Radiometric Validation of ERS-1 Along-Track Scanning Radiometer Average Sea Surface Temperature in the Atlantic Ocean

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ABSTRACT

The ERS-1 along-track scanning radiometer (ATSR) provides a half-degree latitude by half-degree longitude average sea surface temperature (ASST) measurement representative of the thermal skin layer of the ocean that is intended for use in global climate studies. Radiometric skin sea surface temperature (SSST) and bulk sea surface temperature (BSST) observations are presented that have been collected spatially coincident and near contemporaneously with ERS-1 ATSR ASST in the tropical and subtropical Atlantic Ocean during September 1992. Using these data the authors demonstrate that the ERS-1 ATSR ASST (SADIST 600) computed from both forward and nadir observations (dual ASST) has a cool bias of $-0.54$ K, and the ASST computed from nadir-only observations has a bias of $-0.78$ K. The rms scatter about the mean bias for the dual ASST is 0.18 K and for the nadir ASST is 0.22 K, demonstrating the effectiveness of the along-track scanning concept. The difference between SSST and BSST validation techniques is less than 0.05 K because high wind speeds dominate the in situ dataset, preventing an appreciable skin temperature deviation at the air–sea interface. Most of the bias described above can be explained by Saharan dust and aerosols from the Mount Hudson and Mount Pinatubo volcanic eruptions that were present in the atmosphere during the measurement period.

1. Introduction

The first along-track scanning radiometer (ATSR) is a multichannel, multiview infrared radiometer carried aboard the ERS-1 satellite designed to retrieve precision sea surface skin temperature (SSST) for global climate studies. Unlike other spaceborne infrared radiometer systems, the sea surface temperature (SST) retrieval process adopted by the ATSR makes no assumptions about the relationship between the subsurface bulk SST (BSST) and the measured SSST. Thus, the ATSR returns a temperature of a micrometer thin “skin” of the ocean that can be significantly different from the subsurface BSST, which is measured by traditional oceanographic instrumentation.

Although having an extremely small depth, it is through the SSST layer that all exchange of heat and momentum between the atmosphere and ocean takes place (e.g., see Schlüssel et al. 1990; Clayson et al. 1996; Donlon and Robinson 1997), and it is the layer exerting a strong influence on the uptake of temperature soluble gases (Robertson and Watson 1992; van Scy et al. 1995). In this context SSST is arguably one of the most relevant climatic parameters required for the investigation of global climate. It is a diagnostic variable for the validation of coupled atmospheric and oceanic models, it can be used to force such models by acting as a boundary condition at the air–sea interface (Eymard and Taconet 1995), and it can be used to help interpret modeled SST results at the ocean basin scale (Lawrence et al. 1994). Finally, the quasi-synoptic global SSST datasets generated by the ERS-1 ATSR and follow-on missions can be used to investigate the limitations of large-scale temporal and spatial averaging procedures used in blended SST climatology datasets (Bottomley et al. 1990; Reynolds 1988). In these cases the ATSR provides a completely independent measure of an average global SSST.

The importance of accurately validating satellite SSST observations has been discussed by Allen et al. (1994), who demonstrate that for an 11-yr period of continuous satellite SSST observations, there is a greater than 80% probability of directly detecting the trend and magnitude of global warming rates. However, such estimates assume an accurate and stable satellite dataset. Unfortunately, such a long-term climatic dataset must be synergistically derived using several different ATSR instruments deployed by follow-on satellite missions. Consequently, there is an urgent need to fully account for any individual ATSR instrument bias relative to high-quality in situ validation measurements.

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Table 1. Main ERS-1 ATSR validation studies and associated bias values for two-channel dual-SSST algorithm ERS-1 ATSR retrievals. 'Uses 3.7-μm channel, 'uses atmospheric correction smoothing, and 'uses ERS-1 ATSR near-real-time data.

<table>
<thead>
<tr>
<th>Author</th>
<th>Date</th>
<th>Type</th>
<th>Region</th>
<th>Bias, K</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mutchow et al. (1994)</td>
<td>Apr–May 1992</td>
<td>BSST vs ASST</td>
<td>Global</td>
<td>−0.61</td>
</tr>
<tr>
<td>Harris et al. (1996)</td>
<td>Feb–Mar 1992</td>
<td>BSST vs 1 km</td>
<td>Global</td>
<td>−0.30</td>
</tr>
<tr>
<td>Harrison and Jones (1992)</td>
<td>Sep 1992</td>
<td>BSST vs ASST</td>
<td>30°N–30°S</td>
<td>−1.05</td>
</tr>
<tr>
<td>Smith et al. (1994)</td>
<td>Nov 1991</td>
<td>SSST vs 1 km</td>
<td>0°–10°S, 10°–20°W</td>
<td>−0.7</td>
</tr>
<tr>
<td>Barton et al. (1995)</td>
<td>Jul 1991</td>
<td>SSST vs 1 km</td>
<td>10°–20°S, 145°–175°E</td>
<td>+0.23</td>
</tr>
<tr>
<td>Thomas et al. (1995)</td>
<td>Sep 1991–May 1992</td>
<td>SSST vs 1 km</td>
<td>Meridional transect</td>
<td>−0.6</td>
</tr>
</tbody>
</table>

This paper is concerned with the validation of ERS-1 ATSR half-degree latitude by a half-degree longitude (approximately 50 km × 50 km) ASST data product. Section 2 describes our validation methodology and the in situ dataset used to validate ERS-1 ATSR ASST. Section 3 presents our results, which are then discussed in section 4. Finally, our conclusions and recommendations are given in section 5.

2. Methodology

As the sea surface temperature retrieval scheme used by the ERS-1 ATSR is significantly different from other contemporary satellite radiometer systems, it is useful to briefly review the satellite SST validation process. In the case of the pseudobulk SST retrievals, such as those made by the National Oceanic and Atmospheric Administration (NOAA) Advanced Very High Resolution Radiometer (AVHRR), the atmospheric effect modifying and contributing to the upwelling sea surface radiance is accounted for by absolutely calibrating the total system against in situ BSST observations, and the reader is referred to Barton (1995) for an excellent discussion of this process. Thus, the in situ data form a necessary part of the overall calibration procedure as described in McMillin (1975). In contrast, the scheme used to retrieve SSST from the ATSR relies on the pre-launch calibration of the instrument detectors together with a two-point blackbody calibration subsystem and uses an accurate model of the radiative processes occurring in the atmosphere to account for its effect on the upwelling sea surface radiance. When in situ measurements are used to validate SSST from the ATSR, they must adequately specify and account for the conditions and fundamental processes defining the SSST at the air–sea interface. Specifically, the most appropriate method for the validation of ATSR data products is to validate the atmospheric correction model with an SSST measured using a ground-based infrared radiometer having similar spectral channels to that of the ATSR (Mutlow et al. 1994).

The ATSR 1-km resolution SSST product has been validated using aircraft and ship-mounted in situ infrared radiometer measurements by several authors (e.g., Smith and Saunders 1994; Barton et al. 1995; Thomas et al. 1995), although the small number of coincident ship and satellite data is a testimony to the difficulties encountered when operating precision infrared radiometer systems from ships and aircraft. Consequently, other authors (e.g., Harrison and Jones 1993; Mutlow et al. 1994; Forrester and Challenor 1995; Harris et al. 1995) use BSST collected from a variety of sources including buoy, ship, and climatological SST analysis fields to validate SSST observations from the ERS-1 ATSR. Table 1 describes the main characteristics of the validation campaigns discussed above. In the majority of cases the ERS-1 ATSR has a cool bias relative to the validation data. No ERS-1 ATSR validation studies have been reported for dates after September 1992.

a. In situ sampling strategy

In the context of validating satellite SSST Minnett (1991) recommends limiting criteria for the spatial and temporal coincidence of satellite and in situ SST validation data. He suggests that in situ validation measurements should be within plus or minus 2 h of a satellite overpass and within 5 km of a 1-km satellite pixel. These criteria are based on a time series of AVHRR image data, coincident BSST ship observations, and observations made using two drifting buoys in the dynamic SST fields of the southern Norwegian Sea. Such stringent criteria are inappropriate for making comparisons between spatially averaged SST and in situ data. Considering an ATSR ASST measurement, this represents an approximately 50 km × 50 km area and is the average of up to 2500 measurements derived from individual 1-km pixels. Ideally, comparable in situ data should average SSST observations made at regular spatial intervals within an ASST cell at the time of satellite measurement, which is clearly not practical. Single subsurface buoy observations of a BSST are unsatisfactory for comparison with ASST because they are unable to account for the skin temperature deviation or sample the large spatial areas specified by an ASST cell. Buoy BSST observations can also be biased due to the vertical position chosen for the temperature sensor, direct diurnal warming of the temperature sensor, and incomplete thermal contact between the temperature sensor and the surrounding seawater (Bitterman and Hansen 1993). Aircraft-mounted radiometers have been used to validate daytime ERS-1 ATSR data in the tropical Atlantic Ocean.
Table 2. Main characteristics of the tropical and midlatitude ERS-1 ATSR “standard” atmospheres used to derive the ERS-1 ATSR ASST retrieval coefficients used by Závody et al. (1995). Lat is the latitude bounds from which data are derived, mean $T$ is the mean atmospheric temperature with standard deviation $T$, and mean $H_2O$ is the average water content and standard deviation $H_2O$.

<table>
<thead>
<tr>
<th>Region</th>
<th>Lat (°)</th>
<th>Number of observations</th>
<th>Mean $T$ (K)</th>
<th>Std dev (K)</th>
<th>Mean $H_2O$ (g kg$^{-1}$)</th>
<th>Std dev $H_2O$ (g kg$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical</td>
<td>0–25</td>
<td>83</td>
<td>299.8</td>
<td>2.9</td>
<td>43.3</td>
<td>12.3</td>
</tr>
<tr>
<td>Midlatitude</td>
<td>25–50</td>
<td>39</td>
<td>293.8</td>
<td>6.3</td>
<td>30.1</td>
<td>11.6</td>
</tr>
</tbody>
</table>

(Smith et al. 1994), and such instrument platforms offer the best opportunity to adequately sample an ATSR ASST cell. However, even in this case they cannot entirely eliminate atmospheric effects present in the SSST validation measurement and cannot make contemporaneous near-surface BSST measurements. They are also logistically difficult and expensive to operate, bearing in mind that cloud-free conditions must be sought.

Assuming a typical ship speed of 10 kt, it takes approximately 3 h to traverse a single ASST cell. In our case the spatial distribution of in situ data is the average of individual 30-s samples made along the ship track as it traversed the ASST cell, provided that they were within plus or minus 12 h of the ERS-1 overpass. This averaging technique eliminates the problem of spatial temperature gradients advected past a single point that demand Minnett’s strict criteria. The temporal coincidence criterion is based only on a requirement that there should not be a significant overall warming or cooling of the surface water or significant atmospheric change between satellite overpass and in situ measurement. Thus, the in situ validation dataset used in this study offers a compromise between the ideal requirements and that which is logistically possible. However, we acknowledge two major limitations to our strategy.

1) A single ship transect may not adequately describe the wide area mean SSST sampled by the satellite in regions characterized by strong thermal gradients.
2) In the time that it takes a ship to traverse a single ASST cell, the atmospheric and oceanic conditions at the time of satellite measurement may have significantly changed.

To minimize both of these effects, only open-ocean regions characterized by small SST gradients (Viehoff 1989) have been selected as primary validation sites. In such regions the temporal evolution of the SST is much longer than the 12-h validation window used here due to the absence of energetic mesoscale eddies and fronts (Freeland et al. 1975). The second limitation is more complicated and will be discussed further in section 3b.

b. ERS-1 ATSR satellite data

The ATSR instrument has several design features that are significantly different from other earth-orbiting radiometer systems.

1) A continuous onboard calibration of the instrument detectors using two precision blackbody cavities maintained at temperatures slightly above and below the range of sea surface temperatures. The ERS-1 ATSR detectors have been calibrated prior to launch to an accuracy of less than 0.1 K (Mason et al. 1995).
2) A mechanical Stirling cycle cooler that maintains the detector elements at about 90 K, reducing the signal-to-noise ratio for the 11-μm channel to an NEΔT of 0.03 K at 285 K (Mason 1991).
3) The capability to measure the upwelling radiation from the same area of the earth’s surface using two different atmospheric pathlengths for every pixel. This feature facilitates the correction required for atmospheric absorption and emission to better than 0.15 K (Závody et al. 1995). The dual-view capability also means that a correction for tropospheric and stratospheric aerosols can be made based on the temperature difference between the nadir and forward views, as described by Závody et al. (1994).

For a thorough description of the ERS-1 ATSR instrument design and operation, the reader is referred to Edwards et al. (1990).

The primary products generated by the ATSR are nadir view and forward view high-resolution brightness temperature (BT) images derived from three infrared channels having a spatial resolution of 1.1 km at nadir and a swath of 512 km. The ASST is produced by averaging all of the cloud-free high-resolution BT data within 10 arcminute cells (AMCs) to give between 1 and 9 AMCs for the nadir and forward views depending on the amount of cloud cover. An ASST algorithm is then applied to the AMC data of the form

$$\text{ASST} = a_0 + \sum_{i=0}^{n} a_i T_i,$$

where $n$ is the number of BT channels used and $T_i$ is the BT measured in channel $i$. The coefficients $a_i$ have been determined by a multiple linear regression of BT data generated by an atmospheric transmission model (Závody et al. 1995) for a number of measured atmospheric temperature and humidity profiles that specify one of three ERS-1 ATSR “standard” atmospheres. The main characteristics of the ATSR standard atmospheres used in the ERS-1 ATSR ASST retrieval process are given in Table 2. Two ASST algorithms are then applied to the AMC data: a nadir ASST utilizing the nadir view data only and a dual-look ASST that uses both nadir
observations from 15 September to 1 October 1992 as none of the data used in this study have been climatological values using a 6-K threshold. GOSTA climatological values (Bottomley et al. 1990) using a 6-K threshold value. ASST data have been removed for periods of instrument operations including ERS-1 orbit maneuvers and ATSR detector outgassing. ASST data have been removed for periods of instrument operations including ERS-1 orbit maneuvers and ATSR detector outgassing.

1) The success of the radiative transfer model to account for all atmospheric effects, including the difficult problem of transient global stratospheric aerosol loading such as those generated from volcanic eruptions (e.g., Trepte et al. 1993; Saunders 1993; Reynolds 1993).

2) Differences between the actual atmospheric structure at the time of measurement and the regional standard atmospheric profile used in the determination of SSST retrieval coefficients (Barton 1995).

The ERS-1 ATSR ASST data used here are extracted from the ERS-1 ATSR ASST CD-ROM archive produced by Rutherford Appleton Laboratories (Murray 1995), which are generated by the SADIST v600 processing software (Bailey 1994). These data have been subject to the following quality control procedures.

1) ASST data have been removed for periods of instrument operations including ERS-1 orbit maneuvers and ATSR detector outgassing.

2) More than 10% of daytime ASST deviate from the global ocean surface temperature atlas (GOSTA) climatological values (Bottomley et al. 1990) using a 6-K threshold value.

3) More than 40% of nighttime ASSTs deviate from GOSTA climatological values using a 6-K threshold.

GOSTA monthly 1° climatology has been used to fill missing data where ASST data has been discarded due to points 2 and 3, which accounted for less than 0.3% of the entire ASST CD-ROM data archive, although none of the data used in this study have been climatologically filled. Due to the failure of the 3.7-μm channel on 27 May 1992, it is not possible to include the six-channel ERS-1 ATSR SSST algorithm in this analysis.

c. In situ ship data

The RRS James Clark Ross made near-continuous observations from 15 September to 1 October 1992 as part of the British Antarctic Survey (BAS) radiometric observations of the sea surface and atmosphere 1992 (ROSSA) program. Table 3 summarizes the relevant measurements made during this experiment, which is fully reported in Donlon and Robinson (1997). Radiometric SSST was measured by a Satellites International Limited (SIL) STR-100 infrared radiometer mounted on the forward mast of the James Clark Ross. The radiometer measured the SSST using an 11-μm bandpass filter and was internally calibrated every 2 min using two precision blackbody units following Thomas et al. (1995). A SeaBird thermosalinograph (TSG) was used to measure BSST accurately to better than plus or minus 0.02 K at a 5.5-m depth, although the resolution of these data are 0.1 K.

All ship data were transformed from geodetic to geocentric coordinates to conform with the ERS-1 ASST data, and each 30-s data record collected within plus or minus 12 h and geographically coincident with ATSR ASST were then averaged across the ASST pixel. Ship and satellite data were then compared by computing a temperature difference, ΔSST defined as

\[ \Delta SST_{(\text{alg,type})} = \text{ASST}_{\text{alg}} - \text{shipSST}_{\text{type}} \]  

where the subscript “alg” refers to either the dual (D) or nadir (N) ASST algorithm and the subscript “type” indicates the type of ship SST data that was used (BSST or SSST).

d. Quality control of validation dataset

There are several potential sources of error in any in situ SST validation dataset, including the warming of BSST measurements by the ship’s pumps and pipe system, calibration of the infrared radiometer, effects of cloud, and interference from the ship’s radio transmissions. BSST calibration data obtained using U.K. Meteorological Office “bucket” BSST samples and an inline thermistor at the TSG intake aperture confirm that warming of the BSST data was not detected. Calibration of the radiometer system followed the scheme described by Thomas et al. (1995), which has also been used by Kent et al. (1996). As we were able to measure the downwelling radiance using a second radiometer, the SSST data used here are directly corrected for sky radiance reflections at the sea surface. Measurements made in cloudy conditions have been rejected based on a combination of 1-min-average downwelling sky temperature measurements and visual cloud observations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Instrument</th>
<th>Accuracy</th>
<th>Precision</th>
<th>Height (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSST</td>
<td>SIL STR-100 radiometer</td>
<td>0.14 K</td>
<td>0.05 K</td>
<td>+16.5</td>
</tr>
<tr>
<td>Sky radiance</td>
<td>TASC0 THI-300 radiometer</td>
<td>0.25 K</td>
<td>0.1 K</td>
<td>+21.5</td>
</tr>
<tr>
<td>BSST</td>
<td>SeaBird TSG</td>
<td>0.1 K</td>
<td>0.02 K</td>
<td>-5.5</td>
</tr>
<tr>
<td>Solar flux</td>
<td>Kipp and Zonen CM-5 solarimeter</td>
<td>1 W m⁻²</td>
<td>1 W m⁻²</td>
<td>+16</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Cup anemometer</td>
<td>0.1 m s⁻¹</td>
<td>0.1 m s⁻¹</td>
<td>+16</td>
</tr>
</tbody>
</table>
made at 15-min intervals. A full description of the radiometer calibration and other ship measurements is given in Donlon and Robinson (1997).

Although the initial number of ATSR ASST coincidences was small, further quality control was undertaken for the following reasons.

1) All validation data occurring in areas characterized by strong temperature gradients (e.g., the northwest coast of Spain and Cape Verde Islands) have been rejected (section 2b). This accounted for a total of three cases.

2) Extremely cool ERS-1 ATSR nighttime data relative to ship observations have been rejected because the failure of the ATSR 3.7-μm channel. This channel was heavily relied on to identify nighttime cloud contaminated data because of the strong radiance to temperature relationship in the 3.7-μm region. Inclusion of cloud contaminated data would result in unrealistically cool ATSR ASST. A total of two cases were rejected for this reason.

3) There were clear incidences where the ship data were affected by diurnal warming in low wind speed conditions. In these cases, although the in situ SSST measurement is still an appropriate validation measurement when validating single pixel satellite observations, it is not possible to determine the spatial extent of the diurnal warming that is affecting the larger area covered by an ASST cell. Three cases were rejected for this reason.

4) Although the ATSR returned an ASST measurement, by the time that ship data were collected several hours from the satellite measurement, overcast cloud conditions prevailed. This occurred in one case.

5) There were cases where only a small number (less than 100) of ship data were collected due to instrumental failure or the ship track traversing only a small part of an ATSR ASST cell. This accounted for nine cases.

The final validation dataset used in this study consists of 14 of a possible 32 ERS-1 ATSR ASST data records together with associated ship observations located in the tropical and subtropical Atlantic Ocean 10°S, 33°W–20°N, 20°W during the period 23–29 September 1992.

3. Results

Figure 1 shows the position of the validation ERS-1 ATSR ASST cells used in this work, which have been labeled A–N. Table 4 provides further information for the individual validation cases and shows that three cases fulfill the temporal validation criteria of Minnett (1991), five more cases are within plus or minus 3 h of the satellite overpass, and only three cases exceed a temporal coincidence in excess of 10 h. Only five cases are daytime validations (cases C, G, H, M, and N), which have a maximum time difference of less than 4 h. In each of these cases the ship data were collected after the ERS-1 overpass that would have been overhead at approximately 1030 LT. Thus, the ATSR data would have been collected before the time of maximum solar heating, and a warming of the sea surface may have occurred by the time the ship was able to sample the same area (e.g., Fairall et al. 1996). However, we note that although there is a large spread of wind speed within the validation cases, including winds of less than 2 and greater than 15 m s⁻¹, the majority of cases have wind speeds greater than 5 m s⁻¹, which will prevent the formation of a warm diurnal layer. The mean ship BSST–SSST difference (ΔT) is only significant in one case, where ΔT is greater than 0.3 K. The mean cloud cover ranged between 1 and 6 oktas, although the individual ship records have been filtered for clouds, as described in section 2e. In each validation case, the number of 30-s average ship measurements is greater than 100.

Figure 2 plots the comparison between in situ SSST and BSST against the satellite observations for the dual (DASST) and nadir (NASST) ATSR ASST algorithms. In this plot, a perfect correspondence line has been drawn as a hashed line and error bars represent the variability within the average ship and satellite datasets: the ATSR error bar shows the rms deviation derived from the contributing AMC data, and the in situ error bar shows the rms deviation of the in situ SST. In all cases the ATSR data exhibit a cool bias relative to the ship data for a subtropical and equatorial temperature...
Table 4. Summary of the in situ data collected spatially coincident and contemporaneously with ERS-1 ATSR ASST during ROSSA 1992. Date is the validation date, ΔTime is the mean time difference between satellite and ship data, lat and long refer to the central latitude and longitude position of the ERS-1 ATSR ASST cell, ΔT is the mean ship BSST−SSST, $Q_s$ is the solar flux at the sea surface, $u$ is the wind speed at 10 m, and Cl is the amount of cloud cover in oktas. The number of observations refers to the final number of ship observations used for each validation case after filtering.

<table>
<thead>
<tr>
<th>Identification</th>
<th>Date</th>
<th>ΔTime</th>
<th>Lat (°)</th>
<th>Long (°)</th>
<th>ΔT (K)</th>
<th>$Q_s$ (W m$^{-2}$)</th>
<th>$u$ (m s$^{-1}$)</th>
<th>Cl (oktas)</th>
<th>Number of observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>23 Sep</td>
<td>-11.17</td>
<td>17.75</td>
<td>-22.25</td>
<td>0.04</td>
<td>3.8</td>
<td>3.9</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>23 Sep</td>
<td>-9.291</td>
<td>18.25</td>
<td>-22.25</td>
<td>0.07</td>
<td>0.0</td>
<td>2.4</td>
<td>5.4</td>
<td>320</td>
</tr>
<tr>
<td>C</td>
<td>23 Sep</td>
<td>1.071</td>
<td>20.25</td>
<td>-21.25</td>
<td>0.32</td>
<td>369.4</td>
<td>1.5</td>
<td>5.5</td>
<td>174</td>
</tr>
<tr>
<td>D</td>
<td>28 Sep</td>
<td>-2.691</td>
<td>-1.25</td>
<td>-30.75</td>
<td>-0.11</td>
<td>0.0</td>
<td>15.2</td>
<td>3.6</td>
<td>113</td>
</tr>
<tr>
<td>E</td>
<td>28 Sep</td>
<td>-1.407</td>
<td>-1.25</td>
<td>-30.25</td>
<td>-0.12</td>
<td>0.7</td>
<td>14.7</td>
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</tr>
<tr>
<td>F</td>
<td>28 Sep</td>
<td>0.361</td>
<td>-0.75</td>
<td>-30.25</td>
<td>-0.07</td>
<td>0.3</td>
<td>14.8</td>
<td>1.3</td>
<td>278</td>
</tr>
<tr>
<td>G</td>
<td>29 Sep</td>
<td>2.331</td>
<td>-7.75</td>
<td>-33.25</td>
<td>0.12</td>
<td>465.8</td>
<td>11.7</td>
<td>3.7</td>
<td>144</td>
</tr>
<tr>
<td>H</td>
<td>29 Sep</td>
<td>3.582</td>
<td>-7.75</td>
<td>-32.75</td>
<td>0.00</td>
<td>131.3</td>
<td>12.6</td>
<td>3.9</td>
<td>100</td>
</tr>
<tr>
<td>I</td>
<td>29 Sep</td>
<td>5.17</td>
<td>-7.25</td>
<td>-32.75</td>
<td>0.05</td>
<td>4.8</td>
<td>13.2</td>
<td>2.7</td>
<td>266</td>
</tr>
<tr>
<td>J</td>
<td>29 Sep</td>
<td>10.31</td>
<td>-6.25</td>
<td>-32.25</td>
<td>-0.12</td>
<td>0.2</td>
<td>12.7</td>
<td>1.2</td>
<td>119</td>
</tr>
<tr>
<td>K</td>
<td>29 Sep</td>
<td>11.57</td>
<td>-5.75</td>
<td>-32.25</td>
<td>0.04</td>
<td>0.2</td>
<td>12.7</td>
<td>2.5</td>
<td>101</td>
</tr>
<tr>
<td>L</td>
<td>26 Sep</td>
<td>-7.822</td>
<td>4.75</td>
<td>-28.25</td>
<td>0.05</td>
<td>4.1</td>
<td>11.8</td>
<td>4.5</td>
<td>257</td>
</tr>
<tr>
<td>M</td>
<td>26 Sep</td>
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<td>6.75</td>
<td>-27.25</td>
<td>-0.07</td>
<td>273.8</td>
<td>8.4</td>
<td>4.5</td>
<td>214</td>
</tr>
<tr>
<td>N</td>
<td>26 Sep</td>
<td>3.990</td>
<td>7.25</td>
<td>-27.25</td>
<td>-0.14</td>
<td>53.0</td>
<td>8.0</td>
<td>6.1</td>
<td>189</td>
</tr>
</tbody>
</table>

The range of 296–302 K. The smallest bias is found when comparing the DASST to the JCR SSST (skin = −0.539 K, bulk = −0.570 K), and the largest bias is for the NASST compared to the JCR BSST (skin = −0.778 K, bulk = −0.808 K).

Table 5 shows a summary of the comparisons between the different ERS-1 ATSR ASST algorithms and in situ data and clearly demonstrates that the mean bias between ship SSST and ATSR is reduced by about 0.25 K when using the technique of along-track scanning, thereby highlighting the benefits of the ATSR instrument concept. In these comparisons it should be remembered that only ASST data having both nadir and dual-view data have been used and, consequently, the larger bias found for the nadir-only algorithm is not attributable to the fact that nadir-only ASST tends to

![Fig. 2. Plot of in situ BSST and SSST observations vs ERS-1 ATSR ASST data cells. (a) SSST vs dual ERS-1 ASST, (b) SSST vs nadir ERS-1 ASST, (c) BSST vs ERS-1 dual ASST, and (d) BSST vs ERS-1 nadir ASST. Vertical error bars represent the rms deviation of the ASST 10-arcmin cells used to derive the ASST measurement, and the horizontal error bars represent the combined error of Eq. (1). The dotted line represents perfect correspondence between the ship and satellite data.](http://journals.ametsoc.org/doi/abs/10.1175/1520-0426(1998)015<0647:RVOEAT>2.0.CO;2?journalCode=jalt)
TABLE 5. Summary of mean comparison between ERS-1 ATSR ASST and in situ data collected during ROSSA 1992.

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Skin bias (K)</th>
<th>Skin rms (K)</th>
<th>Bulk bias (K)</th>
<th>Bulk rms (K)</th>
<th>∆skin − bulk (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual</td>
<td>−0.539</td>
<td>0.177</td>
<td>−0.570</td>
<td>0.122</td>
<td>0.031</td>
</tr>
<tr>
<td>Nadir</td>
<td>−0.378</td>
<td>0.222</td>
<td>−0.808</td>
<td>0.218</td>
<td>0.030</td>
</tr>
</tbody>
</table>

originate from regions of increased cloud cover, as suggested by Harrison and Jones (1993). It may, however, be the case that the dual-look algorithm benefits from better cloud flagging. In all cases the rms deviation between the ship temperatures and ATSR ASST is better than 0.25 K, and the rms deviation between ship BSST and the dual-ASST data give the lowest value of 0.122 K. Such small rms values are a vindication of the methodology used here to validate ERS-1 ATSR ASST data and demonstrate that the ATSR instrument is potentially capable of meeting the WCRP (1985) accuracy requirements of SSST less than 0.3 K in subtropical waters and less than 0.5 K in tropical waters. However, the fact that a significant bias between satellite and in situ data remains is of concern.

a. Investigation of the validation data

The data shown in Table 5 show that the difference between the ERS-1 ATSR ASST and either SSST or BSST ship data is extremely small, having a value of approximately −0.03 K. This is unexpected, as an SSST measurement should typically be about 0.3 K cooler than the BSST beneath, a phenomenon known as the skin temperature deviation (e.g., Schlüssel et al. 1990; Kent et al. 1996; Donlon and Robinson 1997). Use of in situ SSST validation measurements should therefore result in a smaller bias than if BSST were used when compared to ATSR SSST observations. In order to clarify why there is little difference between SSST and BSST validation measurements, Fig. 3 shows comparisons between ∆SSST [Eq. (2)] for each of ERS-1 ATSR ASST algorithms plotted against the mean wind speed measured by the James Clark Ross reduced to a standard height of 10 m following the procedure of Smith (1988). The importance of measuring in situ wind speed when validating satellite data using SSST has been discussed by Donlon and Robinson (1997), who show that at wind speeds greater than 10 m s⁻¹ the skin–bulk SST difference (∆T) reduces to a value of approximately zero because wind-induced turbulence prevents a thermal skin layer from stabilizing: surface renewal timescales are rapidly increased, and heat is effectively drawn from the ocean to the atmosphere by turbulent processes. Emery et al. (1997) demonstrate similar wind speed dependence using satellite data collocated with in situ BSST buoy observations in the Pacific Ocean, noting that a wind speed of approximately 5 m s⁻¹ marks the transition to negligible ∆T.

![Fig. 3](http://journals.ametsoc.org/doi/pdf/10.1175/1520-0426(1998)015<0647:RVOEAT>2.0.CO;2)
4 shows that 9 out of the 14 cases investigated here correspond to situations when the mean wind speed was greater than 10 m s$^{-1}$. The fact that $\Delta T$ is minimized due to the high wind speeds encountered during many of the validation cases and the BSST is approximately equal to SSST adds confidence to the results shown in Fig. 2. The low wind speeds (less than 2 m s$^{-1}$) measured as the James Clark Ross traversed across ASST cell C is the only case for which a significant $\Delta T$ is measured. The slightly higher rms values associated with the SSST comparisons can be explained by the variability of the measured SSST in high wind speeds, for example, the effect of large waves (Jessup and Hesany 1996) and the difficulty of obtaining high-quality observations in high wind speed conditions (Donlon and Robinson 1997).

Figure 4 plots the $\Delta$SST$_{alg,type}$ against the time difference between the ATSR overpass and the mean time of the ship validation data $\Delta$Time. There is no relationship between any $\Delta$SST$_{alg,type}$ and $\Delta$Time, which is further vindication of the validation methodology adopted in this work. This confirms that the criteria defined by Minnett (1991) for single pixel satellite measurements do not apply to the case of ATSR ASST data if validation regions are carefully chosen to avoid areas characterized by large atmospheric and oceanic variability.

Figure 5 plots $\Delta$SST$_{alg,type}$ against four other parameters contained in the validation dataset: cloud cover at the time of ship measurements (from 15-min visual observations), cloud cover at the time of satellite overpass (the number of AMC data cells used in the ASST derivation is a coarse measure of the amount of cloud cover present in the ASST region at the time of satellite overpass), the position of the satellite measurement with reference to the ATSR swath, and the mean temperature difference between the forward and nadir views (view difference). As the ATSR returns an SSST measurement, we only show comparisons for $\Delta$SST$_{alg,SSST}$ in Fig. 5, which can be considered a review of the validation parameter space used in this study and highlights the fact that the validation data encompass a broad range of conditions.

Figures 5a and 5b demonstrate that there is no clear relationship between $\Delta$SST$_{alg,type}$ and the amount of cloud cover observed from the James Clark Ross at 15-min intervals. Figures 5c and 5d show that there is also no relationship between $\Delta$SST$_{alg,type}$ and the number of AMC used to derive the ASST measurement. These results suggest that the cloud clearing algorithms used in the ATSR SADIST v600 processing scheme are robust (ignoring the nighttime ASST cases that have already been rejected according to section 2e).

The ATSR uses five different sets of SSST retrieval coefficients to account for the different atmospheric pathlengths across the instrument swath. The mean across-track band number (ATBN) describes the average position of all the AMC data in the ATSR swath used to derive the ASST SSST measurement. Figures 5e and 5f plot $\Delta$SST$_{alg,type}$ against the mean ATBN, which demonstrates that the ASST cells used in this validation are spread across only ATBN bands 1–4 and that no ASST data originate from the extreme edges of the ATSR swath. No clear relationship is seen in either of these plots.

Finally, Figs. 5g and 5h plot $\Delta$SST$_{alg,type}$ against the average temperature difference between the dual and
nadir AMC. Typically, for clean air conditions, view differences range between −1.0 and 0 K, and high view difference values are an indication that atmospheric aerosols are making a significant contribution to the ASST measurement (Zavody et al. 1994). In this case, the data show that a mean view difference ranging between −0.1 and 0.6 K was present and indicate that there is a significant atmospheric aerosol presence during the ROSSA 1992 experiment.

b. Investigation of ERS-1 ATSR cool bias using view difference data

The effect of atmospheric aerosols on satellite SST retrievals results in an SST measurement that has a cool bias because the upwelling radiation from the sea surface is first absorbed by the aerosol (which is often located in the middle–upper troposphere or lower stratosphere) and reradiated at the cooler aerosol temperature.
Figure 6. Hovmoeller diagram of ERS-1 ATSR ASST dual–nadir view difference data along the 30°W meridian from 70°S to 70°N for the period August 1991–July 1995.

(May et al. 1992). In August 1991 Mount Hudson, located at 46°S, 73°W in southeast Chile, produced a substantial plinian volcanic eruption, injecting large amounts of ash aerosol into the middle atmosphere. In June 1991 an even larger dacitic volcanic eruption of Mount Pinatubo, located in the Phillipine islands (15°N, 120°E), injected huge amounts of aerosol into the troposphere and stratosphere that rapidly spread to 20°N–20°S, attaining global coverage in approximately 1 year (Reynolds 1993).

If it were not overshadowed by the magnitude of Pinatubo, the Mount Hudson eruption would have been a significant event alone. The effect of the Hudson and Pinatubo aerosol on the operational retrieval of SST using the NOAA AVHRR in the tropical regions was dramatic, resulting in an AVHRR SST cool bias greater than 1.0 K, which required a significant modification to the AVHRR multichannel SST (MCSST) retrieval coefficients (Reynolds 1993).

Figure 6 presents a Hovmoeller diagram of all available ERS-1 ATSR monthly mean view difference data (dual–nadir ASST) for a transect 70°N–70°S located in the mid-Atlantic Ocean at 30°W. A 30°W transect line was chosen to be most representative of the validation dataset used in this study. The data shown span the period starting in August 1991 and continuing to July 1995, as derived from the ERS-1 ATSR ASST CD-ROM archive. Darker shades represent cooler ATSR view differences, and lighter shades denote warmer view difference data, which is indicative of atmospheric aerosols. The rectangular features present in these data are a consequence of the 3-day orbit used by the ERS-1 spacecraft, resulting in incomplete earth coverage. The blank region located at 55°N running throughout the dataset is because there is no ATSR forward view data available preventing the computation of a view difference value.

Several regions of Fig. 6 show high view difference values indicative of atmospheric aerosol, and the Hudson–Pinatubo aerosol is clearly visible between 50°S and 50°N from August 1991 to November 1992. Of particular interest is the spatial extent of the aerosol effect delineated by a change in the sign of the view difference signal. An example of this effect is seen from August 1991 to February 1992 in the latitude range of 40°–60°N. By mid-1993, the effect of the Hudson–Pinatubo aerosol cloud effect is diminished in the midlatitude regions and Southern Hemisphere.

There are three other warm view difference events seen in Fig. 6, occurring at a latitude centered at 18°N.
that exhibit a seasonal cycle occurring in June and July of 1993, 1994, and 1995. These events are associated with large bursts of Saharan dust moving westward across the Atlantic Ocean, as described by Ott et al. (1991) and May et al. (1992). Thus, the validation data used in this study include the effect of Mount Hudson, Mount Pinatubo, and Saharan dust outflow contributing to the bias seen in Fig. 2. Based on Fig. 6 and referring to Table 1, we note that nearly all of the major ERS-1 ATSR validation results published to date were probably contaminated by the Hudson–Pinatubo events shown in Fig. 6 and that several campaigns were based in the tropical Atlantic region where the Hudson–Pinatubo effect was greatest. Apart from the results of Barton et al. (1995), all of the validation campaigns show the ERS-1 ATSR to have a cool bias when compared to in situ BSST, climatological analyses, or in situ SSST. Our data use the most recent ERS-1 ATSR processing algorithms (SADIST v600) and show that a ~0.54-K cool bias was still present in ERS-1 ATSR ASST two-channel nadir and dual-ASST data during September 1992.

The Barton et al. (1995) data are interesting in that they demonstrate the ERS-1 ATSR to have a warm bias relative to in situ SSST measurements made off the east coast of Australia. At the time of these validation campaigns, Barton et al. (1995) report a small aerosol effect seen in routine visible channel AVHRR data, suggesting that some aerosol contamination was present during the validation campaign period. However, they also compute a three-channel dual-view ASST algorithm using the now-defunct ERS-1 ATSR 3.7-μm channel that does have a cool bias of ~0.2 K in keeping with other results. A second ERS-1 ATSR view difference Hovmoeller diagram was constructed along a line at 155°E to investigate the aerosol signal in the region of the Barton et al. (1995) measurements. This region did not have a clear aerosol signal as seen in the Atlantic Ocean shown in Fig. 6 and has therefore not been reproduced. We summarize that the Barton et al. (1995) results represent the only validation dataset that does not include the significant effects of the Hudson–Pinatubo aerosol.

4. Discussion

The results presented here add to the growing list of already published ERS-1 ATSR validation data and explore the methodology for validating large area datasets such as the ATSR ASST product. The main limitations of the results presented are the small number of comparisons and the regional and seasonal nature of the data set. This is a consequence of the narrow swath width used by the ERS-1 ATSR, the effects of clouds, poor weather, and the difficulty of maintaining and operating a well-calibrated radiometer while at sea. However, because these results include in situ SSST measurements, they are directly comparable to the ERS-1 ATSR ASST product. Further, the validation dataset traverses the tropical Atlantic Ocean, which places the heaviest demands on the atmospheric correction algorithms because of the large atmospheric water vapor loading characteristics of tropical regions.

Our analysis of the validation parameter space could find no strong relationship between any of the diagnostic confidence data supplied with the ASST product. In particular, the time difference between satellite and ship coincidence, the ATBN and the number of AMC appear to be of little consequence to the validation dataset. This is due in part to the choice of open-ocean areas typified by small horizontal temperature gradients and confirmed by the low variability of BSST within each cell (less than 0.1 K, except for one case). Note that the SSST variability tends to be greater than the BSST variability due to the extremely transient nature of the thermal and surface renewal processes at air–sea interface (Jessup and Hesaney 1996).

Even though all of the ERS-1 ATSR ASST algorithms produce an ASST value that is biased cool relative to the ship data, all of the rms values are low (less than 0.3 K), suggesting that the ERS-1 ATSR ASST products are relatively well calibrated. The effect of using the along-track scanning technique to produce a dual-view ASST product rather than a traditional two-channel nadir-only measurement is to reduce the cool bias by over 0.2 K and slightly improve the rms value, and these data provide a clear demonstration of the advantage offered by using along-track scanning in difficult atmospheric conditions such as the Tropics.

The small difference between SSST and BSST validation bias values is due to high wind speeds effectively preventing the formation of a thermal skin temperature gradient at the ocean surface by increasing the near-surface turbulence. The fact that such small differences exist between the BSST and the SSST add confidence not only to the in situ dataset (a large difference would suggest a bias in the ship SSST data) but also to the validation dataset as a whole. Considering the possibility of using one of the many skin temperature parameterizations currently available to convert BSST measurements to SSST at high wind speeds, it is easily seen that such a correction would make an additional erroneous contribution to the BSST validation data rather than a corrective one. Clearly, further research, including the collection of high-resolution precision ocean–atmosphere datasets in a variety of conditions, is required to clarify the critical wind speed at which differences between the BSST and SSST may be ignored.

The rapid dissemination and large spatial scale of the Hudson–Pinatubo aerosol cloud is clearly seen in Fig. 6, which, combined with the small but strong Saharan dust aerosol feature located at approximately 20°N, should explain the ATSR cool bias discussed above. The dual-view capability of the ERS-1 ATSR offers the capacity to respond to unexpected atmospheric conditions without requiring any in situ measurements, although confidence in the resulting ASST product can only be gained by validation against in situ measurements. Zá-
vody et al. (1994) describe a scheme for detecting and directly correcting ERS-1 ATSR ASST measurements for the presence of atmospheric aerosols. The technique relies on a proportional relationship between the aerosol concentration and the temperature difference computed by subtracting the dual-ASST from the nadir-only ASST data. This approach contrasts with the use of in situ buoy observations to make a retrospective recalibration of aerosol-contaminated satellite SST data (Reynolds 1993). Figure 7 shows the results obtained when implementing the view difference aerosol correction scheme proposed by Zavody et al. (1994). A value of 0.46 has been used as a multiplier to the view difference value as suggested by Zavody et al. (1994) for the dual-view two-channel algorithm. Comparing Fig. 7 to Fig. 1a, we find that the bias between ship and satellite has decreased negligibly by approximately 0.1 K and that the rms deviation has now increased. Although the correction has reduced the bias, it is not sufficient to account for the differences between the in situ and satellite data, suggesting that further work is required before this type of correction strategy is implemented.

5. Conclusions

In situ radiometric and subsurface bulk sea surface temperature observations have been used to validate the ERS-1 ATSR average sea surface temperature products in the tropical and midlatitude Atlantic Ocean. Fourteen ERS-1 ATSR ASST cells located in the region 10°S, 33°W–20°N, 20°W have been matched to in situ data within plus or minus 12 h of the satellite overpass. Both the dual-view and nadir-only ERS-1 ASST algorithms show a cool bias when compared to in situ data having values of −0.5 and −0.7 K, respectively. Low rms differences of less than 0.3 K between satellite and in situ observations are found and the two-channel dual-view algorithm has the lowest scatter of 0.122 K. These data are consistent with other validation campaigns and further demonstrate the advantages of along-track scanning providing a dual-view SSST algorithm over the typical single view nadir-only SSST retrieval.

Unexpected small differences of less than 0.05 K between the in situ bulk and skin temperatures can be explained by high wind speeds that increase turbulence at the air–sea interface, thus preventing the formation of a large thermal skin temperature gradient. However, this should not be regarded as justification for relying on BSST rather than SSST to validate the ATSR in the future. The use of BSST typically introduces a cool bias to the data, and further observations are required before we can be sure what is the threshold wind speed above which such a bias is acceptably small.

Most of the ERS-1 ATSR cool bias can be explained by the presence of aerosols from the Saharan desert and from the volcanic eruptions of Mount Hudson and Mount Pinotubo. The temperature difference between the ERS-1 ATSR forward and nadir views suggest that many of the ERS-1 ATSR validation campaigns took place when the atmosphere was contaminated by the large aerosol cloud generated by these volcanic eruptions. It is probably unwise to assume that the cool bias discussed in this paper persisted for the lifetime of the ERS-1 ATSR mission. In order to reduce the bias where it exists in the ATSR dataset, one approach is to use the dual–nadir ASST difference to detect and account for the presence of atmospheric aerosol, as described by Zavody et al. (1993). However, the effect of such a correction is negligible when applied to these data. In the longer term, to prevent the corruption of future ATSR-type datasets there is a need to widen the scope of the retrieval algorithms to include typical volcanic and localized seasonal aerosol scenarios.

There remains a serious shortage of radiometric validation data because of the difficulties associated with measuring the skin temperature of the sea having a wide spatial and temporal coverage. As suggested by Thomas and Turner (1995), a new SSST validation approach is required to increase the number of ERS-1 and ERS-2 ATSR SSST validation data—possibly by using semiautonomous radiometer systems mounted on a ship-of-opportunity program. Donlon et al. (1997) report reasonable success using a prototype radiometer system specifically developed to explore the feasibility of such an urgently required system. However, further concerted action is required to develop a global network of SSST measurements to ensure the robust validation of satellite-derived SSST maps for use in climate studies.

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