Use of the ATSR series in the construction of a long-term SST record for climate change detection

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Introduction

Sea surface temperature (SST) has long been recognized as one of the most important parameters in the climate system. It is a key diagnostic for climate change detection, and exerts a controlling influence on the exchange of heat between the ocean and atmosphere. For the past decade and a half, satellite-based retrieval methods have been used to map SST on a routine basis, with all the advantages (and disadvantages) that remote sensing entails. In 1991, the first of a new generation of spaceborne radiometers was launched on the ERS-1 platform. This instrument, the along-track scanning radiometer (ATSR) promised to provide, for the first time, SST measurements to the accuracy required for climate research from a single sensor. The three main improvements over other sensors were much improved calibration sources (3-σ drift error of <0.1 K over the mission, Mason *et al.*, 1996), the use of a two-angle view of the surface to assist in accounting for the contribution of the atmosphere to the measured radiances, and a Stirling cycle active cooling system for the detectors. Early validation results (Mutlow *et al.*, 1994, Harris *et al.*, 1995, Barton *et al.*, 1995, Harris & Saunders, 1996) indicate that the instrument performs well, but some significant problems remain. In order to ascertain the priorities for improvement, we need to review the primary goals of such research. The desire is to construct a long-term record of SST using data from ATSR, ATSR-2 (launched in April 1995) and eventually the advanced-ATSR (AATSR, due for launch at the end of 1999). In order toproduce such a record of SST for climate change detection purposes, the stability of the observing system must be better than 0.1 K decade^{-1} (Allen *et al.*, 1994). It is for this reason that such care has been taken to provide accurate and stable calibration sources. However, there are other effects, both geophysical and instrumental, that can potentially compromise the goal. Firstly, the ATSR SST retrieval process is designed to retrieve the skin temperature, which may be some tenths of a degree different (usually cooler) than the bulk temperature measured by buoys and ships. Secondly, different retrieval algorithms display different sensitivities to changes in stratospheric aerosol loading, and also to water vapour loading. The key point is this: for climate change purposes, changes in retrieved SST resulting from changes in any other parameter affecting the retrieval process cannot be tolerated. Stratospheric aerosols generated by volcanic eruptions are a particular problem since they can cause secular trends in retrieved SST over a period of years.

Skin Or Bulk?

It is important to recognize that, irrespective of algorithm development method, either regression against *in situ* bulk measurements or theoretical brightness temperatures produced by a radiative transfer model, that a spaceborne infrared radiometer detects radiance emitted from no lower than the skin of the ocean. Regressing measured brightness temperatures directly against *in situ* measurements of bulk temperature will remove the mean bias (along with errors in calibration and the radiative transfer model), but it will be unable to deal effectively with the rapid temporal and spatial variability of the skin effect. It might be argued that the skin SST is a better parameter to use than the bulk temperature, since it is that temperature that directly affects the exchange of heat, but there are several problems with this. Firstly, the skin effect is a function of the net heat loss from the ocean surface, combined with the surface renewal of the boundary layer which is almost entirely a function of wind speed. These parameters change with time of day and cloud cover, but sun synchronous polar orbiting satellites view a given part of the ocean at the same time each day, and only provide measurements under cloud-free conditions. Secondly, the temperature of the mixed layer is the best indicator of the store of heat, which is a function of the long-term integral of the heat flux − a far more important diagnostic quantity for climate models than the instantaneous value.

A Staged Approach

In consideration of the above, we have decided to adopt a staged approach to the construction of a bulk SST record of the accuracy required for climate monitoring.

Accurate Retrieval of Skin SST

The first step is to retrieve an accurate skin SST from the satellite radiometer measurements. This precludes the use of regression against *in situ* bulk measurements, and a line-by-line radiative transfer model developed from that of Závody *et al.* (1995) and geographically and seasonally diverse set (~1300) of profiles is used to generate top-of-atmosphere brightness temperatures at 3.7, 11 and 12 μm for both the nadir and forward views (~55° zenith angle) of the ATSR. The radiative transfer model includes updated absorption database information. Stratospheric and tropospheric aerosols are also modeled using a hybrid scheme. Robustness against stratospheric aerosol is achieved by using a Lagrange multiplier constraint within the regression procedure, and is shown, in simulations, to produce zero bias under all realistic aerosol loadings. Absence of a comprehensive set of in situ skin temperatures prevents absolute validation, but when applied to real data, inter-algorithm biases are reduced from ~0.7 K to 0.02 K. The new continuum model is shown to remove the cold bias present in previous algorithms in regions of high water vapour loading such as the W. Pacific Warm Pool. The main reason why it is necessary to achieve zero bias between the 2-channel and 3-channel dual-view retrievals is that ATSR's 3.7 μm channel failed in May 1992, while the aerosol loading from Mt. Pinatubo was still fairly high, and SST records produced using the pre-launch retrieval coefficients showed a pronounced drop after this time which slowly recovered thereafter. This work is described in more detail in a companion paper (Merchant, 1999) and even more comprehensively in Merchant *et al.* (1999) and Merchant and Harris (1999).

Skin to Bulk Conversion

The second step is to use surface fluxes of heat and momentum in models from a numerical weather prediction (NWP) analysis to parametrize the skin effect. A variety of models are examined for their applicability and tolerance to errors in the analysis fluxes. The results of the various models are tested against match-ups of *in situ* temperatures from drifting buoys with ATSR-2 skin SSTs to evaluate their relative success. The criteria for a good validation matchup are also explored at this point in terms of cloud cover, time and space location, etc. and also avoidance of possible diurnal effects. Matchups with high-quality validation data yield a reduction in rms from ±0.31 K to ±0.25 K, which approaches the minimum deviation expected from error analysis.

The Diurnal Thermocline

The third step is to correct for the diurnal cycle of temperature in the top part of the mixed layer. The approach is to use a time history of fluxes from a NWP analysis to force a high resolution vertical mixing model of the near-surface. A variety of bulk and turbulence diffusion models are being evaluated, initially by comparison with SSTs from shallow (~5 cm) sensors such as WOCE SVP drifters which measure the temperature within the stratified layer. High resolution (~10 cm) temperature profile data have been obtained from Univ. Iwate, Japan, and estimates of the fluxes of heat and momentum using *in situ* meteorological measurements are being used to force the models (see Figure 1). Although the diurnal

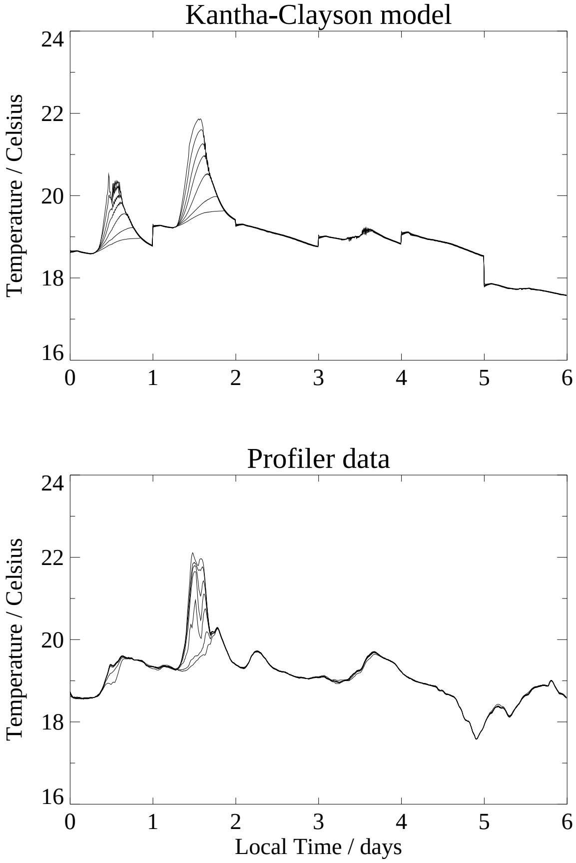

Figure 1: Comparison of 6 days of Mutsu Bay profiler data with temperatures predicted by an adaptation of the Kantha-Clayson turbulence closure model. The time resolution is 10 minutes. The 1-d model is reinitialized to the profiler bulk temperature at the start of each day in an attempt to minimize problems with advection. Temperatures at depths of 1, 10, 20, 30, 50, 100 and 200 cm are plotted. Note that the lines only separate when stratification is present.

thermocline only becomes significant about 15% of the time, it displays strong geographical preferences (see Figure 2) and must therefore be accounted for if one hopes to provide a comprehensive dataset of bulk SST estimated from space. This work also poses some interesting questions regarding the definition of bulk temperature.

Other Issues

Although one conclusion of the above work is that the limit of validation accuracy is already being approached, the exercise has only been conducted for a restricted set of conditions. There are other aspects of the retrieval process and instrument that need to be addressed.

Validation of skin temperatures

Since our initial satellite retrieval is of the skin SST, it will be beneficial to validate the retrievals against high quality *in situ* measurements of skin SST made by specialized ship-borne (and platform-based) thermal IR radiometers. Such measurements are the preserve of specialist oceanographic cruises and are consequently sparsely distributed in both space and time − there have simply been too few to date. However, recent efforts to co-ordinate such measurement activities for the purposes of validating a number of upcoming spaceborne radiometers are to be strongly encouraged, as are the attempts to install stand-alone systems on ships of opportunity. If provided with associated meteorological measurements, then these data will be also be invaluable for use in the development and testing of improved parameterizations of the skin effect, the fruits of which can then be fed back into the skin-to-bulk conversion process described above.

Long-term Validation

Although validation against skin temperatures is desirable, such measurements are never likely to be sufficiently widespread to give full confidence. Indeed, their main purpose will be to form a basis for evaluating and improving the radiative transfer modelling and other aspects of the skin SST retrieval process. In addition, it is the bulk product that is the desired end quantity, and measurements of this are much more widespread. Another consideration is that bulk measurements are the only feasibly sufficient source of validation data for the ATSR mission (and much of the ATSR-2 mission), and they function as the common reference that will be needed to overcome potential effects due to differences in the instruments. Any long-term record of bulk SST produced from satellite data should be continuously checked against high quality *in situ* measurements. We are not advocating empirical tuning of the end-product, however. Instead, the results of this analysis would be used to improve our understanding

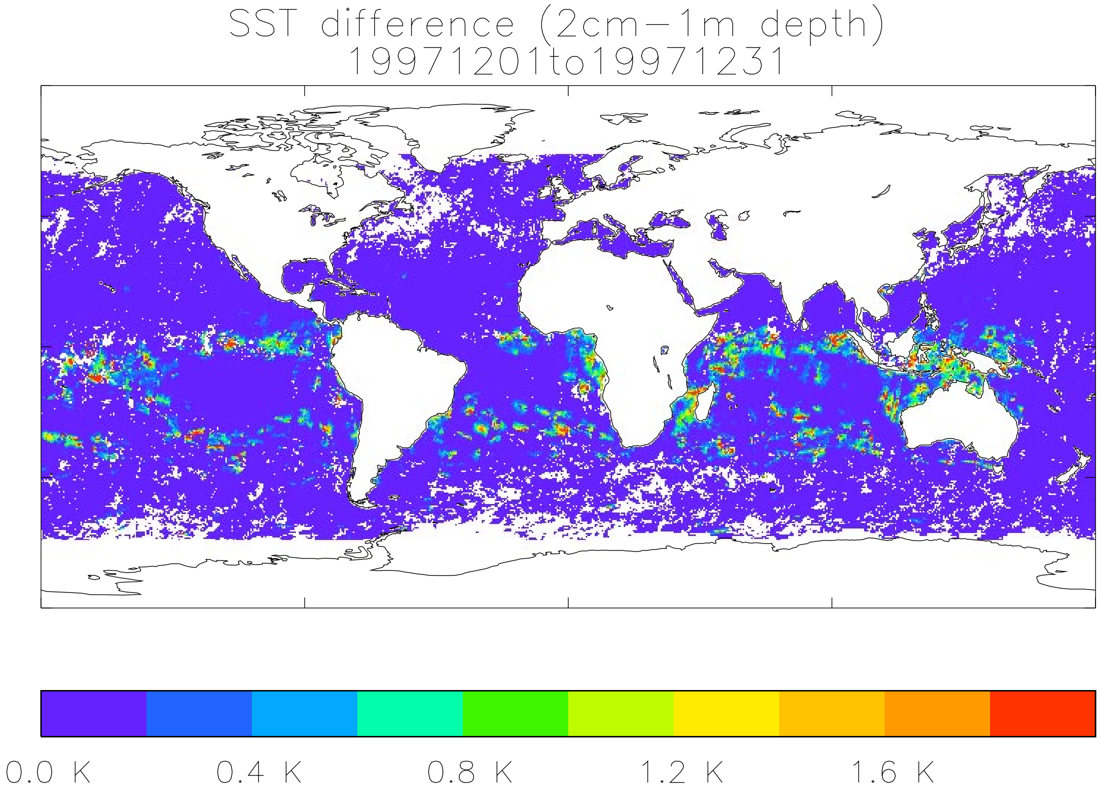

Figure 2: Mean diurnal thermocline temperature excursions for all ATSR−2 daytime passes during the month of December 1997. The values displayed are differences between the model layers at 2 cm and 1 metre depths. The model used in this case is adaptation of the simple energy budget scheme of Kraus and Turner. Note the prevalence of warming in the tropics and the southern hemisphere subtropical high pressure regions. The warming pattern shifts above the equator during the northern hemisphere summer.

of the various physical processes and instrumental effects contributing to the retrieval.

Other Effects

There are a number of areas which require investigation in order to assess their impact on the retrieval scheme. Chief among these is the nature of cloud masking schemes. Primary issues for consideration are:

1) what is the impact of the loss of the 3.7 μm channel on ATSR cloud masking?

2) what is the impact of increased detector noise (due to the gradual degradation of cooler performance) on ATSR cloud masking?

3) what is the impact of the extra channels on ATSR-2 cloud masking relative to that of ATSR? and

4) what is the impact of using different approaches to cloud screening, and might these lead to differences in the retrieved bulk SST record?

In particular, is there likely to be a change in retrieved bulk SST due purely to changes in cloud characteristics over time, and if so, might other cloud masking schemes make the retrieval process more robust to such changes?

Other effects which may compromise the retrieval process include changing concentration of trace gases. In addition, the gradually degrading cooler performance of ATSR results in a small spectral shift in the 12 μm filter function, which could certainly cause a secular trend in retrieved SST of 0.1 − 0.2 K over the lifetime of the mission if not accounted for.

Summary

For the case of SST retrieval, the observing system comprises far more than just the spaceborne radiometer. The requirement of <0.1 K decade^{-1} encompasses the entire retrieval process, from measurement of top-of-atmosphere radiances to final retrieval of bulk SST. It is a stringent target, but one which must be met in order to contribute to the timely detection of climate change.

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