NEW AUSTRALIAN HIGH RESOLUTION AVHRR SST PRODUCTS FROM THE INTEGRATED MARINE OBSERVING SYSTEM

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Abstract - The Australian Bureau of Meteorology (the Bureau) is producing 1 km resolution sea surface temperature (SST) products in real time from data from the Advanced Very High Resolution Radiometer (AVHRR) sensors on board NOAA polar orbiter platforms received at the Bureau's satellite reception facilities. As part of the Australian Integrated Marine Observing System (IMOS: http://www.imos.org.au) the Bureau has recently upgraded its SST processing system to comply with the GHRSST (Group for High Resolution SST) Data Processing Specification v2.0 (Casey et al., 2010a) and up-to-date processing that meets or exceeds worlds best practice. The significant components include the use of regional rather than global buoy SSTs for satellite SST calibration, noise resistant methods of SST coefficient estimation, the development of a match-up database (MDB), calculation of single sensor error statistics (SSES), an improvement in cloud identification, and the generation and distribution of SST products in GHRSST L2P and L3C formats.

Keywords: Sea Surface Temperature, Oceanography.

1. INTRODUCTION

The Bureau of Meteorology operates satellite receiving stations that participate in a National network that acquire NOAA polar orbiter Advanced Very High Resolution Radiometer (AVHRR) High Resolution Picture Transmission (HRPT) data. The AVHRR instrument has been in continuous service on the series of NOAA POES satellites since 1978, and measures Brightness Temperatures (BT) in five wide spectral bands from the red and near infrared (reflectance channels 1 and 2 centred on 0.6μm and 0.9 μm respectively) to the thermal infrared (BT3, BT4 and BT5 centred on 3.5 μm, 11 μm and 12 μm respectively). BT3 is typically available only during night-time on recent NOAA POES satellites.

As part of the Australian Integrated Marine Observing System (IMOS: http://www.imos.org.au) the Bureau has recently upgraded its SST processing system to meet international best practice and to comply with the Group for High Resolution SST (GHRSST) Data Processing Specification v2.0 (Casey et al., 2010a).

The Bureau has computed SST from HRPT AVHRR since the early 1990's using McIDAS software (http://www.ssec.wisc.edu/mcidas/). The native format of McIDAS satellite products (e.g. AREA files) has proved a barrier for many user groups to gain access to Bureau generated SST. The GHRSST format allows users to access SST data through the well described and often familiar netCDF interface. In recent years the Bureau has, where possible and practical, adopted the GHRSST format (Donlon et al., 2005) for storing and distributing SST products.

Previously, there have been no single day and single night HRPT AVHRR composite SST products available for the Australian region. The IMOS Satellite SST Products Sub-Facility now produces not only real-time, single-swath, 1 km resolution, HRPT AVHRR SST GHRSST format "L2P" (level 2 pre-processed) files, but also near real-time, single sensor, composite, GHRSST format "L3C" SST products, gridded at 0.02° x 0.02° over the region 70°E to 170°W, 20°N to 70°S for a single day and a single night of data (Figures 1(a) and 1(b)). Formats for both L2P and L3C products are described in Casey et al (2010a).

The aim over 2010 and 2011 is to reprocess the archive of raw HRPT AVHRR data to produce these L2P and L3C files from NOAA polar-orbiting satellites back to 1992. This paper describes the implementation details of the new real-time and archival processing stream.

2. PROCESSING SYSTEM OVERVIEW – DATA ACQUISITION

The Bureau, in conjunction with a number of partners (Western Australian Satellite Technology and Applications Consortium, Australian Institute of Marine Science, and CSIRO), receives HRPT AVHRR data generated from NOAA-17, NOAA-18 and NOAA-19 satellites from six ground stations located around Australia (Melbourne, Perth, Darwin, Townsville, Alice Springs and Hobart) and two in Antarctica (Casey and Davis stations). The raw data received from a single pass at multiple stations is stitched to produce a single continuous swath using a method developed by Edward King of CSIRO Marine and Atmospheric Research (King, 2003) and SST is calculated and distributed using the processing system outlined Paltoglou et al (2010). Data transmission bandwidth limitations currently restrict the real-time processing to the non-Antarctic stations.
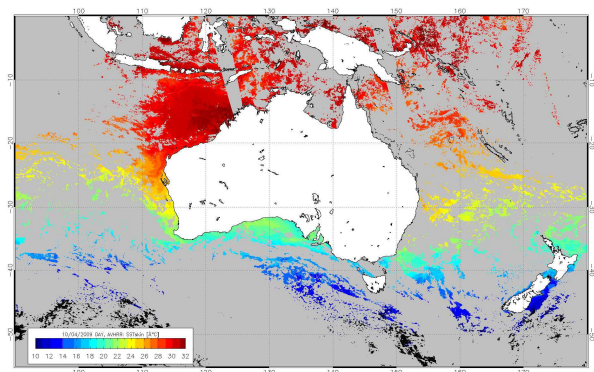
Figure 1. Example of night 0.02°x 0.02°L3C composits from locally received NOAA-18 AVHRR SST data for 10 April 2009. The grey areas represent sensor coverage where the sensor view zenith angle was less than60°. SST is plotted for cloud-free pixels (quality level = 3 to 5)

3. COMPUTATION OF SST

The Bureau processes raw AVHRR data to higher level L2 products with the Common AVHRR Processing System (CAPS) software developed by CSIRO (King, 2003; http://www.eoc.csiro.au/cats/caps). Geolocation is performed by CAPS using near real-time satellite orbital parameters obtained from CSIRO in Hobart. Calibration of the channel counts to Brightness Temperature (BT) is also performed by CAPS using auxiliary bandpass data supplied by NOAA.

SSTs are computed from these BTs using algorithms based on the 2 channel and 3 channel formalism described in Walton et al (1998) and McClain et al (1985) and references therein, but with extensions described here.

The standard day-time algorithm as developed by Walton et al (1998) uses two channels, BT4 and BT5, in what is described as a non-linear form (NLSST). Numerous variations on the NLSST algorithm have been developed from experimental regression against insitu observations (see e.g. Eastwood 2002) but the basis of it, that the difference between AVHRR channels 4 and 5 (T45) is an indicator of the presence of water vapour, and cross-terms between T45 and sec(satellite zenith angle) reduce errors with insitu observations, are common to all. The non-linear formalism derives it name from the requirement that at least one of the coefficients is not constant but is temperature dependent and requires that a solution have a first guess estimate of the sea surface temperature. This first guess SSS may be either from climatology or from the application of a linear SST algorithm (Walton et al. 1998).

The typical night-time algorithm uses the three available BT channels in a linear form and studies of matchup data show that no there is no improvement with the use of non-linear cross terms as is found with the day-time NLSST.

In order to maximise the spatial coverage, we have used the complete swath rather than restricting retrievals to a satellite zenith angle less than 53° (e.g. May et al. 1998). This approach places extra demands on modelling atmospheric attenuation and to obtain the highest possible accuracy requires the use of a different form of airmass term in these equations. In the standard formalism $S = (\sec(\vartheta) -1)$ is used as an approximation of the airmass. It was found that a small latitude dependence remained in our error regression and this dependence was a function of satellite view angle. On the basis that the height of the tropopause decreases with increasing latitude (e.g. Leroux 2010) we have folded a simple model of atmospheric depth as a function of latitiude into the airmass term

$$A = (\cos(lat)+1)*\sec(\vartheta) \qquad (1)$$

which has the effect of decreasing the airmass at high latitudes but is only significant for large satellite view angles. An alternative method is to derive coefficients for different latitude bands, as is used for Pathfinder V6 AVHRR SST (Casey et al., 2010b).

Regression coefficients were determined for a set of test algorithms that combined different parameters. The coefficients for these day/night algorithms were calculated using SST measurements from drifting buoys in the Australian region. The regression method used was Singular Value Decomposition with aggressive zeroing of the weighting matrix to ensure stability of the coefficients and to avoid over-fitting (see Kilpatrick et al., 2001, for a different method of robust coefficient estimation).

From the residuals derived from this set of experimental algorithms its was shown that the form that performed best at both low and high latitudes and at low and high satellite zenith angles were -

Day-time:

$$SST = \alpha_1 BT4 + \beta_1(BT4 - BT5) + \gamma_1(BT4 - BT5)^2 + \delta_1 A(BT4-BT5) + \varepsilon_1 A + \phi_1 \qquad (2)$$

Night-time:

$$SST = \alpha_2 BT3 + \beta_2 BT4 + \gamma_2 BT5 + \delta_2 S + \varepsilon_2 S (BT3-BT5) + \delta_2 \qquad (3)$$

where ϑ is the satellite zenith angle, $\alpha_n \beta_n \gamma_n \delta_n \varepsilon_n$, ϕ_n are constants. Note that our form of the daytime transform includes a square term which is a consequence of computing the first guess SST as a linear 2 channel estimate.

The AVHRR TIR bands are sensitive to the temperature in the top 20 μm of the ocean surface (SSTskin), whereas the *in situ* temperature is measured at a depth typically of 20-30 cm for drifting buoys (SSTdepth). In the absence of any vertical mixing a temperature differential will exist (Gentemann et al., 2003). Therefore, we have restricted our calibration dataset to *in situ* measurements obtained at wind speeds greater than 6 m/s during the day and 2 m/s during the night (Donlon et al.,2002). In addition, a cool skin correction of 0.17 K has been applied to the calibration to correct for the difference between the skin temperature and the drifting buoy SST measurements at 20 to 30 cm depth. The final AVHRR SST product is therefore an estimate of the skin SST.

4. CLOUD IDENTIFICATION

The identification of cloud in AVHRR SST production is a major hurdle. Contamination by cloud will tend to lower the observed temperature and result in an overall negative temperature bias. Consequently it is of critical importance to ensure that all suspect pixels are masked out. On the other hand, to ensure as great a coverage as possible is it important not to mask out pixels needlessly. These competing requirements need to be balanced in a sensible way. The cloud mask in CAPS is based on the original CLAVR algorithm described in Stowe et al (1999). This uses a set of radiance, uniformity, and 2-channel thresholds to identify cloud. An extensive study was undertaken to refine and extend these thresholds.

Uniformity thresholds are very powerful tests as the ocean SST is generally very uniform over small spatial scales (Stowe et al 1999). However, ocean temperature fronts and eddies can sometimes exceed standard threshold values. Therefore we have increased the value so that the majority of these phenomena will not be masked out. For night-time data a new threshold test based on (BT3 - BT4) versus (BT4 - BT5) was found to be very effective at identifying cloud. For daytime data, where the BT3 channel is not available, the reflectance channels, NR1 and NR2, are very efficient at identifying cloud. Clear ocean is dark while cloud is highly reflective, although this is complicated by specular reflection from the ocean at certain satellite view angles. An additional threshold test based on the difference between the band 1 and band 2 reflectances was found to be efficient at identifying cloud while being relatively insensitive to the view angle.

Visual inspection as well as statistics derived from *in situ* SSTs showed that these updated cloud mask thresholds dramatically reduced the incidence of cloud contamination, while at the same time increasing the number of pixels identified as clear.

5. MATCHUP DATABASE

The Bureau has developed a matchup database (MDB) to compare satellite SSTskin and temperature observations from collocated and contemporaneous drifting buoys (converted to SSTskin by subtracting 0.17 K). The Bureau has implemented a MDB following the Medspiration MDB guidelines (Piollé and Prevest 2006). For each *in situ* measurement:

1) Find the closest satellite pixel (valid or not) to the *in situ* measurement.

2) Find the neighbouring pixels that are within a specified spatial and temporal distance to the satellite image pixel identified in step 1. For example, in our case get all satellite image pixels that are ±12 km and ±2 hours from the *in situ* measurement.

3) Select the closest valid pixel in time then distance. This is the matchup.

4) Calculate the following statistics for the neighbouring box identified in step 2:

   a) percentage of valid pixels;

   b) mean sea surface temperature;

   c) standard deviation sea surface temperature;

   d) percentage of pixels having quality level values equal to 0, 1, 2, 3, 4, 5; where 0 = no data; 1 = bad data; 2 = worst quality SST; 3 = low quality SST ; 4= acceptable quality SST ; 5 = best quality SST (Casey et al., 2010a).

The MDB provides the basic dataset from which to derive our single sensor statistics. An analysis of NOAA-17 and 18 data showed that quality level values derived as a fuction of distance to nearest cloud (as defined by the CAPS cloud mask), satellite zenith angle and day/night pass could be used advantageously and was therefore implemented.

6. SST STATISTICS

To aid in the usability of the new SST products, pixel by pixel estimates of SST bias and standard deviation are provided. Uncertainty estimates for valid SST retrievals are determined by comparing the satellite derived SSTskin measurement with quality controlled *in situ* temperature measurements (converted to SSTskin) in our MDB. The bias and variance are computed for each quality level and over a time window of +/- 30 days. In the calculation of the statistics, only matchups that are pixel collocated are used. Tables 1(a) and 1(b) give the bias and standard deviation for NOAA-17, 18 and 19, for day/night, and for quality levels 3, 4, and 5 over the period 1 November 2009 to 31 March 2010.

Table 1(a). Single Sensor Error Statistics (in Kelvin) for NOAA-17, -18 and -19 Daytime pass by Quality Level (QL)

Daytime	QL = 5		QL = 4		QL = 3	
	Bias	StdDev	Bias	StdDev	Bias	StdDev
NOAA-17	0.06	0.35	-0.03	0.45	-0.02	0.46
NOAA-18	0.04	0.35	-0.04	0.46	0.01	0.47
NOAA-19	0.02	0.34	0.03	0.43	0.00	0.54

Table 1(b). Single Sensor Error Statistics (in Kelvin) for NOAA-17, -18 and -19 Night-time pass by Quality Level (QL)

Nighttime	QL = 5		QL = 4		QL = 3	
	Bias	Std Dev	Bias	Std Dev	Bias	Std Dev
NOAA-17	0.02	0.24	0.01	0.29	-0.02	0.40
NOAA-18	0.02	0.27	0.01	0.30	0.02	0.46
NOAA-19	0.01	0.26	-0.04	0.37	-0.03	0.48

The new IMOS HRPT AVHRR L2P SSTs exhibit just over half the standard deviation of the Bureau's pre-existing HRPT AVHRR level 2 SSTblend data from NOAA-17 and NOAA-18 satellites, with standard deviations of quality level 5 L2P SSTskin compared with drifting buoys during night-time of 0.24 to 0.27°C for NOAA-17, -18 and -19 (Table 1(b)), and during daytime of 0.34 to 0.35°C (Table 1(a)). This significant improvement in accuracy is the result of implementing new CLAVR-based cloud clearing algorithms, implementing new BT to SST transforms with new day-time terms including latitude and higher order cross terms, and using regional (rather than global), quality controlled drifting buoy SST observations for the regression.

7. DATA DISTRIBUTION AND ACCESS

The netCDF HRPT AVHRR L2P and L3C data files will be made available to the IMOS Australian Oceans Distributed Active Archive Centre (AO-DAAC). The AO-DAAC is designed to make various remotely sensed ocean products available to researchers through an OPeNDAP interface, associated metadata database and web interface (King, 2008). A web-based interface to the AO-DAAC system has been provided at
http://www.marine.csiro.au/remotesensing/imos/aggregator.html
where the spatial extent of the requested data can be specified using a Google-Maps interface. The requested data can be returned as a set of OPeNDAP URLs, ASCII text, or extracted into a single HDF or netCDF file.

Existing raw, archived, high-resolution HRPT AVHRR data from all operational NOAA polar-orbiting satellites over the Australian region back to 1992 will be progressively reprocessed into SSTskin L2P/L3C files and be available by June 2011. . Real-time HRPT AVHRR SSTskin L2P files from NOAA-18 and NOAA-19 are currently available via FTP from ftp://aodaac2-cbr.act.csiro.au/imos/.

8. CONCLUSION

As part of the IMOS Project the Bureau of Meteorology has recently commenced producing HRPT AVHRR SST level 2 and level 3 products in the GHRSST v2.0 L2P and L3C formats. These files are now available through an IMOS ftp server accessible via ftp://aodaac2-cbr.act.csiro.au/imos/ and will shortly be available through http://www.marine.csiro.au/remotesensing/imos/aggregator.html and the IMOS Ocean Portal at http://imos.aodn.org.au/webportal/. The new IMOS HRPT AVHRR L2P SSTs are significantly more accurate than the Bureau's pre-existing HRPT AVHRR level 2 SST data from NOAA-18 satellites, with standard deviations of night-time matchups with drifting buoys approximately halved through improved processing techniques.

These new AVHRR L2P products are being tested for incorporation into the Regional Australian Multi-Sensor SST Analysis (RAMSSA; Beggs 2007; Beggs et al., 2010) that produces 1/12° resolution, daily SST analyses over the Australian region (20°N - 70°S, 70°E - 170°W). They will also be used in diurnal warming studies of the oceans near Antarctica and the Tropical Warm Pool north of Australia. The single day and single night HRPT AVHRR SST L3C data will be used by researchers at the University of Western Australia in the Transient Coastal Upwelling Along Ningaloo Reef Project. This project is all ready using the Bureau's legacy HRPT AVHRR SST 14-day, 0.01° x 0.01° resolution, Mosaic L3 products, and the enhanced accuracy and smaller temporal resolution is expected to significantly benefit this coral reef study.

9. ACKNOWLEDGEMENTS

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