OSTIA : An operational, high resolution, real time, global sea surface temperature analysis system.

John D. Stark, Craig J. Donlon, Matthew J. Martin and Michael E. McCulloch

Abstract— **A new global, operational, high-resolution, combined sea surface temperature (SST) and sea ice analysis system (OSTIA) has been developed at the Met Office. The output is a daily, global coverage 1/20° (~6km) combined SST and sea ice concentration product, which is generated in near-real time. The analysis has been designed to meet the needs of applications requiring high-resolution space-time scales including global numerical weather prediction (NWP) and operational ocean models and to prepare for future high-resolution global and regional forecast systems.**

***Index Terms*—SST, analysis, optimal interpolation, bias correction.**

I. Introduction

An accurate representation of the global sea surface temperature (SST) is important for many marine applications, numerical weather predication (NWP) and also for monitoring the global climate. Since the SST has a strong influence on many air-sea exchange processes it is a key parameter in many environment and process models. Although there are many in situ observations from moored and drifting buoys and ships, a truly global coverage is only obtainable from an analysis incorporating satellite borne instruments. Each instrument has its own strengths and weaknesses, depending on the sensor type, platform, orbit and so on. The production of an accurate SST is dependent on merging the data from these sources, accounting for the differing measurement methods and accuracies, while maintaining as much of the information in the observations as possible. This fusion of data is a significant challenge for marine remote sensing.

The Global Ocean Data Assimilation Experiment (GODAE) recognized the benefits of global cooperation in the provision of SST data, and launched the GODAE High Resolution SST Pilot Project (GHRSST-PP), [1]. One of the key developments of the GHRSST-PP has been the supply of satellite SST data in a common format [2] in near real time, through a global network of data providers. The development of higher resolution (~5km) NWP models has focused attention on the provision of surface boundary conditions at a comparable resolution. In order to meet these requirements and to take advantage of the developments made by the GHRSST-PP, a new sea surface temperature and sea ice analysis system (OSTIA) has been developed at the Met Office. The output is a daily, global coverage 1/20° (~6km) combined SST and sea ice concentration product, which is generated in near-real time. The analysis has been primarily designed to provide an accurate SST in a robust manner, suitable for NWP at global and regional space and time scales.

This paper presents the OSTIA SST analysis system, discusses the system outputs and presents an intercomparison of OSTIA with other data products and validation against independent in situ observations. OSTIA data products are available free of charge for academic and non-commercial applications from [14].

II. Overview of the OSTIA System

The OSTIA system uses data from a combination of infra-red and microwave satellites as well as in situ data. The fusion of microwave and infrared sensors allows greater coverage which can lead to improved NWP performance, as found by [4]. The differing sensors measure the SST at different depths and with varying sensor characteristics. In order to homogenize the measurements, the OSTIA analysis provides an estimate of the foundation SST (SST_{fnd}). This is the ocean temperature at a depth which is free of diurnal variations [1]. The data ingestion and preprocessing is described in section III. In order to further correct for biases between the sensors, a daily analysis is performed to diagnose a bias field for each sensor, described in section IV. This bias analysis evolves with time alongside the main analysis.

The source data from GHRSST-PP is provided with uncertainty estimates and auxiliary fields which the OSTIA system uses as part of the quality control and analysis procedure. Satellite derived sea ice products from the EUMETSAT Ocean and Sea Ice Satellite application Facility (OSI-SAF) provide sea ice concentration data to the analysis

Manuscript received March 25, 2007. This work was supported in part by the U.K. Ministry of Defence through the Public Weather Service.

J. D. Stark is with the Met Office, FitzRoy Road, Exeter, EX1 3PB, UK. (phone: 01392 885059; fax: 01392 885681; e-mail: john.stark@ metoffice.gov.uk).

C. Donlon is with the Met Office, FitzRoy Road, Exeter, EX1 3PB, UK. (e-mail: craig.donlon@ metoffice.gov.uk).

M. Martin is with the Met Office, FitzRoy Road, Exeter, EX1 3PB, UK. (e-mail: matthew.martin@ metoffice.gov.uk).

M. E. McCulloch is with the Met Office, FitzRoy Road, Exeter, EX1 3PB, UK. (e-mail: mike.mcculloch@ metoffice.gov.uk).

TABLE I
OSTIA SOURCE DATA

Sensor (Platform)	Sensor Type	Resolution	Data Source	Coverage [1]	Subsampling
AATSR (EnviSat)	Infra-red	~1km (swath)	ESA-Medspiration.	Global (~1.5×10^6)	3×3
AMSR-E (Aqua)	Microwave	~25km (swath)	Remote Sensing Systems.	Global (~6×10^5)	2×2
AVHRR -LAC (NOAA 17 & 18)	Infra-red	~1/10° (Gridded)	ESA-Medspiration.	North-East Atlantic and Mediterranean. (~1×10^4)	3×3
AVHRR -GAC (NOAA 18)	Infra-red	~9km (Swath)	JPL PO-DAAC.	Global. (~8×10^5)	None
In situ temperature and salinity.	Ships, drifting and moored buoys.	In-situ	Global Telecommunications System (GTS)	Global (~4×10^4.)	None
Sea ice, primarily SSM/I (DMSP).	Microwave	10km (Polar-stereographic grid)	EUMETSAT OSI-SAF	Global.	None.
SEVIRI (MSG1)	Infra-red	0.1° (Gridded)	ESA-Medspiration.	Atlantic sector (~6×10^4)	None
TMI (TRMM)	Microwave	~25km (swath)	Remote Sensing Systems.	Tropics (~5×10^4)	2×2

1. Figures in parenthesis represent the average daily number of data after sub-sampling and quality control.

system which are used to control SSTs at high latitudes.

III. Data Ingestion and Preprocessing

Source data is collected from a variety of locations, summarized in Table I. The prime delivery method is ftp via the internet. Some data is subsampled using a simple scheme in which only 1 sample is taken from every in $n\times m$ samples in the along and across track directions. The primary benefit of this is to reduce data volume, where the sensor sampling is much higher resolution (e.g. 1km) than the analysis. For the microwave sensors (AMSR-E and TMI) the data is over sampled at around 25km resolution, where the actual sensor footprint is of order 50km. This leads to significant correlations between neighbouring measurements. The subsampling of this data reduces the data volume with while keeping much of the information and reduces the observation correlation, which is important because the analysis assumes that the input observations are uncorrelated.

The input data are filtered to remove those that may represent the temperature of the diurnal layer rather than the SST_{fnd}. This is achieved by removing daytime observations with low wind speeds. Daytime observations are determined by computing the local solar position, and determining whether that is above the horizon. The threshold wind speed used is $6ms^{-1}$, as diurnal warming was found to be very low above this value [6]. In addition, a background check of the observation against the previous days analysis is performed using a Bayesian scheme [7]. This typically rejects around 10% of the observations.

The OSTIA system runs daily at 0600 UTC, using a rolling observation window of 36 hours, centered on 1200UTC the previous day. Since there is overlap in the observation window for consecutive days, there is the potential for observations to be available to the analysis on more than one day. To avoid giving excess weight to these observations, they are not assimilated directly, but the background error variance at their locations is altered [13]. This allows the information provided by these observations to be preserved, without ‘double counting’.

IV. Bias Correction

The analysis system employed by OSTIA assumes that the observation errors are not biased. However, satellite measurements of SST from some sensors are prone to large scale biases for several reasons, including atmospheric anomalies, such as aerosol contamination, or anomalous surface conditions. To address this, the satellite measurements are bias corrected. This occurs in 3 stages.

1) Initially a skin to bulk SST correction is applied to those sensors that provide skin SST (currently only AATSR). This is performed by simply adding 0.17K to the measurement, as this was the mean global skin to bulk temperature difference found in previous work [8]. This is a simple approximation, as the true skin to bulk temperature difference results from a complex balance of fluxes as discussed in [16].

2) The single sensor error statistics (SSES) supplied with the GHRSST-PP data include a bias estimate, which is removed from the observation value.

3) A daily analysis of the bias for each satellite sensor is then performed. First, collocations in space (25km) and time (24 hours) are found between the satellite observations and a set of reference observations. The satellite minus reference value is then stored as a ‘matchup’ observation, with an error estimate derived from the source data. An optimal interpolation analysis is then performed, using the same scheme as the final analysis (described later), but using longer correlation length scales (700km). The first-guess (background) for the bias analysis is the satellite bias analysis from the previous day scaled by a factor which is less than one. This results in an exponential decay of the bias in the absence of any new information. The bias analysis is then interpolated to the locations of the new observations, and the bias is subtracted from them. A sample bias analysis is shown in Fig. 1. The reference set of observations is all in situ observations that have passed quality control, as well as the AATSR data after the skin to bulk and SSES bias corrections. The design of AATSR, especially the dual-view, means that it is a stable instrument with low errors, suitable for use as a reference against which the other satellites are corrected.

.

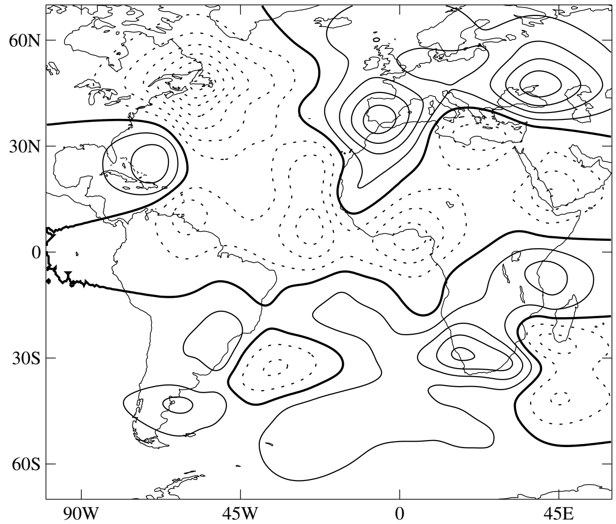

Fig. 1. Bias analysis for SEVIRI observations on 22 March 2007. The contour interval is 0.2K, with negative bias contours dashed, and the zero contour in bold. The biases are significant and must be removed from the observations prior to analysis.

V. Data Analysis

The background for the SST analysis is formed using an SST anomaly persistence, derived from the previous days analysis using

$$X_0 = \lambda\left(P - C_P\right) + C_X\,, \tag{1}$$

where X_0 is the background field, λ is a scalar less than 1, P is the previous analysis, C_P is the climatology valid for the same time as P and C_X is the climatology for the new analysis time. In addition, where the SST is under sea ice, it is relaxed to -1.8°C with a timescale of 5 days. A digital filter is applied to the background field to remove small scale noise. This is a Gaussian with half-width of 4.7km.

The analysis system uses a multi-scale optimal interpolation (OI) scheme to combine the satellite and in situ SST measurements, and is based on a scheme developed for the Met Office Forecasting Ocean Assimilation Model (FOAM) [5]. The scheme is based on the analysis correction method introduced by [9] which provides an efficient means of calculating the OI solution using an iterative procedure. The scheme is particularly efficient at processing large numbers of observations. A priori estimates of the error covariances in the observations and background field are required to run the system. These error covariances have been estimated using several years of FOAM SST data. These will be improved in the near future using a background error analysis based on OSTIA data.

The measurement footprint of SSTs obtained from the microwave sensors AMSRE and TMI are of order 25-50km, which is much larger than the analysis grid, which is less than 6km. To account for this, the model equivalent value for these observations is derived using an area average SST. This observation operator covers a radius of 25km centered on the nominal observation location.

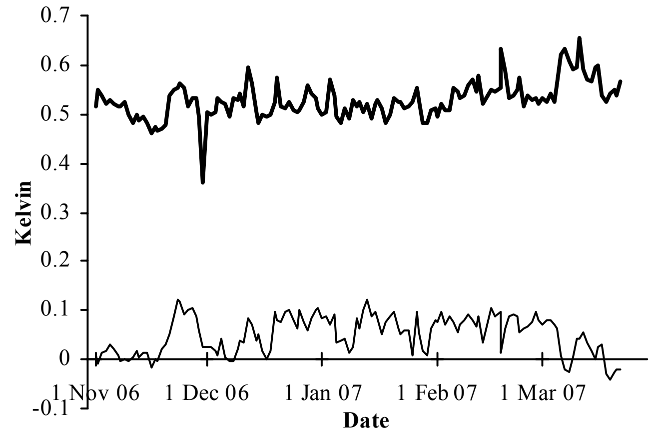

Fig. 2. Observation minus background statistics for in situ SST observations received via the GTS for OSTIA from November 2006 to March 2007. The RMS is shown in bold, and the mean as a plain line.

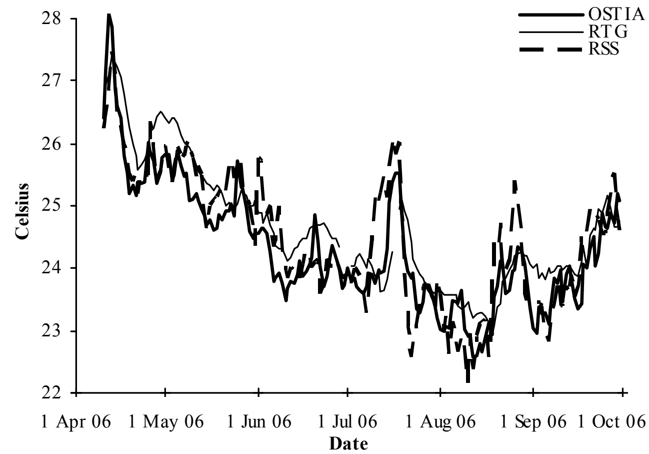

Fig. 3. Comparison of OSTIA, RTG and RSS SST analyses in the vicinity of the Galapagos Islands (110°W, 0°N). The periodic signal of Legeckis (tropical instability) waves can clearly be seen, although the RTG analysis seems to be slower to react.

VI. Validation of OSTIA SSTs

Routine verification of the SST analysis is performed, with observation minus background and observation minus analysis statistics computed daily. When compared against independent observations from the M-AERI radiometer as part of the EGEE / AMMA experiment in the Tropical Atlantic, OSTIA was found to have a cool bias of 0.17K, and RMS error of 0.39K. The RMS error was well within the design specification of 0.8K, but the bias was unexpected. The bias was traced to poorly specified SSES estimates in the AATSR data [10], and recent verification shows less bias, as shown in Fig. 2.

Anomalously low SST values have been detected in OSTIA for short periods in the Barents Sea. These have been traced to cloud contaminated AATSR observations producing unrealistically low SSTs which propagate through the bias analysis. This demonstrates the need for more stringent quality control of the reference set of observations used for bias correction. This is especially challenging at high latitudes, where low SSTs make cloud contaminated measurements more difficult to detect. We hope to reduce the occurrence of these anomalous values through improvements to the background error field discussed earlier.

VII. Intercomparison with Other SST Analyses

Several near real time SST analyses are available. These include the RTG SST analysis [11] which is primarily based on AVHRR data, and Remote Sensing Systems (RSS) OI SST [12], which is based on microwave SSTs from AMSR-E and TMI. An intercomparison of these SSTs is shown in Fig. 3, for the Tropical Pacific. The passing of wave-like features, possibly Legeckis waves, is visible in all the SSTs. The RTG is 0.3K warmer over the period shown in Fig. 3 compared to OSTIA, and shows less variability than the RSS and OSTIA analyses. This may be due to cloud cover limiting the availability of AVHRR data, which delays the response of the RTG analysis relative to OSTIA and RSS, which use microwave SSTs.

Compared to the current NWP SST analysis used at the Met Office, OSTIA offers a significant improvement in the representation of key oceanic features, as shown in Fig. 4.

VIII. Conclusion

The OSTIA SST analysis system has been developed and offers accurate SST data with an RMS error of less than 0.6K at high resolution in near real time. The system builds on data provided by the GHRSST-PP.

Acknowledgment

AATSR SST data were supplied by the ESA Medspiration project under the GHRSST-PP collaborative framework. AMSR-E and TMI SST data are produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project and the AMSR-E Science Team. Data are available at www.remss.com. AVHRR data were supplied by NASA-JPL under the GHRSST-PP collaborative framework.

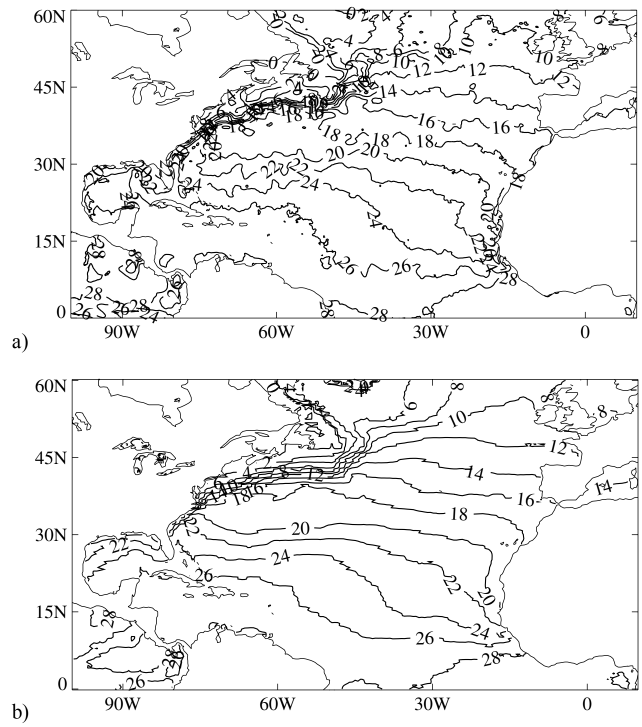

Fig. 4. Comparison of the North Atlantic SSTs in Celsius from the new OSTIA (a) and the current NWP analysis (b) for 24 March 2007. The higher resolution and greater density of observations used by OSTIA significantly improves the representation of strong gradients, such as the Gulf Stream, as well as mid ocean features compared to the NWP analysis.

References

[1] C. J. Donlon, I. Robinson, K. Casey, J. Vasquez, E. Armstrong, C. Gentemann, D. May, P. LeBorgne, J. Piollé, I. Barton, H. Beggs, D. J. S. Poulter, C. Merchant, A. Bingham, S. Heinz, A. Harris, G. Wick, B. Emery, A Stuart-Menteth, P. Minnett, B. Evans, D. Llewellyn-Jones, C. Mutlow, R. Reynolds, H. Kawamura and N. Rayner, "The Global Ocean Data Assimilation Project (GODAE) High Resolution Sea Surface Temperature Pilot Project (GHRSST-PP)", *Bull. Am. Met. Society*, to be published.

[2] C. J. Donlon *et al.*, " The Global Ocean Data Assimilation Experiment High Resolution Sea Surface Temperature Pilot Project (GHRSST-PP) Data Processing Specification version 1.7 (GDSv1.7)", available from the GODAE project Office, Met Office, Fitzroy Road, Exeter, United Kingdom, http://www.ghrsst-pp.org, 2006, pp 270.

[3] M. J. Bell,, R.M. Forbes and A. Hines , 2000, Assessment of the FOAM global data assimilation system for real-time operational ocean forecasting. *J. of Marine Systems*, vol.25, pp. 1-22, 2000.

[4] D. B. Chelton and F. J. Wentz, "Global microwave satellite observations of sea surface temperature for numerical weather prediction and climate research." *Bull. Amer. Meteor. Soc*., vol. 86, pp. 1097-11, 2005.

[5] M. Martin, A. Hines and M. Bell, "Data assimilation in the FOAM operational short-range ocean forecasting system: a description of the scheme and its impact", *Quart. J. Roy. Met. Soc.*,, to be published.

[6] H Kettle and C J Merchant, "The Impact And Mitigation Of Diurnal Variability Within The Ostia System", The University of Edinburgh, pp37, April 2006

[7] N. B. Ingleby and A. C. Lorenc, "Bayesian Quality-Control Using Multivariate Normal-Distributions.", *Quart. J. Roy. Met. Soc.* Vol 119 (513), pp1195-1225 Part B, Jul 1993.

[8] C. J. Donlon, P.J. Minnett, C. Gentemann, T.J. Nightingale, I.J. Barton, B. Ward and M.J. Murray, "Toward Improved Validation of Satellite Sea Surface Skin Temperature Measurements for Climate Research", *J. Climate,* vol. 15, pp353-369. doi:10.1175/1520-0442(2002)015<0353:TIVOSS>2.0.CO;2, 2002.

[9] A. C. Lorenc, R.S. Bell and B. Macpherson, "The Meteorological Office analysis correction data assimilation scheme", *Quart. J. Roy. Met. Soc.*, vol. 117, 497, pp 59 – 89, 1991.

[10] J.D. Stark, C. J. Donlon, A O'Carroll and G Corlett, "Determination of AATSR biases using the OSTIA SST analysis system and a match-up database.", *J. Atmos. Ocean. Tech.* , submitted.

[11] J. Thiébaux, E. Rogers, W. Wang, B. Katz, "A New High-Resolution Blended Real-Time Global Sea Surface Temperature Analysis" *Bull. Am. Met. Soc.*, 2003 84: 645-656 doi: 10.1175/BAMS-84-5-645.

[12] Data and description available from http://www.remss.com

[13] M. J. Bell, A. Hines and M. J. Martin "Variational assimilation evolving individual observations and their error estimates", Ocean Applications Technical Note No. 32, Met Office, Exeter, September 2003.

[14] J. D. Stark OSTIA data home page. Available: http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html.

[15] A. G. O'Carroll, J. G. Watts, L. A. Horrocks, R. W. Saunders and N. A. Rayner, "Validation of the AATSR meteo product sea surface temperature." *J. Atm. Ocean. Tech.*, Vol. 23 (5), pp 711-726, 2006.

[16] C.W. Fairall, E. F. Bradley, J. S. Godfrey, G. A. Wick, J. B. Edson and G. S. Young, "Cool-skin and warm-layer effects on sea surface temperature." *J. Geophys. Res.*, vol. 101, C1. pp1295-1308, 1996.