GLOBAL VALIDATION OF THE (A)ATSR METEO PRODUCT SEA-SURFACE TEMPERATURE AT THE MET OFFICE

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ABSTRACT

The AATSR (Advanced Along Track Scanning Radiometer) Sea Surface Temperature (SST) Meteo product has been available since August 2002. Extended validation has been performed on this SST product on a daily basis at the Met Office (U.K.). Meteo product SSTs have been compared with in-situ measurements from globally distributed buoy data and a climate SST analysis compiled from in-situ and AVHRR (Advanced Very High Resolution Radiometer) measurements. These validation results have confirmed the AATSR Meteo product skin SST to be within $\pm 0.3\ K$ of independent in-situ data. Three-way error analysis of AATSR, Advanced Infra-Red Sounder (AIRS) and in-situ SSTs shows an uncertainty of $0.14\ K$ for AATSR data.

1. INTRODUCTION

The AATSR instrument upon the Envisat satellite aims to observe the skin Sea Surface Temperature (SST) to within $0.3\ K$ accuracy (within 1-σ limits) in order to continue the collection of SST data begun by the ATSR-1 and ATSR-2 instruments upon the Earth Remote-Sensing Satellites 1 and 2 (ERS) since 1991. Meteo product data have been gathered in near-real time at the Met Office (U.K.) from AATSR since 19 August 2002 via the ESA ftp servers. Daily monitoring of these AATSR skin SSTs has been performed, and further validation against various climate data sets undertaken. A skin to bulk correction is estimated using the Fairall [1] model to account for the differences in SST from the surface skin SST to a depth of around $1\ m$. These bulk SSTs are more suitable measurements to compare against in-situ SST measurements and other in-situ based climate data sets.

Along with the skin to bulk conversion, a diurnal thermocline model, based on the Kantha-Clayson model [2], is run at the Met Office in order to gain knowledge of possible diurnal surface warmings. These typically occur more frequently in low-latitudes, and in scenarios 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 either be excluded or corrected before being assimilated into climate SST analyses.

Whilst the Met Office gathers and monitors European Space Agency (ESA) skin SSTs, it also separately calculates the skin SST from the top of atmosphere brightness temperatures using the pre-launch retrieval coefficients supplied by ESA. These values of skin SST, calculated locally, are compared with the ESA product on a daily basis. Recent results suggest that new coefficients adopted by ESA are effective in removing the majority of the global mean bias between the 2 and 3 channel retrievals. However, in order to ensure the ongoing homogeneity of the Met Office AATSR SST product, the pre-launch coefficients are still operationally used by the Hadley Centre.

Meteo product skin and bulk SSTs have been compared with point measurements of globally distributed moored and drifting buoys, a 1° climate SST analysis field compiled from in situ measurements and Advanced Very High Resolution Radiometer SSTs (Hadley Centre Sea Ice & Sea Surface Temperature analyses, HadISST), with SSTs retrieved from TMI measurements, and with SST derived from AIRS measurements. The validation results have confirmed the AATSR Meteo product skin SST to be within $\pm 0.3\ K$ of in situ data.

2. DATA AND METHODOLOGY

2.1. AATSR Meteo product

The AATSR Meteo product [3] is a fast-delivery level 2 product designed for use in meteorological studies. The product contains spatially averaged top of atmosphere brightness temperatures measured in the instruments two views and 4 channels (3 infrared, 1 visible) and skin SSTs in cloud cleared 10 arc minute cells. The SST retrieval used ESA's pre-launch coefficient set, for both the nadir-view and the dual-view combination until 7 Dec 2005, when a new coefficient set was released. In each case, only the 11 μm and 12 μm channels are used during the day (D2), and the $3.7 \mu m$ channel is included during the night (D3). The SST product validation described in this

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paper uses only the dual-view SST both for day and night observations.

2.2. Buoy data

In this study, AATSR skin and bulk SSTs have been compared to moored buoys and ships, plus drifting buoy SST measurements. The in-situ observations are extracted from the Global Telecommunications Sytem and matched up with AATSR observations on a weekly basis [4]. The buoy match-up database is a collection of 79 different fields detailing the buoy observations, AATSR observations and atmospheric and sea surface conditions. The current dataset comprises data from 19 August 2002 to 13 April 2007.

The matching up process of AATSR and in-situ observations involves the following steps:

- in-situ observations must be located within the 10 arc-minute grid box of the AATSR cell
- if 2 buoy observations are matched up to the same AATSR observation, the buoy observation closest in time is chosen
- time difference between the two data types must be within ±3 hours
- cloudy observations are screened out by checking the quality control word calculated during the AATSR processing at the Met Office

2.3. HadISST analyses

The Hadley Centre Sea Ice and Sea Surface Temperature dataset (HadISST) [5] is compiled by the Met Office Hadley Centre for Climate Prediction and Research and is used routinely in AATSR validation. The dataset is a globally complete sea-ice and SST analysis field on a 1° spatial resolution grid, produced on a monthly basis. The SST data which contribute to HadISST come from ships, buoys and the AVHRR on the National Oceanic and Atmospheric Administration (NOAA) satellites. AATSR 10 arc-minutes observations have been averaged to a monthly mean product on a 1° grid. Comparisons have been made against HadISST for each month from September 2002 to February 2007.

2.4. AIRS Instrument

The Atmospheric Infrared Sounder (AIRS) is an infrared spectrometer that covers the $3.7 - 15.4\mu m$ spectral range with 2378 spectral channels. It was launched as part of the National Aeronautics and Space Administration's (NASA's) AQUA satellite in May 2002. AIRS primary purpose is for atmospheric sounding applications. AIRS has a larger footprint than AATSR, with a diameter of 14km (compared to 1km for AATSR). In this study the AIRS SSTs are calculated using information primarily from channel numbers 1291 and 2333 corresponding to $1231.3\ cm^{-1}$ and $2616\ cm^{-1}$ respectively. These are used because $2616\ cm^{-1}$ is the most transparent channel in the AIRS spectrum and $1231\ cm^{-1}$ is the next best window channel [6].

Unlike the AATSR retrieval which uses a combination of channels and views, the AIRS SST retrievals use radiances from the afore mentioned window channels and then apply a small correction due to residual water vapour continuum absorption with a nearby channel which is in a water vapour absorption line. The SST derived at wave number $1231\ cm^{-1}$ (SST_{1231}) is the sea surface temperature assuming an emissivity, $e = 0.98$ under cloud-free conditions [7]. It uses the difference between the $1231.3\ cm^{-1}$ and $1227.7\ cm^{-1}$ channels for a water vapour correction. The SST at wave number $2616\ cm^{-1}$ (SST_{2616}) is calculated using the algorithm from Aumann et al. [6]. This algorithm uses the difference between channels at $2616\ cm^{-1}$ and $2607.8\ cm^{-1}$ for the water vapour correction.

2.5. Met Office processing of skin to bulk SST differences

The Met Office receives the Meteo product containing the ESA skin SST, brightness temperatures and other related information on a daily basis in near-real time (see 2.1). The data is then processed with a time lag of 2 days. The skin SSTs at the Met Office are retrieved from the Brightness Temperatures using ESA launch coefficients and compared to the ESA skin SST. The ESA skin SST is retrieved using December 2005 coefficients from 8 December onwards.

Met Office AATSR skin and bulk SSTs are bias corrected before use. The bias correction is derived by using the AATSR match-up data base with buoy SST observations. This process involves converting the buoy SST to a skin SST by using the Fairall model [1]. This buoy skin SST is then compared with the AATSR skin SST for the 2-channel (D2) and 3-channel (D3) retrieval using only night-time match-ups where the time difference between the different observation types is less than 1 hour. The resulting bias correction for D2 is $-0.05\ K$ and for D3 $-0.22\ K$. Bulk SSTs are then calculated from the bias corrected skin SSTs [8].

The Met Office derived skin SST is then processed to a bulk SST, which is the temperature of the ocean at around $1\ m$ depth. This is done by using the Fairall model [1] and is necessary because the satellite observes a radiative skin temperature which is always cooler than the sub-skin by more than $0.1\ K$. SSTs for climate purposes require a bulk temperature which provides a more comparable measurement when comparing with other SST climate datasets.

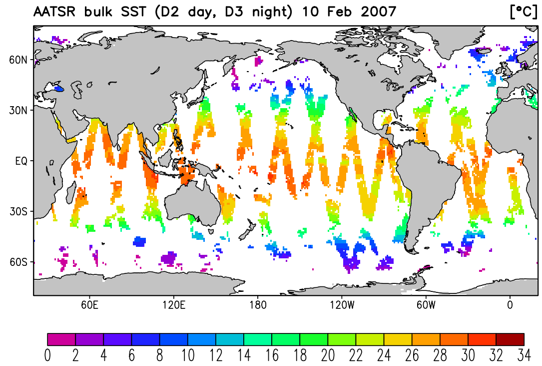

Figure 1. AATSR 2-channel (day) and 3-channel (night) bulk SST from the Meteo product of 10 February 2007.

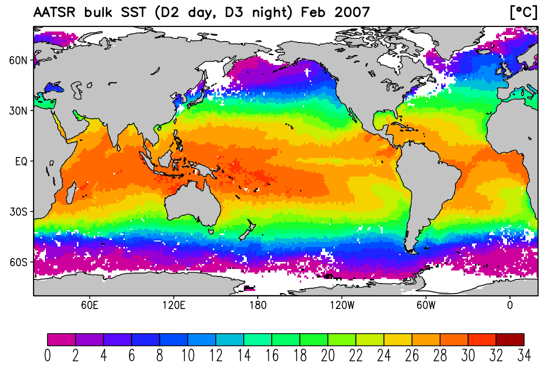

Figure 2. Monthly mean AATSR 2-channel (day) and 3-channel (night) bulk SST from the Meteo product of February 2007.

At night the sub skin SST is representative of the bulk SST at around $1\ m$ in depth. However, during the day the sub-skin SST can become warmer than the bulk SST by several Kelvin, especially in cases of strong insolation and low wind speeds where thermal stratification results. These diurnal warmings effects are modelled at the Met Office, using the Kantha-Clayson model [2] to try to predict occurrences of warming within the 10 arc-minute cell of the AATSR observation. Required fluxes and wind speeds, spanning a 30-hour time frame centred on each satellite observation, are taken from the Met Office Numerical Weather Prediction (NWP) fields. Observations affected by diurnal warming are flagged and not included in further analyses.

3. METEO PRODUCT RESULTS

Global plots of daily and monthly SST measurements have been produced throughout the whole validation period on a daily and monthly basis respectively. As an example for a daily SST validation plot the dual view 2-channel (day) and 3-channel (night) bulk SST for 10th February 2007 is shown in Figure 1. The visible gaps within the AATSR swath are areas covered with clouds or affected by diurnal surface warmings. Figure 2 shows an example of a monthly mean bulk SST for February 2007. The data gaps in the monthly mean are mainly caused by persistent or high frequently cloud coverage and sea-ice.

Table 1. Statistics of co-located AATSR minus buoy SSTs for 01/01/2003 - 31/12/2006

SST type	Subset	Bias [K]	σ [K]
Met Office Skin	Day + Night	-0.12	0.30
Met Office Skin	Day	-0.07	0.33
Met Office Skin	Night	-0.17	0.26
Met Office Bulk	Day + Night	0.03	0.29
Met Office Bulk	Day	0.09	0.33
Met Office Bulk	Night	-0.02	0.25

4. VALIDATION RESULTS

4.1. Comparisons with buoy SSTs

Figure 3 shows the coverage of buoy SSTs matched up with AATSR observation for the time period 19 August 2002 to 13 April 2007. The blue crosses indicate match-ups with drifting buoys, which comprise the majority and show a good global distribution. The purple crosses indicate match-ups with moored buoys. These are limited mainly to the North American and Europe coastal regions and the TAO/PIRATA array in the tropical Pacific/Atlantic.

A statistical comparison of bulk and skin bias-corrected AATSR SSTs with the matched-up buoy SSTs was carried out for the time period from 1st January 2003 to 31st December 2006. In addition to the filtering described in section 2.2 a 3-sigma standard deviation filter was applied in order to screen out outliners from the analyses. The results of this comparison are shown in Table 1. The

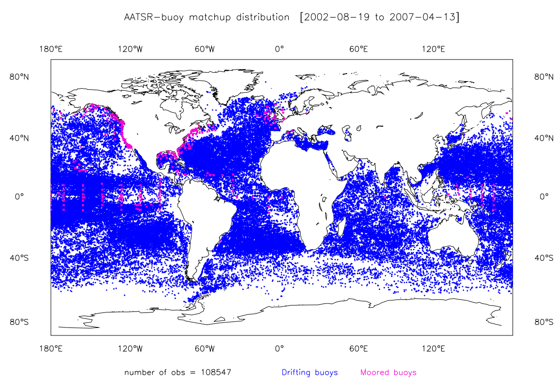

Figure 3. Locations of moored (purple) and drifting (blue) buoy SSTs matched with AATSR SSTs from 19 August 2002 to 13 April 2007.

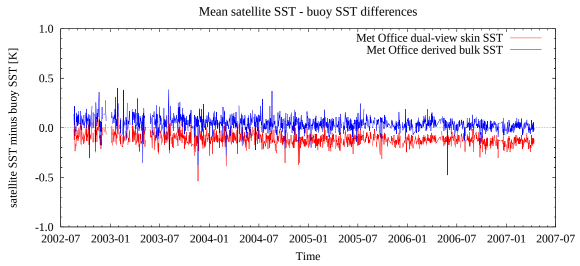

Figure 4. Time series of bias corrected bulk (blue) and skin SST (red) minus buoy SST from 19 August 2002 to 13 April 2007.

Table 2. Statistics of new-retrieval coefficients for 2003 (night-time observations)

retrieval	Bias [K]	σ [K]	n
D2 (Dec 2005)	0.16	0.33	3946
D3 (Dec 2005)	0.16	0.25	3947

AATSR bulk SST during night-time is in good agreement with the matched-up buoy SST, indicating a good performance of the applied bias correction. The day-time AATSR bulk SST is about $0.1\ K$ warmer than the corresponding buoy SST. As the bias correction for the 2-channel algorithm is calculated using only night-time observations, this warm bias against buoy SSTs might be caused by undetected thermocline warmings during the day. The AATSR skin SST shows a cold skin of $-0.17\ K$ during night-time compared to the buoy observations. The standard deviations are generally lower during night-time ($0.25\ K$) than during day-time ($0.33\ K$), indicating a better performance of the 3-channel SST algorithm compared to the 2-channel SST algorithm.

Figure 4 shows the daily averaged differences between the bias-corrected satellite bulk and skin SSTs with the matched-up buoy SST. The bias-corrected AATSR SSTs show a good constant performance throughout the whole time period with the majority of the differences being less than $0.3\ K$.

4.2. Comparison with new retrieval coefficients

ESA released the new retrieval coefficient set operationally on 07 December 2005 to supersede the AATSR pre-launch coefficients. A comparison of the AATSR SSTs retrieved by using the new coefficients against the AATSR/buoy match-up database for 2003 has been carried out. The results, summarised in Table 2, show that the global bias between the D2 and D3 retrievals of the ESA launch coefficients (D2 = 0.06K, D3 = 0.21K) has been removed. A global bias with respect to in-situ observations remains. The new retrieval coefficients are currently not operationally used, because an ongoing homogeneity of the operationally Met Office AATSR SST product has to be ensured for the use in climate applications.

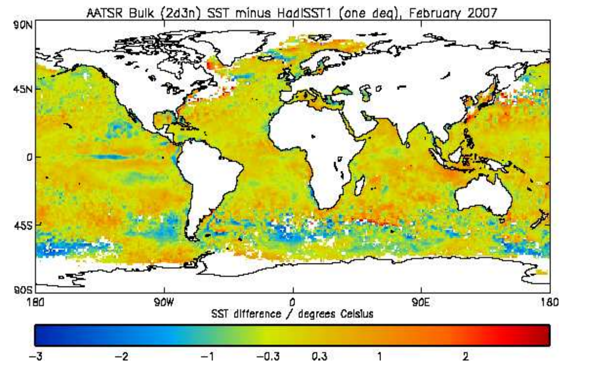

Figure 5. Monthly mean difference between AATSR 2-channel (day) and 3-channel (night) bulk SST−HadISST, February 2007.

4.3. Comparison against HadISST

For comparisons against HadISST1, the AATSR 10 arc-minutes observations have been averaged to a monthly mean product on a 1° grid. Validation against HadISST is routinely performed on a monthly basis and has been done for the whole AATSR lifetime. Figure 5 shows the difference between the Met Office AATSR bulk SST product and the HadISST1 climatology for February 2007. The global averaged difference is $-0.06\ K$ with a standard deviation of $0.6\ K$. The largest differences can be found in regions with fewer number of observation and a high spatial variability due to persistent or high frequently cloud coverage (Southern Oceans, Kuroshio Current, Gulf stream), when no SST can be retrieved from AATSR observations.

4.4. Comparison with AIRS

Both the AATSR bias corrected skin and AIRS SSTs have been averaged to a monthly mean product on a 1° grid for January, April and June 2006. The differences between AIRS and AATSR SSTs have been carried out with both of the AIRS SSTs (SST_{2616} and SST_{2616}) separately and gives two AIRS comparisons with AATSR. In addition to the Global analysis, statistics are also collected in three latitude bands: latitudes greater than 30N (Northern band), latitudes between 30N and 30S (Tropics) and latitudes less than 30S (Southern band). Figure 6 shows an example anomaly plot of AATSR minus AIRS night-time SST_{2616} for January 2006.

The statistical results of the comparisons for January 2006 are shown in Table 3. Overall AATSR minus AIRS gives a positive bias. This means AIRS is giving colder SSTs than AATSR. Globally this bias is in the region of $0.5\ K$. The global standard deviation is in the

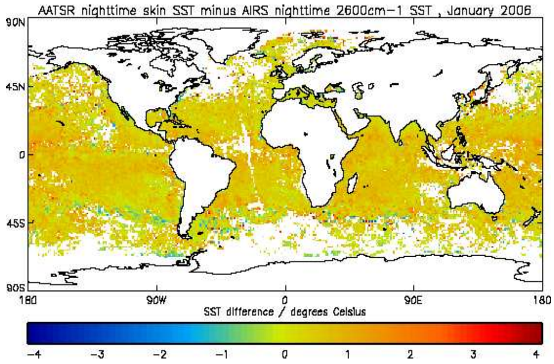

Figure 6. Monthly mean difference between AATSR night-time skin SST minus AIRS night-time SST_{2616}, January 2006.

Table 3. Statistics for AATSR (bias-corrected, night-time) D3 skin SST minus AIRS night-time SST_{1231} (upper part) and SST_{2616} (lower part) for January 2006 (April 2006 and June 2006 give similar results).

Area	Bias [K]	σ [K]	n
Global	0.51	0.62	25363
$> 30\ N$	0.37	0.72	3567
$30\ S - 30\ N$	0.71	0.51	14346
$< 30\ S$	0.19	0.62	7408
Global	0.49	0.52	25365
$> 30\ N$	0.36	0.65	3564
$30\ S - 30\ N$	0.60	0.40	14384
$< 30\ S$	0.32	0.59	7404

region of $0.6\ K$. The bias is partly due to the different cloud detection schemes applied to the data from each instrument. Some of the difference can also be attributed to the different retrieval algorithms for the two datasets. The AIRS dataset uses individual narrow channels that can see between absorption lines, while the AATSR SST dataset uses a combination of three wider channels and two coincident views. There is also some contribution from the slightly different absorption characteristics of the atmospheric windows that the different instruments use. A difference between the biases and standard deviations is evident when using the two different AIRS channels. The bias between AATSR and AIRS is larger when using the AIRS SST_{1231} than when using the AIRS SST_{2616}. This is particularly seen in the tropics where the water vapour effects have the greatest impact, and this effect is diluted by the dryer high latitude air in the global statistics. For the 3 months studied the difference in bias between the channels in the tropics is between $0.11\ K$ and $0.14\ K$. The standard deviation is also larger by around $0.1\ K$ in the tropics when using AIRS SST_{1231}. Both the smaller bias and the smaller standard deviation show that AIRS SST_{2616} is better suited for SST measurements than SST_{1231}.

Saunders [9] discusses the transmittance at various frequencies and the attribution of this to various gases. In both these windows water vapour is the main absorber, with other gases contributing little to the absorption. Globally averaged the effect of water vapour absorption is greater in the $1231\ cm^{-1}$ channel than the $2616\ cm^{-1}$ channel making the latter more transparent to radiation, therefore giving a more accurate SST. The difference is largest for high water vapour columns in the tropics.

Table 4. Biases and Standard deviations from three-point, AATSR, AIRS, Buoy Match-ups for a mean of three months in 2006 (January, April and June), SST_{1231} (upper part) SST_{2616} (lower part)

Comparison	Mean Bias [K]	σ [K]	n
AATSR-AIRS	0.60	0.52	267
Buoy-AIRS	0.61	0.55	267
AATSR-Buoy	-0.01	0.26	267
AATSR-AIRS	0.56	0.43	268
Buoy-AIRS	0.56	0.46	268
AATSR-Buoy	-0.01	0.26	268

4.5. Three-point Comparison with AIRS and buoy observations

An extension to the three-point error analysis carried out by O'Carroll et al. [10] was done for AATSR, AIRS and Buoy SSTs. From the co-located mean values and standard deviation of the difference between each of the three observation sets information can be gained to enable the error of each observation to be derived. Assuming the errors in the three observation types are uncorrelated, the error is calculated using equation 1. The appendices of O'Carroll et al. [10] explains in more detail the calculation and gives a discussion of the validity of assuming the errors are uncorrelated.

$$\begin{aligned} \sigma_1^2 &= \frac{1}{2}\cdot(var_{12}+var_{31}-var_{23}) \qquad (1)\\ \sigma_2^2 &= \frac{1}{2}\cdot(var_{23}+var_{12}-var_{31})\\ \sigma_3^2 &= \frac{1}{2}\cdot(var_{31}+var_{23}-var_{12}) \end{aligned}$$

Where σ_i is the estimated error for observation type i (where i = 1,2, or 3) and var_{ij} is the variance of the difference between observation types i and j.

The three-point match-up uses the existing global AATSR and buoy match-up file (see section 2.2). Match-ups are only selected if they occurred during the night and if the AATSR and Buoy measurements were taken within 3 hours of each other. Both drifting and moored buoy SSTs are used. The AIRS SSTs, which are not bulk adjusted, are then matched with the remaining AATSR-buoy match-ups and the statistics are calculated. The 3-sigma standard deviation test is applied to filter out any

Table 5. Error Analysis using three-point match-up statistics. Derived standard deviation of error for each observation type [K]

AIRS Channel	AATSR	AIRS	Buoy
1231 cm^{-1}	0.13	0.50	0.22
2616 cm^{-1}	0.14	0.41	0.22

extreme outliers. Future work could involve bulk adjusting the AIRS SSTs using the Fairall model [1] to convert to bulk SSTs in order to provide a better comparison with AATSR bulk SST and buoy SST. The biases and standard deviations calculated using this method are shown in Table 4.

AIRS SST is cooler than bulk AATSR and buoy SST by about $0.6\ K$. This would have been expected, because AIRS observes the temperature of the ocean skin, the top few microns, which is generally a few tenths of a Kelvin cooler than just below the ocean skin. The AATSR skin SST measures the same part of the ocean skin and a comparison with AIRS SST gave a bias of around $0.4\ K$ to $0.5\ K$ (see section 4.4). For the three-point match-up the AATSR SST has been adjusted to give a bulk SST to be directly comparable with buoy SST. Because of this adjustment the AATSR SST would be expected to become warmer still by a few tenths of a Kelvin. This would increase the bias between AATSR and AIRS SST, which explains larger bias in this comparison.

Because of the bulk adjustment of AATSR SST and the bias correction applied to it, the AATSR SST minus buoy SST gives a very small bias, hundredths of a degree and a small standard deviation, only a few tenths of a degree. There is a larger bias and standard deviation when using AIRS SST_{1231} than AIRS SST_{2616}. This pattern agrees with the AATSR-AIRS comparison shown in section 4.4 and is explained by differences in the water vapour continuum absorption between the two channels.

An error analysis has been carried out using the method described at the beginning of this section (equation 1). The results of this analysis for the three month mean shown in Table 5 give very similar results to those in the three-point AATSR, Buoy, AMSR-E comparison O'Carroll et al. [10] which show an error of $0.16\ K$ for the AATSR bulk SST, $0.42\ K$ for the AMSR-E SST and $0.23\ K$ on the buoy SST. The error is smallest for AATSR. Buoys have the next smallest error and AIRS has the largest error. The errors of the AIRS SST are comparable with the error of AMSR-E SST shown by [10].

The AIRS SST errors are smaller when using the $2616\ cm^{-1}$ channel than when using the $1231\ cm^{-1}$ channel. This supports the earlier AATSR-AIRS comparison which gives a smaller bias and standard deviation using the $2616\ cm^{-1}$ channel, suggesting it to be more accurate for calculating SST.

5. CONCLUSIONS

Comparisons of the AATSR Meteo product against various SST datasets has confirmed that the AATSR instrument and SST retrieval are all performing well. Comparisons against buoy SSTs and HadISST climatology have confirmed that the AATSR skin and bulk SSTs are of high quality. The AATSR SST will become part of the next HadISST version and will also be used as the reference SST. The requirement for each AATSR SST measurement to be precise to $0.3\ K$ has been achieved, with the standard deviation of the mean difference between colocated bias corrected night-time AATSR bulk and skin SSTs with buoy SSTs to be $0.25\ K$ and $0.28\ K$ respectively.

The three-point comparison involving AATSR, AIRS and buoys suggests that AIRS gives a cooler SST than AATSR by about $0.5\ K$. This method also gives an error for each data source. Using the AIRS $2616\ cm^{-1}$ channel, AATSR SST has the smallest error, $0.14\ K$, followed by buoys with an error of $0.22\ K$ and AIRS SST_{2616} has the largest error, $0.41\ K$. These results are very similar to the three-point comparison using AATSR, AMSR-E and buoys carried out by O'Carroll et al. [10].

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