin agree within this 1% during the times considered here, adding confidence to this estimate. Clearly, however, other factors can affect comparisons of FTIR measurements and radiative transfer calculations. Spatial and temporal differences, especially on a moving ship, can become significant. Therefore for this paper we have chosen two periods for which the FTIR spectra were measured during the beginning of a radiosonde ascent.

Atmospheric Profiles

The radiative transfer calculations are based on water vapor and temperature profiles measured by radiosondes launched from the ship. The radiosondes were of the cross-chain Loran atmospheric sounding system (CLASS). The spectra discussed here were taken under clear-sky conditions within 4 min of the radiosonde launch. For the two spectra considered in this paper, the integrated water vapor contents, measured by a collocated two-channel microwave radiometer [*Snider et al.,* 1995], were 5.7 and 4.8 cm. The integrated water vapor from the radiosonde profiles agree within 2 mm of these values. The time required for the radiosonde to ascend to a height of 3 km is about 16 min. In that amount of time for the two cases considered here, variations in the window brightness temperature seen by the FTIR were of the order of 1 K.

Radiosonde profiles of atmospheric state variables provide the largest uncertainties in this analysis. There is no reliable way of assessing the absolute accuracy of individual radiosonde profiles, so we instead investigated the residuals that arise from typical radiosonde errors. An increase in the window brightness temperatures by about 1 K results from either adding 1% relative humidity to the radiosonde profile or distributing a 1 mm total vapor increase through adjusting the radiosonde vapor density profile by a constant factor. Similarly, adding 1°C to the radiosonde temperature profile while maintaining the relative humidity unchanged increases the window brightness temperatures by about 4 K, and adding 1°C to the profile while maintaining water vapor density unchanged increases the window brightness temperatures by about 0.5 K. Additional differences due to spatial or temporal sampling likely exist also.

Comparison of Measured and Calculated Spectral Radiances

For radiative transfer calculations we used the LBLRTM line-by-line code [*Clough,* 1995; *Clough et al.,* 1992] with the CKD_1 and CKD_2.2 water vapor continuum models. The CKD_2.2 model includes a modification based on our measurements from Kavieng, Papua New Guinea. Here we demonstrate the general validity of the continuum model improvement by showing that the modified codes agree much more closely with the new measurements than they did prior to the continuum correction.

Figure 2 is a typical clear-sky radiance measurement, taken at 2214 UTC, March 27, 1996, from the NOAA R/V *Discoverer,* shown on the top in radiance units and on the bottom in brightness temperature. Note that the level of the continuum radiation in the window region between about 800 and 1200 cm^{-1} is high in the tropics due to the large water vapor content. Figure 3 shows the brightness-temperature difference (measurement minus calculation) for the LBLRTM code with the CKD_1 (Figure 3a) and the CKD_2.2 (Figure 3b) continuum models. There is clearly significantly improved compari-

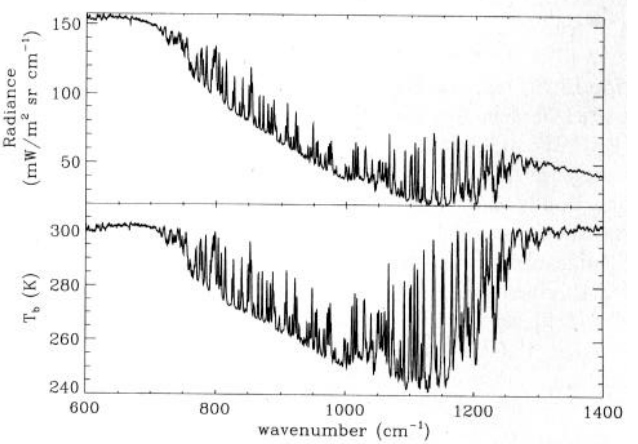

Figure 2. (a) A typical clear-sky radiance and (b) brightness-temperature spectrum measured on the NOAA R/V *Discoverer,* March 27, 1996, at 2214 UTC. The precipitable water vapor was 5.7 cm.

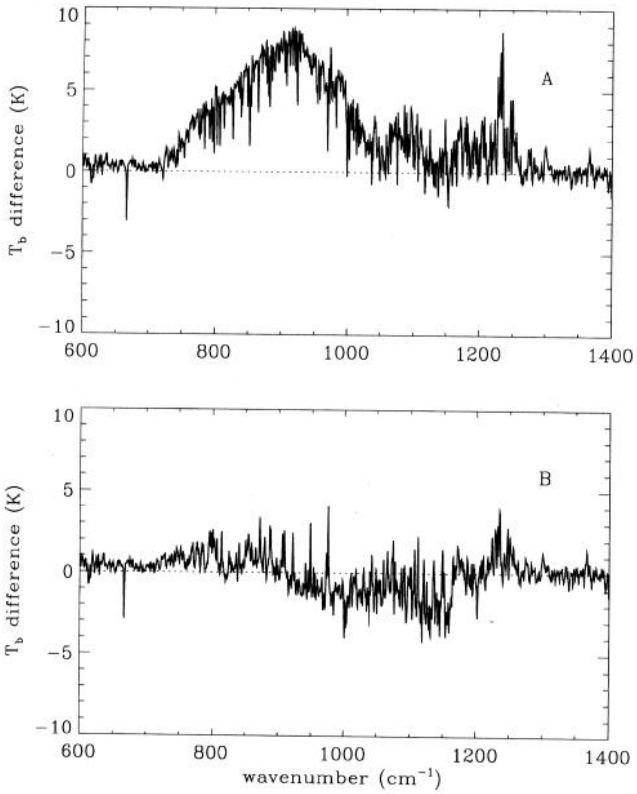

Figure 3. Brightness temperature difference (measurement minus calculation) for the spectrum in Figure 2, using LBLRTM with the CKD_1 (a) and CKD_2.2 (b) water vapor continuum models. The calculation uses atmospheric water vapor and temperature profiles from a radiosonde launched from the ship at 2218 UTC.

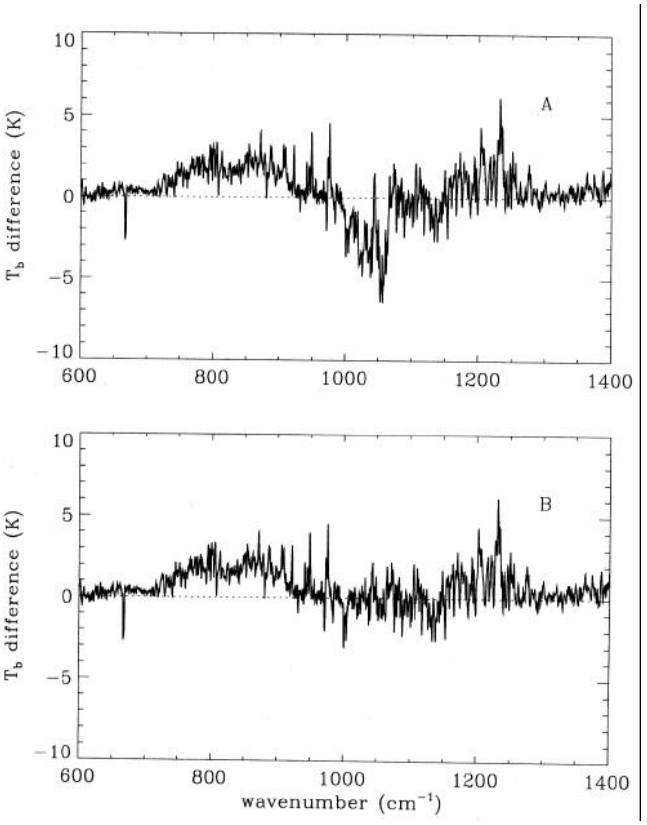

Figure 4. Brightness-temperature (T_b) difference (measurement minus calculation) for a measurement at 2213 UTC, April 4, 1996 (radiosonde at 2210), using LBLRTM with the CKD_2.2 water vapor continuum model. The precipitable water vapor was 4.8 cm. (a) Calculation using the default ozone profile, shown as the solid line in Figure 5; (b) calculation using an adjusted ozone profile shown as the dashed line in Figure 5.

son with the new continuum model. The residuals shown in Figure 3b are mostly less than 3 K. Typical radiosonde uncertainties alone could account for these differences, especially with the expected temporal and spatial sampling differences encountered on a moving ship. It is also important to note that these residuals are similar to those being found in a similar comparison that is ongoing at the Department of Energy Atmospheric Radiation Measurements (ARMs) Southern Great Plains site in Oklahoma; that is, the residuals do not appear to vary significantly for measurements throughout the large measurement region encountered during the CSP cruise, or for measurements made in a midlatitude central United States location.

We find that there is some variation in the ozone profile required to achieve good agreement between measurements and calculations in the 1043 cm^{-1} region. We adjusted the default ozone profile below 35 km by a factor that minimized the difference between the measurements and the calculations. The factor was calculated as factor $= 1/\{1 + \alpha[(35 - z)/35]^2\}$, where $0 < z < 35$ km and the α is a parameter. Figure 4 shows the brightness-temperature difference (measurement minus calculation) for a measurement at 2213 UTC, April 4, 1996, and a radiosonde launched at 2210 UTC. Figure 4a is the difference of measurement minus calculation for the default ozone profile, shown as the solid line in Figure 5, and Figure 4b is the difference for the adjusted ozone profile ($\alpha = 2.0$) shown as the dashed line in Figure 5. The intermediate line (dashed-dotted) in Figure 5 indicates the ozone profile used for the comparison in Figure 3 (with $\alpha = 0.7$). This underscores the need for more complete and accurate measurements of the atmospheric constituents in comparisons with measured and calculated spectral radiances.

Finally, we present a brief comparison with the popular

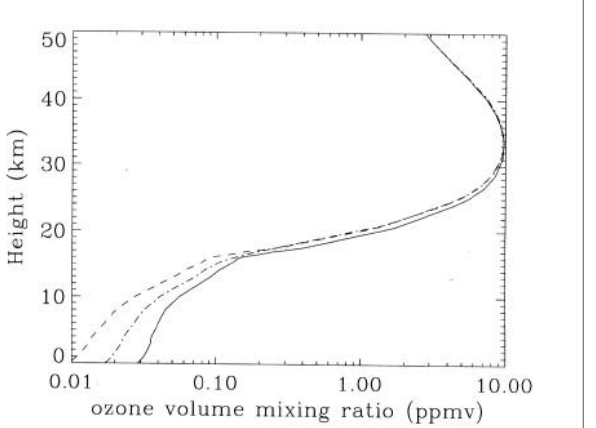

Figure 5. Ozone profiles used in calculations. The dashed-dotted line was used for the calculation in Figure 3; the solid line is the default profile used for the calculation in Figure 4a; and the dashed line is the adjusted profile used for the calculation in Figure 4b.

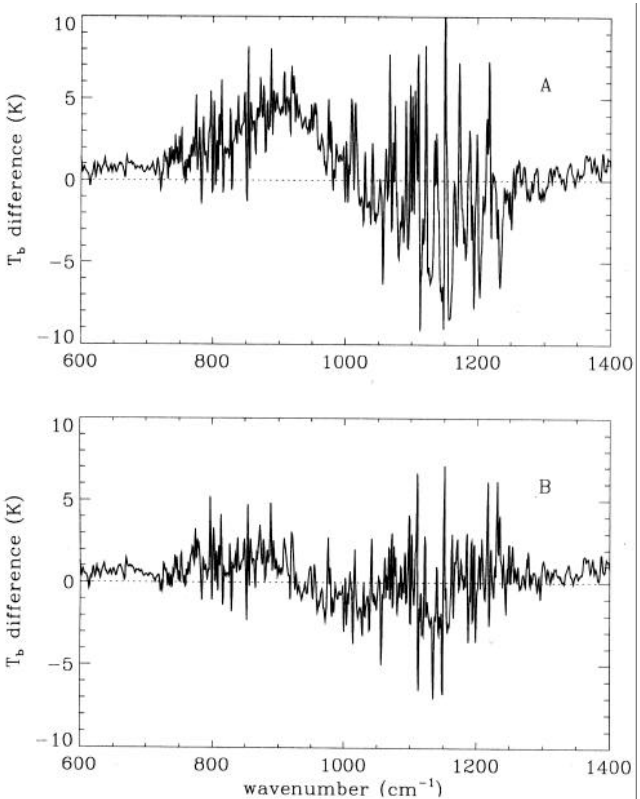

Figure 6. Difference of measurements minus MODTRAN calculations (both filtered with triangle filter to 2 cm^{-1} resolution). (a) Difference using MODTRAN2 with the CKD_1 water vapor continuum model; (b) difference using MODTRAN3 with the CKD_2.2 continuum model.

MODTRAN band-model code, which shares the same CKD_2.2 water vapor continuum as LBLRTM. Figure 6 shows brightness-temperature differences (measurement minus calculation), using the default ozone model, for MODTRAN, with a triangular filter passed over both the measurement and the calculation, thus reducing the spectral resolution to 2 cm^{-1}. Figure 6a is the difference using MODTRAN2 with the CKD_1 continuum model, and Figure 6b is the difference using MODTRAN3 with the new CKD_2.2 continuum model. Although we do not expect MODTRAN to perform as well as a line-by-line model, the comparison does demonstrate rather good performance of this model.

Conclusions

We conclude that the modified (CKD_2.2) water vapor continuum model used in the LBLRTM radiative transfer program, which includes a correction based on our earlier tropical radiance measurements, is significantly improved from the previous versions. The residual differences between measured and calculated radiance spectra are comparable to the uncertainties expected in radiosonde measurements of atmospheric constituents. This validation of the continuum-model improvement is important because the new FTIR data were taken with an improved system under much more reliably clear-sky conditions than the previous data on which the continuum correction is based. Furthermore, this new data set covers a much larger geographic range throughout the tropical Pacific than the original data set, and the residuals we find are similar to those resulting from studies in the central United States. We are currently working on further refinements, including investigating aerosol influences, with these new data.

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