Analysis and Prediction Operations Bulletin No. 77

Operational Implementation of Global Australian Multi-Sensor Sea Surface Temperature Analysis
2 October 2008

1. Introduction

Global weekly 1^o spatial resolution optimum interpolation sea surface temperature (SST) analyses have been produced at the National Meteorological and Oceanographic Centre (NMOC) since 1994, developed jointly by Dr Neville Smith (BMRC) and Graham Warren (NMOC). Sea surface temperature analyses are widely used as a surface boundary condition for numerical weather prediction models (NWP), such as Global Assimilation Prediction Model (GASP), and other atmospheric model simulations. In addition, accurate estimation of current and historical global sea surface temperature provides the National Climate Centre (NCC) with crucial information on oceanic conditions for climate monitoring and prediction, e.g. ENSO prediction, seasonal outlooks and climate change. Therefore, this so-called "climate-scale" analysis, which is defined here as spatial scales of 1^o and temporal scales of one week, will continue to be produced and maintained by NMOC, in particular to support the Bureau's ongoing climate services.

A new high resolution Global Australian Multi-Sensor Sea Surface Temperature Analysis (GAMSSA) has been developed by Helen Beggs in the Centre for Australian Weather and Climate Research (CAWCR), as part of the BLUElink> Ocean Forecasting Australia project, primarily aimed at improving the spatial and temporal resolution of the current operational global weekly SST analysis for input to the Bureau's seasonal and global NWP models. This GAMSSA system is based on the operational, daily, 1/12° resolution, Regional Australian Multi-Sensor Sea Surface Temperature Analysis (RAMSSA) system (Beggs, 2007). The new global SST analysis system uses satellite data sets additional to those used for the global weekly 1° analysis to produce a global, daily, 1/4° resolution, "foundation" SST that is largely free of any diurnal variations (e.g. daytime warming or nocturnal cooling) (Beggs et al. 2006; Beggs, 2007). This new higher-resolution analysis is designed to better resolve the location of isotherms and ocean eddies than the global weekly 1° analysis.

The new global, daily SST analysis system was introduced to NMOC as a parallel operational trial on 19 May 2008. Since then, this analysis system has been tested and input into the Australian Community Climate Earth System Simulator (ACCESS) global numerical weather prediction model, originally developed by the United Kingdom Met Office (UKMO). The importance of making this new daily SST analysis operational in NMOC is demonstrated in the ACCESS global NWP model requirement for high resolution space-time scales SST forcing. The new ACCESS global unified model/variational assimilation system is scheduled to replace the current GASP, which currently uses more than one week old SST data, as the Bureau's NWP forecast system during 2009.

This bulletin describes the new GAMSSA SST analysis system, discusses the system outputs and presents an inter-comparision of GAMSSA with other data products including the current weekly SST analysis. Comparisons of analysed SST with independent buoy foundation SSTs for the period 20 May to 31 August 2008 have indicated that the new analysis system has a lower bias and standard deviation than the existing weekly SST analysis. The new daily GAMSSA foundation SST analyses were compared with the latest high-resolution, multi-sensor SST analyses from the UK Met Office (UKMO) and NOAA for the period 20 May to 31 August 2008. Results showed that this new analysis is closer to the UKMO OSTIA analyses than the NOAA Reynolds product. Similar results were obtained for the period 7 January to 31 March 2008 for the test GAMSSA system and have been reported in Beggs (2008).

2. Input Data Sources and Blending Method

The existing weekly SST analysis uses the in situ "bulk" SST measurements (roughly 0.5 m to 5 m in depth) from drifting and moored buoys, ships, Argo floats and Conductivity Temperature Depth profiles (CTDs) obtained from the Global Telecommunications System (GTS), and the satellite data taken by the Advanced Very High Resolution Radiometer (AVHRR) instrument carried on the US polar orbiting NOAA series of satellites (NMOC Operations Bulletin, No. 25). The new GAMSSA system uses the same in situ data plotted as in Figure 1(a) for one day coverage. These in situ data are then blended with satellite measurements from the Naval Oceanographic Office (NAVOCEANO) Global Area Coverage (GAC) AVHRR data from polar-orbiting satellites NOAA-17, NOAA-18 and METOP-A operated by the European Organisation for the Exploitation of Meteorological Satellites (Figure 1(b)). The horizontal resolution of the NAVOCEANO GAC AVHRR data is 9.9km by 4.4km. The AVHRR, being an infrared sensor, is unable to accurately measure SST in cloudy regions, which leads to sparse coverage particularly over the South East Asia during its active and wet monsoon season in June-August (Figure 1(b)).

In order to improve the spatial data coverage, particularly in cloudy regions, data products from two additional satellites sensors are included in this new system. They are the 25 km resolution, microwave AMSR-E SST from the Aqua polar-orbiting satellite (Figure 1(c)), which is largely unaffected by cloud but can be contaminated by precipitation, and the 1/6° resolution, Advanced Along Track Scanning Radiometer (AATSR) "Meteo Product" SST from the EnviSat polar orbiting satellite (Figure 1(d)), which has a narrow swath path, but is more accurate than the AVHRR or AMSR-E (Beggs, 2007). After applying bias corrections related to buoy observations to AATSR, AVHRR and AMSR-E data, the GAMSSA system applies a cool skin correction to the AASTR data since the AATSR measures true skin temperature. The method of removing the cool skin effect on AATSR SSTs during day and/or night is based on Donlon et al (2002). Wind data currently used is derived from the Bureau's Global Assimilation Prediction System (GASP) forecasts (0.75^{o} horizontal resolution, 3 hourly).

In order to homogenise the different measurements, it is essential to convert all satellite and in situ bulk SST data to foundation temperature estimates by removing suspected diurnal warming events using the empirical temperature difference to wind speed relationships reported in Donlon et al. (2002). SST observations are rejected at the locations where the surface wind speeds are below 6 m/s during the day and less than 2 m/s during the night.

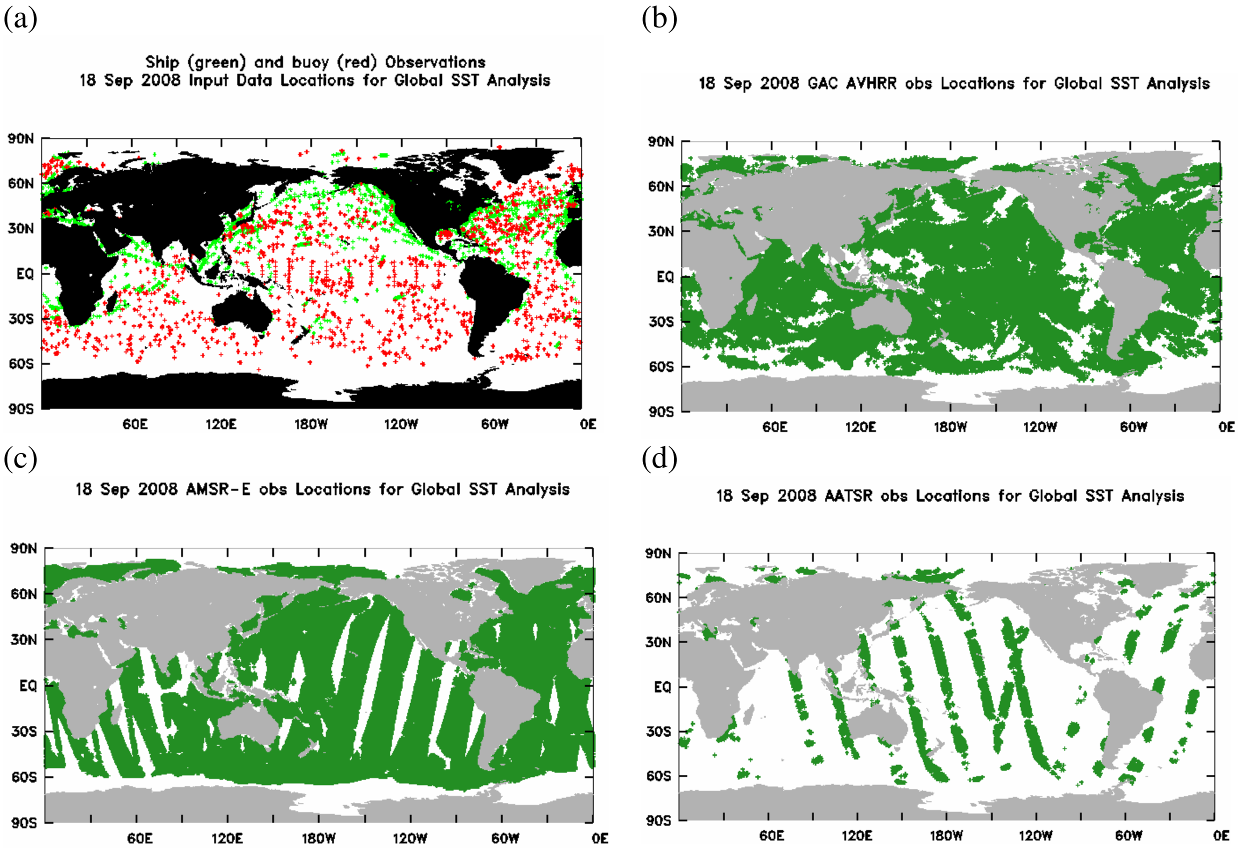

Figure1. Maps of the locations of observational data input into the GAMSSA system for 8 September, 2008: (a) ship (green) and buoy (red) data, (b) NAVOCEANO GAC AVHRR satellite data, (c) AMSR-E satellite data and (d) AATSR satellite data.

The principle of this statistical analysis method was described in the Operations Bulletin No. 68 in detail. To summarise the GAMSSA system, the background correlation length scale is set to 50km and observation correlation length scale is 20km and observation correlation time scale is 0.5 days for all input observations. The background field is a weighted combination of the previous day's analysis and the Reynolds climatology for the period of 1961-1990 (Reynolds and Smith, 1994). Satellite derived 1/12° sea ice products from NCEP provide ice edge data to the analysis system which are used to control SSTs at high latitudes.

4. Assessment of System Performance

It is important that there is continuous and systematic evaluation of the performance of any analysis scheme. This new SST analysis has been running in parallel with the existing operational weekly SST analysis system since 19 May 2008. This provides a good opportunity to calculate verification statistics for the new system and to compare its performance against the weekly analysis as a benchmark.

a. Analysis Innovation Bias

One common approach is to use statistics on the difference between observed values and the first guess (*i.e.* the previous analysis), which gives an estimate of the analysis bias compared with independent observations and indicates how accurately the analysis represents the actual conditions. Figure 2(a) shows the monthly average of observations minus first guess (OmF) that is computed and averaged over the regional analysis domain (60°E to 170°W, 20°N to 70°S) for the period October 2006 to August 2008. The green line illustrates the OmF for the weekly SST analysis, the red line shows the OmF for the RAMSSA analysis and yellow line represents the OmF for the GAMSSA system. It is worth noting that GAMSSA analyses from the research version of the GAMSSA system are available from December 2007. Because this new system is based on RAMSSA, the authors include innovation statistics for RAMSSA inferring the likely performance of GAMSSA over the same regional domain for the past two years. Figure 2(a) shows that there is considerable month-to-month variation in the SST bias. In general, the large SST bias is most evident in the weekly SST analysis (average of 0.13°C over the period 1 October 2006 to 31 August 2008) than in the new GAMSSA (0.09°C) and RAMSSA system (0.05°C). For instance, during January 2008, there was a 0.2°C bias in the weekly SST analysis, indicating that the previous analysis provided a poor estimate for the rapid warming of the surface ocean during the Austral summer. Overall, the GAMSSA SST averaged globally is up to 0.1°C too cool during May to August 2008 compared with independent observations. In contrast, the weekly SST analysis is about 0.2 to 0.3°C less than observations for the same four month period (Helen Beggs, pers com.)

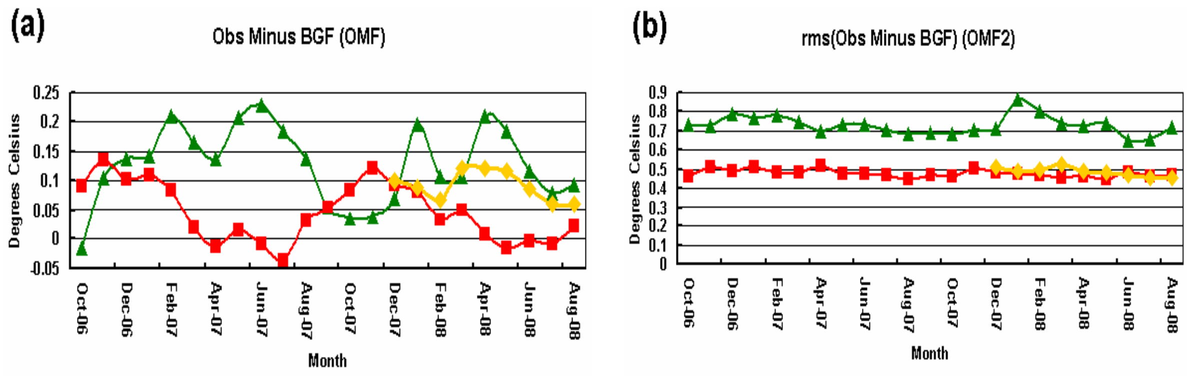

Figure 2. (a) The monthly mean SST observation minus first guess difference (OmF) averaged over 60°E to 170°W, 20°N to 70°S. (b) The root mean squared difference between the observed values and the first guess (rmsOmF). The red line represents RAMSSA, the dark green line the weekly SST analysis and the yellow line GAMSSA. Figures courtesy Helen Beggs.

b. Analysis Innovation RMS Error

Figure 2(b) represents the root mean square (rms) difference between the observed values and first guess (rms OmF), averaged over the regional analysis domain as above. There is small monthly variation and minimal seasonal variation in rms OMF in both the RAMSSA and GAMSSA analyses. Anomalously large errors in the first guess in January 2008 are evident in the weekly analysis system. The rms error plot shows that GAMSSA and RAMSSA are less noisy than the Bureau's current operational weekly SST analysis (shown in dark green) (as one would expect for a daily 1/4° compared to a weekly 1° analysis). The average of rms OmF for GAMSSA for the period of December 2007 to August 2008 is 0.5°C and is consistently well below the error in the weekly SST analysis with around 0.7°C. It is interesting to point out that the performance of the analysis 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 GAMSSA and RAMSSA, known biases with respect to buoys in the AMSR-E, GAC AVHRR and AATSR data have been removed and all observations filtered to remove data possibly affected by diurnal warming. Therefore it is not surprising to see that the errors in the weekly SST are relatively larger than the RAMSSA and GAMSSA. However, there is still scope for possible improvement to the methods used for bias correction and diurnal warming correction for any future upgrade to this analysis system.

c. *Intercomparison of SST analyses*

The GAMSSA system has been compared with other independent multi-sensor SST analyses such as the UKMO OSTIA daily SST analysis (Stark et al., 2007) and the NOAA Reynolds AMSR-E + AVHRR daily SST analysis (Reynolds et al. 2007). The OSTIA system uses data from a combination of infrared (AVHRR and AATSR) and microwave satellite sensors (AMSR-E and TMI) as well as in situ data from ships and drifting and moored buoys to produce a global, daily, 1/20° resolution, foundation SST, that is free of diurnal variation (Stark et al., 2007). This system is very similar to the GAMSSA and RAMSSA systems, except for the sea ice products used in OSTIA from EUMETSAT Ocean and Sea Ice Satellite Application Facility and the method for removing biases from the input satellite data. In OSTIA biases in the input data are removed by comparing against an optimum interpolation analysis of buoy and AATSR SST observations (Stark et al., 2007) whereas in GAMSSA satellite data is debiased by comparison to buoy data only. The NOAA global, daily, 1/4° resolution, blended SST analysis uses infrared satellite data from AVHRR and microwave data from AMSR-E only. This product uses the in situ data from ships and buoys and includes a large-scale adjustment of the satellite biases with respect to the in situ data. The spatial resolution of this analysis is the same as GAMSSA. However, the Reynolds analysis represents a "blended" SST as, unlike GAMSSA or OSTIA, input data is not filtered to remove observations affected by diurnal warming in order to produce a foundation SST.

The large-scale spatial differences between the global SST analyses for 28 August 2008 are illustrated in Figure 3 as an example. Analyses are interpolated to the minimum grid resolution before the inter-comparison. Figure 3(a) displays the difference between the GAMSSA and weekly SST analysis, Figure 3(b) the difference between the GAMSSA and OSTIA SST analysis and Figure 3(c) the difference between the GAMSSA and NOAA Reynolds SST analysis. The results show that the largest differences among the four analyses occur between 40°S to 60°S. This is a region of the ocean with poorest in situ data coverage, thus the true bias is not well known. Many of the other differences with respect to weekly SST are evident in the eastern equatorial Pacific region and the western boundary current regions (e.g. Gulf Stream and Kuroshio) due to the increased resolution and inclusion of satellite microwave data from AMSR-E in the new GAMSSA system (Figure 3(a)).

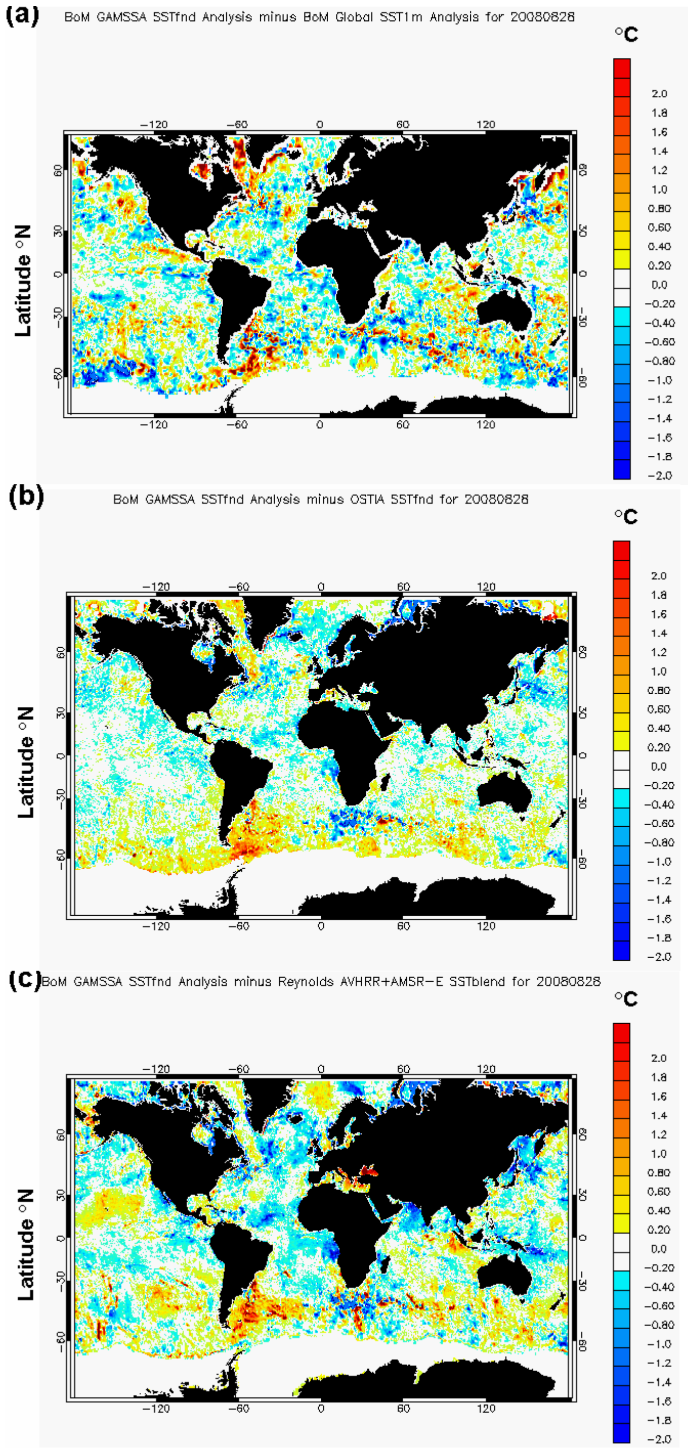

Figure 3. Analysis differences for 28 August 2008 between GAMSSA and (a) weekly SST analysis centred on 28 August 2008, (b) OSTIA foundation SST analysis, and (c) NOAA Reynolds blended SST analysis. Figures courtesty Helen Beggs.

The results from the comparisons with the two independent analyses suggest the GAMSSA is in better agreement with OSTIA than with NOAA Reynolds SST analyses, since although all three analyses use similar data inputs, GAMSSA and OSTIA use a similar method to remove diurnal warming events to produce foundation SST analyses. In contrast, the Reynolds analysis system produces “blended” SST that is similar to the Bureau’s weekly SST analysis, possibly explaining the relatively large differences between GAMSSA and Reynolds analyses, particularly over the tropical regions of the eastern and western Pacific, Atlantic and Indian Oceans.

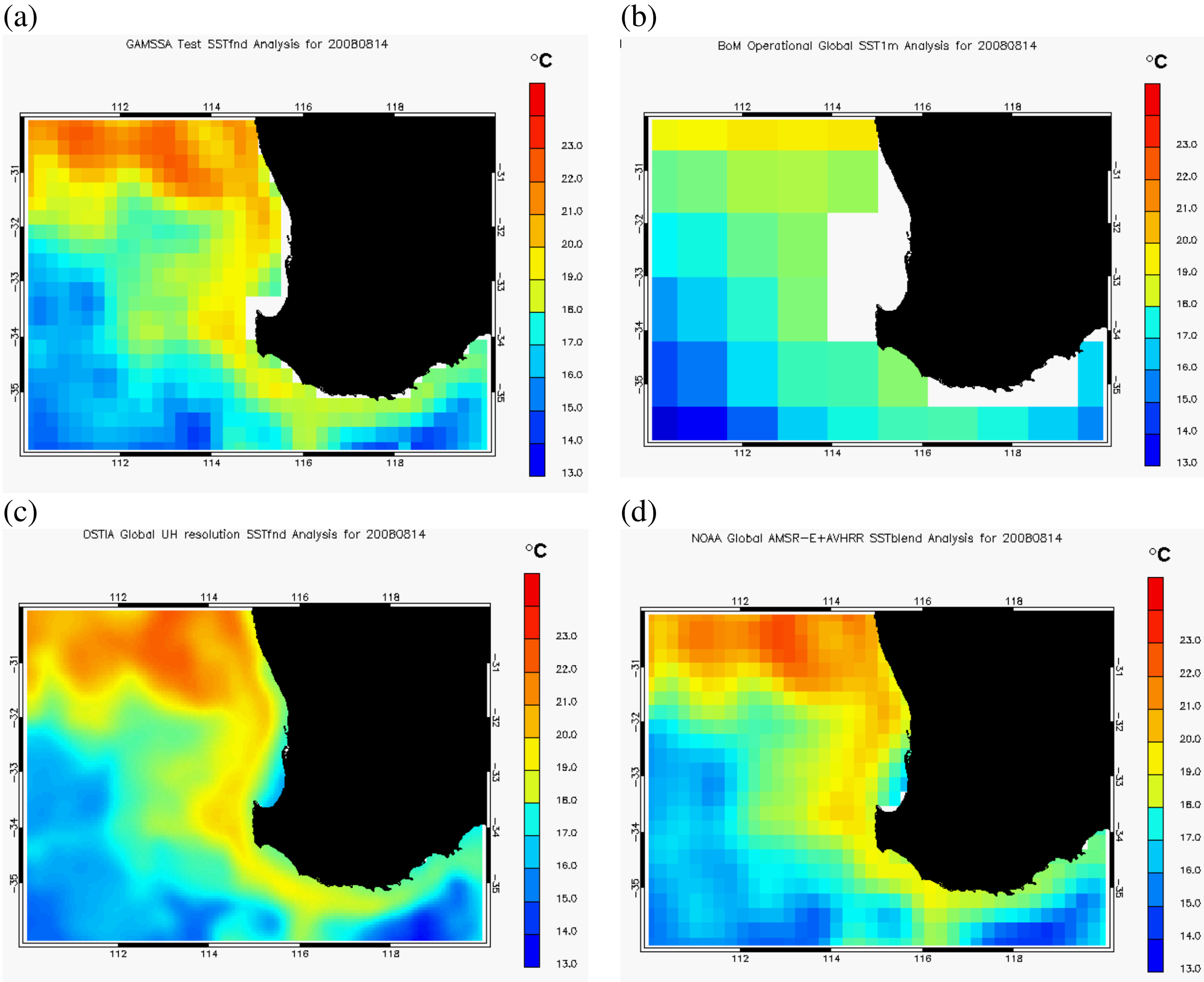

Figure 4. An example of the (a) GAMSSA foundation SST analysis, (b) weekly blended SST analysis (centred 14 August 2008), (c) the UKMO Operational SST and Sea Ice Analysis (OSTIA) daily 1/20° foundation SST analysis, and (d) NOAA Reynolds daily 1/4° SST blended analysis for 14 August 2008 over the region 110°E to 120°E, 30°S to 36°S. Figures courtesy Helen Beggs.

To illustrate the differences on a smaller scale, the new daily SST was compared with three analyses over the western coast of Australia in Figure 4. The top left panel (Figure 4a) is the daily SST (GAMSSA) for 14 August and the right panel (Figure 4b) is the weekly SST analysis centre on 14 August, the bottom two panels are from OSTIA (Figure 4c) and NOAA Reynolds SST (Figure 4d). As illustrated in Figure 4a, the warm southwards flowing Leeuwin Current along the western coast of Australia is clearly evident in GAMSSA analysis, OSTIA and NOAA Reynolds SST analysis, but is absent in the weekly SST analysis due to its relatively coarse resolution. The higher resolution and great density of observations used by GAMSSA significantly improves the representation of SST gradients along the western coast of Australia.

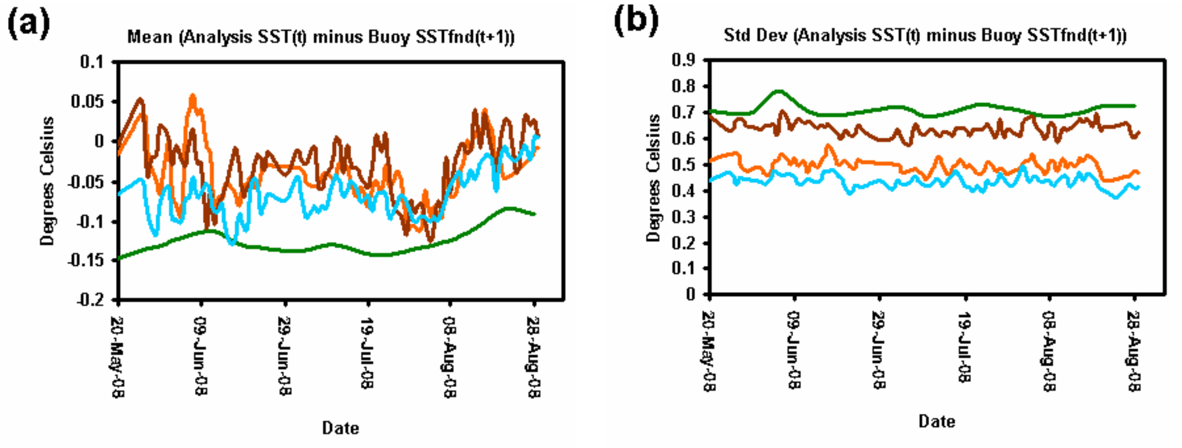

Figure 5. Global (a) mean and (b) standard deviation of the SST analysis differences with respect to the buoy foundation SST observations from the following day. GAMSSA is represented in orange, Weekly SST in green, OSTIA in blue and Reynolds in brown. The statistics for all the line plots have been calculated over the global domain. Figures courtesy Helen Beggs.

Finally, the four global SST analyses were compared against the independent buoy foundation SST observations from the following day. Figure 5 shows the global weekly SST analyses were 0.15 to 0.10°C cooler and with standard deviation error between 0.7 and 0.8°C compared with the independent buoy data during the period 20 May to 28 August 2008. Reynolds SST products show the second largest error compared with buoys with standard deviation of around 0.65°C. This is not surprising because both the Bureau's weekly and Reynolds daily SST analysis systems produce a "blended" SST at indeterminate depth, which may not compare well with buoy foundation SST. Over the same time period, both GAMSSA and OSTIA foundation SST analyses compared well with buoy foundation SSTs with mean differences of -0.04 ± 0.50°C and -0.07 ± 0.44°C, respectively.

5 Products

As with the current system, the following SST charts are delivered to the Bureau's external website daily which include the global SST analysis and daily SST anomaly:

http://www.bom.gov.au/oceanography/oceantemp/sst.shtml

6. Future Developments

Further enhancements envisaged to the operational SST analysis scheme include the development of methods to improve the bias correction and diurnal warming correction.

In addition of new satellite datasets are likely to further improvements. New satellite products will be added when the SST analyses show a significant improvement. Finally, an improved land mask will be tested and is expected to further enhance the resolution of coastlines.

Acknowledgements

The work of Helen Beggs (Ocean Prediction Group) is fully acknowledged. The helpful comments from Terry Skinner and Graham Warren are appreciated.

Please send your comments to Aihong Zhong (a.zhong@bom.gov.au)

6. References

Beggs, H., N. Smith, G. Warren and A. Zhong, 2006: A method for Blending High –Resolution SST over the Australian Region, *BMRC Research Letter* no. **5**, Bureau of Meteorology Research Centre, 7-11.
http://www.bom.gov.au/bmrc/pubs/researchletter.htm

Begges, H. 2007: A High-Resolution Blended Sea Surface Temperature Analysis over the Australian Region, BMRC Research Report, Bureau of Meteorology, Melbourne, Australia, 43pp.

(http://www.bom.gov.au/bmrc/pubs/researchreports/RR130.pdf)

Beggs, H., 2008: GAMSSA – A New Global Australian Multi-Sensor SST Analysis, *Submitted to Proceedings of the 9th GHRSST–PP Science Team Meeting, Perros-Guirec, France, 9-13 June 2008.*

(http://www.bom.gov.au/bmrc/ocean/Bluelink/SST/GHRSST9/9th_GHRSST_PP_Meeting_GAMSSA_paper.doc)

Donlon, C.J., P. Minnett, C. Gentemann, T. J. Nightingale, I. J. Barton, B. Ward and J. Murray, 2002: Towards Improved Validation of Satellite Sea Surface Skin Temperature Measurements for Climate Research, *J. Climate*, 15, No. **4**, 353-369.

Reynolds, R. W. and T. H. Smith, 1994: Improved global sea surface temperature analyses using optimum interpolation, *j. Climate*, **7**, 929-948.

Reynolds, R.W., T.M. Smith, C.Liu, D.B. Chelton, K.S. Casey and M. G. Schlax, 2007, Daily High-Resolution-Blended Analyses for Sea Surface Temperature, J. Climate, DOI: 10.1175/2007JCLI1824.1.

Stark, J.D., C.J. Donlon, M.J. Martin and M.E. McCulloch, 2007, OSTIA: An operational, high resolution, real time, global sea surface temperature analysis system, Oceans `07 IEEE Aberdeen, conference proceedings, Marine challenges: coastline to deep sea, Aberdeen, Scotland. IEEE.