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DISCOLOURED WATERS IN THE MELANESIAN ARCHIPELAGO (NEW CALEDONIA AND VANUATU). THE VALUE OF THE NIMBUS-7 COASTAL ZONE COLOUR SCANNER OBSERVATIONS.

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ABSTRACT. Final conclusions are given to the study of discoloured waters as they can be observed with the NIMBUS-7 Coastal Zone Colour Scanner (CZCS) in the oligotrophic waters of the southwestern tropical Pacific, in the Melanesian archipelago, around New Caledonia, Vanuatu (and Tonga). An attempt was made to define, in the four CZCS channels, the reflectance properties of these blooms attributed to *Trichodesmium*, a nitrogen-fixing cyanobacterium commonly found in that region. The capacity and limitations of the CZCS sensor used in the past as well as the SPOT imager are discussed in this respect. The usefulness of past and future ocean colour satellites in identifying zones of high chlorophyll concentration and bright linear patterns is demonstrated.

1. Introduction

The goal of the study was to determine how ocean colour imagery could help to characterize the *Trichodesmium* blooms commonly found in the Melanesian archipelago, around New Caledonia, Vanuatu (and Tonga) in the southwestern tropical Pacific. In a first paper (Dupouy *et al.*, 1988), a CZCS image of a particularly bright and extensive area of discoloured water, presumably caused by *Oscillatoria (= Trichodesmium)*, was described in detail. Using *in situ* data from Capone and Carpenter (1982), we were able to estimate its nitrogen fixation capacity at about one ton.

An examination of the whole CZCS series for the region (Dupouy, 1990a,b) gave new insight into the distribution of surface chlorophyll in the Melanesian archipelago. Conclusions were that discoloured waters occur primarily in summer (December to March) and that surface chlorophyll-rich zones usually extend far eastward from New Caledonia, (over 500 km) on the convergence zones of currents.

The purpose of this study was to determine if these observations could be generalized to provide a detecting method of the *Trichodesmium* blooms. At first, a review was made of the occurrence of *Trichodesmium* in the western Pacific, and of its repetitivity in the Caledonian archipelago (Loyalty Islands) based on *in situ* ORSTOM data. Secondly, the CZCS four band reflectances were examined for blooms at different dates. The SPOT imagery available over the Caledonian lagoon was used in order to illustrate the spatial organization of the bloom on a much finer scale.

E. J. Carpenter et al. (eds.), Marine Pelagic Cyanobacteria: Trichodesmium and other Diazotrophs, 177–191.

2. Occurrence of *Trichodesmium* in the western Pacific and in the Melanesian archipelago

According to Sournia (1968, 1970), the marine cyanobacterium (blue-green alga) genus *Trichodesmium* can be assumed to be the genus *Oscillatoria (= Trichodesmium)* Vaucher ex Gomont, in the order Hormogonales.

A review of the occurrence of *Trichodesmium* in the Pacific has been made by Carpenter (1983). In the northern hemisphere, between 1892 and 1950, several naturalists observed blooms during their exploratory cruises, in the Java Sea, near Borneo, in Indonesian regional seas, the East China Sea, in waters around Japan and in the Kuroshio current (as referenced by Bowman and Lancaster (1965) and Asaoka and Marumo (1987)). Similarly, in the southern ocean, the first surveys confirming the occurrence of *Trichodesmium* blooms were made near the Guinea coast, in the Arafura Sea and on the Great Barrier Reef. Recent studies have been made on the GBR region (Revelante and Gilmartin, 1982, Hallegraef and Reid, 1986). The western Australian coast is also known to be the site of frequent *Trichodesmium* blooms (Creagh, 1985). Far from these coastal areas, in the northwestern Pacific, eastern currents such as the Kuroshio Current or the equatorial counter current are sites of blooms in summer (Asaoka and Marumo, 1987). North of the Hawaiian Islands (at 28°N, 155°W in the North Pacific gyre) a *Trichodesmium* bloom was studied in detail by Mague *et al.*, (1974, 1977). In the southwestern Pacific, Baas-Becking (1951) reported observations of blooms around New Caledonia and the Fiji Islands and even at 25°S. A "gray tide" caused by *Trichodesmium* was reported by Bowman and Lancaster (1965) in the Tonga Islands, near 170° W, 10°S.

Visual observations of yellow waters by merchant ships' crews are available in the southwestern Pacific: between 1976 and 1982, the maximum occurrence of yellow stripes (supposedly formed by *Trichodesmium*) was between January and March, and northeast of New Caledonia. Dandonneau and Gohin (1984) suppose that the summer maxima of sea surface chlorophyll concentration at 165°E, 20°S are due to *Trichodesmium* blooms. Dessier (1988) explains the dominance of the Copepod *Macrosetella gracilis* (Harpacticoïda) around the New Caledonia-Vanuatu-Fiji archipelago by its well-documented association with *Trichodesmium*. Airborne observations in the oceanographic region around New Caledonia and Vanuatu confirm the fact that streaks forming "yellow tides" are typically found, between September and March, at convergence fronts in the northeastern region of New Caledonia (Petit and Hazane, 1982, Petit and Gohin, 1983).

Around the corallian Loyalty Islands, ten PREFIL (Production and Islands Effect) cruises were made between 1982 and 1984 (Le Borgne, 1986, map on Figure 1a). The positions of the fixed stations during the eight cruises (P3 to P10) are indicated. The presence of *Trichodesmium* was confirmed at all seasons, and all stations, between depths of 0 and 100 meters (Le Borgne, 1986). Figure 1b shows the visual observations of the occurrence of *Trichodesmium* puffs and tuffs forms, made from sieved water collected at various depths with a 30-liter Niskin bottle (Le Borgne, unpublished results; two abundance indexes are available). A vertical migration of *Trichodesmium* colonies is visible. Yellow streaks were indeed observed between Lifou and Ouvea islands, in May 1984, when *Trichodesmium* occurrence was maximum. Inside the lagoon, red tides are common, mainly on the northeastern coast, although there is no published report on this phenomenon.

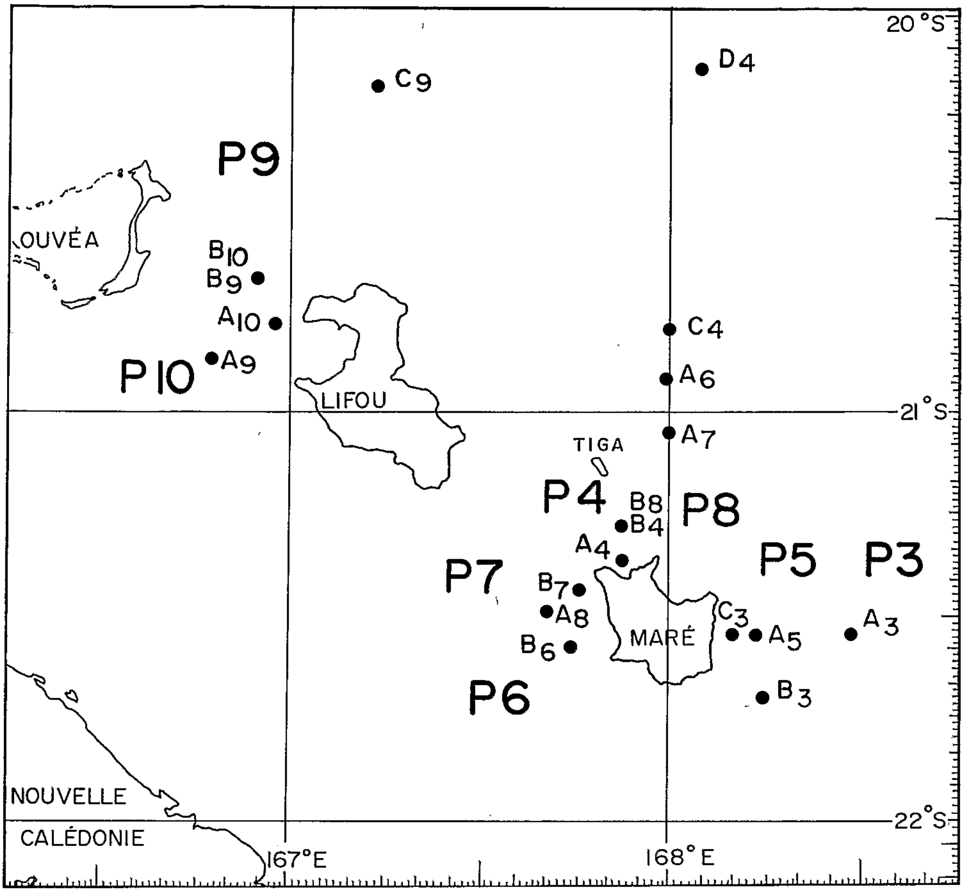


Figure 1a. Location of the fixed stations of the PREFIL cruises around the Loyalty Islands Maré, Lifou and Ouvea (Le Borgne, 1986). The cruises were undertaken in:
P3 : January-February 1982; **P4** : February 1983; **P5** : April 1983; **P6** : September 1983;
P7 : November 1983; **P8** : February 1984; **P9** : May 1984; **P10** : September 1984.

In April 1988 and November 1989, transects along 165°E confirmed that *Trichodesmium* was consistently found from 16°S to 8°S, on the entire water column and in surface waters where it caused a chlorophyll maximum (Blanchot *et al.*, 1988, Le Bouteiller *et al.*, 1991). *Trichodesmium thiebautii* was found at 15°S, and remained present for one week in November 1989 (Blanchot, personal communication). It is unknown within the equatorial region (Le Bouteiller, personal communication). For historical reasons, only a few references exist for the open waters of the southwestern Pacific. Nevertheless, it appears that in this area *Trichodesmium* blooms are a common phenomenon.

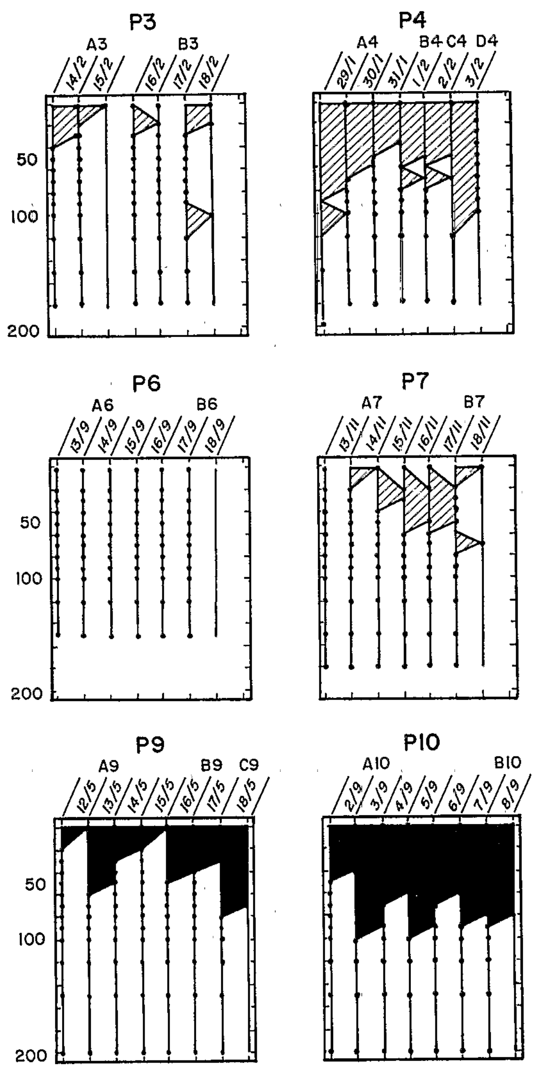


Figure 1b. Vertical distribution of the presence of *Trichodesmium* colonies observed at the fixed stations, as seen from samples collected with a 30-L Niskin bottle, and sieved on a 200-micron mesh. Two indexes of abundance are available. Vertical profiles are identified by date and by station number.

3. Bio-optical characteristics of oligotrophic and *Trichodesmium*-rich waters

A reflectance (*R*) model of marine waters has been developed by Morel (1980), which helps in computing for each wavelength the value of *R* as 0.33 b_b/a, where b_b and a are respectively the backscattering and absorption coefficients of the water body. The influence on *Rsat* of sediment and phytoplankton concentrations has also been modellised (André and Morel, 1991). In turbid waters, the sediment charge increases reflectance at all wavelengths due to an increase of backscattering (Viollier and Sturm, 1984). With very high concentrations of phytoplankton, green and yellow reflectances increase, blue strongly decreases due to chlorophyll absorption, and red slightly increases due to biological turbidity, as has been seen on the CZCS images of the Senegalese upwelling (Dupouy and Demarcq, 1987). According to Morel's model, when chl *a* varies from 0 to 0.25 $mg.m^{-3}$, green and yellow reflectance values are expected to vary from 0.9 to 1.5 %; blue reflectance between 3 and 1.5 %, and red reflectance from 0.06 to 0.17% (see Table 2 for reference values). According to this model, blue oligotrophic waters give almost no signal in the red.

Spectral reflectance measurements made over *Trichodesmium*-rich waters by Borstad *et al.* (1989) with concentrations varying between 100 and 1400 $filaments.liter^{-1}$ show striking features, mainly: a general increase of reflectance values at all wavelengths and four major dips in the spectra, corresponding to phycourobilin (495), phycoerythrin (625) and chlorophyll a (440 and 670) absorption peaks (Lewis *et al.*, 1988, Haxo *et al.*, 1987, Ohki *et al.*, 1986). High reflectance observed in the near infra-red (after 700 nm) is similar to the response of the terrestrial vegetation (Gausman, 1974). A high concentration of humic acids may follow *Trichodesmium* blooms (Jones *et al.*, 1986). Though these dissolved acids ("yellow substances") mainly absorb in the UV (Bricaud *et al.*, 1981), their absorbance may be large at 443 nm (Carder *et al.*, 1989).

The range of values for chlorophyll concentration around New Caledonia and the Loyalty Islands was observed to be 0.05 - 0.3 $mg.m^{-3}$ (Lemasson et Crémoux, 1985; Dandonneau and Gohin, 1984). Since the higher values were not common, those waters were assumed to be oligotrophic.

4. CZCS and SPOT observations

4.1. DATA

Observing a CZCS time series (60 images) taken from 1979 to 1984 has enabled us to describe the spatial and temporal distribution of discoloured waters. Dates and conditions of satellite acquisition are summarized in Table 1. CZCS images taken during summer (December to March) are often taken during sun glint conditions (despite the ability of the CZCS to avoid solar specular reflection by tilting). This may enhance the visible signal in a geometrically defined area and may alter the chlorophyll algorithm in that area only. Nevertheless, spectral signatures have been extracted in zones removed from these areas. SPOT images over the lagoon were also taken in sun glint conditions. In this case also, our observations were made outside these zones.

4.2. CZCS AND SPOT SENSOR PERFORMANCES

The CZCS sensor (Hovis *et al.*, 1980) has four bands in the visible domain: the blue (443 nm),

TABLE 1. Satellite observations in the 4 CZCS bands of NIMBUS-7 images of the Melanesian archipelago.

Months CZCS	Glitter	Channels 520,550	Channel 670	Channel 440	Chl *a* mg.m^{-3}
Nov 78*	-	+	+	+	0.11
Mar 79*	-	-	-	-	0.27
Apr 79*	-	-	-	-	0.12
Jun 79**	-	-	-	-	0.15
Jul 79**	-	-	-	-	0.15
Sep 79*	-	-	-	-	0.13
Nov 79*	+	-	-	-	0.19
Dec 79**	+	+	+	-	0.20
Mar 80**	-	-	-	-	0.15
Apr 80*	-	-	-	-	0.16
Jul 80*	-	-	-	-	-
Aug 80**	-	-	-	-	0.30
Sep 80*	+	-	-	-	0.18
Nov 80**	+	+	+	-	0.16
Dec 80*	-	+	+	+	0.19
Fev 81***	+	+	+	+	0.18
Mar 81**	-	+	+	-	-
Apr 81***	-	-	-	-	0.18
May 81*	-	-	-	-	0.16
Jun 81*	-	-	-	-	0.19
Jul 81**	-	-	-	-	0.19
Aug 81*	-	-	-	-	0.22
Nov 81*	-	-	-	-	-
Jan 82**	+	+	+	+	0.14
Mar 82**	-	+	-	-	0.19
Apr 82**	-	+	-	-	-
May 82*	-	-	-	-	-
Jun 82*	-	-	-	-	-
Jul 82*	-	-	-	-	-
Oct 82*	-	-	-	-	0.19
Apr 83*	-	-	-	-	0.14
Sep 83*	-	-	-	-	0.14
Oct 83*	-	-	-	-	0.14
Mar 84*	-	+	+	+	0.14
Apr 84*	-	-	-	-	-
Aug 84*	-	-	-	-	0.14
Sep 84**	-	-	-	-	0.10
Oct 84*	-	-	-	-	0.10
Dec 84**	-	-	-	-	0.10
Month SPOT					
Dec 86 +	+	+			

green and yellow (520 and 550 nm) and red (670 nm). It also has a near infra-red channel at 750 nm used to discriminate land areas. The "penetration depth" corresponding to 90% of the satellite signal is maximum in the blue oligotrophic waters of the southwestern Pacific. Computed as the reverse of the attenuation coefficient from the PREFIL data around the Loyalty Islands and PROPPAC data (Le Bouteiller, personal communication), it varies from 16 to 25 meters (depending on the wavelength). Conversely, the red wavelength is totally absorbed by water and the signal then corresponds to depths of only a few centimeters. As a result, this channel is used to extract the atmospheric contribution from the total signal (Viollier *et al.*, 1980, Deschamps and Viollier, 1987). When an accumulation of algae occurs near the sea surface, the near infra-red signal may be high. It has been widely used to detect cyanobacterial blooms with high biomass levels or intense surface scums (Horstmann *et al.*, 1978, Galat and Verdin, 1989). The pixel size is 825 m x 825 m and the swath width is 1600 km.

The SPOT sensor has three wide bands centered at 550, 650 and 850 nm. The penetration depth is about 15 m for band 1, a few centimeters for band 2. The last channel is sensitive to the first few centimeters and mainly to the near infra-red reflectance of terrestrial vegetation ("red edge"). Pixel size is 20 m x 20 m, and swath width is 60 km.

4.3. CZCS AND SPOT SENSOR RESPONSES

Around New Caledonia and Vanuatu, except for lagoon waters and turbid river runoffs, there should be no signal in the 670 nm band. Following chlorophyll concentrations found by the CZCS (Table 1), the four-band spectra should be those of oligotrophic waters. This is mostly the case in the CZCS series, except in summer, where many images show well-organized bright linear patterns with relatively high reflectance in the red and green-yellow channels. On Table 1, signs (+) and (-) indicate the presence on the individual channel of reflectant waters. Chl *a* is the mean chlorophyll concentration of the CZCS image (1600 km x 900 km) with an accuracy of 30% (Hovis *et al.*, 1978). All images were atmospherically corrected using the concept of the "clear water" pixels (Gordon *et al.*, 1983) and only 2 Angström exponents (0.8 and 1). (*) represents the number of images available for the month. In the "true colour mode" (Viollier and Belbeoch, 1984), these bright waters appear red, gold-yellow, or even white on the CZCS images, when their blue reflectance is higher than for blue oligotrophic waters.

In Table 2, CZCS reflectance values in the four bands are compared for pixels chosen in different parts of the image: in the most reflectant rows, in blue clear waters, in chlorophyll-rich surrounding waters. In every case, the bright water reflectances differ from the model, for all bands. For January 82 and February 1981, all reflectance values are particularly high from the blue to the red bands. For December 1980, only green and yellow reflectance values are high. This variability in the blue reflectance shows that "red tides" can have a variable CZCS signature in the Melanesian archipelago. They never reach the high CZCS reflectance values of coccolithophorid-rich waters where calcareous plates increase the backscattering of light (Viollier and Sturm, 1984, Viollier *et al.*, 1988). The effect of the phycoerythrin pigment is slightly detectable as the reflectance is generally lower at 550 nm than at 520 nm.

SPOT numerical counts of pixels in the streaks show that reflectances are lower than those of the coral barrier reef, but are much higher than those of the blue surrounding waters. The signal is higher in the first two bands, but comprehensive atmospheric corrections will be necessary before this can be confirmed. The SPOT image was taken in December 1986, just after the tropical storm "Patsy" (Territorial Meteorological Service, Noumea).

TABLE 2. Reflectances in % in the four CZCS bands for different water types selected on the image: blue water, rich water ($Csat$ = 0.3 mg m^{-3}), bright water (detected white or yellow on the true colour mode, see text).

Water type	Band 1	Band 2	Band 3	Band 4
Reference: André and Morel, (1991)				
Blue water	3	0.9	0.9	0.07
Rich water	1.5	1.5	1.5	0.17
Coccolithophorids: Viollier and Sturm, (1984)				
Bright water	9-5	7-5	6-4	1.5-1
4 January 82				
Bright water	5-3.5	3.8-2.9	3.8-2.7	1-0.4
Blue water	3.2	1.2	1	0.2
Rich water	1.1	0.8	0.6	0.2
4 February 1981				
Bright water	5-4	5-3	4-2.1	1
Blue water	3-2	1.5	1.5	0.3
Rich water	2	1.5	1.5	0.3
27 December 1980				
Bright water	3-2.2	2.1-1.8	2-1.6	0.4
Blue water	3	1.2	1	0.2
Rich water	1.2	0.8	0.8	0.2

4.4. SPATIAL DISTRIBUTION

In almost all summer images, bright elongated streaks and meandering rows, a few kilometers large, and hundreds of kilometers long (Plate I) are detected. These patterns are similar in shape to those detected by the Space Shuttle and reported by Kuchler and Jupp, (1988) on the Great Barrier Reef, where surface streaks of a "red tide" presumably formed by *Trichodesmium* were trapped.

On January 4, 1982, the bright linear structure could be followed, along 400 km, in the axis of the chlorophyll-rich waters, from New Caledonia (165°E) to Vanuatu (170°E). Two days earlier, similar bright meanders could be followed from Vanuatu to Fidgi (180°E) and even to Tonga (175°W). This indicates that blooms can be followed along 10 degrees of longitude. In March 1984 as well as in February 1981, meandering rows covered the chlorophyll-rich image, between 170°E and 175°E. In December 1980, the "red tide" was found on the exact border of the green waters. In the other images, well-organized gyres were restricted to smaller areas, as in November 1978, November 1980, December 1979 and March 1982. The advantage of the CZCS is that it gives two items of information simultaneously: one integrated over 20 meters in the blue band, and one for the surface in the red band. The chlorophyll-rich waters can reach 90 000 km^2, while bright linear patterns represent only 10 per cent of this surface. Comparison of the two bands for the same image gives a complete set of useful information on these discoloured waters. This is well shown on Figure 2.

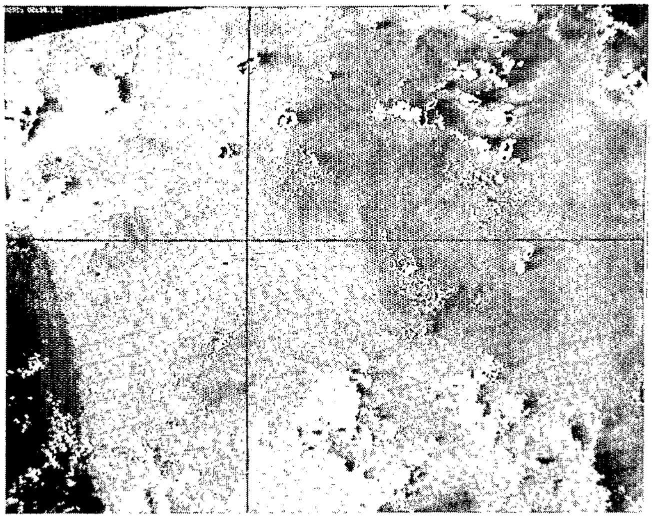


Plate I. CZCS image of a bright meandering pattern off the southern Fidgi Islands at 20°S, 180°E. Enhanced channel 3 (550 nm). Meanders are a few pixels wide. 2 January 1982.

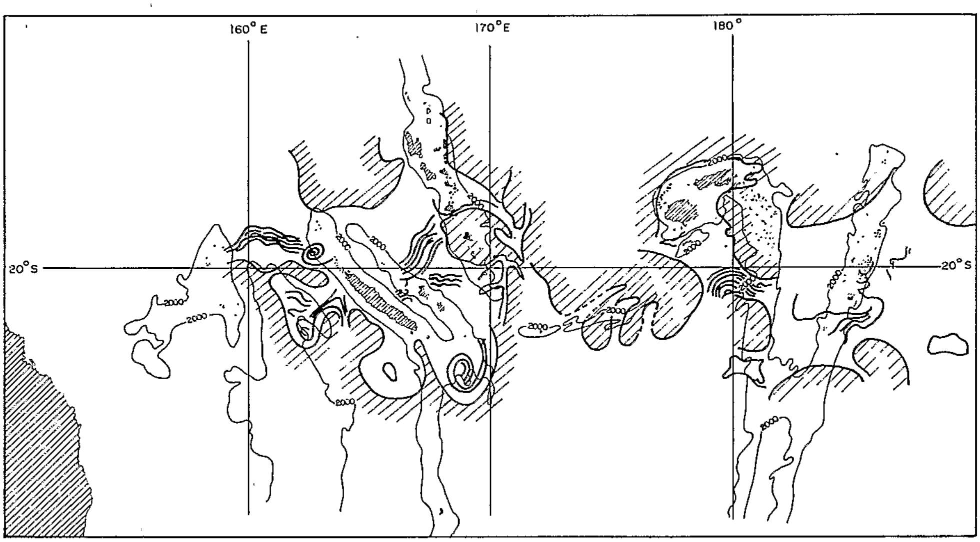
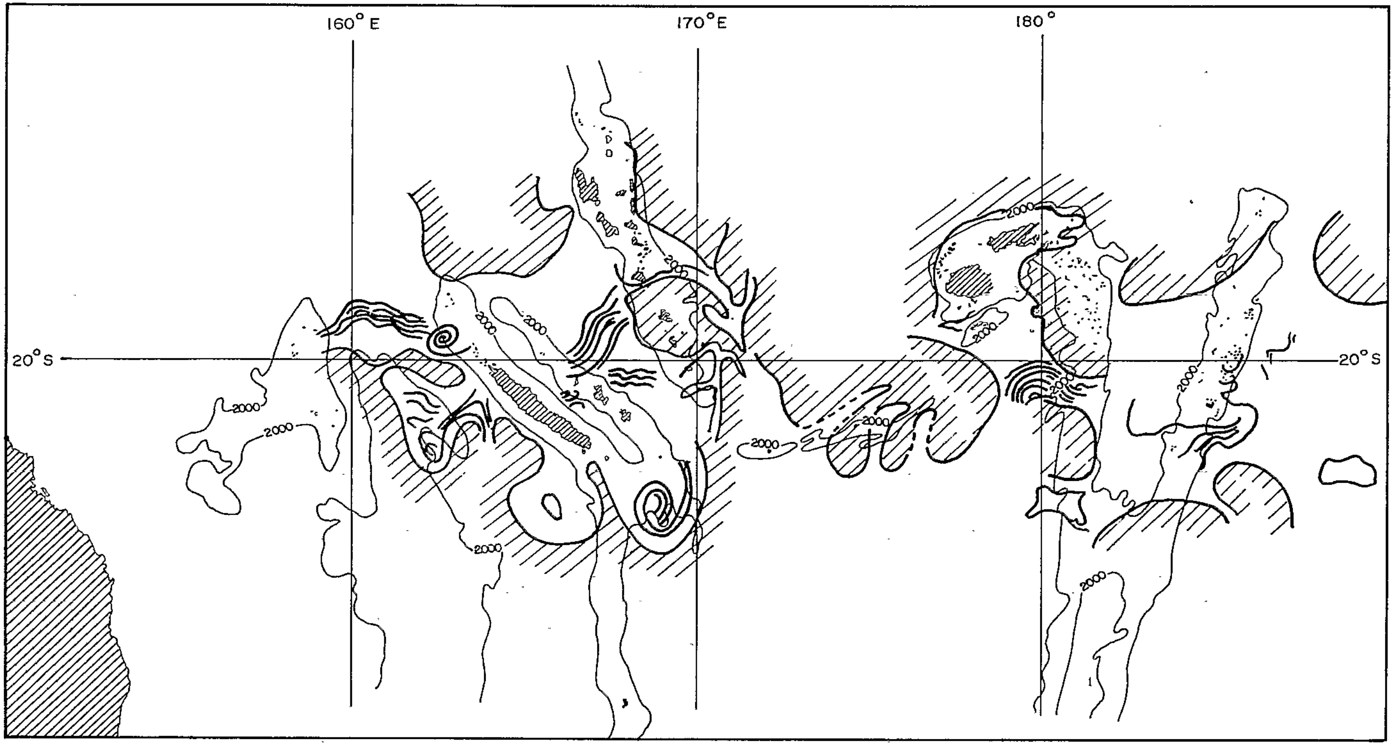


Figure 2. Area of discoloured waters observed by NIMBUS 7 Coastal Zone Colour Scanner around New Caledonia, Vanuatu and Tonga. Schematic mapping of chlorophyll-rich waters (inside of the hatched areas), with an outline of distinguishable bright linear patterns. West of 180°E, mosaic of images taken on several dates (November-December 1979, December 1980, February 1981, 2-4 January 1982, March 1982, March 1984). East of 180°E, one image taken on 2 January 1982.



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The SPOT images taken in December 1986 in the lagoon waters off St. Vincent Bay (Plate II, west coast) and off Canala (east coast) show white lines and eddies. They are one or two pixels wide and a few kilometers long. These patterns are found parallel to the coast, but perpendicular to the wave direction, and resemble cyanobacterial streaks observed by previous authors.

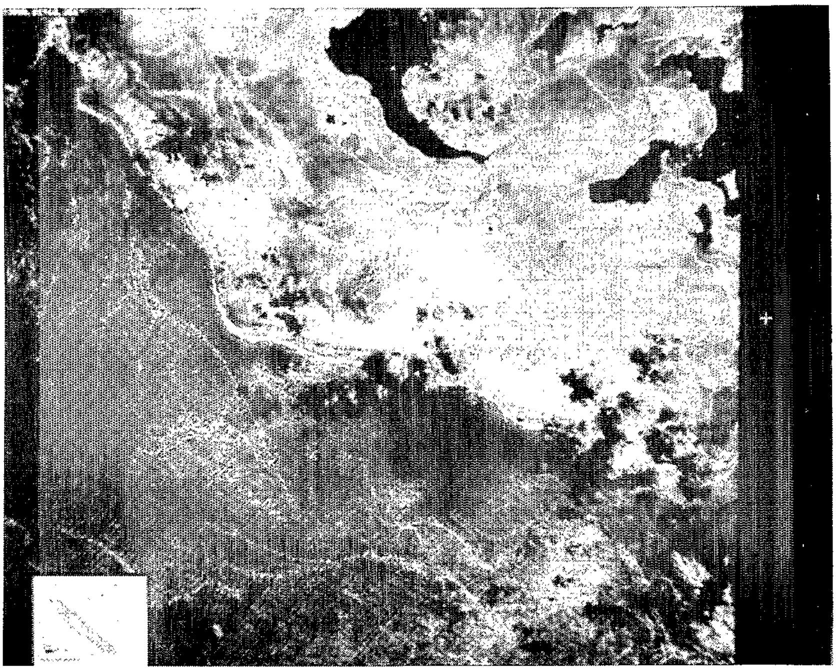

Plate II. C Copyright SPOT 1986 under license SPOT Image. Image of St. Vincent's Bay (west coast of New Caledonia). Enhanced XS1 channel. The figure represents a surface of 20 km x 20 km. The area of the pixel is 20 m x 20 m. Characteristics of the image: orientation: 8°6, incidence: 13.8°, solar azimuthal and zenithal angles: 98.2° and 68°3. Clouds and land are masked in black. Bright streaks are 20 meters wide. They appear around the small islands inside the coral barrier (white), as well as outside it, where they appear to be disrupted by waves.

5. Discussion and conclusion

CZCS and SPOT spectra show high reflectances over the entire spectrum. These high reflectance values have been discussed by Dupouy *et al.* (1988). They are explained by a highly diffusive biological phenomenon due to mass accumulation of algae. *Trichodesmium* colonies are known to form dense windrows of white to brown coloration at the sea surface. The CZCS spectra measured *in situ* by Borstad *et al.* (1989) on concentrated colonies corroborate this assumption. Other cyanobacteria are known to be part of the phytoplankton of archipelago waters. Picoplanktonic cyanobacteria dominate the phytoplankton in the southwestern Pacific (Blanchot *et al.*, in press), but do not form diffusive streaks. Coccolithophorids are a major group in the Caledonian lagoon (Desrosières 1969, 1975). They are known to form very intense white patches of highly diffusing coccolith plates (Le Fèvre *et al.*, 1983; Holligan *et al.*, 1983; Viollier and Sturm, 1984; Viollier *et al.*, 1988). CZCS-derived spectra over bright Pacific waters never reach such values. The effect of phycoerythrin is not as clear as expected on these CZCS examples and requires further study (Subramanian, unpublished results).

The examination of the 60 images of the series confirms the conclusion of Dupouy, (1990a,b). The majority of the summer images show high chlorophyll concentration zones and distinguishable patterns. These patterns corresponding to "red tides" are not systematically bright as for February 1981, January 1982 or March 1984, despite the probable presence of *Trichodesmium*. This variability of CZCS signatures is plausible, as the state of *Trichodesmium* blooms can vary with time and oceanographic conditions. The comparison of the blue and red bands of the CZCS is meaningful in this sense. The percentage of floating and buoyant colonies is given by the red band image, while the total bloom surface is given by the blue band. Present SPOT or NOAA satellites lack the blue band and therefore can describe only the surface of the bloom. The SPOT images of the Caledonian lagoon were taken after a tropical storm. Heavy rains may have caused extensive land water runoffs. On the other hand, *Trichodesmium* blooms are known to occur after tropical storms (Petit, personal communication). Patterns are likely those of *Trichodesmium*. It must still be confirmed that *Trichodesmium* is responsible for the extensive chlorophyll increases as well as for the "bright red tides", and that no other phytoplanctonic species can form the same patterns.

The circumstantial evidence in favour of *Trichodesmium* blooms is high. The discoloured waters with red tide signatures are commonly found during the austral summer (December to March), or after calm spells. The oceanographic context is favourable: off eastern New Caledonia, a year-round convergence zone is known to occur between the Trade Drift zone and the west-flowing southern equatorial current (Rotschi and Lemasson, 1967). High sea temperatures from January to March are favourable to *Trichodesmium* blooms.

Western Pacific discoloured waters are well documented by the CZCS. Their origin must still be confirmed by *in situ* observations extended to the whole Melanesian archipelago. The diazotrophic *Trichodesmium* is the most probable cause of such blooms, according to Loyalty Islands field measurements. If so, they constitute a major event for nitrogen fixation (Capone and Carpenter, 1983), and organic matter input in the oligotrophic waters. Because of the permanent stratification of these waters, nutrient inputs are reduced; the ecological impact of such nitrogen-fixing blooms may therefore be large.

Because of better repetitivity and oceanic global coverage, additional channels (mainly at 495 nm for phycourobilin pigment), and the probability of improved atmospheric corrections and radiometric resolution, future ocean color sensors will help in more confidently detecting *Trichodesmium* blooms. Airborne and *in situ* radiometric measurements will still be fully necessary in order to determine the evolution of the optical properties of blooms, which are undoubtedly related to concentration, age and the state of *Trichodesmium* colonies. Even before bio-optical studies are undertaken, better documentation on bloom occurrences of *Trichodesmium* in the region and over the global ocean will be essential.

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