Recent Progress in Retrieving Air Temperature Profiles and Air-Sea Temperature Differences from Infrared and Microwave Scanning Radiometer Data

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Introduction

A system of two scanning radiometers has been developed by National Oceanic and Atmospheric Administration (NOAA) Environmental Technology Laboratory (ETL) and deployed on the NOAA Ron H. Brown (RHB) Research Vessel (RV) during the Nauru99 cruise in the Tropical Western Pacific, in June/July 1999. Measurements were taken in a vertically scanning mode, sounding radiation intensity at different elevation angles. In a full scanning cycle, we sequentially measured natural emission intensity from the atmosphere (upward looking) and from the ocean (downward looking). Relative measurement of the air and sea skin temperatures is the key of the robustness of this technique. At the same time, this technique can recover boundary layer air temperature profiles and air-sea temperature differences, providing a relatively simple, yet powerful tool for marine boundary layer study. In this work, we first compare radiometric data collected during the experiment with simulations obtained by atmospheric and ocean Radiative Transfer Models (RTM). Then we use up- and down-looking measurements to retrieve air temperature profiles and air-sea temperature differences, respectively. Finally, we determine the achieved retrieval accuracy and we compare radiometric estimates with in situ measurements, discussing similarities and discrepancies.

Instrumental Set-Up

Our system is composed of two vertically scanning radiometers (SR), one operating in the microwave (MW) and the other in the infrared (IR) spectral region, and a high-quality air-temperature sensor

(Vaisala HMP 233 Met sensor). A picture and a drawing of the deployment are shown in Figure1. The MWSR was built by the Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia, while the IRSR was designed and built at NOAA/ETL (Shaw et al. 2001) and it was first deployed during this experiment. Each radiometer beam is scanned continuously in a vertical plane using a different rotating mirror, so that the radiometers measure air and sea brightness temperature at a variety of angles. A summary of the radiometers' main characteristics is shown in Table 1. Both radiometers measure emission from a uniformly mixed atmospheric gas: O2 for MWSR (60 GHz) and CO2 for IRSR (14.2 microns). The high atmospheric absorption at these frequencies allows one calibration point from the horizontal atmospheric view using the in situ temperature sensor measurements as a

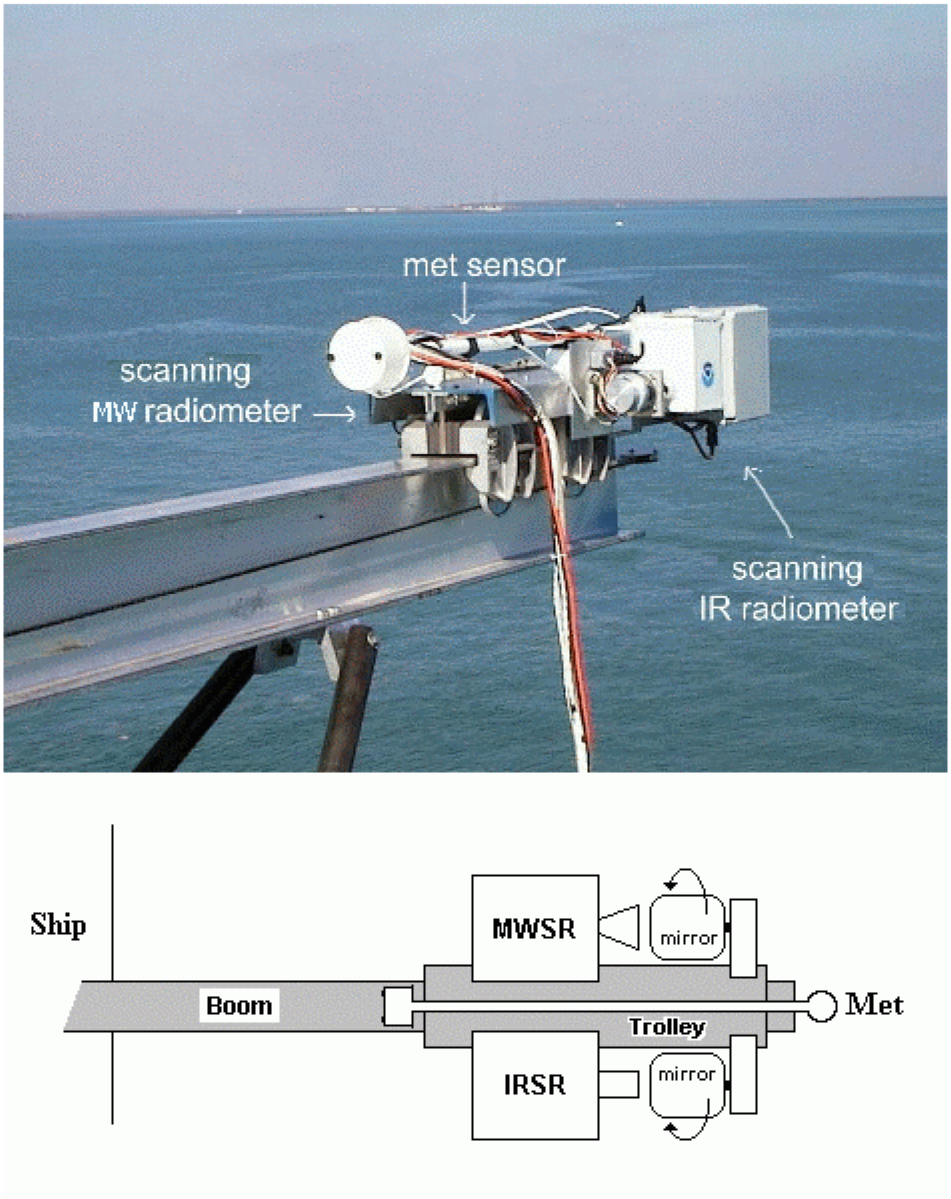

Figure 1. Picture and diagram of the SR system.

Table 1. Main characteristics of SR system.

	MWSR	IRSR
Central Line	60 GHz	14.2 mm
Band Width	4 GHz	1.1 mm
Beam Width	6°	1°
Scanning Rate	0.55 Hz	0.55 Hz
Main Emitter	O2	CO2
Sea Emissivity	0.45	0.98
Atmospheric Depth	300 m	150 m
Ocean Skin Depth	300 mm	3 mm
Polarization	V	Negligible

reference. The signal at all other scan angles is scaled relative to that at the horizontal, resulting in a differential technique that is independent from calibration offset. This technique provides continuous and accurate estimates of boundary layer air temperature profile and air-sea temperature difference. Notice that the IR SR water penetration depth is approximately two orders of magnitude smaller than for MWSR. According to theoretical computations (Trokhimovski et al. 1998), the difference between the sea surface temperature measurements from the two radiometers can be up to 0.4 K. The two scanning radiometers, together with the Met sensor, were mounted on a trolley, able to move back and forth along a boom mounted on the roof of a mobile laboratory built from a standard sea container. The boom extended 5 m beyond the port side of the RHB R/V, at a height of 10 m ASL. The current system allows a variable scan rate that has been set at the same frequency (0.55 Hz) for both the mirrors, corresponding to one scan each 1.8 seconds. No additional modulation except the antenna beam rotation was applied to the radiometers. Analyses presented in following sections were made using data with 10 minutes averaging. For such an averaging time, radiometer noise contributes only negligibly to errors of air and water temperature determination.

Retrieval Techniques

Atmospheric radiation observations from the upward-looking scan were used to estimate air temperature profiles, using a variation of linear statistical inversion. An a priori set of contemporary profiles and ground-based radiometric measurements was required. We collected a set of ship-based radiosonde observations (RAOBs), launched during Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment (1992/1993). For each of the RAOBs we computed a simulated measurement scan for the MWSR and one for the IRSR. In the MW, we used the NOAA/ETL Radiative Tranfer Equation routines with the absorption model described in (Rosenkranz 1998), while in the IR we ran MODTRAN4. Thus, we obtained an a priori dataset composed of 1455 atmospheric temperature profiles and simultaneous MWSR and IRSR simulated measurements. We next performed Empirical Orthogonal Function (EOF) decomposition and we found that to capture variations above the instrumental noise level of 0.2 K, only three EOFs were required for MWSR and four for the IRSR. From the prepared a priori data set we are also able to predict the expected retrieval error for each of the instruments: with this technique, air temperature profile retrieval accuracy is estimated to be better than 0.4 K RMS up to 500 m for the IRSR and better than 0.3 K for MWSR.

For air-sea temperature difference retrieval, we used a physical, rather than statistical, inversion method, since in contrast to air temperature profile, air-sea temperature difference retrieval is a “well-posed” problem. Theoretically, given the complete angular set of downwelling radiation, a measurement from one single downward-looking angle would provide an air-sea temperature difference estimate, but to reduce errors induced by inhomogeneity, we average the retrieval results from about ten angles. Although our inverse model accounts for sea surface roughness, we used elevation angles between 220 and 230 degrees (45 deg off nadir, ±5 deg) to minimize the uncertainty related to sea surface roughness. In the MW region, we used an approach similar to the one described in (Trokhimovski et al. 1998). In the IR region we solved the radiative transfer equation to obtain the integrated “black body” radiance emitted by the sea surface and we computed the difference between this quantity and the integral of the Planck black body function at temperature T*. The estimated sea temperature is finally computed as the value that minimizes this difference over the set of observation angles.

Observations

We collected MWSR and IRSR measurements with the same time stamp, but we calibrated and processed them independently, obtaining two completely independent retrievals.

Air Temperature Profiles

During Nauru99, balloons were launched from 4 up to 8 times per day, while scanning radiometers were working continuously. Figure2 shows an 18-day time series of air temperature retrieved from 10-min. averaged MWSR scans. In order to determine the air temperature profile retrieval accuracy, we compare radiometric estimates with in situ measurements. By considering the whole set of RAOBs launched from RHB R/V between 1999/07/03 and 1999/07/07, we can compute statistics of the overall comparison. In Figure 3, we plot the mean value (BIAS), the standard deviation (STD), and the root mean square (RMS) of the difference between radiometric estimations and in situ measurements for the whole sample. The MWSR (left panels) shows an air temperature profile retrieval accuracy comparable with the predicted error estimated from the a priori dataset. The RMS is smaller than 0.35 K up to 500 m, while the BIAS does not exceed 0.16 K. The IRSR (right panels) shows a STD profile that increases with height, reaching almost 0.6 at 500 m, which is consistent with the prediction from the a priori dataset. On the other hand, it is affected by a fairly high BIAS (up to 0.3 K). This might be related to the relatively small sample (22 cases), but also to the IRSR calibration procedures, which relies on simultaneous measurements from a fourier transform infrared radiometer interferometer.

Air-Sea Temperature Differences

In Figure4a, we show a 5-day time series of air-sea temperature difference retrieved from downward looking MWSR and IRSR scans. For the same time interval, in Figure4b, we show the interface effect, which is the difference between the radiometric skin temperature (from MWSR and IRSR) and the in situ bulk temperature measured at 5 m depth. Although there are some differences, the interface effect measured by MWSR and IRSR show a similar behavior. The main departures happen during local daytime (around midnight Universal Time Coordinates [UTC]), remaining qualitatively within the values predicted by the theory. During local nighttime (around noon UTC), the agreement is impressive.

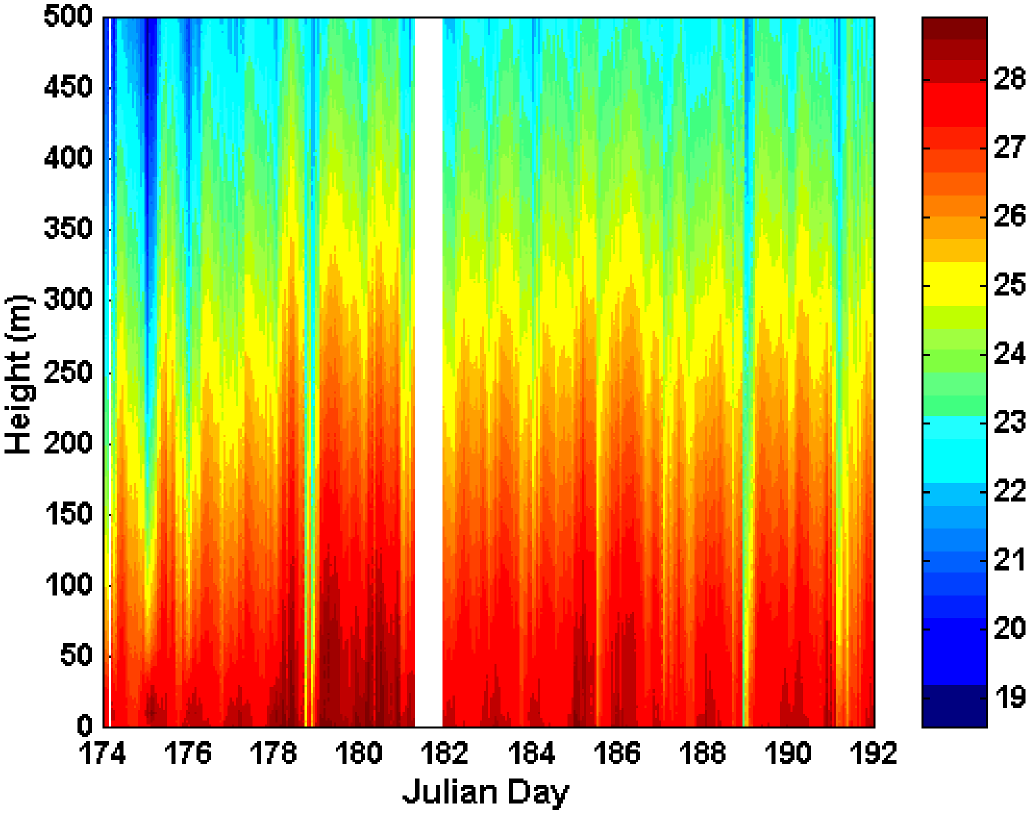

Figure 2. 18-day time series of air temperature (color scale is in °C) retrieved from 10-min. averaged MWSR scans.

For convenience, BIAS, STD, and RMS of the differences between the three independent sources (in situ, MWSR, IRSR) are summarized in Table 2. Statistics confirm that MWSR and IRSR retrievals are in good agreement during nighttime. Both of them appear to measure a sea skin colder then the bulk, with a difference ranging from 0.1 to 0.5 K, except sharp spikes. These are qualitatively and quantitatively in agreement with the theory of cooling heat flux, which predicts a cool skin during nighttime (Fairall et al. 1996; Wick et al. 1996). Comparing the radiometric estimations with each other, we obtain an RMS difference of about 0.15 K. During daytime, the situation is much different, with a BIAS and a STD between MWSR and IRSR measurements twice as large than during nighttime. The strong solar radiation causes a “warm layer” at the top of the sea, which leads to a temperature difference between the skin and the bulk (5 m depth) ranging from 0 to 3 K, depending on wind speed and solar flux. This effect has a diurnal time scale and so can compensate the cool skin during daytime (Fairall et al. 1996). Considering the total set, we obtain an RMS difference of 0.28 K.

Conclusions and Future Plans

Some adjustments could be suggested to improve the current system in future deployments. Although we believe that the overall calibration was as accurate as 0.2 K and that short time scale gain fluctuations are negligible for our averaging time interval (10 min.), it would be useful to modify the present system in order to include at least one external calibration source. The experimental set up could

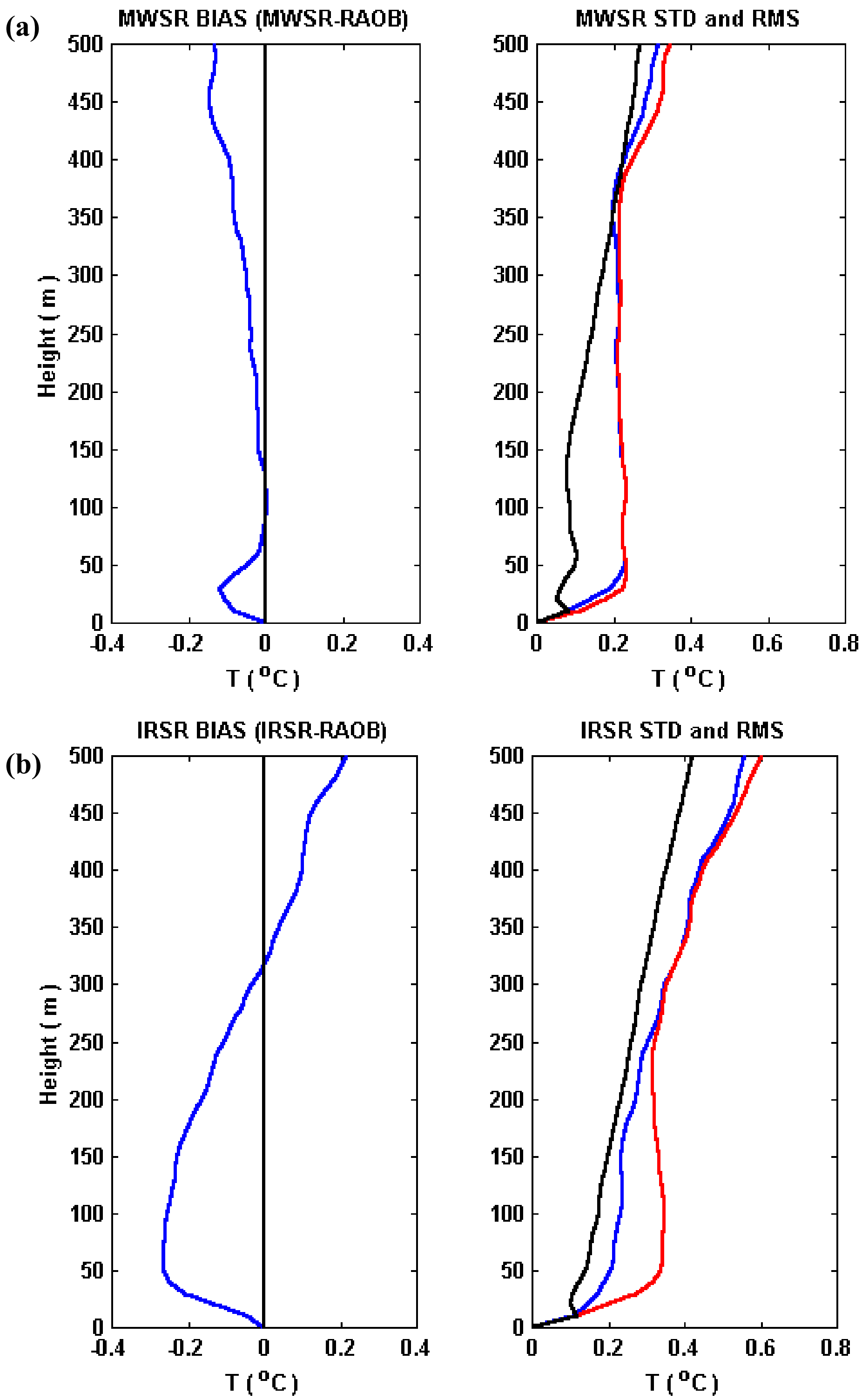

Figure 3. Statistics of the difference between air temperature profiles derived by scanning radiometers and measured by RAOBs (a: MWSR; b: IRSR). The predicted BIAS and RMS estimated from the a priori dataset are shown in black, the experimental BIAS and STD are shown in blue, while the RMS is shown in red.

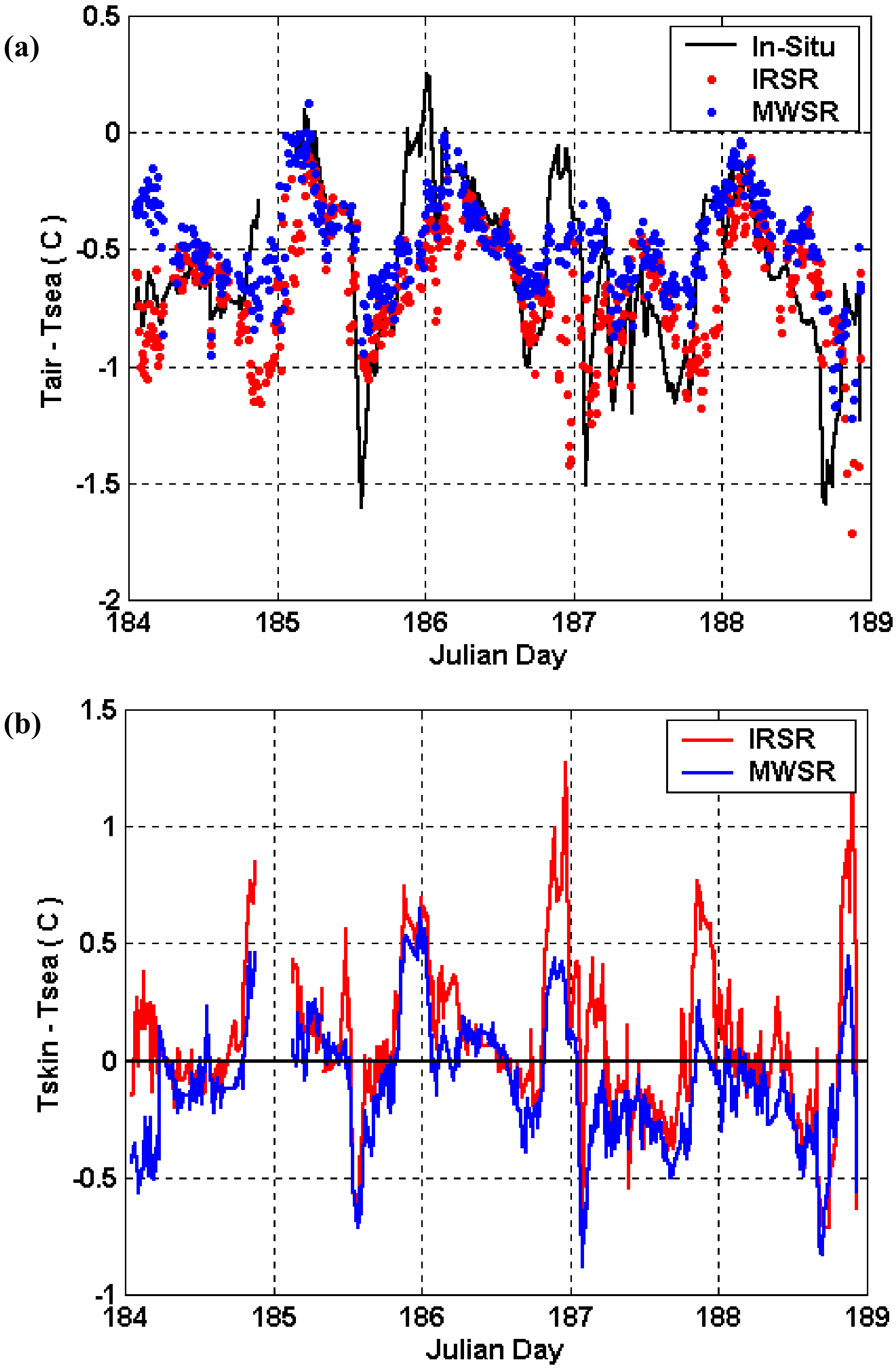

Figure 4. (a) Five-day time series of air-sea temperature difference as retrieved from MWSR (blue dots) and IRSR (red dots) downward looking scans, and as measured by in situ sensors (black line). (b) Interface effect, i.e., the difference between radiometric sensed skin temperature (blue: MWSR; red: IRSR) and in situ measured sea temperature.

Table 2. Statistics of the air-sea temperature difference (K) derived from the three independent sources (in situ, MWSR, and IRSR)

	BIAS	STD	RMS
	Total		
MWSR vs. in situ	-0.106	0.243	0.265
IRSR vs. in situ	0.071	0.309	0.317
MWSR vs. IRSR	-0.177	0.218	0.281
	Day Time		
MWSR vs. in situ	-0.029	0.277	0.279
IRSR vs. in situ	0.261	0.308	0.404
MWSR vs. IRSR	-0.291	0.237	0.376
	Night Time		
MWSR vs. in situ	-0.174	0.183	0.253
IRSR vs. in situ	-0.100	0.184	0.210
MWSR vs. IRSR	-0.074	0.131	0.151

be improved by locating the system on the ship's bow, with the boom extending forward of the bow and the radiometers scanning in a plane perpendicular to the ship direction. This would allow the radiometers to scan over undisturbed and foam-free water even if the ship is moving, unless the wind speed exceeds the breaking waves threshold or the ship speed is high enough to generate forward propagating waves. Besides this, we showed that with such an instrumental design, coupled with the appropriate inversion techniques, we achieve RMS differences better than 0.35 K for air temperature profiles up to 500 m, and about 0.28 K for air-sea temperature differences, which becomes 0.15 K for nighttime measurements. Assuming that the instrumental random errors for the MWSR, the IRSR and the in situ sensors are uncorrelated, we are able to say that the experiment achieved a RMS retrieval accuracy as low as 0.21 K for air temperature profiles up to 500 m and 0.20 for air-sea temperature differences, which becomes 0.11 K for nighttime measurements. These values validate the accuracy estimated by previous investigators (Trokhimovski et al. 1998; Shaw et al. 2001), who considered one single scanning radiometer. The nighttime values also meet the accuracy required by marine boundary layer models to study the parameterization of atmosphere-ocean interactions (Fairall et al. 1996; Wick et al. 1996).

To our knowledge, this experiment was the first comparing two independent scanning radiometers. We have demonstrated that scanning radiometry can provide accurate, continuous, simultaneous estimates of air temperature profile and air-sea temperature difference, and so we believe that scanning radiometry represents a powerful tool to study the marine boundary layer environment (Cimini et al. 2001).

Future plans rely on the advantage of this technique to allow measurements of the water skin temperature without disturbing the skin layer (magnitude orders of microns) at different optical depths (two full magnitude orders: 3 microns for IRSR and 300 microns for MWSR). It might be possible to use simultaneous MWSR and IRSR measurements to examine small-scale skin-temperature gradients, providing crucial information for air-sea interaction studies.

Acknowledgments

The work presented in this paper was sponsored by the Environmental Science Division of the Department of Energy as a part of their Atmospheric Radiation Program. Part of this work has been carried out when D. Cimini was a Ph.D. student at University of L'Aquila, Italy, under the European Social Funding Program.

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