Evaluation of a Scanning 5-mm Radiometer for Obtaining Air-Sea Temperature Difference and Low-Level Atmospheric Stability

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Introduction

Several papers have reported the importance of stability and air-sea temperature difference in determining the signatures of signals either scattered or emitted from the ocean surface. In addition, the air-sea temperature difference is an important factor in determining the transport from the surface to the atmosphere. Conventionally, the air-sea temperature difference has been obtained by two separate instruments: one measuring the sea surface temperature (SST), and the other measuring that of the air. Measurements of the SST can either be made by "bulk" methods, in which the temperature is measured from roughly 1 cm to several meters below the surface, or by infrared (IR) measurements of the so-called "skin" temperature (Wick et al. 1996). As Wick et al. pointed out, there can be a considerable difference between the two. The skin temperature is important for determining transport into the atmosphere since the surface is in direct contact with the air. Air temperature is measured by an in situ sensor, usually placed about 10 m above the surface. However, whether bulk or IR measurements are used, the air-sea temperature is determined by measurements from two sensors, each independently calibrated. The scanning 5-mm-wavelength radiometer that we describe below determines this temperature difference by relative measurements from the same instrument.

In atmospheric studies, low-level temperature gradients are also important to meteorology and air pollution studies. The gradients can be determined from radiosondes, released on a twice-daily basis at National Weather Service field office locations, or those released on an episodic basis for research purposes. In addition, several locations have instrumented towers, such as the Boulder Atmospheric Observatory near Erie, Colorado, which has a 300-m tower, or the U.S. Department of Energy's Cloud and Radiation Testbed (CART) site near Lamont, Oklahoma, which has a 60-m tower that is instrumented at two levels. Clearly, a small, easily deployable remote sensor, especially a passive one, could play an important role in boundary-layer studies.

In this paper, we describe the deployment of a 5-mm scanning radiometer in two completely different field experiments: one devoted to ocean studies; the other to studies of water vapor in the atmosphere. However, the experiments had one thing in common: excellent sources of ground truth were available.

Description of 5-mm Scanning Radiometer

The 5-mm (60 GHz) radiometer is designed for precise, continuous measurements of air-water temperature difference and for recovery of air temperature profiles (height from 0 to 300 m) and was built by the Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia. The main idea of the technique is to measure oceanic and atmospheric emission in a wavelength band that exhibits relatively high atmospheric attenuation. In this case, the radiation in the horizontal direction can be used as a reference level since the brightness temperature is nearly equal to the air temperature at the measurement height. Radiometric measurements are made in a scanning mode, and the radiometer measures brightness temperature relative to the air temperature. The radiometer is a total power system with automatic compensation of the direct current in the output signal (a compensation-type radiometer). No additional modulation, except for the antenna beam rotation, is done in the radiometer. The scanning mirror of the radiometer rotates at 1.3 Hz. Details of the radiometer are given by Trokhimovski et al. (1997) and by Westwater et al. (1997).

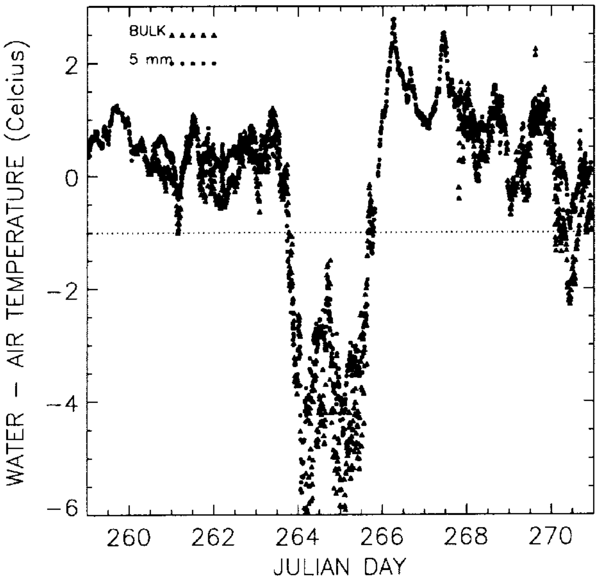

Figure 1. Time series of water-air temperature difference as measured by the scanning 5-mm radiometer and by bulk methods. The data were obtained during the COPE experiment in September and October 1995.

Results from COPE

During September and October 1995, the Environmental Technology Laboratory(ETL) organized the Coastal Oceans Probing Experiment (COPE) off the Oregon coast. The principal objectives of the study were to observe the signatures of the ocean surface with radars, lidars, and radiometers and to correlate these signatures with in situ measurements. The in situ observations were primarily taken from the Floating Instrument Platform (FLIP), a research vessel operated by the Scripps Institute of Oceanography, and are summarized in Westwater et al. (1997). The data are 10-min averages. The 5-mm radiometer was mounted on the port boom at a distance of about 10 m from FLIP's main structure. The altitude of the radiometer relative to the water surface was about 6 m. On the same boom were located the flux packages of ETL.

Preliminary retrievals of air-water temperature were based on the brightness temperature measurements at angles of 48° - 57° from nadir and with an averaging time of 12 min. A time series of retrieved sea-air temperature difference, $\Delta T = T_{sea} - T_{air}$, is shown in Figure 1. Also shown is the corresponding temperature difference obtained by the bulk method. It is obvious from the figure that at least a qualitative agreement exists between the datasets. During COPE, both stable (air warmer than water) and unstable (air colder than water) conditions were encountered; e.g., the data roughly between Julian days 264 and 266 are stable. This change was associated with winds coming from off the Oregon coast.

To evaluate the accuracy, or at least the precision, of our measurements, we prepared scatterplots between the 5-mm data and ΔT as derived from both the bulk and the IR methods. These scatterplots, as well as the regression lines of best fit, are shown in Figure 2. The regression fits were done using an algorithm that assumes that both variables are in error. We note that substantially better agreement is achieved between the 5-mm and the IR methods of determining ΔT. This is probably expected, since both the 5-mm and the IR radiometers measure T_{sea} in the first few millimeters (or less) of the ocean surface, i.e., the "skin layer."

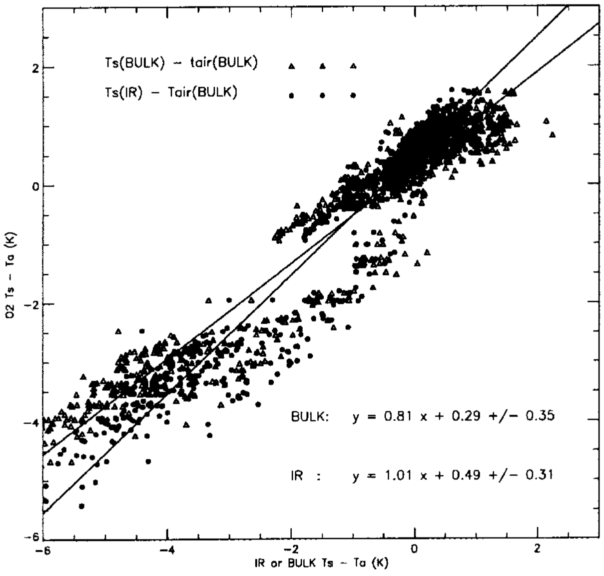

Figure 2. Scatterplots and regression lines of Ts - Ta (water-air temperature difference) as measured by the scanning 5-mm radiometer and by bulk and IR methods. The data were obtained during the COPE experiment in September and October 1995.

The skin depth of the 5-mm measurements is about 0.3 mm, and that of the IR data is about 10 µm. We note that the slope of the regression line is close to unity for 5-mm and IR measurements, with an offset of about 0.5° C. The corresponding slope and offset for 5-mm and bulk measurements is 0.81 and 0.3°C. As discussed by Westwater et al. (1997), these differences are entirely due to T_{sea} differences.

Results from the SGP CART Site

During September 10 - 30, 1996, an Intensive Operating Period (IOP) was conducted at the Southern Great Plains (SGP) CART site. The IOP, although focused primarily on measurements of water vapor, also provided an excellent set of data for temperature. We operated the scanning 5-mm radiometer on the top of a seatainer (3 m above ground level [AGL]) that housed an ETL water vapor radiometer. The radiometer was deployed at the top northeast edge of the seatainer and scanned in the east-west direction; a complete 360° scan was performed. Data obtained during the upper portion of the scan were used to derive temperature gradients; observations during the lower portions of the scan viewed a shallow valley containing grass to the east and a plowed field to the west. At times, nonsymmetric scan patterns were suggestive of differences in solar heating on the two different surfaces.

Ground truth for the radiometer was obtained from two sources: 3-hourly radiosonde releases from a location about 200 m to the north of the radiometer and from tower measurements (about 40 m to the south) of temperature. The tower contained instruments at 25 and 60 m AGL. The tower was about the same altitude as the radiometer, and both were about 4 m higher than the radiosonde release site (the standard meteorological shelter was at 2 m AGL). Thus when making comparisons between air temperature measurements, and using the CART surface meteorological station as a reference, relative altitudes are 5 m for the 5-mm radiometer and 27 and 62 m for the tower.

Figure 3 shows time series plots of retrieved, tower, and radiosonde values of ΔT for the two tower levels. Here, we selected the west scan, since this direction was closest to the tower. In general, the correspondence between all measurement is reasonable, considering the spatial differences between the sensors. In Figure 3, there is closer agreement between the radiometer and the radiosonde than with the tower. We think that the relatively small differences that do occur are the result of spatial inhomogeneity in the temperature field.

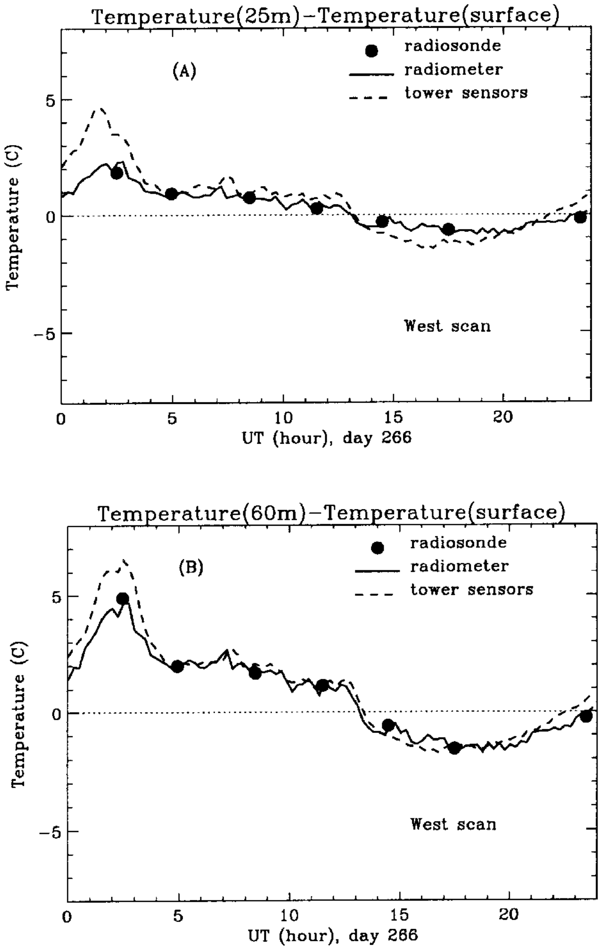

Figure 3. Time series of air temperature gradients measured by three sensors during September 1996 (Julian day 266) at the SGP CART site. (a) 25-m level; (b) 60-m level.

We also computed statistics between the radiometer and the tower for both the east and the west scan; in Figure 4, the results at 60 m are shown. Here we see substantial differences between the scans during the day. Remembering that the west scan is closest to the tower, and that substantial differences between surface heating occur during the day, the results are quite suggestive that lack of horizontal stratification is a major reason for the radiometer and tower differences. We consider the rms differences of about 0.7 K, achieved on the west scan, to be somewhat greater than the inherent instrumental accuracy.

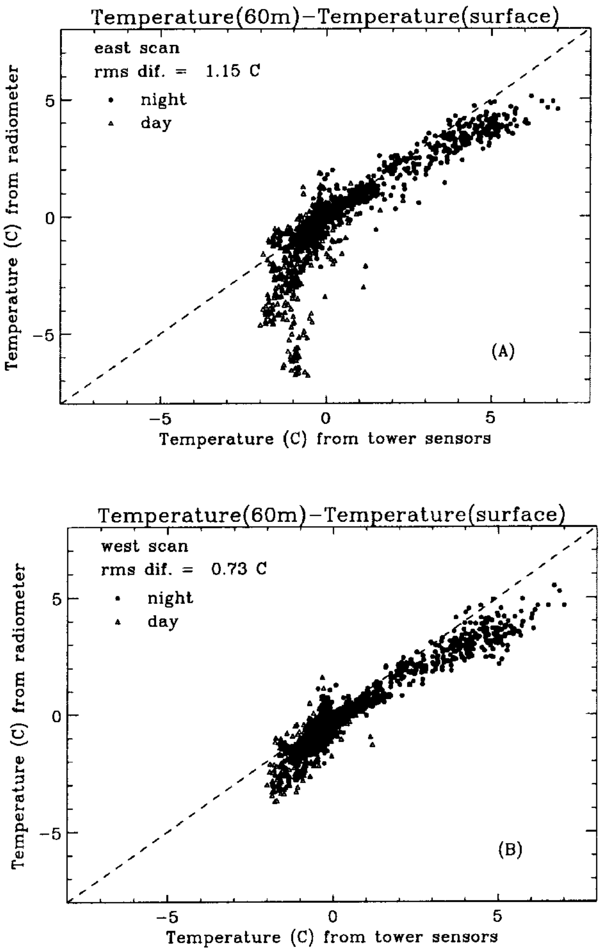

Figure 4. Scatterplots of temperature difference between 60 m and the surface as derived from the 5-mm radiometer and the tower sensors. (a) east scan of radiometer; (b) west scan of radiometer. The data were taken during September 1996 at the SGP CART site.

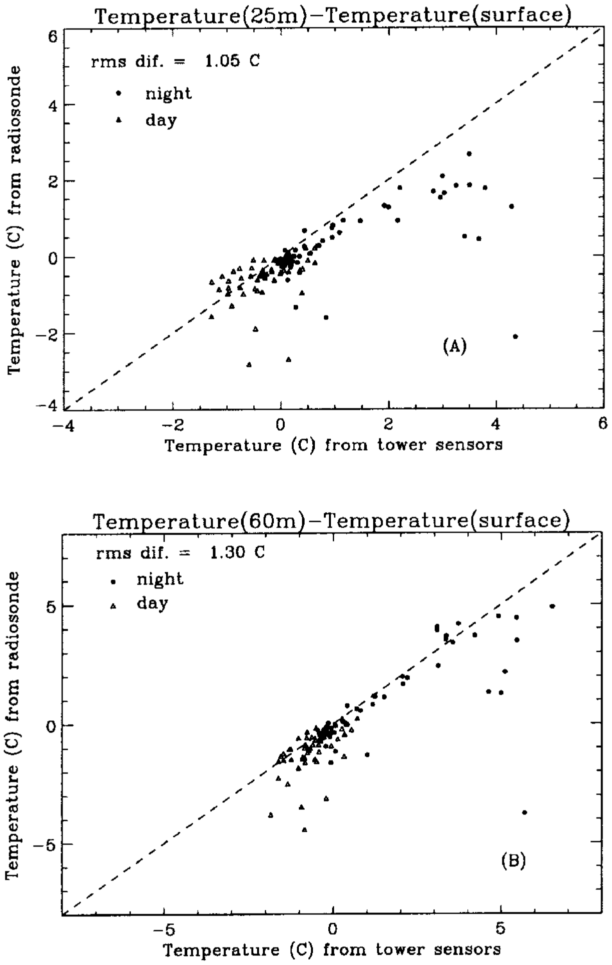

Figure 5. Scatterplots of temperature difference between 25 m and the surface and between 60 m and the surface as derived from radiosondes and the tower sensors. (a) 25-m level; (b) 60-m level. The data were taken during September 1996 at the SGP CART site.

These results become even more impressive if radiosonde and tower measurements are compared. In Figure 5, both the ΔT between 25 m and the surface and the ΔT between 60 m and the surface are compared for the radiosonde and the tower. In both cases, the root mean square (rms) differences are substantially poorer than those between the radiometer and the tower.

Summary and Conclusions

We evaluated the performance of a rapidly scanning 5-mm-band radiometer in two widely different environments. In the first, we compared radiometric soundings of air-sea temperature difference with in situ ground truth measurements that were available on FLIP. Here, we showed excellent agreement between the radiometric retrievals and data derived from IR measurements of SST and thermistor measurements of air temperature. We also showed that there were substantial differences between bulk (floating thermistor) and IR measurements of SST. These are not inaccuracies of the separate sensors, but reflected the difference between bulk and skin temperatures. The 5-mm radiometer, because of its simplicity and ruggedness, could be a useful addition to oceanographic research measurements.

In the second environment, that of the SGP CART site, excellent agreement (rms differences of 0.7 K) was found between the radiometer and measurements at 25- and 60-m levels of a meteorological tower. The agreement with the tower was substantially better than that with nearby radiosondes. It was found that substantial differences existed between temperatures derived from scans to the west and those to the east. Thus, some information on horizontal thermal gradients is also available from this instrument. The instrument could be easily deployed for air pollution studies and in environments where knowledge of low-altitude temperature gradients is important. Since the deployment of towers is difficult, and radiosondes may not always yield reliable measurements in the first few tens of meters, we suggest that this instrument could be a useful research and monitoring tool.

References

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