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Cécile Dupouy[1], Guillaume Wattelez[1,2], Rosalie Fuchs[1], Jérôme Lefèvre[1], Morgan Mangeas[2]
Hiroshi Murakami[3], Robert Frouin[4]

[1] MIO, CNRS/IRD/AMU/USTV, 7295, 235, Centre IRD de Nouméa, BPA5, 98848 New Caledonia
[2] ESPACE-IRD 140, Centre IRD of Noumea, Univ. New Caledonia, 98848 New Caledonia,
[3] Japan Aerospace Exploration Agency (JAXA), Tsukuba, Ibaraki 305-8505, Japan
[4] Scripps Institution of Oceanography, La Jolla, California, USA
Corresponding author: cecile.dupouy@ird.fr

Abstract. Satellite and in situ chlorophyll concentration data collected as part of VALidation HYperspectral of a BIOgeochemical model (ValHyBio), a PNTS-sponsored project dedicated to satellite ocean-colour imaging of the Southwest Pacific, are analyzed to describe chlorophyll variability in the Coral Sea, a vast oligotrophic region characterized by a deep chlorophyll maximum and blue waters of high transparency. Average chlorophyll concentrations estimated from MODIS-Aqua are very low (<0.2 mg m^{-3}) except in the vicinity of main islands and coral reefs, where enrichment may occur due to upwelling or internal waves that bring nutrients to the euphotic zone from the deep part of the water column. During the summer season, blooms of cyanobacteria (*Trichodesmium*) develop in the surface waters and may form large slicks. The nitrogen fixed by these slicks is a potential source of new nitrogen later assimilated by picoplankton and the marine food chain. Coastal areas exhibit higher chlorophyll concentrations because of nutrient input from the land, as observed in 2008 around New Caledonia. In lagoon areas, the sea colour is influenced by turbidity and bathymetry, and the MODIS OC3 algorithm is inadequate, with a systematic overestimation of chlorophyll concentration in the New Caledonia lagoon. Improved bio-optical algorithms are needed for those turbid and shallow waters, to allow not only a better description of chlorophyll variability, but also evaluation of chlorophyll simulations by recently developed biogeochemical models.

Key words: Coral Sea, MODIS-DB, VALHYSAT, VALHYBIO, Chlorophyll, *Trichodesmium*

Introduction

The Coral Sea extends more that 2000 km from about 10°S to 30°S in the South Western Tropical Pacific. This vast oligotrophic area is bounded in the North by Papua New Guinea and Solomon Islands, in the East by Vanuatu and New Caledonia, in the West by the East coast of Australia and in the South by the Tasman Front. The region is subjected to frequent rains and tropical cyclones and exhibits a strong seasonal temperature cycle. Surface waters are blue and highly transparent, and a deep chlorophyll maximum is present everywhere (Dandonneau and Gohin, 1984). However, chlorophyll concentration is higher in coastal areas of New Caledonia due to upwelling (Ganachaud et al., 2010), or/and tide-related internal waves (Neveux et al., 2010) that bring nutrients from below. During the summer season, blooms of *Trichodesmium* develop, enhancing surface chlorophyll concentrations over large areas (Dupouy et al., 1988; 1990; 1992; 2000; 2004, cited within review Dupouy et al. 2011). In optically-deep waters, chlorophyll drives variability of bio-optical properties (absorption and backscattering) (classified as Case 1 waters).

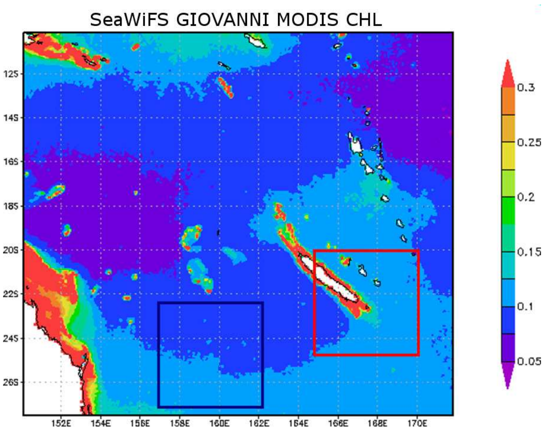

Figure 1: The chlorophyll concentration (mg m^{-3}) of the Coral Sea obtained by MODIS (1997-2010 average). The red square depicts the area of bio-optical algorithm evaluation (PNTS VALHYBIO project). The blue square delineates a typical zone in the south-western Coral Sea.

The New Caledonia lagoon (22 177 km^2 in size and 25 m depth on average) lies in the Coral Sea from 20°S to 22°S, and 166° to 167°E, with a heterogeneous bathymetry due to a complex geomorphology, and a variety of different bottom colours. The New Caledonian lagoon has low input from rivers and is largely connected to the open ocean in the southern part, but only by narrow passes in the southwest. It is very sensitive to anthropogenic perturbations (e.g. nutrients, mining) as well as inter-annual changes linked to the balance between dry El Nino and wet La Nina episodes (Ouillon et al., 2010).

Ocean-colour satellite imagery is the best tool to monitor remote oligotrophic areas. 'Satellite chlorophyll' is a proxy for phytoplankton chlorophyll, itself a proxy for phytoplankton biomass (Yoder et al., 1993). Average chlorophyll concentrations as detected by satellites are very low in the Coral Sea except in the vicinity of main islands and coral reefs, and during summer in the north-east of the area (Fig. 1). Classical MODIS algorithms work well everywhere in Case 1 tropical waters, except around islands, over coral reef areas (Chesterfield atolls, around New Caledonia) and above shoals. In lagoon areas, sea colour is influenced by turbidity and bathymetry (Ouillon et al., 2008; Minghelli-Roman et al., 2010). The lagoon exhibits optically complex waters (classified as Case 2 waters) where mineral particles and coloured dissolved organic matter mix with phytoplankton (Dupouy et al., 2010). Current algorithms such as OC3 for MODIS developed for optically-deep waters have not been adapted to lagoon waters (Dupouy et al., 2010).

In this paper, we present the first MODIS validation of chlorophyll concentration in tropical waters of the Coral Sea (Case 1 waters), and in the New Caledonia lagoon (Case 2 waters). Regressions for MODIS match-ups in chlorophyll are established in the New Caledonia lagoon and adjacent waters as a function of bathymetry (Fig. 1). Here we examine how chlorophyll concentration is estimated from satellite images in different water types, according to their transparency. This is a prerequisite for describing seasonal and inter-annual variability of chlorophyll by remote sensing in the Coral Sea.

Methods

Cruise data

All surface chlorophyll data were compiled from different sampling programs: INSU-PROOF DIAPAZON (2001-2003) and ZONECO-ZONALIS in the open Ocean and INSU-PNEC-EC2CO (Camelia project, IRD-Nouméa, 1997-2004), CNRS-INSU (BISSECOTE, 2006; ECHOLAG, 2007), Programme National de Télédetection Spatiale (PNTS) (VALHYBIO, 2008) in the lagoons. The MODIS/in situ match-up data set, acquired as part of VALHYSAT, a project sponsored by IRD-SPIRALES is comprehensive with over 1000 stations during 2002-2010 and 270 matchup data on the same day (Fig. 2).

In situ chlorophyll measurements

Chlorophyll measurements were analyzed either by spectrofluorometry, with a Hitachi F4500 spectrofluorometer operating in ratio mode (Neveux et al., 2009) or/and by fluorometry (Holm-Hansen et al., 1965). Total chlorophyll (sum of chlorophyll a + divinyl-chlorophyll-a by spectrofluorometry) and chlorophyll-a concentrations by fluorometry are comparable in the study area.

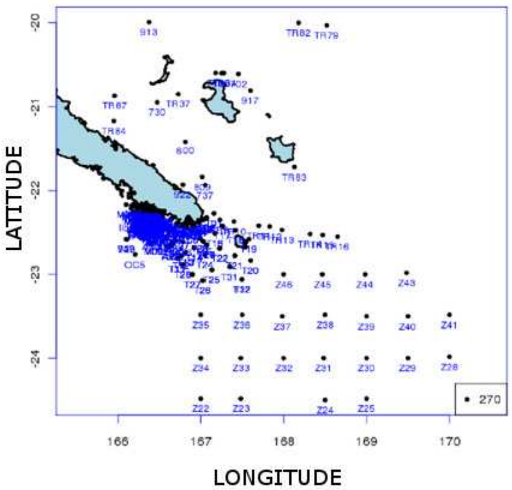

Figure 2: Location of the 270 stations where a coincidence exists between a MODIS-Aqua image and in situ chlorophyll data compiled in the IRD data set (2002-2010).

MODIS-DB satellite data and match-up extraction

MODIS-Aqua is a NASA sensor dedicated to ocean-colour radiometry. As a result of the VALHYSAT project, MODIS Level 2 products in the MODIS-DB database were calculated with Ocean Colour IDL SeaDAS routines for atmospheric correction and MSL12 (Multi Sensor L1 to L2) for chlorophyll determination (Lefèvre, 2010). Satellite reflectance and L2 products were processed at the nominal 1 km x 1 km resolution and also at 500 m x 500 m resolution with the sharpening procedure. Experimental products are maps of chlorophyll concentration obtained with OC3 for MODIS, turbidity, and remote sensing reflectance. Each netcdf file product contains geographic location and bathymetry information (in situ and from MODIS), which allows one to search the mean value of the pixels around the in situ station. A specific mask for the New Caledonian lagoon was made (a composition of 7 SeaDAS masks). Match-ups were selected according to a statistical analysis of standard deviation for pixels acquired within a distance of 1.5 km of the in situ station (Bailey and Werdell, 2006) and observed within 1 to 5 days of the in situ measurement.

Results

The central New Caledonian lagoon is characterized by oligotrophic to mesotrophic waters (yearly average chlorophyll concentration of 0.25 ± 0.01 mg m^{-3}) (Neveux et al., 2009, Fig. 3A).

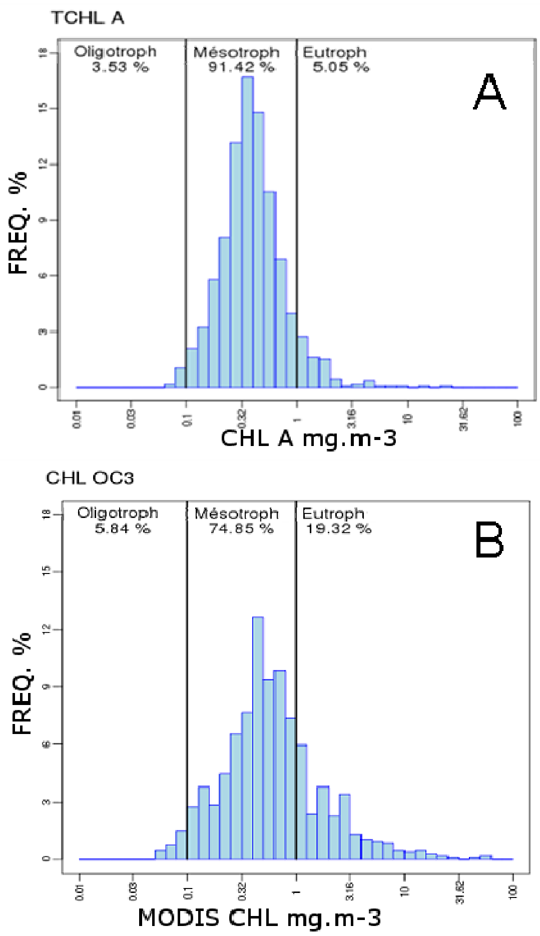

Figure 3: Frequency histogram of in situ chlorophyll measurements archived in the IRD database (top) and frequency histogram of MODIS-DB estimates (bottom).

Three chlorophyll concentration classes were discriminated (oligo-, meso- and eutrophic) with thresholds from Morel and Maritorena (2001). The frequency distribution OC3 MODIS chlorophyll concentration, on the other hand, exhibits a relatively larger proportion of eutrophic waters (Fig. 3B).

The performance of the OC3 algorithm is shown for three data subsets in Fig. 4: open ocean waters, deep (20-70 m) lagoon waters, and shallow (< 20 m). The OC3 algorithm is inadequate for deep lagoon waters (Fig. 4, dark blue points) and shallow stations (Fig. 4, orange points).

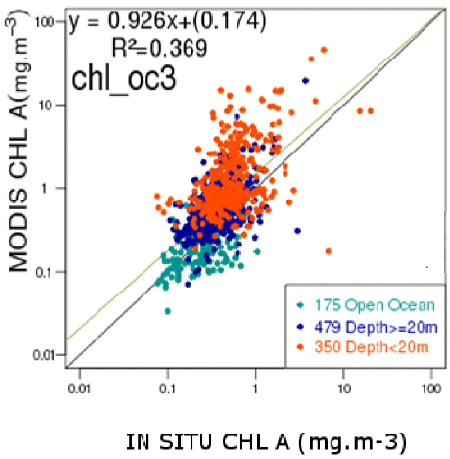

Figure 4: OC3 performance for chlorophyll concentration (CHL A) retrieval in open ocean and lagoon waters. Match-up from 1 to 5 days.

For the open-ocean stations (0.0., Table 1), MODIS underestimates chlorophyll concentration with a normalized mean bias (NMB) of -23%.

Table 1: Statistical results for OC3 chlorophyll retrieval from MODIS- Aqua in the New Caledonian lagoon and adjacent waters. N: data number; CV: variation coefficient; NMB: normalized mean bias; R^2: regression coefficient; O.O.: open ocean. Match-up (1 day coincidence, N=270)

OC3	N	Slope	Intercept	R²	Min	Max
O.O.	47	0.673	-0.34	0.44	0.08	1.3
bathy>20m	74	0.644	0	0.35	0.09	2.02
bathy<20m	21	0.514	0.059	0.29	0.37	2.22

OC3	Avg	Median	CV %	NMB %
O.O.	0.24	0.15	104.36	-23.18
bathy>20m	0.55	0.47	59.27	53.04
bathy<20m	0.79	0.68	57.3	75.17

Overestimation of chlorophyll concentration by OC3 (Table 1) is observed for both stations with depths > 20 m (R^2=0.35 and NMB=53%) and <20m (R^2 = 0.29 and NMB= 75%). This is explained by bio-optical properties driving remote sensing reflectance, for which the absorption and Hydroscat-6 backscattering coefficients are poorly related to chlorophyll (Dupouy et al., 2010). This is also explained by the fact that the signal received by the satellite is influenced by bottom reflectance.

Discussion

Satellite imagery can be analyzed conveniently from the NASA Giovanni ocean colour site. Having determined bias for MODIS chlorophyll estimates, it now becomes possible to monitor chlorophyll from space in the Coral Sea (by applying corrections). As an example, average chlorophyll in the Coral Sea area during the period 1997-2010 is shown in Fig. 5 for the two areas shown in Fig. 1 (extracted from the NASA Giovanni site, uncorrected data). A strong inter-annual signal is observed in the western Coral Sea (in blue). In the eastern zone, where evaluation was done by IRD (in red), the seasonal cycle is not as smooth, with chlorophyll peaks occurring earlier almost each year.

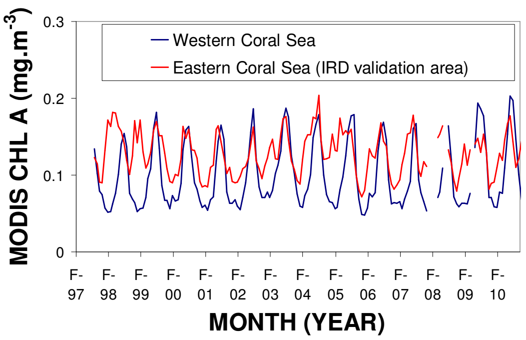

Figure 5: Inter-annual chlorophyll concentration (CHL A) cycle in the two areas of Fig. 1 (from Giovanni, NASA).

More work is required, however, to better interpret this inter-annual variability of chlorophyll concentration in the Eastern Coral Sea (IRD validation zone). In this region, summer blooms have been associated with filamentous cyanobacteria (Moutin et al., 2005; Dupouy et al., 2011). Indeed, cyanobacteria were found to dominate phytoplankton biomass especially during summer seasons (Campbell et al., 2005; Neveux et al., 2006, 2008; Moisander et al., 2010). Their nitrogen fixation can be a source of new nitrogen later assimilated by picoplankton and the marine food chain (Garcia et al., 2007; Masotti et al., 2007). Apart from *Trichodesmium*, other non-filamentous cyanobacteria are also present in the north of the area (Papua-New Guinea) and in lagoon waters (Biegala and Raimbault, 2008). In coastal areas as well as lagoons, chlorophyll concentration increase is related to land inputs, and enrichments are associated with river discharge or land-based water runoff after rain (Dupouy et al., 2008; 2009). Other species (e.g. diatoms), which may be influenced by heavy land runoff during rainy periods and resulting from a succession of different groups, may also occur.

For lagoon waters inside the barrier reef, an overestimation of chlorophyll concentration by MODIS was observed with OC3 as colour is influenced by other components (sediments, Dissolved Organic Matter). Improved algorithms have to be developed to deal with those situations. This will allow the validation of chlorophyll simulations by recently developed coupled biogeochemical models in the New Caledonian lagoon (Fuchs et al., 2010).

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