Comparison of Boundary-Layer Temperature Retrievals from a FTIR and a 5-mm Microwave Radiometer During the 1997 Water Vapor Intensive Observation Period

Y. Han and E. R. Westwater
Cooperative Institute for Research in Environmental Sciences
University of Colorado
NOAA-Environmental Technology Laboratory
Boulder, Colorado

J. A. Shaw and J. H. Churnside
NOAA-Environmental Technology Laboratory
Boulder, Colorado

Introduction

During both the 1996 and the 1997 Water Vapor Intensive Observation Periods (WVIOPs), the National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL) operated a scanning 5-mm wavelength radiometer to determine low-altitude temperature profiles. During WVIOP'96, a radiometer was leased from the Lebedev Physical Institute of the Russian Academy of Sciences; during WVIOP'97, ETL operated its own radiometer that was constructed during 1997. The new radiometer was constructed with a design similar to that of the earlier Russian version (Trokhimovski et al. 1998; Westwater et al. 1998a). Earlier results had indicated that the scanning radiometer could derive temperature profiles from the surface to 300 m with an accuracy of 1 °C root mean square (rms), with a vertical resolution of better than 50 m, and with a temporal resolution of 10 min. (Westwater et al. 1997).

ETL also constructed a Fourier transform infrared spectroradiometer (FTIR) (Shaw et al. 1995) that was originally operated during the Spectral Radiance Experiment (SPECTRE), in Coffeyville, Kansas, in 1991, and later, during the Atmospheric Radiation Measurement (ARM)-sponsored Pilot Radiation Observation Experiment (PROBE) in Papua, New Guinea in 1993 (Westwater et al. 1994). Most recently, it was operated on the NOAA R/V Discoverer in the tropical Pacific in early 1996 (Han et al. 1997) where there was close agreement during SPECTRA with those measured by an atmospheric emitted radiance interferometer (AERI). Because of the implementation and evaluation of the AERI retrievals at the Southern Great Plains (SGP), it was of interest to compare the NOAA/FTIR temperature profiles with those derived from our 5-mm radiometer data; the instruments were collocated and operated from the same seatainer. On the longer term, we plan to compare results with AERI retrievals from the University of Wisconsin, as well as our own retrievals of precipitable water vapor from ETL's dual-channel microwave radiometer that operated at 20.6 GHz and 31.65 GHz (Westwater et al. 1998b).

Instruments

5-mm Scanning Radiometer

The 5-mm (60-GHz) radiometer (Westwater 1998a) is designed for precise, continuous measurements of air-water temperature difference and for recovery of air temperature profiles (height from 0 m to 300 m). The main idea of the technique is to measure oceanic and atmospheric emission in a wavelength band that exhibits relatively high atmospheric absorption. Near the peak of the 5-mm O_2 oxygen band, an optical depth of unity is reached over a horizontal distance of ~300 m. In this case, we use the radiation in the horizontal direction as a reference level (height = h_R), because the brightness temperature, T_b, in this direction is nearly equal to the air temperature at h_R. Radiometric measurements are made in a scanning mode, and the radiometer measures T_b relative to the air temperature T at h_R. The scan rate of the radiometer is 1.3 Hz and we usually average the data to 10-min. intervals.

Fourier Transform Infrared Spectro-Radiometer

Our FTIR is an instrument similar to the AERI of the University of Wisconsin. It is based on a Bomem Michelson interferometer with a 1 cm^{-1} spectral resolution over a range of 500 cm^{-1} to 2000 cm^{-1}. The instrument is operated with a 1-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. Here, the calibration target temperatures were 30 °C and 55 °C. The temporal resolution was about 6 min. for calibrated atmospheric radiance spectra.

Brightness Temperature Data

Examples of measured data from the FTIR and from the 5-mm radiometer are shown in Figure 1 for a linear "lapse" profile and a profile with a temperature inversion. In the spectral region used for temperature recovery by the FTIR, roughly 625 cm^{-1} to 725 cm^{-1}, note the change in spectral shape between the two types of profiles. Similarly, there is a completely different angular shape for the 5-mm radiometer in the two cases. Physically, channels with weighting functions close to the surface see warmer temperatures during lapse conditions and colder temperatures during inversions.

Retrieval Method and Accuracy Estimates

Temperature profiles are derived from both the 5-mm radiometer and the FTIR from measurements of T_b. However, as shown in Figure 1, T_b's from the microwave radiometer are an angular spectrum while those from the FTIR are a frequency (or wave number) spectrum. For the 5-mm radiometer, the information on profile structure is contained in the slant path measurements because the radiometer "sees" different portions of the atmosphere with different elevation angles. Temperature weighting functions for this radiometer are given by Trokhimovski et al. (1998). For the FTIR retrievals, information comes from the differences in optical depths sensed by the different frequencies in the FTIR spectra (see Han and Westwater 1994 for

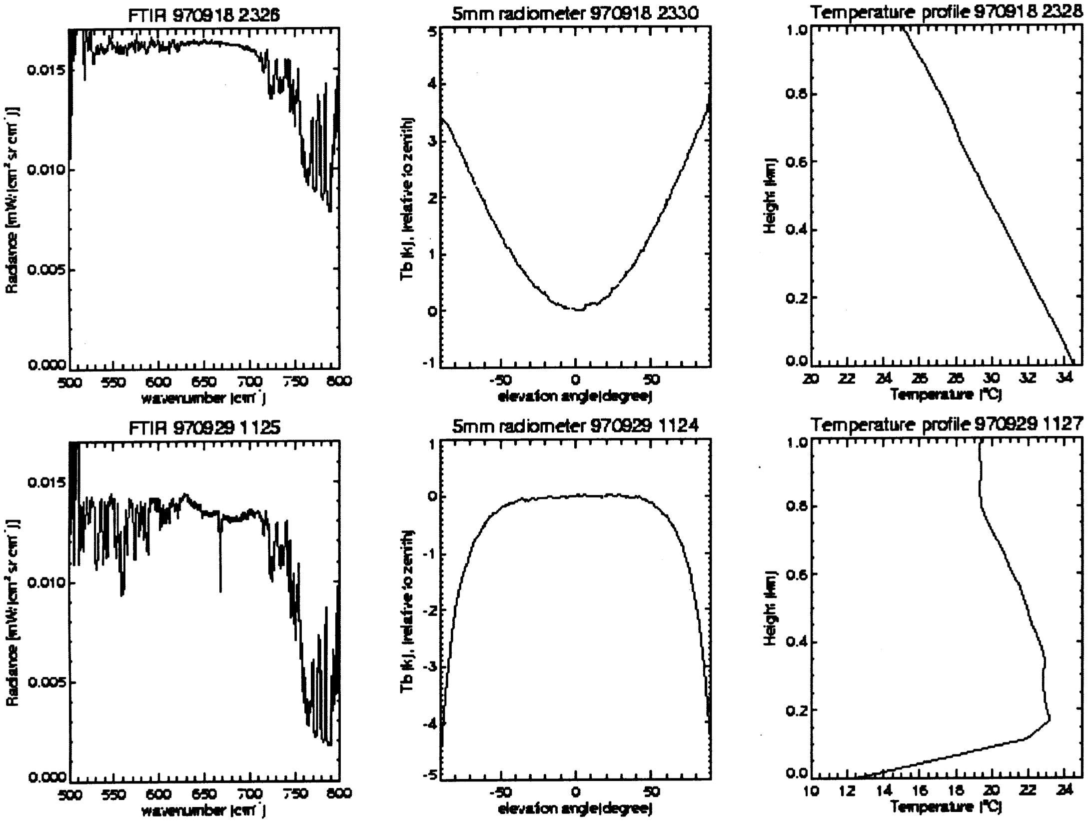

Figure 1. Measured wave-number spectra from the FTIR, angular spectra from the scanning 5-mm radiometer, and associated temperature profiles measured by the Balloon Borne Sounding System (BBSS). The upper three plots show results during a lapse rate profile; the lower three from a temperature inversion. Data were taken during WVIOP'97 at the SGP CART site.

FTIR weighting functions). To derive a temperature profile, we first project the T_b angular or frequency spectra on a set of empirical orthogonal functions (EOFs; five were used here) and then use the set of projected values and an in situ surface temperature measurement as components of a data vector used in linear statistical inversion. Using our method, the accuracy in retrieval depends on the instrument(s)' accuracy, the measurement ordinates of T_b, and the representativeness of the EOFs. Accuracy estimates of the two techniques, for the climatology of the SGP Cloud and Radiation Testbed (CART) site in September and October, as a function of assumed measurement noise levels, are shown in Figure 2. For the achievable noise level of 0.5 K, the accuracies of the two systems are similar.

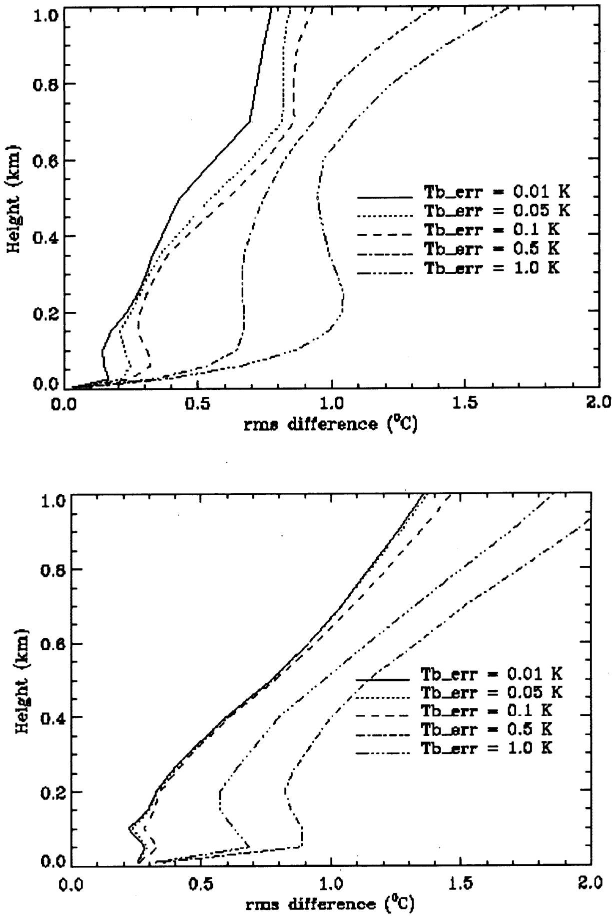

Figure 2. Theoretical accuracies in retrieving temperature profiles from measurements with the indicated T_b accuracies. Upper figure—scanning 5-mm radiometer; lower figure—FTIR. These simulations were based on data climatologically similar to those of the SGP CART site.

Retrieval Results

Typical results from the two systems are shown in Figure 3, in which temperature retrievals are shown roughly every hour; 3-hourly radiosonde measurements are also indicated. We note the evolution from an established temperature inversion (16:24 CDT) through its decay (starting at 8:54 CDT) and its re-establishment (starting at 18:54 CDT). We also note the apparent problem with the radiosonde at 6:24 CDT.

Conclusions

Both theoretical and achieved results indicate that either the scanning radiometer or the FTIR can retrieve boundary-layer temperatures up to 300 m with an rms accuracy of about 0.5 K and a vertical resolution of about 50 m. Above 300 m the accuracy degrades to about 1 K rms. We first investigated retrievals using a Line By Line Radiative Transfer Model (LBLRTM) (Clough et al. 1992) to generate retrieval coefficients for our FTIR, which is very computer-intensive; to speed up these calculations we also investigated use of MODTRAN3. However, the accuracy of the forward model calculations using MODTRAN3 was not sufficient to reproduce the accuracy achieved by using LBLRTM.

We intend to compare our retrievals, both from our scanning 5-mm radiometer and FTIR with those achieved by AERI. However, at present, minor differences exist between our methodologies: we need to use exactly the same frequency bands as AERI in the retrievals and, in addition, we need to use the same method for obtaining surface temperature. AERI uses a combination of very strong absorption lines, while we used surface values obtained from CART in situ sensors. After a coincidence of measurement ordinates is achieved, a meaningful statistical comparison can be obtained.

References

Clough, S. A, M. J. Iacono, and J.-L. Moncet, 1992: Line-by-line calculation of atmospheric fluxes and cooling rates: Application to water vapor. *J. Geophys. Res.*, **97**, 15,761-15,785.

Han, Y., J. A. Shaw, J. H. Churnside, P. D. Brown, and S. A. Clough, 1997: Infrared spectral radiance measurements in the tropical Pacific Ocean. *J. Geophys. Res.,* **102**, 4353-4356.

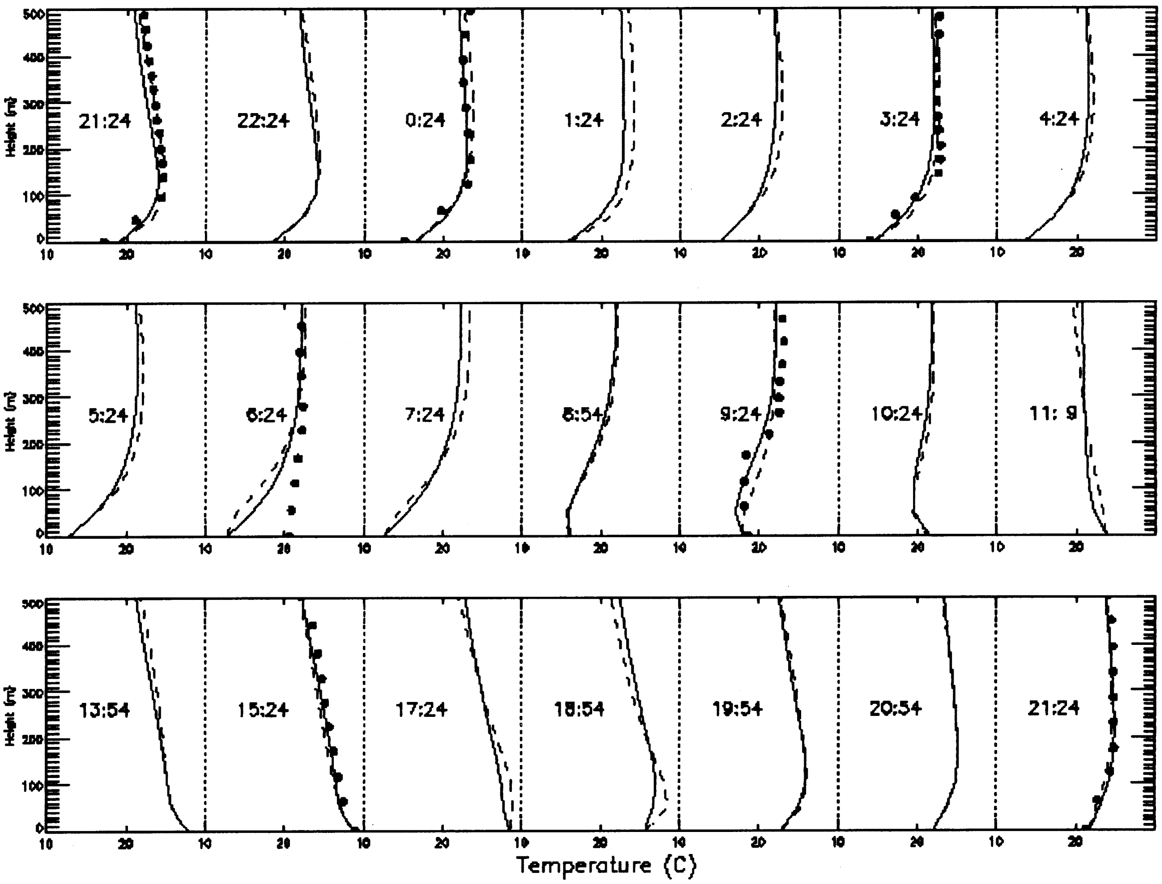

Figure 3. Temperature retrievals from the scanning 5-mm radiometer (solid line), the FTIR (dashed line), and the BBSS (solid circles) at the WVIOP'97. Times are CDT on September 30 and October 1, 1997.

Han, Y., and E. R. Westwater, 1994: Remote sensing of water vapor by combined infrared and microwave radiometry. Preprints, 5th Conf. on Global Change Studies, Nashville, Tennessee, Jan. 23-28, 1994, Amer. Meteor. Soc, pp. 221-226.

Shaw, J. A., J. B. Snider, J. H. Churnside, and M. D. Jacobson, 1995: Comparison of infrared atmospheric brightness temperatures measured by a Fourier transform spectrometer and filter radiometer. *J. Atmos. Ocean. Technol.,* **12(5)**, 1124-1128.

Trokhimovski, Y. G., E. R. Westwater, Y. Han, and V. Ye. Leuskiy, 1998: The results of air and sea surface temperature measurements using a 60 GHz microwave rotating radiometer. *IEEE TGARS*, **36**, 3-15.

Westwater, E. R., J. B. Snider, J. Churnside, and J. A. Shaw, 1994: Ground-based microwave and infrared radiance observations during PROBE. Preprints, 8th Conf. on Atmospheric Radiation, Nashville, Tennessee, Jan. 23-28, 1994, Amer. Meteor. Soc, pp. 272 - 275.

Westwater, E. R., Y. Han, V. Leuskiy, V. Irisov, E. Kadygrov, and S. A. Vaizankin, 1998: Multi-sensor measurements of boundary-layer temperature profiles. In *Proceedings of the Seventh Atmospheric Radiation Measurement (ARM) Science Team Meeting,* CONF-970365. U.S. Department of Energy.

Westwater, E. R., Y. Han, V. G. Irisov, V. Ye. Leuskiy, Yu. G. Trokhimovski, C. W. Fairall, and A. Jessup, 1998a: Sea-air and boundary layer temperatures measured by a scanning 5-mm wavelength (60 GHz) radiometer: Recent results. *Radio Sci*, **33**, 291-302.

Westwater, E. R., Y. Han, S. I. Gutman, and D. E. Wolfe, 1998b: Remote sensing of total precipitable water vapor by microwave radiometers and GPS during the 1997 Water Vapor Intensive Operating Period. Proc. IGARSS'98 6-19 July, 1998, Seattle, Washington, in press.