The Miami2001 Infrared Radiometer Calibration and Intercomparison. Part II: Shipboard Results

I. J. BARTON,* P. J. MINNETT,+ K. A. MAILLET,+ C. J. DONLON,# S. J. HOOK,@ A. T. JESSUP,&
AND T. J. NIGHTINGALE**

**CSIRO Marine Research, Hobart, Tasmania, Australia*
+Division of Meteorology and Physical Oceanography, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida
#Inland and Marine Water Unit, Institute for Environment and Sustainability, European Commission Joint Research Centre, Ispra, Italy
@Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California
&Applied Physics Laboratory, University of Washington, Seattle, Washington
***Space Science and Technology Department, Rutherford Appleton Laboratory, Chilton, Didcot, Oxfordshire, United Kingdom*

(Manuscript received 27 August 2002, in final form 6 May 2003)

ABSTRACT

The second calibration and intercomparison of infrared radiometers (Miami2001) was held at the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS) during a workshop held from May to June 2001. The radiometers targeted in these two campaigns (laboratory-based and at-sea measurements) are those used to validate the skin sea surface temperatures and land surface temperatures derived from the measurements of imaging radiometers on earth observation satellites. These satellite instruments include those on currently operational satellites and others that will be launched within two years following the workshop. The experimental campaigns were completed in one week and included laboratory measurements using blackbody calibration targets characterized by the National Institute of Standards and Technology (NIST), and an intercomparison of the radiometers on a short cruise on board the R/V *F. G. Walton Smith* in Gulf Stream waters off the eastern coast of Florida. This paper reports on the results obtained from the shipborne measurements.

Seven radiometers were mounted alongside each other on the R/V *Walton Smith* for an intercomparison under seagoing conditions. The ship results confirm that all radiometers are suitable for the validation of land surface temperature, and the majority are able to provide high quality data for the more difficult validation of satellite-derived sea surface temperature, contributing less than 0.1 K to the error budget of the validation. The measurements provided by two prototype instruments developed for ship-of-opportunity use confirmed their potential to provide regular reliable data for satellite-derived SST validation. Four high quality radiometers showed agreements within 0.05 K confirming that these instruments are suitable for detailed studies of the dynamics of air–sea interaction at the ocean surface as well as providing high quality validation data. The data analysis confirms the importance of including an accurate correction for reflected sky radiance when using infrared radiometers to measure SST. The results presented here also show the value of regular intercomparisons of ground-based instruments that are to be used for the validation of satellite-derived data products—products that will be an essential component of future assessments of climate change and variability.

1. Introduction

Detailed modeling of the earth's physical environment requires accurate measurements of physical parameters both for the initialization of numerical models and as validation of their outputs. This is true for numerical models at all scales from global to local areas. For large-area and global models the grid scale is quickly decreasing as computer technology improves; global models with grid scales of 10 km or less are now common. Providing datasets on this scale is only possible with satellite measurements, and sophisticated models are relying more and more on these sources of data. Recently launched environmental and meteorological satellites, and those planned for launch in the near future, will supply regular, global measurements at scales of 1 km. These data are used to generate global datasets of vital parameters that are ideal for use with the latest numerical models. There are also many cases where these high spatial resolution data are used in environmental and commercial applications.

One of the most basic geophysical parameters is the temperature of the earth's surface over both the land and ocean. Most of the interaction between the atmosphere and the surface beneath is highly dependent on this surface temperature. Almost 20 yr ago, a World Climate Research Program (WCRP) workshop specified

Corresponding author address: Dr. P. J. Minnett, MPO Division, RSMAS, University of Miami, 4600 Rickenbacker Cswy., Miami, FL 33149-1098.
E-mail: pminnett@rsmas.miami.edu

© 2004 American Meteorological Society

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

an accuracy of 0.3 K for measurements of sea surface temperature (SST) to be useful in climate research applications (see WCRP 1984). This figure is still appropriate today, and global SST accuracies are now approaching this level (Kearns et al. 2000). However, as the instrumentation and analysis procedures are refined, achieving this goal has become a more complicated task. The effects of wind speed, surface–atmosphere heat flux, and remote measurement technique all become important in the interpretation of surface temperatures derived from satellite data (Donlon et al. 2002). Geophysical validation faces the same complications, and it is no longer possible to use a simple in situ measurement of bulk SST for accurate validation (Barton 2001; Donlon et al. 2002). For the measurement of land surface temperature, the accuracy requirement is not so demanding, but the validation is more difficult due to the heterogeneous nature of the surface, the strong variations in surface emissivity, and the large diurnal fluctuations in surface temperature.

The most accurate measurements of SST from satellites are provided by multichannel infrared radiometers on orbiting satellites. The longest and most reliable datasets have been provided by the Advanced Very High Resolution Radiometers (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) operational satellites. These instruments have provided global datasets of SST with accuracies better than 1 K but not yet at the climate-required level of 0.3 K, at least not consistently and globally (Kearns et al. 2000). Improved radiometers [the three Along-Track Scanning Radiometers (ATSR, ATSR-2, and AATSR) on European Space Agency (ESA) satellites, and the Moderate Resolution Imaging Spectroradiometers (MODISs) on *Terra* and *Aqua*] have been launched and datasets now have accuracies approaching this target. Validation of these more accurate products has required the use of shipborne radiometers to gather data collocated with the satellite measurements (Barton et al. 1995; Minnett et al. 2001). The collection of these validation data at sea is difficult and expensive, so international collaboration between the different space agencies and individual scientists is required to ensure that adequate data are available. An essential ingredient of this philosophy is to ensure that the radiometers used in the provision of validation data are accurate and reliable. One way to ensure this is for the instruments to be calibrated against a common high quality blackbody target and for the radiometers to be tested alongside each other in field conditions. These are the two components of the Miami2001 exercise.

The results of the laboratory measurements are reported on in Part I of this paper (Rice et al. 2004, this issue); here we concentrate on an analysis of the data collected by seven different radiometers during a 2-day cruise of the research catamaran R/V *F. G. Walton Smith.* The primary comparison is undertaken using the skin sea surface temperature derived from radiometer measurements of the sea brightness temperature corrected for the effect of reflected sky radiation due to the nonunity emissivity of the sea surface. This parameter should be consistent for each radiometer; measurements of the sea surface brightness temperature provided by each radiometer will be slightly different due to different view angles, spectral bandwidths, directions of view, noise levels, and digitizer characteristics. Secondary comparisons between sea and sky brightness temperatures are also described as these provide valuable insights into the performance of each radiometer as well as an improved understanding of measurement and analysis techniques.

2. Background

The first attempt to bring the international infrared radiometer community together was under a program funded through the European Commission Framework IV Program on Environment and Climate. This project was termed the Combined Action to Study the Ocean's Thermal Skin (CASOTS) and held two meetings in Europe: one in 1996 and the second during the following year (Donlon et al. 1999). The first of the CASOTS meetings did include a preliminary attempt at radiometer calibration, but only a small selection of radiometers and blackbodies were involved. However, these meetings were important in bringing the community together and were thus instrumental in leading to the two workshops that have now been held in Miami during 1998 and 2001. One other important output from CASOTS was the development of portable field blackbody calibrating units, which have been included in both the Miami workshops and were also characterized using the National Institute for Standards and Technology (NIST) Thermal-infrared Transfer Radiometer (TXR; Rice and Johnson 1998). These CASOTS calibrating units have been successfully used in several field campaigns (see Donlon et al. 1999).

The first intercomparison of infrared radiometers was held at the University of Miami's Rosenstiel School of Marine and Atmospheric Science (RSMAS) during March 1998. This involved several purpose-built radiometers and some off-the-shelf devices. NIST provided their standard blackbody target (Fowler 1995) for calibration of each radiometer. Other blackbodies available for calibration included a NIST water bath blackbody calibration target provided by the University of Washington, a smaller unit from the Jet Propulsion Laboratory (JPL), the CASOTS blackbody, and a portable unit designed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) of Australia. Since the first intercomparison several new radiometers have been constructed [e.g., the Calibrated Infrared In situ Measurement System (CIRIMS), the Infrared SST Autonomous Radiometer (ISAR-5); see Table 1] and were able to participate in Miami2001. It is important that these radiometers be calibrated against the NIST-developed

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

TABLE 1. Infrared radiometers deployed on the R/V *F.G. Walton Smith.*

Radiometer	Agency	Waveband (μm)	Detector	Sea-view angle (°)	Sky-view angle (°)
M-AERI	RSMAS	3–18	Cooled HgCdTe	55	55
ISAR-5	JRC/EEC[a]	9.6–11.5	Heitronics KT15.85D[b,c]	43	43
SISTeR	RAL/UK[d]	10.3–11.3	Pyroelectric	40, 45	40, 45
JPL NNR	NASA/JPL[e]	7.8–13.6	Thermopile	45	No sky view
CIRIMS	APL[f]	Up: 9.6–11.5; down: 7–16	Heitronics KT11.85[b]	40	40
DAR011	CSIRO	10.4–11.4	Pyroelectric	45	45 (backward)
TASCO	CSIRO	8–14	Thermopile	45	45

[a] European Commission Joint Research Centre (JRC)
[b] The Heitronics radiation pyrometer is based on a chopped pyroelectric detector.
[c] The ISAR-5 Heitronics is modified to allow the measurement of temperatures down to −100°C.
[d] Rutherford Appleton Laboratory (RAL).
[e] National Aeronautics and Space Administration (NASA).
[f] Applied Physics Laboratory (APL), University of Washington.

blackbody target as well as compared with the other radiometers. Details of the first calibration and intercomparison can be found online (http://www.rsmas.miami.edu/ir/) and in a report by Kannenberg (1998).

3. Instruments

a. Radiometers

Each of the radiometers participating in the intercomparison is briefly described below. The relevant parameters are also included in Table 1. Details of the data analysis for each instrument are included in a later section.

1) M-AERI

The Marine–Atmospheric Emitted Radiance Interferometer (M-AERI; Minnett et al. 2001) is a Fourier transform infrared (FTIR) spectroradiometer that measures spectra in the infrared ($\lambda \sim 3$ to ~ 18 μm) with a resolution of ~ 0.5 cm^{-1}. It uses two infrared detectors cooled to ~ 78 K by a Stirling-cycle mechanical cooler to reduce the noise equivalent temperature difference to levels well below 0.1 K. The radiometric calibration of the M-AERI is accomplished using two internal blackbody cavities, each with an effective emissivity of >0.998. The mirror scan sequence includes measurements of the reference cavities before and after each set of spectra from the ocean and atmosphere, which in the routine use of the M-AERI includes measurements of the sea surface, at a nadir angle of 55°, of the atmosphere at 55° to provide a correction for the reflected sky radiance in the derivation of sea surface temperature, and of the atmosphere at zenith. The absolute accuracy of the M-AERI calibration is monitored by episodic use of a NIST-certified water bath blackbody calibration target (Fowler 1995), and residual errors in the M-AERI measurements at temperatures characteristic of the sea surface are typically <0.03 K (Minnett et al. 2001). The interferometer integrates measurements over a preselected time interval, usually a few tens of seconds, to obtain a satisfactory signal-to-noise ratio, and a typical cycle of measurements, including two view angles to the atmosphere, one to the ocean, and calibration measurements, takes about 10 min. The correct combination of ocean and sky measurements results in an accurate measurement of the skin SST (Smith et al. 1996; Minnett et al. 2001).

2) ISAR-5

The Infrared SST Autonomous Radiometer (ISAR-5) provides a dedicated autonomous package developed for the validation of infrared satellite instruments. The ISAR-5 system is capable of measuring in situ sea surface skin temperature accurate to ±0.1 K rmse for deployment periods of up to 3 months. It uses two precision calibration blackbody cavities to maintain the radiance calibration of a modified Heitronics KT15.85D radiation pyrometer having a spectral window of 9.6–11.5 μm. All ISAR-5 target views are made using a single-route optical path via a protective scan drum arrangement that allows the target view to be accurately positioned over a range of 180°. The blackbody apertures are completely sealed from direct water ingress using a patent-pending shutter mechanism triggered by an optical rain sensor that completely seals the ISAR-5 from the external environment. Because a comprehensive validation of satellite skin SST and other SST data products requires a suite of specific measurements, additional ocean–atmosphere sensors can be attached, controlled, and logged via a dedicated ISAR-5 RS485 expansion port. In this way, the ISAR-5 system is designed to provide a complete infrared satellite SST product validation solution.

3) SISTeR

The Scanning Infrared Sea Surface Temperature Radiometer (SISTeR) is a compact self-calibrating filter

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

radiometer. The instrument is divided into three compartments containing, respectively, the foreoptics, the scan mirror and two reference blackbodies, and a small-format PC with signal processing and control electronics. The foreoptics and electronics compartments are waterproof and the scan mirror and blackbodies are protected with interleaved baffles. The foreoptics compartment contains a pyroelectric detector and preamplifier; a filter wheel with narrowband filters centered at 3.7, 10.8, and 12.0 μm; and a black rotating chopper, which chops the beam at 100 Hz. The detector views a 45° scan mirror via an ellipsoidal mirror and through an antireflection-coated zinc selenide window. The scan mirror can select either of the internal blackbodies or any external view in a range spanning 180° from nadir to zenith. The full cone angle of the instrumental field of view is approximately 13°.

The entire optical system is referred to the two blackbodies. One floats near the ambient temperature and the other is heated by approximately 10 K. Embedded in each blackbody is a rhodium–iron thermometer. The entire blackbody cavity can be installed in a specially constructed calibration block maintained by Oxford University. With this, the thermometers are calibrated to an accuracy of better than 4 mK relative to the 1990 International Temperature Standard (ITS-90).

All aspects of the instrument can be interrogated or controlled from a laptop computer. Typical measurement sequences contain repeated measurements of its two internal blackbodies. In addition, to calculate the skin SST, the SISTeR is programmed to make measurements both of upwelling radiances from the sea surface and complementary downwelling sky radiances. For a 1-s sample, the noise temperature at typical SSTs in the SISTeR longwave channels is less than 30 mK.

4) JPL NNR

The Jet Propulsion Laboratory (JPL) Near-Nulling Radiometer is an autonomous, self-calibrating, field-portable radiometer. Calibration is achieved with a near-nulling approach. This involves the radiometer viewing the scene and then adjusting the temperature of an accurate cone blackbody target until its radiance is very close to the scene radiance. The blackbody measurement is then used to calibrate the scene measurement. The unit is completely self-contained with its own onboard computer and memory and operates autonomously. The unit can store data on board or transfer data to an external datalogger. The external datalogger can be downloaded via cellular telephone and the unit can be reprogrammed via cellular telephone. The current design of the radiometer does not include a sky view and therefore the correction for the reflected sky radiation is made using a radiative transfer model (MODTRAN). The sensor in the optical head is a thermopile detector with a germanium lens embedded in a copper thermal reservoir. The sensor detects radiation with wavelengths between 7.8 and 13.6 μm.

5) CIRIMS

The Calibrated Infrared In situ Measurement System (CIRIMS) is an autonomous instrument with a design accuracy of ±0.1 K that can be deployed on an ocean-going vessel for a period of at least 3 months without maintenance (Jessup 2002). The normal configuration uses two Heitronics KT-11.85 radiation pyrometers with a 9.6–11.5 μm passband to simultaneously measure sea and sky radiance. The downlooking sensor is stabilized at a constant temperature and calibrated using a precision water bath blackbody that is adjusted to two points approximately ±2 K around the scene temperature. The downlooking sensor and blackbody are protected by an IR transparent window. The measurement cycle includes a method to correct for the effect of the window. The uplooking sensor is in an open housing and is uncalibrated. During the Miami2001 workshop, the normal downlooking sensor was inadvertently replaced with a version of the KT-11.85 with a spectral response of 7–16 μm, which means the sky correction necessary for the derivation of the skin SST could not be made to the accuracy that is usually achieved with radiometers with matched passbands.

6) DAR011

The DAR011 radiometer is a single-channel, self-calibrating, infrared radiometer developed specifically for the validation of satellite-derived SST measurements. The radiometer has a long heritage going back many years and is the culmination of developments leading to a reliable accurate instrument. Full details of the instrument are provided by Bennett (1998). A rotating 45° plane mirror sequentially views the sea, a hot blackbody (BB) calibration target, the sky, and finally an ambient temperature blackbody calibration target. The incoming radiation is physically chopped against a second ambient temperature blackbody and the chopped radiation is focused with a 45° parabolic front surfaced mirror onto a pyroelectric detector. Before reaching the detector the radiation passes through an interference filter that passes radiation with wavelengths between 10.5 and 11.5 μm. The temperatures of the two calibration blackbodies are accurately monitored providing good absolute radiometric accuracy.

7) TASCO

TASCO THI-500L noncontact infrared radiometers are available off the shelf and provide an economical means of remotely measuring surface temperatures. In geophysical applications the radiometers must be used with great care and require frequent calibration, but if handled correctly they can provide surface temperatures

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

TABLE 2. Surface meteorological variables measured on the R/V *F.G. Walton Smith.*

Parameter	Instrument	Accuracy
Wind speed	R. M. Young 05103 wind monitor	Speed, ±0.3 m s^{-1}; direction, ±3°
Air temperature	YSI 44018 thermistor	0.1 K
Relative humidity	Vaisala HMM20D humidity sensor	±2 K in the range of 0%–90% RH
Atmospheric pressure	Model 270 barometer	0.2 mb
Downwelling shortwave radiation	Eppley model 8-48 pyranometer (s/n 32641)	2%
Downwelling longwave radiation	Eppley model PIR pyrgeometer (s/n 32685F3)	2%

well within their quoted accuracy of ±2 K. The TASCO samples radiation with wavelengths between 8 and 12 μm with a peak response near 8.5 μm.

b. Supporting instruments

1) THERMOSALINOGRAPH (TSG)

Bulk SST and salinity were measured with a SEACAT SBE 21 thermosalinograph [Sea-Bird Electronics (SBE) s/n 2119286-2726] as part of the suite of instruments aboard the *Walton Smith.* The TSG sample interval was 12 s. The seawater intake on the *Walton Smith* is at a depth of approximately 1 m.

Salinity was calculated from the measured TSG conductivity. The SBE 21 conductivity sensor has a stated accuracy of ±0.001 S m^{-1} and stated resolution of ±0.0001 S m^{-1}.

SST was measured with an SBE 38 remote temperature sensor that has a stated accuracy of ±0.01 K and stated resolution of ±0.0003 K. A faulty remote temperature sensor resulted in no bulk SST measurements between the start of the cruise and 31 May at 0000 UTC. After the faulty sensor was replaced, bulk SST measurements were made continuously.

2) HARD-HAT THERMOMETER

Bulk SST was also measured at a depth of approximately 10 cm with a temperature probe mounted in an inverted hard-hat float. The probe is a YSI 071 deepwater probe with a YSI 44032 thermistor. The YSI 071 probes have a time constant of 5 s and an accuracy of 0.01°C over the temperature range 0°–50°C. The probe resistance is measured at 1-s intervals using an HP 34401 digital multimeter. The data are logged onto a personal computer and temperature is calculated for 10-s averages by solving the Steinhart–Hart equation. Comparison against NIST-traceable transfer standard thermometers has shown the thermistor probes to be remarkably stable with a drift of <0.01°C yr^{-1}. The hard-hat float was deployed from the ship's bow only for short periods when the ship speed was reduced to allow the float to remain upright on the sea surface and ahead of any disturbance from the vessel.

3) METEOROLOGICAL INSTRUMENTS

A suite of meteorological sensors (Table 2) provided various data throughout the cruise. All sensors were part of a Weatherpak-2000 Automatic Weather Station (Coastal Environmental Systems s/n 784). All data were logged at an interval of 20 s.

4) ATMOSPHERIC PROFILES

Six balloon-borne radiosondes were launched during the cruise to assist with possible validation of temperatures derived from the MODIS and AVHRR instruments on the *Terra* and NOAA satellites. Data from the radiosondes have not been used in this analysis.

4. Data collection

At the start of the cruise, all computer clocks were synchronized to GPS time as all subsequent comparisons use UTC time as the independent variable. During May the local sun time for the longitude of the cruise is ~5 h, 20 min later than UTC.

a. Cruise track

The ship track is shown in Fig. 1. From Miami the track was east across the Gulf Stream current between

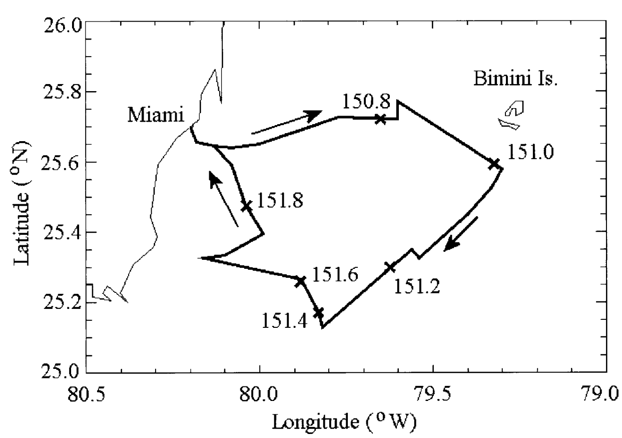

FIG. 1. The track of the R/V *Walton Smith* during the 2-day cruise. The times are day of year plus decimal days (UTC). Day 151.0 is equivalent to 2000 LT 30 May.

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

Florida and Bimini Island. From Bimini Island the track was southwest toward the coast south of Miami. Finally the track was northwest, with a westerly diversion toward the coast, to return to Miami after 32 h at sea. During the cruise the winds were light and cloud cover ranged from thin cirrus to dense stratocumulus. Unfortunately, there were no periods when entirely clear skies were present. Three times during the cruise the hard-hat thermometer was deployed, which limited the ship speed to less than 1 m s^{-1} through the water. During these periods, which can be easily identified on the ship track, the ship moved slowly northward under the influence of the Gulf Stream.

During the period 150.854–150.875 days the ship stopped to allow photography from a small vessel. At this time the wind was light, and the sea looked ''glassy''—conditions suitable for the formation of a diurnal thermocline. Comparisons of the radiometer and bulk SST data during this period may be unreliable due to disturbance of the sea surface by both the *Walton Smith* and the smaller vessel.

The weather conditions throughout the cruise were dominated by light winds and extensive cloud cover. The wind speeds were always less than 5 m s^{-1} and varied from northeasterly to southeasterly for most of the cruise except for northerlies between 0300 and 0800 local time (LT) on 31 May. The sky brightness temperatures measured by the radiometers can be used as a surrogate for cloud cover: high temperatures are associated with low, thick cloud, while low temperatures are indicative of high or thin cloud. For the entire cruise the surface air temperature and relative humidity ranged between 26° and 29°C and 65% and 90%, respectively. Full-cruise meteorological and navigation data are provided in Fig. 2.

b. Bulk SST measurements

The thermosalinograph was faulty for the first half of the cruise and data are only available from time 151.59 days (1010 LT 31 May) to the end of the cruise. Bulk SST measurements using the hard-hat thermometer were recorded during the following periods: 150.82–150.875, 151.128–151.167, and 151.30–151.61 days. During these periods the ship speed was maintained at approximately 1 m s^{-1} to provide a reliable water temperature measurement.

c. Ship deployment of radiometers

All the radiometers listed in Table 1, except the JPL nulling radiometer and the TASCO, were mounted on the port side of the bridge deck on the *Walton Smith.* The radiometers were mounted as far forward as possible with view angles between 40° and 55° from nadir ensuring that their line of sight was outside the ship's wake under normal cruise conditions. These radiometers all viewed the sea directly abeam of the ship except SISTeR, which viewed slightly forward of abeam. The JPL radiometer was mounted on the foredeck and viewed the sea surface in front of the vessel between the two hulls at a view angle of 45°. The radiometer view was thus clear of any disturbed water from the ship's two wakes. The TASCO radiometer was operated in a hand-held mode and not mounted in a fixed position on the ship. A view of the portside radiometers from the sea is shown in Fig. 3.

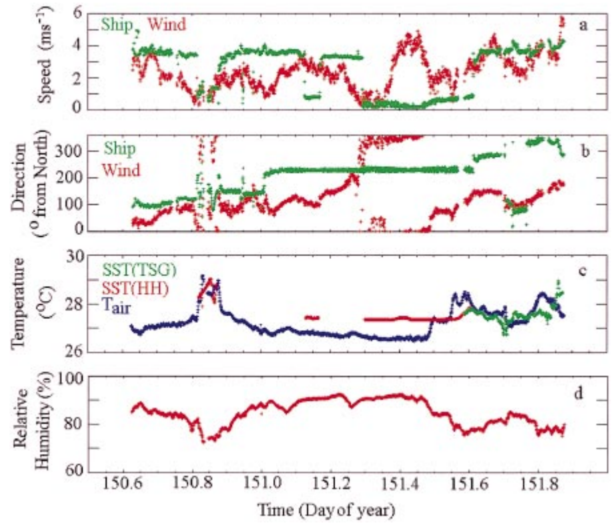

FIG. 2. Meteorological and navigation data collected throughout the cruise. (a) Ship and wind speeds, (b) ship and wind directions, (c) air and sea surface temperatures, and (d) relative humidity. In (c) SST-TSG refers to thermosalinograph measurements and SST-HH refers to those from the hard-hat thermometer.

At infrared wavelengths the emissivity of seawater is less than unity so a correction for reflected sky radiation is required to convert the sea brightness temperature to a physical temperature. To enable this correction to be applied ISAR, SISTeR, CIRIMS, and M-AERI all measured the sky brightness temperature at a zenith angle equal to the nadir angle of the sea view. For these four radiometers both the sea and sky views were made in the same azimuthal direction relative to the ship. The DAR011 radiometer also measured a sky temperature, but in this case the sky view was directly opposite to the sea view, that is, to the opposite side of the ship. The JPL radiometer has a single view direction and was pointed at the surface throughout the campaign and thus did not obtain a sky view.

d. Radiometer data collection

Data from all radiometers were recorded on dedicated computers, except for the TASCO data, which were recorded in a logbook and the JPL NNR data, which were stored on static memory within the unit and downloaded after the vessel returned to port.

The radiometer measurements and derived skin SST have been supplied by the operator of each instrument.

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

FIG. 3. The infrared radiometers mounted on the upper deck. From the left these are SISTeR, ISAR-5, CIRIMS, M-AERI, DAR011, and the hand-held TASCO. The JPL radiometer was mounted on the foredeck, viewed the sea between the two hulls of the *Walton Smith,* and is not visible in this photograph.

These data files have been collected together in a single dataset that includes data for each minute of the cruise from 1000 LT 30 May to 1700 LT 31 May (1400 UTC 30 May–2100 UTC 31 May; day 150.583–day 151.875). Where no data were available, a ''missing data'' value of zero was used. This combined file has been used for all the analyses in the following sections. For each radiometer the measurement strategy was as follows.

1) M-AERI

Sea and sky spectra are taken over an 11-min cycle and a sky correction is applied automatically. M-AERI data are thus included once every 11 min and are given for the minutes closest to the sea observation at a wavelength of 11 μm. All other minutes are set at the missing data value. The M-AERI provides a full spectrum of the radiance from both the sea and the sky, but no attempt is made to convolve these data to give a sea or sky brightness temperature. Even if this was done, the derived temperatures would not compare with other radiometers as the view angle of 55° is larger than that used by the other instruments. The sky measurement used for the sky correction is completed ~45 s after the completion of the sea view or vice versa as the sequence of mirror positions is executed in reverse order on alternate sets.

2) ISAR-5

The duty cycle is fully programmable and used the following configuration during the Miami2001 cruise: 3-min cycle consisting of 40 s at BB1, 40 s at BB2, 60 s at sea, and 40 s at sky. Sky measurements are averaged and interpolated to the sea measurements, which are then used to calculate the skin SST. These data are then averaged on to a 1-min grid. ISAR data were not recorded during the period 151.292 and 151.793 days.

3) SISTeR

The SISTeR measurement cycle contained seventy-two 0.8-s samples: 32 ocean samples at 40° or 45° from nadir; 4 sky samples each at 60°, 40°, or 45° and 0° from zenith; and 8 samples each of the hot and ambient blackbodies. The balance of the samples contained scan mirror movements. The 10.8-μm filter was used throughout. Skin SSTs were calculated for each ocean sample and subsequently binned into 2-mm intervals. Sea and sky measurements were taken at 40° from the vertical up until day 151.63 and at 45° from then on, to accommodate an increased wake from the bow of the R/V *Walton Smith.*

4) JPL NNR

A measurement was recorded approximately every 10 s and a calibration performed every 5 min.

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

5) CIRIMS

Provided a sea brightness temperature once every 6 min and a sky temperature every minute. CIRIMS used separate up- and downlooking sensors with mismatched spectral characteristics (see Table 1). This configuration made an accurate sky correction impossible and thus no sky correction or SST values are reported in this paper.

6) DAR011

This radiometer operates on a 10-min cycle with 7 min viewing the sea, and 1 min each viewing the hot blackbody calibration target, the sky, and the ambient temperature blackbody target. In all cases readings are taken once every 0.4 s and are averaged up to 1-min values. The sky radiances are interpolated with time to provide a value to be used for the sky correction of the seaview measurements.

7) TASCO

This portable hand-held radiometer was used on 24 occasions to measure the sea and sky temperatures at view angles of about 45° to the nadir and zenith, respectively.

5. Data analysis

a. Sky correction

Except for the JPL and CIRIMS radiometers the sky brightness temperature measurements made by each radiometer were used to correct the sea brightness temperatures for reflected sky radiation and thus derive skin SST estimates. The skin SST was derived using the following expression:

$$\text{Skin SST} = [T_{\text{sea}} - (1 - \varepsilon)T_{\text{sky}}]/\varepsilon, \qquad (1)$$

where T_{sea} and T_{sky} are the sea and sky brightness temperatures measured by the radiometer and ϵ is the sea surface emissivity, which is a function of emission angle and wavelength, and, for the radiometers used here, is between 0.975 and 0.995. Lambertian reflection of the sky radiation is assumed at the sea surface, which is a reasonable approximation for wind speeds less than 5 m s^{-1} as encountered in this campaign (Watts et al. 1996). The M-AERI skin SST measurements are made at a wavelength of $\sim$7.7 μm (see section 6), and the absorption and emission of the atmospheric layer between the sea surface and the height of the instrument are corrected using a parameterization based on radiative transfer simulations as a function of the local air temperature and humidity (Smith et al. 1996).

Since the JPL NNR does not make a direct measurement of the sky, the contribution from the sky was determined using a radiative transfer code, MODTRAN 3.5. The code was driven using the default tropical profile included with the code. The JPL NNR is typically used for validation of satellite temperature data over a high-altitude freshwater lake (e.g., Lake Tahoe, 1895 m MSL). The use of model-derived values for sky correction is appropriate over this target where the range in clear-sky atmospheric conditions, in particular, total column water, is far less than is encountered over the world's oceans.

b. Full cruise data comparison

The 1-min measurements and retrievals of skin SST were used for the main data analysis. The data for the entire cruise are shown in Fig. 4.

The measurements taken on the R/V *Walton Smith* for the entire cruise that are shown in Fig. 4 indicate that the SST ranged between 26.5° and 29.0°C. The radiometric sky brightness temperatures (BTs) ranged between 260 K when high or thin cloud was present to 290 K when low and thick cloud persisted. The radiometer measurements plotted in this figure are difficult to separate, so smaller time intervals are used to assist with the analyses in the following sections. The top panel of Fig. 4 shows the measurements made of the upwelling radiation comprising the sea surface emission and reflected sky radiance, and the second panel shows the corresponding measurement of the sky emission. The third panel shows the derived skin temperatures from the radiometers, plus the bulk measurement from the ship's thermosalinograph and the hard-hat sensor. The bottom panel shows the correction applied to compensate for the reflected sky radiance, expressed as a temperature.

The M-AERI provides a measurement of skin SST approximately every 11 min. For the full cruise analysis the M-AERI has been taken as the yardstick for the following two reasons: it has been shown to provide accurate validation data for satellite-derived SST (Minnett et al. 2001), and it provides a skin SST estimate less frequently than the other radiometers (except the TASCO). For the main comparison the other radiometer data have been averaged over 5-min periods centered on the time that the M-AERI measured the sea brightness temperature. This has provided a dataset that allows direct comparison between the sea and sky brightness temperatures, and the estimates of skin SST. The differences have also been averaged over periods of 0.1 day (2.4 h) and the results are plotted in Fig. 5.

Simple statistical analyses have been used to provide a bias and standard deviation between the different radiometer measurements. For the sea and sky measurements these analyses must be treated with care as different view angles, different spectral bandpasses, and different integration times mean that these measurements should not be identical, but should be similar. For skin SST (which is the prime target of the measurements) the values should be very close even with different radiometer and viewing characteristics assuming that the surface temperature, surface roughness, and sky

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

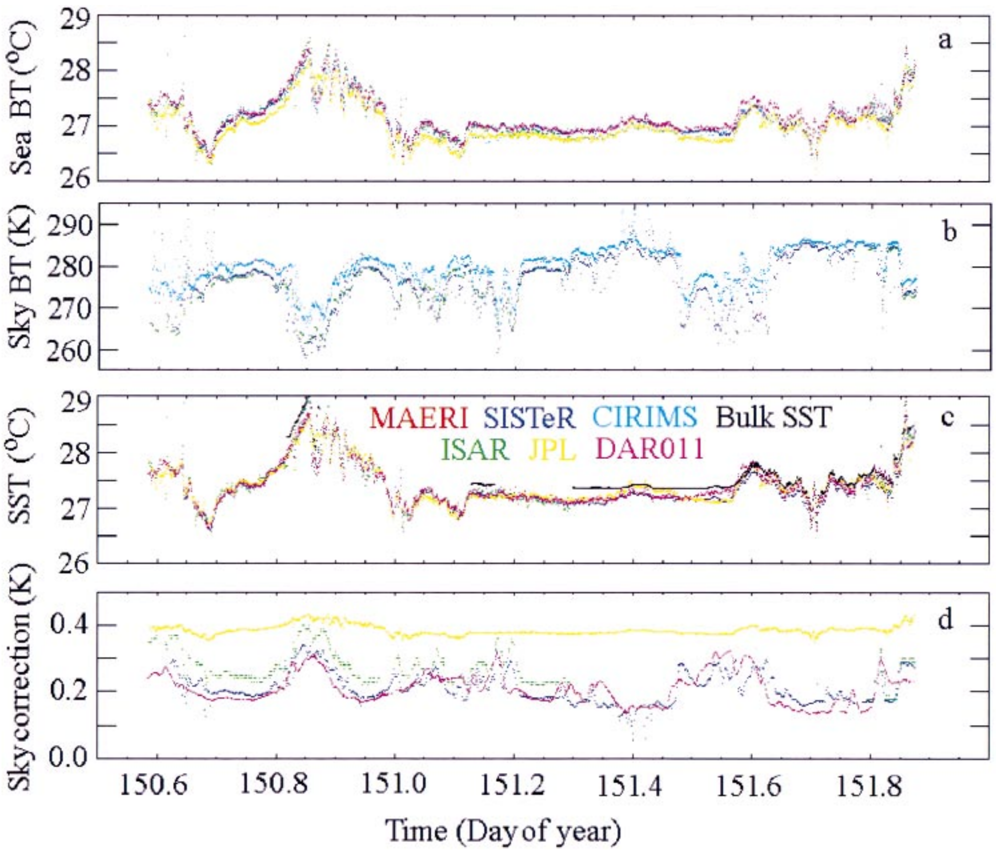

FIG. 4. Measurements and results from all radiometers (except the TASCO) throughout the *Walton Smith* cruise. (a) Sea (BTs) as measured by the radiometers (note: complete agreement is not expected with these temperatures due to the different view angles and spectral characteristics of individual radiometers), (b) sky brightness temperatures as measured by the radiometers, (c) skin SST values derived from the sea and sky measurements, and (d) the sky correction added to the sea BT to account for reflected sky radiation.

conditions remain similar throughout the (different length) duty cycle of all instruments.

For the derived skin SST values the comparisons between each pair of radiometers for the entire period of the cruise is shown in Table 3. The results show very good agreement with the mean values of differences being of the order of 0.05 K.

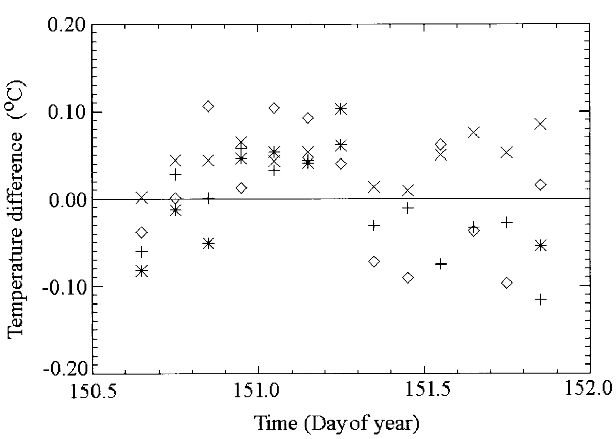

FIG. 5. The differences between the M-AERI skin SST and those derived using the other radiometers averaged over a 2.4-h period: ISAR-5, *; SISTeR, ×; JPL, ◇; and DAR011, +.

While Table 3 gives a statistical breakdown of the data for the full cruise and the two halves, Fig. 5 gives a detailed insight into the differences between the radiometers and how these differences varied over shorter time periods during the cruise. SISTeR and M-AERI showed the most consistent agreement during the cruise with M-AERI being 0.05 K higher. M-AERI and DAR011 showed good agreement on average over the cruise, but DAR011 was lower in the first half and higher in the second half of the cruise. MAERI and ISAR-5 also showed reasonable agreement, but with ISAR-5 being higher during the first 7 h of the cruise and lower for the second 7-h period. The standard deviation of the differences for ISAR-5 was twice that for SISTeR and DAR011. During Miami2001 the ISAR-5 was operated with a digitization level equivalent to 0.075 K, which could explain this feature. Future deployments of ISAR-5 will use a smaller digitization increment with a likely increase in noise-level performance. Like the DAR011

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

TABLE 3. Means and std devs of the estimated skin SST differences between pairs of radiometers for the entire cruise period and for each half of the cruise.

Time	150.50–152.00			150.50–151.25			151.25–152.00		
Radiometer pair	Mean (K)	Std dev (K)	No.	Mean (K)	Std dev (K)	No.	Mean (K)	Std dev (K)	No.
MAE–ISA	0.002	0.135	80	0.005	0.135	69	−0.015	0.135	11
MAE–SIS	0.046	0.066	144	0.046	0.066	74	0.045	0.068	70
MAE–JPL	0.007	0.114	148	0.052	0.111	77	−0.042	0.096	71
MAE–DAR	−0.008	0.076	149	0.022	0.071	78	−0.041	0.067	71
ISA–SIS	0.038	0.101	79	0.030	0.101	67	0.085	0.093	12
ISA–JPL	0.026	0.142	81	0.027	0.141	70	0.018	0.150	11
ISA–DAR	0.007	0.114	80	0.019	0.112	69	−0.064	0.107	11
SIS–JPL	−0.048	0.099	144	−0.009	0.103	74	−0.088	0.078	70
SIS–DAR	−0.053	0.074	144	−0.019	0.054	74	−0.088	0.076	70
JPL–DAR	−0.014	0.103	148	−0.028	0.102	77	0.000	0.102	71

radiometer the JPL radiometer was consistently cooler than M-AERI in the first half and warmer in the second.

c. Sea and sky comparisons

The same dataset used to produce Table 3 was used to analyze the sea and sky brightness temperature differences between the radiometers. For this analysis there were no data from the M-AERI for either sea or sky, and no sky data for the JPL radiometer. The results of the statistical analysis are included in Table 4. The significant results in this table are the standard deviations between different sensors. The mean differences are due to view angle and spectral effects, while the standard deviations provide an assessment of the consistency of the measurements between each pair of radiometers. This analysis also enables an assessment of the performance of CIRIMS, which has been excluded from the comparisons of derived skin SST estimates.

For the sea brightness temperatures the standard deviations between CIRIMS and the other radiometers are similar to those between ISAR-5 and the others. This suggests that the two radiometers (ISAR-5 and CIRIMS) will provide estimates of skin SST with similar accuracy. The table also suggests that the sea temperatures obtained with JPL, DAR011, and SISTeR may provide a more accurate estimate of the skin SST than the former two radiometers, provided an accurate sky correction can be made.

TABLE 4. Means and std devs of the sea and sky brightness temperature differences between pairs of radiometers for the entire cruise period.

	Sea brightness temp			Sky brightness temp		
Radiometer pair	Mean (K)	Std dev (K)	No.	Mean (K)	Std dev (K)	No.
CIR–ISA	−0.018	0.138	73	3.871	2.036	82
CIR–SIS	−0.037	0.124	101	3.508	2.968	145
CIR–JPL	0.093	0.125	106			
CIR–DAR	−0.098	0.115	106	2.813	4.165	150
ISA–SIS	0.000	0.115	81	0.441	1.907	81
ISA–JPL	0.138	0.129	82			
ISA–DAR	−0.047	0.106	81	−1.585	4.246	82
SIS–JPL	0.124	0.083	145			
SIS–DAR	−0.057	0.071	145	−0.764	4.767	145
JPL–DAR	−0.186	0.091	150			

The standard deviations from the sky brightness temperature analysis show the effect of the DAR011 sky view being in the opposite direction to the other measurements; the standard deviations are all greater than 4 K compared to less than 3 K for the other radiometer pairs. The mean differences are due to a combination of spectral band width and view angle. CIRIMS and ISAR-5 both used a similar detector system for their sky views so the measurements are expected to be similar. However, the table suggests that the CIRIMS sky measurements are too high by approximately 3–4 K. The cause of this anomaly is not yet understood and is under investigation.

d. Detailed analysis

In this section four different periods are selected for a detailed analysis.

1) PERIOD 151.130–151.170

This period is selected because it is a period during the night (2307–0005 LT) when the hard-hat sensor was deployed. The ship speed was a steady 0.8 m s^{-1} through the water with a heading of 230° (with the Gulf Stream the ship actually drifted to the northwest) and the wind speed was 3 m s^{-1} from the east-southeast. The data for the period 151.13–151.17 are shown in Fig. 6. The four plots are the same as those given in Fig. 4 and the symbols are defined in the caption.

Comments: The M-AERI estimates of SST are in good agreement with those from SISTeR, DAR011, and ISAR-5 except for the measurement at time 151.156. This measurement was taken at a time when the radiometers were showing fluctuations in sky brightness temperature measurements suggesting the presence of low broken clouds. The anomalous M-AERI SST es-

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

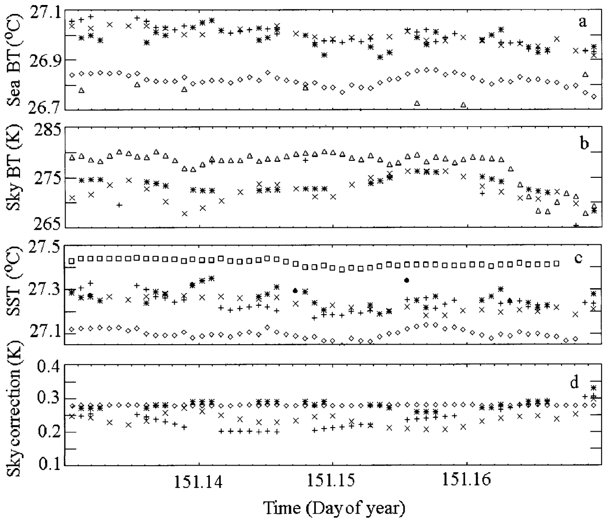

FIG. 6. Radiometer data for the period 151.13–151.17. The data symbols are identified as follows: M-AERI, ●; ISAR-5, *; SISTeR, ×; JPL, ◇; CIRIMS, Δ; DAR011, +; and hard-hat sensor □. The four panels are the same as in Fig. 4.

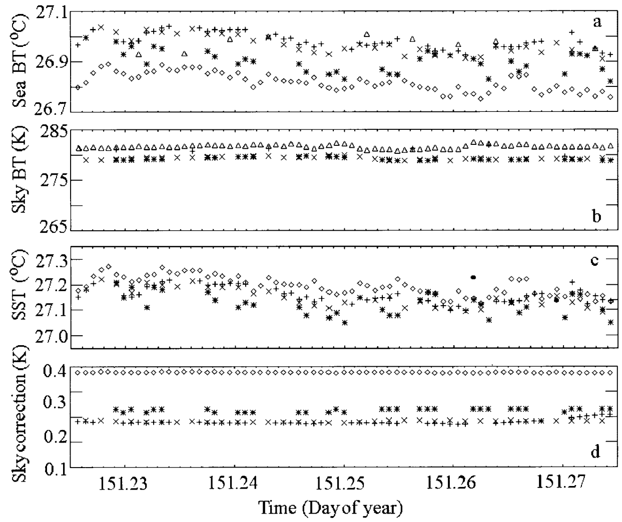

FIG. 7. Radiometer data for the period 151.225–151.275. The data symbols are identified as follows: M-AERI, ●; ISAR-5, *; SISTeR, ×; JPL, ◇; CIRIMS, Δ; and DAR011, +. The four panels are the same as in Fig. 4.

timate is most likely due to an incorrect sky correction. This phenomenon is discussed further later in the paper.

SISTeR and DAR011 show good agreement with the sea BT. The subtle effect of poor sky correction is evident; when the DAR011 sky temperature is low at 151.134 and 151.161, the sky correction is too large and the derived skin SST is thus also too high. The opposite is true for the times 151.141 and 151.148. If the SISTeR sky radiance were to be used to correct the DAR011 sea brightness temperature instead of the backward DAR011 sky temperature, then the derived skin SST would agree almost perfectly.

The CIRIMS and JPL sea brightness temperatures are approximately 0.2 K less than the other radiometers due to their wider spectral passband giving a lower surface emissivity and consequently a larger sky correction. Masuda et al. (1988) show that, in the thermal infrared spectral band, surface emissivity has a maximum at 11 μm and decreases at lower and higher wavelengths. This also explains the higher sky temperatures shown by CIRIMS. During this 1-h period the sky correction for the JPL radiometer results in a good SST agreement with the other radiometers.

The ISAR-5 radiometer gives consistent measurements of sea brightness temperature when compared with those from SISTeR and DAR011, although the data seem to be more noisy (variable). There is also evidence of some slight increase during a sampling cycle (e.g., at 151.140, 151.145, and 151.162). The ISAR-5 sky temperature does not show the same variability as those from SISTeR and DAR011

2) PERIOD 151.225–151.275

This period is selected because it is a period during the night (0124–0236 LT) when ISAR-5 data were still available and the sky temperature was uniform. The data are shown in Fig. 7.

Comments: Throughout this period the sky temperatures measured by each radiometer were relatively steady. The sky temperatures from ISAR-5 and SISTeR agree closely while those from CIRIMS and DAR011 also agree well but are slightly higher than the other two. The sky corrections for DAR011 and SISTeR are similar while that for ISAR-5 is approximately 0.05 K higher. The JPL sky correction is another 0.15 K higher, and the JPL SST is higher than those from the other radiometers.

SISTeR and DAR011 sea temperatures and SST values agree well. ISAR-5 SST values also appear to agree well, but again there is evidence of more variability due to the 0.075-K equivalent digitization level used during Miami2001.

ISAR-5 and JPL both have lower sea temperatures, which is partly compensated with a higher sky correction due to the lower surface emissivity of these wider spectral band instruments. CIRIMS sea temperatures are lower for the first half of this interval and then higher. These data are in contrast with those in Fig. 6 where CIRIMS has values that are less than JPL and considerably less than the other radiometers.

During this time interval M-AERI provided only two measurements, at 151.262 and 151.269. The second of these has good agreement with SISTeR, ISAR-5, and DAR011. The first is higher by 0.1 K and follows a period when the M-AERI was not operating so the internal calibration may not be reliable.

3) PERIOD 151.340–151.430

This period is selected because it is a period before sunrise (0410–0619 LT) when the sky temperatures

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

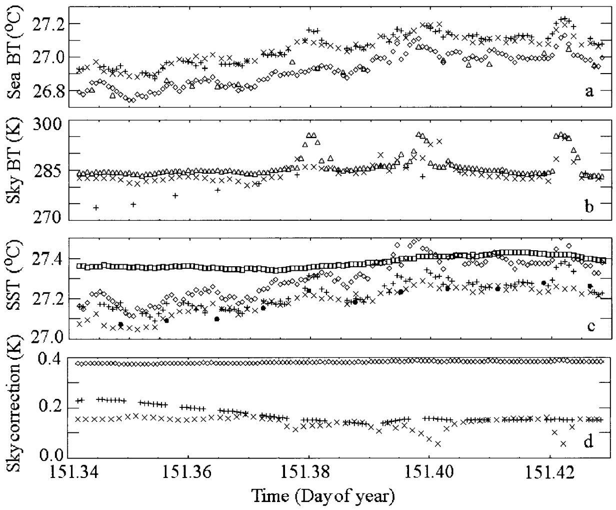

FIG. 8. Radiometer data for the period 151.340–151.430. The data symbols are identified as follows: M-AERI, ●; SISTeR, ×; JPL, ◇; CIRIMS, Δ; and DAR011, +. The four panels are the same as in Fig. 4.

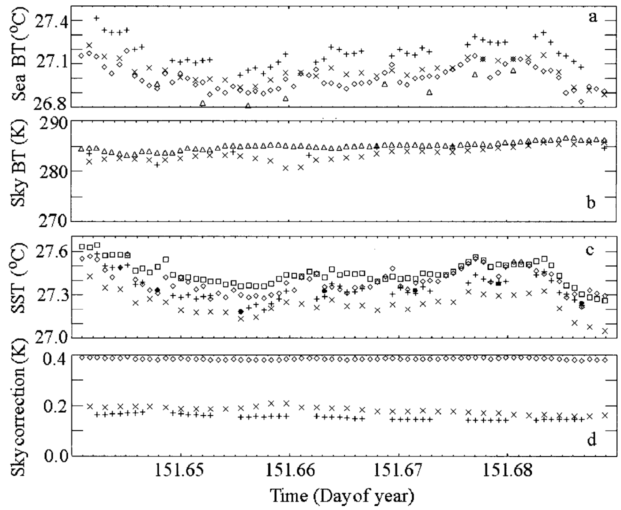

FIG. 9. Radiometer data for the period 151.640–151.690. The data symbols are identified as follows: M-AERI, ●; SISTeR, ×; JPL, ◇; CIRIMS, Δ; and DAR011, +. The four panels are the same as in Fig. 4.

were uniform except for three occasions when low clouds were evident. The data are shown in Fig. 8.

Comments: During this period M-AERI shows extremely good agreement with the SST values derived by SISTeR. From 151.36 to 151.43 the SISTeR and DAR011 sea temperatures and SST values agreed well except for one occasion at 151.38 (see below). As with Fig. 6 the early part of the time interval showed DAR011 with a lower sky temperature giving a larger correction and a larger SST when compared to SISTeR. The CIRIMS and JPL sea temperatures were again less than the other two radiometers and the JPL SST values were higher than those from SISTeR and DAR011. For the second half of this period, when the sky temperatures suggested that there were low clouds present, the sky correction assumed for JPL is too large, in some cases giving skin temperatures in excess of the bulk temperature measured with the hard-hat thermometer.

An interesting feature of this figure is the three occasions in the sky temperature when low clouds were detected, raising the sky temperature to values close to the SST values. None of these episodes was detected with the DAR011 radiometer (which looks backward) and on each occasion the DAR011 SST is overestimated due to an overcorrection for the sky effect. The first of these episodes is also interesting as it was detected in the sky measurements by CIRIMS but not by SISTeR. In the sea temperatures an increase is evident in the DAR011 data but not in the SISTeR nor the CIRIMS measurements. For the episode at 151.422 both CIRIMS and SISTeR detected the cloud in the sky view and all the radiometers detected the (reflected) cloud in the sea view although the increase in CIRIMS temperature is marginal.

4) PERIOD 151.640–151.690

This period is selected because it is a period around local noon with uniform sky temperatures (1122–1234 LT). The data are shown in Fig. 9.

Comments: The main feature of this period is the higher sea temperature measured by the DAR011 radiometer. The other radiometers show typical values with the CIRIMS and JPL having sea brightness temperatures slightly less than SISTeR. The skin SST values for SISTeR are lower than those for M-AERI, JPL, and DAR011. These broad features of the radiometer differences can also be seen in Fig. 5. The increase in DAR011 sea brightness temperature may have been due to a change in the ship's wake with the radiometer partly viewing disturbed water with a bulk temperature rather than the slightly lower skin temperature. The causes of some of these minor differences are not yet completely understood.

e. TASCO data analysis

The TASCO radiometer was analyzed separately due to the small amount of data, none of which were coincident with the M-AERI measurements. In the same manner as above the measurements from the ISAR-5 SISTeR, JPL, and DAR011 radiometers were averaged over a 5-min period centered on the TASCO measurement time. The same statistical analysis gave the results shown in Table 5.

These results should be treated with caution. The almost exact agreement between the TASCO and the other radiometers is quite fortuitous. Experience has shown that TASCO radiometers can have absolute errors of much more than 1 K, and regular absolute calibration is recommended if these radiometers are to be used in

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

TABLE 5. Means and std dev of the differences between the TASCO and other radiometers.

Radiometer pair	Mean (K)	Std dev (K)	No.
TAS–ISA	−0.608	0.188	12
TAS–SIS	−0.001	0.157	24
TAS–JPL	0.069	0.196	24
TAS–DAR	−0.054	0.163	23

the field. However, with good absolute calibration, the analysis suggests that standard errors of the order of 0.2 K are possible, making these off-the-shelf radiometers useful in many applications.

6. Discussion

a. Reflectance of sky radiation

When reviewing the results presented in the previous section it is evident that one of the major contributors to the variance between the different radiometer measurements is the variable sky radiance, which limits the accuracy of the sky correction. ISAR-5, SISTeR, and DAR011 all view the sky at the same angle to the vertical as they view the sea. All three radiometers use similar wavelengths in the 10–12-μm atmospheric ''window'' for both the sea and sky views. As there is little atmospheric absorption (mainly by water vapor) in this spectral region the clear-sky brightness temperatures are dependent on the water vapor present in the atmosphere. For tropical conditions (as experienced in Miami2001) the clear-sky brightness temperatures are close to 260–270 K, but for higher latitudes these can be less than 240 K. Under cloudy conditions the sky brightness temperature will be close to the cloud-base temperature. Under partly cloudy skies the brightness temperature will fluctuate between the cloud-base and clear-sky temperatures and an accurate estimate of the skin SST, and the intercomparison of radiometer performances, are most difficult.

The data analysis in the previous section has shown that, at times, a radiative transfer model with a standard atmosphere can provide a good sky correction for the JPL Near-Nulling Radiometer. However, there are also times when this method does not work as well and a more accurate estimate of the downwelling sky radiance will be required if a reliable skin SST is to be obtained.

Under clear skies, when the sky brightness temperature is stable, measurements of skin SST will be most accurate and radiometer intercomparisons more reliable, even though the magnitude of the sky correction will be greater than under cloudy conditions.

For the M-AERI, the skin SST values are derived routinely using a narrow spectral interval at a wavelength of ~7.7 μm (1302–1307 cm^{-1}). This spectral interval was selected to reduce the dependence of the accuracy of the retrieved SST on the correction for the reflected sky radiance (Smith et al. 1996). As there is significant water vapor absorption at these wavelengths the sky brightness temperature is close to the air temperature and is unaffected by clouds as is the case for the window radiometers. At the 7.7-μm wavelength used by M-AERI the atmospheric pathlength is much shorter by several hundred meters, so the variance in the reflected sky radiation is much smaller, by more than an order of magnitude (Minnett et al. 2001). The M-AERI skin SST retrievals are therefore less sensitive to uncertainties in the sky radiance corrections than the radiometers using the long pathlength wavelengths.

As the sea surface becomes rough in response to the wind or swell, the assumption of specular reflection implicit in Eq. (1) becomes less realistic, with sky radiance being reflected into the beam from other parts of the sky. In situations where there is broken cloud, as was the case for most of the Miami2001 cruise, the spatial variations in the brightness temperature of the sky, ranging from the cold, clear sky to the warm bases of clouds, can be a significant source of error in the SST (Donlon and Nightingale 2000) if the spatial and temporal averaging inherent in the sky-view measurement is not an accurate estimate of the sky radiance in the reflected component of the sea-view measurement.

b. Interpolation effects

Rapidly varying sky brightness temperatures due to the partly cloudy conditions experienced during the Miami2001 cruise introduced errors into the skin SST estimates. The only radiometer that collected simultaneous views of both the sea and sky was CIRIMS. All other radiometers used a rotating mirror system to view the sea and sky sequentially with a preset duty cycle. The duty cycle of each radiometer is 2 min for SISTeR, 3 min for ISAR-5, 10 min for DAR011, and 11 min for M-AERI. The time between sea and sky measurements is 30 s for SISTeR, 40 s for ISAR-5, 45 s for M-AERI, and 2 min for DAR011. In all cases the sky brightness temperatures were interpolated with time to provide an estimate for application to the sea-view data. As shown in Fig. 8 and the subsequent discussion this approach has resulted in some errors in deriving the skin SST due to the application of erroneous sky temperatures. However, as discussed above, these errors are likely to be quite small in the clear-sky conditions required for the validation of satellite-derived SST estimates.

c. Day–night differences

The analysis presented in Fig. 5 shows that the most consistent results were obtained during times 150.9 and 151.3, which occur during the night. Before and after this period the different radiometers showed a wider spread of values when compared to the M-AERI. The cause for this anomaly is most likely due to variations in radiometer performance rather than being due to variations in the SST.

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

Accurate infrared radiometry requires that a radiometer view the calibration blackbody cavities through the same optical path as the sea surface. Thus the calibration blackbody cavities and the beam scanning mechanism need to be open to the marine atmosphere, but must be protected from sea spray and sudden changes in ambient temperature. The DAR011 and M-AERI instruments have circular viewing apertures of 5.0 and 6.9 cm, respectively, while SISTeR and ISAR-5 use elliptical optical systems that allow viewing apertures of less than 1-cm diameter. Changes in insolation, air temperature, and wind velocity can all affect the operating environment within the radiometer, and much of the design strategy for a good radiometer needs to account for these factors.

Small-scale variations in the SST are not expected to affect the measurements, nor is the fact that the radiometers were viewing in slightly different directions. The radiometer measurements were averaged over periods of at least 1 min in which time the ship had traveled 48 m when the hard-hat instrument was deployed, and longer distances at other times.

The intercomparison measurements thus suggest that validation of satellite-derived SST estimates during the night may provide marginally better results than those during the day. However, this advantage may be offset by the difficulty of detecting the presence of small and thin clouds in both satellite and ship-based measurements during the night.

d. Assessment of each radiometer

1) M-AERI

Unlike the other instruments in this intercomparison, the M-AERI is a spectroradiometer, measuring broad infrared spectra. This has the advantage that more variables, other than skin SST, can be derived, but it has several disadvantages when compared to the other radiometers, including size, weight, and power requirements. It is not as portable, nor so easily mounted on ships. The need to integrate the measurements over a longer period than the filter radiometers, to achieve a good signal-to-noise ratio over the entire spectrum, causes the sampling cycle to be longer. This also means the temporal separation between the sea and sky views is longer, and in situations of changing cloud, this can lead to a potential source of error. This is ameliorated by the choice of the 7.7-μm wavelength for the skin SST measurement, and in conditions of broken cloud, the longer integration period can give a more stable estimate of the sky correction. However, this can also be achieved for the more rapidly sampling radiometers by averaging high-frequency data.

A difference in the way the M-AERI was used during this exercise, compared to the other radiometers, is the use of a shallower angle of incidence. Measurements were made at 55° to the vertical. This is to ensure that the field of view is beyond the influence of the ship, both in terms of surface disruption of the bow wave, and the possibility of the field of view being in the lee of the hull, thereby changing the size of the skin–bulk temperature differences in response to a reduced local wind. This could be important when the data are used to validate satellite measurements. Greater zenith angles are not used, as this would introduce a wind speed dependence of the surface reflectivity.

The comparisons of skin SSTs measured by the M-AERI and the other radiometers with a sky-view correction are reassuring, with small mean errors and small scatter (when compared to other pairs of radiometers). Some of the scatter is undoubtedly environmental in origin, resulting from temporal and spatial variability between the different fields of view and integration times.

2) ISAR-5

The instrument deployed during the Miami2001 cruise was not of the optimal configuration. The selection of a lower digitization level and the inclusion of a more transparent window in front of the detector should lead to improved performance. Even without these added attributes ISAR-5 demonstrated its potential as an autonomous radiometric system suitable for deployment on volunteer observing ships. The mechanical shutter designed to close the viewing apertures during rain or excess sea spray operated several times during the cruise. Such a mechanism is a necessary requirement for autonomous radiometers that view the sky without a protective window in front of the scanning mirror and calibration blackbody targets.

3) SISTER

Table 3 shows that SISTeR provided good agreement with the other radiometers, especially the M-AERI. For both halves of the cruise there is a consistent difference between M-AERI and SISTeR with the former instrument giving skin SST estimates that were 45 mK higher. Like the DAR011, SISTeR requires continual attention to protect the instrument against rain or sea spray damage. The SISTeR optics that are based on an ellipsoidal collection mirror allows a small viewing aperture, which minimizes the risk of water entry into the system. However, it is still necessary to manually cover the instrument at times when rain or sea spray are a threat. An automated door is currently under development.

4) JPL NNR

The JPL NNR showed good agreement with the skin SST provided by the other radiometer. However, the lack of a sky measurement is likely to increase the error in partly cloudy conditions. Under these conditions the radiometer could be used for SST validation if a second

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

system was deployed to provide an accurate sky correction.

5) CIRIMS

The instrument deployed during the Miami2001 campaign was not an optimal configuration of the instrument. Different spectral responses of the sea and sky views meant that it was not possible to derive a skin SST value for comparison with the other radiometers. However, the measurements have allowed a limited comparison between the sea and sky views. The results presented in Table 4 show that the mean value of the sea brightness temperature differences are less than 0.1 K when CIRMIS is compared with the other radiometers. The standard deviations of the difference are all of similar value.

6) DAR011

The DAR011 radiometer showed good agreement with the skin SST provided by the other radiometers—especially M-AERI and ISAR-5. Like M-AERI the DAR011 was approximately 50 mK higher than SISTeR, but this was not a consistent difference during the cruise. While the other radiometers showed consistent differences throughout the cruise, the results in Table 3 suggest that the DAR011 radiometer gave higher SST values in the second half of the cruise by 35 mK. This effect became evident at 151.490 (0745 LT) when the wind changed from a northerly to an easterly and reduced speed to around 2 m s^{-1}. There is also some visual evidence that, after this time, the DAR011 radiometer (which was located farther aft than the other instruments) occasionally viewed water that was disturbed by the ship's wake. It is worth noting here that the operator of the SISTeR radiometer was also concerned that the ship's wake could be present in the radiometer view and increased its viewing angle to 45° for the last 6 h of the cruise.

7) TASCO

The TASCO measurements taken during the cruise suggest that, if great care is taken with the measurement, then a reasonable skin SST estimate can be made with these off-the-shelf instruments. For useful SST validation an accurate system that includes frequent calibration will be required. The results in Table 5 suggest that an accuracy of better than 0.2 K is possible, which is an order of magnitude better than the absolute accuracy figures quoted by the manufacturer.

7. Conclusions

The second infrared radiometer calibration and intercomparison, which was held in Miami from 27 May to 2 June 2001, has provided a valuable dataset that has allowed a full comparison and calibration of several infrared radiometers to be used for the future validation of surface temperature products from satellite instruments. Also, each radiometer participating in the campaign now has calibration measurements that are traceable to a blackbody target developed by NIST.

The final analysis of the results has confirmed that all participating radiometers are suitable for the validation of land surface temperature, and the majority are able to provide high quality data for the more precise validation of satellite-derived sea surface temperature. The differences between the radiometer measurements are close to the limits imposed by the measurement technique as discussed by Donlon and Nightingale (2000). The measurements provided by two prototype instruments developed for ship-of-opportunity use [the Infrared SST Autonomous Radiometer (ISAR-5) and the Calibrated Infrared In situ Measurement System (CIRIMS)] confirmed their potential to provide regular reliable data for satellite-derived SST validation. The intercomparison has also paved the way for international collaboration in the joint provision of ground-based data for the validation of SST to be provided by new instruments launched during 2002, namely, AATSR on ESA's *Environmental Satellite* (*Envisat*) and MODIS on *Aqua*.

The ship measurements have also shown the importance of having a reliable estimate of sky radiance to correct for the reflected radiance at the sea surface. Autonomous systems that view the sky through an open aperture also need a reliable system for protection against rain and sea spray.

Following the radiometer calibration, intercomparison, and testing under field conditions, the international community will now have increased confidence in the results to be provided by these instruments for the validation of satellite-derived surface temperatures. High quality radiometric measurements for such validation are difficult to obtain, and are thus a scarce resource. Bringing the international community together in campaigns such as these will assist with future international collaboration to provide sufficient data to allow reliable validation of surface temperature products for MODIS, ASTER, AVHRR, the Visible Infrared Scanner (VIRS), AATSR, and other spaceborne infrared radiometers.

Acknowledgments. Funding to support the calibration and intercomparison was sought through the international Committee on Earth Observation Satellites (CEOS). Following a proposal to the 14th CEOS Plenary Meeting in 2000, funding was made available by three CEOS members: EUMETSAT, NOAA, and ESA. These contributions to ensure the success of the laboratory and ship campaigns are gratefully acknowledged. The support for travel and other expenses by all participants' institutes or other funding agencies is also acknowledged. The crew of the R/V *Walton Smith* provided valuable support, as did the laboratory staff at

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC

RSMAS. The University of Miami provided laboratory and workshop support for all participants. The authors are also indebted to Erica Key, Ruth Fogelberg, Trina Litchendorf, Marianne Edwards, Gary Wick, and Mike Reynolds for assistance with the data collection on board the *Walton Smith.* Ali Abtahi developed the JPL radiometer and helped with the Miami2001 deployment. Ron Alley assisted with the reduction of the JPL data. The research described in this paper was carried out in part at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA as part of the EOS Mission to Planet Earth.

REFERENCES

Barton, I. J., 2001: Interpretation of satellite-derived sea surface temperatures. *Adv. Space Res.,* **28/1,** 165–170.

——, A. J. Prata, and R. P. Cechet, 1995: Validation of the ATSR in Australian waters. *J. Atmos. Oceanic Technol.,* **12,** 290–300.

Bennett, J. W., 1998: CSIRO single channel infrared radiometer—Model DAR011. CSIRO Atmospheric Research Internal Paper, 19 pp.

Donlon, C. J., and T. J. Nightingale, 2000: The effect of atmospheric radiance errors in radiometric sea-surface skin temperature measurements. *Appl. Opt.,* **39,** 2387–2392.

——, ——, L. Fiedler, G. Fisher, D. Baldwin, and I. S. Robinson, 1999: The calibration and intercalibration of sea-going infrared radiometer systems using a low cost blackbody cavity. *J. Atmos. Oceanic Technol.,* **16,** 1183–1197.

——, P. J. Minnett, C. Gentemann, T. J. Nightingale, I. J. Barton, B. Ward, and M. J. Murray, 2002: Toward improved validation of satellite sea surface skin temperature measurements for climate research. *J. Climate,* **15,** 353–369.

Fowler, J. B., 1995: A third generation water bath based blackbody source. *J. Res. Natl. Inst. Stand. Technol.,* **100,** 591–599.

Jessup, A. T., 2002: Autonomous shipboard infrared radiometer system for in-situ validation of satellite SST. *Proc. SPIE,* **4814,** 222–229.

Kannenberg, R., 1998: IR instrument comparison workshop at the Rosenstiel School of Marine and Atmospheric Science (RSMAS). *Earth Observer,* **10** (3), 51–54. [Available online at http://eospso.gsfc.nasa.gov/eos_observ/5_6_98/p51.html.]

Kearns, E. J., J. A. Hanafin, R. H. Evans, P. J. Minnett, and O. B. Brown, 2000: An independent assessment of Pathfinder AVHRR sea surface temperature accuracy using the Marine–Atmosphere Emitted Radiance Interferometer (M-AERI). *Bull. Amer. Meteor. Soc.,* **81,** 1525–1536.

Masuda, K., T. Takashima, and Y. Takayama, 1988: Emissivity of pure and sea waters for the model sea surface in the infrared window regions. *Remote Sens. Environ.,* **24,** 313–329.

Minnett, P. J., R. O. Knuteson, F. A. Best, B. J. Osborne, J. A. Hanafin, and O. B. Brown, 2001: The Marine–Atmosphere Emitted Radiance Interferometer (M-AERI), a high-accuracy, sea-going infrared spectroradiometer. *J. Atmos. Oceanic Technol.,* **18,** 994–1013.

Rice, J. P., and B. C. Johnson, (1998): The NIST EOS Thermal-infrared Transfer Radiometer. *Metrologia,* **35,** 505–509.

——, and Coauthors, 2004: The Miami2001 infrared radiometer calibration and intercomparison. Part I: Laboratory characterization of blackbody targets. *J. Atmos. Oceanic Technol.,* **21,** 258–267.

Smith, W. L., and Coauthors, 1996: Observations of the infrared radiative properties of the ocean—implications for the measurement of sea surface temperature via satellite remote sensing. *Bull. Amer. Meteor. Soc.,* **77,** 41–51.

Watts, P. D., M. R. Allen, and T. J. Nightingale, 1996: Wind speed effects on sea surface emission and reflection for the along track scanning radiometer. *J. Atmos. Oceanic Technol.,* **13,** 126–141.

WCRP, 1984: Report of the TOGA workshop on sea surface temperature and net surface radiation. WCP-92, World Climate Research Programme, 41 pp.

Unauthenticated | Downloaded 04/21/21 08:33 PM UTC