GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

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Validation of MODIS Imagery in the Great Australian Bight

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GREAT AUSTRALIAN BIGHT RESEARCH PROGRAM

The Great Australian Bight Research Program is a collaboration between BP, CSIRO, the South Australian Research and Development Institute (SARDI), the University of Adelaide, and Flinders University. The Program aims to provide a whole-of-system understanding of the environmental, economic and social values of the region; providing an information source for all to use.

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INTRODUCTION

Satellite systems are able to obtain global environmental data with great temporal coverage, and have provided important insights into marine ecosystem dynamics (Bousquet et al. 2006; Mohr and Forsberg 2002; Bosc et al. 2004; Krishna and Rao 2008). In some areas, ocean colour-based chlorophyll-*a* (chl) concentration and sea surface temperature data are used operationally to indicate potential fishing and conservations zones (Petit et al. 2003; Royer et al. 2004). In addition, measurements of ocean colour-based euphotic depth (Z_{eu}) are essential for modelling primary productivity within the ocean (Behrenfeld and Falkowski 1997). However, satellite images must be calibrated with *in situ* measurements to ensure the quality of the data for different biomes (Tilstone et al. 2013; Lapucci et al. 2012; Salyuk et al. 2010; van Ruth et al. 2010a).

The processing of satellite ocean colour data requires an atmospheric correction and the development of in-water bio-optical algorithms. Phytoplankton is the main optically active component of open marine waters, where changes in the optical properties are directly related to the chl concentration. These waters are known as Case 1 waters (Gordon and Morel 1983; Morel and Prieur 1977). In coastal waters, colored dissolved organic matter (CDOM) and suspended inorganic matter, together with bottom reflectance, can also contribute significantly to changes in optical properties. In these cases, the different optically active constituents need to be characterized to accurately estimate the chl concentration (Darecki and Stramski 2004; Cannizzaro and Carder 2006). These waters are known as Case 2 waters (Bukata et al. 1995; Sathyendranath et al. 2001).

Most operational satellite chl algorithms are based on empirical relationships between chl concentration and the reflectance ratio in several spectral bands. These algorithms perform well in open waters (O'Reilly et al. 1998; O'Reilly et al. 2000; Sathyendranath et al. 2001) but may fail in coastal waters due to the presence of additional optically active substances (Sathyendranath 2000; Barbini et al. 2003; Prieur and Sathyendranath 1981). Semi-analytical ocean colour algorithms use a model to obtain characteristics of seawater optical components (Lee et al. 2002; Maritorena et al. 2002; Tilstone et al. 2012), but these algorithms are more sensitive to errors in the atmospheric correction than empirically derived algorithms (Salyuk et al. 2010). Similarly, the Z_{eu} can be estimated empirically (derived from surface chl measurements) or by determining the vertical distribution of light from the optical properties (Lee et al. 2002; Soppa et al. 2013), and therefore is also influenced by water type and atmospheric corrections.

The MOderate Resolution Imaging Spectro-radiometer (MODIS) onboard the Aqua Satellite is the moderate resolution mission from NASA. Currently, MODIS standard products (http://oceancolor.gsfc.nasa.gov/) include both empirical and semi-analytical global

algorithms. Since general regressions are hard to establish for all water cases and locations, it is necessary to locally validate the different algorithms against *in situ* measurements (Tilstone et al. 2013; Lapucci et al. 2012; Salyuk et al. 2010). Owing to the remoteness of the Great Australia Bight (GAB) region in southern Australia (Fig .1), there has been a paucity of *in situ* data available for the assessment of satellite algorithms. Previous validation studies in southern Australia have focused on the Spencer Gulf region; in particular the southern area of the Gulf surrounding Port Lincoln, which supports the lucrative Southern Bluefin Tuna aquaculture industry (Bierman et al. 2009; Bierman 2010).

The purpose of this report is to evaluate the performance of satellite-based measurements of chl, Z_{eu} and SST using field-based measurements in the GAB in order to: (1) determine whether the imagery is a reliable data source, (2) identify the most accurate products available for on-going monitoring and various research applications in the region, and (3) if possible, provide locally improved products using a simple tuning of global algorithms through redefinition of the regression coefficients. Satellite products evaluated in this report include: the standard OC3M (O'Reilly et al. 1998; O'Reilly et al. 2000), Carder (Carder et al. 1999; Carder et al. 2004) and Garver-Siegel-Maritorena (GSM; (Maritorena et al. 2002)) chl algorithms, Z_{eu} derived from surface chl (Morel et al. 2007) and semi-analytically (Lee et al. 2002), and the standard SST product from MODIS-Aqua.

DATA AND METHODS

Study area

The area of interest includes the Great Australian Bight and the gulfs of St Vincent and Spencer, going from 130°S to 139°S and 31°SE to 37°E (Figure 1), and includes different ecological provinces. The GAB is a northern boundary current ecosystem (Middleton and Cirano 2002). During winter the GAB experiences downwelling, enhanced in the east through the outflow of cold, saline water formed in shallow regions of the GAB and gulfs. During summer, wind-driven upwelling events occur off the southern Eyre peninsula and south-western Kangaroo Island, while downwelling continues in the west (Middleton et al. 2014; Kampf et al. 2004; Cirano and Middleton 2004; van Ruth et al. 2010a, 2010b). The summer upwelling is linked with a sub-surface chl maximum centred between Kangaroo Island and the southern tip of the Eyre Peninsula in the eastern GAB (McClatchie et al. 2006; Kampf et al. 2004; van Ruth et al. 2010b, 2010a). The summer upwelling system presents ecological similarities to the productive western boundary upwelling systems in other regions of world, which are characterised by enhanced plankton production (Lewis 1981; Kampf et al. 2004; van Ruth et al. 2010a, 2010b).

Gulf St Vincent and Spencer Gulf are large inverse estuaries and experience seasonally limited exchange with the adjacent shelf waters (Lewis 1982). Gulf St Vincent extends ~170km with a maximum width of ~60km and a typical depth of 35m and shallower than 15m in the northernmost third of the Gulf. Spencer Gulf has a triangular shape and extends ~320 km with a maximum width of 130km and an average depth of 24m. During austral summer, temperature fronts form across the mouth of the gulf reducing the exchange with upwelled waters on the shelf (Petrusevics 1993).

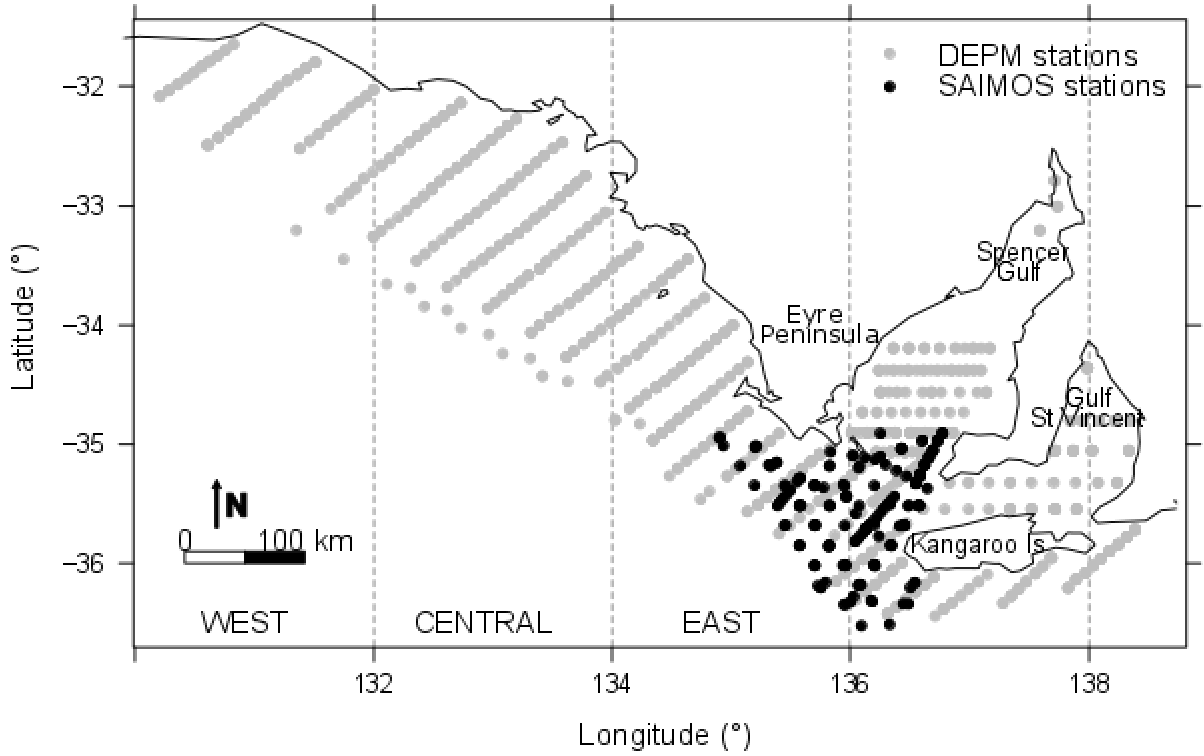

Figure 1. Study area and locations of the field stations visited during the sampling campaigns of the sardine daily egg production method surveys (grey circles) and the South Australian Integrated Marine Observing System (black circles).

Field data

Chlorophyll-a

We used two separate datasets of in situ chl obtained from water samples taken: (1) at 3m depth during February and March from 2004 to 2006 as part of the sardine daily egg production method (DEPM) surveys (Ward et al. 2011) (hereafter DEPM dataset) conducted by SARDI and (2) at either 10 or 15m depth during several monthly trips from 2008 to 2014 as part of the South Australian Integrated Marine Observing System (SAIMOS). From each water sample, 1L (DEPM) or 4L (SAIMOS) samples were filtered through a Whatman GF/C filter and kept in the dark at < 5°C until returned to the laboratory. Samples

were extracted in 90% methanol over 24 hours, with absorbance read at 750 nm (background) and 665 nm (chl) using a Hitachi U-2000 spectrophotometer with 1 cm path length. Chl concentrations were then calculated using the formulae of Talling and Driver (1963). The DEPM dataset included a total of 851 stations with *in situ* data, but only 145 matched with available MODIS data (see details below). Similarly, the SAIMOS dataset included a total of 118 stations, but only 10 matched with the MODIS data.

During both projects, *in vivo* chl measurements were taken from CTD casts using either a Chelsea Aqua tracka III fluorometer (Chelsea Technologies Group, Surrey, UK) or an ECO FL fluorometer (WetLabs, Rhode Island, US) attached to the CTD. From the fluorescence profiles we extracted the *in vivo* surface chl values at 5m depth. In cases where two surface chl values (i.e. upcast and downcast) were available, we used an average of the two readings and excluded those values where the logarithmic differences were greater than 0.5.

Euphotic depth

During the DEPM surveys and SAIMOS project, profiles of photosynthetically active radiation (PAR) of the water column were recorded from CTD casts, using either a Satlantic PAR-LOG-600m PAR sensor (Satlantic LP, Halifax, Canada) or a Biospherical QSP-200L Log Quantum Scalar Irradiance Sensor (Biospherical Instruments Inc. San Diego, CA) attached to the CTD. From the PAR profiles we calculated the Z_{eu}, defined as the depth where PAR is reduced to 1% of the initial value at the surface. Firstly we calculated the PAR attenuation coefficient (K_d) as the slope of the regression line of the log-transformed PAR with respect to depth, and then used the standard way to calculate the euphotic depth following the Beer-Lambert equation:

$$Z_{eu}=1/K_d*Ln(100/1)$$

Since the PAR profiles could be influenced by the boat shadow, we calculated the Z_{eu} including only PAR values corresponding to depths greater than 5m. In cases where two PAR profiles (i.e. upcast and downcast) were available, we used an average of the values calculated from the two casts and excluded those were the differences were greater than 5m.

Sea surface temperature data

During the DEPM and SAIMOS projects, temperature profiles of the water column were recorded using a SBE 19plus V2 SeaCAT Profiler CTD (Sea-Bird electronics, Washington, US). We extracted the uppermost SST values from the CTD profiles (at a depth between 1m and

5m). In cases where two SST values (i.e. upcast and downcast) were available, we used an average of the two readings and excluded those values were the temperature differences were greater than 0.5^{o}C.

MODIS imagery

MODIS Aqua level-2 daily imagery was obtained from the IMOS archive for Australia. These data were derived by processing raw 5-minute granules to level-1b and then level-2 using the NASA SeaDAS (Baith et al. 2001) processing package (v7.0.1). The level-2 processing step includes a correction for contribution of the atmosphere and results in data products with the native nadir resolution of approximately 1km^2. MODIS data was only extracted from the archive for days where the difference between the time of the data collection and the satellite overpass did not exceed 5 hours. We selected the following level-2 products: the standard OC3M, Carder and GSM chl algorithms, their corresponding level 2 flags, the Z_{eu} and the SST values.

The OC3M is an empirical algorithm, a fourth degree polynomial regression between the pigment concentration and the spectral ratios of ocean reflectance (O'Reilly et al. 1998; O'Reilly et al. 2000). The GSM is a semi-analytical algorithm based on the bio-optical model inversion algorithm of Garver and Siegel (1997), and optimized using a simulated annealing technique (Maritorena et al. 2002). The Carder algorithm is also semi-empirical, but uses a more complex approach than the GSM algorithm. The algorithm calculates the spectral absorption properties of the sea water and splits them into those associated with phytoplankton pigments and those associated with biological degradation products (e.g. CDOM). The absorption coefficient of phytoplankton chl is then adjusted in relation the chl concentration and the availability of light and nutrients (Carder et al. 1999; Carder et al. 2004).

The Z_{eu} is based on the semi-analytical algorithm of Lee et al. (2007), computed from the absorption and backscattering coefficients. In addition, we used the surface chl values (OC3M algorithm) to compute the empirical Z_{eu} (Z_{eu}_chl) following the approach of Morel et al. (2007);

$$\text{Log}(Z_{eu}\_\text{chl}) = 1.524 - 0.436x - 0.0145x^2 + 0.0186x^3$$

$$x = \log(\text{chlorophyll-}a \text{ concentration})$$

Comparison between field-based and MODIS data

We compared the measurements obtained via the field-based sampling (both *in situ* and *in*

vivo chl) with those derived from MODIS for each of the three chl algorithms, the two Z_{eu} values and SST following a modified general match-up exclusion protocol (McClain et al. 2000). We edited the dataset using the Level 2 processing flags and masked out those pixels where any of the NASA operational Level 3 Ocean Color Processing flags (Table 1) were set. We identified and averaged the 9 pixels closest to the field-based measurement (within an array of 9 by 9 pixels centred on each of the locations). Only match-ups where at least 5 out of the 9 pixels contained valid data were included.

We calculated the relationship between the field-based value and the MODIS value via linear regression, and determined the goodness of fit through the coefficient of determination (R2) and the Root Mean Square Error (RMSE). We tested the data for normality and log-transformed the values prior to the calculations when necessary.

Table 1. Operational Ocean Color Processing masks

Level-2 flags
Atmospheric correction failure
Pixel is over land
High sun glint
Observed radiance very high or saturated
High sensor view zenith angle
Straylight contamination is likely
Probable cloud or ice contamination
Coccolithophores detected
High solar zenith
Very low water-leaving radiance (cloud shadow)
Derived product algorithm failure

Navigation quality is reduced Aerosol iterations exceeded max Derived product quality is reduced Atmospheric correction is suspect Bad navigation

RESULTS

Chlorophyll-a

The relationship between the MODIS OC3M algorithm and the DEPM in situ chl was weak (Table 2; Figure 2), with an R^2 value of 0.32 and a root mean square error (RMSE) of 81%. Bottom reflectance and the presence of different optical substances in shallow nearshore and gulf waters may play a role in the poor relationships shown, so we repeated the regression excluding locations where the water depth is less than 50m (which excludes the gulfs). In doing so, the relationships improved considerably (R^2 = 0.46), although the RMSE remained over the 35% linear accuracy goal set by NASA for chlorophyll retrievals (McClain et al, 2004). The correlation, however, varied spatially: in the west of the GAB the correlation was considerably better (R^2=0.66, RMSE=21%), while non-statistically significant relationships were found within the east GAB.

The Carder and GSM algorithms, which were designed for Case 2 waters, were not affected by the exclusion of shallow waters from the analysis (Table 2), and their RMSE were within the 35% limit. Both algorithms still showed correlation coefficients lower than 0.5. As per the OC3M, both algorithms showed a better relationship with in situ data in the west GAB (R^2 ~0.35) and also around Kangaroo Island (R^2 >0.5) and no significant relationships in the east GAB.

The method used to calculate the in situ chl concentration from the water samples was unable to resolve small variations in concentrations, leading to an apparent quantisation, or binning, of the field-based values (Figure 2). To account for these apparent errors, we repeated the analysis with a second field-based dataset based on in vivo chl values measured using a CTD fitted with a fluorometer (CTD-F) during DEPM surveys (Ward et al. 2011). Chl data derived from fluorometers should be used with caution, since changes in the phytoplankton population, environmental state, physiological state, quenching, instruments

and calibrations may all lead to erroneous or biased measurements (Falkowski and Kolber 1995; Babin et al. 1996; Babin 2008; Krause and Jahns 2004; Dandonneau and Neveux 1997; Xing et al. 2012). In order to minimize the bias within and between instruments, we considered each instrument calibrated within a period of a year as a separate dataset.

Table 2. Regression statistics for MODIS and in situ chlorophyll-a data for the DEPM dataset.

Algorithm	**n**	R^2	**RMSE(ug/L)**	**RMSE (%)**	**p-value**	**intercept**	**slope**
OC3M (All)	121	0.32	0.29	81%	<0.01	-0.42	0.90
OC3M (>50m)	98	0.46	0.15	48%	<0.01	-0.51	0.92
OC3M (West GAB)	30	0.66	0.07	21%	<0.01	-0.44	1.01
OC3M (Central GAB)	39	0.4	0.20	65%	<0.01	-0.40	1.09
OC3M (East GAB)	15	0.20	0.12	40%	0.11	-0.82	0.50
OC3M (KI)	14	0.68	0.12	42%	<0.01	-0.49	1.01
Carder (All)	105	0.34	0.07	35%	<0.01	-1.07	0.71
Carder (>50m)	84	0.37	0.07	35%	<0.01	-1.05	0.75
Carder (West GAB)	29	0.35	0.06	27%	<0.01	-1.01	0.71
Carder (Central GAB)	34	0.37	0.07	40%	<0.01	-1.03	0.80

Algorithm	n	R^2	RMSE(ug/L)	RMSE (%)	p-value	intercept	slope
Carder (East GAB)	10	0.01	0.07	38%	0.90	-7.74	0.04
Carder (KI)	11	0.56	0.03	27%	<0.01	-0.51	1.35
GSM (All)	111	0.45	0.11	28%	<0.01	-0.45	0.60
GSM (>50m)	92	0.49	0.12	30%	<0.01	-0.45	0.63
GSM (West GAB)	29	0.34	0.09	21%	<0.01	-0.50	0.55
GSM (Central GAB)	38	0.52	0.08	24.2%	<0.01	-0.48	0.66
GSM (East GAB)	13	0.17	0.11	32%	0.16	-0.75	0.31
GSM (KI)	12	0.84	0.07	17%	<0.01	0.12	1.09

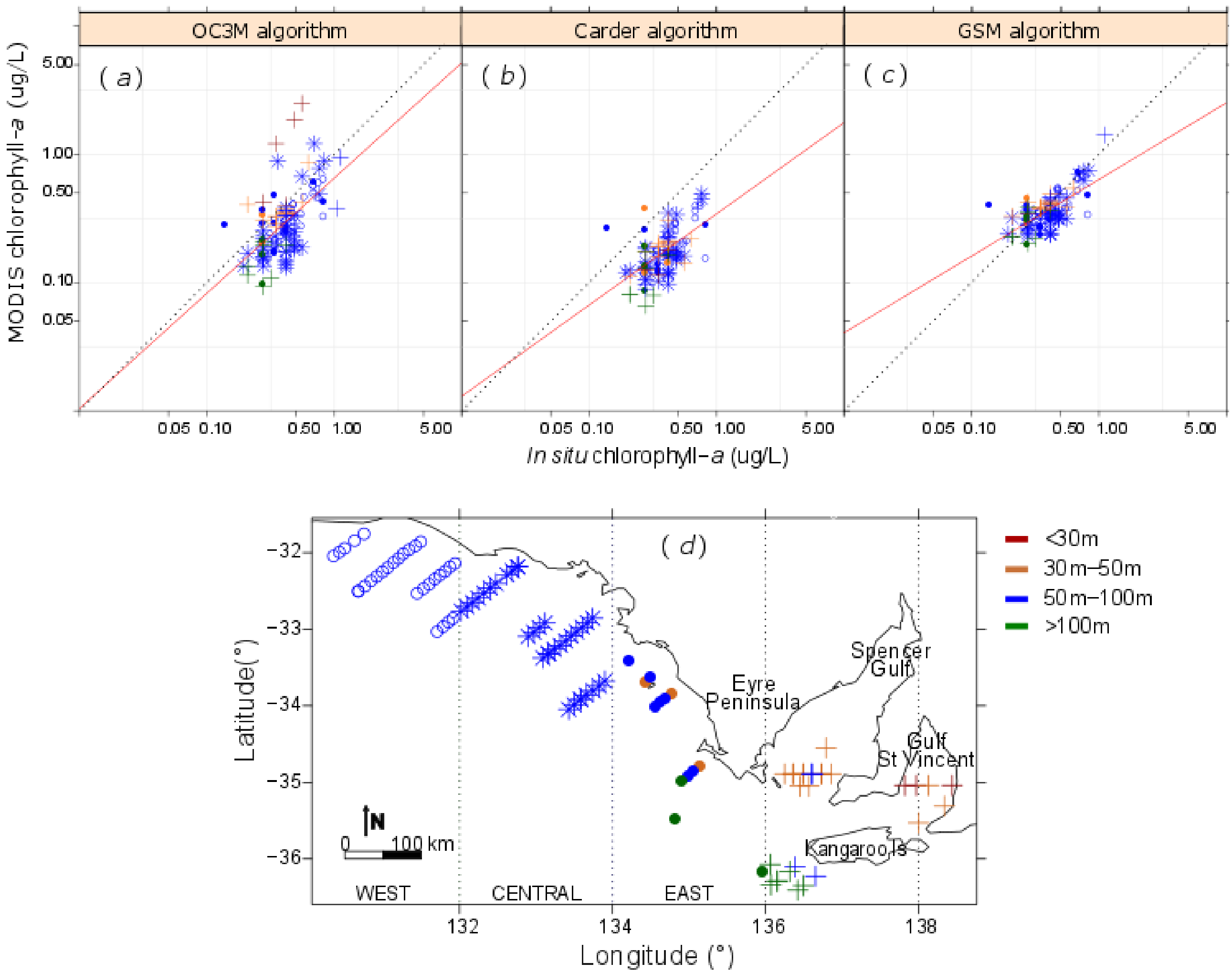

Figure 2. Relationships between MODIS (a) OC3M, (b) Carder and (c) GSM algorithms with the in situ chlorophyll-a from the DEPM dataset. The red line corresponds to the fitted line and the black line represents a perfect fit (1:1). The symbols correspond to (d) the different sampling stations from the DEPM surveys that matched MODIS data. Colours represent different bathymetric depths (green>100m, blue=100-50m, orange=50-30m, red=<30m).

The relationships between the MODIS and *in vivo* chl data are generally stronger than with the *in situ* data, with R^2 values >0.5 for all regressions performed, except for the Carder algorithm (Table 3, Figure 3). However, most of the MODIS data overestimated the *in vivo* chl values. Such bias is likely due to the methodology used to measure *in vivo* chl rather than an overestimation from MODIS, since fluorometers tend to underestimate the chl concentrations present in sea water (Xing et al. 2012). For 2004, the OC3M achieved the best relationship in terms of R^2 values (R^2=0.83), however, it also had the greatest RMSE (36%). In contrast, for 2005, OC3M performed the best on both criteria, with an R^2 and RMSE of 0.86 and 21%, respectively. Differences between the performances of the algorithms may be related to the location of the sampling stations within the years (Figures 3 & 4). During 2004, a number of stations were located in shallow waters within the gulfs, while in 2005 all the

stations were located in open waters with more stations in the west GAB and KI areas.

We repeated the regressions for 2004 excluding locations with depth < 50m (which excludes the gulfs). This improved the OC3M relationship (RMSE =29%), while the results for the other two algorithms remained the same. As before, the RMSEs for all the algorithms were lower for the West GAB region.

Table 3. Regression statistics for MODIS and in vivo chlorophyll-a data for the DEPM dataset.

Algorithm	**n**	**R^2**	**RMSE(ug/L)**	**RMSE (%)**	**p-value**	**intercept**	**slope**
				2004			
OC3M (All)	26	0.83	0.1	36%	<0.01	1.97	1.28
OC3M (>50m)	23	0.83	0.07	29%	<0.01	1.75	1.21
Carder (All)	21	0.49	0.05	34%	<0.01	0.46	0.88
Carder (>50m)	19	0.58	0.05	33%	<0.01	1.72	1.31
GSM (All)	25	0.75	0.04	12%	<0.01	0.24	0.53
GSM (>50m)	23	0.72	0.04	13%	<0.01	0.20	0.51
				2005			
OC3M (All)	34	0.86	0.08	21%	<0.01	0.86	0.86

Algorithm	n	R^2	RMSE(ug/L)	RMSE (%)	p-value	intercept	slope
OC3M (West GAB)	15	0.76	0.07	17%	<0.01	0.42	0.62
Carder (All)	29	0.82	0.06	28%	<0.01	0.58	0.89
Carder (West GAB)	15	0.72	0.05	19%	<0.01	0.07	0.06
GSM (All)	29	0.83	0.08	18%	<0.01	0.50	0.59
GSM (West GAB)	15	0.73	0.08	16%	<0.01	0.42	0.51

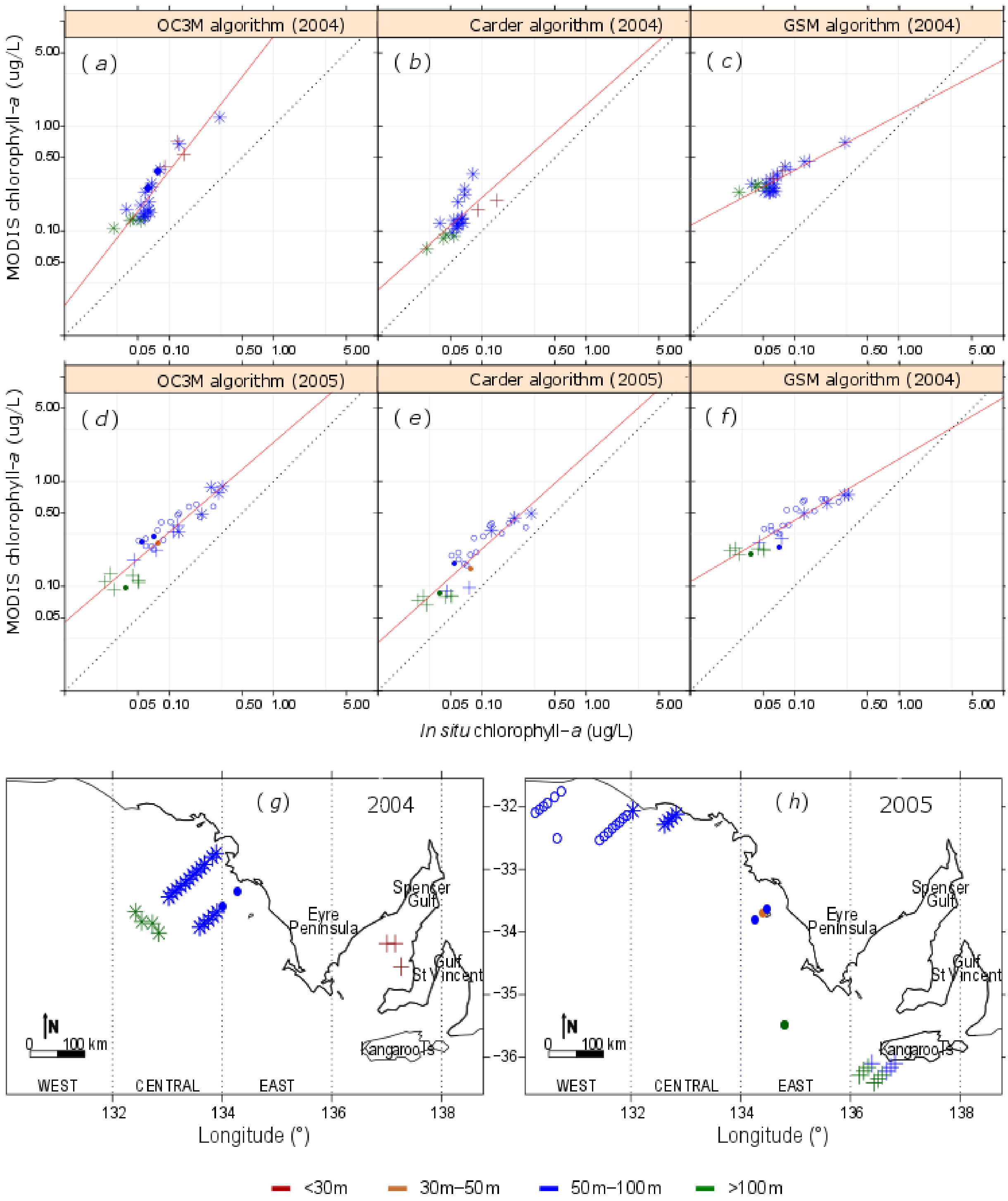

Figure 3. Relationships between MODIS (a) OC3M, (b) CARDER and (c) GSM algorithms with the in vivo chlorophyll-a dataset during 2004 and between MODIS (d) OC3M, (e) CARDER and (f) GSM algorithms with the in vivo chlorophyll-a dataset during 2005. The red line corresponds to the fitted line and the black line represents a perfect fit (1:1). The symbols correspond to the different sampling stations from the DEPM surveys that matched MODIS data during (g) 2004 and (h) 2005. Colours represent different bathymetric depths (green>100m, blue=100-50m, orange=50-30m, red=<30m).

The relationship between the MODIS and the SAIMOS *in situ* chl (Table 4) was moderate, with an R^2 value > 0.5 for all algorithms. The number of data points used for the regressions, however, is very small, and the results are not significant at the 99% level (n<10, p=0.02), hence the results should be used with caution. Regressions between MODIS and the *in vivo* data from SAIMOS were non-significant due to the low number of data points (n<10, p-value>0.05; not shown)

Table 4. Regression statistics for MODIS and in situ chlorophyll-a data for the SAIMOS dataset.

Algorithm	**n**	R^2	**RMSE(ug/L)**	**RMSE (%)**	**p-value**	**intercept**	**slope**
OC3M	9	0.58	0.15	34%	0.02	-0.65	0.85
Carder	9	0.58	0.20	44%	0.02	-0.55	1.2
GSM	8	0.62	0.11	22%	0.02	-0.46	0.65

Euphotic depth

The relationships between the MODIS and the *in situ* Z_{eu} from the DEPM dataset were generally good (Table 5 Figure 4). The Z_{eu} estimated from the surface chl values (R^2=0.73, RMSE=11%) were better than those derived by the semi-analytical algorithm (R^2=0.69, RMSE=18%), however, the former tended to underestimate the Z_{eu} of the clearest waters. There were no substantial differences in the performance of both algorithms when disregarding the shallow waters (depth <50m). As with the chl values, the correlations between the satellite and *in situ* data varied between the different areas of the GAB and the best matches occurred within the West GAB, where the RMSE from both algorithms fell below 10%.

In contrast, the relationships between MODIS and the SAIMOS *in situ* Z_{eu} were less robust and the best matches occurred for the chl derived Z_{eu} within the East GAB. Again, there were a smaller number of data points for this comparison, and the data collected by SAIMOS was not only from the upwelling season (February and March) but across seasons.

Table 5. Regression statistics for MODIS and in situ euphotic depth data

Algorithm	n	R^2	RMSE(m)	RMSE (%)	p-value	intercept	slope
				DEPM			
Lee (All)	175	0.69	9.67	18%	<0.01	6.8	0.84
Lee (<50m)	131	0.57	9.66	16%	<0.01	16.1	0.71
Lee (West GAB)	20	0.89	2.73	6%	<0.01	14.99	0.62
Lee (Central GAB)	59	0.64	7.67	12%	<0.01	19.43	0.67
Lee (East GAB)	42	0.40	12.5	20%	<0.01	21.5	0.68
Lee (KI)	10	0.80	7.39	12%	<0.01	6.02	0.81
Chl (All)	64	0.73	6.00	11%	<0.01	16.5	0.64
Chl (<50m)	51	0.70	6.47	12%	<0.01	16.1	0.65
Chl (West GAB)	14	0.85	2.59	5%	<0.01	23.3	0.48
Chl (Central GAB)	21	0.69	6.66	11.5%	<0.01	19.3	0.63
Chl (East GAB)	11	0.62	8.01	16%	<0.01	11.1	0.68

Algorithm	**n**	R^2	**RMSE(m)**	**RMSE (%)**	**p-value**	**intercept**	**slope**
Chl (KI)	5	0.98	2.03	3.54%	<0.01	12.96	0.69
				SAIMOS			
Lee (All)	61	0.36	14	22%	<0.01	-1.86	0.94
Lee (East GAB)	22	0.35	5.28	10%	<0.01	11.12	0.62
Lee (KI)	34	0.25	15.08	21%	<0.01	11.48	0.85
Chl (All)	22	0.52	4.83	8%	<0.01	12.16	0.71
Chl (East GAB)	10	0.67	3.83	6%	<0.01	2.79	0.82
Chl (KI)	12	0.38	4.81	7%	0.03	25.8	0.54

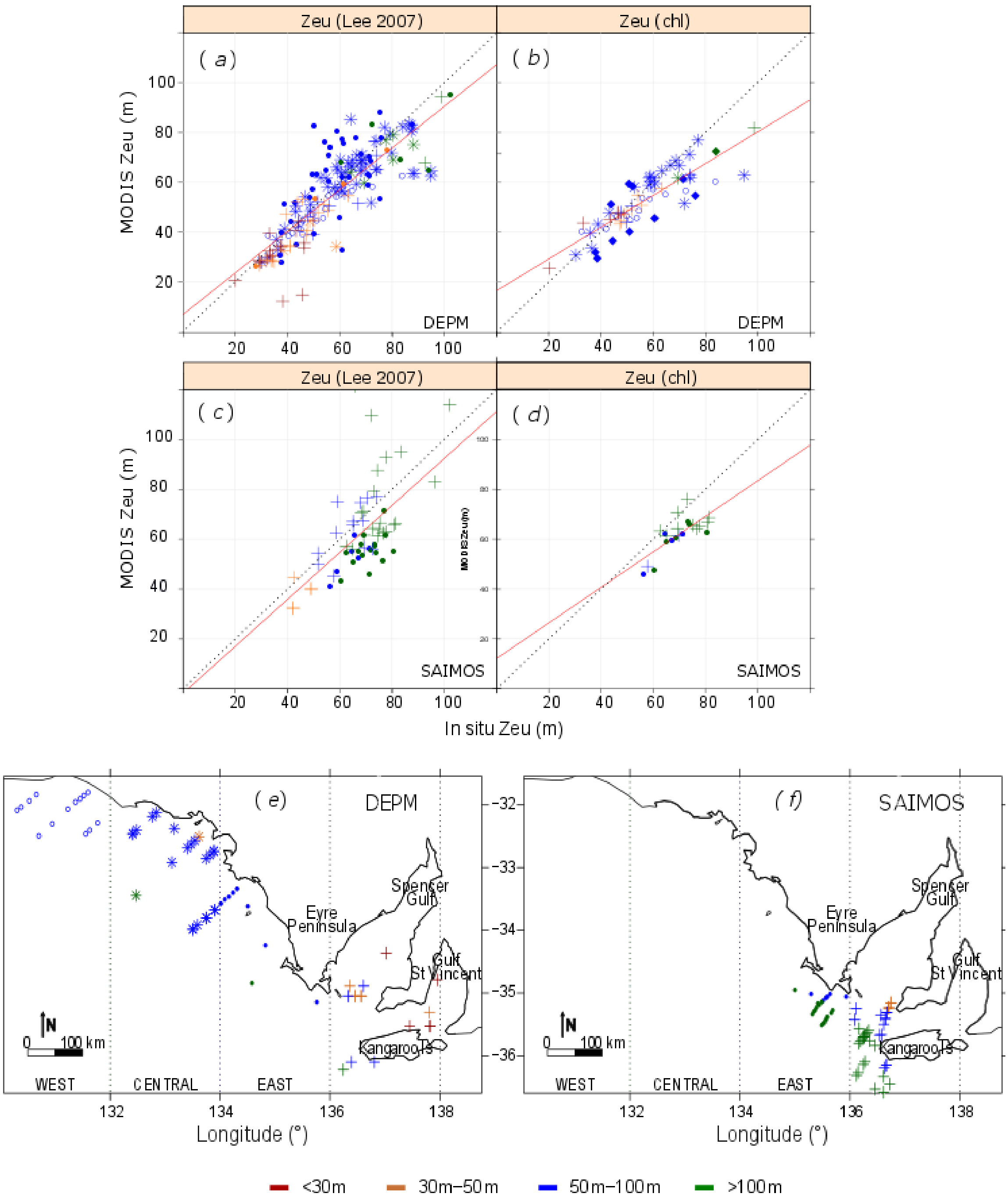

Figure 4. Relationships between MODIS euphotic depth based on (a) Lee (2007) algorithm and (b) surface chlorophyll-a concentration with the field-based euphotic depth data from the DEPM surveys and between MODIS euphotic depth based on (c) Lee (2007) algorithm and (d) surface chlorophyll-a concentrations with the field-based euphotic depth data from the SAIMOS project. The red line corresponds to the fitted line and the black line represents a perfect fit (1:1). The symbols correspond to the different sampling stations from the (e) DEPM and (f) SAIMOS surveys that matched MODIS data. Colours represent different bathymetric depths (green>100m, blue=100-50m, orange=50-30m, red=<30m).

Sea surface temperature

The relationships between MODIS and the field-based SST datasets are good (Figure 5), with an R^2 of 0.84 (n=523, p-value<0.01) and 0.88 (n=190, p-value<0.01) and an RMSE of 0.57°C (2.9%) and 0.53°C (2.95%) for the DEPM and SAIMOS projects, respectively. The MODIS SST followed the field-based measurements well, although it tends to overestimate the SST. A likely cause of this overestimation is diurnal warming, which induces a temperature difference between the surface skin of the sea, observed by the satellite, and the bulk surface temperature (Schluessel et al. 1990).

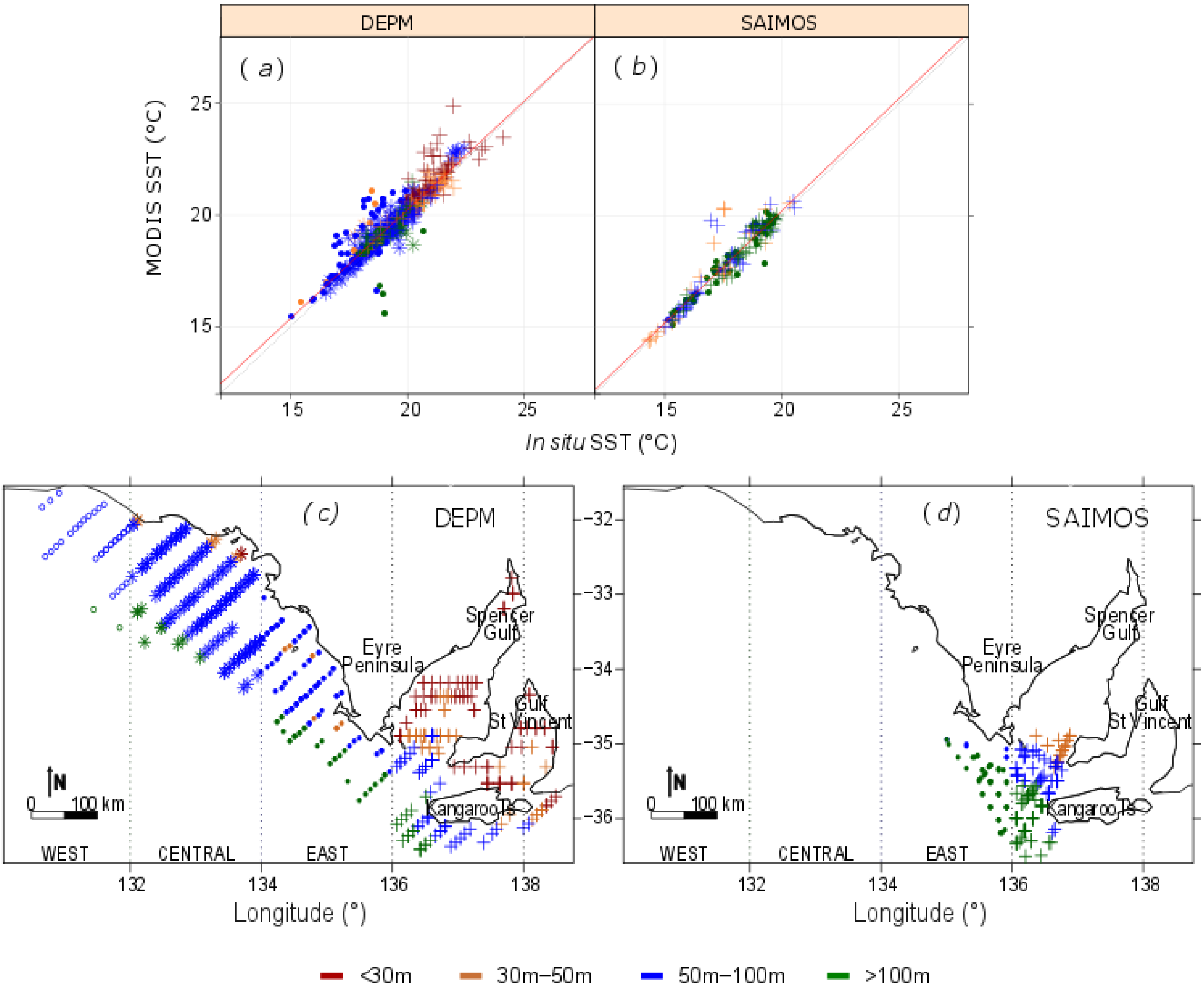

Figure 5. Relationships between MODIS SST and the field-based surface temperature data from the (a) DEPM and (b) SAIMOS projects. The red line corresponds to the fitted line and the black line represents a perfect fit (1:1). The symbols correspond to the different sampling stations from the (c) DEPM and (d) SAIMOS surveys that matched MODIS data. Colours represent different bathymetric depths (green>100m, blue=100-50m, orange=50-30m, red=<30m).

DISCUSSION

To guarantee the quality and consistency of remote sensing data it must be calibrated and validated against field-based observations (Tilstone et al. 2013; Lapucci et al. 2012; Salyuk et al. 2010; van Ruth et al. 2010a). Validation exercises have been performed around the world resulting in improved regional algorithms (Barton 2007; Chang and Gould 2006; Krishna and Rao 2008; Lapucci et al. 2012). We analysed the performance of the MODIS operational chl, Z_{eu} and SST algorithms using historical field-based datasets collected by local sardine DEPM and SAIMOS projects between 2003 and 2014 in the GAB and gulf regions of southern Australia. To our knowledge, this is the first study presenting a validation of remote sensing Z_{eu} and chl concentration imagery in the GAB area using *in situ* and *in vivo* measurements. Previous validation exercises have been carried out in Spencer Gulf in the vicinity of the Port Lincoln aquaculture Tuna Farming Zone (Bierman et al. 2009; Bierman 2010) for chl and SST and their findings are consistent with the results shown here for gulf waters.

In general, the empirical OC3M chl algorithm performed better in open waters, while it tended to overestimate chl values in shallow (depth < 50m) waters. The OC3M was designed primarily for case 1 waters and hence the overall poor performance in the gulfs and shallow waters (which are also generally coastal) is not surprising. Removing data from shallow waters improved the accuracies, with RMSE errors falling below the accepted 35% error limit (Hooker and McClain 2000). In contrast, the semi-analytical algorithms based on the model of Carder et al. (1999) and GSM, which were designed to have an improved performance in optically complex waters, produced consistent results irrespective of whether shallow waters were included. The GSM semi-analytical algorithm produced the lowest errors, although it presented an average slope of ~0.6, overestimating low concentrations of chl and vice versa. Based on these results, the standard OC3M chl algorithm provides the most reliable estimates of chl and is recommended for further applications of MODIS imagery, if the limitations in shallow waters are taken into account. Alternatively, the GSM algorithm could be a better option if the algorithm were locally adjusted.

The correct evaluation of the different satellite products requires accurate field-based measurements; however the methodology used to infer chl concentration was subject to errors (due to limited precision and bias inherent to the methodology). The use of a high-performance liquid chromatography (HPLC) method (currently used by the SAIMOS project) will improve the accuracy of the *in situ* chl data, while developing strict calibration and quality control protocols for the *in vivo* data will provide a more consistent dataset (Guinet et al. 2013).

Optical variability across the study environment affected the performance of the three

operational chl algorithms examined here, and further improvements would be necessary before their utilization for an operational monitoring of the GAB shallow waters. All algorithms showed better relationships with the DEPM *in situ* data within the west GAB and failed to give significant results in the eastern GAB. Such differences may be due to the fact that the east GAB is characterised by a subsurface chl maximum (Kampf et al. 2004; McClatchie et al. 2006; van Ruth et al. 2010a, 2010b) during the upwelling season (Feb/Mar). To generate a locally improved algorithm, sampling efforts should be directed to collecting a comprehensive bio-optical dataset, including *in situ* remote sensing reflectance and spectral absorption coefficients, that would help to determine whether the performance of the algorithms is related to the effect of the spectral ratios considered or to the determination of the spectral contributions of different seawater constituents (Tilstone et al. 2013; Kampel et al. 2009; Lapucci et al. 2012).

The relationships between the MODIS and *in situ* Z_{eu} were robust, with RMSE lower than 20%. For the GAB, the Z_{eu} values derived from the surface chl value were better in terms of RMSE, although they had lower slopes. As with the chl data, the relationships with the *in situ* data from the DEPM surveys (collected during the upwelling season) in the East GAB were notably weaker. The results of the MODIS Z_{eu} derived from surface chl profiles were robust even in shallow waters. The Z_{eu} does not depend on a specific absorption coefficient and, compared to chl, it is much easier and more accurate to determine in the field and less subject to errors due to limited precision and bias inherent to the methodology, thus Z_{eu} produced very small errors compared with the chl data. Our results indicate that derived Z_{eu} could be used with confidence in applying MODIS products for monitoring water clarity and, ecosystem health or primary productivity in the region.

The relationships between MODIS SST and the field-based SST were good, with RMSE lower than 3% (<0.6°C) for the two datasets examined. Although the satellite data showed a general overestimation of temperature values, this may be due to the "skin effect" (Schluessel et al. 1990): the satellite measures the temperature of the immediate skin of the sea surface (first few millimetres), which has higher temperatures relative to the deeper waters due to absorption of incoming shortwave radiance. In contrast, field-based temperature, obtained from the CTD, measures the bulk surface temperature at depths between 1m and 5m, hence the SST measured by the satellite appears to overestimate the *in situ* temperature. This effect occurs during the day and, in particular, during low wind conditions when the vertical mixing is reduced. Despite this, the validation of the satellite SST showed good results and hence SST may be used for further applications within the GAB.

CONCLUSIONS

We have evaluated the performance of the satellite-based measurements of chl, Z_{eu} and SST against field-based measurements within the GAB. The performance of the OC3M chl algorithm, although reliable within open waters, is poor within the gulfs, while the GSM algorithm produced the least errors but less dynamic range. The chl algorithms could be re-evaluated and improved to be used with confidence in the GAB area. The Z_{eu} and SST showed good performance, and form a reliable dataset to be used for future applications within the GAB.

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