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An algorithm for detecting *Trichodesmium* surface blooms in the South Western Tropical Pacific

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Abstract

Trichodesmium, a major colonial cyanobacterial nitrogen fixer, forms large blooms in NO_3-depleted tropical oceans and enhances CO_2 sequestration by the ocean due to its ability to fix dissolved dinitrogen. Thus, its importance in C and N cycles requires better estimates of its distribution at basin to global scales. However, existing algorithms to detect them from satellite have not yet been successful in the South Western Tropical Pacific (SWTP). Here, a novel approach based on radiance anomaly spectra (RAS) observed in SeaWiFS imagery is used to detect *Trichodesmium* during the austral summertime in the SWTP. Selected pixels are characterized by a restricted range of parameters quantifying RAS spectra quantitative parameters (e.g. slope, intercept, curvature). The fraction of valid pixels identified as *Trichodesmium* surface blooms in the region 5° S–25° S 160° E–190° E is low (between 0.01 and 0.2 %), but is about 100 times higher than suggested by previous algorithms. This represents a total surface area which varies from 1500 to 20 000 km^2. A monthly distribution of *Trichodesmium* surface accumulations in the SWTP is presented which demonstrates that the number of selected pixels peaks in November–February each year, consistent with field observations. This approach was validated with in situ observations of *Trichodesmium* surface accumulations for the period 1998–2010.

1 Introduction

The balance between oceanic N_2 fixation and nitrogen losses (denitrification) in the ocean has been postulated to regulate atmospheric CO_2 over geological time via the enhancement of biological sequestration of CO_2 (Falkowski, 1997; Gruber and Sarmiento, 1997; Deutsch et al., 2007). Unicellular (Zehr et al., 2001, 2011; Montoya et al., 2004; Church et al., 2008, 2009) and filamentous cyanobacteria (Capone et al., 1997, 2005; LaRoche and Breitbarth, 2005; Bonnet et al., 2009; Moisander et al., 2010) incorporate this form of "new" nitrogen (N) into the marine food web of tropical and subtropical oceans (Berman-Frank et al., 2004; Mahaffey et al., 2005; Mulholland, 2007). N_2 fixation is considered to be the major source of new N in stratified, oligotrophic tropical oceans (Capone et al., 1997; Karl et al., 2002). Future change in sea surface temperature (Breitbarth et al., 2006) or/and CO_2 concentration are expected to stimulate photosynthesis (C fixation) and N_2 fixation by filamentous cyanobacteria, particularly by *Trichodesmium* spp. (Barcelos et al., 2007; Hutchins et al., 2007; Kranz et al., 2009; Levitan et al., 2010). This enhancement of *Trichodesmium* growth could compensate the decreased growth of other phytoplankton owing to a presumed decrease of nitrate supply.

Trichodesmium spp. can form extensive blooms which have been observed for a long time in the Western Pacific Ocean, particularly in austral summer (Dandonneau and Gohin, 1984). The presence of four major archipelagos (Solomon, New Caledonia, Vanuatu and Fiji-Tonga), and their potential for oceanic iron enrichment from land may trigger these cyanobacterial blooms (Bowman and Lancaster, 1965). The blooms appear as brown or orange meandering patterns around those archipelagos (Dupouy et al., 1988; Dupouy, 1990; Tenório, 2006; Hashihama et al., 2010), are clearly detected from the International Space Shuttle (December 2001 around Tonga Islands), and were recently highlighted by the NASA Ocean Color Website (Feldman et al., 2010). Blooms are also regularly observed in waters of the Dampier Archipelago, the Arafura Sea (Neveux et al., 2006) and off the Great Barrier Reef (Kuchler and Jupp, 1988; Furnas, 1989; Bell et al., 1999). *Trichodesmium* was reported in the Western North Pacific (Shiozaki et al., 2009; Kitajima et al., 2010; Konno et al., 2010). Nevertheless, observations in the SWTP contradict the recently published global map of *Trichodesmium* analogs based on ecosystem model results that indicate a predominance of higher densities in the North Pacific than in the South Western Pacific Ocean (Monteiro et al., 2010).

Estimating the occurrence of *Trichodesmium* surface blooms from satellite is a major challenge, but will be required for large-scale estimates of nitrogen fixation (e.g., Westberry et al., 2005; Westberry and Siegel, 2006). Regional algorithms have been successfully applied on the Atlantic continental shelf (Subramaniam et al., 2002), off Canary Islands (Ramos et al., 2005) as well as the Indian coast (Sarangi et al., 2004) and with higher resolution sensors like MODIS (Hu et al., 2010; McKinna et al., 2011). Global algorithms have also been recently developed for estimating phytoplankton community structure in the surface oceans. PHYSAT algorithm was successful in identifying *Synechococcus*-like cyanobacteria with maxima in the tropics, and found that they are particularly abundant in the SWTP (Alvain et al., 2005). The SCHIAMACHY sensor also detects a cyanobacterial signal within the same latitudinal band (Bracher et al., 2008). However, all algorithms generally fail at identifying seasonality of *Trichodesmium* blooms in the SWTP and none retrieve the relatively high abundance of *Trichodesmium* surface blooms expected and observed in situ during austral summer (November to March). Here we develop an algorithm to detect *Trichodesmium* surface blooms in the SWTP which is based on SeaWiFS radiance anomalies (similar to PHYSAT) and apply it to SeaWiFS data from 1997–2010.

2 Material and methods

2.1 Data

2.1.1 In situ observations

Aerial photographs provided by the French Navy around New Caledonia and whole water samples collected with a bucket during transects and cruises conducted on French Navy and research vessels between New Caledonia, Vanuatu, Fiji and Wallis and Futuna Islands were compiled (15° S to 23° S, 160° E to 180° E) (Dupouy et al., 2004a). Samples were preserved on board in a 4 % formalin solution. Identification of diazotroph morphological groups was made under a Zeiss microscope. In addition, sampling was done with 8 l Niskin bottles (sometimes with bucket sampling for comparison) during nine independent cruises as part of the DIAPAZON research program

(Diazotrophy in a PACific Zone) between October 2001 and October 2003. In this case, chlorophyll and phycoerythrin measurements were obtained from spectrofluorometry (Lantoine and Neveux, 1997; Neveux et al., 1999, 2006) and filamentous cyanobacteria counts obtained from inverted microscopy (Tenório, 2006). A slightly higher concentration of chlorophyll was observed from bucket samples compared to those from Niskin samples.

2.1.2 Satellite ocean color data

For the development of the new algorithm, representative global SeaWiFS Level3 data (R2009) were selected at summer and winter seasons, and included normalized water leaving radiance, nLw (λ), at 6 channels (412, 443, 490, 510, 555, and 670 nm) as well as SeaWiFS chlorophyll and the diffuse attenuation coefficient at 490 nm (K490 product). From these data, a Look Up Table (LUT) relating K490 to remote sensing reflectance was created (see Sect. 2.2). However, to avoid compositing artifacts upon application of the LUT, daily SeaWiFS Level-2 GAC (R2009) between 1998–2010 and covering the Western Pacific Ocean (160° E–160° W/25° N–25° S area), were used.

2.2 Methods

The general approach was to define a spectral radiance anomaly from SeaWiFS nLw (λ) that was specifically related to *Trichodesmium* surface blooms. It aimed at removing the first order variability in ocean color caused by chlorophyll concentration while preserving the variability that may be specifically caused by individual phytoplankton species or other optically active components. This objective is similar to the PHYSAT classification method (Alvain et al., 2005) that was initially developed for discrimination of major phytoplankton groups in Case 1 waters. Waters dominated by diatoms, *Prochlorococcus*, *Synechococcus*-like cyanobacteria or haptophytes could thus be classified according to their radiance anomaly spectra (RAS):

$$nL*w(\lambda) = nLw(\lambda)/\langle nLw(\lambda)\rangle \quad (1)$$

where $\langle nLw(\lambda)\rangle$ is the expectation of nLw at a given chlorophyll concentration, computed as the average of a large global SeaWiFS dataset, and $nL*w$ is the radiance anomaly relative to this average. The main advantage of PHYSAT is to provide thresholds allowing characterization of RAS at each pixel. PHYSAT uses Look Up Tables (LUT) of $\langle nLw(\lambda)\rangle$ as a function of chlorophyll (chl-*a*).

Here, we employed a LUT based on the diffuse attenuation coefficient at 490 nm (SeaWiFS "K490"). K490 has the advantage over chlorophyll of being computed straightforwardly while operational SeaWiFS chlorophyll estimates result from switching between three wavelength ratios. This new LUT was built using four daily, global Level-3 images from 15 February, 15 May, 15 August and 15 November 2002, in order to encompass a seasonal cycle. It contains the likelihood of SeaWiFS radiances, noted $\langle nLw(\lambda)_{K490}\rangle$, for all K490 values in the $0.0186\,\mathrm{m}^{-1}$ to $0.2499\,\mathrm{m}^{-1}$ interval. Radiance anomaly spectra (RAS) are then computed as

$$nL*w_{K490}(\lambda) = nLw(\lambda)/\langle nLw(\lambda)_{K490}\rangle \quad (2)$$

where $nLw(\lambda)$ are the SeaWiFS radiance estimates. At the end, we checked that results are strictly equivalent than when chl-*a* is used as in PHYSAT. Radiance anomaly spectra $nL*w\_K490$ hereafter denoted RAS can thus be considered as equivalent to PHYSAT $nLw*$.

There is another significant difference between the approach used here compared to the previous PHYSAT effort. Instead of defining RAS thresholds and associating them with pigment classes (and thus, different phytoplankton groups), the new algorithm defines quantitative shape and magnitude criteria of the RAS itself. Eighteen summer scenes around New Caledonia in 2003 (Yeardays: 6, 13, 18, 32, 35, 40, 44, 47, 49, 52, 59, 62, 66) and in 2004 (Yeardays 41, 48, 53, 63, 77) were selected as they correspond to periods where high abundance of *Trichodesmium* was observed in the surface ocean (Tables 1 and 2). The definition of the RAS of *Trichodesmium* surface blooms on the SeaWiFS satellite imagery was generated for pixels around New Caledonia and Fiji from these 18 scenes. The RAS was calculated and the "shape" and magnitude criteria of this RAS examined as shown in Fig. 1a. The criteria have been chosen in such a way that they permit to rebuild RAS spectra.

RAS spectra could be described by the coefficients of a polynomial fit (degree 2). However, such coefficients do not provide an easy to understand image of these spectra; for instance, the square term coefficient is not representative of concavity or convexity of spectra between 412 and 670 nm when the top of the parabola is far away from this interval. We thus retained the following criteria for an objective description of the *Trichodesmium* RAS (Fig. 1a): (1) slope of the linear fit of RAS vs. wavelength (S), (2) curvature as given by the coefficient of the square term in the second degree polynomial fit after removal of the linear trend (a), (3) the ordinate of the second degree fit for which the tangent is parallel to linear fit (Yt). Additional criteria related to the shape of the RAS were defined as the major positive and major negative deviations relative to the second degree polynomial fit (largest "bump" noted Bu. or largest "trough" noted Tr., respectively). Knowledge of these criteria permits to rebuild the RAS spectra.

3 Results

3.1 Field observations

In situ visual observations of *Trichodesmium* blooms around New Caledonia between 1998 and 2004 are presented in Table 1 and average cruise and transect water column surface biomass and abundance are presented in Table 2. The abundance of *Trichodesmium* spp. in the SWTP exhibited a strong seasonality as previously pointed out (Dupouy et al., 2004a; Moutin et al., 2005) with the highest number of visual observations (65 % or 61 over 93 total observations) over the study period (November 1998 to June 2010) occurring between December and February (Table 1, Fig. 2a, b). Surface blooms were never detected during winter (Table 1). In the Loyalty Channel (2001–2003), direct visual bloom observations were available during three of the nine Diapalis dedicated cruises (Table 2). Nearly every year, surface blooms developed between New Caledonia and Vanuatu and one of these blooms was exceptionally well tracked (February 2004, Table 1). Slicks were first observed in November 2003 near Vanuatu (17.65° S, 167.56° E), in December 2003 at the north and south of New Caledonia, in January (on 26 at 22° S and on 29–30 at 20.33° S/166.12° E) then in February 2004 (on 1st around New Caledonia and on 12–16 near Vanuatu and again north of New Caledonia at 19.499° S, 169.54° E). The surface bloom persisted after heavy rains and wind-mixing by Category 4 cyclone Ivy on 24 February. It was detected near New Caledonia (on 26 February), and under calm meteorological and sea conditions, its slick was sampled on 28 February showing an orange surface scum (around 21° S, New Caledonia) or large flocks of dead colonies (at 18.55° S, 166.05° E, Vanuatu) which disappeared in the evening (17.38° S, 166.07° E) (Motevas cruise, Table 2). In March, white senescent *T. erythraeum* (1–4 March, at 22° S, 167° E and 20.16° S/168.71° E) and remnant coastal slicks on (29 March) were seen near Vanuatu (17° S, 167° E). In April, remnant slicks were seen nearby Lifou Island (Table 1).

Among the pelagic species described in the Pacific region (Revelante and Gilmartin, 1982; Carpenter et al., 1993), a high morphological diversity of filamentous cyanobacteria as described by Lundgren et al. (2005) and Tenório (2006) was observed in our surface samples. Colonies were essentially composed of small rafts from 10 to 50 filaments, small in length (noted *T. erythraeum*), or long and twisted rafts (noted *T. thiebautii*) of 50–100 filaments. Long and curved filaments composed of cells larger than long, and some thinner filaments with cells 5–6 fold longer than wide were noted *K. pelagica* and *T. tenue*, respectively. The distribution of these four morphotypes is shown in Fig. 2b. There is no evidence that the same *Trichodesmium* genus or species is widespread all over the tropics except for the *Katagnymene* form (Lundgren et al., 2005). We tended to find *T. erythraeum* near the New Caledonia mainland but elsewhere most of the morphotypes were mixed. During the peak observed *Trichodesmium* abundance in 2004, and along a transect from New Caledonia (20–21° S) to Vanuatu (19° S–17° S), short tufts of *T. erythraeum* were observed at the beginning of the transect (NC) and a mix of *T. thiebautii* (50 %), *T. tenue* (25 %), *erythraeum* (15 %), and *Katagnymene pelagica* and *spiralis* (10 %) dominated populations at the end (Vanuatu). This population change was also seen in fluorescence excitation spectra of phycoerythrin (change in the phycourobilin/phycoerythrobilin ratio, as in Neveux et al., 2006). Mixed assemblages of *T. erythraeum*, *T. thiebautii*, and *T. contortum* filaments were also observed on the 2 and 9 February 2005 around Fiji and Tonga Islands (Hashihama et al., 2010), while floating puffs and tufts of mixed taxonomy were observed in March 2007 (I. C. Biegala, personal communication, 2008). Only *K. pelagica* + *T. tenue* colonies were found isolated near the Niue Island (Table 1, Fig. 2b). The determination of biomass in surface slicks was often difficult (e.g., chl-*a* up to $20\,\mathrm{mg\,m^{-3}}$, Tenório, 2006).

Low filament densities characterized the end of the bloom season in April 1998 (Dupouy et al., 2000; Campbell et al., 2006). During the 2001–2002 Diapalis cruises and along the 2002 transects, densities were rather low except along the transect 5 in May 2002, where phycoerythrin spectral characteristics confirmed the dominance of *Trichodesmium* between New Caledonia and Vanuatu. *Trichodesmium* was abundant in 2003, in the vicinity of the islands during transect 5 in April 2003 (Table 2). Maximal *Trichodesmium* contribution to chl-*a* of 50–70 % was observed with a high density of 5000 filaments/L and maximal biomass 1.9 and $14\,\mathrm{mg\,m^{-3}}$ for chl-*a* and phycoerythrin, respectively during Motevas in February 2004 (Dupouy et al., 2004b, 2008). Densities were similar to those observed during February 2003 during the DIAPAZON program (Tenório, 2006; Neveux et al., 2006; Masotti et al., 2007).

3.2 Detection of *Trichodesmium* in satellite data

In summer 2003 and 2004, the majority of pixels for the region around New Caledonia exhibited a peculiar RAS. These RAS characteristics were examined under the assumption that instances where chl-*a* $> 0.2\,\mathrm{mg\,m^{-3}}$ were dominated by *Trichodesmium* while those with $< 0.2\,\mathrm{mg\,m^{-3}}$ were not, similar to in situ observations. For chl-*a* $> 0.2\,\mathrm{mg\,m^{-3}}$, linear slopes of the RAS varied between -0.005 and $0.008\,\mathrm{nm^{-1}}$, and the tangent ordinate Yt varied within a range of 0.8 to 1.4. For chl-*a* $< 0.2\,\mathrm{mg\,m^{-3}}$, the RAS slope varied within -0.005 to 0.012, while Yt also varied between 0.8 to 1.4.

It was found that RAS of pixels corresponding to *Trichodesmium* surface blooms had a specific shape. These RAS spectra were characterized by: (1) lack of a "bump" at 555 nm (flat RAS or trough at 555 nm) and (2) always a "bump" at 670 nm and never a trough at 670 nm (Fig. 1b). Criteria for 412, 443, 490 and 510 nm were rather neutral. No weighting of these criteria was necessary for the selection of pixels which approach this ideal shape. The criteria of the RAS for the 555 nm and 670 nm SeaWiFS channels were essential while the criteria for other wavelengths were less useful. On the contrary, quantitative criteria of the RAS defined as in Fig. 1b were discriminant. A narrow range of slopes S (S between −0.0019 and −0.0017) and intercepts Yt (Yt between 0.9725 to 1.0175) characterized *Trichodesmium* pixels (Fig. 1b). These ranges corresponded to low but not minimal values of the total slope range (−0.005 to +0.01), and to a narrow interval of values of the total intercept Yt range (0.8 to 1.4) (Fig. 1b). Ultimately, it appeared that the peculiar RAS shape and quantitative criteria was independent of the chl-*a* of the pixels.

The application of *Trichodesmium* RAS criteria to all SeaWiFS Level-2 data from 1997 to 2010 within the whole Western Pacific ocean region (25° N–25° S and 160° E–160° W, noted WP) is shown in Fig. 3. The application of the shape criteria and the quantitative criteria separately were not sufficient to discriminate *Trichodesmium* surface bloom pixels (Fig. 3b, c). The TRICHOSAT (TRICHOdesmium by SATellite) algorithm finally selected the pixels which satisfy both criteria (Fig. 3d), i.e. the intersection of the two groups selected by the shape criteria or the quantitative criteria. Note that the algorithm selection differs markedly from the distribution of pixels with chlorophyll concentration greater than 0.2 $\mathrm{mg\,m^{-3}}$ (Fig. 3a). *Trichodesmium* flagged pixels are not necessarily associated with high chlorophyll content pixels, similar to Westberry and Siegel (2006).

In order to get statistically coherent results for the comparison of the percentage of *Trichodesmium* pixels identified for each year and season, it was verified that a large number of processed SeaWiFS Level-2 GAC images ($5 \times 10^4 – 1 \times 10^6$ pixels with quasi equivalent numbers of non-cloudy valid pixels) were screened (Fig. 4).

Figure 5 shows the temporal evolution of the percentage of *Trichodesmium* bloom pixels identified by TRICHOSAT. The algorithm was applied to the WP defined as in Fig. 3, and to the "SP" box corresponding to the South Western Tropical Pacific (5° S–25° S, 150° E–190° E). Regular peaks were observed from December–February nearly every year over the 12-year period examined, albeit with strong inter-annual variations in the monthly maximum percentage of retrieved *Trichodesmium* pixels exhibited strong inter-annual variations. For the SP box, the percentage was above 0.2 % in 1999 and in 2004–2005 and dropped to 0.01 % in winter. This is equivalent to total surface areas varying between 1500 km^2 in winter and 10 000 km^2 in summer with a grand maxima in January 1999 of 26 000 km^2. For the WP box, the percentage was much reduced with a maximum of 0.03 %. Indeed, the percentage was comparatively greater for SP box because there were only a few *Trichodesmium* pixels detected in the Northern half of the domain. Note that only a few *Trichodesmium* peaks correspond to a secondary chlorophyll maximum, which further illustrates the independence of bloom occurrence and chlorophyll concentration.

A composite of all *Trichodesmium* surface pixels detected for the 1997–2010 period in the SWTP is shown at Fig. 6. A higher number of selected *Trichodesmium* pixels in summer is visually evident (Fig. 6a), as well as the very low number of retrieved pixels for the interseason (Fig. 6b) and the winter season (Fig. 6c). In February 2003 (summer), TRICHOSAT selected pixels spread out between Vanuatu and the northwestern part of New Caledonia and Fiji (Fig. 7a). During winter (July), no pixels were detected around New Caledonia (Fig. 7b). The few *Trichodesmium* pixels at the southern limit of the equatorial upwelling could correspond to observations of *Trichodesmium* blooms in the southern and northern convergence zones of the upwelling (Lebouteiller et al., 1992; Blanchot and Rodier, 1996). The reproduction of the temporal evolution of the 2003–2004 surface bloom observations by TRICHOSAT was striking as a result of a successful in situ survey by the French Navy and the *Alis* ship (Fig. 8).

4 Discussion

4.1 General considerations of the algorithm

4.1.1 A rather linear RAS spectrum

TRICHOSAT identifies pixels for which the RAS is characterized by a narrow range of S (small negative numbers) and of Yt (values near 1) which implies a relatively linear RAS spectrum compared with the total range of S and Yt found within the whole Pacific Ocean. Shape criteria (bumps and troughs), of the RAS are also essential as the intersection between shape and RAS quantitative criteria is required for the successful selection of *Trichodesmium* bloom pixels (Fig. 3). This means that the RAS spectra of *Trichodesmium* blooms are very similar to what is expected at a given chlorophyll concentration contrary to other phytoplankton groups for which the PHYSAT approach is based specifically on low or high reflectance relatively to the detected chlorophyll content (Alvain et al., 2005). Westberry et al. (2005) also found remarkably similar bulk reflectance spectra for cases which contained moderate amounts of *Trichodesmium* compared to those where it was absent.

4.1.2 A rather weak relationship with biomass

The RAS is by definition, independent of chlorophyll concentration (second order anomaly). Therefore, it is not surprising that selected pixels correspond to a large range of chl-*a* values, from 0.07 to 0.3 $\mathrm{mg\,m^{-3}}$. It has already been shown that chlorophyll associated with surface accumulations of *Trichodesmium* is highly variable. Also, a well-known underestimation of chlorophyll by SeaWiFS due to a strong package effect in filaments and colonies (Subramaniam et al., 1999; Dupouy et al., 2008) was observed but this would concern only living colonies. As TRICHOSAT probably screens pixels containing high *Trichodesmium* concentrations mixed in the upper oceanic layer or forming surface accumulations, this might alter the relationship between reflectance and chlorophyll concentration.

4.1.3 Comparison with previous algorithms

The percentage of TRICHOSAT selected pixels in the New Caledonia region (Fig. 7a, b) is low (maximum 0.2 % of total valid pixels). Nevertheless, the algorithms of Subramaniam et al. (2002) and Westberry et al. (2005) (hereafter denoted as W05) detect even fewer pixels (100 times less). In the SWTP, the W05 algorithm retrieves only highly reflectant pixels, most of which correspond to the extremely high reflectance of New Caledonia or Fijian sandy lagoons or Islands. Further, apart from the coastal lagoon pixels, only 15 points are identified as *Trichodesmium* by W05 and there is no indication of seasonal variation. Recall that the W05 algorithm was built to detect *Trichodesmium* at bloom concentrations (chl-*a* threshold for a bloom was set to 0.8 mg m^{-3}) while TRICHOSAT detection does not imply chl-*a* concentration threshold. The rather weak spectral anomalies of *Trichodesmium* pixels may explain why W05 does not detect more blooms in the South Western Tropical Pacific. The first published set of criteria for screening pixels containing *Trichodesmium* overemphasized backscattering (for $\lambda > 500$ nm) and Colored Dissolved Organic Matter (CDOM) absorption (for $\lambda < 440$ nm) so that finally a refined model using subtle variations in reflectances between phytoplankton and *Trichodesmium* spectra had to be used (Westberry and Siegel, 2006). In the SWTP, *Trichodesmium* bloom signatures may not be strong enough to be detected by W05, or blooms occur in filaments whose signatures may not be strong enough to affect 16 km^2 pixels. Finally, living colonies of *Trichodesmium* are often associated with other phytoplankton as observed during the Diapalis 7 cruise (Tenório, 2006) and serve to create a mixed optical signal obfuscating detection. *Trichodesmium* biomass could then be well below the W05 detection threshold, and/or the other phytoplankton biomass would be higher in proportion in the SWTP than in the Northern Hemisphere. This may also explain why the W05 algorithm detects similar *Trichodesmium* pixel numbers in winter and in summer. Overall, TRICHOSAT was tuned to detect the *Trichodesmium* blooms that we have observed in the field in summer, and the W05 algorithm fails to detect these blooms.

4.2 Optical validation of the algorithm

Ideally, one would validate the RAS of TRICHOSAT detected *Trichodesmium* pixels with *in situ* radiometric measurements made in *Trichodesmium* surface blooms. Unfortunately, such a task is difficult as there is no direct measurement of the RAS which would require accurate measurements of above/in water reflectance. Past work has recognized this as problematic (Subramaniam et al., 1999; Kutzer, 2009). Recall that the *Trichodesmium* bloom RAS is defined by a very small range of S and Yt. This implies that Level2-GAC (4 × 4 km) SeaWiFS spectra are not so different from what they are expected at a given K_{490} (i.e. at a given chl-*a*) despite the fact that filamentous cyanobacteria blooms appear brighter than surrounding water areas due to high backscattering associated with gas vesicle and to a microbiotope (bacteria, detritus) (Subramaniam et al., 1999).

One of the TRICHOSAT shape criterion is that the RAS must never show a bump at 555 nm. It is well known that reflectance spectra of colonies, assembled on filters (Dupouy et al., 2008) are characterized by a succession of troughs, each trough corresponding to different pigment absorption maxima (e.g., chlorophyll, phycourobilin and phycoerythrobilin). Phycoerythrin absorption in yellow wavelengths are observed in *Trichodesmium* suspension (PSICAM measurements, Dupouy and Röttgers, 2010), in raw H6-backscattering spectra (absorption at 550 nm along the pathway of backscattered light, Dupouy et al., 2008, and observed in situ during the 2004 bloom, unpublished data).

The second robust criterion is that the RAS must never show a trough at 670 nm (rather a bump at 670 nm). It has been shown that high near-infrared reflectance is observed if colonies are accumulated on top of the water (Subramaniam et al., 1999; Dupouy et al., 2008). RAS would then depend on the proportion of colonies lying above the water surface which will depends on thickness, or/and on the physiological characteristics of colonies, or age of the bloom (Dupouy et al., 1990, 1992, 2008). The high reflectance of blooms at 670 nm which was observed with CZCS could provide an approach to detecting slicks for MODIS (McKinna et al., 2011; Hu et al., 2010) or IRS-P4 OCM (Sarangi et al., 2004).

There was no robust criteria for the RAS at 412 nm even though a significant RAS feature was expected at this wavelength as it has been shown that colonies are heavily protected against UV due to the presence of Mycosporine-like Amino Acids (MAAs), and that Dissolved Organic Carbon (DOC) and CDOM is released from dead or living colonies (Subramaniam et al., 1999). Such a high absorption by *Trichodesmium* colonies at 330 and 360 nm was effectively observed along Motevas (February 2004, Table 2; Dupouy et al., 2008) with ~10× higher absorption at 0 m than at 5 m and an increase along the transect from New Caledonia to Vanuatu at both depths.

Optical characteristics of surrounding waters may also be important for defining RAS of *Trichodesmium* blooms. As seen in Fig. 5b, the dissolved matter + detritus absorption coefficient, ACDM (derived from the GSM optical inversion model at 412 nm; Maritorena et al., 2002), for the SP box experiences a strong seasonal variation due to the well documented annual cycle of solar bleaching and photolysis in the South Pacific (Siegel et al., 2002; 2005). *Trichodesmium* surface blooms correspond to the period of minimum CDOM concentration in summer. In the SP, some peaks are associated with a secondary CDOM maximum which could be produced by blooms (e.g., February 1999, 2003, 2004 and 2006). In contrast, the particulate backscattering coefficient, *bbp* (also derived from Maritorena et al. (2002) was rather constant over the 12-year period (Fig. 5 b). *Trichodesmium* blooms correspond to the period of minimum backscattering, as a weak maximum appears in June–September (more or less in phase with chlorophyll concentration). The *bbp* cycle in the SWTP could be linked to small-sized detritus as suggested by Loisel et al. (2006) rather than to *Trichodesmium* blooms.

4.3 Relationships with other cyanobacteria in the water column

We find austral summer maxima of surface blooms detected with TRICHOSAT (Fig. 5a) to correspond with the inter-annual variations of *Trichodesmium* abundances in the surface layer (0–150 m, Table 2). Low densities were observed in situ in April–May

2002–2003 and October 2002–2003 (Table 2) which also appear as minima of surface bloom extent identified by TRICHOSAT. A surprisingly low *Trichodesmium* concentration (200–400 trichomes/L) was observed in December–January 2001 compared to summers in 2002 and 2003. In June–August 2003 (winter season), *Trichodesmium* was rare and total chlorophyll in the $>10\,\mu m$ fraction was less than 10 % (Table 2). Thus, the community was dominated by picoplankton.

The number of selected pixels by TRICHOSAT is however small. It corresponds to surface blooms, occurring in summer, which occupy a large area according to sea color maps and to field observations. These surface blooms correspond to a physiological state where colonies become buoyant because they cannot synthesize ballast anymore due to phosphate limitation in; colonies thus float as dead material and accumulate at the surface (Moutin et al., 2005). Such conditions may be spatially and temporally de-coupled from sub-bloom *Trichodesmium* concentrations and may not correspond to actively growing *Trichodesmium* colonies. So, the global estimation of dinitrogen fixation by TRICHOSAT remains to be estimated.

Last, the spatio-temporal coupling between *Trichodesmium* and other nitrogen-fixing cyanobacteria needs to be elucidated. Coccoid cyanobacteria (*Chrocosphera*, *Cyanothece*) have been detected from their phycoerythrin signature (Neveux et al., 2006) and flow cytometric properties in the SWTP (Garcia et al., 2007; Campbell et al., 2006; Moisan et al., 2010; Sato et al., 2010). Nitrogen-fixing heterotrophic bacteria have also been identified in the SWTP (Rieman et al., 2010). During summer, nitrogen fixation both from filamentous and coccoid cyanobacteria (Garcia et al., 2007; Hynes et al., 2009) experienced high rates ($151–703\,\mu M\,N_2\ m^{-2}\,d^{-1}$) compared to rates measured at the north of Papua-New Guinea (Bonnet et al., 2009). Late 2007 field observations confirmed the dominance of *Trichodesmium* in association with *Crocosphaera* in the South Pacific, spatially decoupled from unicellular cyanobacteria (Hewson et al., 2009; Moisander et al., 2010; Sato et al., 2010). Despite their low biomass, *Croscosphaera, cyanothece* and picocyanobacteria populations may form a high fraction of total nitrogen fixation which will not be detected by TRICHOSAT.

5 Conclusions

The TRICHOSAT algorithm is efficient at discriminating *Trichodesmium* surface accumulations in the Western Tropical Pacific Ocean. Its results can complement the identification of major functional groups provided by PHYSAT. TRICHOSAT was developed for the SWTP and is even able to follow the weekly evolution of surface blooms within a month (in 2004, Fig. 8). Its application at a global scale requires that the RAS criteria in TRICHOSAT is representative of *Trichodesmium* blooms in other regions, and also that surrounding waters characteristics resemble those in the SWTP, which may not be satisfied elsewhere than in the SWTP. Reasons why detection of *Trichodesmium* with TRICHOSAT was much more successful than with other algorithms (100 times more pixels and strong seasonality) in the Western Tropical Pacific Ocean may be, (1) low *Trichodesmium* concentrations, (2) a weak discriminating optical signal such as that due to a mixed optical assemblage, and (3) a significantly different *Trichodesmium* optical signature in the SWTP.

Applications of the algorithm for an estimate of potential nitrogen fixation would require a better understanding of the succession between surface blooms and *Trichodesmium* specific biomass integrated over the whole water column. Indeed, a better knowledge of their spatial and temporal association with *Trichodesmium* (Campbell et al., 2006; Sato et al., 2010; Moisander et al., 2010), would help in getting a global view of all of nitrogen fixing organisms.

Trichodesmium experienced a high inter-annual variability in the region with maxima in 1999, 2003, 2004 and 2005, while 2001 and 2002 were less favourable. This inter-annual variability might be related to large scale circulation dynamics. For example, the bifurcation latitude of the South Equatorial Current is found to move southward from about 15° S near the surface to south of 22° S in the intermediate layers (Qu and Lindstrom, 2002) associated with large scale changes in the phosphate pool (Dyrhman et al., 2006; Tadokoro et al., 2009). Also, iron-rich dust deposition patterns (Gao et al., 2001) may be highly variable. Whether other phytoplankton blooms are triggered by

Trichodesmium decomposition of organic matter is also of interest (Chen et al., 2008; 2011). Late summer chlorophyll blooms in the oligotrophic North Pacific subtropical gyre may be fuelled by *Trichodesmium* (Wilson and Qiu, 2008).

TRICHOSAT demonstrated that *Trichodesmium* blooms are a common feature in the SWTP during austral summer (October to March). They are temporally and spatially linked to diverse nitrogen-fixing populations and can be identified as a major potential carbon sink in the SWTP. A large-scale physical and biogeochemical modeling of the distribution of *Trichodesmium* is required in the SWTP.

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Table 1. In situ *Trichodesmium* bloom observations for the period 1998–2010 in the South Western Tropical Pacific (NC, New Caledonia). Data from aerial observations, and/or bucket sampling from cruises and various transects effected by the French Navy ships and the R/V *Alis*. Abreviations: T. e., T. t. and T. ten., K., for *Trichodesmium erythraeum*, *thiebautii*, and *tenue*, *Katagnymene* spp., respectively. Col. = colonies; fil. = filaments.

Date	Latitude	Longitude	Observed species	Observed form	Location in the Tropical Pacific	Observation mean
11 Apr 1998	17° S	179° E	T. t.	Large col.	Fiji Isl.	R/V *Revelle*, NSF
11 Apr 1998	18° S	188° E	T. t.	Large col.	Vavau Isl.	F. Navy, J. Cartier
18 Nov 1998	22°35′ S	168°58′ E	und.	Slicks	Walpole Isl.	F. Navy aerial
18 Nov 1998	24°21′ S	170°40′ E	und.	Slicks	S NC	F. Navy aerial
25 Nov 1998	22°15′ S	163°35′ E	und.	Slicks	W NC	F. Navy aerial
25 Nov 1998	21°20′ S	164°10′ E	und.	Slicks	W NC	F. Navy aerial
25 Nov 1998	19°35′ S	160°55′ E	und.	Slicks	NW NC	F. Navy aerial
18 Dec 1998	22°40′ S	165°50′ E	und.	Slicks	SW NC	F. Navy aerial
8 Jan 1999	23° S	166° E	und.	Slicks	SW NC	F. Navy aerial
8 Jan 1999	24°10′ S	166°15′ E	und.	Slicks	SW NC	F. Navy aerial
8 Jan 1999	23°50′ S	164°20′ E	und.	Slicks	SW NC	F. Navy aerial
9 Nov 1999	20° S	170° E	und.	Slicks	Vanuatu to NC	R/V *Alis* (Wespalis)
7 Jan 2000	21°49′ S	165°11′ E	und.	Slicks	W NC	F. Navy aerial
7 Jan 2000	20°30′ S	161°52′ E	und.	Slicks	W NC	F. Navy aerial
28 Dec 2000	19°57′ S	162°58′ E	und.	Slicks	Belep	F. Navy aerial
28 Dec 2000	21°20′ S	164°12′ E	und.	Slicks	Poum	F. Navy aerial
28 Dec 2000	21°48′ S	163°35′ E	und.	Slicks	Poum	F. Navy aerial
8 Jan 2001	22°20′ S	172° E	und.	Slicks	Hunter Isl.	F. Navy aerial
18 Jan 2001	21°11′ S	164°17′ E	und.	Slicks	NW Kone, NC	F. Navy aerial
18 Jan 2001	18°31′ S	164°28′ E	T. e., T. t., T. Ten.	Large col., green	Petri Reefs	F. Navy aerial
23 Jan 2001	22°11′ S	161°79′ E	T. e.	Isolated fil.	S NC	F. Navy aerial
23 Jan 2001	22°10′ S	161°79′ E	T. e.	Flocks		F. Navy, La Moqueuse
29 Jan 2001	24°53′ S	161°40′ E	und.	Flocks	Coral Sea	F. Navy, La Moqueuse
29 Jan 2001	24°47′ S	162°37′ E	und.	Flocks	Coral Sea	F. Navy, La Moqueuse
7 May 2001	20°12′ S	163°29′ E	T. e.	Green col.	Belep	F. Navy
5 Sep 2001	20°08′ S	170°45′ E	und.	Slicks	Anatom	F. Navy
5 Sep 2001	20°41′ S	170°16′ E	und.	Slicks	Anatom	F. Navy aerial
12 Oct 2001	22°16′ S	167°27′ E	K. (idem Diapalis)	Flocks	E NC	R/V *Alis* (Diapalis 1)
3 Nov 2001	20°47′ S	167°03′ E	T. e.	Grey col.	Lifou Isl.	F. Navy aerial
13 Nov 2001	22°09′ S	167°19′ E	T. e., T. t., K.		East Coast	F. Navy, La Glorieuse
13 Nov 2001	22° S	167°29′ E	T. e., T. t., K.		Loyalty Channel	F. Navy, La Moqueuse
30 Jan 2002	22°22′ S	166°50′ E	T. e.	Green col.	Uitoe Pass.	F. Navy aerial
30 Jan 2002	22°12′ S	166°01′ E	und.	Slicks	Uitoe Pass.	F. Navy aerial
8 Feb 2002	21°26′ S	162°32′ E	und.	Slicks	Chesterfields Isl.	R/V *Alis*
21 Apr 2002	23°29′ S	162°53′ E	T. e.		SW NC	F. Navy, J. Cartier
24 Apr 2002	22°28′ S	169°12′ E	T. e.	Pink col.	E Walpole Isl.	F. Navy, J. Cartier
10 May 2002			und.	Low PUB/PEB	NC to Vanuatu	R/V *Alis* transect
8 Jul 2002	19°08′ S	176°41′ W	T. e.	Grey col.	Fiji Isl.	F. Navy, J. Cartier
16 Jul 2002	23°03′ S	164°42′ E	Slicks	Slicks	W NC	F. Navy, J. Cartier
10 Dec 2002	18°40′ S	168°59′ E	Large K. + T. e. + T. t.	Large col.	Erromango Isl.	F. Navy, J. Cartier
13 Dec 2002	19°07′ S	167°20′ E	Large K. + T. e. + T. t.	Large col.	Erromango Isl.	F. Navy, J. Cartier
11 Dec 2002	20°05′ S	167°30′ E	und.	Slicks	E Lifou Bay	Visual obs

Table 1. Continued.

Date	Latitude	Longitude	Observed species	Observed form	Location in the Tropical Pacific	Observation mean
12 Dec 2002	19°19′ S	164°51′ E	T. e., K.	Green, grey col., pummices	Surprises Isl.	F. Navy, La Glorieuse
12 Dec 2002	19°19′ S	164°51′ E	T. e. + K.	Green/grey col.	Surprises Isl.	F. Navy, La Glorieuse
16 Dec 2002	20°48′ S	170°09′ W	T. ten., K.	Grey, long thin fil.	Niue Isl.	R/V *Alis*
16 Dec 2002	20°51′ S	170°33′ W	T. ten., K.	Grey, long thin fil.	Niue Isl.	R/V *Alis*
18 Dec 2002	21°11′ S	174°08′ W	T. ten., K.	Grey, long thin fil.	Niue Isl.	R/V *Alis*
18 Dec 2002	21°11′ S	173°57′ W	T. ten., K.	Grey, long thin fil.	Niue Isl.	R/V *Alis*
25 Dec 2002	20°11′ S	169°04′ E	und.	Slicks	W Tanna Isl.	Ship obs
17 Feb 2003	23°14′ S	165°29′ E	und.	Slicks	Santo Isl.	F. Navy aerial
20 Feb 2003	15°04′ S	166°30′ E	und.	Slicks	W NC	F. Navy aerial
28 Mar 2003	24°44′ S	163°21′ E	T. e.	Pink col.	S NC	F. Navy, J. Cartier
17 Apr 2003	19°31′ S	167°31′ E	und.	Low PUB/PEB, slicks	Vanuatu	F. Navy, J. Cartier
22 Apr 2003	21° S	166° E	und.	Low PUB/PEB		F. Navy, J. Cartier
25 Apr 2003	17°57′ S	168°10′ E	und.	Slicks	Efate Isl.	F. Navy, J. Cartier
30 Oct 2003	14°50′ S	168° E	und.	Slicks	Bank Isl.	Ship of opportunity
4 Nov 2003	17°39′ S	167°33′ E	T. e.	Red col.	Vanuatu	F. Navy, La Moqueuse
5 Nov 2003	20° S	166°30′ E	und.	Slicks	Ouvea Isl.	Visual obs
9 Dec 2003	20°24′ S	167°51′ E	und.	Slicks	Lifou to Vanuatu	R/V *Alis*
18 Dec 2003	24°03′ S	168°02′ E	und.	Slicks		F. Navy, La Glorieuse
17 Jan 2004	23°20′ S	168°20′ E	und.	Slicks		F. Navy
23 Jan 2004	20°16′ S	161°00′ E	und.	Slicks		F. Navy
26 Jan 2004	22°11′ S	167°22′ E	T. e.	Small col.	Loyalty Channel	F. Navy, La Glorieuse
29 Jan 2004	20°20′ S	166°07′ E	T. e.	Large pink flocks	Beautemps-Beaupré	R/V *Alis* (PIL)
30 Jan 2004	20°17′ S	166°17′ E	T. e.	Large pink flocks	NE NC	R/V *Alis* (PIL)
1 Feb 2004	21°20′ S	167°35′ E	T. e.	Large pink flocks	NE NC, Oua Isl.	R/V *Alis* (PIL)
12 Feb 2004	18°30′ S	166°30′ E	und.	Slicks		F. Navy aerial
13 Feb 2004	19°50′ S	169°54′ E	und.	Slicks	N NC Balabio Isl.	visual obs
16 Feb 2004	18°49′ S	168°30′ E	und.	Slicks	Vanuatu Isl.	Air Vanuatu
28 Feb 2004	21°10′ S	168°30′ E	T. e.	Large puffs/tufts long fil.	NE NC coast	R/V *Alis* (Motevas)
29 Feb 2004	17°23′ S	166°04′ E	T. t. + K.	Large puffs/tufts long fil.	Vanuatu	R/V *Alis* (Motevas)
1 Mar 2004	22° S	167° E	T. e.	White col.	Yate Barrier Reef	F. Navy
4 Mar 2004	20°09′ S	168°43′ E	und.	Slicks	Vanuatu	F. Navy aerial
29 Mar 2004	17° S	167° E	und.	Slicks	Masquilignes Isl.	Air Vanuatu
26 Apr 2004	20°09′ S	163°01′ E	und.	Slicks	Aircraft	F. Navy aerial
1 Oct 2004	21°30′ S	165° E	und.	Slicks	Lifou	F. Navy aerial
11 Nov 2004	18°30′ S	168° E	und.	Slicks	Vanuatu	F. Navy aerial
12 Dec 2004	22°29′ S	169°50′ E	und.	Slicks	E Pine Isl., Walpole Isl.	F. Navy aerial
31 Mar 2007	22°49′ S	169°59′ E	T. e.	Floating Puffs	Walpole Isl.	R/V *Kilo Moana* cruise
8 Apr 2007	15°00′ S	169°59′ W	K. + T.c. + T. te + T. t.	Floating Puffs	NE Vanuatu	R/V *Kilo Moana* cruise
12 Apr 2007	14°59′ S	178°45′ E	K. + T.c. + T.t.	Surface Bloom	N Fiji Isl.	R/V *Kilo Moana* cruise
3 Mar 2010	19°11′ S	166°57′ E	T. e.	Col.	Beautemps-Beaupre Reef	F. Navy aerial
3 Mar 2010	19°06′ S	166°07′ E	T. e.	Col.	Beautemps-Beaupre Reef	F. Navy, J. Cartier
12 Apr 2010	22°48′ S	165°17′ S	und.	Slicks	W NC	Ship of opportunity
12 Apr 2010	22°06′ S	165°26′ E	und.	Slicks	idem	Ship of opportunity
21 May 2010	15°19′ S	166°30′ E	T. e.	Slicks	Sabine Bank	R/V *Alis* (Geodeva4)
27 Oct 2010	19° S	165°30′ E	und.	Slicks	W NC	Ship of opportunity
28 Oct 2010	22° S	167° E	und.	Slicks	W NC	Ship of opportunity
3 Nov 2010	19°15′ S	166°47′ E	T. e.	Slicks	SE Vanuatu	F. Navy, R/V *Prairial*
3 Nov 2010	19°27′ S	166°52′ E	T. e.	Slicks	SE Vanuatu	F. Navy, R/V *Prairial*
4 Dec 2010	22°12′ S	169°42′ E	und.	Slicks	SE NC	F. Navy aerial
4 Dec 2010	21°26′ S	167°19′ E	und.	Slicks	W NC	F. Navy aerial
4 Dec 2010	22°12′ S	167°42′ E	und.	Slicks	W NC	F. Navy aerial

Table 2. Average in situ observations at the surface layer (0–30 m) of filamentous cyanobacteria during the DIAPAZON Program from Tenório (2006), the Motevas cruise, and the transects effected by the French Navy ships from New Caledonia to Tr 1: Vanuatu, Tr 2: Walpole, Tr 3: Vanuatu, Tr 4: Vanuatu, Tr 5: Fiji, Vanuatu, Tr 6: Wallis and Futuna and Vanuatu. Transects: bucket samples and Cruises: Niskin bottle. Tchl-*a* = chlorophyll-*a* + divinyl chlorophyll-*a*; PE = phycoerythrin; chl > 10 = percentage of Tchl-*a* associated with the > 10 µm fraction.

Cruise name	Date DD/MM/YY	Tchl-*a* (mg m^{-3})	PE (mg m^{-3})	chl > 10 (%)	Cp (m^{-1})	Trich. Ab. (L^{-1})	Bloom obs
Trichonesia	15 Apr 1998	0.14		20	nd	298*	No
Diapalis01	27 Oct 2001	0.14	0.16	16	nd	411	Yes
Diapalis02	15 Dec 2001	0.13	0.15	10	0.072	474	No
Diapalis03	17 Jan 2002	0.1	0.09	8.8	0.062	401	No
Diapalis04	6 Apr 2002	0.11	0.1	9	0.059	347	No
Diapalis05	25 May 2002	0.11	0.23	9.3	0.046	1000	No
Transect 1	14 May 2002	0.26	0.83	nd	nd	nd	Yes
Diapalis06	9 Aug 2002	0.22	0.19	9	0.069	76	No
Diapalis07	5 Feb 2003	0.23	0.6	53	0.1	2176	Yes
Transect 2	28 Feb 2003	0.29	0.45	nd	nd	nd	nd
Transect 3	15 Mar 2003	0.29	0.33	nd	nd	nd	nd
Transect 4	17–24 Apr 2003	0.21	0.53	nd	nd	nd	No
Transect 5	22–23 Apr 2003	0.18	0.44	nd	nd	nd	No
Diapalis08	12 Jun 2003	0.2	0.3	7	0.051	510	No
Transect 6	7 Jul 2003	0.25	0.09	nd	nd	nd	No
Diapalis09	10 Oct 2003	0.099	0.08	9	0.057	9	No
Motevas	29 Feb 2004						
Niskin		0.48	0.37	70	nd	3500	Yes
Bucket		0.84	3.4	70	nd	6500	Yes

E. J. Carpenter, personal communication, 1998.

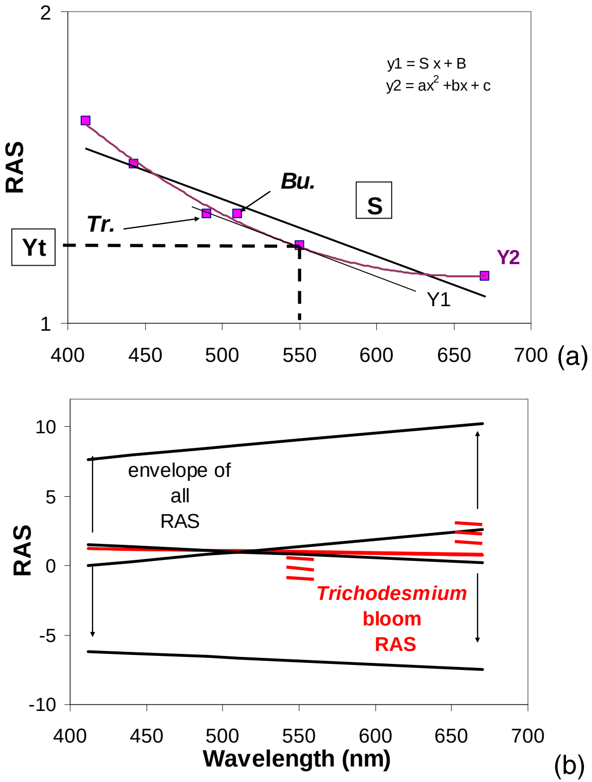

Fig. 1. (a) Descriptive parameters to characterize the SeaWiFS radiance anomaly spectra relative to K490 for *Trichodesmium* detection in surface oceanic waters: S = slope of the linear fit; *a* = coefficient of the square term in the degree 2 polynomial fit; Yt = ordinate of the second degree fit for which tangent is parallel to linear fit; "Bu." and "Tr." are the wavelengths of the major positive and major negative deviations relative to the second degree polynomial fit (largest "bump" or largest "trough", respectively). **(b)** Ranges of S and Yt for all RAS of all pixels (black). In red, specific S and Yt and positions of bumps and troughs schematically shown for RAS of a *Trichodesmium* bloom.

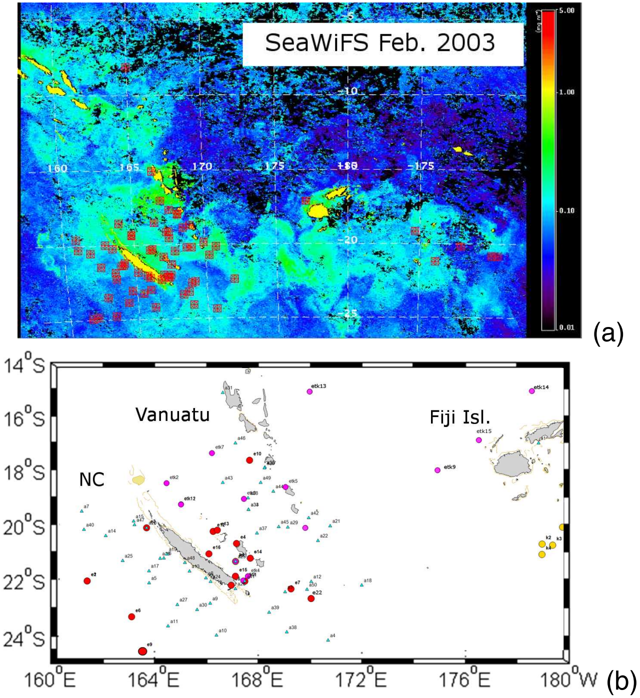

Fig. 2. **(a)** Mean SeaWiFS composite image of chl-*a* (mg m^{-3}) in the South Western Tropical Pacific Ocean in February 2003 (austral Summer) with observations of *Trichodesmium* surface accumulations for December 2002–March 2003. Main lands are indicated in yellow (New Caledonia, 20–22° S, 165° E), Vanuatu (15–20° S, 168° E), Fiji (17° S, 180° E) and South Tonga Islands (21° S, 175° W). (**b**) French Navy observations of *Trichodesmium* surface blooms (1998–2010), with: light blue – aerial observations; red – small form filaments (named *T. erythraeum* spp. after Tenório, 2006); magenta – mix of small *T. erythraeum* and long forms (filaments of *Trichodesmium thiebautii* and *T. tenue*); yellow – mix of *T. tenue* and *Katagnymene* sp. (observations at the South of Fiji are those of Tonga Islands at 175° W reported at 180° E, see Table 1 and Fig. 1a).

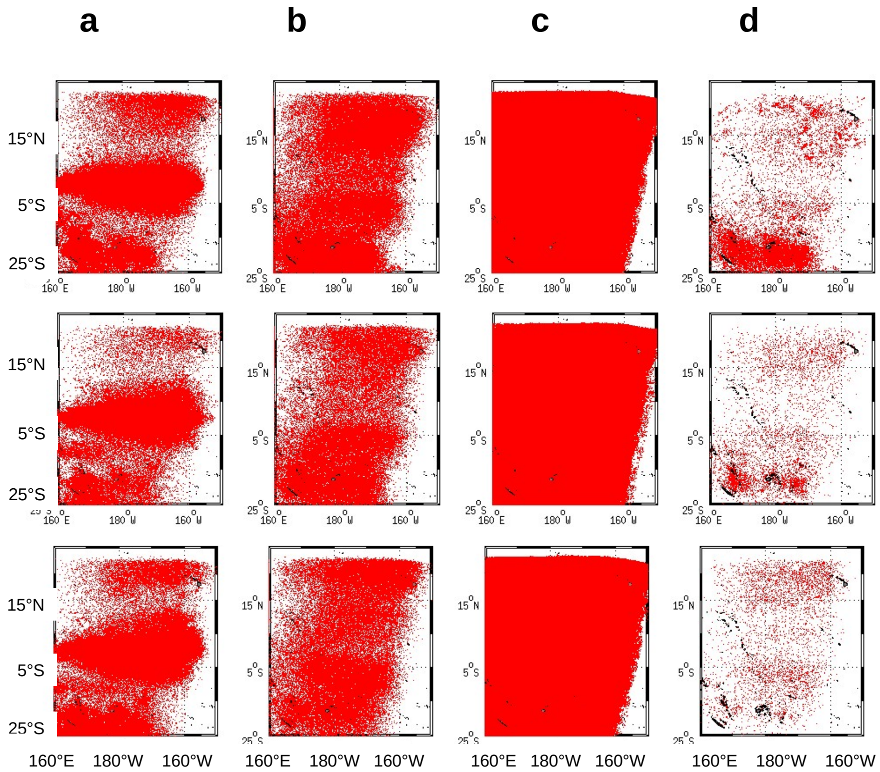

Fig. 3. Application of the TRICHOSAT algorithm to satellite data (1997 to 2010) over the large box corresponding to the Northern and Southern Western Pacific Ocean (WP: 25° N–25° S/160° E–160° W). Top panels: austral summer (November to March); middle panels: intermediate season (April–May and October); bottom panels: austral winter (June to September). **(a)** All pixels for which Chl-$a > 0.2\,\mathrm{mg\,m^{-3}}$; **(b)** pixels satisfying the slope and intercept criteria of the RAS; **(c)** pixels satisfying the shape criteria, **(d)** pixels satisfying all criteria. The main islands of New Caledonia at 20° S, Vanuatu at 15° S, Fiji Islands at 17° S, Hawaii Islands at 20° N are indicated in black.

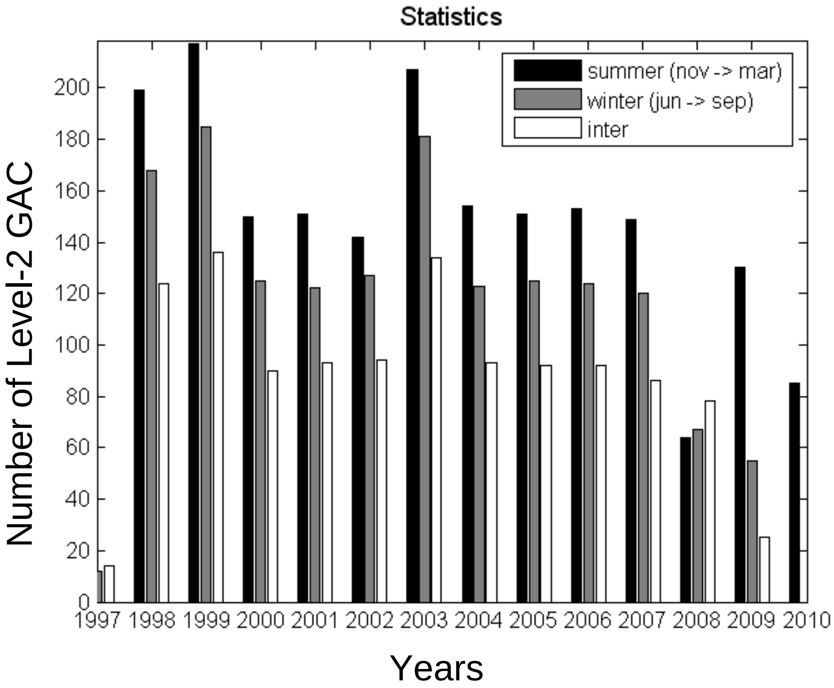

Fig. 4. Statistics of the number of SeaWiFS Level_2 GAC images used to determine the spatio-temporal distribution of *Trichodesmium* accumulations in the SWTP between 1997 and 2010 by year and season. Definitions of seasons as in Fig. 3.

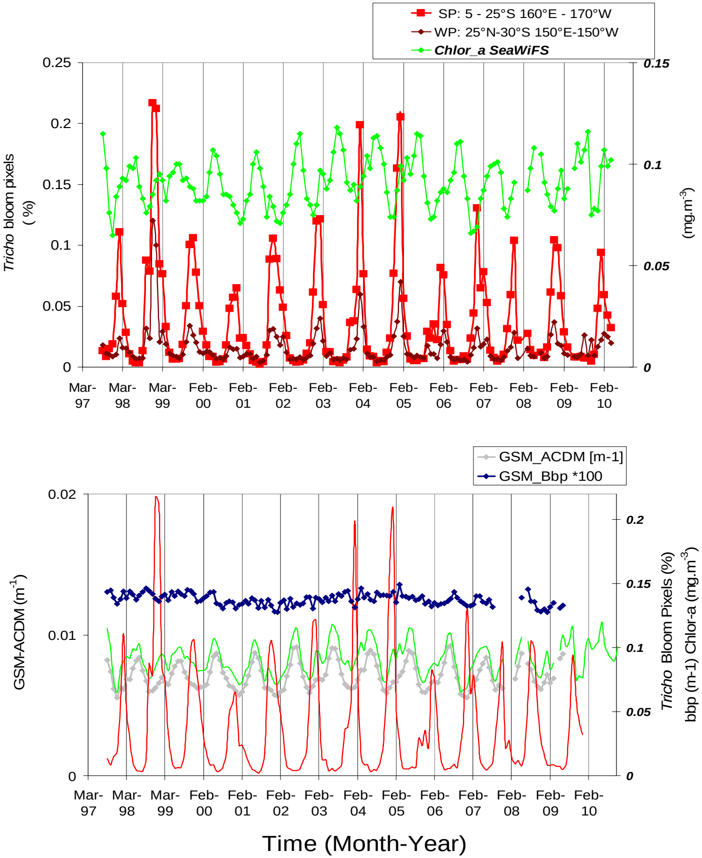

Fig. 5. (top) Monthly percentage of valid pixels identified as *Trichodesmium* when applying the TRICHOSAT algorithm to SeaWiFS Level-2 imagery (4 × 4 km). Results are shown for the Southern Pacific Ocean box (SP: 5° S–25° S, 150° E–190° E/170° W) in red and for the WP (WP: 25° N–25° S/160° E–160° W) as brown. *Trichodesmium* blooms occur regularly during the austral summer and peak in February. SeaWiFS chlorophyll-*a* for SP also shown as green line (bottom) GSM-derived ACDM absorption coefficient (m^{-1}) (grey line) and scaled particulate backscattering coefficient (m^{-1}) (dark blue line). Also reproduced from above are *Trichodesmium* bloom occurence and Chl-*a*.

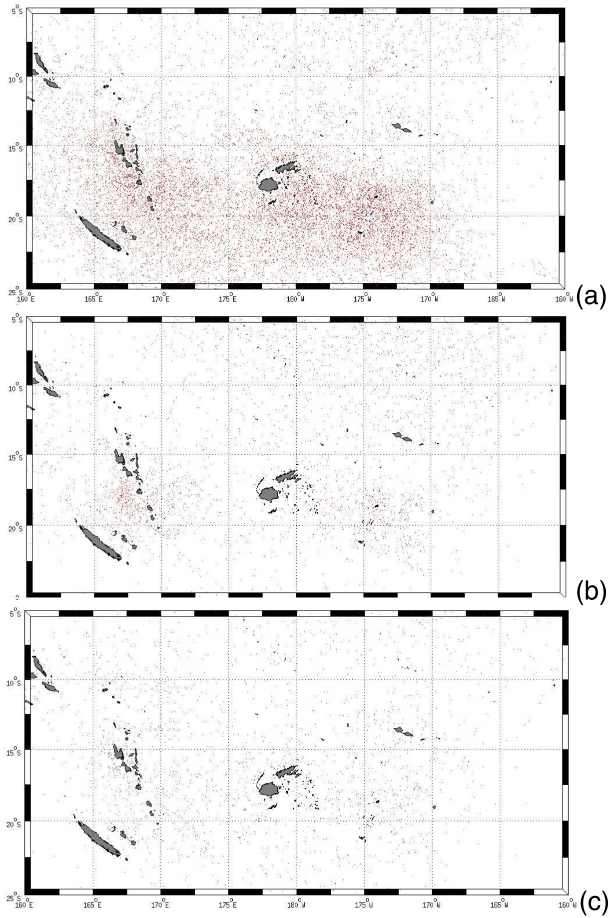

Fig. 6. Composite of spatial distributions of *Trichodesmium* deduced from the TRICHOSAT algorithm for the SP box (5° S–25° S 160°–170° W) applied to the whole SeaWiFS series 1997–2010 **(a)** Summer season **(b)** interseason **(c)** winter season; winter retrievals at the convergence zones have often been observed. In black, the main lands of New Caledonia at 20° S, Vanuatu at 15° S and Fiji Islands at 17° S. Each pixel represents a surface of 16 km^2.

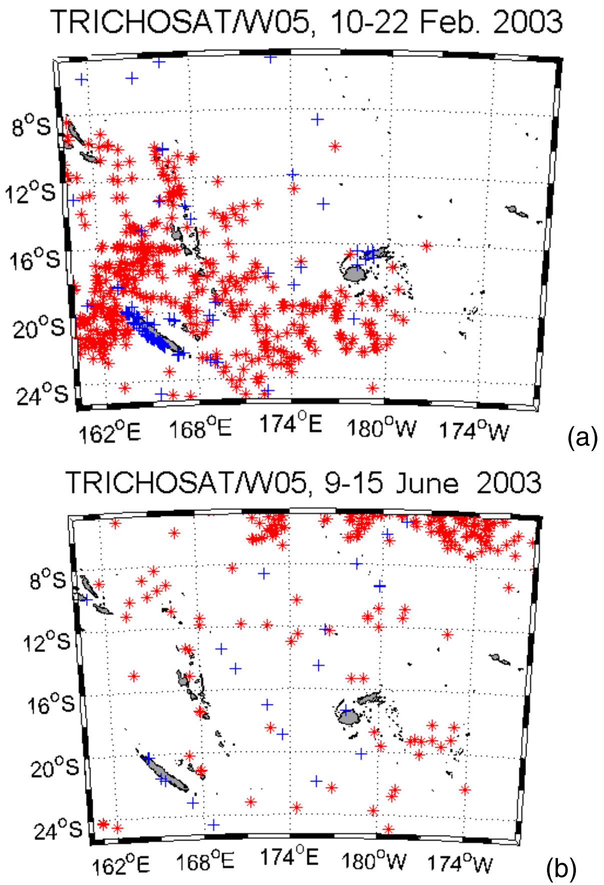

Fig. 7. Spatial distributions of *Trichodesmium* bloom pixels retrieved with TRICHOSAT in the SP box [5° S–25° S 160°–170° W] **(a)** during Austral summer, 10–22 February 2003 and **(b)** during winter, 9–15 June 2003 (red crosses). Also shown are results obtained from Westberry et al. (2005) (blue crosses) for the same time periods. Each pixel represents a surface of 16 km^2.

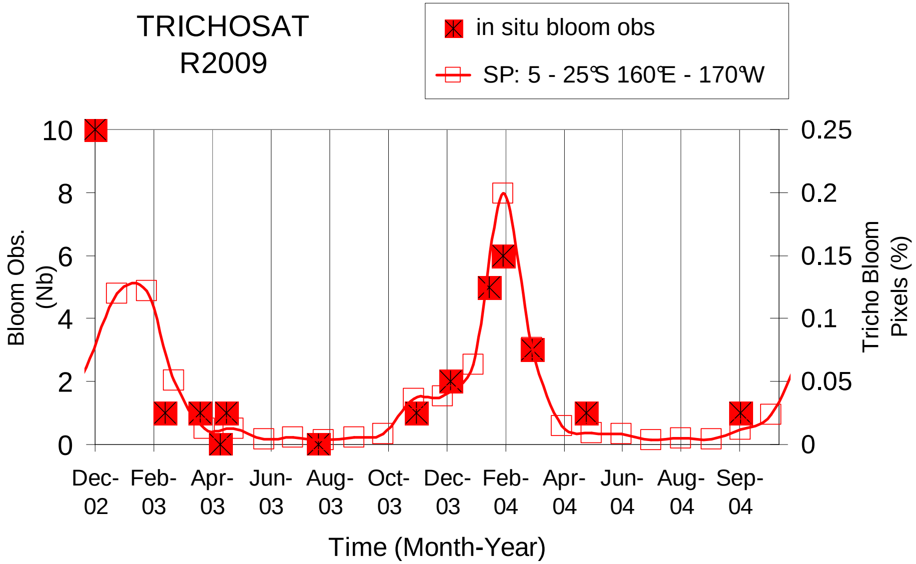

Fig. 8. Temporal evolution of the *Trichodesmium* bloom occurrence for the period December 2002–October 2004. TRICHOSAT retrievals shown in red (in % pixels, over the SP domain) and in situ observations in red (number of surface slicks observed, Nb).

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀▮
▶▮
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion