GEOPHYSICAL RESEARCH LETTERS, VOL. 25, NO.17, PAGES 3363-3366, SEPTEMBER 1, 1998

Potential for improved ATSR dual-view SST retrieval

M. J. Murray,[1] M. R. Allen,[1,2] C. J. Merchant,[3] and A. R. Harris[4]

Abstract. Recent validation studies have confirmed that the first along-track scanning radiometer (ATSR) can retrieve sea surface temperature (SST) to an accuracy of 0.3K even in the presence of heavy atmospheric aerosol. However, using the standard (pre-launch) retrieval, this accuracy is achieved only when data from all three thermal channels (3.7, 11 and 12 μm) are available; in the absence of 3.7 μm data, retrieved SSTs are subject to significant cold bias. As 3.7 μm data are useful only for nighttime observations, and ATSR's 3.7 μm channel failed in May 1992, only 11 and 12 μm data informed SST derivation for most of the 1991–1996 mission. We demonstrate the potential for improvement in this retrieval, based on comparison of observed brightness temperatures with precise SSTs derived using 3.7 μm data. A reduction in global-mean cold bias from >0.6K to <0.1K is achieved, with standard deviation approximately halved. We also examine the treatment of optical pathlength variation around the ATSR swath.

Introduction

ATSR is a dual-view, self-calibrating infrared radiometer with spatially coregistered spectral channels centered at 1.6, 3.7, 10.8 and 12.0 μm [*Mutlow et al.*, 1994]. The instrument's conical scanning technique results in two separate views of the Earth's surface: one close to nadir, and a 'forward' view at 55° to nadir, which is acquired several minutes before the nadir view of the same location. As these observations are associated with different optical path lengths, an accurate correction for atmospheric absorption can be determined. ATSR operation commenced in July 1991, a period characterized by very high stratospheric aerosol loading in the tropics due to the June eruption of Mount Pinatubo. This aerosol had a serious impact on satellite infrared SST retrievals, with multi-channel SSTs (MCSSTs) [*McClain et al.*, 1985] derived from the AVHRR showing a cold bias >1K compared to in situ observations [*Reynolds*, 1993]. *Murray et al.*, [1998] (plate 3) compared ATSR SSTs with the NOAA blended analysis of AVHRR and in situ SST observations [*Reynolds and Smith*, 1994], and showed that 'six-channel' ATSR SSTs retrieved using dual-view data from the 11, 12 and 3.7 μm channels are within the 0.3K rms error expected for the instrument (1.6 μm data are used only for cloud discrimination). Even with the dual view, however, 'four-channel' SSTs (derived in the absence of the 3.7 μm data) exhibit a ubiquitous cold bias of >0.3K with respect to the six-channel retrieval, and are further depressed in the presence of heavy atmospheric aerosol. Considering the coefficients used in the ATSR retrieval scheme were based on a pre-launch calculation which assumed only climatological tropospheric aerosol, the success of the six-channel retrieval is reassuring, since it indicates that this retrieval is, as designed, largely robust to mis-specification of the atmospheric model.

We seek here to quantify the potential for improvement in the four-channel retrieval by evaluating the extent to which six-channel SSTs can be reproduced from a linear model based on 11 and 12 μm brightness temperatures (BTs). We stress this is not proposed as a final solution since a key objective of the ATSR mission is to provide physically-based retrievals of radiometric (skin) SST. *Brown et al.*, [1997] accounted for the effects of stratospheric aerosol by including a layer of aged volcanic aerosol in the *Závody et al.*, [1995] radiative transfer model, but the long-term performance of their algorithm under changing aerosol loads has yet to be evaluated. The present exercise is necessary to define the criterion of success for any proposed 'aerosol robust' retrieval scheme, and to inform the ATSR reprocessing strategy of the limitations inherent in an independent (time-invariant) linear four-channel retrieval.

Data and Methodology

ATSR SSTs are calculated by taking the linear sum of N infrared BTs:

$$\mathrm{SST} = a_0 + \sum_{i=1}^{N} a_i T_i \qquad (1)$$

where the a_i are coefficients (dependent only on latitude and position within the ATSR swath) and T_i is the cloud-free scene BT as observed by ATSR either in the nadir or forward view for the 3.7, 11 and 12 μm channels. In contrast to MCSST and Pathfinder which use a fit (non-linear in the case of Pathfinder) between AVHRR BTs and in situ SSTs, the ATSR coefficients were determined using a physically-based atmospheric radiative transfer model, with separate sets of coefficients derived for polar, middle and tropical latitudes [*Závody et al.*, 1995]. Spatially-averaged SSTs for the complete ATSR mission have been provided at half-degree spatial resolution [*Murray*, 1995], a choice associated with the original mission requirement to provide precision SSTs for 50km×50km areas (the approximate size of a half-degree cell at the equator). A modified version of the ATSR processing software was used to generate global SSTs, together with the constituent BTs at 10′ (ten arcminute) resolution (these data will be generated for the full ATSR mission in 1998/9).

Two periods of ATSR observations are considered here: September 14th to October 18th 1991, and April 22nd to May 26th 1992; these correspond to the first and last 35-day periods when 3.7 μm data were available, giving the

---

[1] Space Science Department, Rutherford Appleton Laboratory, Chilton, England, United Kingdom

[2] Also at Dept. of Physics, University of Oxford, U.K.

[3] Department of Space and Climate Physics, University College, London, U.K.

[4] United Kingdom Meteorological Office, Bracknell, U.K.

Paper number 98GL02389.
0094-8534/98/98GL-02389$05.00

maximum spread of aerosol loading as the Pinatubo plume dispersed (the 35-day period was chosen to obtain uniform global coverage). Only those 10′ cells for which dual-view data for all three thermal channels were available have been considered (i.e. nighttime data only). Data which gave rise to a six-channel SST ($\mathrm{SST_6}$) more than 6K from GOSTA climatology [*Bottomley et al.*, 1990] were excluded ($\sim$0.1%).

We applied a standard linear regression to model $\mathrm{SST_6}$ (from the original six-channel retrieval) in terms of the corresponding 11 and 12 μm nadir and forward BTs:

$$\mathrm{SST_6} = \hat{a}_0 + \sum_{i=1,4} \hat{a}_i T_i + \text{noise} \qquad (2)$$

where the estimated $\hat{a}_i$ are analogous to the a_i coefficients for the four-channel case in equation (1), and the noise term represents that atmospheric contamination which cannot be eliminated by a four-channel retrieval. We assume this noise is spatially uncorrelated; this is clearly a simplification, but since the volume of data for each regression is large ($\sim$20,000 points to generate 15 coefficients), and we use out-of-sample cross validation, the use of a more complex noise model is not justified. We assume instrumental noise is negligible since several hundred 1km^2 measurements contribute to a 10′ cell, so the effect is $\sim$0.05K/$\sqrt{200}$.

Three regressions were performed to assess the impact of changing aerosol load: (i) using all data from the 1991 35-day period only, (ii) using all 35 days from 1992 only, and (iii) using data from the first $17\frac{1}{2}$ days of both periods combined (composite regression). The sum of the absolute magnitudes of the statistically-derived coefficients is >20% smaller than that of the original ones (excluding the constant term a_0). As larger coefficients amplify noise, the new retrieval scheme should be less sensitive to BT contamination from residual cloud.

Table 1. Global-mean $\mathrm{SST_4}-\mathrm{SST_6}$ bias and σ

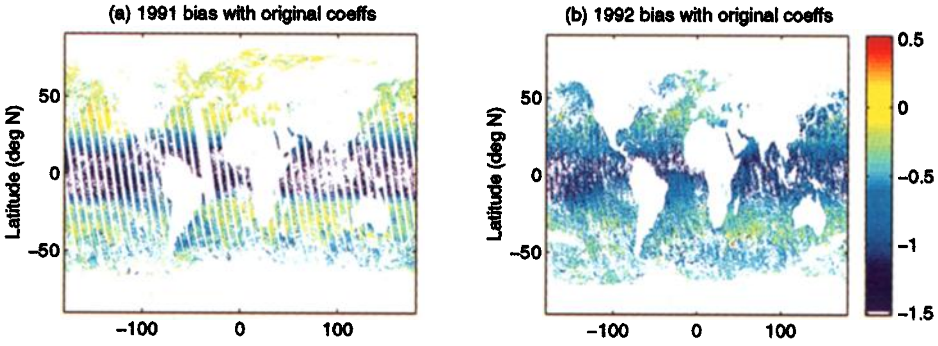
	1991		1992	
Retrieval	Bias (K)	σ (K)	Bias (K)	σ (K)
Original	-0.68	0.58	-0.70	0.48
Brown	-0.01	0.23	-0.12	0.29
1991 coeffs	*0.00	*0.22	-0.10	0.25
1992 coeffs	0.09	0.22	*0.00	*0.24
Composite	0.00	0.22	-0.04	0.23

Each set of derived coefficients was used to calculate four-channel SSTs for the 1991 and 1992 periods, and also for a ten-day period (30th July – 8th August) in 1995, chosen as six-channel SSTs from ATSR-2 were available for comparative purposes. Additionally, both four- and six-channel SSTs were calculated using the coefficients presented in *Brown et al.*, [1997], table 4.

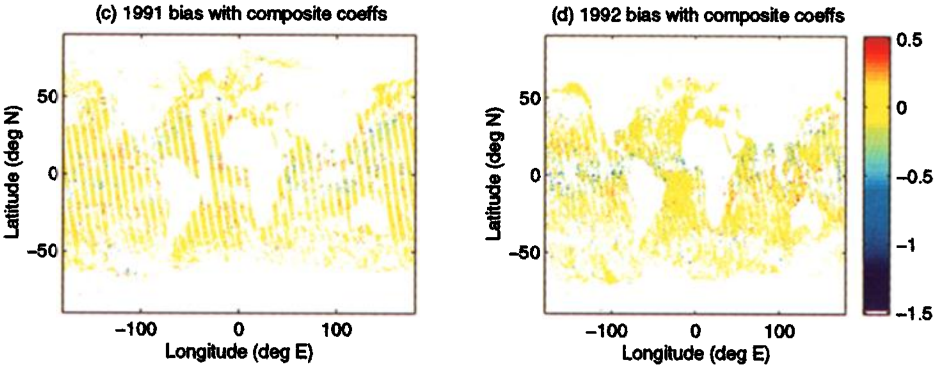
We also performed an analogous calculation to the composite regression (iii) above, but using all three nadir-view BTs only. This retrieval scheme simulates the performance of a nadir-viewing instrument

Comparison of SST Retrievals

In the following discussion, $\mathrm{SST_6}$ is considered to represent 'truth' – an assumption supported by the validation results – but in any case, our key conclusions, concerning the *potential* for consistency between algorithms should apply equally to improved six-channel retrievals. Table 1 summarizes the global-mean bias and standard deviation with respect to $\mathrm{SST_6}$ observed for four-channel SSTs ($\mathrm{SST_4}$). Bias is given as $\mathrm{SST_4}-\mathrm{SST_6}$, thus a negative value indicates $\mathrm{SST_4}$ is colder. All $\sim10^6$ 10′ SSTs were given equal weight; equal


(a) 1991 bias with original coeffs

(b) 1992 bias with original coeffs


(c) 1991 bias with composite coeffs

(d) 1992 bias with composite coeffs

Figure 1. Global distribution of $\mathrm{SST_4}-\mathrm{SST_6}$. Gaps in 1991 are due to the incomplete coverage associated with the 3-day repeat cycle in use at that time.

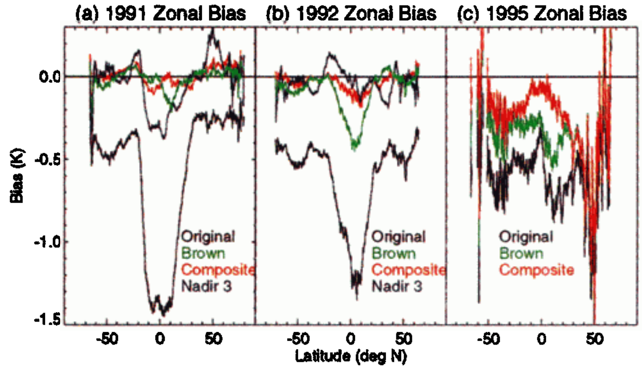


Figure 2. $SST_{4(3)}-SST_6$ zonal mean biases in ATSR retrievals for periods in 1991, 1992 and 1995 (the subscript denotes the number of BTs used in the retrieval). For 1995, SST_6 is from ATSR-2 observations acquired 24 hours later than the corresponding ATSR data.

area weighting gives very similar results. Regressions (i) and (ii) were tested using all data from the 1991 and 1992 35-day periods, thus the statistics indicated with an asterisk represent in-sample tests (for which the mean bias is zero by construction). For the composite regression, only data from the second half of each 35-day period (not used in the regression) were used for testing. The large cold bias observed in the original retrieval is not present in any of the alternative schemes. Of course the in-sample regressions are guaranteed unbiased, but it is encouraging that the standard deviation is only ~0.2K for both 1991 and 1992 datasets. This indicates the lower limit of SST_4-SST_6 consistency which can be achieved under these conditions. A similar standard deviation is associated with the out-of-sample comparisons, and each case exhibits an absolute bias ~<0.1K. SST_6 and SST_4 calculated using the Brown coefficients are in very good agreement in 1991, but exhibit a larger bias than the regression-based schemes in 1992.

Figures 1a and 1b show the global distribution of the SST_4-SST_6 bias derived using the original coefficients for the 1991 and 1992 periods respectively. In 1991, SST_4 exhibits a deficit of up to 1.5K with respect to SST_6 in tropical regions, and a cold bias $\simeq$0.3K at high latitudes. Nine months later, the cold bias has reduced slightly in the tropics, but at higher latitudes has increased to $\simeq$0.5K. The temporal evolution of the bias may be associated with the changing pattern of atmospheric aerosol; heavy aerosol loading was confined to the tropics in October 1991, but significant transport to higher latitudes had occurred by April 1992. This association of too-cold SST_4 with atmospheric aerosol loadings suggests that inadequate treatment of aerosol is one factor compromising the original SST_4 retrieval. Figures 1c and 1d show the corresponding maps for the case where SST_4 is calculated using the composite regression-based retrieval. Close to zero bias is achieved for most regions, but the residual bias in the tropics suggests that the closest possible agreement between four- and six-channel retrievals may require time-dependent coefficients as in MCSST and Pathfinder.

Figures 2a and 2b show the zonal mean bias with respect to SST_6 for various retrievals for the 1991 and 1992 datasets respectively. The scale of the problem with the original four-channel retrieval is again evident. Averaging zonally results in very low biases for the in-sample comparisons, and these are not shown. The composite regression is chosen to represent out-of-sample testing again, and observed biases are all well within 0.2K. The zonal bias associated with the Brown SST_4-SST_6 for the 1991 data indicates a good correction for aerosol, but a cold bias of ~0.4K is observed in the tropics in 1992 when equatorial aerosol loadings were lower. The advantage inherent in the dual-view compared to nadir-only observations can be evaluated by considering the performance of the retrieval scheme based on the three nadir channels. Despite the inclusion of the 3.7 μm data, the nadir-only retrieval (indicated as 'nadir 3') is unable to match SST_6 to the extent achieved by the four-channel retrieval.

The value of statistically-derived coefficients depends on the extent to which numbers derived from one set of observations are appropriate to a different set, characterised by different atmospheric conditions. The four-channel retrieval coefficients considered above were derived solely from nighttime observations, but as they encompass large seasonal water vapour variation, they should be equally applicable to daytime data, as diurnal humidity differences are comparatively small.

However, as a restricted range of aerosol loading is represented by the data, it is of interest to explore the long-term performance of the derived coefficients as the Pinatubo aerosol subsides. Following its launch in 1995, ATSR-2 followed the ATSR ground track with a temporal lag of almost exactly 24 hours. Although the ATSR-2 validation programme is at an early stage, the six-channel SSTs provide the best comparative dataset for our purposes, and these are compared to collocated ATSR observations acquired 24 hours earlier, within the aforementioned ten days in 1995. Figure 2c shows the zonal mean bias for several of the four-channel retrievals considered above (only the composite regression results are shown; the nadir-only three-

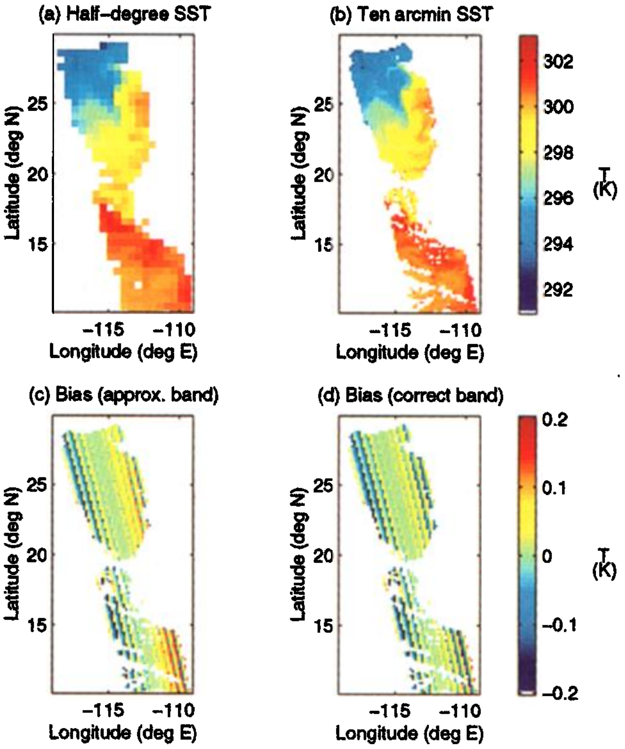


Figure 3. Comparison of SSTs from band-based and pixel-interpolation retrieval schemes.

channel retrieval was not considered as the previous comparisons demonstrated its inadequacy). Interpretation of this figure is complicated by several factors, not least the intrinsic variability in SST over the 24-hour period separating the observations. Inspection of ATSR-2 SSTs acquired three days apart suggests that at latitudes south of 20°N, intrinsic SST variability over three days is <0.2K, but above this latitude, much larger variation occurs (>0.5K), with later observations being warmer (as observed also in Figure 2c.) Excluding the observations north of 20°N, it is encouraging to note that the statistically-derived retrievals give SSTs within 0.2K of ATSR-2 SSTs, although both seasonal water vapour and atmospheric aerosol load differed markedly from the periods used in the regression calculations. We stress this does not represent an attempt to perform ATSR/ATSR-2 cross validation; for example, no attempt has been made to correct for the known ATSR detector temperature drift, which causes a cold bias of order 0.1K in the tropics [*Murray et al.*, 1998].

ATSR swath position correction

For both nadir and forward observations, optical path variations of up to 8% are associated with the difference in viewing angle between the centre and edge of the ATSR swath. The original SST retrieval scheme addresses this by dividing the ~500km swath into ten 50km-wide bands symmetrically placed about the sub-satellite track; separate coefficients are used for each band, and the band is assigned from the position of the first observed 1km^2 pixel which contributes to a 10′ cell. *Harris and Saunders* [1996], calculated ATSR SSTs by interpolating the original coefficients to obtain a much finer correction, with the swaths divided into ~500 parts (the number of pixels in the nadir swath, hence 'pixel-interpolation').

Figure 3a shows original half-degree SSTs derived from 10 minutes of data acquired on October 14th, 1991. Much better delineation of SST features is obvious in Figure 3b where the individual 10′ SSTs are shown. Figure 3c shows the difference between 10′ SSTs calculated using the original and the pixel-interpolation schemes (bias is shown as band-based minus pixel-interpolation). Two problems are apparent. First, temperature discontinuities are evident at the band boundaries; these increase from zero close to the sub-satellite track to >0.2K towards the swath edge. Secondly, with respect to the pixel-interpolation SSTs, band-based SSTs are biased warm on the western side of the swath and cold on the eastern side.

The latter effect is caused by the 'first pixel' approximation, which for these observations causes ~20% of data to be assigned a band displaced to the west. As this is too far from the swath centre on the western side, the result is an over-correction for atmospheric path and a too-warm SST, with the converse situation on the eastern side. The effect increases in magnitude towards the equator as higher humidity renders the retrieval more sensitive to band choice. Figure 3d shows the bias for the case where the band is assigned by evaluating the mean position of all pixels within a 10′ cell. Discontinuities due to the banding scheme remain, but the asymmetry about the sub-satellite track is rectified.

Conclusion

The discrimination of secular trends in SST from satellite infrared data relies on a retrieval unaffected by variations in atmospheric parameters such as water vapour and volcanic aerosol which may themselves be subject to long-term change. ATSR six-channel SSTs are capable of meeting this requirement, with further data adding to the global record since ATSR-2 operation commenced in April 1995. We have explored the performance of the ATSR four-channel SST retrieval using coefficients derived from periods differentiated both by aerosol loading and by seasonal water vapor differences. Our main conclusion is that four-channel SSTs have the potential for much smaller bias and scatter than were obtained using the pre-launch retrieval. Work is underway to develop a physically-based algorithm to exploit this potential. This should allow the continuation of a low-bias, precise ATSR SST record using four-channel retrievals throughout the full period of the ATSR and ATSR-2 missions.

Acknowledgments. ATSR data were provided courtesy of ESA and were processed at RAL. MJM and MRA were funded by the Natural Environment Research Council (NERC) via the Ocean Dynamics and ATSR postlaunch support lines. CJM was funded by NERC on a doctoral studentship award together with the UK Meteorological Office. ARH was funded under the Climate Prediction Programme of the Department of the Environment, Transport and the Regions. We would also like to thank C. Mutlow, T. Nightingale, R. Reynolds, P. Watts, A. Zavody and anonymous reviewers for helpful comments.

References

Bottomley, M., C.K. Folland, J. Hsiung, R.E. Newell, and D.E. Parker, *Global Ocean Surface Temperature Atlas*, 20pp., Her Majesty's Stn. Off., Norwich, England, 1990.

Brown, S.J., A.R. Harris, I.M. Mason, and A.M. Závody, New aerosol-robust sea surface temperature algorithms for ATSR *J. Geophys. Res., 102*, C13, 27,973–27, 1997

Harris A.R. and M.A. Saunders, Global validation of the along-track scanning radiometer against drifting buoys, *J. Geophys. Res., 101*, 12,127–12,140, 1996.

McClain, E.P., W.G. Pichel, and C.C. Walton, Comparative performance of AVHRR based multichannel SSTs, *J. Geophys. Res., 90*, 11,587–11,601, 1985.

Murray, M.J., *Sea surface Temperatures from ATSR (August 1991 to July 1995)*, [CD-ROM], Rutherford Appleton Lab., Chilton, England, 1995.

Murray, M.J., M.R. Allen, C.T. Mutlow, A.M. Závody, M.S. Jones, and T.N. Forrester, Actual and potential information in dual-view radiometric observations of sea surface temperature from ATSR, *J. Geophys. Res., 103*, C4, 8153–8165, 1998.

Mutlow, C.T., A.M. Závody, I.J. Barton, and D.T. Llewellyn-Jones, Sea surface temperature measurements by the ATSR on the ERS-1 satellite: Early results, *J. Geophys. Res., 99*, 575–588, 1994.

Reynolds, R.W., Impact of Mount Pinatubo aerosols on satellite-derived sea surface temperatures, *J. Clim., 6*, 768-774, 1993.

Reynolds, R.W., and T.M. Smith, Improved global sea surface temperature analyses, *J. Clim.*, *7*, 929–948, 1994.

Závody, A.M., C.T. Mutlow, and D.T. Llewellyn-Jones, A radiative transfer model for SST retrieval for the ATSR, *J. Geophys. Res., 100*, 937–952, 1995.

M.R. Allen and M.J. Murray, Space Science Department, Rutherford Appleton Laboratory, Didcot, OX11 OQX, U.K. (e-mail: M.R.Allen@rl.ac.uk; Jo.Murray@rl.ac.uk)

C.J. Merchant, Climate Physics Group, University College London, Mullard Space Science Laboratory, Holmbury St Mary, Dorking, Surrey RH5 6NT, U.K. (e-mail: cjm@mssl.ucl.ac.uk)

A.R. Harris, The Met Office, London Road, Bracknell, Berkshire, RG12 2SZ, U.K. (e-mail arharris@meto.gov.uk)

(Received February 13, 1998; revised June 29, 1998;
accepted July 6, 1998.)