(A)ATSR Exploitation Plan
Volume 4

Review of Remotely Sensed Sea Surface Temperature

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1 INTRODUCTION

Sea surface temperature (SST) provides a fundamental measure of the state of the ocean surface. It encapsulates at a global and regional level the effects of greenhouse gas warming on climate. At regional level, SST reflects the structure of the major ocean currents, the large-scale wind forcing near the surface and radiative heating and cooling. At small scales, SST is a balance between the underlying ocean and vertical mixing, the overlying atmosphere and solar forcing; hence SST is diurnally varying. Physically, SST provides a critical interface to the atmosphere through air-sea latent heat fluxes which regulate the atmosphere-ocean interface. SST is therefore implicated in both energetic processes such as convection and hurricane intensification, but also forcing of large scale climate extending into the stratosphere, e.g. through El Niño and convection. SST further regulates the exchange of gases such as carbon dioxide across this interface, providing a link to the carbon cycle. This is extended in the biological ocean pump for carbon since SST is an important parameter in the evolution of ocean biology.

Remote sensing of SST is used increasingly to address some key science challenges, to improve operational numerical weather prediction (NWP) and operational oceanography, and for a range of specific applications involving variously scientists, end users and the public. The key science challenges include climate trends, quantification of natural ocean processes and variability, improvements in ocean models, and better understanding and interpretation of SST effects on atmospheric trends and variability. The operational applications will also benefit from improvements in ocean models but also require, as a first step, continued work on optimal analysis schemes combining SST datasets. Applications vary considerably from changes in SST at the ice margins, studies of ocean currents and gyres to the impacts of SST on changing ocean biology, on mammalian life at the sea-ice interface and on coral reefs.

Hence SST has a number of differing facets:

- As a marker of global and regional climate change
- As an index of natural variability such as El Niño and the North Atlantic Oscillation
- As a delineator of ocean currents and heat transport
- As a proxy, with other variables, of air-sea heat flux and surface ocean heat content
- As the major driver for thermal forcing of the atmosphere and surface radiation to space
- As an initiator of atmospheric circulation through thermal forcing and convection

- As a modulator of sea ice evolution at the sea-ice interface
- As a moderator of ocean biology and life at the sea-ice interface.

The greatest progress in recent years has been made in improving the accuracy of SST measurements and, in particular, using (A)ATSR as a reference sensor to understand the SST climate record based on long-standing buoy and ship records. It has also helped in progressing towards high resolution grids of SST for model comparisons and climatologies. Particular steps forward have been more vigorous and substantive programmes of validation for satellite SST as exemplified by the AATSR programme, the use of operational, user-orientated data formats such as the Group on High Resolution Sea Surface Temperature (GHRSST) L2P product, and the improved representations of sea surface state through data quality improvements and labelling. The AATSR delivers SST with single sounding precision of 0.3 K for its best data and with absolute accuracies of better than 0.2 K.

The following sections consider remote sensing of SST, the (A)ATSR and other SST products, the applications of SST data that are of relevance to the (A)ATSR Exploitation Plan and finally, possible exploitation of (A)ATSR data products.

2 REMOTE SENSING OF SEA SURFACE TEMPERATURE

2.1 Theoretical basis

SST can be derived from measurements of the thermal upwelling radiance from the ocean to the top of the atmosphere (TOA). The radiation observed by an instrument on a satellite is essentially the sum of three components: the Planck radiation from the ocean surface (modified by the emissivity of the water surface), absorption and re-emission processes in the atmosphere, and a small term comprising downwelling radiation from the atmosphere to the surface reflected upwards with further attenuation by the atmosphere. The understanding of this physics is high, giving the ability to observe SST in both the thermal infra-red (typically in the 8 to 12 micron window and at wavelengths less than but close to 4 microns) and the microwave (typically near 7 GHz).

Both thermal infra-red and microwave measurements have strengths and weaknesses. Thermal infra-red measurements offer high spatial resolution (typically 1 km for low Earth orbiting platforms and 3-5 km for geostationary platforms), high sensitivity to temperature changes (arising from Planck function stability), accuracy through good calibration systems, and long heritage. The Advanced Very High Resolution Radiometer (AVHRR) and the (A)ATSR series of instruments have 15+ year records. The (A)ATSR series of instrument has the highest intrinsic radiometric performance with two on-board blackbodies. Data from thermal instruments requires algorithms to mitigate atmospheric interference effects and are cloud-cleared; these instruments do not give good SST in the presence of clouds. Microwave instruments have an excellent ability to see through most clouds, and lower sensitivity to atmosphere effects (typically also improved by inclusion of water vapour correction data from channels near 21 GHz). Systems such as the Advanced Microwave Scanning Radiometer - Earth Observing System (AMSR-E) achieve spatial resolutions of close to 25 km but cannot measure close to coasts also because of sidelobe effects.

There is a fundamental difference also between thermal and microwave measurements of SST which relates to the depth of penetration of water at the relevant wavelengths. An excellent description can be found on the GHRSST web-site (http://www.ghrsst-pp.org/SST-Definitions.html). Thermal SST measurements effectively determine the “sea surface skin temperature” which is the temperature of the conductive diffusion dominated sub-layer at a depth of approximately 10 to 20 microns in the ocean surface. Microwave radiation is more related to the “sea-surface sub-skin temperature” which is more of the order of mms of depth and is related to the temperature at the base of the conductive laminar sub-layer of the ocean surface. Therefore, the relationship between thermal and microwave SST measurements is complicated by the gradient of temperature at these depths and is related to diurnal warming from solar radiation, evaporative cooling, night-time clear sky cooling and winds.

Both for the thermal infra-red and microwave instruments, the fundamental quantity measured is the integrated upwelling or TOA radiance within an instrument-defined spectral passband. The integrated measurements must then be converted to SST using algorithms which account for the radiative transfer for the surface through the atmosphere in the different channels of each instrument. The details of this vary from instrument to instrument and from product to product so the theoretical description here concentrates on that apposite to thermal infra-red SST derivation, following the treatment in Noyes (2006). Note that there is an intrinsic difference between (A)ATSR and other SST instruments in that the data analyses for (A)ATSR are the only ones which perform a completely internal derivation of SST rather than utilising a tie to selected buoy data.

Radiative transfer equations tell us that with knowledge of surface emissivity and atmosphere conditions, then one can derive SST in a straightforward manner. Sea surface emissivity is relatively well-known at least in the thermal infra-red (Watts et al (2006), Masuda et al (1988)) and therefore the problem reduces to that of correcting for atmosphere effects, which can be done by utilising multi-channel approaches. These are based on the fact that atmospheric absorption varies with wavelength (see for example, Deschamps & Phulpin (1980), McMillin (1984) and Becker & Li (1990)). By utilising measurements from at least two different spectral channels, an estimate of the attenuation due to the atmosphere can be obtained. The most common form of the multi-channel method is to use two spectral channels at approximately 11 and 12 microns, known as the split-window channels. This is sometimes supplemented by a third channel at approximately 3.7 microns (triple-window method). In the case of the (A)ATSR instruments, this is further augmented by including data from two viewing angles, which provides further information about the state of the atmosphere (dual-view method).

The overall solution to the radiative equations can be shown, for the split window channels, to be of the form $Ts = a_1T_1 + a_2T_2 + a_0$ where the a_i are coefficients applied to channels 1 and 2 and a_0 is a constant. This approach can be generalised to larger numbers of channels simply by extending the number of coefficients used (e.g. McClain, 1985). For (A)ATSR data, these coefficients are further refined to be (stratospheric) “aerosol robust” (Merchant et al, 1999).

The retrieval coefficients are derived by regressing measured or simulated TOA brightness temperatures (BTs) against “known” SSTs to obtain ‘best-fit’ coefficients; the spread in the regression data will be due to noise on the BTs, atmospheric variability and errors in the input SSTs. The coefficients for the AVHRR SST retrievals, for example, are derived empirically by regression of many satellite TOA BTs against coincident *in situ* observations of SST obtained from buoy data (e.g. Li et al. 2001). In contrast, the operational (A)ATSR SST retrieval coefficients are derived theoretically by regressing modelled TOA BTs against the surface temperatures used to simulate those BTs (Zavody et al. 1994, 1995, Merchant et al. 1999). The advantage of this latter approach is that the retrieved satellite SSTs are independent of any surface measurements and this is the method that has always been employed by the (A)ATSR data processing. Increasingly, this approach is being taken for the processing of data from other instruments.

2.3 Satellite SST products

A number of thermal infra-red and microwave instruments produce SST data products. The differences between them are principally independence from or tie to buoys, accuracy, spatial resolution and coverage, temporal resolution and re-visit time, and sensitivity to clouds. The (A)ATSR data stream is truly independent of other SST sensors, whilst instruments such as AVHRR are currently tied to buoys. The (A)ATSR data also offer the highest calibration and accuracy due to the combined effects of blackbody calibration and dual-view. Only microwave instruments offer SST measurements in cloud-covered scenes but at lower spatial resolution than thermal infra-red instruments, and with limited cloud information. Therefore, inter-comparison of thermal infra-red and microwave data can be difficult. Nonetheless, there has been very strong progress in the ability to utilise multiple satellite datasets as a result of the GHRSST project (see section 3.4).

2.2.1 (A)ATSR SST products

The (A)ATSR operational processing scheme makes available a number of SST products at high spatial resolution (1 km) and at a lower averaged spatial resolution. It has been a deliberate decision to re-process all of the (A)ATSR data to ENVISAT data so as to have the first consistent processing of all three instrument datasets (this is designated ‘Version 2’). In addition, (A)ATSR data, i.e. for the whole mission, are now being produced in GHRSST L2P format at the ESA and NERC/DECC archives.

The (A)ATSR products available are:

- Gridded Sea Surface Temperature (ATS_NR_2P)
    - Nadir view and ,where available, dual view SSTs are given with a resolution of 1 km. Confidence flags are provided for each pixel: these are used to indicate if the 3.7 µm channel is used in the retrieval and also to show which cloud-clearing tests indicate cloud.
- Area Averaged Sea Surface Temperature (ATS_AR_2P)
    - This product contains four temperature datasets: two datasets that are averaged with respect to a longitude-latitude grid, at 0.5 ° x 0.5 ° and at 30 arcminutes x 30 arcminutes; and two products averaged relative to an equal area grid, one with a resolution of 17 km x 17 km and one at 50 km x 50 km.

- Meteo product (ATS_MET_2P)
  - This product is designed for use by meteorological organisations and contains brightness temperature and SST data at 10 arcminute resolution.
- L2P (ATS_NR_2P)
  - The L2P product conforms to the standard produced by the GHRSST project and contains the 1 km SST data, error estimates (bias error and standard deviation) for each pixel and a series of ancillary fields which aid interpretation and use of the SST data.

These products are comprehensively described in ESA's Envisat AATSR Product Handbook, Issue 2.2, dated 27 February 2007.

The nature and quality of (A)ATSR SST for ocean and climate change is extremely mature in terms of instrument design and calibration, although some small improvements in system performance are required; for ocean applications swath width is the major drawback but this is being addressed in the Sentinel-3 mission.

At the time of writing, the engineering design and performance of (A)ATSR are close to ideal and the main limitation to accuracy is the atmospheric correction. As such, there is a continued need to investigate the basic spectroscopic properties of the atmosphere at the (A)ATSR wavelengths and to generally improve the clear-air retrieval scheme. Some continuing attention will need to be paid to characterisation of instrument drifts, which are believed to be extremely small but nevertheless quantifiable.

At present the operational coefficient-based retrieval scheme for SST is mature and undoubtedly performs very well. However, some deficiencies are manifested in the observed latitude-dependence of the accuracy, in differences seen between 4-channel and 6-channel retrievals and in dependences on clouds. It is clear that there are still some small effects within the atmospheric correction, either with the spectroscopic data used or the actual formulation of the retrieval algorithms, which are still being addressed. A particular interesting and potentially significant development is the use of optimal estimation either for the SST alone (e.g., Merchant 2008) or as an extension of the aerosol retrieval (Thomas et al. 2007).

Perhaps a more important scientific aspect of system performance is that of cloud detection when retrieving SST. The methods used by (A)ATSR are very well developed and are mainly based on several threshold and spatial uniformity criteria. However, the operational cloud identification over sea (based on Zavody et al, 2000) is by no means perfect, deliberately tending to be conservative but also showing residual cloud-clearing failures. Indeed a number of papers (e.g. Simpson et al, 1998, and Merchant et al, 2005) have shown that methods involving visible channels or Bayesian estimation promise to deliver improved performance. Thus, work which seeks either to improve the existing cloud detection scheme or to explore new and different methods which have the potential for operational implementation need to be given high priority in the system performance area. It should be noted that the ability to detect clouds quantitatively is also a priority in a significant area of atmospheric and climate research, which further strengthens the case for promoting further work in this area of (A)ATSR system performance.

2.2.2 Other SST products

The chief products from other satellite sensors are summarised in the Table below.

Sensor	**Resolution**	**Advantages and Disadvantages/ Version number**
AVHRR	1km, Two satellites Twice per day	Operational SST products with Local or Global Area Coverage are provided by several different institutions (for example, the OSI-SAF and EUMETSAT,NOAA CoastWatch). Pathfinder version 5.0 SST is a reanalysis of the operational AVHRR data stream between 1985 and December 2007. Daytime, night-time and combined day and night products are provided and have a resolution of 4 km.
MODIS	1km, Twice per day Terra: 10:30am/pm local time Aqua: 1:30am/pm local time	Two products are available: Aqua/Terra MODIS Global Level 3 Mapped Thermal IR SST, derived using the thermal IR (11-12 μm) channels; and MODIS Global Level 3 Mapped mid-IR SST, derived using 2 channels in the mid-IR region (3.8-4.1 um). Both products are available at 4 km and 9 km resolution.
SEVIRI	3-5km, 15mins MSG	MEDSPIRATION SEVIRI SST L2P product over the Atlantic Ocean is provided through the MERSEA web site. MSG is a geostationary satellite. Coverage is restricted to between 100 °W and 45 °E and 90 °N and 70 °S but a complete scan is repeated every 15 minutes.
AMSR-E	0.25 Aqua 1:30am/pm local time	AMSR-E is a microwave radiometer and can therefore retrieve SST through cloud (although not in the presence of precipitable water).
TMI	40 km TRMM	TRMM is in a semi-equatorial orbit and travels west to east. This produces data at changing local times between 40 °S and 40 °N.

Table 2-1: A summary of current remotely sensed SST products

2.4 In situ SST observations

2.4.1 Ships, buoys and radiometers

There are three essential systems for measurements of SST: ships, buoys (moored and drifting), and infra-red radiometers. Of these, the most important for SST applications are the first two whereas the radiometers have been primarily used for the critical validation of satellite SST products. Over time it is possible that the radiometers can provide climate trend information but this would require a long data series of consistent operations in a particular region and radiometer deployments to date have not achieved this goal, although ISAR in the Bay of Biscay and M-AERI in the Caribbean could potentially provide such datasets.

Naval vessels and Voluntary Observing Ships (VOS) contribute SST measurements. The method of measurement varies from ship to ship: a thermometer may be used to measure the temperature of a bucket of water drawn from the sea; more commonly the temperature of engine intake water is measured (the depth of this measurement may vary considerably). Another method is to measure the temperature using thermistors on the inside of the ship's hull. Although there are clearly limitations to ship measurements in terms of quality control and varied measurement patterns, ship data provide a very long time series and therefore have been of considerable value in constructing SST records for the 20th century.

Measurements of SST are also made by temperature sensors on drifting or moored buoys. Moored buoys are often found in coastal areas but there are also two arrays of mid-ocean moored buoys: one the TAO/TRITON array in the tropical Pacific Ocean, designed to monitor ENSO; and a second the PIRATA array in the Atlantic Ocean. Data from buoys have provided both monitoring of ocean current flows and good data for climatological records and blended climate data analyses in the regions of the world in which they exist.

2.3.1 HadSST2

Given the importance of *in situ* records for long-term climate data records, compilations have been constructed for climate studies, particularly as part of the IPCC process (see section 3.1.1). HadSST2 is the Met Office's *in situ* data product and is produced from in-situ measurements of SST from ships and buoys. The SST data are taken from the International Comprehensive Ocean-Atmosphere Data Set, ICOADS, from 1850 to 1997 and from the NCEP-GTS from 1998 to present. Measurements which fail quality checks are rejected. The SST measurements are converted to anomalies by subtracting climatological SSTs. A robust average of the resulting anomalies is calculated on a 5 ° x 5 ° monthly grid. After gridding the anomalies, bias corrections are applied to remove spurious trends caused by changes in SST measuring practices before 1942. The methods used are described in Rayner *et al*, 2006.

3 THE APPLICATIONS OF SEA SURFACE TEMPERATURE DATA

As discussed in the introduction, SST data has important scientific utility in a number of areas:

- climate trends and climate models
- ocean processes and ocean modelling
- SST driving of the atmospheric transport.

In addition, there are excellent operational applications of SST in NWP, operational oceanography and a range of applications connected to ocean biology/life changes, fishing and tourism. These applications are now briefly reviewed.

The key science challenges related to the above points include the need:

- To observe climate trends with higher confidence and to improve predictability in climate models
- To quantify natural ocean processes/variability and improve ocean model representations
- To embed SST knowledge more firmly in the driving of atmospheric models and in analysis of atmosphere transport mechanisms and variability.

Operational applications would expect:

- To see a continued flow of high quality reference SST in suitable data formats
- To see optimal analysis schemes in place for combination of SST datasets from different sources
- To quantify the impacts of SST on NWP schemes and operational oceanography models
- To investigate how SST knowledge can lead to improvements in operational oceanography models.

3.1 SST and climate

The strategic scientific issues in climate flow from the top level question:

"To what extent are the observed changes due to anthropogenic causes?"

There are consequential questions concerning impacts. However, for the AEP, it is desirable to confine discussion to those issues which will be directly served by the analysis of observations. In this case the high-level questions are:

- What is the integrity of the ECV record and how does satellite SST contribute to it?
- Does the satellite SST record achieve the appropriate accuracy to observe the climate-related changes expected in each ECV?
- What is the geographic distribution of these changes (the fingerprint)?
- Are the patterns of change observed in the SST record consistent with expectations of 'natural variability'?
- In what other ways can observations of SST improve our knowledge of the climate system and its modelling?

The needs of policy makers in the areas of environment and climate are related to the science questions above but are broader. Several European governmental bodies, including Defra and DECC in the UK, are required to monitor climate change, and to devise and deliver policies to meet national and regional government priorities. The critical interests of these agencies include the following:

1. Information concerning past and present geophysical behaviour (i.e. observations)
2. Predictions of future geophysical behaviour
3. Analyses of the relationships between anthropogenic activities and the observed geophysical behaviour
4. Prompt information on unexpected or unusual environmental events.

Of these, 1 and 4 are the aspects that space SST observations contribute to directly. However, space observations are also inextricably linked to items 2 and 3, which are in the realms of scientists who investigate and seek to understand geophysical processes either directly using data or using models. Space datasets are used to initialise the models, test their closeness to current geophysical behaviour, and provide realistic forcing terms for model simulations.

Global SST is a primary indicator of climate change and a prime objective of current SST measurements, and particularly those of (A)ATSR, is to generate precise measurements of this Essential Climate Variable (ECV). The IPCC projects that temperatures are highly likely to continue to increase, with the likely range of increase being 1.1°C to 2.9°C or 2.4°C to 6.4°C over the next 100 years depending on the scenario for greenhouse gas emissions.

Climate data records for SST also have important utility for climate science in terms of models and predictions. The SST data records enable climate models to be tested for performance against known history (“hindcasts”). The trends in climate SST, globally and regionally, can provide a testable fingerprint of climate change mechanisms. The SST datasets can be used to verify climate model runs and modify understanding of ocean processes, Climate sensitivity, particularly in atmospheric parameters can be better estimated if observed SST changes are used to drive model calculations. Decadal prediction requires good initial values for models (“model initialisation). Hence a primary utility for SST is the ECV climate data record.

3.1.1 SST climate data records

As an ECV, the SST climate data record can be examined in two ways:

1) individual SST data records, and

2) blended climate analyses.

The distinction is a useful one because each has particular attributes. The individual SST data records provide a more consistent record of SST evolution since they are technique-consistent and will have similar errors throughout the record. This if often achieved at the expense of coverage of the ocean. Comparison of individual records provides increased confidence in the observed SST change and hence likely surface temperature change of the planet. Blended analyses provide more complete global datasets, gridded at regular intervals, which may be more representative of the overall global SST change and are more suitable for delivering climatologies which can drive climate and atmosphere models or provide initial conditions.

O’Carroll *et al* (2006) examined the long-term AVHRR and (A)ATSR records, the short-term microwave records from the AMSR-E and the Tropical Rainfall Measuring Mission (TRMM) mission, and one blended analysis. They concluded that the use of all four datasets allowed significant biases between instruments to be detected, which was important for understanding the record.

Analyses of global SST are based on ship and buoy measurements or use blended satellite SSTs that are in turn empirically tied to subsets of the same *in situ* measurements. Each data source may be characterized by different random and systematic errors which change in time, and the balance of data sources in the observing network also evolves, potentially introducing artefacts into the present SST record. In addition, SST analyses have larger errors over the extensive regions of the ocean that have been sparsely sampled, e.g. the seas south of 20ºS and the south-eastern Pacific Ocean. Nonetheless, these analyses have been a mainstay of IPCC work because of the long time series that can be achieved and their foundation *in situ* datasets. The chief analyses used in IPCC (2005) have been the Met Office HadSST2 (Rayner *et al*, 2006), the National Climatic Data Center (NCDC) SST series (Smith *et al*, 2005) and the Centennial *in situ* Observation-Based Estimates of SSTs (COBE-SST) from the Japan Meteorological Agency (JMA) (Ishii *et al*, 2005).

While painstaking research has been pursued to characterize and minimize artefacts in existing SST analyses, the temperature changes apparent in existing analyses will be more certain if tested against a record that is sufficiently independent. To be suitable, the new SST record needs to:

- Contain at least 15 years of continuous data
- Be independent from *in situ* records
- Have a stability of 0.05 K per decade
- Have biases less than 0.1 K
- Have estimates of both bulk and skin SST
- Have a comprehensive error characterisation

Whilst the AVHRR data and (A)ATSR data both have long records of SST, currently only (A)ATSR data is close to meeting these criteria. The (A)ATSR data, and possibly AVHRR in time, can help to achieve the goal, at least since the era of satellite SST measurements began, of a more accurate climate SST ECV record that also draws on the higher temporal coverage provided by other satellite measurements and *in situ* data from buoys and ships. In turn these new more accurate datasets can be blended with care into global analyses, if desired, in order to improve these records.

3.1.2 Climate trends

A critical aspect of SST climate data records is the fact that these data represent not only the natural variability of the large scale ocean phenomena but also any component which would be expected from global surface warming due to anthropogenic greenhouse gases. Very important work is therefore ongoing to understand the SST record and look critically at the evidence for anthropogenic warming. The following discussion is largely reproduced from Good et al (2007) as it summarises well the trend work up to now.

If reliable estimates of trends are to be found, datasets covering long time periods are required (Allen et al. 1994). For SST, these exist through *in situ* observations (e.g. from buoys and voluntary observing ships) and satellite observations. Casey and Cornillon (2001), for example, used SSTs from the *World Ocean Atlas 1994* and ICOADS to determine trends in SSTs since 1942. They found a warming trend of between 0.09 and 0.14 K per decade (depending on dataset and averaging approach). IPCC (2001) quote a global increase of 0.14±0.04 K per decade between 1976 and 2000, from Jones et al. (2001). Studies have also attempted to use satellite data alone to detect trends. Although they span relatively short time periods compared to *in situ* data, satellite datasets have the advantage that they can provide almost global ocean coverage, allowing global trends to be determined. Datasets made up of *in situ* observations must utilise a large number of sources to achieve coverage over a wide area and a long time period, each of which has a different bias and sensitivity to observing conditions and might experience drift in their measurements. Only a single satellite instrument is required to achieve almost global coverage of the oceans, and entire datasets consist of data from only a relatively small number of similar instruments. Although it is true that inconsistencies will exist between these instruments, effort has been put into minimising these problems, for example the Pathfinder project (Kilpatrick et al. 2001).

Two global satellite SST datasets currently exist that are long enough for climate change detection. The AVHRRs have been operating on board National Oceanic and Atmospheric Administration (NOAA) polar orbiting satellites since 1981, providing a continuous source of SSTs. The (A)ATSR series has spanned three instruments with the data record beginning in 1991. Using a 13-year time series of AVHRR data, Strong et al. (2000) determined that globally averaged SSTs had a positive trend, although the error on the trend was larger than the trend itself. Anderson et al. (2002), utilising almost 8 years of (A)ATSR data, identified significant spatial variability in SST trends. They found that the highest increases in SST were to be situated in the north-west Atlantic, the north- and south-west Pacific, and in areas to the south of Africa and to the west of Australia. Negative trends were also found in the mid and north-east Pacific and at the lowest latitudes. Most recently, Lawrence et al. (2004) compared global trends determined from 16 years of the Pathfinder reprocessing of AVHRR data (version 4.1) and 8 years of (A)ATSR data. Their methodology included removing the El Niño component from the data, which can reduce the length of time series required to detect trends with confidence by 1-2 years (Allen et al. 1994). They found consistent trends of 0.09±0.03 and 0.13±0.06 K per decade from AVHRR and (A)ATSR, respectively. Good et al, 2007, noted that the consistency between the independent datasets indicates that the trends are not significantly biased by instrumental drift, but represent a real warming of the ocean surface.

They further found significant warming of 0.18±0.04 and 0.17±0.05 K per decade from daytime and night-time data, respectively, for the period from 1985 to 2004 in AVHRR data,

At the current time, it is particularly important to continue to monitor temperature in the first decade of the twenty-first century where it is possible that overall global temperatures have not risen as fast as in the 1985 to 2000 period. This development illustrates the complexity of the relationship between climate change, natural variability and the behaviour of average global SST. It also underlines the need for detailed analyses of regional changes and the relationship between SST and the heat content of the oceans. The increasing longevity of the satellite SST record, along with programmes to re-analyse the data in a careful way, will most likely result in key advances in the determination of the global trend in the SST record. In addition, efforts will continue to begin to address regional SST changes.

3.1.3 Climate monitoring

Our climate is the result of a multitude of diverse physical, chemical and biological processes, whose interactions are so highly complex that even the most sophisticated of mathematical models, based on the best of current knowledge and understanding and powered by computers of unprecedented power, still struggle to make predictions of the type needed. In the case of sudden events, the models can fall seriously short of the capabilities which would allow instant interpretation and prediction. Meaningful observations are, therefore, of the highest importance, not just to feed and validate the models, but also to signal and quantify changes, particularly the onset and the evolution of climatically important events.

Systematic monitoring of global SST is increasingly recognised as an essential part of a long-term strategy for climate change monitoring. The monitoring provides the ability to measure large-scale ocean-atmosphere indices which describe the key phenomena such as El Niño and the Arctic Oscillation, to detect climate shifts and divides such as is believed to have occurred around 1976 (e.g., Trenberth et al, 1990), and to report as rapidly as possible climatically unusual events such as the dramatic warming of the Chuckchi Sea in 2007.

A striking example of the use of long-term satellite data to monitor changes in the characteristic SST of climatically important regions has occurred recently. In the year 2007, Arctic sea ice decreased much more strongly than had been observed in the previous two years, which had already shown the strongest ever decreases in Arctic ice cover. Regular SST analyses conducted at the Hadley Centre using the OSTIA system showed unexpectedly high SSTs in the Arctic Ocean, Chuckchi and Beaufort seas. The use of long-term (A)ATSR archive data has confirmed that SST in this region was anomalously large compared to the long-term (A)ATSR record and it is believed that this temperature pattern is a fundamental part of the story of sea ice decrease (an important impact of climate change).

Figure 4-1 and Figure 4-2 show the salient results. Figure 4-2 shows, for 17 successive summers, the temperature of a small region of sea (the Beaufort Sea) in the middle of the anomaly. Notice that 'normally' there is an anomaly of around 2 degrees, with an extraordinary departure in 2007. It is clear that the size of the 2007 anomaly is quite exceptional and is the signature of a major and sudden environmental event.

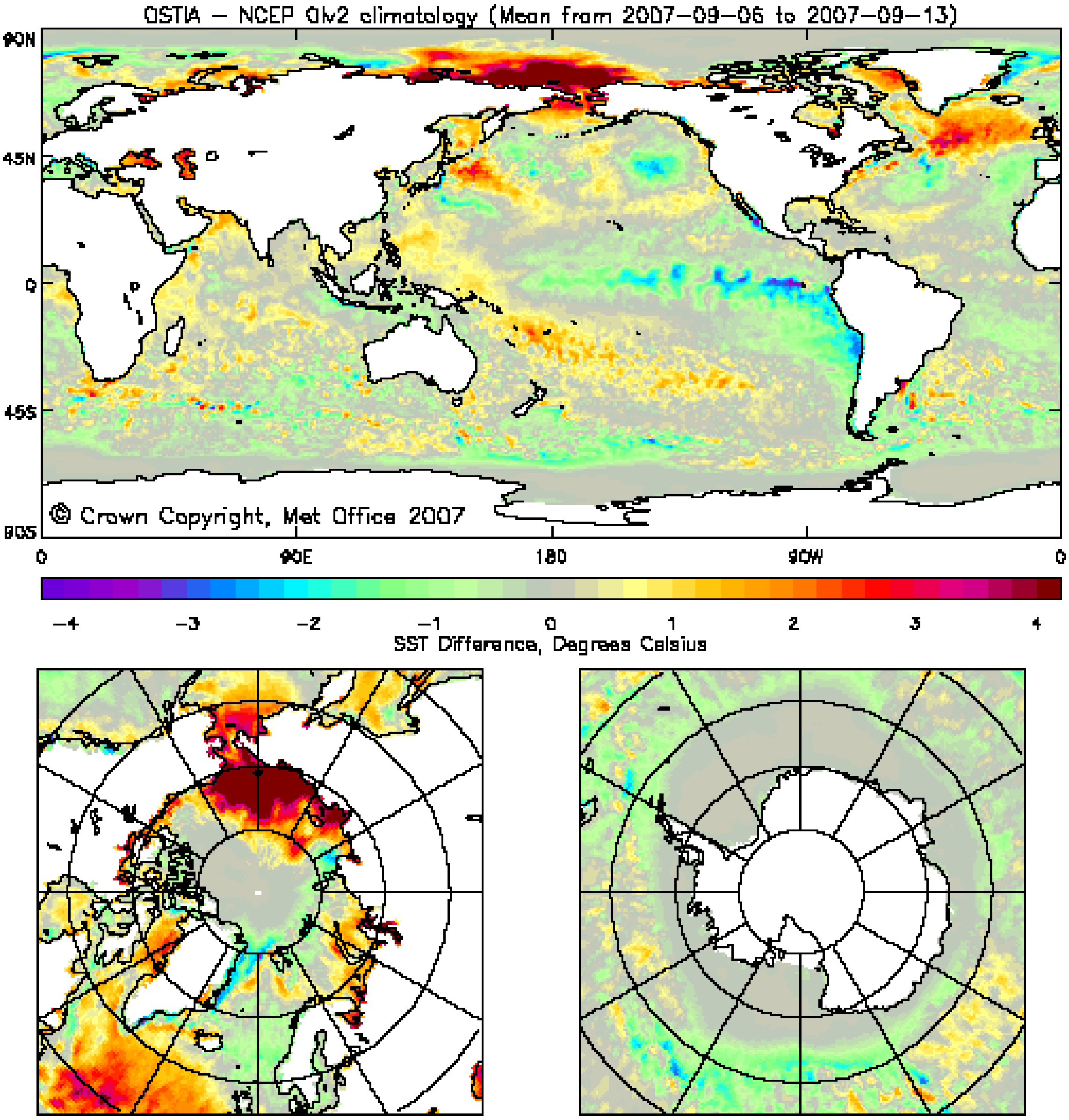

Figure 4-1: OSTIA minus NCEP OI v2.0 SST anomalies for 06/09/2007 to 13/09/2007

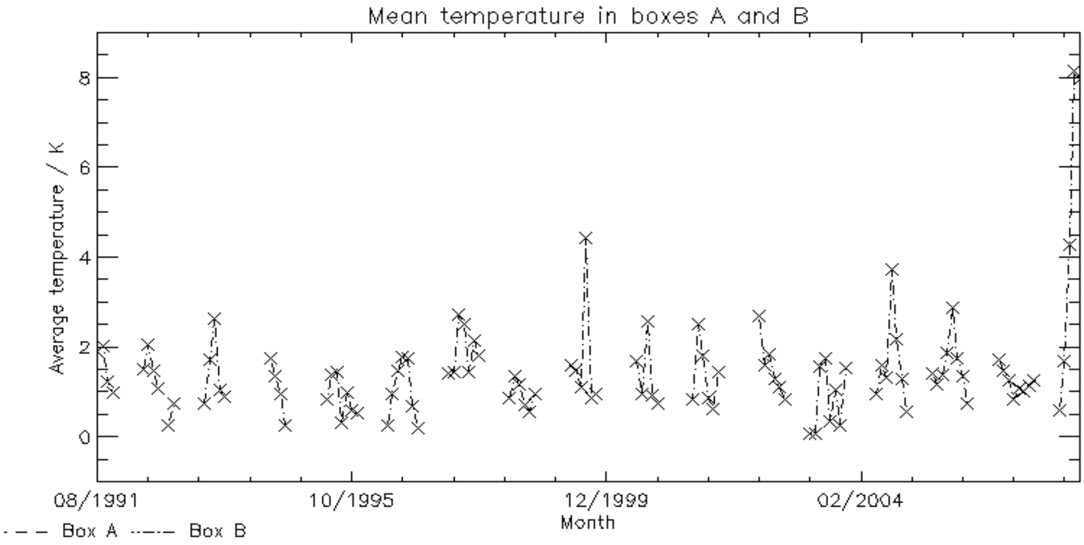

Figure 4-2: Average SSTs estimated by the (A)ATSR series from 1991 to date for a small region of the Beaufort Sea

3.2 SST and ocean studies

Clearly SST is a major parameter for ocean studies, and these studies provide also a clear linkage to climate processes in the ocean which need to be understood. For example, if SST is to be used as a true indicator of climate change, it is important that ocean processes that have a strong SST signature are well understood. The strategic question is probably:

"Can we detect departures from the normal regimes of natural variability in the behaviour of ocean processes?"

Major processes with the potential to perturb the global SST signature include El Niño, the Somali upwelling, the Gulf Stream, the Kuroshio Current and the Agulhas Current. Research into the behaviour of such phenomena, particularly with respect to quantifying their intensity and geographical extent, should receive high priority. A highly relevant scientific question concerns the relationship between global SST and the heat content of the oceans. In particular, as the oceans warm, is it appropriate to assume that the relationship between SST and heat content remains constant? Intuitively, increased heat input to the oceans should lead to increased vertical mixing and a changed relationship between SST and heat content. Research in this area will need to receive high priority.

There are a number of ways in which satellite SST can be used to improve this understanding of ocean phenomena: it can provide time-resolved averages of data for testing of models; it can provide high resolution SST fields to test fine scale phenomenon; it can be analysed to deliver wave analyses which are important for momentum transfer; and it can provide indications of developing changes to large scale circulation such as the El Niño circulation.

Most of the well-known dynamical ocean processes can be observed in (A)ATSR data, as SST is an excellent tracer for currents and other dynamic structures at the surface. For this, accurate quantitative data are required, but, for meso-scale or smaller processes, both the temporal and spatial coverage of a single sensor is probably inadequate and (A)ATSR data, with a particularly narrow swath width, are best used in conjunction with other sensors which give greater coverage. The methods by which such data are combined are referred to in section 3.4. Hence there are likely to be two routes for exploitation of (A)ATSR data, i.e. direct comparison with, or use of (A)ATSR SST data and indirect (but important) exploitation of (A)ATSR data via an operational analysis or model assimilation system.

Given the spatial and temporal coverage of (A)ATSR, many of the direct uses of (A)ATSR data will either be in the form of averaged datasets, e.g. weekly, seasonal, regional, global averages, or use of either single or a few images of ocean phenomena. This review concentrates more on the former application. Where higher spatial and temporal coverage is required, the OSTIA system, developed and operated by the UK Met Office and further described in section 4 of this volume, is a daily multi-satellite SST analysis, which gives the improved temporal and spatial coverage needed, combined with the high levels of accuracy provided by the (A)ATSR data. The analysis field is very well suited to the investigations of meso-scale oceanic processes, which need good SST accuracy as well as good spatial and temporal coverage.

It should also be noted that the climate analysis of (A)ATSR data, reviewed in the previous section, will likely shed much light on ocean processes and so there is much synergy between the understanding of climate and the understanding of departures from the normal regimes.

3.2.1 El Niño

The oceanic manifestation of an El Niño event begins with an increase in surface temperature in the equatorial eastern Pacific Ocean, along with the generation of solitary waves along the equator. The warming pattern is easily recognizable in SST datasets, such as those produced by (A)ATSR. Currently a number of theories still exist as to the mechanisms for triggering of an El Niño (Wang and Picaut, 2004). If the warming and associated waves (see next section) can be identified in (A)ATSR data prior to El Niño taking place, predictability in models may be enhanced. At the same time, the driving mechanisms and response to those waves could be identified, so that the excitation mechanisms for El Niño, which may involve the atmosphere, could potentially be explored. In particular, recent research (Bosc and Delcroix, 2008) has shown that the understanding of warm water movements and sea level may have changing relationships to the observed SST anomaly fields. This requires further investigation for the El Niño case. Furthermore, the same may be true of other ocean circulations such as those of the Atlantic Ocean.

3.2.2 Rossby waves

Rossby waves, also known as planetary waves as they owe their origin to the shape and rotation of the earth, are one of the most intriguing of natural phenomena. On account of the large spatial and temporal scales over which they occur, they are implicated in climatically important processes. Rossby waves are easily observed in the atmosphere (i.e. as large-scale meanders of the mid-latitude jet stream), but their existence in the oceans, first suggested by Carl-Gustav Rossby (Rossby, 1939) in the 1930s, had only been confirmed indirectly before the advent of satellite oceanography. Rossby waves are particularly difficult to observe without the spatial and temporal coverage of satellites. This can be seen from Figure 4-3 below, which is a schematic representation of a "first-mode baroclinic" Rossby wave.

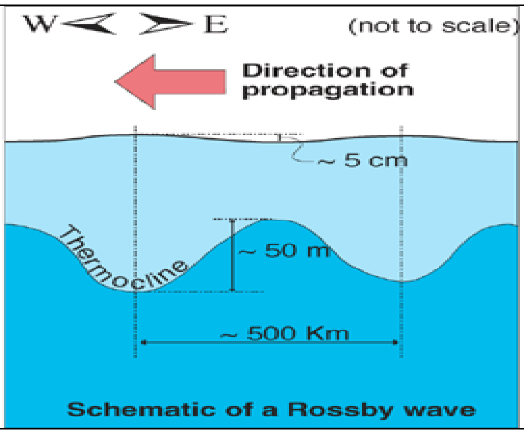	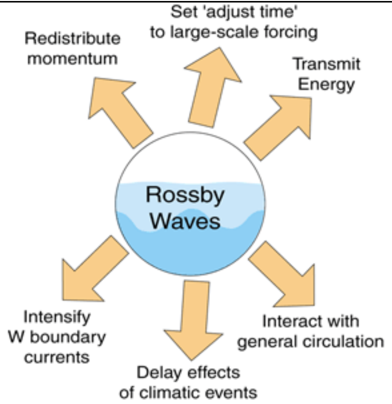
Figure 4-3: The nature of Rossby waves	**Figure 4-4: The importance of Rossby waves**

Rossby waves always travel from east to west, following the lines of latitude. They have particularly low propagation speeds, varying with latitude and increasing equator-ward, but of the order of just a few cm/s (i.e. a few km/day). This means that at mid-latitudes (say, 30 degrees N or S) one such wave may take several months - or even years - to cross the Pacific Ocean. In some cases they may cross an entire oceanic basin, being originated close to the eastern boundaries and being (as a first approximation) non-dispersive. Their horizontal scale is of the order of hundreds of km, while the amplitude of the oscillation at the sea surface is just a few centimetres, practically impossible to measure with *in-situ* techniques. However, the horizontal scale of these waves and their speeds mean they can ideally be observed by satellite as was first performed for ATSR-2 data by Hill et al (2000).

Despite their very small physical manifestation on the ocean surface, Rossby waves have major effects on the large-scale ocean circulation, and thus on weather and climate (see Figure 4-4). Perhaps the most important effect of these waves is on western boundary currents, such as the Gulf Stream. Rossby waves can intensify the currents, as well as push them off their usual course. If we keep in mind that those currents transport huge quantities of heat, we can easily understand that even a minor shift in the position of the current can dramatically affect weather over large areas of the globe. Jacobs et al. (1994) presented evidence for the existence of an extra-tropical Rossby wave in the North Pacific, generated by the El Niño event of 1982–1983, and suggested that after a decade’s delay this wave induced a shifting of the Kuroshio Current in the north-west Pacific.

Rossby waves still present some interesting puzzles which could ideally be observed. Their near-ubiquitous nature needs further explanation and theories are still being updated to address their observed propagation speeds. Long-term observations of ocean basin SST therefore have the potential to determine more of their nature and their potential interaction with ocean phenomena such as El Niño.

3.2.3 Ocean eddies

Several studies indicate that eddies in the oceans are an important process for driving heat vertically, or for providing nutrients through the associated upwelling and downwelling fields. Eddy-induced vertical mixing will also affect the relationship between SST and oceanic heat content, a very important topic mentioned above. The (A)ATSR data can provide very high spatial resolution observations of eddies, albeit with some assessment of cloud clearing and dual-nadir alignment, and ocean models are now beginning to approach the required resolutions. Studies of the ability of (A)ATSR data to provide statistical information on the mean state and evolution of eddies would be timely and particularly important for the interpretation of the relationship between SST and planetary heat content.

3.3 SST and atmosphere studies

The chief effects of SST are on troposphere circulation, resulting in influences on convection, precipitation and transport of heat in the atmosphere, and on heat fluxes. These aspects provide a coupling between atmosphere and ocean systems that result in teleconnections between different regions of the world. The SSTs also play a potentially direct role in forcing the development of hurricanes and tropical cyclones, and in tropical convection over sea.

Recent research indicates that trends and spatial structure of SSTs can play a significant role on transport into the stratosphere, and potentially on the subsequent evolution of the middle atmosphere dynamics. Finally, it is well understood that SST plays a role in modulating the transfer of carbon dioxide between the atmosphere and the ocean, both directly in a physical sense, but also indirectly through the ties between SST and phytoplankton productivity.

The effects of SST in tropical regions are clearly of importance as noted in section 3.2.1. One particularly challenging and very important topic is the relationship of the El Niño phenomenon to atmospheric mechanisms. For example, El Niño clearly co-exists with fundamental changes in the location of tropical convection and in the strength of the Walker and Hadley cells. These can in turn lead to major synoptic changes world-wide in ways which are not clearly understood at the current time (e.g., Lee et al, 2008). The change in tropical SST can feed through into further regions of the stratosphere. Garny et al, 2009 and Braesicke and Pyle, 2004, amongst others, have noted the influence of SSTs on the circulation in the stratosphere and ozone trends, potentially a result of deep convection and planetary wave activity.

The connections between particular ocean regions and wider scale climate are well known to exist, and are not just tropical phenomenon. For example, Sutton and Hodson (2005) present evidence that large scale changes in the Atlantic Ocean have driven multi-decadal changes in the summertime climate of North America and Europe. The influence of the Atlantic Multi-decadal Oscillation has been noted by a number of studies. More broadly, we can say that good long-term characterisation of ocean SST is highly significant in improving abilities to look at the details of regional climate over many years.

These connections extend to storm development and storm intensity, which are currently the subject of much research into the dependence on SST. Microwave sensors are more the instrument of choice here because of their ability to see through cloud so the subject is not explored in depth in this exploitation plan. However, it is worth noting that there is still an important role for thermal sensors in observing the developing state of the ocean surface prior to the storm season. In addition, sensors like (A)ATSR, may play indirect roles in advances, either through direct bias-correction of microwave data or else through combination with microwave data in the operational SST analyses.

The role of SST in atmosphere circulation is now beginning to achieve a full recognition but much work remains to be done in exploring exactly how the thermal infra-red SST datasets, such as (A)ATSR, can best make a contribution to atmospheric circulation studies.

3.4 Operational applications of SST

This section describes operational services using (A)ATSR data. The section includes a brief description of the highly successful GODAE High Resolution SST Pilot Project (GHRSST-PP) (Donlon et al, 2008), which has developed the basis for what is now an operational service (although it is based on a pre-operational satellite, Envisat). This section also describes in outline the operational services now being put in place within the GMES programme.

3.4.1 GHRSST-PP and Medspiration

During the past two years, the operational use of (A)ATSR data has taken a major step forward as a result of the ESA-funded Medspiration project, which formed the European backbone of the international GHRSST-PP. This highly successful series of initiatives has produced a new generation of global NRT SST data.

GHRSST-PP has developed and introduced a new format, Level 2P, which is based on the standard ESA gridded level 2 SST products and which is especially tailored to the needs of operational users. The L2P format is based on NetCDF and, most importantly, includes Single Sensor Error Statistics (SSES). This innovation means that confidence flags can be derived on a pixel-by-pixel basis, thereby giving operational users an automatic means of deriving appropriate weight to data as they are ingested. The (A)ATSR SSES are particularly sophisticated and effective because (A)ATSR’s unique dual view, when compared to the single view, provides a quantitative and independent indication of data quality. The L2P format also has the ability to include data from both satellite and *in situ* sources.

Medspiration was an ESA-funded Data User Element (DUE) project which constituted the European element of GHRSST-PP. Medspiration has led to the parallel generation of SST data streams, in L2P format and from several satellite and *in situ* sources. Both Medspiration and GHRSST-PP have been highly successful projects, especially when considered in combination, which have led to operational exploitation of (A)ATSR data and SST data from other sources. Following the end of the Medspiration project in December 2008, ESA are now generating the L2P product as an official ESA data product.

As a result of the GHRSST-PP, meteorological services in Europe and USA have been using and evaluating (A)ATSR data. A consensus view is emerging that (A)ATSR data, although offering less coverage than other sensors, are the most accurate available and can be used in multi-sensor analysis schemes as the benchmark against which data from other sensors can be bias-corrected. (A)ATSR data are now used in operational NWP services from both the UK Met Office and ECMWF. This is done via the OSTIA analysis (see next section), of which

(A)ATSR is a fundamental and the most accurate element. This has arguably been the most significant development in the exploitation of (A)ATSR data to date.

3.4.2 The OSTIA analysis

The Operational SST and Sea Ice Analysis (OSTIA) is a daily analysis scheme developed and operated by the UK Met Office. Its main product is a daily global SST field (Stark et al, 2008) derived from a variety of satellite and *in situ* sources, principally those serviced by the GHRSST-PP programme, where the data are delivered with error statistics. Full details of OSTIA and the various products and analysis functions it provides, can be seen at:

http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html

In 2007, the OSTIA SST Analysis underwent evaluation by the UK Met Office and was subsequently incorporated into the daily NWP process, where its impact has so far been positive. On the basis of this experience, ECMWF also use OSTIA in that way. Thus, as a result of the GHRSST and Medspiration initiatives, and the development of OSTIAA, AATSR data have acquired operational status.

4 POSSIBLE EXPLOITATION OF (A)ATSR SST PRODUCTS

It is evident that there are numerous strategic scientific, climate and operational challenges issues which can be addressed with SST data. It is therefore clear that there are some important activities that should be undertaken and these have been categorised into the main areas described in the previous sections.

For climate, the primary role of (A)ATSR data is for exploitation in terms of development of the SST ECV, in detection of anthropogenic climate trends and the characterisation of natural variability, in climate monitoring for El Niño, Arctic Oscillation and sudden events, in improvement of blended analyses and long-term climatologies, and in climate model verification and initialisation. The following actions are recommended:

- IPCC datasets for surface temperature should be inter-compared to (A)ATSR data to reduce the errors associated with global temperature analyses.
- Suitable (A)ATSR datasets should be examined for their long-term behaviour in conjunction with equivalent *in situ* data records.
- Effort should be put into data product improvements to climate quality where required.
- Climate models should be inter-compared to (A)ATSR datasets for the relevant time periods.
- Some additional effort should be put into the understanding of instrument and atmosphere effects in the ATSR-1 period.

For ocean studies, many of the direct uses of (A)ATSR data will either be in the form of averaged datasets e.g. weekly, seasonal, regional, global averages, or use of either single or a few high resolution, fine scale datasets of ocean phenomena. In addition, there will be indirect (but important) exploitation of AATSR data via an operational analysis or model assimilation system. Hence the following actions are recommended.

- The development of gridded SST data for (A)ATSR at temporal and spatial scales which are useful to ocean modellers.
- The promotion of (A)ATSR SST plotting utilities and easy access imagery.
- The promotion of increased interaction between the (A)ATSR SST community and the wider oceanographic community, particularly with respect to El Niño, North Atlantic and boundary current studies.

- The support of studies into the assimilation of (A)ATSR SST data into ocean models.
- Provision of an operational sub-skin SST product from (A)ATSR

For atmosphere applications, the (A)ATSR applications are most likely to come from use of the (A)ATSR climate data record to drive model simulations of decadal climate or else to provide initial datasets to examine atmospheric transport. Similarly to other application areas, exploitation in the fields of convection and hurricane development are more likely to come through usage of combined microwave and (A)ATSR data or through SST analyses like OSTIA.

Operational applications of SST fall into the use of SST analyses for NWP and assimilation of SST into operational oceanography models (important for both physical oceanography and for ocean biology). These are increasingly significant areas of engagement for (A)ATSR SST products and indeed have overseen a major growth in the take-up and exploitation of these data. The critical areas identified for future work are:

- Quantification of the impact of AATSR data on the accuracy of OSTIA
- Assessment of the impact of AATSR data on ocean model assimilation schemes via OSTIA.
- Promotion of AATSR data to other meteorological services for similar applications.

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APPENDIX A: LIST OF ACRONYMS

AATSR	Advanced Along-Track Scanning Radiometer
(A)ATSR	All three ATSR instruments
AMSR-E	Advanced Microwave Scanning Radiometer - Earth Observing System
ATSR	Along-Track Scanning Radiometer
ATSR-1	The ATSR instrument on the ERS-1 satellite
ATSR-2	The ATSR instrument on the ERS-2 satellite
AVHRR	Advanced Very High Resolution Radiometer
BT	Brightness Temperature
COBE	Centennial *in situ* Observation-Based Estimates
DECC	Department of Energy and Climate Change
Defra	Department for Environment, Food and Rural Affairs
DUE	Data User Element
ECMWF	European Centre for Medium Range Weather Forecasting
ECV	Essential Climate Variable
Envisat	Environmental Satellite
EO	Earth Observation
ESA	European Space Agency
GHRSST	Group for High Resolution Sea Service Temperature
GMES	Global Monitoring for Environment and Security
GTS	Global Telecommunications System
ICADS	International Comprehensive Ocean-Atmosphere Data Set
IPCC	Intergovernmental Panel on Climate Change
ISAR	Infrared SST Autonomous Radiometer
JMA	Japanese Meteorological Agency
M-AERI	Marine-Atmosphere Emitted Radiance Interferometer
MERSEA	Marine Environment and Security for the European Area
MODIS	Moderate Resolution Imaging Spectroradiometer
NCEP	National Centers for Environmental Protection

NCDC	National Climatic Data Center
NERC	Natural Environment Research Council
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time
NWP	Numerical Weather Prediction
OSI-SAF	Ocean and Sea Ice Satellite Application Facility
OSTIA	Operational SST and Sea Ice Analysis
PI	Principal Investigator
PIRATA	Prediction and Research Moored Array in the Atlantic
SEVIRI	Spinning Enhanced Visible and Infra-Red Scanner
SSES	Single Sensor Error Statistics
SST	Sea Surface Temperature
TAO	Tropical Atmosphere Ocean
TMI	TRMM Microwave Imager
TOA	Top Of Atmosphere
TRITON	TRIangle Trans Ocean buoy Network
TRMM	Tropical Rainfall Measuring Mission
VOS	Voluntary Observing Ships