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Using AATSR data to assess the quality of in situ sea-surface temperature observations for climate studies

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ABSTRACT

In situ data are widely used to provide a ground truth for the calibration and validation of satellite sea-surface temperature (SST) retrievals. They are also used to monitor long-term changes in the climate. For these applications, and others, it is necessary to understand the uncertainties in the data. Near-coincident SST observations from the Advanced Along-Track Scanning Radiometer (AATSR) and in situ platforms were used to understand the characteristics of errors in the measurements. The mean random error on the AATSR retrievals was found to be 0.14 K. The in situ errors were modelled as a constant offset plus a random error. For ships, the standard deviation of the constant offset was estimated to be 0.71 K and the mean random error was 0.74 K. For drifting buoys, the standard deviation of the constant offset was estimated to be 0.29 K and the mean random error was 0.26 K. These results suggest that there is a need to revisit current assessments of the adequacy of in situ observing systems. The trend in global-average SST between 1991 and 2007 calculated from in situ data was compared to its counterpart calculated from the ATSR instruments. The in situ record warms more slowly than the ATSR record, probably due to a decrease in the fraction of relatively warm-biassed ship observations contributing to the global-average SST over the period and a corresponding increase in the fraction of relatively unbiassed drifting buoy observations.

1. Introduction

Sea-surface temperature (SST) measurements constitute one of the longest global climate data records and are used extensively in climate analyses. Skilful forecasts of the climate can be made at seasonal (Folland, Parker, Scaife et al., 2006) and decadal (Keenlyside, Latif, Jungclaus et al., 2008) lead times due to the persistence of SST anomalies from month to month and year to year. Consequently, it is essential to be able to measure accurately the state of the sea surface and to understand the uncertainties in those measurements. As the focus of climate monitoring and forecasting shifts to a more regional scale, a comprehensive understanding of the uncertainties in climate measurements will become even more important, particularly in areas where observations are sparse and potentially unreliable (Goddard, DeWitt, & Reynolds, 2009).

The majority of the climate record for SST comes from measurements made in situ by ships, drifting buoys and moored buoys (Rayner, Brohan, Parker et al., 2006, Worley, Woodruff, Reynolds et al., 2005). Although the measurements can be used to estimate such metrics as the global annual average temperature as far back as 1850, they are often sparsely distributed, yielding little information on short period events or at small spatial scales. Since the 1970s, satellite measurements of the sea surface have provided this additional detail (e.g. Chiodi & Harrison, 2006) and almost-global coverage is achieved by infra-red instruments starting in the early 1980s.

An important question is whether the observations – both satellite and in situ – constitute a record of SST that is adequate for the purposes of climate analyses. Global Ocean Observing System (GOOS, 1999)

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requirements state that, for climate change detection, the benchmark accuracy of the processed SST signal should be 0.1 K on 200–500 km squares monthly. It places a constraint both on the measurement error of the instruments and on the long-term stability of the observing network. Another consideration is that the sampling for in situ observations should be sufficient to remove bias from satellite products, both for climate applications and when atmospheric aerosol loading is high. The GOOS requirement recommends an accuracy of 0.1 K in 500 km squares on weekly time scales. However, it should be noted that some satellite instruments, for example the Along Track Scanning Radiometers, do not need to be calibrated using in situ observations.

In order to establish whether the accuracy of the observed SST record is adequate for such applications, it is necessary to characterise the uncertainties in the data. Because of the difficulties involved in measuring the temperature of a micrometre-thin film of sea surface through several kilometres of atmosphere, some satellite measurements are calibrated against in situ data. Ideally, the calibration would be made against equivalent radiometric measurements, but the cost of such devices means that it is not practical to deploy them in large numbers. In situ thermometric data are available in large numbers but are of variable quality and introduce a further uncertainty because the skin temperature as measured by the satellite needs to be converted to an equivalent bulk temperature as measured by the in situ thermometer. Uncertainties are largest during the day particularly when wind speeds are low and insolation is high, thus allowing a near surface warm layer to form that can be several degrees warmer than the water at depth.

The ATSR (Along Track Scanning Radiometer) instruments were designed to deliver SST measurements that meet the demanding requirements of climate analyses (Llewellyn-Jones, Edwards, Mutlow et al., 2001). The dual-view configuration allows aerosol biasses to be detected and removed from the data without recourse to in situ measurements; the on-board calibration ensures the long-term stability of measurements from the instrument. O'Carroll, Eyre, and Saunders (2008) have demonstrated that ATSR retrievals have relatively low measurement errors. Corlett, Barton, Donlon et al. (2006) and Barton (2007) showed that the biasses and other errors in ATSR retrievals are generally lower than for other satellite SST retrievals making them an ideal reference data set. A reanalysis of the SST record produced by the ATSR instruments will provide the backbone for future climate quality analyses of SST (Merchant, Llewellyn-Jones, Saunders et al., 2008).

The adequacy of the global ocean observing system has been assessed by Zhang, Reynolds, and Smith (2006) and Zhang, Reynolds, Lumpkin et al. (2009). They calculated the number of buoys and ships needed in each 10° square to reduce satellite biasses of 2 K to below 0.5 K and biasses of 1 K to below 0.3 K. This approach has been used to target the deployment of drifting buoys since 2005 and thereby make best use of the available resources. Their approach depends on a thorough assessment of the uncertainties in the in situ data.

So, a key question for understanding both in situ and satellite records is, how accurate are the in situ data?

Until the 1990s, most in situ measurements were made by Voluntary Observing Ships (VOS). In the past, the measurements from VOS ships were not made with the needs of climate researchers in mind and the variation in bias and accuracy means that they do not often meet the stringent GOOS requirements. Several analyses have attempted to quantify the uncertainties associated with in situ SST measurements. The biasses associated with the different methods used by ships to make SST measurements have been analysed by a number of authors, most recently Kent and Kaplan (2006). Emery, Baldwin, Schlussel et al. (2001), Smith and Reynolds (2002), Kent and Challenor (2006), and O'Carroll et al. (2008) made estimates of the random measurement uncertainties in ship and buoy data. More recently, Kent and Berry (2008) proposed a new error model for in situ data that combines the usual random term (intra-platform error) with a bias term that varies from ship to ship (the inter-platform error). The basic rationale is that a ship's thermometer which is mis-calibrated such that it reads 0.5 K too high (inter-platform error) will never get closer than 0.5 K to the true SST other than by a chance combination of random errors (intra-platform error). In this scheme, aggregating the observations from many ships or buoys with independent inter-platform errors is the only way to reduce the average error to zero. Brasnett (2008) used this error model implicitly in a scheme for calculating bias corrections for individual ships.

The analysis of measurement uncertainties is complicated by the fact that in situ observations are typically widely separated. Ideally, high quality, well-calibrated, coincident observations would be used to characterise the data, but these are rarely available in large quantities and, where they are available, it is not given that the results will generalise to other times and locations. Usually, pairs of in situ observations are compared making it harder to disentangle the individual error components.

For the purposes of the analysis presented here, the ATSR instruments are used as a consistent reference field with low measurement error (O'Carroll et al., 2008) and low detector bias (Barton, 2007, Corlett et al., 2006) that is independent of the in situ record. Near-coincident pairs of in situ and AATSR observations are used to assess the error characteristics of the in situ data.

The in situ and ATSR data are described in Section 2. A basic error analysis is detailed in Section 3 for comparison with earlier studies and to further establish the low-error character of the AATSR retrievals. In Section 4, the error model is extended to include inter- and intra-platform errors. In Section 5 the consequences of non-normal error distributions are explored. The insights gained from the first five sections are used in Section 6 to reassess whether the in situ network is fit for purpose as assessed against the GOOS requirements for satellite calibration. In Section 7, attention is turned to the longer term and the ATSR instruments are used to verify the accuracy of long-term trends in the in situ global climate record. Summary and conclusions are given in Section 8.

2. Data

The ATSR (Along Track Scanning Radiometer) series of instruments provide an almost complete record of SST from 1991 to the present. ATSR-1 flew from 1991 to 1995 and ATSR-2 from 1995 to 2008. The AATSR instrument is mounted on the ESA (European Space Agency) Envisat satellite which was launched in 2002. Envisat is in a near-polar sun-synchronous orbit, which crosses the equator at 10:00 local time on the descending node. The AATSR instrument has an inclined conical scan configuration, observing in the forward (55°) and nadir directions. Three infra-red channels centred in the atmospheric windows at 11 μm, 12 μm and 3.7 μm are used to retrieve the skin SST and additional channels in the visible spectrum are used for cloud clearing. During daylight hours, there is the possibility of solar contamination of the 3.7 μm channel. Therefore retrievals using all three channels are only available at night. The instrument was designed to give SST retrievals with an accuracy of better than 0.3 K and a long term stability of better than 0.1 K decade^{-1}.

The AATSR record from 2002 to 2007 was consistently reprocessed at the Met Office from the ESA AATSR METEO product and the level 1b brightness temperatures using the December 2005 Case C retrieval coefficients (http://earth.esrin.esa.it/services/auxiliary_data/aatsr/ATS_SST_AXVIEC20051205_102103_20020101_000000_20200101_000000) that were made operational on 7th December 2005 as recorded in the change log (http://earth.eo.esa.int/pcs/envisat/aatsr/events/) and are based on the HITRAN 2000 database. ATSR1 and ATSR2 data are processed using version 2 of the METEO product from NEODC (http://neodc.nerc.ac.uk/?option=displaypage&Itemid=