Multi-Sensor Measurements of Boundary Layer Temperature Profiles

E. R. Westwater, Y. Han, V. Leuskiy and V. Irisov
CIRES, University of Colorado/
NOAA, Environmental Technology Laboratory
Boulder, Colorado

E. Kadygrov and S. A. Viazankin
Central Aerological Observatory
Microwave Remote Sensing Laboratory
Moscow, Russia

Introduction

Remote sensing of low-altitude temperature profiles is important for a variety of studies, including air pollution, air/sea interaction, and short-term meteorological forecasting. A recently developed radiometric technique shows promise for routine unattended sensing of profiles during non-precipitating conditions; two versions of the technique were evaluated. The first uses a commercially available discrete-scanning single frequency 5-mm (60-GHz) microwave radiometer to measure temperature and temperature gradient profiles (Troitsky et al. 1993; Kadygrov et al. 1997). The second uses a continuously scanning radiometer with a receiver similar to that of the first (Trokhimovski et al. 1997). These radiometers have a wide bandwidth (4 GHz) and excellent sensitivity (0.03 K rms @ 1 s). Typically, profiles are produced every 15 min.

During November 1996 to January 1997, several remote sensing and in situ measurements were operated at the Boulder Atmospheric Observatory (BAO). The BAO has an instrumented 300-m tower with 5-min measurements of temperature and relative humidity available at the surface and at altitudes of 10, 50, 100, 200, and 300 m. The tower measurements were occasionally supplemented with radiosonde releases and with hand-held meteorological measurements taken on the tower elevator. In addition to the elevator, the tower also has a carriage that is moveable from the bottom to the top of the tower. In the first month of the experiment, both the scanning radiometer operated by the Russian firm ATTEX, in cooperation with the Central Aerological Observatory, and the one operated by the Environmental Technology Laboratory (ETL) were operated at about the same altitude (10 m). The ETL radiometer was suspended from the carriage on a boom at the 10-m tower level, while the ATTEX radiometer was located on a trailer about 25 m away. Finally, a 915-MHZ Radio Acoustic Sounding System (RASS) was operated about 1 km from the tower (reflections from the tower preclude closer deployment). During the second month of the experiment, the ETL 5-mm radiometer was raised to the 300-m level and operated viewing both up and down.

Data from both the ATTEX and the ETL radiometers were used to derive temperatures at the tower levels so that they could be compared directly with the in situ measurements. The ATTEX radiometric system had its own calibration reference, consisting of an in situ measurement of temperature at the height of the radiometer. This reference therefore constrained the brightness temperature in the horizontal direction to be equal to the reference temperature. The ETL system did not have an associated in situ measurement; therefore, with the radiometer mounted at the 10-m tower level, we used the tower temperature measurement as the horizontal reference. In anticipated deployments in the North Slope of Alaska, in situ temperature measurements will also be available and could be used as a reference.

Two profile retrieval algorithms were used to derive profiles from the 5-mm radiometer brightness temperature data. The first, used on the ATTEX radiometer data, was a variation of the Twomey-Tikonhov retrieval algorithm (Twomey 1977). The second, used on the ETL data, used a variation of linear statistical retrieval (Westwater 1993) that derives lapse rate profiles from a projection of angular brightness temperatures on a set of empirical orthogonal functions (Westwater et al. 1997). A complete analysis, in which various retrieval algorithms are tested on our entire data set, is planned.

Results

Time-Height Cross Sections

One of the advantages of the 5-mm radiometric data is continuity in time, which allows time series and time-height cross sections to be derived. We show, in Figures 1 and 2, examples of time-height cross-sections taken during periods of substantial change in the temperature profiles. Figure 1 shows a 10-day segment of data taken during the transition between warm and cold conditions. The lower cross-sections were obtained from BAO tower data (0 - 300 m) and the upper from the ATTEX radiometer (0 - 300 m); local time (MST) is used. We note a good qualitative agreement between the two data sets, each of which portrays the evolution of the atmospheric boundary layer. From January 4 to 5, 1997, a cold air mass moved into the Rocky Mountain Region and the resulting surface temperature at the BAO changed from 7° to - 9° C. The cold air reached a minimum temperature on January 7, and then a sharp transition to a warm regime occurred about 12 pm on that day. Warm temperatures then persisted for the next 3 days. As is seen, the tower and radiometer data agree in their depiction of the variable temperature structure. Figure 2 shows a 6-day cross-section taken by the ETL radiometer during which there were again substantial changes in the temperature structure. As in the previous figure, the tower and radiometer data are in excellent agreement.

Time Series

Figures 3 and 4 show time series of temperature at the 200-m level for the two systems. In Figure 3, ATTEX, BAO, and RASS temperatures are shown. The 915-MHZ RASS system has range gates centered at 135, 195, 255, and 315 m, each with a vertical resolution of 60 m; for our comparisons we interpolated these data to tower levels. From Figure 3, it is seen that all of the data follow each other closely, with the largest differences associated with the RASS system. Note

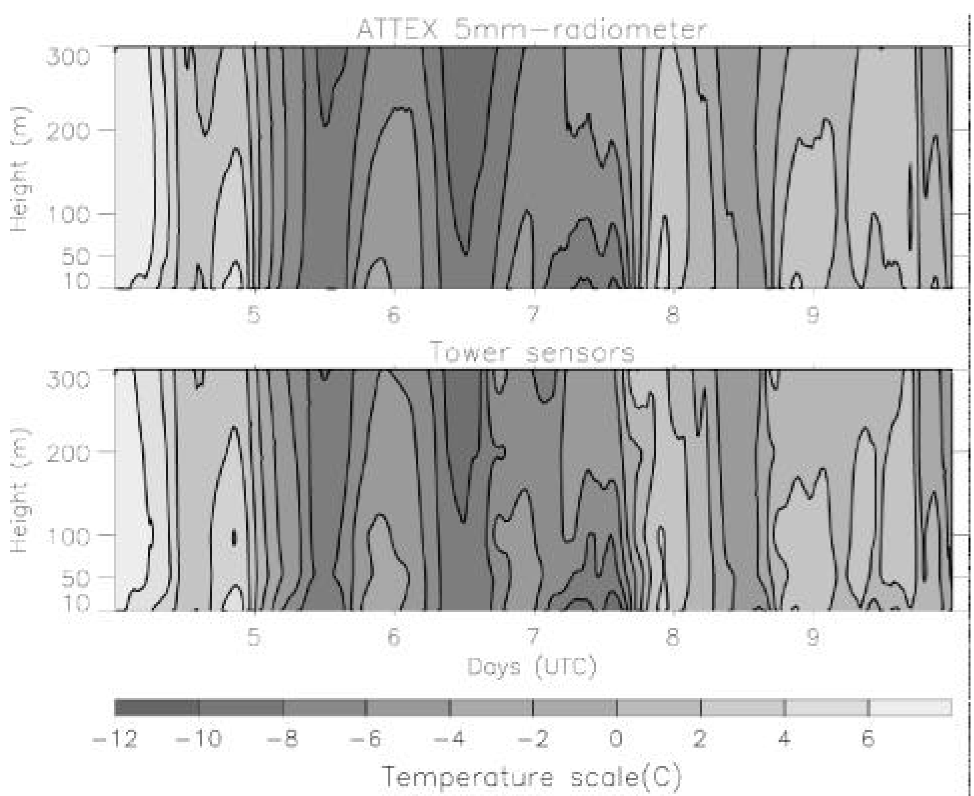

Figure 1. Temperature time-height cross sections derived from ATTEX radiometer (top curve) and in situ sensors on BAO 300-m tower (bottom curve). January 4-10, 1997.

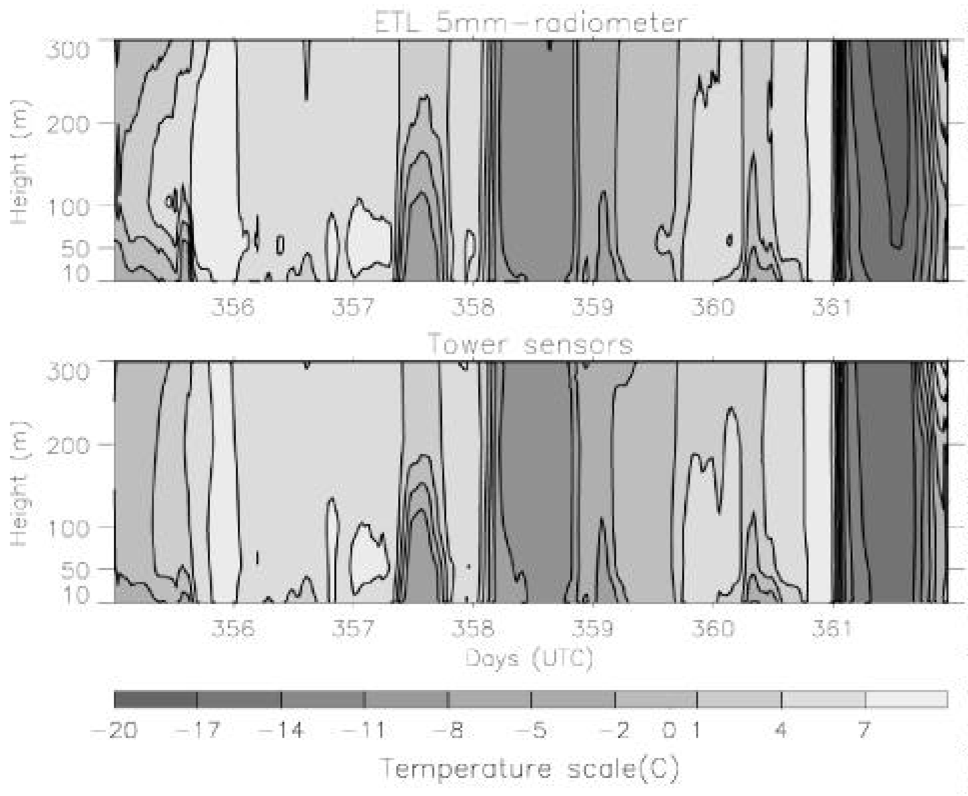

Figure 2. Temperature time-height cross sections derived from ETL radiometer (top curve) and in situ sensors on BAO 300-m tower (bottom curve). December 20-27, 1997.

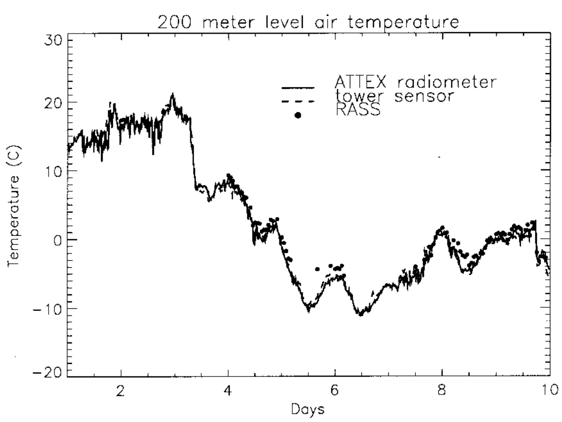

Figure 3. A 10-day time series of temperature at 200 m as measured by the ATTEX radiometer, by the in situ measurement on the tower, and by RASS. January 1 to 10, 1997.

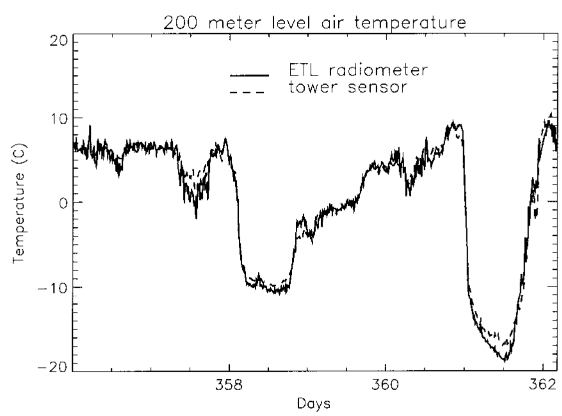

Figure 4. A 6-day time series of temperature at 200 m as measured by the ETL radiometer and by the in situ measurement on the tower. December 21 to December 27, 1996.

the roughly 30° C range in temperatures during this 10-day time period and the rapid drop in temperature during January 3. In Figure 4, we show a 6-day comparison of the ETL and the tower measurement. Again, over a 30° C range in temperatures and very sharp temporal changes in temperature, the radiometer and in situ sensor track each other to within about 2° C.

Statistical Comparisons

We prepared scatter plots and regression statistics for ATTEX and ETL radiometers vs. the in situ tower data. Due to a problem that developed with the 300-m level on the tower, this level was excluded from analysis, although we are trying to identify periods in which these data are valid. In Figures 5 and 6, we show scatter plots from the two systems. We note that to within an rms difference of 0.1° C, the two radiometric systems performed essentially the same, and gave rms differences of about 1° C. We summarize the statistical results in Tables 1 and 2.

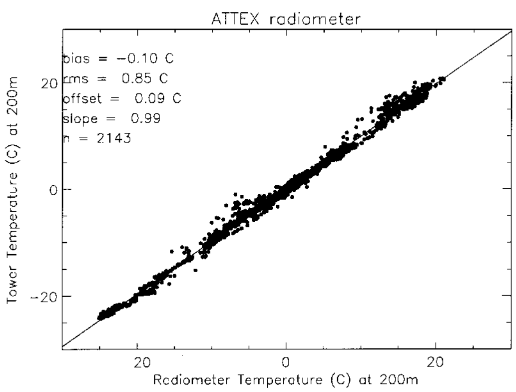

Figure 5. Scatter plot of ATTEX vs BAO tower measurements at 200 m.

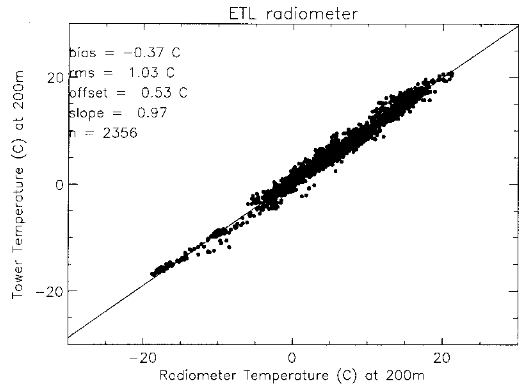

Figure 6. Scatter plots of the ETL vs BAO tower measurements at 200 m. The ETL instrument derived relative temperatures and used the 10-m tower level as a reference.

Summary and Conclusions

In anticipation of potential deployment of scanning 5-mm radiometers in arctic conditions, we tested two instruments during winter conditions at the BAO's 300-m meteorological tower. Both the ATTEX and ETL radiometers compared well with in situ tower measurements during atmospheric conditions that exhibited a substantial amount of temperature variability. Several major snowstorms occurred as well; no impact on the radiometric measurements was seen. Statistical comparisons of radiometric retrievals with tower measurement yielded rms differences of about 1 K. Comparison of carefully edited 915-MHZ RASS data indicated similar agreement. In anticipation of aircraft deployment of the scanning radiometer, the ETL radiometer was deployed at the 300-m level for one month of the 2-month experiment. The analysis of these data, as well as comparing the results of different profile retrieval algorithms, is continuing.

Table 1. Statistical comparisons of ATTEX and BAO Tower temperature measurements in ° C.

Tower Level (m)	rms	Bias	Slope	Intercept	Sample size
10	0.89	0.28	1.00	-0.29	2143
50	0.85	-0.23	0.99	0.23	2143
100	0.93	-0.31	0.98	0.30	2143
200	0.85	-0.10	0.99	0.09	2143

Table 2. Statistical comparisons between ETL and BAO Tower temperature measurements in ° C.

Tower Level (m)	rms	Bias	Slope	Intercept	Sample size
10	0.00	0.00	1.00	0.00	2356
50	1.04	0.07	0.95	0.26	2356
100	1.17	-0.57	0.97	0.72	2356
200	1.03	-0.37	0.97	0.53	2356

References

Kadygrov, E., B. Zak, K. Stamnes, J. Simmons, and R. Storvold, 1997: A microwave temperature profiler and a tethersonde: a comparative study in interior Alaska. (This Proceedings)

Troitsky, A. V., K. P. Gaikovich, V. D. Gromov, E. N. Kadygrov, and A. S. Kosov, 1993: Thermal sounding of the atmospheric boundary layer in the oxygen band center at 60 GHz . *IEEE Trans. Geosci. Remote Sens.*, vol. 31, no. 1, pp. 116-120.

Trokhimovski, Yu. G., E. R. Westwater, Y. Han, and V. Ye. Leuskiy, 1997: Air and sea surface temperature measurements using a 60 GHz microwave rotating radiometer. *IEEE Trans. Geosci. Remote Sens*. (in press).

Twomey, S., 1977: *Introduction to the Mathematics of Inversion in Remote Sensing and Indirect Measurements*. Elsevier, New York, 243 pp.

Westwater, E. R., 1993: Ground-based microwave remote sensing of meteorological variables. In *Atmospheric Remote Sensing by Microwave Radiometry*, J. Wiley & Sons., Inc., Michael A. Janssen, ed., Chapter 4, pp. 145-213.

Westwater, E. R., Y. Han, V. G. Irisov, V. Ye. Leuskiy, Yu G. Trokhimovski, and C. W. Fairall, 1997: Air-sea and boundary-layer temperatures measured by a scanning 60-GHz radiometer: Recent results (submitted to *Radio Sci*.).