ATSR Reprocessing for Climate (ARC): Stability of the ATSR data versus *in situ* observations

National Oceanography Centre
NATURAL ENVIRONMENT RESEARCH COUNCIL

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Introduction

The ATSR Reprocessing for Climate (ARC) project aimed to homogenize the skin and bulk Sea Surface Temperature (SST) estimates from the Along Track Scanning Radiometer (ATSR) series of satellites. Two of the targets specified by the project were (Merchant *et al.*, 2008):

- The reduction of inconsistencies between sensors to << 0.1°C for all regions
- Temporal stability of better than 0.05 °C decade^{-1}

This poster presents an assessment of whether these targets have been met for the bulk SST (bSST) through comparison with selected *in situ* measurements.

Data Used

The ATSR bSST values used are the "best estimates". For all three satellites this corresponds to dual view and the "ARC linear" SST retrieval model (Merchant *et al.*, 2008). During the day 2-channel retrievals are used (11μm and 12μm) and also for ATSR1 nighttime retrivals (as the 3.7μm channel failed shortly after launch). During the nighttime for ATSR2 and AATSR 3-channel retrievals are used (adding the 3.7μm channel). ATSR1 uses the "Bayes minimum" cloud screening (11μm and 12μm) and the later satellites "Bayes maximum" (adding the 3.7μm channel during the night and 1.6μm during the day, Merchant *et al.*, 2008).

Moored buoy SSTs for the period 1991 – 2009 have been extracted from the International Comprensive Ocean-Atmosphere Data Set (ICOADS, Woodruff *et al.*, 2011). Observations within 2 hours of the overpass times (~1030 and 2230 local solar time) and 0.1° spatially have been matched to the bSSTs. ICOADS QC flags have been used to discard any gross errors outside the 4.5σ trimming limits.

Assessment of the overlap adjustments

The brightness temperatures for the different channels and ATSR satellites have been adjusted into radiometric consistency for the overlap periods independently of the *in situ* data. The consistency of the bSST following these adjustments has been assessed using a repeat measures analysis of variance (RM-ANOVA).

Global Consistency

For each buoy and satellite overlap period the mean satellite – buoy bSST difference has been calculated separately for each satellite and for daytime and nighttime overpasses. For each overlap period (ATSR1/ATSR2 & ATSR2/AATSR) and buoy we therefore have a set of four mean differences. The source of variation for these mean differences is then examined using a RM-ANOVA. The buoys act as the subjects in the RM-ANOVA and the satellite and time of day as the factors (see Table 1). Only buoys with estimates for all 4 factor levels are used. The RM-ANOVA results for the two overlap periods are shown to the right (Table 2).

For both overlaps, there is significant variation due to the subjects (buoys), indicated by the large F values. For the ATSR1/2 overlap there are no other significant sources of variation. For the ATSR2/AATSR overlap period, the variations due to the time of day and the interactions between time of day and satellite are significant. Table 3 lists the contrast (i.e. differences) between the different factor levels for the ATSR2/AATSR comparison. Whilst the majority of the contrasts are significant at the 95% family confidence level, all the contrasts are below 0.05°C. These results suggest that globally the bSSTs from the different satellites are consistent to better than 0.1°C.

Table 1: Treatments used in the RM-ANOVA

Treatment	ATSR1 / ATSR2 overlap		ATSR2 / AATSR overlap	
	Satellite	Time of day	Satellite	Time of Day
1 (S1N1)	ATSR1	Day	ATSR2	Day
2 (S1N2)	ATSR1	Night	ATSR2	Night
3 (S2N1)	ATSR2	Day	AATSR	Day
4 (S2N2)	ATSR2	Night	AATSR	Night

Table 2a: Results of the RM-ANOVA for the ATSR1 / ATSR2 overlap period *(blue italics indicates a significant result)*

Source of variation	SS	df	MS	F
Subject (buoy)	*14.8252*	*73*	*0.2031*	*11.48*
Factor A (satellite)	0.0188	1	0.0188	1.06
Factor B (time of day)	0.0001	1	0.0001	0.01
Interactions	0.0009	1	0.0009	0.05
Error	3.8727	219	0.0177	

Table 2b: Results of the RM-ANOVA for the ATSR2 / AATSR overlap period

Source of variation	SS	df	MS	F
Subject (buoy)	*7.0641*	*103*	*0.0686*	*13.89*
Factor A (satellite)	0.0010	1	0.0010	0.19
Factor B (time of day)	*0.0938*	*1*	*0.0938*	*19.01*
Interactions	*0.0263*	*1*	*0.0263*	*5.33*
Error	1.5252	309	0.0049	

Table 3: Contrasts between the different treatments for the ATSR2 / AATSR overlap period

Treatment 1	Treatment 2	Contrast (L) (°C)	Confidence interval (°C)
ATSR2 Day	AATSR Day	-0.0129	-0.0260 < L < 0.0002
ATSR2 Day	*AATSR Night*	*-0.0279*	*-0.0401 < L < -0.0139*
ATSR2 Night	*AATSR Day*	*0.0331*	*0.0200 < L < 0.0462*
ATSR2 Night	*AATSR Night*	*0.0189*	*0.0058 < L < 0.0320*
ATSR2 Day	*ATSR2 Night*	*-0.0459*	*-0.0590 < L < -0.0328*
AATSR Day	*AATSR Night*	*-0.0141*	*-0.0272 < L < -0.0010*

Regional Consistency

Figure 1 shows an example of regional boxplots for the different factor levels for the ATSR2/AATSR overlap period. Similar results are seen for the ATSR1/ATSR2 overlap period. Table 4 lists the differences between factor levels. Whilst there are large regional variations in the mean differences the differences between satellites are generally small. In most of the cases listed in Table 4, the differences are smaller than 0.1°C in magnitude. However, the uncertainty in the differences are large, overlapping the consistency target of 0.1°C. This suggests that it is not possible to detect differences of O(0.1°C) regionally through comparison with the moored buoys. In order to improve our confidence in these results more buoys are needed.

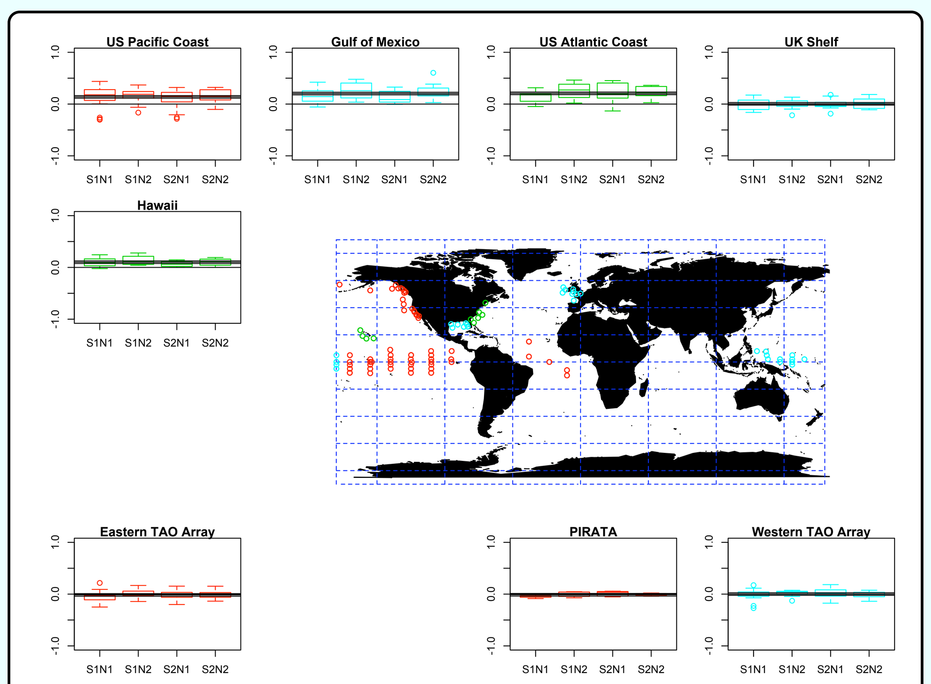

Figure 1: Regional boxplots comparing the different treatment levels for the ATSR2 / AATSR overlap period

Table 4a: Regional contrasts for the ATSR1 / ATSR2 overlap period

Region	Number of buoys	Daytime		Nighttime	
		Contrast (L) (°C)	Confidence interval (°C)	Contrast (L) (°C)	Confidence interval (°C)
Eastern TAO Array	25	-0.020	-0.070 < L < 0.031	-0.035	-0.089 < L < 0.019
Gulf of Mexico	8	0.133	-0.087 < L < 0.352	0.058	-0.009 < L < 0.124
Hawaii	5	0.010	-0.062 < L < 0.082	-0.020	-0.126 < L < 0.087
UK Shelf	11	-0.087	-0.214 < L < 0.040	-0.092	-0.254 < L < 0.071
US Atlantic Coast	8	-0.163	-0.352 < L < 0.026	-0.030	-0.176 < L < 0.117
US Pacific Coast	9	0.024	-0.145 < L < 0.194	-0.008	-0.199 < L < 0.182
Western TAO Array	8	0.063	-0.099 < L < 0.226	0.050	-0.096 < L < 0.196

Table 4b: Regional contrasts for the ATSR2 / AATSR overlap period

Region	Number of buoys	Daytime		Nighttime	
		Contrast (L) (°C)	Confidence interval (°C)	Contrast (L) (°C)	Confidence interval (°C)
Eastern TAO Array	33	-0.034	-0.060 < L < -0.007	0.028	0.007 < L < 0.048
Gulf of Mexico	7	0.023	-0.044 < L < 0.090	0.010	-0.126 < L < 0.147
Hawaii	4	0.030	-0.089 < L < 0.149	0.036	-0.060 < L < 0.132
PIRATA	5	-0.053	-0.135 < L < 0.028	-0.000	-0.069 < L < 0.068
UK Shelf	9	0.004	-0.042 < L < 0.049	-0.024	-0.069 < L < 0.020
US Atlantic Coast	6	-0.060	-0.190 < L < 0.070	0.034	-0.037 < L < 0.104
US Pacific Coast	21	0.038	-0.000 < L < 0.077	0.008	-0.026 < L < 0.042
Western TAO Array	15	-0.028	-0.089 < L < 0.032	0.034	-0.006 < L < 0.073

Assessment of the temporal stability

The temporal stability of the ARC bSST record has been assessed by performing a trend and change point detection analysis on regional averages of the satellite – buoy bSST differences. Buoys with short time series (<120 months containing match-ups to the ARC dataset) or containing step changes are excluded from the analysis. Additionally, due to seasonally varying biases in the ARC bSST estimates (thought to be due to the cloud screening) and intermittent match-ups with the buoy data it has been necessary to deseasonalise the satellite – buoy differences before averaging. This is to avoid aliasing of the seasonal cycles and biases specific to individual buoys into the averaged time series.

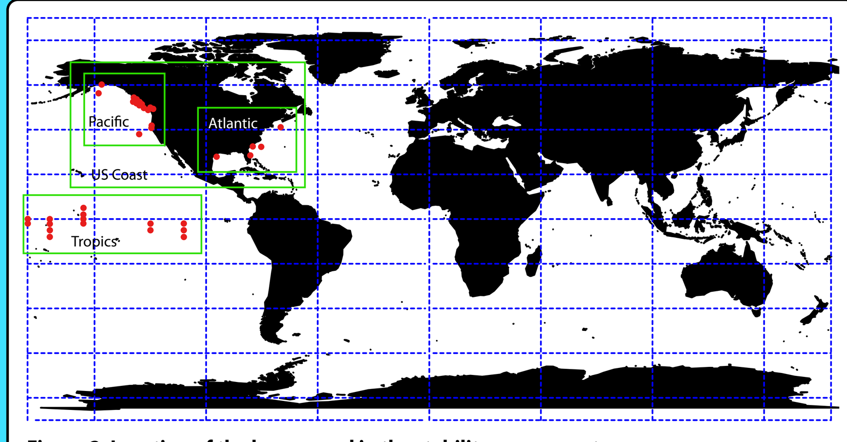

Figure 2: Location of the buoys used in the stability assessment

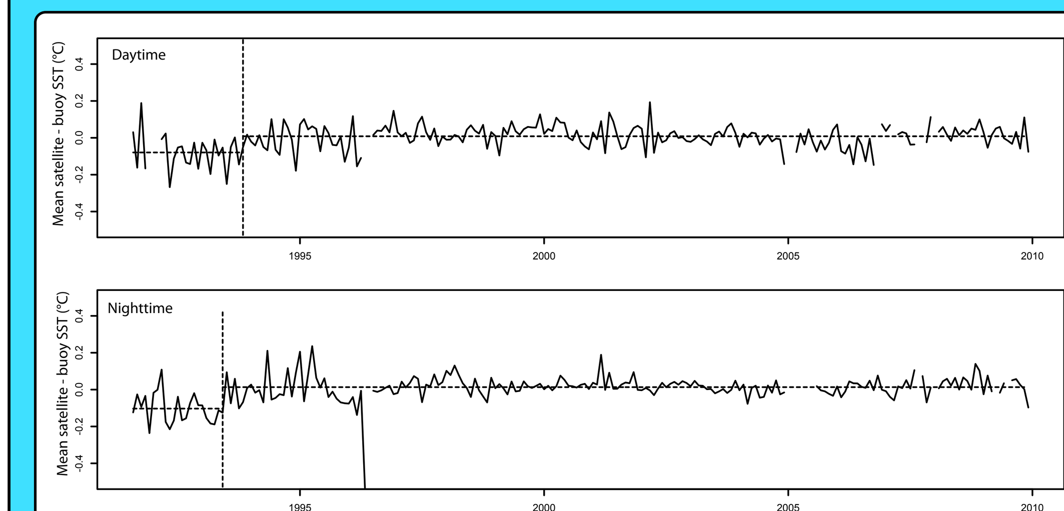

Figure 3: Time series of the monthly mean satellite - buoy bSST in the tropical Pacific

Only two regions are found to contain enough buoys with long enough records, these are the tropical Pacific and the US coastal (both Atlantic and Pacific) regions (Figure 2). The time series for the tropical Pacific is shown in Figure 3 – change points detected using a Penalized Maximal t Test (PMT; Wang *et al.*, 2007) are highlighted by vertical dashed lines. The time series is found to contain a step change during 1993 consistent with the reduction in atmospheric aerosols from the Pinatubo eruption – the actual change is likely to have occurred over a period of several years. Table 5 lists the trend estimates (and confidence intervals) for the tropical Pacific region using an AR1 trend model. When the data prior to the identified change are excluded no significant trends are found for the tropical Pacific and the confidence intervals for the trend estimates are small. Both the PMT and the AR1 model assume constant error variances in the models used but these are known to be larger for the ATSR1 data. If the ATSR1 data are excluded similar results are found, with no change points or significant trends identified. These results suggests that the stability target of 0.05°C decade^{-1} has been met in this region, but only when the data prior to 1994 are excluded.

When the PMT is performed on the US coastal data only a step change is identified in the daytime data. However, as noted above, the PMT assumes a constant error variance and this is known to be larger for the ATSR1 data. If the ATSR1 data are excluded, further change points are identified and these are shown in Figure 4. Table 6 lists the change points detected and Table 7 the trends for the time series analysis excluding the ATSR1 data. The change points detected lead to significant negative trends in both the daytime and nighttime differences, with the trend for the daytime values exceeding the stability target. The trend in the nighttime data is close to the stability target, with a confidence interval that overlaps the target of ±0.05°C decade^{-1}. These results suggest that the ARC bSST estimates do not meet the target stability in this region.

Table 5: Trend estimates for the satellite - buoy bSST differences in the tropical Pacific

Region	Period	Time of day	Trend (°C decade^{-1})	95% confidence interval (°C decade^{-1})
Tropics	*All (1991 – 2009)*	*Day*	*0.026*	*0.006 < trend < 0.045*
Tropics	*All (1991 – 2009)*	*Night*	*0.044*	*0.020 < trend < 0.069*
Tropics	> 1993	Day	-0.006	-0.026 < trend < 0.015
Tropics	> 1993	Night	0.010	-0.014 < trend < 0.034
Tropics	ATSR2/AATSR	Day	-0.014	-0.037 < trend < 0.009
Tropics	ATSR2/AATSR	Night	-0.002	-0.020 < trend < 0.016

Table 6: Change points identified in the US Coastal region (combined Atlantic and Pacific, excl. ATSR1)

Region	Time of day	Month	Size (°C)	Event
US Coast	Night	Nov-1995	0.095	Initial problems with ATSR2 (scan mirror failure)
US Coast	Night	Feb-2006	-0.055	ECMWF upgrade from 60 to 91 levels
US Coast	Day	Mar-1998	0.0629	ATOVS data starts to be assimilated into ERA40
US Coast	Day	Sep-2002	-0.0586	End of ERA40
US Coast	Day	Feb-2006	-0.0438	ECMWF upgrade from 60 to 91 levels

Table 7: Trend estimates for the satellite - buoy bSST differences in the US Coastal regions (excl. ATSR1)

Region	Time of Day	Trend (°C decade^{-1})	Confidence interval (°C decade^{-1})
US Coast	*Day*	*-0.052*	*-0.097 < trend < -0.007*
US Coast	*Night*	*-0.038*	*-0.075 < trend < -0.000*
Atlantic	*Day*	*-0.286*	*-0.382 < trend < -0.190*
Atlantic	*Night*	*-0.248*	*-0.335 < trend < -0.160*
Pacific	Day	-0.007	-0.057 < trend < 0.043
Pacific	Night	0.006	-0.031 < trend < 0.043

Table 8: Change points identified in the US Coastal Atlantic region (excl. ATSR1)

Region	Time of Day	Month	Size (°C)	Event
Atlantic	Day	Oct-1998	0.180	ATOVS assimilated
Atlantic	Day	May-1999	-0.288	None
Atlantic	Day	Jun-2003	-0.092	End of ATSR2 data
Atlantic	Day	Jan-2006	-0.101	ECMWF upgrade from 60 to 91 levels
Atlantic	Night	Jun-1999	-0.173	None
Atlantic	Night	Feb-2006	-0.103	ECMWF upgrade from 60 to 91 levels

Whilst the ARC bSST estimates do not meet the stability target in the US coastal region the majority of change points identified coincide with changes to the model used in the Bayesian cloud screening. Since the cloud regimes are different on the Pacific and Atlantic coasts the analysis has been repeated for the two regions separately. When the ATSR1 data are excluded no significant change points or trends are found for the US Pacific coastal region. Similar trends are found when the ATSR1 are included but with potential change points identified in the ATSR1 data. These coincide with the end of the ATSR1 data and initial problems with the ATSR2 satellite.

In contrast to the Pacific coast, significant change points (Table 8), and as a result trends (Table 7), are found for the combined US Atlantic Coast and Gulf of Mexico (GoM) data (excluding ATSR1). The identified change points tend to coincide with a change to the model used in the Bayesian cloud screening suggesting that the problems lies with the cloud screening. It should be noted that the results for the Atlantic and GoM are based on only 5 buoys and may not therefore be representative of the wider region.

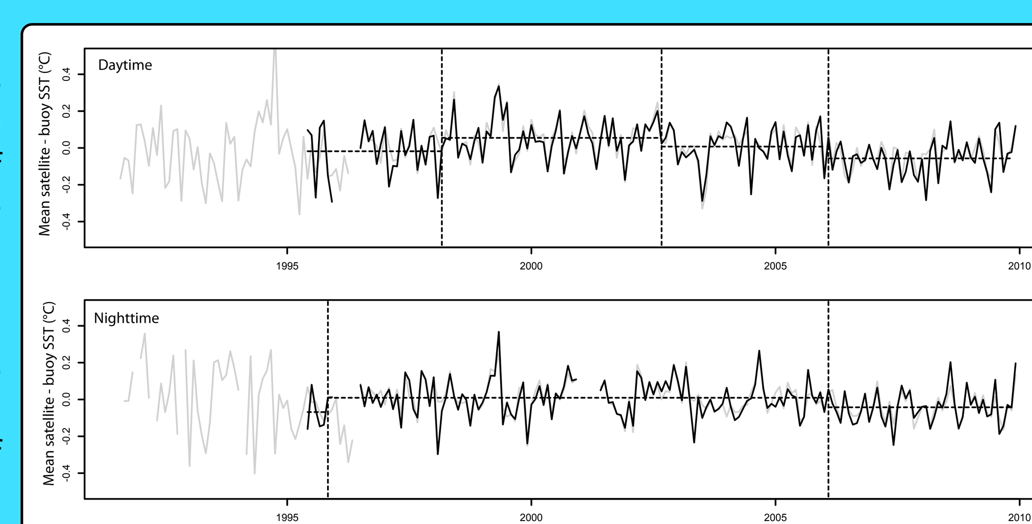

Figure 4: Time series of the monthly mean satellite - buoy bSST in the US Coastal region. Values for ATSR1 are shown in grey.

Summary

An assessment of the consistency of the ARC bSST estimates during the overlaps of the ATSR satellites has been made and the estimates found to be consistent to < 0.1°C globally. Regionally, the consistency between sensors also appears to be better than 0.1°C, however there is more uncertainty in this results due to a low number of suitable buoys in the regions examined.

The stability assessment of the ARC bSSTs found the data to meet the stability target in the tropical Pacific but only when data prior to 1994 were excluded. The data prior to 1994 are thought to be contaminated by aerosols due to the Pinatubo eruption. The data for the US Pacific coast were also found to be stable during the ATSR2 / AATSR period with no step changes identified and no significant trends. When the ATSR1 data were included significant change points were identified that coincided with the end of the ATSR1 record and start of the ATSR2 record but no significant trends found.

In contrast to the other regions, the data for the US Atlantic coast and Gulf of Mexico were found to contain multiple step changes that coincided with changes to the model used in the Bayesian cloud screening. These steps combined into large negative trends (order -0.25 °C decade^{-1}). These step changes mean that the stability target is not met for this region. Whilst the step changes identified are likely to be due to the Bayesian cloud screening and the seasonally varying bias, further work is needed to confirm this and to understand the extent of the problem.

References

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