RAMSSA - An operational, high-resolution, Regional Australian Multi-Sensor Sea surface temperature Analysis over the Australian region

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(Manuscript received January 2010; revised August 2010)

An operational, high-resolution, Regional Australian Multi-Sensor Sea surface temperature Analysis (RAMSSA) system has been developed at the Australian Bureau of Meteorology as part of the BLUElink Ocean Forecasting Australia project. The pre-existing operational, 1/4° resolution, regional sea surface temperature (SST) analysis system has been modified to produce 1/12° resolution, daily SST analyses over the Australian region (20°N–70°S, 60°E–170°W). The new RAMSSA system combines SST data from infrared and microwave sensors on polar-orbiting satellites with *in situ* measurements to produce daily 'foundation' SST estimates, free of nocturnal cooling and diurnal warming effects. The RAMSSA analyses exhibited significantly less standard deviation than the pre-existing regional SST analyses when compared with independent buoy SST observations for the period 1 October 2007 to 31 March 2008 (0.42 °C compared with 0.55 °C) and agreed closely with those from daily foundation SST analyses produced by the UK Met Office and Ifremer using similar data sources (0.39 °C and 0.49 °C, respectively). The major differences between RAMSSA and these other foundation SST analyses relate to RAMSSA's method for creating super-observations and assigning weights to the various input data streams, and Ifremer and the Met Office analysis systems' bias-correction of all satellite input data using SST data from the Advanced Along Track Scanning Radiometer (AATSR). The lack of bias-correction of data input into RAMSSA has minimal effect north of 40°S where RAMSSA is on average within ±0.07 °C of other multi-sensor SST analyses. South of 40°S, RAMSSA is on average 0.09 °C to 0.25 °C warmer than bias-corrected analyses studied, mainly due to systematic biases over this region in satellite SST data streams from the Advanced Very High Resolution Radiometer (AVHRR) and Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) input into the analyses.

Introduction

The Australian Bureau of Meteorology (Bureau) runs regional high-resolution (5–12 km) Numerical Weather Prediction (NWP) models and eddy resolving 10 km ocean forecast models (Brassington et al. 2007). These models require 5–10 km resolution, real-time, daily analyses of sea surface temperature (SST) over the Australian region for ingest and validation, respectively. Ideally the SST should be free of diurnal variation due to daytime warming and surface cooling. Donlon et al. (2007) defines this as the foundation SST (SSTfnd), considered equivalent to the 'sub-skin' ocean temperature (below the ocean's cool skin layer) in the absence of any diurnal signal. The 'cool skin layer' exists both day and night and is a thin, thermally stratified ocean layer at the air-sea interface that results from the upward air-sea heat flux. The foundation SST is a better defined form of the

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historical 'bulk' SST, measured over a depth range of 1–20 m, and approximates closely the ocean mixed layer temperature (Robinson 2004; Donlon et al. 2007). Foundation SST is therefore the temperature that most closely represents the top layer (10 m) for ocean models. In addition, the foundation temperature being more stable and predictable over daily time-scales, is likely to be a more accurate representation of the oceanic mixed layer temperature, currently used for the ocean-atmosphere boundary layer temperature in NWP models.

In recent years, polar-orbiting satellites have been launched carrying microwave sensors capable of measuring surface ocean temperatures through cloud. This has enabled a number of relatively high-resolution global SST analyses to be produced by blending surface temperatures from infra-red sensors on satellites with measurements from microwave sensors. Some examples include the NCDC[1] global, daily, 1/4° resolution, blended SST analysis (Reynolds et al. 2007), the UK Met Office OSTIA[2] global, daily, 1/20° resolution, foundation SST analysis (Stark et al. 2007), Ifremer[3] ODYSSEA[4] global, daily, 1/10° resolution, foundation SST analysis (Autret and Piollé 2007), and the RSS[5] global, daily, ~1/11° resolution, IR+MW foundation SST analysis[6]. However, the Bureau's regional NWP systems require the production of in-house, high-resolution products using locally processed satellite data tuned to local conditions.

From 1997 the Bureau has produced a regional, daily, 1/4º resolution, blended SST analysis from *in situ* and satellite SST data (Smith et al. 1999). The production in recent years of higher resolution NWP models and implementation of an eddy-resolving BLUElink[7] ocean model precipitated in 2004 the development of a daily, 1/12º resolution, foundation SST analysis system called the Regional Australian Multi-Sensor SST Analysis (RAMSSA) system as part of the BLUElink Ocean Forecasting Australia Project.

The RAMSSA analysis system is based the univariate statistical or 'optimal' interpolation (OI) system ('SIANAL') developed at the Bureau of Meteorology originally for an oceanic subsurface temperature analysis system (Blomley et al. 1989; Smith et al. 1991; Smith 1995) and later modified for global and regional sea surface temperature analysis systems (Smith et al. 1999). OI is a widely used method in oceanography and meteorology that makes use of the statistical properties of irregularly spaced observations (in time and space) combined with a first guess to produce the best possible estimate of a state, in this case over a regular space-time grid. The error characteristics of each data-set included in the analysis must be estimated. A first-guess (or 'background' field) is used to calculate data increments, calculated from nearby observations minus the first-guess field. The new SST estimate is formed by a weighted sum of increments, with the weights calculated by the OI method, added to the first-guess values (Smith 1995).

This paper documents the RAMSSA version 1.1 (v1.1) analyses produced in test mode from 1 October 2006 to 22 December 2007 and operationally at the Bureau of Meteorology from 26 October 2007. For a description of the original RAMSSA v1.0 system, operational from 13 June to 27 October 2007 the reader is referred to Beggs (2007). The next section documents the data streams that are used in the RAMSSA v1.1 system and how they are processed prior to input into the Bureau's SIANAL OI analysis system. The diurnal variation mitigation method used to produce estimates of foundation SST is described and assessed. The following section documents the changes made to the SST analysis version of the SIANAL system (Smith et al. 1999) to produce the RAMSSA v1.1 SSTfnd analyses. For a fuller description of the SIANAL system the interested reader is referred to Blomley et al. (1989), Smith et al. (1991) and Smith (1995). In the later section the RAMSSA v1.1 analyses are assessed using statistical measures and comparisons against independent observations and other high-resolution SST analyses. Possibilities for potential modifications and improvements to the RAMSSA system are then outlined in the section on 'Further work'.

Observations and pre-processing

In this section, the SST data streams used in the RAMSSA v1.1 SST analysis system are first described, then the pre-processing steps applied to these data are described, then each satellite data stream's errors relative to buoy observations are presented, and finally the ice concentration analyses used in RAMSSA are described.

In Situ SST

The legacy regional 1/4° and new regional 1/12° SST analysis systems use SSTdepth measurements from drifting and moored buoys, ships, expendable bathythermographs (XBTs), Argo floats and Conductivity Temperature Depth profiles (CTDs) obtained from the Global Telecommunications System (GTS). An example of one day of *in situ* buoy SST data used in the analysis is shown in Fig. 1(a), illustrating the relative sparseness of this data stream, particularly over the Southern Ocean and the Indonesian archipelago.

The *in situ* SST records for the calendar day are extracted at 0130 UTC on the following day and screened for unwanted duplications.

AVHRR SST

Both the legacy regional and RAMSSA v1.1 systems use measurements from the Advanced Very High Resolution Radiometers (AVHRR) on board the NOAA[8] series of

[1]US National Climatic Data Center
[2]Operational Sea surface Temperature and sea Ice Analysis
[3]Institute français de recherche pour l'exploitation de la mer
[4]Ocean Data analYsis System for merSEA
[5]Remote Sensing Systems
[6]http://www.remss.com/sst/microwave_oi_sst_browse.html
[7]http://www.bom.gov.au/bluelink

[8]US National Oceanic and Atmospheric Administration

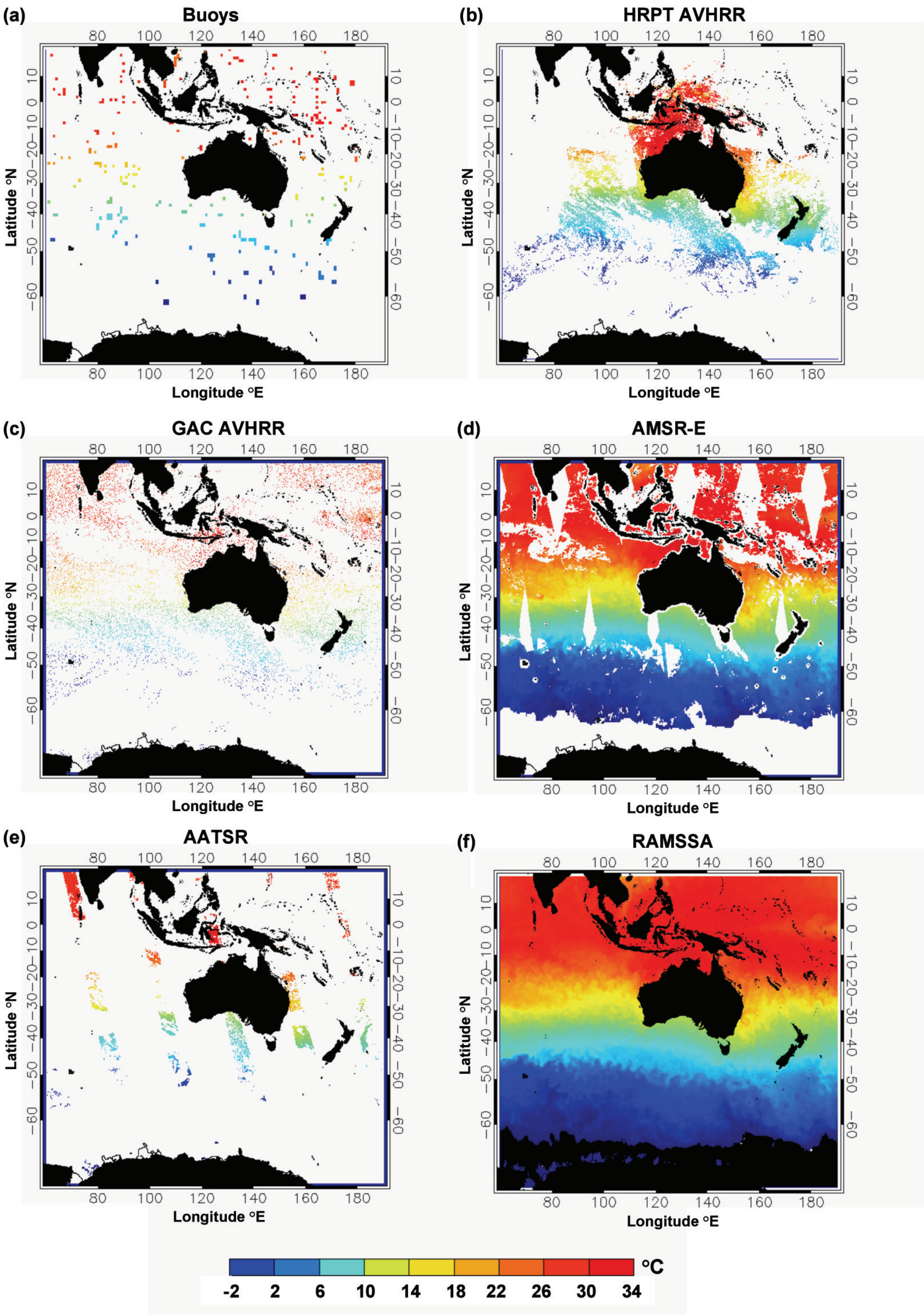


Fig. 1. Typical day's SST data (in this example, 20 November 2007) available for blending from (a) *in situ* buoy SSTdepth (GTS), (b) Local 1.1 km HRPT AVHRR SSTblend from NOAA-17 and NOAA-18 satellites averaged over 8 x 8 pixels (Bureau), (c) GAC 9 km x 4 km AVHRR SSTblend from NOAA-17 and NOAA-18 satellites (NESDIS), (d) 25 km AMSR-E swath L2P SSTsubskin from Aqua satellite (Remote Sensing Systems), and (e) 1/6° AATSR gridded Meteo Product SSTskin from ENVISAT (ESA). The plots represent the data available by ~0130 UTC on the day following data measurement, except for AMSR-E (~1900 UTC). (f) The RAMSSA daily regional 1/12° resolution SSTfnd analysis resulting from blending the data presented in (a) – (e). The region shown is the RAMSSA domain, 60°E–170°W, 20°N–70°S.

operational polar orbiting satellites and ESA's[9] METOP-A[10] polar-orbiting satellite. During the period covered by this study, the NOAA satellites used were NOAA-17 and NOAA-18.

The AVHRR, infrared sensors measure radiances from the ocean 'skin' at ~10 μm depth which are used to derive SSTskin. These measurements are converted to SST at approximately 20 cm to 1 m depth ('SSTblend') using an empirical method derived by regression against buoy SST measurements shortly after each satellite's launch (Walton et al. 1998).

The Bureau produces SSTblend measurements at a resolution of 1.1 km x 1.1 km at nadir from direct broadcast, HRPT[11] AVHRR raw data received from the operational NOAA polar-orbiters. The AVHRR SSTblend values are calculated from brightness temperature measurements using non-linear SST (NLSST) algorithms and coefficients derived by NOAA/NESDIS using buoy match-ups (Walton et al. 1998). Currently, the Bureau produces real-time (< 10 min) HRPT AVHRR SSTblend data from receiving stations located at Darwin, Alice Springs, Perth, Townsville, Melbourne and Hobart (in Australia), and Casey and Davis Stations in Antarctica.

Both these HRPT AVHRR SSTblend (Fig. 1(b)) and GAC AVHRR SSTblend data at a resolution of 9 km along scan x 4 km along track resolution at nadir (Fig. 1(c)) are used in the regional SST analysis system. The Global Area Coverage (GAC) AVHRR SST data originally used in the RAMSSA system was the operational global SST product received from NESDIS[12]. This was replaced on 10 June 2008 by the NAVOCEANO[13] GAC AVHRR SST L2P product in the Group for High Resolution SST (GHRSST[14]) format (obtained from ftp://podaac.jpl.nasa.gov/pub/GHRSST/data/L2P/).

For the RAMSSA analysis system, the individual HRPT AVHRR SST values are averaged over 8 x 8 pixels, resulting in one SST value for every 6 km along scan x 9 km along track resolution at nadir. SST values outside ±2 °C of the mean value are excluded from the averaging process. Prior to input into the RAMSSA OI analysis system, the NAVOCEANO GAC AVHRR SST values from each individual L2P (swath) file are averaged over the RAMSSA analysis resolution, 1/12° x 1/12°.

Although the AVHRR sensor provides wide swath data, it is unable to accurately measure ocean temperature in cloudy regions, leading to sparse coverage at some times over some areas.

AMSR-E SST

In order to increase the spatial resolution of the new RAMSSA analysis, it was necessary to improve the daily spatial data coverage, particularly in regions affected by cloud. The Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) on the Aqua polar-orbiting satellite is relatively insensitive to atmospheric effects compared with AVHRR and is largely unaffected by cloud but is sensitive to precipitation. The AMSR-E microwave sensor measures the 'sub-skin' radiances at ~1 mm depth which are used to derive SSTsubskin. The AMSR-E instrument extends the daily spatial coverage but has a coarse spatial resolution of ~25 km compared to an ~1 km resolution for AVHRR. Figure 1(d) shows the typical coverage of AMSR-E swath sub-skin SST data available in GHRSST format L2P files from Remote Sensing Systems[15] by ~1800 UTC on the day following data measurement. Prior to input into the RAMSSA OI analysis system, the AMSR-E SST values from each individual L2P (swath) file are averaged over the RAMSSA analysis resolution, 1/12° x 1/12°.

AATSR SST

The RAMSSA v1.1 system also ingests the 'ATS_MET_2P' Meteo Product derived using infrared data from the European Space Agency's 1/6° resolution Advanced Along Track Scanning Radiometer (AATSR) onboard the Envisat polar-orbiting satellite. This product provides a skin SST at ~10 μm depth ('SSTskin'). Figure 1(e) shows the typical coverage of AATSR Meteo Product data available by 0100 UTC of the day following data measurement. The AATSR has a smaller footprint (narrower swath) than the AVHRR or AMSR-E, but more accurately measures SST in cloud-free regions (Table 1 and Corlett et al. 2006).

Bias correction

The optimal interpolation method assumes the input data do not contain long-term relative biases. Hence, before data are ingested into the Bureau's OI analysis system (SIANAL), all observations must be adjusted for bias. In the cases of AATSR Meteo Product SSTskin, L2P AMSR-E SSTsubskin and L2P GAC AVHRR SSTblend, measured biases with respect to drifting buoy SSTdepth are applied.

The AATSR Meteo Product (ATS_MET_2P) skin SSTs are corrected following the test for 'standard atmospheric conditions' as described in Corlett (2005) and updated by Gary Corlett in May 2007 (*pers. comm.*). The standard atmospheric condition case is defined when:

$$\text{AATSR Dual View SST} - \text{AATSR Nadir View SST} \leq 0.2\ °\text{C (D2)} \quad \ldots(1)$$

$$\text{AATSR Dual View SST} - \text{AATSR Nadir View SST} \leq 0.6\ °\text{C (D3)} \quad \ldots(2)$$

where 'D2' denotes SST derived from the 11 and 12 micron channels during day or night and 'D3' denotes SST derived from the 3.7, 11 and 12 micron channels during night only.

The warm bias corrections to the skin SSTs chosen for the RAMSSA v1.1 system (Gary Corlett, *pers. comm*, May 2007) were –0.20 °C (D2) and –0.20 °C (D3) for data measured

[9]European Space Agency
[10]Meteorological Operational satellite
[11]High Resolution Picture Transmission
[12]US National Environmental Satellite, Data and Information Service
[13]US NAVal OCEANographic Office
[14]http://www.ghrsst.org

[15]ftp://ssmi.com/sst/misst/amsre/swath/nc/

under standard atmospheric conditions (Australian region, using AATSR SSTskin measurements converted to sub-skin temperatures matched with buoy SSTdepth data). AATSR SSTs measured under non-standard atmospheric conditions were rejected.

In the case of the AMSR-E and NAVOCEANO GAC AVHRR data streams, the SST measurements in the swath L2P SST files were corrected for bias using the bias estimates for each SST value reported in the files. The AMSR-E bias estimates were calculated by using collocations with buoys from the GTS to calculate a 'global' daily mean bias, then adjusting these values using static look-up tables based on *a priori* knowledge of other error sources (Gentemann 2004). The NAVOCEANO GAC AVHRR global bias estimates are regularly updated using the previous month of drifting and moored buoy SST observations matched with SST data (Cayula et al. 2004). Buoys are matched to GAC AVHRR SST data if they are within 25 km and four hours of the satellite retrieval.

Bias correction was not applied to the HRPT AVHRR and NESDIS GAC AVHRR SST estimates from NOAA-17 or NOAA-18. A Bureau study of satellite SSTfnd to buoy SSTfnd comparisons over the Australian analysis region (20°N–70°S, 60°E–170°W) (Fig. 2(a)) has shown that average monthly biases between AVHRR and buoy foundation SST measurements are between –0.1 °C and 0.2 °C. The observations were matched if within the same twenty four hour period and within 1/24° of latitude and longitude (half the analysis resolution). Future BLUElink work will concentrate on reducing these biases further by improving the calibration of the HRPT AVHRR SST data by using regional rather than global buoy SST observations.

Cool skin correction

AATSR is the only data stream used in the RAMSSA v1.1 analyses supplied as a true skin temperature measurement. In order to blend this data set with other SSTs measured or calibrated to depths below the skin layer, it was necessary to convert the AATSR skin SSTs to sub-skin estimates.

The empirically-derived Donlon et al. (2002) skin to foundation temperature conversion algorithms (Eqns 3 and 4 below) apply a small correction to convert from skin to sub-skin SST, depending on surface wind speed, and filter out SST values suspected to be affected by diurnal warming by excluding cases which have experienced recent surface wind speeds of below 6 m s^{-1} during the day and less than 2 m s^{-1} during the night. Under the remaining wind speed regimes SSTfnd approximates SSTsubskin and therefore under these conditions SSTfnd – SSTskin approximates SSTsubskin – SSTskin, ΔT (in °C), and can be written as (Donlon et al. 2002):

$$\Delta T = 0.17 \qquad \text{...(3)}$$

when surface wind speed exceeds 6 m s^{-1} (night and day conditions), and

$$\Delta T = 0.14 + 0.3\exp\left(-\frac{u}{3.7}\right) \qquad \text{...(4)}$$

when surface wind speed, u, is between 2 m s^{-1} and 6 m s^{-1} (night conditions only).

For reasons of consistency with the conversion of the other data streams to foundation SST (see next subsection) and processing efficiency, the Donlon equations were selected for the RAMSSA v1.1 analysis system.

Diurnal warming correction

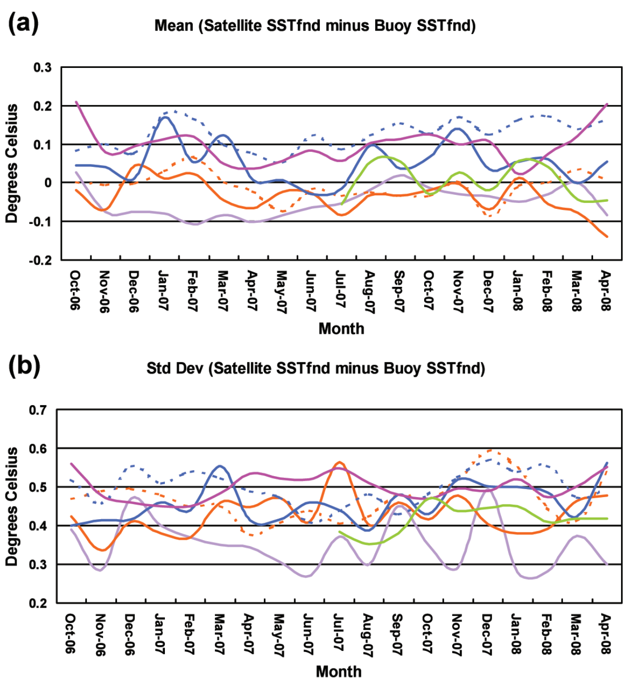
Table 1 presents one month's (November 2006) mean difference between each de-biased satellite SST data stream at the calibration depth (skin, sub-skin and ~1 m) and buoy foundation SSTs, and the same satellite data streams converted to foundation temperature estimates. The criteria used for selecting match-ups for the difference calculations between satellite and buoy measurements were that observations were within the same twenty four-hour period, and satellite and buoy observation positions were within half the RAMSSA analysis spatial resolution (i.e. 1/24°). In this study, the AATSR skin SST data were converted to foundation SST using the Donlon et al. (2002) skin to foundation temperature conversion algorithms (see previous subsection). The wind speeds used were the 0.375° horizontal resolution, hourly, instantaneous 10 m winds derived from the Bureau's LAPS NWP forecasts (Puri et al. 1998), over the region 17.125°N to 65°S, 65°E to 175.375°W. A two-year verification of the LAPS winds against satellite winds showed that the modelled surface winds are typically underestimated by around five per cent (Schulz et al. 2007). The remaining satellite SSTsubskin or SSTblend and *in situ* SSTdepth data were similarly filtered to remove suspected diurnal warming events using calculated times for sunrise and sunset at the measurement location, LAPS forecast winds and the same wind speed thresholds as applied to the AATSR data. That is, *in situ* or satellite SST observations were rejected if the forecast wind speed was less than 2 m s^{-1} during the night and less than 6 m s^{-1} during the day. Conversion of the buoy SSTdepth, AATSR SSTskin, AVHRR SSTblend and AMSR-E SSTsubskin measurements to SSTfnd estimates reduced the mean and standard deviation of the difference between SST from satellites and buoys for the period 1 – 30 November 2006, particularly reducing the relative bias between satellite data and buoys to within ±0.1 °C (Table 1). It is therefore expected to be advantageous to correct the input data streams to a common foundation SST provided that data spatial coverage is not significantly reduced, particularly in cloudy regions with calm ocean conditions.

The abovementioned method for converting SST data to foundation temperature estimates was adopted for the RAMSSA analysis system and its impact is assessed in the 'Evaluation' section later in this paper.

Table 1. Comparisons of SST measurements from each satellite data stream used in the RAMSSA analysis system with collocated buoy foundation SST measurements over the region 60°E–170°W, 20°N–70°S for the period 1–30 November 2006. Data are considered 'matched' if measured within same 24-hour period, centres of observations are separated by no more than half the RAMSSA resolution (1/24°), and satellite SST values are within 3 °C of buoy observations. The first set of columns give statistics (mean, standard deviation and total number of match-ups) for measurements at the satellite SST data product native depth (skin, sub-skin, ~1 m) and the second set of columns give the same set of statistics for the satellite SST data sets converted to foundation SST estimates.

Satellite Data Stream	*Satellite SST – Buoy SSTfnd*			*Satellite SSTfnd – Buoy SSTfnd*		
	μ (°C)	σ (°C)	N	μ (°C)	σ (°C)	N
AATSR 1/6° Meteo Product	–0.25	0.32	710	-0.04	0.30	612
HRPT 6 km x 9 km NOAA-17 AVHRR	–0.06	0.55	14060	-0.01	0.49	10002
GAC 9 km x 4 km NOAA-17 AVHRR	–0.05	0.37	728	-0.07	0.34	508
HRPT 6 km x 9 km NOAA-18 AVHRR	0.09	0.60	18790	0.10	0.46	12650
GAC 9 km x 4 km NOAA-18 AVHRR	0.11	0.50	1025	0.04	0.42	497
25 km AMSR-E L2P	0.12	0.47	22853	0.06	0.47	15759

Fig. 2. Monthly mean and standard deviation of foundation SST measurements from each satellite data stream used in the RAMSSA analysis system minus collocated buoy foundation SST measurements over the region 60°E–170°W, 20°N–70°S for the period 1 October 2006 to 30 April 2008. Data are considered 'matched' if measured within same 24-hour period, centres of observations are separated by no more than half the RAMSSA resolution (i.e. 1/24°), and SST values are within 3 °C. Statistics for foundation SST from AATSR are shown in violet, AMSR-E in pink, AVHRR from NOAA-17 in orange, AVHRR from NOAA-18 in blue and AVHRR from METOP-A in green. HRPT AVHRR is represented by dashed lines and GAC AVHRR as solid lines.



Evaluating the satellite data streams

Figure 2 shows the mean monthly buoy SSTfnd match-up statistics over the RAMSSA domain for the satellite SSTfnd data streams ingested into the RAMSSA system for the period 1 October 2006 to 30 April 2008. Over this nineteen month period the average monthly standard deviation of AATSR SSTfnd when matched with buoy foundation SST estimates was 0.35 °C compared with 0.43 °C and 0.46 °C for NESDIS GAC AVHRR from NOAA-17 and NOAA-18 satellites and 0.50 °C from AMSR-E (Fig. 2(b)).

Sea-ice analysis inputs

At high latitudes, the RAMSSA analysis system uses the daily sea-ice concentration analysis from NOAA/NCEP[16] to constrain the SST, by setting the SST at a given grid point to –1.8 °C if the concentration of NCEP ice data in that grid cell is greater than 50 per cent. Until 12 March 2008, the 0.5° resolution sea-ice analysis was used and after that date, the 1/12° resolution sea-ice analysis (Grumbine 1996).

The analysis system

Summary

The RAMSSA system, based on the SIANAL analysis scheme (Blomley et al. 1989), considers each variable separately as statistically independent (univariate) fields, with characteristic decorrelation, variance and signal-to-noise properties. All data are transformed into deviations away from the first-guess, and normalised by the estimated error of the first-guess field. The analysis system validates the input observation against the background field and flags data with differences greater than three times the specified background field error (Blomley et al. 1989). Unflagged neighbouring data closer than a decorrelation scale (dependent on the background field correlation length scale) are combined into a 'super-observation'. Each datum is validated against an interpolated value from other members of the group. If

[16]http://polar.ncep.noaa.gov/seaice/Analyses.html

this check fails a prescribed tolerance, the datum is flagged and removed from further super-observation formations (Blomley et al. 1989). In this way the analysis method uses the estimated errors and decorrelation length scales of the observational data to thin the observations in order to achieve computational efficiency.

The aim of the RAMSSA analysis system is to resolve SST features at ~10 km over the Australian region at a temporal resolution of one day. As the major data stream for the system is GAC 9 km x 4 km resolution AVHRR data, with many gaps due to cloud filled by 25 km resolution AMSR-E data, a cylindrical equidistant analysis grid of 1/12° (~9 km) was chosen. Measurements for the twenty-four hour UTC day are input into the analysis for that date. Since the optimal interpolation method produces point analyses in space and time, the daily OI SST analyses are valid for 1200 UTC of the measurement day. Until 9 April 2009, the pre-existing 1/12° resolution land-sea mask was used (from the legacy regional 1/4° resolution SST analysis system). After this date, the higher resolution 1/120° land-sea mask from NAVOCEANO[17] was used.

The pre-processed foundation SST data streams described earlier are input into the RAMSSA version 1.1 OI analysis system. HRPT AVHRR data are available several minutes after measurement, AATSR data within 3 hours, GAC AVHRR data within 6 hours, but the AMSR-E L2P data from Remote Sensing Systems may be more than 6 hours old by the time the files are downloaded to the Bureau. The RAMSSA operational daily analysis is run first at 0130 UTC and then later at 1900 UTC in order to include more of the previous day's AMSR-E SST data in each daily analysis (see Fig. 1(d)). The first analysis run at 0130 UTC (fv01) or second analysis run at 1900 UTC (fv02) provides the latest real-time SST analysis for input into the Bureau's Limited Area Prediction System (LAPS) NWP models, superseded on 1 September 2009 by ACCESS-R (Puri et al. 2010). The output from the second analysis (fv02) provides the major input into the background field for the following day's fv01 SST analysis. An example of the RAMSSA analysis is shown in Fig. 1(f) for 20 November 2007.

There are a number of issues to resolve when blending satellite data from different sensors. These include dealing with relative RMS errors, choice of correlation length and time scales and design of a 'background' or 'first-guess' field. These methods used to deal with each of these issues in the operational RAMSSA analysis system are discussed in the following subsections.

Relative weighting of data streams

The estimated observation standard deviation errors input into the OI analysis system provides the system with the weight to give each observation in the analysis relative to other observations and the background field. These observation errors are a combination of instrument error and representativeness errors (both spatial and temporal). The representativeness errors must be estimated over the target field, in this case chosen to be the analysis spatial resolution (1/12°) and temporal resolution (twenty-four hours).

For the RAMSSA v1.1 system, observation standard deviation errors are estimated for each satellite data stream by using a month of match-ups between foundation SSTs from the various input satellite data streams and buoy foundation SSTs, such as those shown in Table 1 and Fig. 2. The standard deviation of all matches over a month is considered by the authors to be an effective estimate of the total relative standard deviation error between estimates of SSTfnd from the particular satellite and buoy SSTfnd. The error estimate incorporates instrument errors from each type of sensor, spatial representativeness error over the analysis grid resolution, and temporal representativeness error over the analysis period (in this case twenty-four hours). In order to account for the residual biases between the pre-processed satellite SSTfnd data streams and buoy SSTfnd, the absolute bias (Fig. 2(a)) is added to the monthly standard deviation (Fig. 2(b)) to obtain a total relative estimated error. These estimated observation errors are then used in the RAMSSA analysis system and automatically recorded in the header of each analysis L4 netCDF file (Beggs and Pugh 2007).

Correlation scales

In the Bureau's OI SST analysis systems, the *background field* correlation length scale effectively gives the radius of influence of an observation to changes in the background field (see next subsection). Any feature smaller than the *observation* correlation length scale in extent and within the observation correlation *time* scale in time is treated by the OI analysis as noise. Observations separated by less than the observation correlation length scale and the observation correlation time scale will not have independent errors.

The RAMSSA v1.1 analysis system uses a background field correlation length scale of 20 km, an observation correlation length scale of 12 km and observation correlation time scale of 0.5 days for all input observations. An observation correlation length scale of 12 km was chosen as it is approximately half the resolution of the AMSR-E observations and is slightly larger than the analysis grid resolution of approximately 9 km. A background field correlation length scale of 20 km was selected by tuning to optimise the resolution and accuracy of eddy-scale SST features around the Australian coast.

Background or 'first-guess' field

An important component of any OI analysis system is the formulation of the background field, which provides the first-guess field. At each grid point k and time t in days the background field SST for the RAMSSA analysis, $f_k(t)$, is calculated using the optimum forecast method following Smith (1995) and the Bureau's legacy operational, regional, 1/4° resolution, SST analysis system (Smith et al. 1999),

[17] http://www.ghrsst-pp.org/GHRSST-PP-NAVO-Land-and-sea-Mask.html

$$f_k(t)=a_k^{glob}(t_{glob})+r(a_k(t-1)-a_k^{glob}(t_{glob})) \quad ...(5)$$

where $a_k^{glob}(t_{glob})$ is the most recent Bureau global, weekly, 1° resolution SST analysis at time t_{glob}, and $a_k(t - 1)$ is the previous day's regional 1/12° SST analysis (usually the fv02 file from the analysis run at 1900 UTC the previous day). The relative weight, r, to give each analysis in the background field, is given by autocorrelation of the one day separated analysis increments:

$$r = \alpha_1+\alpha_2\exp(-0.5(\lambda/d)^2) \quad ...(6)$$

where λ is the latitude of the grid point and d is the spatial decorrelation constant at low latitudes, currently set to 9° of longitude in all the Bureau's SST analysis systems. Note that the correlations between the global weekly and regional daily SST analyses are highest in the equatorial region where the dominant large-scale equatorial waves provide high levels of short-term predictability (Smith 1995). The autocorrelation function factors at mid-latitudes, α_1, and at low latitudes, α_2, are given by:

$$\alpha_1 = \exp(-0.5(\Delta t/d_1)^2) \quad ...(7)$$

$$\alpha_2 = \exp(-0.5(\Delta t/d_2)^2) - \alpha_1 \quad ...(8)$$

where Δt is the time difference (in days) between the current regional analysis and a_k(t - 1), d_1 is the temporal decorrelation constant at mid-latitudes and d_2 is the temporal decorrelation constant at low latitudes (both in days).

In the Bureau's global 1° and legacy regional 1/4° SST analysis systems, d_1 is set to four days and d_2 is set to ten days due to the higher correlation between SSTfnd observations over time at low latitudes compared with mid-latitudes. In the legacy regional analysis system, Δt is generally one day and therefore r is between 0.969 and 0.995 over the analysis region.

In the legacy regional 1/4° and RAMSSA analysis systems, the estimated error of the background field at each grid point is (Smith 1995)

$$E_k^{\,f}(t)=\sqrt{(1-r^2)(E_k^{\,glob}(t_{glob}))^2+r^2(E_k^{\,a}(t-1))^2} \quad ...(9)$$

where $E_k^{glob}(t_{glob})$ is the error of the most recent global weekly analysis and $E_k^a(t - 1)$ is the error of the previous day's legacy regional 1/4° or RAMSSA analysis at the same grid point.

Equation 9 implies that for values of r approaching 1, if today's analysis has the same number of observations with the same estimated errors as the previous day's analysis, then today's background field error at grid point k, $E_k^f(t)$, will approach yesterday's analysis error, $E_k^a(t -1)$. This would result in the background field being given equal weight to today's observations at grid point k in today's analysis. During late austral spring when waters surrounding Australia warm at a rapid rate this persistence problem was particularly marked in the legacy regional 1/4° analyses (Fig. 3(c)).

To mitigate the persistence problem, the RAMSSA v1.1 system input parameters and Eqns 7 and 8 have been optimised using observations minus analysed SST and the RMS error of observations minus the background field, and comparisons between the efficacy of the reanalyses resolving high-resolution ocean features in the Leeuwin and East Australian Currents (see 'Evaluation' section below). The input parameters chosen for the operational version 1.1 of RAMSSA were d1 = 2 days and d2 = 5 days, resulting in r = 0.98 at 0°N and 0.88 at 70°S. On 7 October 2008 d_2 was changed to 2 days.

Evaluation

The RAMSSA v1.1 analysis system became operational at the Bureau on 26 October 2007 and RAMSSA v1.1 reanalyses performed back to 1 October 2006. By 0500 UTC each day, 1/12° resolution, foundation SST analyses are produced by the Bureau based on the previous day's observations and may be downloaded in real-time from an OPeNDAP server accessible via http://godae.bom.gov.au/ or from ftp://podaac.jpl.nasa.gov/pub/GHRSST/data/L4/AUS/ABOM/RAMSSA_09km/ .

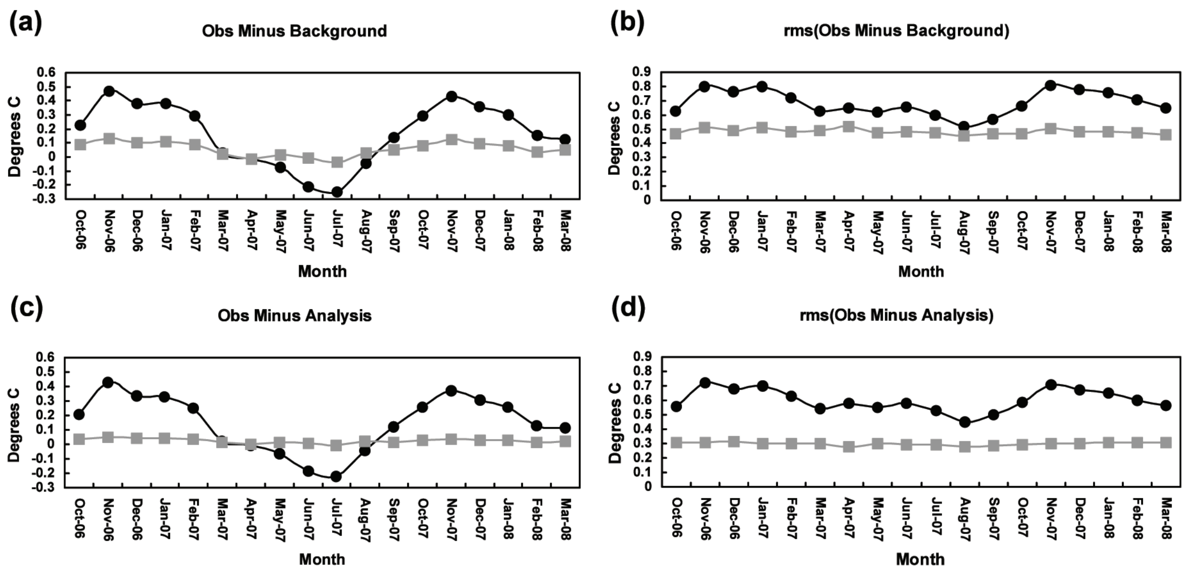
The impact on RAMSSA of the diurnal warming mitigation method described earlier is illustrated in Table 2. The same satellite input data as used in RAMSSA v1.1 for November 2006 (see Table 1) were reanalysed without any *in situ* observations. In the first case ('fv52') no satellite observations were rejected on the basis of time of day or wind speeds, although AATSR skin SST observations were converted to foundation SST following the method described earlier in the 'Cool skin correction' subsection. In the second reanalysis ('fv53') all satellite data were filtered depending on day/night and NWP winds as described in the 'Diurnal warming correction' subsection. In the third reanalysis ('fv57') no daytime satellite data were blended (only night-time). The reanalyses were compared with buoy foundation SST observations (filtered following the method described earlier). Data were considered matched if measured within the same twenty-four hour period, buoy observations were located within the analysis SST grid cell (1/12º x 1/12º) and analysis SST values were within 3 ºC of buoy observations. The monthly mean statistics for November 2006 are listed in Table 2 which indicates that removing daytime observations under low wind speed conditions reduces the bias of the analyses when compared with buoy SSTfnd observations (from 0.08 °C to 0.03 °C) but increases the standard deviation slightly (from 0.44 °C to 0.46 °C), possibly due to the reduction in the total number of observations being analysed between the SSTblend and SSTfnd analyses. Removal of all daytime satellite SST data from the reanalysis (fv57) likewise increased the standard deviation slightly further to 0.47 °C, possibly due to further reduction in total observations blended. In contrast, Table 1 indicates that removing satellite observations during low winds generally reduced the standard deviation when comparing the satellite data to buoys. It is possible that comparing against relatively sparse buoy observations is not an effective statistical measure of the RMS error of an SST analysis. There are relatively few buoy SST observations available in the ocean regions south of 55ºS, close to the Australian coast and within the Indonesian Archipelago (Zhang et al. 2009; Fig. 1(a)). Incorporating accurate, *in situ* SST observations from ships of opportunity in these regions may improve SST analysis validation. As more high quality ship SST observations become available through the Integrated Marine Observing System (IMOS[18]), combining ship and buoy observations for analysis validation will be assessed.

A useful measure of the efficacy of an analysis system is to calculate innovation statistics based on all observations from the current day minus the analysis of the previous day's observations. Observations minus background field calculations provide an estimate of the analysis bias compared with innovation observations. In the RAMSSA system, these are the observations from the following day which have not yet been used for the analysis. Figure 3 presents mean monthly statistics for 1 October 2006 to 31 March 2008 of observations minus background field (OMF) and observations minus analysis (OMA), along with their RMS errors (rmsOMF and rmsOMA), for RAMSSA v1.1 and the Bureau's legacy daily, regional, 1/4° resolution, SSTblend analyses. The new RAMSSA v1.1 analysis performed significantly better, both in OMA (Fig. 3(c)) and rmsOMF (Fig. 3(b)), than the regional SST analysis that it replaced (0.05 °C compared with 0.43 °C and 0.51 °C compared with 0.80 °C, respectively, for November 2006). The major cause

Table 2. Test RAMSSA analysis SST (for date *t*) minus Buoy foundation SST (for date *t*) for the region 60°E–180°E, 20°N–70°S, averaged over the period 1–30 November 2006. Data are considered 'matched' if measured within same 24-hour period, buoy observations are within the analysis SST grid cell (1/12° x 1/12°) and analysis SST values are within 3 °C of buoy observations. μ and σ are the average and standard deviation of all the differences and N is the number of all match-ups. Note that no in situ data were blended in the test RAMSSA analyses fv52, fv53 or fv57. For the fv52 SSTblend analysis all the satellite SST data shown in Table 1 were blended without any filtering for day/night or wind speed. For the fv53 SSTfnd analysis the same satellite SST data used in fv52 were filtered to remove suspected diurnal warming events following the method described in the *Diurnal warming correction* sub-section. For the fv57 SSTfnd analysis no daytime data were blended.

RAMSSA Test Analysis	*Day/Night*	*Wind Speed*	*Analysis (t) – Buoy SSTfnd(t)*		
	Filtering	*Filtering*	μ (°C)	σ (°C)	N
RAMSSA fv52 SSTblend (no in situ data)	No	No	0.08	0.44	21865
RAMSSA fv53 SSTfnd (no in situ data)	Yes	Yes	0.03	0.46	21853
RAMSSA fv57 SSTfnd (no daytime or insitu data)	Yes	No	–0.06	0.47	22552

Fig. 3. Monthly (a) mean (observations minus background field), (b) RMS(observations minus background field), (c) mean(observations minus analysis) and (d) RMS(observations minus analysis) for the RAMSSA v1.1 SSTfnd analysis (grey squares) and Bureau legacy regional daily, 1/4° resolution, SSTblend analysis (black circles) for the period 1 October 2006 to 31 March 2008 over the region 60°E–170°W, 20°N–70°S.



[18]http://www.imos.org.au

of the improvement in accuracy between RAMSSA and the legacy regional analysis system was increasing the weight of the global SST analysis in the background field by decreasing *r* in Eqn 9, thereby increasing the overall background field error and reducing its variability. Due to the background field error increasing, the background field has a smaller weight in the RAMSSA analysis thereby reducing persistence. It is highly likely that analysis persistence caused the large annual cycle in the legacy regional analysis OMA and OMF values (Fig. 3(a) and (c)).

The rmsOMF plots (Fig. 3(b)) and the rmsOMA plots (Fig. 3(d)) indicate that RAMSSA is significantly less noisy than the Bureau's legacy regional 1/4° SST analysis, due in part to the tuning of the RAMSSA correlation length scales (see 'Correlation scales' subsection) and autocorrelation function decorrelation constants (see "Background or 'first-guess' field" subsection). A comparison of analysed SST with buoy foundation SSTs for the period 1 October 2007 to 31 March 2008 over the region 60°E to 180°E, 20°N to 65°S (Table 3), indicates that the RAMSSA v1.1 analysis has smaller mean bias and standard deviation when matched with buoy SSTfnd measurements (within the same analysis grid cell and next calendar day), than the Bureau's legacy regional SSTblend analyses.

This performance analysis of the RAMSSA system does, to some extent, reflect the accuracy of the input observations. More noisy, or biased, input data would result in larger rmsOMF. In the case of RAMSSA v1.1, known biases in the AMSR-E and AATSR data have been removed and all observations filtered to remove data possibly affected by diurnal warming (see 'Diurnal warming correction' subsection). However, there is still a need to improve the methods used to correct for biases and diurnal warming in AMSR-E SST and also AVHRR SST, as illustrated in Fig. 2. The SST observations from HRPT AVHRR on NOAA-18 (dashed blue line) and AMSR-E on Aqua (pink line) were biased more than 0.1 °C too warm during Austral spring–summer (Fig. 2(a)) at the same time that the RAMSSA analysis was on average 0.1 °C cooler than the following day's observations due to persistence (Fig. 3(a)). The equator crossing times of NOAA-18 and AMSR-E are approximately 1330 local time (LT), close to the peak of the diurnal warming cycle at around 1500 (Gentemann et al. 2003). If the diurnal warming mitigation method used in RAMSSA does not totally remove NOAA-18 and AMSR-E observations affected by diurnal warming then this might result in a warm bias in RAMSSA with the same annual cycle as persistence but opposite sense. The residual persistence present in the RAMSSA system therefore counteracts the residual warm bias in RAMSSA caused by diurnal warming not being fully removed from the observations blended, as is demonstrated by the test RAMSSA fv53 SSTfnd analyses being on average 0.03 °C warmer than buoy SSTfnd observations during November 2006 (Table 2).

Table 3. Analysis SST (for date *t*) minus Buoy foundation SST (for date *t* + 1 day) statistics for the region 60°E–180°E, 20°N–70°S, averaged over the period 1 October 2007-31 March 2008. Data are considered 'matched' if measured within same 24-hour period and buoy observations are within the particular analysis SST grid cell. <μ> is the average of all daily means of the differences and <σ> is the average of all daily standard deviations of the differences. <N> is the average number of daily match-ups.

SST Analysis	*SST Analysis (t) – Buoy SSTfnd(t+1)*		
	<μ> (°C)	<σ> (°C)	<N>
RAMSSA v1.1 1/12° SSTfnd	0.03	0.42	814
Bureau Regional 1/4° SSTblend	–0.06	0.55	431
Ifremer ODYSSEA 1/10° SSTfnd	0.09	0.49	653
RSS IR + MW ~1/11° SSTfnd	–0.03	0.58	698
Met Office OSTIA 1/20° SSTfnd	–0.05	0.39	978
NCDC AVHRR + AMSR-E 1/4° SSTblend	–0.04	0.57	406

The RAMSSA v1.1 SSTfnd analysis was also compared with the following near real-time, multi-sensor, optimal interpolation SST analyses from other agencies:

- Ifremer's ODYSSEA daily, global, 1/10° resolution, foundation SST analysis[19] (Autret and Piollé 2007);
- RSS daily, global, ~1/11° resolution, IR+MW SSTfnd analysis[20];
- The UK Met Office OSTIA daily, global, 1/20° resolution SSTfnd analysis21 (Stark et al. 2007); and
- The NCDC daily, global 1/4° resolution AVHRR+AMSR-E SSTblend analysis (Reynolds et al. 2007).

Data inputs, bias correction method, diurnal variation mitigation method, analysis time window and spatial correlation length scales for each of the SST analyses compared in this study are summarised in Table 4. All these analyses are available in GHRSST-L4 format from the GHRSST Long Term Stewardship and Reanalysis Facility[22].

The RAMSSA v1.1 analyses were compared with the aforementioned multi-sensor SST analyses over small coastal Australian regions with good local HRPT AVHRR coverage (clear skies) and well-defined surface ocean features. Figure 4 shows the various SST analyses over the region to the southeast of Australia (showing the southern section of the East Australian Current) for 20 November 2007. Figure 4(f) presents the ~1/25° resolution CSIRO 3 Day Composite AVHRR SSTblend product[23] (Griffin et al. 2004) which contains no interpolation and has gaps where there were no AVHRR measurements during the three day period 18 to 20 November 2007. For cloud-free ocean regions around the coast of Australia this product provides a good representation

[19]http://cersat.ifremer.fr/data/discovery/by_parameter/sea_surface_temperature/odyssea_global_sst_analysis
[20]http://www.remss.com/sst/microwave_oi_sst_browse.html
[21]http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html
[22]http://www.nodc.noaa.gov/SatelliteData/ghrsst/
[23]http://www.marine.csiro.au/remotesensing/oceancurrents

Table 4. Daily, multi-sensor, OI SST analyses compared in this study. All analyses except for RAMSSA are global.

SST Analysis	*SST Data Inputs*	*Bias Correction Method*	*Diurnal Variation Mitigation Method*	*Spatial Correlation Length Scales*
RAMSSA v1.1 1/12° SSTfnd	In situ, L2 products from AATSR and HRPT AVHRR, L2P products from AMSR-E and GAC AVHRR	Global bias corrections applied to AATSR, GAC AVHRR and AMSR-E	Discard observations during day for winds < 6 m/s and during night for winds < 2 m/s	Observation: 12 km Background field: 20 km
Ifremer ODYSSEA 1/10° SSTfnd	L2P products from FRAC/HRPT/LAC/GAC AVHRR, AATSR, AMSR-E, TMI, GOES-11, GOES-12, SEVIRI	Bias correct regionally against analysis of AATSR and buoy SSTs	Discard all daytime observations	Observation: None Background field: Range from 80 km on equator to 20 km at high latitudes
RSS IR + MW ~1/11° SSTfnd	L2 products from MODIS, TMI and AMSR-E	AMSR-E/TMI globally bias corrected against 5 days of buoy SSTs, then adjusted for environmental conditions using static lookup table. MODIS is corrected for diurnal variation then adjusted to AMSR-E bias.	Convert observations to SSTfnd using skin to foundation and sub-skin to foundation SST models described in Gentemann et al. (2003)	Decorrelation space scale: 1.5° (zonal) and 1.5° (meridional)
Met Office OSTIA 1/20° SSTfnd	In situ, L2P products from LAC/GAC AVHRR, AATSR, AMSR-E, TMI, SEVIRI	Bias correct regionally against analysis of AATSR and buoy SSTs	Discard daytime observations for winds < 6 m/s	Observation: None Background Field: 10 km and 100 km depending on data density
NCDC AVHRR + AMSR-E 1/4° SSTblend	In situ, L2 products from Pathfinder AVHRR and AMSR-E, and L2P products from GAC AVHRR	Bias correct regionally against drifter and ship SSTs	None	Observation: None Background Field: 151 km (zonal) and 155 km (meridional)

of mesoscale ocean features such as eddies. All the analyses compared very closely with the composite product in this example. However, mapping the SST spatial gradient magnitudes of the analyses over the same day (Fig. 5) shows that the higher resolution 1/20° OSTIA SSTfnd analysis in Fig. 4(d), represents eddies and other features in less detail than the 1/12° resolution RAMSSA analysis, 1/10° ODYSSEA (Fig. 4(b)) or ~1/11° RSS (Fig. 4(c)) analyses. This is most likely due to the OSTIA analyses applying longer background correlation length scales (100 km) in this region than RAMSSA (20 km), ODYSSEA (25 – 35 km) or RSS. Finer analysis grid resolution therefore does not necessarily mean greater resolution of mesoscale features. Under conditions of prolonged cloud cover, where higher resolution infrared satellite SST data from AVHRR, AATSR and MODIS are not available, SST gradients decreased markedly in those analyses with shorter background correlation length scales (RAMSSA, ODYSSEA and RSS) and mesoscale features were less defined. Figures 6 and 7 illustrate this for 3 November 2007, showing the same region as Figs 4 and 5 but for a period where cloud obscured much of the East Australian Current for at least three days.

Over the region 60°E to 180°E, 20°N to 65°S, during the period 1 October 2007 to 31 March 2008, the RAMSSA SSTfnd analysis agreed most closely with the ODYSSEA SSTfnd analysis, closely followed by OSTIA (Table 5). For the same period and study region, the RAMSSA analysis showed mean bias and standard deviations compared with SSTfnd measurements from buoys (measured on the following day) of 0.03 ± 0.42 °C, comparable with those obtained from the OSTIA analyses (–0.05 ± 0.39 °C) (Table 3). The agreement between buoy SSTfnd measured on the following day and ODYSSEA, NCDC and RSS daily analyses was less strong (Table 3). In the case of ODYSSEA and RSS analyses, this may be simply due to buoy observations not being blended, unlike RAMSSA, OSTIA and NCDC analyses. The relatively close agreement between RAMSSA, OSTIA and ODYSSEA (Table 5) may be linked to similar data inputs and similar methods used to convert these satellite data to foundation SST estimates (Table 4). The OSTIA system rejects daytime observations where NWP surface winds are less than 6 m/s and the ODYSSEA system rejects all daytime observations. It should be noted that even removing all daytime observations from an SST analysis would not produce an exact 'foundation' SST since the polar-orbiting satellites currently producing SST data ingested into the SST analyses used in this study have equator-crossing times of approximately 0100 to 0200 LT and 1000 to 1100 LT that are several hours before or after local sunrise. However, by filtering out night-time observations for winds less than 2 m/s (as in the RAMSSA system) it is more likely that any nighttime diurnal warm layer will have been dissipated by the time the ocean surface is observed by a polar-orbiting satellite, in the case of NOAA-17 and EnviSat ~ 2230 LT, METOP-A ~ 2130 LT and Aqua and NOAA-18 ~ 0130 LT.

In addition to the broadscale (both in space and time) comparisons of RAMSSA with other SST analyses (Tables 2, 3 and 5), smaller scale comparisons were also made to investigate potential regional biases. Mean and standard deviation maps of the RAMSSA v1.1 analysis minus other SST analyses, linearly interpolated to the finest resolution grid of each analysis (Figs 8 and 9), indicate regional average temperature differences between the RAMSSA SSTfnd analysis and the Bureau legacy, ODYSSEA, RSS, OSTIA and NCDC analyses for the period 1 to 30 November 2007 exceeding ±1 °C, with standard deviations exceeding 1 °C in smaller areas. The legacy regional analysis exhibited a marked warm bias compared with RAMSSA north of the equator and a cold bias in the southern hemisphere (Fig. 8(a)). These hemispheric biases are most likely due to persistence in the legacy regional analyses, as described in the 'Background or first-guess field' subsection and earlier in this section. In contrast, the discrepancies between the RAMSSA SSTfnd analysis and ODYSSEA, RSS, OSTIA and NCDC analyses (Figs 8(b)–(e)) showed no obvious hemispheric bias but were particularly marked over the Southern Ocean. Several possible reasons for these differences are listed below.

- Linear interpolation between analyses: A possible source of difference between RAMSSA at 1/12° spatial resolution and the legacy regional analysis (Fig. 8(a)) and the NCDC analysis (Fig. 8(e)), both 1/4° resolution, may be due to the linear interpolation of the coarser resolution analyses onto the 1/12° grid causing bias adjustment.
- Prolonged cloud cover: There are generally less infra-red satellite radiometer data available over the Tropical Warm Pool region and Southern Ocean due to cloud (eg. Figs 1(b), (c) and (e)).
- Sea-ice inputs: Different sea-ice products are used in the various SST analyses causing discrepancies between the analyses south of 60°S.
- Methods for thinning observations: The ODYSSEA, RSS, OSTIA and NCDC analysis systems average or thin satellite SST observations prior to ingestion into their OI analysis systems, unlike the Bureau regional analyses which use a sophisticated 'super-obbing' procedure ('Correlation scales' subsection).
- Methods for weighting observations: The various analysis systems also apply different methods to 'weight' their input satellite SST data streams in the OI systems ('Relative weighting of data streams' subsection) and produce a background field ('Background or "first-guess" field' subsection).
- Bias–correction of observations: The SST analysis systems use different methods for correcting biases in the input satellite data (Table 4), as discussed in the following section.

During November 2007, the only satellite SST input streams corrected for bias by the RAMSSA v1.1 system were AMSR-E and AATSR, using match-ups with global and regional buoy SSTs, respectively ('Cool skin correction' subsection). As already discussed, it would appear from Fig. 2(a) that either further removal of regional AMSR-E SSTsubskin biases may be necessary, or the RAMSSA method used to mitigate the effects of diurnal warming needs to be improved. In contrast, Met Office and Ifremer use regional AATSR combined with buoy SSTs to de-bias the other satellite data inputs into the OSTIA and ODYSSEA analysis systems (Stark et al. 2007; Autret and Piollé 2007). The NCDC AVHRR+AMSR-E analysis system debiases all satellite data inputs regionally using both buoy and ship SST observations from the GTS (Reynolds et al 2007). The RSS AMSR-E+TMI+MODIS analysis system globally bias-corrects the satellite data using five days of buoy observations then adjusts for environmental conditions using a static look-up table (Chelle Gentemann, pers. com. 2009). Reynolds et al. (2010) indicated that for the years 2006 to 2008 the mean difference between AVHRR and AATSR SST night-time observations south of 40°S ranges up to +0.25 °C for NOAA-17 and +0.4 °C for NOAA-18. Following the same method as used for Table 1, a comparison between each of the satellite SSTfnd inputs to RAMSSA v1.1 with buoy SSTfnd over the region 60°E to 170°W, 40°S to 70°S, for the period 1 to 30 November 2007, indicated that AVHRR and AMSR-E SSTfnd were generally biased warm by 0.1 to 0.3 °C (Table 6(b)) while over the region 60°E to 170°W, 20°S to 40°S, the same satellite SSTfnd data streams were within ±0.1 °C of the buoy SSTfnd observations (Table 6(a)). South of 40°S, the mean difference between RAMSSA and the other IR+MW analyses (ODYSSEA, RSS, OSTIA and NCDC) for the period 1 October 2007 to 31 March 2008 was much higher (0.09 to 0.25 °C, Table 7(b)) than over the RAMSSA domain north of 40°S (–0.07 to 0.06 °C, Table 7(a)). It would appear therefore from Tables 6 and 7 that much of the warm bias between RAMSSA and other analyses over the Southern Ocean might be mitigated by using input satellite data streams which use regional calibrations and contain bias estimates per pixel based on regional *in situ* observations rather than global, removing the need for analysis systems to perform their own bias-correction of satellite data. In order to achieve this, the spatial coverage and quality of *in situ* SST observations over the Southern Ocean needs to be improved as there are insufficient buoy SST observations south of 50°S to perform as accurate calibration and bias-correction of satellite data over this region compared with north of this latitude (e.g. Fig. 1(a); Zhang et al. 2009; George Paltoglou *pers. comm.*) In addition, one could use a physical retrieval method such as is applied to AATSR SST (Merchant and Le Borgne, 2004) to produce less regionally biased AVHRR SST products.

Table 5. RAMSSA v1.1 1/12° resolution SSTfnd analysis (for date t) minus Analysis SST (for date t) statistics for the region 60°E–180°E, 20°N–65°S, averaged over the period 1 October 2007–31 March 2008. <μ> is the average of all daily means of the differences and <σ> is the average of all daily standard deviations of the differences. <N> is the average number of daily match-ups. For comparison, the coarser resolution analyses have been linearly interpolated to the grid resolution of the higher resolution analysis.

SST Analysis	*RAMSSA (t) – SST Analysis (t)*		
	<μ> (°C)	<σ> (°C)	<N>
Bureau Regional 1/4° SSTblend	0.07	0.46	1241108
Ifremer ODYSSEA 1/10° SSTfnd	–0.02	0.40	1245342
RSS IR + MW ~1/11° SSTfnd	0.07	0.53	1250849
Met Office OSTIA 1/20° SSTfnd	0.10	0.35	3466228
NCDC AVHRR + AMSR-E 1/4° SSTblend	0.00	0.54	1260139

Table 6. Comparisons of SST measurements from each satellite SSTfnd data stream used in the RAMSSA analysis system with collocated buoy foundation SST measurements over the region (a) 60°E–170°W, 20°N–40°S, and (b) 60°E–170°W, 40°S–70°S, for the period 1–30 November 2007. Data are considered 'matched' if measured within same 24-hour period, centres of observations are separated by no more than half the RAMSSA resolution (i.e. 1/24°), and satellite SSTfnd values are within 3 °C of buoy observations. Each set of columns give statistics (mean, standard deviation and total number of match-ups).

Satellite Data Stream	Satellite SSTfnd – Buoy SSTfnd			Satellite SSTfnd – Buoy SSTfnd		
	μ (°C)	σ (°C)	N	μ (°C)	σ (°C)	N
	(a) 20°N to 40°S			(a) 40°S to 70°S		
AATSR 1/6º Meteo Product	-0.04	0.40	1311	-0.02	0.33	522
HRPT 6 km x 9 km NOAA-17 AVHRR	-0.05	0.54	3287	0.14	0.54	1913
GAC 9 km x 4 km NOAA-17 AVHRR	0.05	0.56	596	-0.01	0.37	141
HRPT 6 km x 9 km NOAA-18 AVHRR	0.11	0.52	5461	0.34	0.42	3732
GAC 9 km x 4 km NOAA-18 AVHRR	0.12	0.49	668	0.33	0.50	230
GAC 9 km x 4 km METOP-A AVHRR	0.02	0.43	504	0.08	0.36	210
25 km AMSR-E L2P	0.14	0.50	136384	0.25	0.59	84306

Table 7. RAMSSA v1.1 1/12° resolution SSTfnd analysis (for date t) minus Analysis SST (for date t) statistics for the region (a) 60°E–180°E, 20°N–40°S, and (b) 60°E–180°E, 40°S–65°S, averaged over the period 1 October 2007–31 March 2008. <μ> is the average of all daily means of the differences and <σ> is the average of all daily standard deviations of the differences. <N> is the average number of daily match-ups. For comparison, the coarser resolution analyses have been linearly interpolated to the grid resolution of the higher resolution analysis.

SST Analysis	RAMSSA (t) – SST Analysis (t)			RAMSSA (t) – SST Analysis (t)		
	<μ> (°C)	<σ> (°C)	<N>	<μ> (°C)	<σ> (°C)	<N>
	(a) 20°N to 40°S			(b) 40°S to 65°S		
Bureau Regional 1/4° SSTblend	0.06	0.47	839079	0.08	0.44	405574
Ifremer ODYSSEA 1/10° SSTfnd	–0.07	0.35	844692	0.09	0.45	400048
RSS IR + MW ~1/11° SSTfnd	0.06	0.52	841102	0.16	0.56	404842
Met Office OSTIA 1/20° SSTfnd	0.03	0.32	2366684	0.24	0.34	1101011
NCDC AVHRR+AMSR-E 1/4° SSTblend	–0.07	0.51	852508	0.25	0.55	408888

Fig. 4. An example of the (a) RAMSSA v1.1 daily, 1/12° resolution, SSTfnd analysis, (b) Ifremer ODYSSEA daily, 1/10° resolution, SSTfnd analysis, (c) RSS daily, ~1/11° resolution, IR + MW SSTfnd analysis, (d) Met Office Operational SST and Sea Ice Analysis (OSTIA) daily, 1/20° resolution, SSTfnd analysis, (e) NCDC Reynolds et al. (2007) daily, 1/4° resolution, AVHRR + AMSR-E SSTblend analysis, and (f) CSIRO 3 Day Composite 1/25° resolution AVHRR SSTblend product for 20 November 2007 over the oceans south-east of Australia (148°E to 170°E, 26°S to 40°S), showing the East Australian Current under mainly cloud-free conditions. Note that the CSIRO product shown here is a composite of HRPT AVHRR SST data from 18 to 20 November 2007.

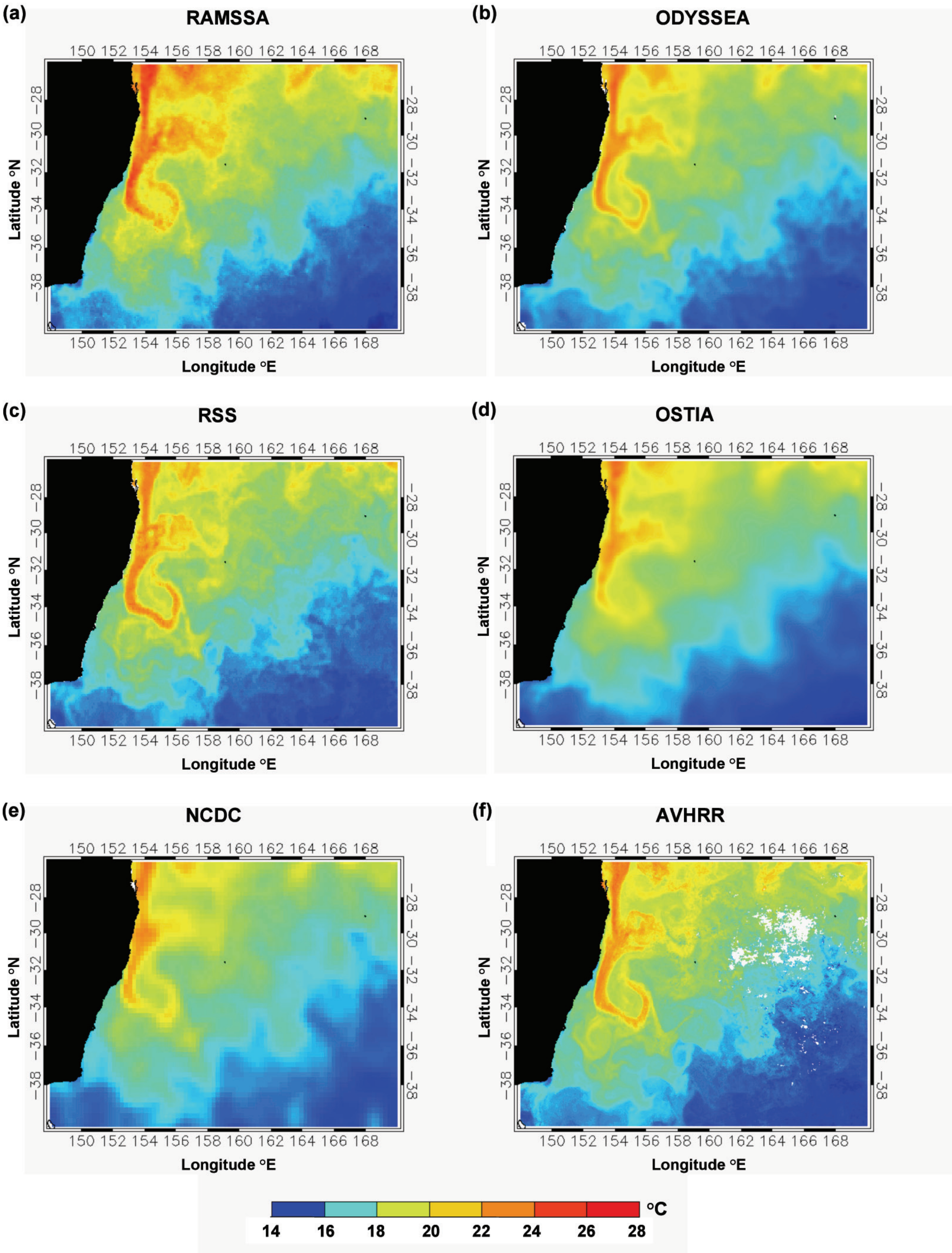


Fig. 5. Single day SST gradient magnitudes for the same analyses and composite AVHRR product shown in Fig. 4, for the same area and date.

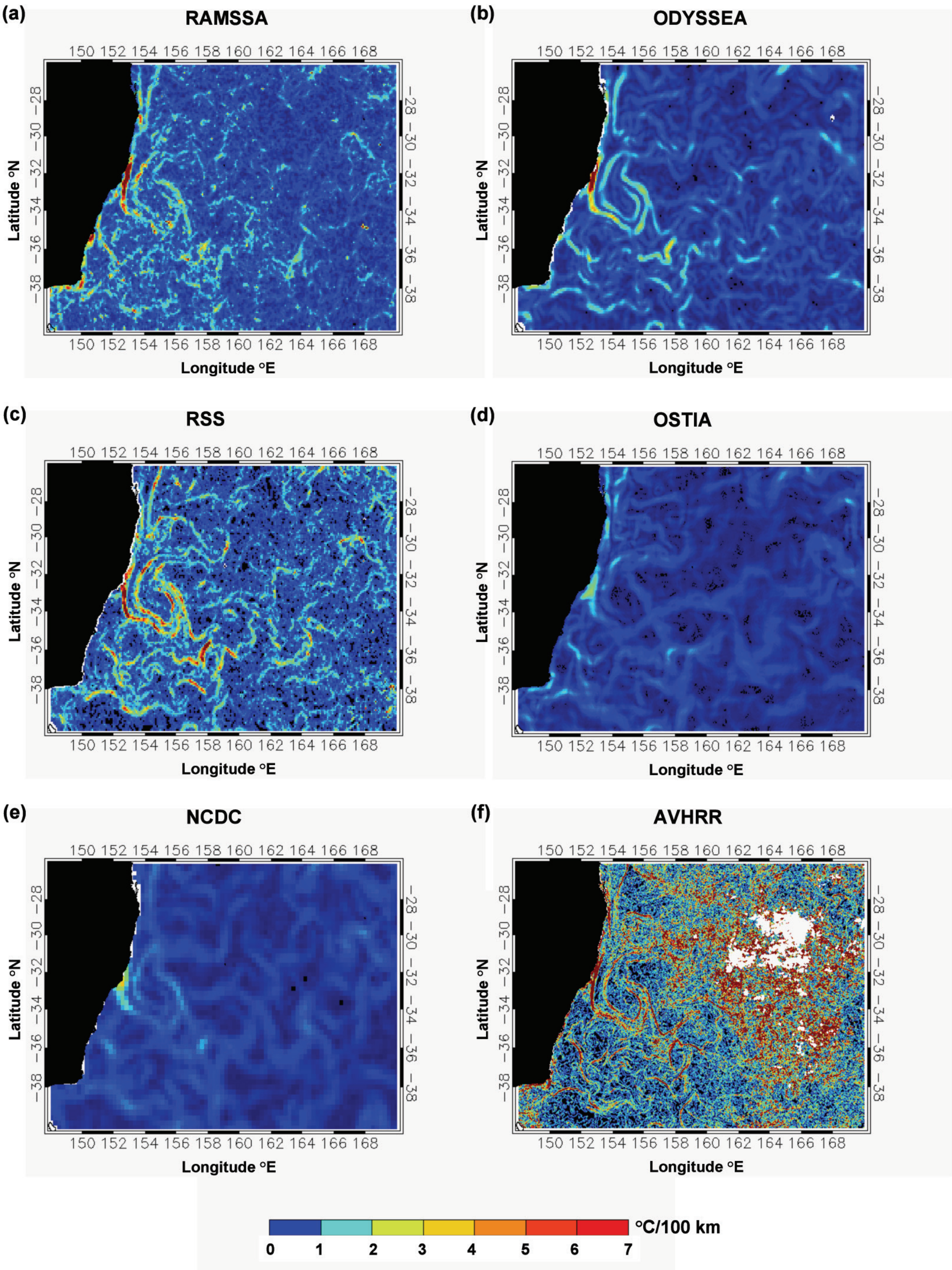


Fig. 6. SST analyses and AVHRR composite SST product for 3 November 2007 following a period during which much of the East Australian Current was obscured by cloud for at least three days; otherwise as in Fig. 4.

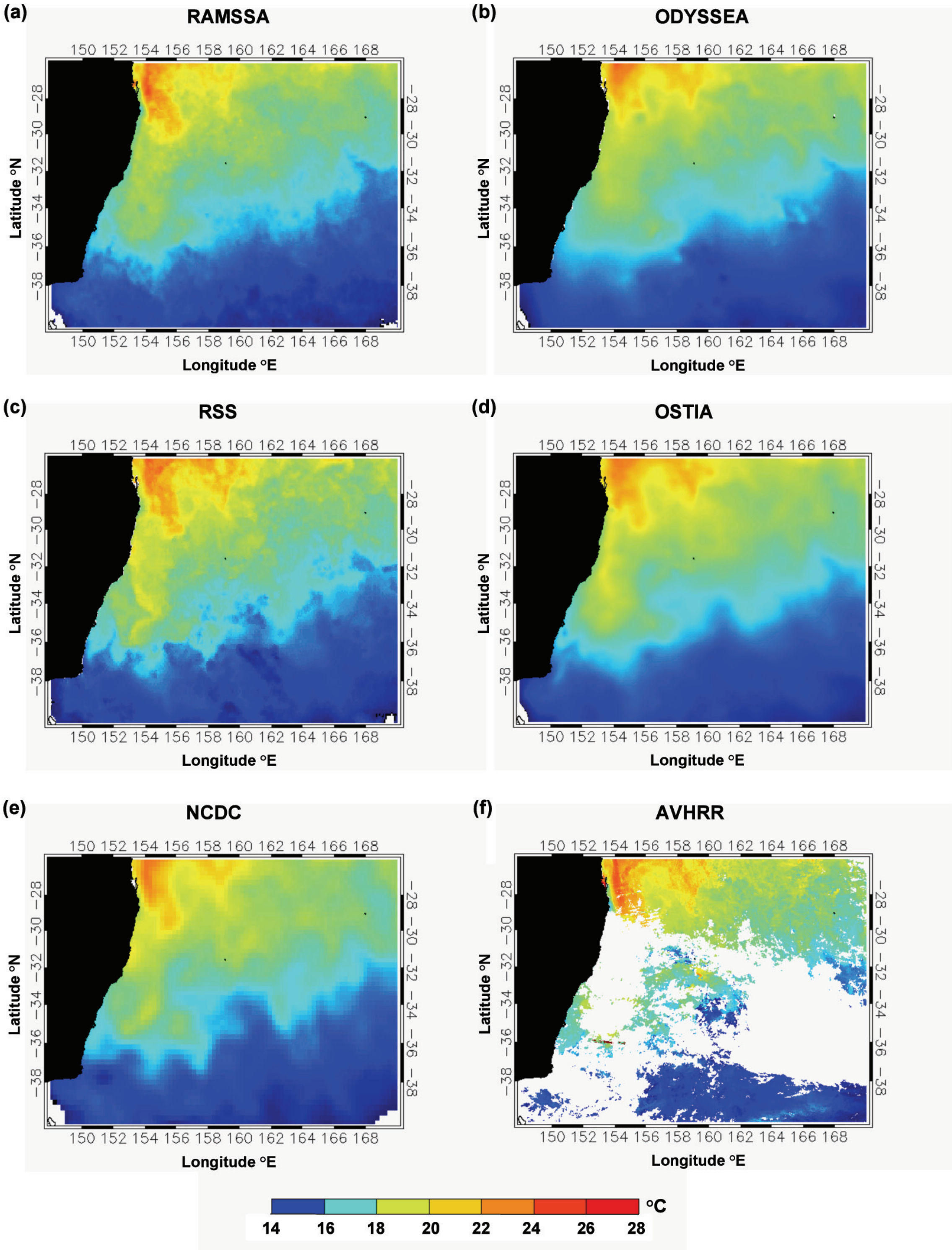


Fig. 7. Single day SST gradient magnitudes for the same analyses and composite AVHRR product shown in Fig. 6, for the same area and date.

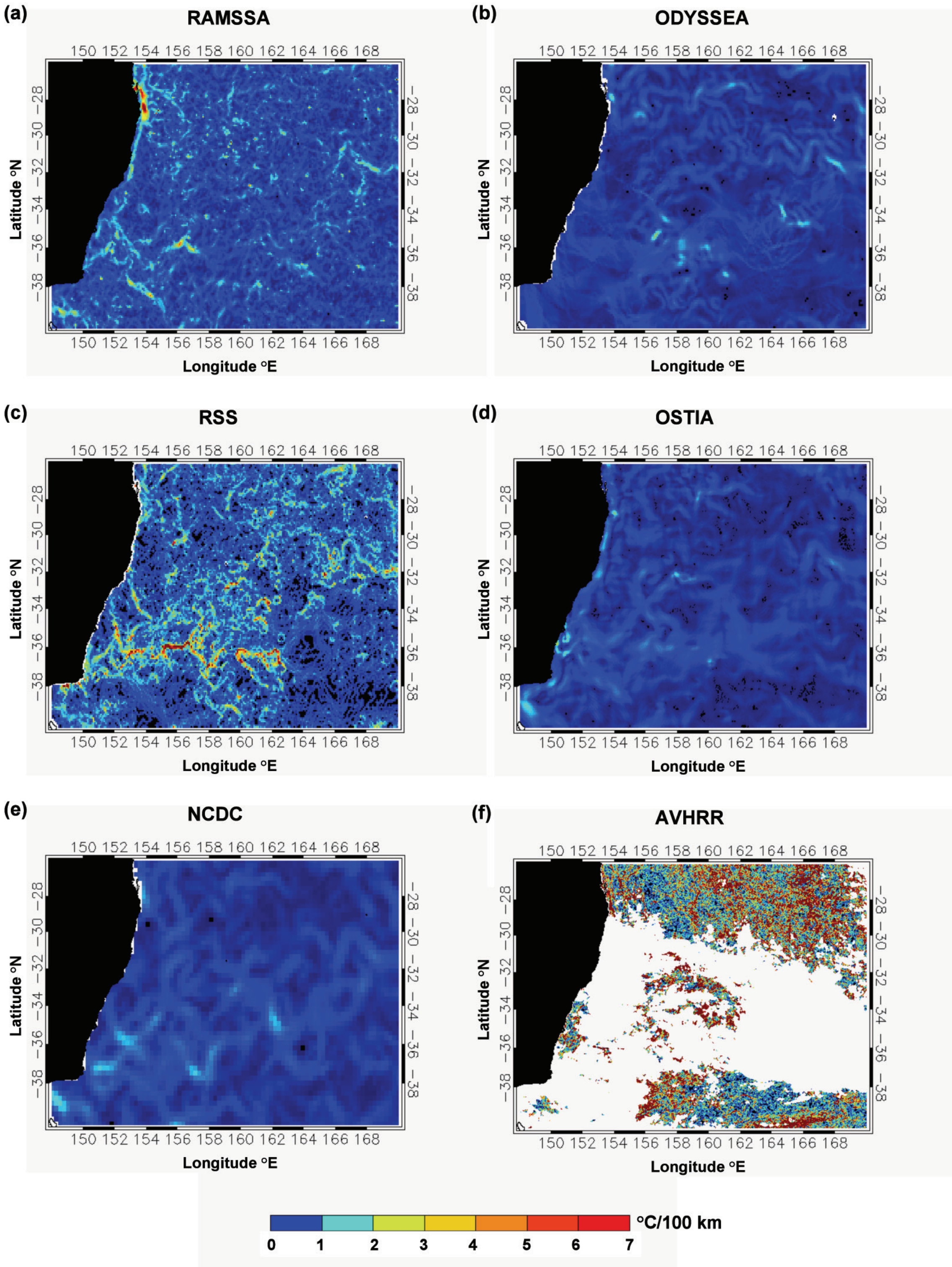


Fig. 8. The mean of the daily RAMSSA v1.1 SSTfnd analysis minus the (a) Bureau daily regional legacy operational, 1/4° resolution, SSTblend analysis, (b) Ifremer ODYSSEA daily, 1/10° resolution, SSTfnd analysis, (c) RSS daily, ~1/11° resolution, IR + MW SSTfnd analysis, (d) Met Office Operational SST and Sea Ice Analysis (OSTIA) daily, 1/20° resolution, SSTfnd analysis, and (e) NCDC Reynolds et al. (2007) daily, 1/4° resolution, AVHRR + AMSR-E SSTblend analysis for the period 1–30 November 2007 over the region 60°E–180°E, 20°N–65°S. For comparison, the coarser resolution products have been linearly interpolated to the grid resolution of the higher resolution products.

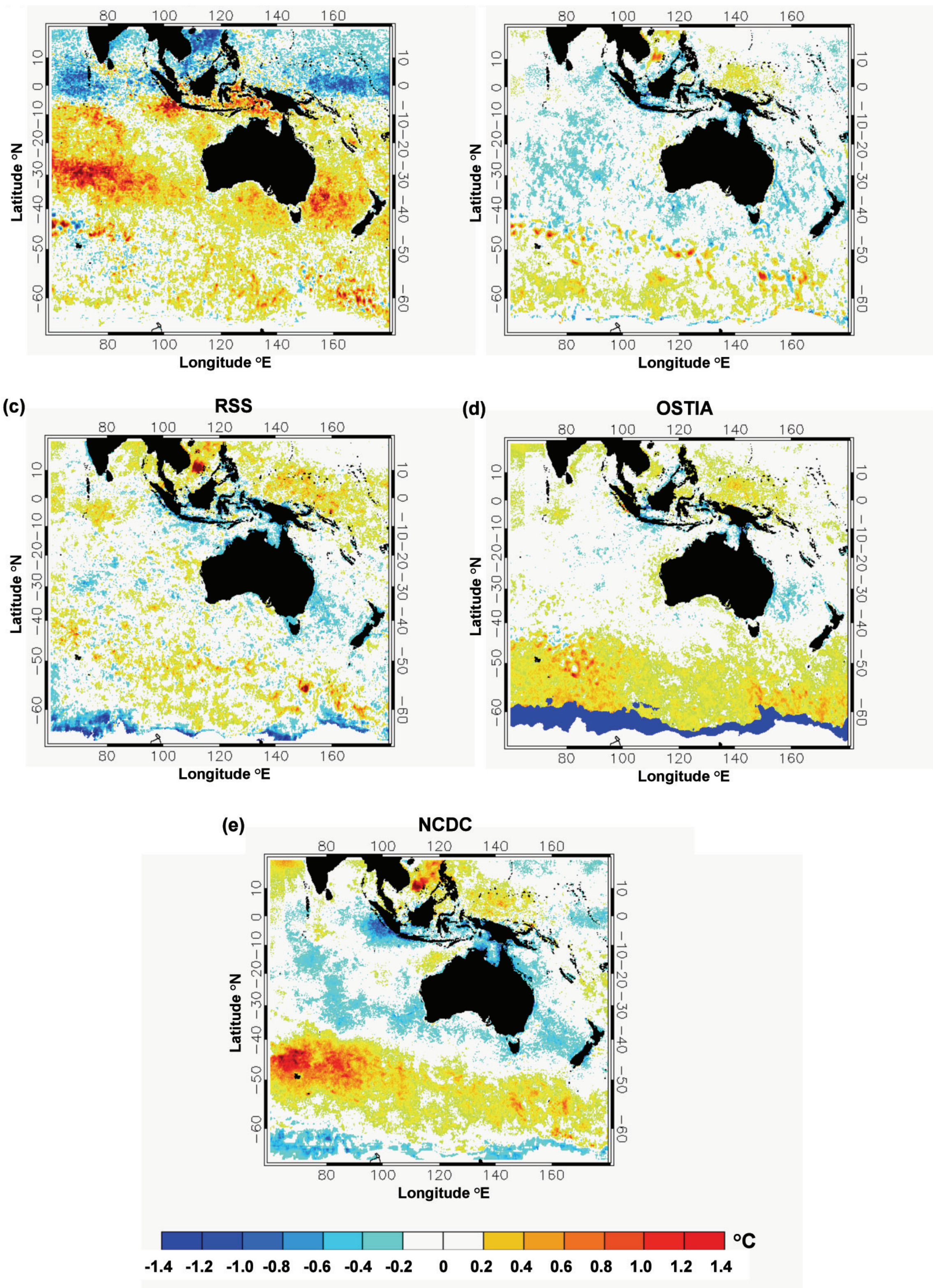
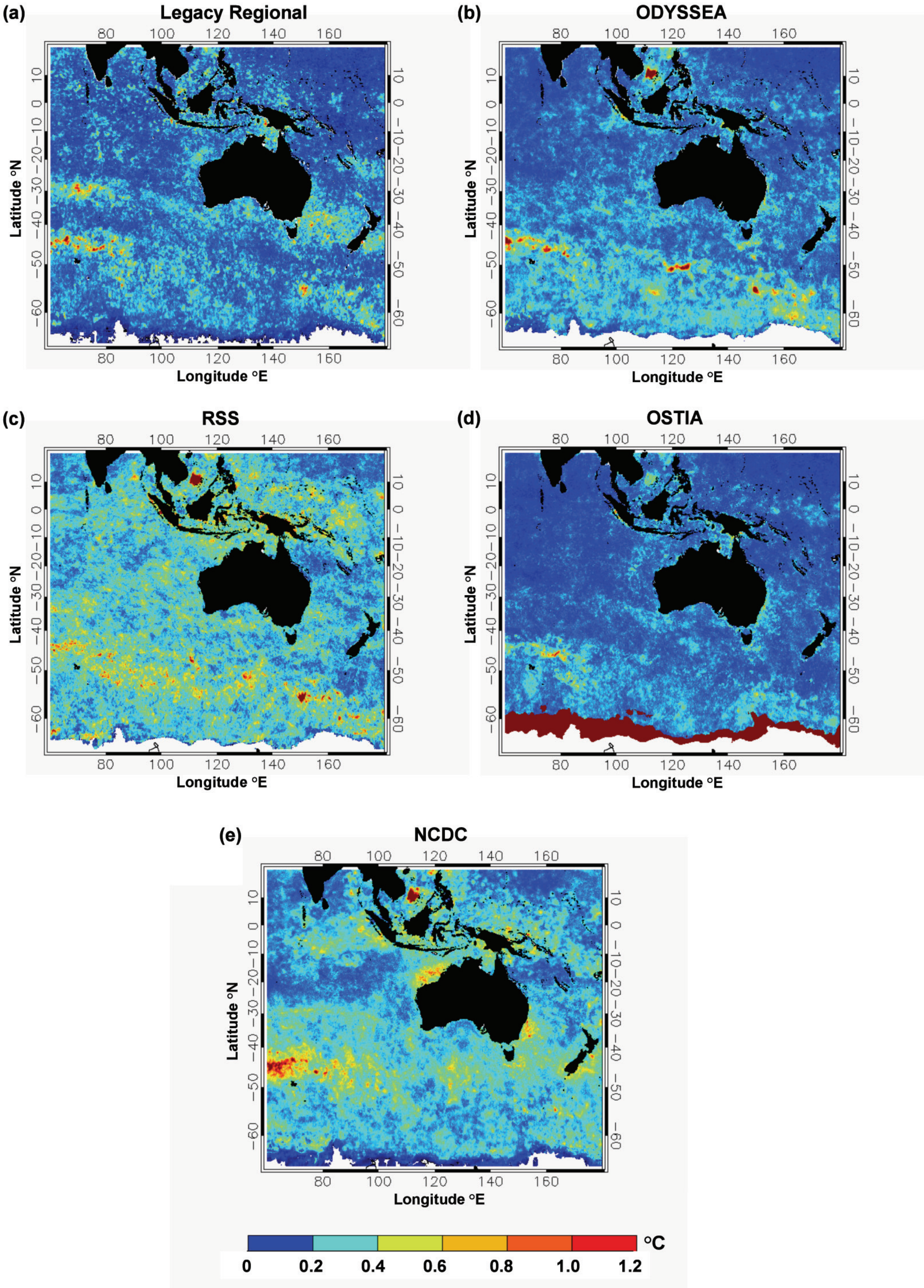


Fig. 9. The standard deviation of the daily RAMSSA SSTfnd analysis minus each of the other daily SST analyses; otherwise as in Fig. 8.



Further work

Future work on the RAMSSA system will include investigating the blending of additional satellite SST L2P files available through GHRSST (especially 1 km ATS_NR__2P AATSR SSTskin). The AMSR-E SSTsubskin L2P files are already used in the RAMSSA v1.1 analysis and since 10 June 2008 GAC AVHRR SSTblend L2P files from NAVOCEANO have replaced the NESDIS GAC AVHRR SSTblend files. The NAVOCEANO GAC AVHRR data is not sub-sampled during processing, unlike the NESDIS operational GAC product over the Australian region (Fig. 1(c)). L2P files contain estimates of bias and standard deviation error obtained using near real-time match-ups with *in situ* SST measurements, along with confidence flags and auxiliary data, which are useful for correcting for bias, assigning weights to the individual observations and correcting for diurnal warming. As part of an upgrade to using only L2P-format products in RAMSSA, supported by the IMOS and BLUElink Projects, the Bureau now produces real-time, 1 km resolution, HRPT AVHRR SSTskin L2P files (Paltoglou et al. 2010) and ~4 km resolution, hourly, geostationary satellite MTSAT-1R (replaced on 1 July 2010 by MTSAT-2) SSTskin L2P files (Beggs et al. 2010). The HRPT AVHRR L2P SSTskin retrievals are produced using regional buoy SST data for calibration using the non-linear regression method based on Walton et al. (1998), whereas the MTSAT-1R/2 SSTskin retrievals use a physical retrieval method based on Merchant and Le Borgne (2004) and implemented by Andy Harris and Jon Mittaz (NOAA Cooperative Institute for Climate and Satellites). Ingesting HRPT AVHRR and MTSAT-2 L2P SSTskin files into RAMSSA may reduce spatial differences between RAMSSA and ODYSSEA, RSS, OSTIA and NCDC SST analyses and their impact will be assessed in a future study.

Other improvements to RAMSSA will include the incorporation of new, high-quality, SST observations from ships of opportunity over the Australian region and Southern Ocean (Beggs et al. 2009; Beggs et al. 2010), available from the IMOS Project, for validation of the satellite SST data streams and analyses. Bias correction of RAMSSA's satellite SST inputs using OI analyses of *in situ* SST only or *in situ* and AATSR SST observations will also be investigated.

Conclusions

A method for blending SST data from different satellite sensors, with the aim to produce more accurate and higher spatial resolution analyses of SST over the Australian region, has been presented. The RAMSSA v1.1 analysis system became operational on 26 October 2007 as part of the Bureau's NWP suite. The regional foundation SST analyses are output in the internationally recognized netCDF L4 format (Donlon et al. 2005) as specified by the Global Ocean Data Assimilation Experiment High Resolution SST Pilot Project, now Group for High Resolution SST (GHRSST). These analysis files are provided in real-time to GHRSST and disseminated with other high-resolution SST analysis products via http://ghrsst.jpl.nasa.gov/. The RAMSSA L4 files with additional 'experimental fields', documented in Beggs and Pugh (2009), can be obtained in real-time for research purposes from http://godae.bom.gov.au/. Maps of the SST analyses are available from http://www.bom.gov.au/oceanography/oceantemp/sst.shtml. The most recent RAMSSA analyses are used as the boundary condition for the Bureau's operational regional NWP models (LAPS, ACCESS-R, ACCESS-A and ACCESS-City) and used to validate the Bureau's operational OceanMAPS[24] (Brassington et al. 2007) SST5m analyses.

After witholding all *in situ* data from the reanalyses, the test RAMSSA v1.1 SSTfnd analyses were 0.03 ± 0.46 °C warmer than buoy SSTfnd measurements during the period 1–30 November 2006. Removing daytime observations for winds < 6 m/s and night-time observations for winds < 2 m/s from an OI SST analysis of satellite data only reduced the mean difference between the analysis and collocated, filtered buoy SST observations by approximately 0.05 °C but increased the standard deviation by approximately 0.02 °C (Table 2). This result conflicts with the observed generally significant reduction in standard deviation of the individual satellite SST data streams compared with buoys over the same region and period when the data were filtered in a similar fashion for day/night and surface winds. The discrepancy may be due to filtering of satellite observations resulting in removal of all observations within particular RAMSSA grid cells and the RAMSSA SSTfnd in that grid cell reverting to the background field. The observation-free RAMSSA SSTfnd values would generally exhibit higher relative errors when compared with actual buoy observations. Regions of consistently low winds, such as the Tropics, would be particularly affected. A solution would be to implement a computationally fast diurnal variation model to convert skin and sub-skin SST observations to foundation SST estimates rather than removing SST observations in regions experiencing low wind speeds. Different methods for converting from skin and sub-skin satellite SST observations to foundation SST are being investigated in collaboration with the GHRSST Diurnal Variation Working Group[25].

The new regional, daily, 1/12° resolution, foundation SST analyses (RAMSSA) exhibited significantly less bias and RMS error than the Bureau's legacy regional, daily, 1/4° resolution, SST analyses, when compared with independent buoy SST measurements from the following day (0.03 ± 0.42 °C compared with –0.06 ± 0.55 °C for 1 October 2007 to 31 March 2008). The RAMSSA analyses were also compared with the latest high-resolution multi-sensor SST analyses from Ifremer, Remote Sensing Systems, UK Met Office and NCDC for the same period. In the region 60°E to 180°E, 20°N to 70°S, there was closer agreement with

[24]Ocean Model, Analysis and Prediction System

[25]http://www.ghrsst.org/GHRSST-PP-Diurnal-Variability-Working-Group-(DV-WG).html

Ifremer's ODYSSEA and the Met Office OSTIA SSTfnd analyses (which employ a similar method to RAMSSA to filter observations to a foundation SST estimate) than with the RSS AMSR-E+TMI+MODIS foundation SST and NCDC Reynolds AVHRR+AMSR-E blended SST analyses. Of the six SST analyses studied, RAMSSA SSTfnd and OSTIA SSTfnd compared most closely with independent, next day, buoy SSTfnd observations over the period 1 October 2007 to 31 March 2008 (0.03 ± 0.42 °C and -0.05 ± 0.39 °C, respectively). However, over small spatial scales for the period 1–30 November 2007 all these daily, multi-sensor SST analyses exhibited mean temperature differences with respect to RAMSSA in excess of 1 °C with standard deviations above 1 °C. The ODYSSEA, RSS, OSTIA and NCDC analysis systems use different methods to the Bureau to correct for biases, produce super-observations and assign estimated errors (weights) to the input SST data prior to OI analysis. These differences in analysis systems combined with prolonged cloud cover over some areas, differing sea-ice inputs and regional biases in the AVHRR and AMSR-E data used for the analyses may be the cause of the spatial differences, particularly over the Southern Ocean.

Further work needs to be done on the RAMSSA system to improve the bias correction and/or calibration of all input data streams to meet WMO goals for SST accuracy of 0.3 °C (bias + RMS error) for NWP models (Eyre et al. 2009), particularly south of 40°S where RAMSSA was on average 0.09 °C to 0.25 °C warmer than ODYSSEA, RSS, OSTIA and NCDC analyses during the period 1 October 2007 to 31 March 2008. North of 40°S, RAMSSA was relatively unbiased compared with the other multi-sensor SST analyses studied, being within ±0.07 °C. The incorporation of new *in situ* and satellite SST L2P data streams from the Integrated Marine Observing System combined with improved regional calibration of global AVHRR and AMSR-E SST data streams may assist in the reduction of biases and RMS error in RAMSSA analyses.

Acknowledgments

This research was supported by the BLUElink Ocean Forecasting Australia Project (comprising contributions from the Australian Bureau of Meteorology, CSIRO Marine and Atmospheric Research and the Royal Australian Navy). The authors would like to thank the GHRSST Science Team for their advice and Gary Corlett (University of Leicester) for estimates of AATSR SST errors over the Australian region. The authors would also like to thank Neville Smith (Bureau of Meteorology) and Ian Barton (CSIRO Marine and Atmospheric Research) for helpful discussions on the research for this paper, and Isabel Andreu-Burillo (Bureau of Meteorology), Peter Turner (CSIRO Marine and Atmospheric Research) and the external reviewers for helpful feedback on the manuscript. The AMSR-E L2P data (obtained from ftp://ssmi.com/sst/misst/amsre/swath/nc/) are produced by Remote Sensing Systems and sponsored by the NASA Earth Science REASoN DISCOVER Project, the AMSR-E Science Team, the National Oceanographic Partnership Program (NOPP), and the NASA Earth Science Physical Oceanography Program. The European Space Agency kindly supplied the AATSR Meteo product (ATS_MET_2P) files and NESDIS supplied the operational GAC AVHRR data for this study. CSIRO Marine and Atmospheric Research supplied the Composite AVHRR SST Product and Remote Sensing Systems supplied the RSS IR + MW SST analysis files (ftp://ftp.discover_earth.org/sst/daily/mw_ir). The ODYSSEA SST analysis files were developed by the Centre de Recherche et d'Exploitation Satellitaire (CERSAT), at Ifremer, Plouzané (France). They are produced in the frame of GMES Mersea and MyOcean projects (http://cersat.ifremer.fr/data/discovery/by_parameter/sea_surface_temperature/odyssea_global_sst_analysis). The NCDC Reynolds AVHRR+AMSR-E, UK Met Office OSTIA and Ifremer ODYSSEA SST analysis files used in this study were obtained as GHRSST L4 format files from the GHRSST Global Data Assembly Centre hosted by NASA JPL's PO.DAAC via http://ghrsst.jpl.nasa.gov/.

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Web Sites

Australian Bureau of Meteorology GODAE Products Web Page (including SST): http://godae.bom.gov.au/

Australian Bureau of Meteorology Operational SST Analysis Web Page: http://www.bom.gov.au/oceanography/oceantemp/sst.shtml

BLUElink Ocean Forecasting Australia Project Web Site: http://www.bom.gov.au/bluelink/

CSIRO Marine and Atmospheric Research Ocean Current and SST web page: http://www.marine.csiro.au/remotesensing/oceancurrents/

Group for High-Resolution Sea Surface Temperature (GHRSST) Web Site: http://www.ghrsst.org/

GHRSST Global Data Assembly Centre Web Site: http://ghrsst.jpl.nasa.gov/

GHRSST Long Term Stewardship and Reanalysis Facility: http://www.nodc.noaa.gov/SatelliteData/ghrsst/

Met Office OSTIA 1/20° Daily SST Analysis web page: http://ghrsst-pp.metoffice.com/pages/latest_analysis/ostia.html

NCDC Optimal Interpolation 1/4° Daily SST Analysis web page: http://www.ncdc.noaa.gov/oa/climate/research/sst/oi-daily.php

ODYSSEA SST analysis web page:http://cersat.ifremer.fr/data/discovery/by_parameter/sea_surface_temperature/odyssea_global_sst_analysis

Remote Sensing Systems OI SST analysis web page:http://www.remss.com/sst/microwave_oi_sst_browse.html

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