Validation of the AATSR Meteo Product Sea Surface Temperature

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ABSTRACT

The Advanced Along Track Scanning Radiometer (AATSR) Sea Surface Temperature (SST) Meteo product, a fast-delivery level-2 product at 10 arc min spatial resolution, has been available from the European Space Agency (ESA) since 19 August 2002. Validation has been performed on these data at the Met Office on a daily basis, with a 2-day lag from data receipt. Meteo product skin SSTs have been compared with point measurements of buoy SST, a 1° climate SST analysis field compiled from in situ measurements and Advanced Very High Resolution Radiometer (AVHRR) SSTs, and a 5° latitude-longitude 5-day averaged in situ dataset. Comparisons of the AATSR Meteo product against Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) SSTs are also presented. These validation results have confirmed the AATSR Meteo product skin SST to be within ±0.1 K of in situ data.

Comparisons of the AATSR skin SSTs against buoy SSTs, from 19 August 2002 to 20 August 2003, give a mean difference (AATSR – buoy) of 0.04 K (standard deviation = 0.28 K) during nighttime, and a mean difference of 0.02 K (standard deviation = 0.39 K) during the day. Analyses of the buoy matchups have shown that there is no cool skin effect observed in the nighttime observations, implying that the three-channel AATSR product skin SST may be 0.1–0.2 K too warm. Comparisons with TMI SSTs confirm that the lower-latitude SSTs are not significantly affected by residual cloud contamination.

1. Introduction

The Advanced Along Track Scanning Radiometer (AATSR) instrument upon the Environmental Satellite (Envisat) aims to observe skin sea surface temperature (SST) to within 0.3-K accuracy (within 1-sigma limits) in order to continue the collection of SST data begun by the Along Track Scanning Radiometer (ATSR)-1 and -2 instruments upon the European Remote Sensing-1 and -2 (ERS-1 and -2) satellites since 1991. Meteo product data have been gathered in near–real time at the Met Office (United Kingdom) from AATSR since 19 August 2002. Daily monitoring of these AATSR skin SSTs has been performed, and further validation against various climate datasets undertaken. A skin to bulk conversion is estimated using the Fairall model (Fairall et al. 1996) to account for the difference between skin and “bulk” SST at a depth of around 1 m. These bulk SSTs are more suitable for comparison against buoy SSTs and other in situ–based climate datasets.

Other validation activities involve the comparison of European Space Agency (ESA) skin SSTs against those observed from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). While the Met Of-
face gathers and monitors ESA skin SSTs, it also separately calculates the skin SST from the top-of-atmosphere brightness temperatures also received using the retrieval coefficients supplied by ESA. These values of skin SST, calculated locally, are compared with the ESA product on a daily basis to ensure consistency of the ESA processing.

Along with the skin to bulk calculations, a diurnal thermocline model is used at the Met Office, based on the Kantha and Clayson model (Kantha and Clayson 1994), in order to gain knowledge of possible diurnal surface warmings, which are then flagged within the output data. These typically occur more frequently in low latitudes, and in conditions of high insolation and low wind speeds. SSTs influenced by these surface warmings are less characteristic of the overall heat budget of the ocean and so should be excluded or corrected before being assimilated into climate SST datasets.

This paper details the validation carried out on AATSR skin SSTs from 19 August 2002 to 20 August 2003, the first year of AATSR data, and analyses the results. Additional results are reported on SST retrieval algorithm comparisons, mean biases in retrieved SSTs, and finally future work and conclusions.

2. Data used and processing methodology

a. AATSR data

The AATSR instrument was launched upon the polar-orbiting Envisat satellite in March 2002, and is designed for dual-view, high-resolution SST retrievals, having a 1-km spatial resolution at nadir. The AATSR Meteo product (ATS_MET_2P; ESA 2004) is a fast-delivery level-2 product designed for use in meteorological studies, which contains spatially averaged top-of-atmosphere channel brightness temperatures and skin SSTs in cloud-cleared 10 arc min cells. The SST retrieval uses ESA’s prelaunch coefficient set, for both the nadir-view and for the dual-view combination (refer to section 2e for information on the SST retrieval). In each case, only 11- and 12-μm data are used during the day, but valid 3.7-μm data (unaffected by reflected solar radiation) are also included during the night. The product validation described here has used only the dual-view SST both for day and nighttime.

Envisat makes 14 orbits of the earth each day, of which data from up to 10 can be downloaded directly from the Kiruna receiving station. Meteo product files encoded in binary universal form for representation of data (BUFR) format for these data have been made available in near–real time (NRT) on the Kiruna FTP site from 19 August 2002. The remaining orbits are generally out of the receiving range of the Kiruna station and so their data are not added to the Kiruna FTP site. These “Kiruna blind” orbits contain nighttime observations over most of the Atlantic and part of the east Pacific Ocean and daytime data across parts of the Indian and the west Pacific Oceans. However, the Svalbard receiving station was introduced into the data distribution chain on 7 November 2002, receiving the Kiruna-blind orbits, which have been sent in real time to a second FTP site at ESA’s European Space Research Institute (ESRIN). A few other gaps in the data availability have resulted from satellite and ground-based technical problems, as detailed in O’Carroll et al. (2004).

b. Buoy data

In this study, AATSR skin SSTs, converted to a bulk SST at around 1-m depth, have been compared with moored buoy, ship, and drifting buoy SST measurements. The buoy observations are obtained on a weekly basis via the Global Telecommunications System, after which the buoy matchup processing at the Met Office (B. Candy and L. A. Horrocks 2002, personal communication) is performed and analyzed. The buoy matchup database is a collection of 79 different fields detailing the buoy observations, AATSR observations, and atmospheric conditions from numerical weather prediction (NWP) model analyses. The dataset from which these analyses are presented in this paper are from 19 August 2002 to 20 August 2003.

A weekly quality control of individual buoys was performed, in which the mean difference between reported SST and the Met Office NWP analyzed SST field was considered. Buoys that showed a mean weekly bias of more than 1.2 K or standard deviation of greater than 0.6 K compared with NWP SST were screened out. The thresholds were chosen as it is expected that the biases between AATSR and NWP SSTs should be less than 1 K with a standard deviation of less than 0.5 K. Additionally, each single buoy SST report was required to agree within gross limits (8 K) with climatology. Analyses have shown that a sensible threshold limit would lie within the range 3–5 K for comparisons with climatology; however, a more conservative gross limit of 8 K was chosen in this case. On the basis of these tests, up to 25% of the buoy reports received each week were filtered out. Although these tests are designed to remove unreliable buoy SST observations, it must be considered that they may also have some impact of artificially improving the results of the comparisons.

The matching up of the two observation types involves choosing buoy observations that are located within the 10 arc min resolution grid box of the AATSR observation (or cell). The time difference between the
two data types must be within ±3 h. In the event that two buoy SSTs are matched up to the same AATSR observation, the buoy observation closest in time to the AATSR observation is chosen. Efforts to screen out cloudy observations are made by checking a quality control (QC) word within each observation record. The QC word contains information on the quality of the observation classified during the Met Office processing of the AATSR skin and bulk SSTs. This QC was assigned from various checks. The first check considers the number of 1-km pixels contributing to each AATSR 10 arc min cell. If the number of pixels is less than 15% of the total number of pixels possible in a cell at a particular latitude, then the observation box is deemed to be cloudy. Three further tests consider the difference between dual-view and nadir-only two-channel and three-channel retrievals. If the differences are greater than a threshold then this is recorded in the QC word. Studies of histograms of the differences between coincident dual-view two-channel skin SSTs (hereafter D2) and dual-view three-channel skin SSTs (hereafter D3) retrievals ensures that the threshold chosen is conservative enough to not exclude good data. Additionally, careful screening of duplicate matchups, where the same AATSR observation matched with consecutive reports from a single buoy, was performed. Then the matchup with the smallest time difference is chosen. The number of matchups per week varied according to gaps in AATSR provision, but could be up to ~200.

c. MOHSST and HadISST analyses

Two of the climate datasets for global SST provided by the Met Office Hadley Centre are used routinely in AATSR validation: the Met Office Historical Sea Surface Temperature (MOHSST) and the Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST). MOHSST (Parker et al. 1995) is a gridded dataset of sea temperatures at a depth of 1–10 m. Its data are quality controlled in situ observations from ships and buoys, averaged at 5° spatial resolution, usually available as monthly SST anomalies. A 5-day average version of the MOHSST dataset was made available to us in near–real time to provide a gross validation of AATSR every 5 days. The 10 arc min AATSR SSTs are averaged over the same 5-day periods at 5° spatial resolution for their validation against MOHSST.

The HadISST (Rayner et al. 2003) dataset is a globally complete 1° spatial resolution sea ice and SST analysis field, produced on a monthly basis, available from 1870 to two months before the current date. The SST data that contribute to HadISST come from ships, buoys, and the Advanced Very High Resolution Radiometer (AVHRR) on the National Oceanic and Atmospheric Administration (NOAA) satellites. Before combining the in situ and AVHRR data, the latter are bias-corrected relative to the in situ data. The ship and buoy data are averaged into a 1° latitude–longitude globally complete field, from which a nighttime AVHRR SST field is subtracted. The difference is smoothed to create a bias field for which the AVHRR data can be corrected. The corrected AVHRR and in situ fields are then averaged together onto a 2° latitude–longitude grid that is reconstructed as a 1° spatial resolution field, with gaps covered by reduced-space optimal interpolation (Kaplan et al. 1997) and sea ice fields added to produce the HadISST1 field.

AATSR comparisons have been made against the monthly HadISST1 fields for each calendar month from September 2002 to August 2003 inclusive. Daily 10 arc min AATSR SSTs are subtracted from daily (1961–90) climatology SST fields which are at 1° spatial resolution. These anomalies are averaged to daily 1° spatial resolution and subsequently averaged over the monthly period. A calendar monthly climatological SST (1961–90), averaged over the same period at 1° resolution, is added to this, creating a monthly AATSR SST, the spatial resolution of which matches the HadISST1 analyses. The averaging of the anomalies, rather than actuals, is performed in this way to reduce representativity errors in the analysis.

d. TRMM Microwave Imager

The TMI instrument is on board TRMM, a joint National Aeronautics and Space Administration (NASA) and National Space Development Agency of Japan (NASDA) mission, which was launched in November 1997. The TRMM satellite moves from west to east in an inclined orbit providing data at various local times between latitudes 40°S and 40°N. The TMI is a conical scan microwave radiometer with channels at five separate frequencies: 10.7, 19.4, 21.3, 37, and 85.5 GHz and a spatial resolution of about 50 km at 10.7 GHz. The 10.7-GHz channel is used to retrieve SST as it is insensitive to water vapor and cloud. This gives an advantage over infrared sensors as cloudy (although nonprecipitating) coverage can be viewed with the TMI. In addition to precipitation, the TMI does have sensitivities to sea surface roughness and so the microwave SST retrieval attempts to account for these effects. Details of the physical retrieval algorithm, which aims to derive SST to an accuracy better than 0.5 K, are given in Wentz and Meissner (2000). The TMI SSTs have been retrieved as daily averaged files from the Remote Sensing Systems Web site (http://www.ssmi.com).
TABLE 1. Regression coefficients for the calculation of skin SST from AATSR brightness temperatures. Three versions of weights are shown for different latitude bands. (Latitude band 1 lies between absolute latitudes 90° to 62.5°; band 2 between 37.5° and 62.5°; and band 3 between 12.5° and 37.5°.) Center and edge refer to swath position. These coefficients are valid from the start of AATSR operations to spring 2005.

<table>
<thead>
<tr>
<th>View</th>
<th>Swath</th>
<th>Lat band</th>
<th>Offset term</th>
<th>12 nadir</th>
<th>11 nadir</th>
<th>3.7 nadir</th>
<th>12 forward</th>
<th>11 forward</th>
<th>3.7 forward</th>
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<td>Nadir2</td>
<td>Center</td>
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<td>3.439 580</td>
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<tr>
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<td>3.506 970</td>
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<td>0.654 392</td>
<td>-0.731 561</td>
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<td>0.645 261</td>
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<td>5.592 140</td>
<td>-3.263 510</td>
<td>0.0</td>
<td>-3.300 600</td>
<td>1.953 710</td>
<td>0.0</td>
</tr>
<tr>
<td>Dual 2</td>
<td>Edge</td>
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<td>4.949 140</td>
<td>7.104 840</td>
<td>-4.250 130</td>
<td>0.0</td>
<td>-4.786 370</td>
<td>2.911 380</td>
<td>0.0</td>
</tr>
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<td>Dual-3</td>
<td>Center</td>
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<td>0.440 050</td>
<td>-0.657 117</td>
<td>2.620 830</td>
<td>-0.226 492</td>
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<td>Edge</td>
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<td>1.001 520</td>
<td>0.587 045</td>
<td>-0.841 773</td>
<td>3.222 820</td>
<td>-0.361 424</td>
<td>0.532 535</td>
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</tbody>
</table>

e. Met Office processing of skin to bulk SST differences

The Met Office receives the AATSR Meteo product containing skin SST, brightness temperatures (BTs) and other related information in near–real time. On a daily basis, the skin SSTs at the Met Office are retrieved from BTs using ESA prelaunch retrieval coefficients (shown in Table 1) and compared with the ESA skin SSTs, which are retrieved using the same retrieval coefficients, and comparisons made to check for any inconsistencies. To date, these comparisons have shown that these skin SST retrievals agree exactly. Note that the nadir-view SST coefficients are latitude dependent while the dual-view coefficients are global. These radiative skin temperatures are retrieved from satellite observations by linear combination of BTs measured in different thermal channels and or views, multiplied by appropriate regression coefficients (e.g., Zavody et al. 1995; Merchant et al. 1999). Four different derivations of the approximation can be made dependent on the number of channels and views used in the regression. For the forward (F) and nadir (N) views, and with channels at 3.7, 11, and 12 μm the derivations of the retrieved skin temperature ($T_S$) become

$$T_S^{du,3} = a_0 + a_1 T_{11}^N + a_2 T_{11}^F + a_3 T_{3.7} + a_4 T_{11}^F + a_5 T_{12}^F + a_6 T_{3.7}^N$$  \hspace{2cm} (2.1a)

$$T_S^{du,5} = b_0 + b_1 T_{11}^N + b_2 T_{11}^F + b_3 T_{3.7}^N$$  \hspace{2cm} (2.1b)

$$T_S^{du,2} = c_0 + c_1 T_{11}^N + c_2 T_{12}^F + c_3 T_{11}^F + c_4 T_{12}^F + c_5 T_{12}^N$$  \hspace{2cm} (2.1c)

$$T_S^{du,2} = d_0 + d_1 T_{11}^N + d_2 T_{12}^N$$  \hspace{2cm} (2.1d)

where Eqs. (2.1a) to (2.1d) are relevant to the dual-view three-channel, single-view three-channel, dual-view two-channel, and single-view two-channel retrievals, respectively; $T_i$ are the brightness temperatures measured in each of $n$ channels and views, and $a$, $b$, $c$, and $d$ are the regression coefficients. For daytime data, a two-channel retrieval is necessary due to the 3.7-μm channel having a solar contribution to its signal during the daytime. The coefficients are weighted according to the pixel position in the swath and latitude.

These Met Office–derived skin SSTs are then processed to a bulk SST, which is here defined to be the temperature of the ocean at around 1 m in depth. This is done using the Fairall model (Fairall et al. 1996) of the skin effect and is necessary because the satellite observes a radiative skin temperature that is most fre-
f. Error estimation

We attempt to assess the uncertainty in each two- or three-channel bulk SST retrieval. The uncertainties are within the 10 arc min resolution cells, with NWP fluxes and wind observations needed for inclusion in the models. Such predictions are flagged in the observation record and affected observations are not included in further analyses.

A diagram showing the processing scheme at the Met Office and how the data are received from ESA is shown in Fig. 1. The validation datasets used are measures of the bulk SST, and so comparisons of AATSR bulk SST against our validation datasets have been made to assess indirectly the accuracy of the skin SST analyses.

**Table 2a. List of contributions to final error estimation value.**

<table>
<thead>
<tr>
<th>Tests to calculate error components</th>
<th>Error component</th>
<th>Assigned error (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The number of pixels making up each 10 arc min cell</td>
<td>Npixels_error</td>
<td>0.9, 0.7, 0.5, 0.3, 0.1</td>
</tr>
<tr>
<td>Error contribution from SST algorithm</td>
<td>Retrieval_error</td>
<td>Dual-view: two channel = 0.1, three channel = 0.05</td>
</tr>
<tr>
<td>Error contribution due to type of skin model used</td>
<td>Bulk_error</td>
<td>0.1 (subsequently replaced by results in Table 2b from 0.1; Horrocks et al. 2003)</td>
</tr>
<tr>
<td>Do we consider that sea ice exists within the observation cell?</td>
<td>Ice_error</td>
<td>0.1</td>
</tr>
</tbody>
</table>
estimated partly to allow AATSR data to be assimilated into the HadISST analyses. The method uses a variety of factors and is intended to evolve.

The error estimate (or uncertainty) for each observation is calculated in kelvins, and has contributions as listed in Table 2a. The final error (in kelvins) is computed as the square root of the sum of the squares of all the components of individual errors.

\[
\text{Final error} = \sqrt{N_{\text{pixels\_error}}^2 + \text{ice\_error}^2 + \text{retrieval\_error}^2 + \text{bulk\_error}^2}
\]  
(2.2)

where \(N_{\text{pixels\_error}}\), \(\text{ice\_error}\), \(\text{retrieval\_error}\), and \(\text{bulk\_error}\) are given in Table 2a.

The \(N_{\text{pixels\_error}}\) describes the number of clear pixels contributing to a 10 arc min cell, which has an impact on the quality of the observation (due to the varying amounts of cloud in the cell). This test sets a higher error to those cells that have fewer clear pixels contributing to them. This component is partly a representivity error, and will also depend on the cloud-clearing method used. If the number of nadir pixels in a 10 arc min cell is less than \(A \times \text{maxpix} \times \cos(\text{latitude})\), then \(N_{\text{pixels\_error}}\) is assigned as a particular error. The test is performed with \(A\) varying as one of 0.9, 0.7, 0.5, 0.3, or 0.1. Whichever threshold the number of nadir pixels is just less than, then the \(N_{\text{pixels\_error}}\) is then set to either \(\text{pix\_pt1\_thresh}\), \(\text{pix\_pt3\_thresh}\), \(\text{pix\_pt5\_thresh}\), \(\text{pix\_pt7\_thresh}\), or \(\text{pix\_pt9\_thresh}\) (which are defined as 0.1, 0.3, 0.5, 0.7, 0.9 dependent on the value of \(A\), respectively). The value of \(\text{maxpix}\) is 51, which is roughly equal to 15% of the maximum number of pixels that can be in a cell. The test is dependent on the cosine of the observation latitude due to the latitude dependent nature of the maximum number of pixels in a cell. When the number of nadir pixels is greater or equal to \(A \times \text{maxpix} \times \cos(\text{latitude})\), then \(N_{\text{pixels\_error}}\) is set to 0 K.

If the derived AATSR dual-view skin SST is less than 274 K, then \(\text{ice\_error}\) is set equal to 0.1 K as shown in Table 2a, otherwise \(\text{ice\_error}\) is equal to 0 K. Although this may well be a bias rather than a random error, it still represents an increased uncertainty in the AATSR
measurements close to the ice edge. The retrieval_error is simply set to the values listed in Table 2a, dependent on whether a three-channel or two-channel SST retrieval has been performed. The bulk_error for the Fairall model (Fairall et al. 1996) is used to describe the skin to bulk temperature difference error and is listed in Table 2a. These values have been used with the processing of data presented in this paper. However, further research has been done since to collate information on skin SST retrieval errors, which is reported in Horrocks et al. (2003), and should be applied to future AATSR processing. This new scheme combines the retrieval_error and the bulk_error into the “bulk SST random error” as outlined in Table 2b.

3. Meteo product results

a. Retrieved AATSR SSTs

Global plots of daily and monthly sea surface temperature from the Meteo product have been produced throughout the validation period. As an example the dual-view skin SST for 3 June 2003 is shown in Fig. 2. On this day, all 14 orbits of the satellite were available.

The monthly mean SSTs have been plotted globally for three months in 2003, in Fig. 3. One clear feature is the cool SST in the southeast Atlantic to the west of South Africa, and in the northeast Pacific near the west coast of the United States, due to the cold Benguela and California Currents, respectively, in the oceanic gyres. The seasonal variations in SST can be seen in both hemispheres and the gaps in monthly mean SSTs suggest areas of persistent cloud cover, such as that in the southeast Pacific near the coast of Peru.

b. SST retrieval comparison

Different retrieval coefficients are used to calculate D2 and D3. A bias between these two retrievals has been observed to exist, showing that the nighttime skin SSTs are not cooler than daytime skin SSTs, as would normally be expected due to diurnal warming, implying that D3 retrievals may be too warm. From the period September 2002 to August 2003, results of mean differences show that nighttime D2 retrievals are cooler than nighttime D3 by ~0.14 K (σ = 0.2 K, number of cells = 9,511,981), where all skin SSTs calculated using ESA coefficients in Table 1 that pass a data confidence word are used. Figure 4 shows the latitudinal and longitudinal variation of D2 minus D3 differences averaged over the period from December 2002 to April 2003 that lead to a day–night bias in the retrievals. Further studies of D2 and D3 retrievals separately compared to in situ data, which have been corrected to a skin SST have shown that the D3 SSTs are warm by ~0.2 K and the D2 SSTs are warm by ~0.05 K.

Comparisons of the dual-view skin SSTs against the HadISST1 climate dataset show that the D3 values are similar to HadISST, while the D2 are cooler (see Table 3). The subset of statistics is taken where successful skin to bulk calculations are performed on the skin SSTs for September 2002–August 2003.

Biases in SST retrievals are caused by two main factors. First, there is a global mean bias in retrieved SST due to systematic errors contained in the process of deriving the retrieval coefficients using a Radiative Transfer Model (RTM). These errors arise from uncer-
tainties in the underlying spectroscopic parameters and the model formulation itself (Merchant and Le Borgne 2004). Second, there are systematic errors on the retrieved SSTs that can be considered in two parts. There is a bias to the prior (Eyre 1987) that varies with atmospheric state and arises as a different mean atmosphere (i.e., the mean of the diverse profile set) was used by the RTM to calculate the retrieval coefficients than the state at the time of satellite measurement. This leads to the retrieval errors varying with latitude, longitude, and season. An example of the variation of the D2 minus D3 bias with latitude is shown in Fig. 5. Additionally, there is also a contribution to this systematic error due to the brightness temperatures being nonlinearly related to SST and atmospheric state (C. J. Merchant 2004, personal communication).

4. Validation results

a. Comparisons with buoy SSTs

Figure 6 shows the coverage of buoy SSTs matched up with AATSR observations from 19 August 2002 to 20 August 2003. They were matched up when the buoy SST measurement was coincident in a 10 arc min AATSR observation cell, and where the two measurements were taken within 3 h of each other. A good global spread of matchups has been obtained for the period, but with fewer in the Southern Oceans, as expected.

Table 4 shows statistics (using an initial 3-sigma standard deviation test to screen out outliers) from these analyses of buoy SSTs matched up with AATSR skin and bulk SSTs during this same period. For these analyses, D3 SSTs during nighttime and D2 SSTs during the

<table>
<thead>
<tr>
<th>Retrieval type</th>
<th>Mean (skin SST – HadISST1), K</th>
<th>Std dev, K</th>
<th>No. in sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three channel</td>
<td>0.03</td>
<td>0.59</td>
<td>260 476</td>
</tr>
<tr>
<td>Two channel</td>
<td>−0.14</td>
<td>0.62</td>
<td>260 640</td>
</tr>
</tbody>
</table>

Fig. 4. Global map of mean D2–D3 skin SSTs.

Fig. 5. Variation of D2 minus D3 retrievals with latitude for an AATSR sample from December 2002 to April 2003.
day are used. The results display how a cool skin with respect to buoy SSTs are not observed at night, which leads to the conclusion that the nighttime (three channel) SST retrievals are too warm. The AATSR bulk SSTs are around 0.2 K warmer than the buoy SSTs, for both nighttime and daytime results. Although we conclude that the nighttime (three channel) bulk SSTs are too warm, the daytime (two channel) bulk SSTs show a similar warm bias against buoys. A diurnal thermocline model has been applied to the observations, which will attempt to flag affected observations; however, as it is a difficult problem, it is likely that not all thermoclines are detected, indicating that the D2 SSTs may be slightly too warm. If we do not wholly identify the occurrence of diurnal thermoclines in the observations, then we may expect to observe a warm skin during the day compared to the bulk SST. However, the only slight warm bias in the daytime AATSR (D2) skin SSTs of 0.02 K could indicate the D2 retrievals as being too cool, although it is difficult to assess without knowledge of the occurrence of diurnal thermoclines.

The accuracy of the buoy SST observations used within this study is not known; however, it is important to note that the errors on buoy SSTs may be significant. Emery et al. (2001) find that buoy SSTs have residual bias errors of ~0.15 K with root-mean-square errors closer to 0.5 K. It is possible that errors of this extent may impact the conclusion that the nighttime AATSR skin SSTs are too warm. However, attempts have been made to quality control the buoy SST observations as explained in section 2b. Additionally, there may be errors on the buoy SSTs due to uncertainties in the geolocation of the drifting buoy SSTs, which could impact the choice of matchup cell.

Figure 7 shows the time series for the year for skin and bulk SSTs against buoy SSTs. The results show that the buoy SSTs are closer to AATSR skin SSTs than they are to bulk SSTs, indicating a bias between the AATSR bulk SSTs and the buoy (bulk) SSTs. The daily mean differences of AATSR SSTs with buoy SSTs throughout the year are less than 0.5 K, where the majority is less than 0.3 K.

Regional samples from the buoy matchup files have also been analyzed in order to look for characteristics in the main ocean basins. Table 5a displays the statistics for the analyzed regions, and Table 5b describes the latitude–longitude boundaries of the regions chosen for a matchup period of 19 August 2002 to 20 August 2003. Statistics for bulk SST are only presented where a “good” skin–bulk temperature difference has been calculated, which is why a lower sample of bulk SSTs is included.

The regional AATSR bulk SSTs have a slightly higher mean difference from buoy SSTs than the skin SST differences. The nighttime AATSR bulk SST–buoy SST differences range from 0.16 to 0.32 K over most regions, with the exception of the North Atlantic where the nighttime mean difference is ~0.13 K for skin SSTs and ~0.02 K for bulk SST differences. In general, for most regions, the buoy SSTs have a better agreement with the AATSR skin SSTs than the bulk SSTs.

Results during nighttime for the tropical Atlantic and Indian Ocean regions show that the mean difference indicates that AATSR skin SSTs are warmer than the buoy SSTs by 0.18 and 0.09 K, respectively. These differences are slightly larger than for the other regions and for the overall global means. The statistics are only calculated on nighttime matchups where a diurnal thermocline is thought not to exist.

During the day, the mean (AATSR skin SST–buoy SST) for the Southern Ocean is ~0.07 K (standard deviation = 0.3 K), while the nighttime mean difference is 0.06 K. So here the buoy SSTs are slightly warmer than the AATSR SSTs during the day, but cooler at night.
Slight cloud contamination may be a contributing factor in this region in the daytime observations.

b. Comparisons against MOHSST and HadISST

AATSR skin SSTs have been converted to estimated bulk SSTs using the processing scheme described in section 2e. For comparisons against MOHSST, the skin and bulk SSTs have been averaged over 5-day periods (pentads) at 5° resolution and the corresponding MOHSST datasets have been subtracted from them. The global mean skin and bulk SST–MOHSST differences with standard deviation are plotted for each pentad of 19 August 2002–18 August 2003 in Fig. 8. No
Meteo product was available during the pentad of 17–21 March 2003, and the mean differences for skin and bulk–MOHSST of −0.66 and −0.48 K, respectively, on 17–21 December 2002 were calculated using only 96 means at 5° resolution, due to the low availability of AATSR data in this period. For the other 50 pentads, between 100 and 1000 grid cells at 5° were used to produce the global means, all of which lay within ±0.3 K for both skin and bulk SST comparisons against MOHSST. The high standard deviations can partly be attributed to the coarse resolution, as the largest differences tended to be found in regions of strong SST gradients such as the Gulf Stream, or regions where small numbers of in situ data contributed to MOHSST, such as the Southern Oceans. The fall in standard deviations during November 2002 coincided with the introduction of Kiruna-blind orbits into the data distribution chain, perhaps the existence of more uniform areas in the Kiruna-blind orbits led to this characteristic. While the mean bias between AATSR bulk SST and MOHSST is −0.1 K, the equivalent bias for AATSR bulk–buoy SST is 0.21 K. However, the standard deviation for the buoy comparisons is much smaller at 0.4 K rather than −1.5 K for the MOHSST comparisons.

For comparisons against HadISST1, the skin and bulk SSTs have been averaged monthly at 1° resolution and the monthly HadISST1 fields have been subtracted from them, using the method described in section 2c. Global plots of the monthly SST differences have been produced for each calendar month of the validation period, with the August 2003 skin SST minus HadISST1 plot in Fig. 9. This demonstrates that the SST differences are generally within ±1 K away from the poles, although many regions such as across the South Atlantic and northwest Pacific, where much of the AATSR data are significantly warmer or cooler than HadISST1, tend also to be regions where cloud detection has frequently resulted in the unavailability of AATSR SSTs. In these regions where AATSR is cooler than HadISST1 it is possible that the fewer number of cloud-free pixels within each AATSR cell is causing this bias. However, it must be considered that residual cloud contamination may have also affected the AATSR SST retrievals in these regions. Comparisons against TMI data shown in section 4d support this, where AATSR is significantly cooler than TMI in parts of the Southern Ocean. However, TMI data are not available poleward of 40° latitude so it is not possible to compare the behavior of AATSR–HadISST1 in the North Pacific with TMI comparisons for the same location.

Monthly and annual global differences between AATSR ESA skin or bulk SSTs and HadISST1 at 1° resolution and standard deviations are listed in Table 6. Results are presented for the ESA skin SST, while the

<table>
<thead>
<tr>
<th>Region</th>
<th>Sample</th>
<th>Mean diff, K</th>
<th>Std dev, K</th>
<th>No. of matchups</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Atlantic</td>
<td>Night</td>
<td>0.18</td>
<td>0.27</td>
<td>181</td>
</tr>
<tr>
<td>Atlantic</td>
<td>Day</td>
<td>0.12</td>
<td>0.28</td>
<td>420</td>
</tr>
<tr>
<td></td>
<td>Night/day</td>
<td>0.12</td>
<td>0.33</td>
<td>611</td>
</tr>
<tr>
<td>Indian</td>
<td>Night</td>
<td>0.09</td>
<td>0.30</td>
<td>49</td>
</tr>
<tr>
<td>Ocean</td>
<td>Day</td>
<td>0.23</td>
<td>0.34</td>
<td>31</td>
</tr>
<tr>
<td></td>
<td>Night/day</td>
<td>0.15</td>
<td>0.32</td>
<td>80</td>
</tr>
<tr>
<td>North</td>
<td>Night</td>
<td>−0.13</td>
<td>0.39</td>
<td>36</td>
</tr>
<tr>
<td>Atlantic</td>
<td>Day</td>
<td>0.00</td>
<td>0.40</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td>Night/day</td>
<td>−0.03</td>
<td>0.36</td>
<td>91</td>
</tr>
<tr>
<td>Southern</td>
<td>Night</td>
<td>0.06</td>
<td>0.27</td>
<td>299</td>
</tr>
<tr>
<td>Ocean</td>
<td>Day</td>
<td>−0.07</td>
<td>0.30</td>
<td>293</td>
</tr>
<tr>
<td></td>
<td>Night/day</td>
<td>−0.01</td>
<td>0.30</td>
<td>594</td>
</tr>
<tr>
<td>Tropical</td>
<td>Night</td>
<td>−0.04</td>
<td>0.23</td>
<td>217</td>
</tr>
<tr>
<td>West</td>
<td>Day</td>
<td>0.01</td>
<td>0.41</td>
<td>81</td>
</tr>
<tr>
<td>Pacific</td>
<td>Night/day</td>
<td>−0.02</td>
<td>0.28</td>
<td>297</td>
</tr>
</tbody>
</table>
bulk SST is derived from the Met Office–derived skin SST, and both represent D2 daytime retrievals combined with D3 nighttime retrievals. Statistics for bulk SST are only presented where a “good” skin–bulk temperature difference has been calculated, which is why a lower sample of bulk SSTs are included. Factors such as whether NWP model fields are available for a particular observation affect the calculation of the modeled skin minus bulk difference. The annual comparison takes a mean and standard deviation for all 1° spatial resolution comparisons in each of the 12 months. The mean differences between AATSR skin SST and HadISST1 are generally closer to zero than the mean differences between AATSR bulk SST and HadISST1, although these results make no correction for the bias between D2 and D3 retrievals highlighted in section 3b. The increase of standard deviation to 1.02 K, for the ESA skin SST results for July 2003, coincides with a period where we observed anomalously cooler skin SSTs by about 1 K in the global results when compared with bulk SST, possibly due to sampling errors. An increase in the standard deviation in the comparisons with MOHSST also occurs during this period, possibly for the same reason. This increase in standard deviation...
is not seen in the bulk SST statistics in July 2003 perhaps because a smaller subset of data was used, limited due to the need for a successful calculation of skin to bulk temperature difference needed to calculate the bulk SST from the skin SST observation.

c. Impact of AATSR in HadISST

Section 4b concerns the HadISST1 product in which in situ SST data are used to correct a 1° gridded nighttime AVHRR SST field. However, studies to produce a parallel version of the HadISST1 product using nighttime AATSR SST data in place of AVHRR have been made. Comparisons between the preliminary HadISST products for September 2003, constructed in the same way as described for the HadISST1 product in section 2d (see also Rayner et al. 2003) before the corrections are made for the ice fields, have produced the plots in Fig. 10. Here, the corrected AATSR HadISST1 field has been subtracted from the corrected AVHRR

![Fig. 10. Global differences in K between HadISST analyses using AVHRR and AATSR SST fields, September 2003.](Fig_10_live_4C)
HadISST1 field, to give a mean global difference of 0.01 K and standard deviation of 0.12 K.

Larger differences between the two products can be detected on regional scales. The east Atlantic, particularly near Africa, appears as an area where the HadISST product using AVHRR is cooler than that using AATSR. Comparison of the September HadISST product using AVHRR with and without the in situ SST correction, and the same comparison using AATSR data, confirm that AVHRR requires a greater correction in the east Atlantic region than AATSR. This could be showing how the dual-view AATSR SSTs are less affected by desert dust than the single-view AVHRR SSTs. Further information on the AVHRR SSTs used within HadISST1 is given in Rayner et al. (2003), but it should be noted that the algorithms used to retrieve the AVHRR SSTs had been tuned by regression of the AVHRR brightness temperatures onto in situ SST data from a set of drifting buoys. Therefore, the competence of the AVHRR SSTs retrievals will vary globally according to the varying spatial distribution of drifting buoy observations. The initial AVHRR data are more than 0.3 K warmer than the corrected AVHRR data through much of this region, while the initial AATSR is generally within ±0.1 K of the corrected AATSR here. This provides evidence that the greater accuracy of the AATSR SST data gives them an advantage over AVHRR in this region.

The greatest differences between initial and corrected AATSR data are seen in the Southern Hemisphere around 40°S, where the initial AATSR is around 0.4 K warmer than the corrected product in the southwest Indian Ocean, and around 0.3 K cooler than the corrected product in the southwest Pacific Ocean. However, these regions also require large corrections to their AVHRR SST data. Globally, the mean corrected AATSR data are 0.04 K cooler than its initial data, while the mean corrected AVHRR data are 0.03 K warmer than its initial data, but these differences have a standard deviation of 0.13 K for AATSR compared with 0.16 K for AVHRR, suggesting that AATSR SSTs are slightly more consistent than AVHRR SSTs in their comparison against in situ data.

d. Comparisons of AATSR against TMI

Comparisons of AATSR against TMI data have been made for June, July, and August 2003. Table 7 displays the differences statistics, and Fig. 11 shows an AATSR skin SST–TMI plot for August 2003. Only nighttime AATSR data are included to avoid diurnal thermocline effects. Significant differences between the plots of

<table>
<thead>
<tr>
<th>Month</th>
<th>AATSR skin two-channel SST–TMI</th>
<th>AATSR skin three-channel SST–TMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean, Std dev, Mean, Std dev,</td>
<td>K</td>
<td>K</td>
</tr>
<tr>
<td>Jun 2003</td>
<td>−0.27 0.59 18 245</td>
<td>−0.14 0.59 18 252</td>
</tr>
<tr>
<td>Jul 2003</td>
<td>−0.3 0.58 17 717</td>
<td>−0.15 0.56 17 731</td>
</tr>
<tr>
<td>Aug 2003</td>
<td>−0.37 0.58 17 352</td>
<td>−0.23 0.58 17 352</td>
</tr>
</tbody>
</table>

Fig. 11. Global map of mean AATSR channel-3 skin SST–TMI SST for August 2003.
AATSR skin SST minus HadISST1 (Fig. 9) and AATSR skin SST minus TMI (Fig. 11) are observed, especially in the Southern Hemisphere.

Overall, the results indicate that the AATSR skin two-channel SST is \(\sim 0.3\) K cooler than TMI, and the AATSR skin three-channel SST is \(\sim 0.14\) to \(0.23\) K cooler than TMI. The difference between D3 and D2 when compared to TMI is around 0.15 K, which agrees with the mean D2–D3 difference reported in section 3b. TMI SSTs are sensitive to subskin SST; that is, during nighttime we could expect the TMI SSTs to be warmer than the skin SST but similar to the bulk SST. The AATSR skin SSTs are cooler than the TMI SSTs are expected. After allowing for skin effects of \(\sim 0.1\) to 0.2 K the AATSR bulk SSTs are likely to be similar or slightly cooler than the TMI SSTs. There is a large regional variation in the differences, with SSTs warmer than TMI in the Northern Hemisphere and cooler than TMI in the Southern Hemisphere. The large negative differences south of 20°S may be influenced by some residual cloud contamination in the AATSR data. Similar comparisons using ATSR-2 SSTs have given similar hemispheric patterns (Saunders et al. 2004), which are not seen in the comparisons of AATSR with HadISST1 shown in Fig. 9. This perhaps suggests that the hemispheric patterns arise from the TMI SST data, not the AATSR SST data.

5. Conclusions and future work

Comparison of the AATSR Meteo product against various SST datasets over a full year (August 2002 to August 2003) has confirmed that the AATSR instrument, data processing, and SST retrieval are all performing well. Comparisons against in situ buoy SSTs and the MOHSST and HadISST fields have confirmed that the AATSR skin and bulk SSTs are of high quality. Indications are that the requirement for each AATSR SST to be precise to 0.3 K has been achieved (ESA 2004), with the standard deviation of the mean difference between collocated AATSR bulk and skin SSTs with buoy SSTs to be 0.26 and 0.28 K, respectively. However, the skin SSTs are too warm being closer to the buoy AATSR SSTs than the bulk SSTs, with the mean nighttime AATSR skin SST–buoy SST at 0.04 K and the mean nighttime AATSR bulk SST–buoy SST at 0.20 K. The same feature has been seen with HadISST1, as the mean AATSR skin SST–HadISST1 is \(-0.04\) K, compared with the mean AATSR bulk SST–HadISST1 of 0.11 K.

A bias of \(-0.14\) K in the mean between dual-view three-channel SSTs and dual-view two-channel SSTs has been confirmed for the year’s results, where the D3 SSTs are warmer than the D2. These biases were not corrected for during this work, and it is observed from comparisons that the D2 SSTs are closer to the buoys and analyses, implying that the D3 SSTs are too warm. Further analyses of D2 and D3 against skin-corrected in situ SSTs have shown that the D2 SSTs have a small warm bias with respect to in situ of \(\sim 0.05\) K and the D3 SSTs have a warm bias of \(\sim 0.2\) K. The differences between D2 and D3 SST retrievals indicate that actual day/night differences in SST from diurnal warming will be influenced by the biases in the two retrieval methods. This suggests for a climate dataset that either the two retrievals should be made consistent or only nighttime data should be used.

A number of different validation datasets/analyses have been used in this study, each providing different insights into the quality of the AATSR SSTs. Generally, the results from all the comparisons support each other and the conclusions that the D3 AATSR SSTs are warmer than D2 AATSR SSTs. Both the buoy SST observations and the HadISST1 analyses provide ideal validation data sources providing good-quality global and continuous validation data.

Future work should aim to provide an SST product that is unbiased between day and night and different retrieval methods, through empirical and theoretical studies of the biases. First, the differences between D2 and D3 retrievals should be understood fully, and second a scientifically robust means of correcting them should be produced. Specific questions arising within this paper could be further validated using high-quality in situ radiometer SST data.

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