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Satellite detected cyanobacteria bloom in the southwestern tropical Pacific

Implication for oceanic nitrogen fixation

CÉCILE DUPOUY

Centre ORSTOM de Brest, IFREMER, BP70, 29263 Plouzané, France

MICHEL PETIT

Centre ORSTOM de Montpellier, 2051, avenue du Val de Montferrand, B.P. 5045, 34032 Montpellier Cedex, France

and YVES DANDONNEAU

Centre ORSTOM de Nouméa, BP A5, Nouméa Cedex, Nouvelle Calédonie

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Abstract. Tropical seas are major sites for extensive cyanobacterial (= blue–green algal) developments. The oceanic nitrogen fixation caused by such blooms may be of relatively great importance in regard to the global nitrogen budget. A Nimbus-7 Coastal Zone Colour Scanner (CZCS) image on 4 January 1982 shows a large phytoplankton bloom (90 000 km^2) around New Caledonia and the Vanuatu archipelago, located east of Australia in the Coral Sea (165° E, 20° S). The bloom is caused by cyanobacteria, presumably *Oscillatoria* (= *Trichodesmium*) spp. which occur systematically in this region. This assertion was not controlled by simultaneous sea-truths, but several indices and current knowledge of the region indicate that our hypothesis is reasonable. By using the CZCS image, an estimation is made for the nitrogen fixation of the bloom. It suggests that such a biological event plays a significant role in the global nitrogen oceanic budget.

1. Introduction

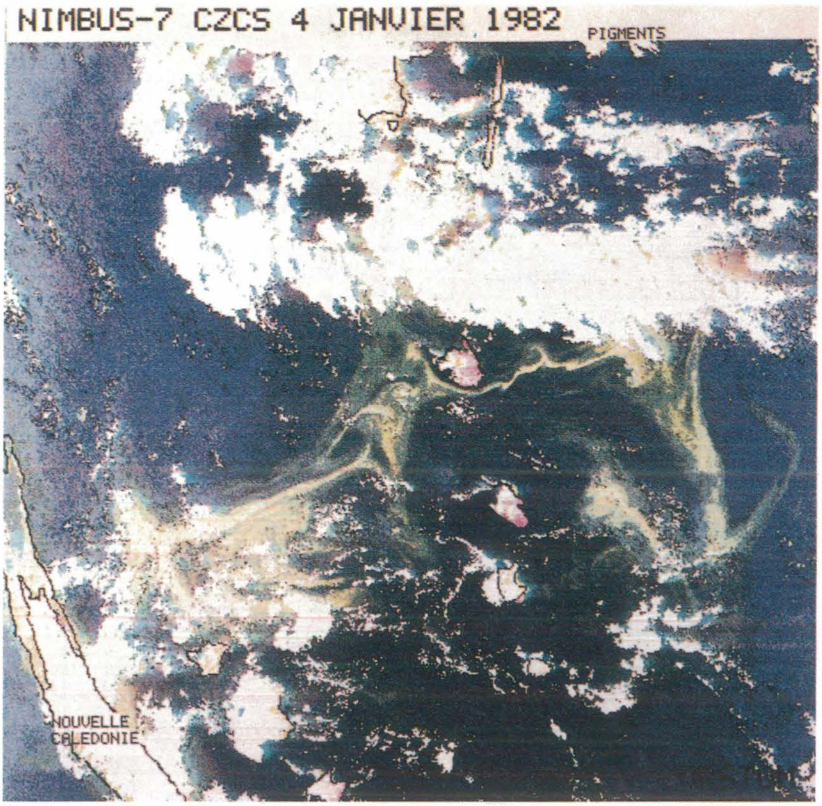
Discoloured waters of brick-red to bright yellow colour are often reported in the tropical and subtropical oceans, particularly in the tropical southwestern Pacific (Dandonneau 1982, Dandonneau and Gohin 1984, Dandonneau and Charpy 1985), where they usually occur during austral summer (November to March) when light winds (calms) and storms replace the prevailing trade winds. Proliferations of such discoloured phytoplankton blooms have been observed in coastal areas (Great Barrier Reef or Caledonian lagoon) and in passages between islands (Caribbean, Hawaiian or Maldive Islands) (Carpenter and Price 1976, 1977, Carpenter, 1983). In the open ocean as well, visual observations of meandering plankton patterns have frequently been reported by merchant ships over the South Pacific (Dandonneau and Gohin 1984), at a survey in the north Pacific gyre (Mague *et al.* 1977) and also during oceanographic cruises in the Coral Sea (New Caledonia and Vanuatu) (Le Borgne *et al.* 1985, Le Borgne 1986). Discoloured waters due to cyanobacteria were also frequently observed in this zone during aerial radiometry surveys made between 1979 and 1983 (15° S–25° S, 160° E–175° E) (Petit and Henin 1982, Petit and Gohin 1982, Petit and

Hazane 1983). Yellow stripes occupied 0·07 to 0·83 per cent of the observed areas, with maximum aerial coverage east of Caledonia. Maximum occurrence was in January (summer). Cyanobacteria are indeed a major component of the phytoplankton of the southwestern tropical Pacific and in the Coral Sea. Since 1951, the presence of *Oscillatoria* (= *Trichodesmium* spp., Sournia 1968, 1970) was detected in this region (Baas-Becking 1951, Wood 1955). The *Oscillatoria* colonies were found at all PREFIL (Production and Island Effect) cruises, around the Loyalties Islands, with highest concentrations during summer or after a calm period when they can reach 83 per cent of the total counts (Le Borgne 1986). *Oscillatoria* spp. are nitrogen fixing filamentous non-heterocystous cyanobacteria. Filaments (or trichomes) measure from 3 to 30 μm in diameter and become visible by eye, as they bundle together to form a bright golden dust over the sea surface. They remain at or near the surface by regulating their buoyancy with the help of gas vacuoles (Carpenter 1983) but are also usually scattered down into the first 100 m of the water column (L. Lemasson 1987, personal communication). Chlorophyll *a*, which represents their main pigment, is accompanied by accessory pigments (carotenoids and the phycobilins, phycocyanin and phycoerythrin) similar to those found in the Rhodophyceae (Sournia 1986) which allow them to absorb light throughout the visible spectrum (Ohki *et al.* 1986) and give a brown colour to the cells. Since 1978, the remote sensing of ocean colour has provided exceptionally valuable data for studies of the optical properties and productivity of the ocean (Hovis *et al.* 1980, Gordon *et al.* 1980). The Nimbus-7 Coastal Zone Colour Scanner (CZCS) sensor is expected to document precisely the large scale distribution and variability of the discoloured blooms over the Coral Sea. Satellite images from Landsat in the Baltic distinctly show the marine patterns caused by the cyanobacteria *Aphanizomenon flos aquae*, despite the inadequacy of the Landsat sensor at sea, due to a very high signal from this alga in the visible spectrum (Ulbricht 1983).

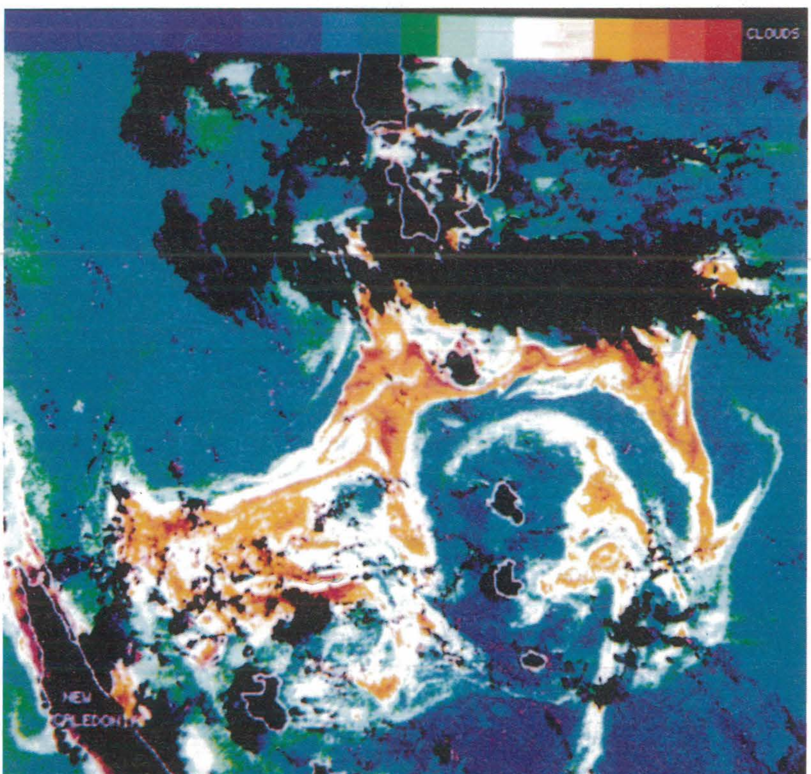
2. Satellite ocean colour observation

The CZCS image (figure 1 (*a*)) was taken on 4 January 1982 at 12.00 local time and is one of the 200 acquisitions by Nimbus-7 over the Coral Sea. It includes an area from 165 to 173° E, 17 to 22° S and therefore a surface of 800 km by 500 km. Each pixel in the image corresponds to 1650 m by 1650 m. The image is centred on the Vanuatu archipelago (21° S, 168° E, figure 1 (*b*)). New Caledonia and the Loyalties Islands are visible on the lower left corner. Convective clouds are situated above the islands of Mare, Lifou, Ouvea (Loyalties) and the southern islands of the Vanuatu archipelago (figure 1 (*c*)). In the north a large horizontal cloud related to the intertropical convergence zone covers Malekula and Espiritu Santo. The processing was performed on a VAX and COMTAL VISION hardware at IFREMER using atmospheric corrections (Viollier *et al.* 1980) taking into account the decrease of sensitivity of the sensor (Viollier 1982), and choosing a mean Angström exponent (0·5). The 'true

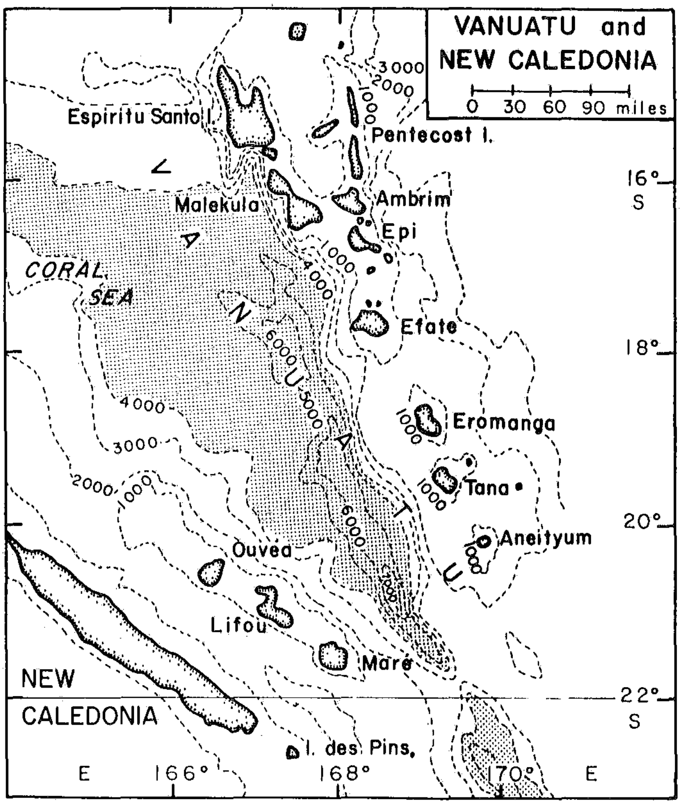
Figure 1. Nimbus-7 Coastal Zone Colour Scanner (CZCS) picture, orbit 16390, 4 January 1982, 12.00 local time, over New Caledonia and Vanuatu (165 to 180° E, 23 to 15° S). (*a*) True colour representation of subsurface upwelling radiances in channels 1, 2 and 3 of the visible spectrum in blue, green and red respectively. Clouds are masked in white, land in brown. Saturation of the sensor is observed east of the islands or clouds. (*b*) Location map for the CZCS scene and bathymetry. New Caledonia and Vanuatu Islands are pointed out. (*c*) Colour-coded map of phytoplankton pigment concentrations derived from (*a*). Clouds and land are in black. Yellow-orange areas correspond to low reflectance values in red areas to high reflectance values in channels 1, 2 and 3 (440, 520 and 550 nm).


NIMBUS-7 CZCS 4 JANVIER 1982
PIGMENTS
NOUVELLE
CALEDONIE

(*a*)


CLOUDS
NEW
CALEDONIA

(*c*)



(*b*)

colour' mode (figure 1 (*a*)) consists of a colour composite of channels 1, 2 and 3 after atmospheric correction (Viollier 1984). Despite heavy cloud cover, a very large dark and yellow discoloured water mass is visible at the centre of the field of view, spreading from west to east of the area and assuming the shape of a large cyclonic gyre (400 km in width). In particular, a bright yellow meander can easily be followed in the main stream of the gyre; it starts from the Loyalties (20° S, 166° E), then reaches the southern coast of Efate island, and continues east, before finally curving south (18° S, 173° E). In some places, the meander is distorted by small eddies with horizontal scale of 30 km (as east of Efate). The gyre ends in a jet heading south in a large arrow shape. The extent of this bloom is slightly detectable around the northern islands of Vanuatu. North of Loyalties, narrow parallel bands of yellow colour (width of 6·6 km) are visible. There is a lack of simultaneous measurements of *Oscillatoria* concentrations. Nevertheless, the characteristics of the CZCS image, described in more detail in §3, are in agreement with the knowledge of the biology and ecology of this cyanobacteria.

3. Satellite information and cyanobacteria evidence

The 'true colour' information helps, in this case, in determining the type of alga involved. No ambiguity exists about the phytoplanktonic origin of the bloom as no mineral turbidity occurs around the islands (except inside the lagoons). The analysis of CZCS spectral signatures (figure 2) allows one to distinguish clear waters from the bloom-type waters. The reflectances in the three CZCS channels for the clearest water (1 in figure 2) fit in with the clear water spectrum in Sargasso Sea (DISCOVERER

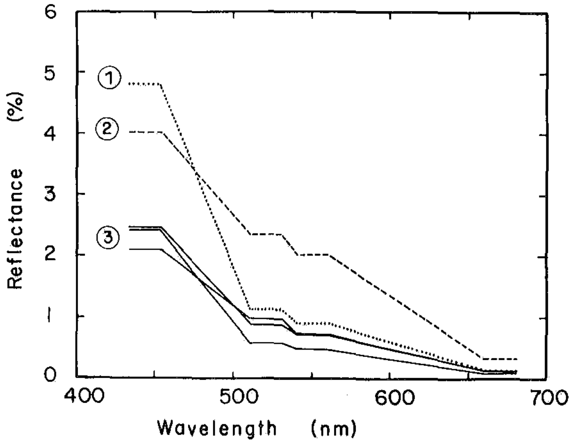


Figure 2. CZCS spectral signatures from three locations of the CZCS image for 4 January 1982. The reflectances in CZCS channels 1, 2 and 3 (440, 520 and 550 nm respectively) are corrected for atmospheric contribution. See §3.

oceanographic cruise). These blue oligotrophic Pacific water points far from islands or cloud, differ from highly absorbing waters inside the bloom (3 in figure 2) which is in accordance with *in situ* and modelled spectra for clear and phytoplankton rich waters (0·1 to 0·3 mg/m^3 of chlorophyll *a*, 3 in figure 2) (Morel 1982). The highest reflectances in the green and yellow colour channels are only measured in the narrow meander in the main stream of the gyre and south of Efate in sea-slicks of scum-forming cyanobacteria. Typically 20 000 filaments per litre are found here which enhances the scattering and produces this spectral signature (2 in figure 2). Such a signature is found twice in the total series November 1978 and March 1984 where it characterizes spiral eddies or meandering patches. On winter images, this signature is never found, because we only get non-*Trichodesmium* blooms. Thus, this could be caused by yellow substances, as products of degradation of senescent phytoplankton (Jones *et al.* 1986). Therefore, the colour of the bloom as seen by CZCS, with a mixing of two types of waters from dark green to bright gold, is attributable to superficial blooms of cyanobacteria with varying concentrations of colonies.

The chlorophyll map (figure 1(*c*)) is derived from the true colour image by using algorithm of Gordon *et al.* (1980) using the ratio of channels 1 and 3, which gives the near-surface pigment concentration over one attenuation depth (inversely related to the attenuation coefficient). Chlorophyll concentrations measured by the satellite (0·35 mg/m^3) are relatively high for the region. Chlorophyll values corresponding to the most reflectant waters within the meander—and for which the retrieval is ambiguous because of scattering by cells (Morel 1982)—appear as a bright red colour. Satellite chlorophylls are in good agreement with *in situ* recordings of high chlorophylls, between 160° E and 175° E, in summer 1982. These merchant-ship chlorophyll maxima are attributed to the *Oscillatoria* summer blooms, because during the stratification period only nutrient-dependent phytoplankton like cyanobacteria can grow in the warm depleted photic layer (Dandonneau and Gohin 1984).

The great surface area covered by discoloured waters on the CZCS image (90 000 km^2) is also characteristic of a cyanobacteria bloom which corroborates the merchant-ships reports of large red tides. A stratification of the water column is a necessary condition of *Oscillatoria* bloomings, as these phytoplankton cells are floating to the surface due to their gas vacuoles and also as stability of the surface waters is necessary for protection of the nitrogenase (Carpenter and Price 1976). In summertime, a negative wind effect is found on the sea surface chlorophyll concentration, explained by the fact that surface slicks of *Oscillatoria* are easily dispersed (Dandonneau and Gohin 1984). As the weather was calm during 8 days in December 1981 (Lifou Island, Direction of National Meterology, Noumea), the large pattern observed on the CZCS image may be seen as the result of a regular population increase of *Oscillatoria* during this calm period.

High spatial heterogeneity of some locations of the CZCS image is also in agreement with sea or aerial observations. Stripes, slicks and parallel bands are observable at a horizontal scale from 200 m to 2 km. The superficial colonies of *Oscillatoria* may be considered as passive tracers of the drift of surface waters. These buoyant algae are concentrated in converging cells of Langmuir circulation in the surface waters and can form bands parallel to the current direction. Such patterns are evident on the CZCS image in some places north of Ouvea (width of 6·6 km) and south of Efate. It must be noted that the CZCS infrared signal is noisy and not sensitive enough to define the physical superficial structures of the thermal field. Other CZCS images over the same area in summer show similar yellow regular patterns rather like spiral eddies (November 1978, April 1983). Such an extensive discoloured surface is only found in December 1980 and constitutes the second largest cyanobacteria bloom in the CZCS series.

Are the shape and position of the gyre in agreement with the general thermal horizontal structure? Yellow waters are indeed observed preferentially in the region of thermal fronts (Petit and Henin 1982). In January the trades are weak and the South Tropical Counter Current (STCC) is dominant. The general oceanic circulation is directed towards the south-east (Donguy *et al.* 1970). In December 1981, there was a weak thermal gradient (29–26°C), with east–west isotherms between 17° S and 22° S (from GOSSTCOMP-NOAA charts). The gyre is probably at the southern boundary of the warm and less saline waters carried out by the STCC and cells are spreading in a convergence zone between northern and southern water masses. More remarkably, the planktonic bloom seen by CZCS is geographically trapped by the islands. This may be the most significant evidence of occurence of *Oscillatoria* at sea; its blooms are frequently found in straits or in the wakes of islands (Caribbean Sea, Carpenter and Price, 1977) or in channels where they are the main factor responsible for the 'island mass effect' (Hawaiian islands) (Gilmartin and Revelante 1974). In our area, the highest *Oscillatoria* concentrations are recorded at sea between the two adjacent Loyalties Islands, Lifou and Ouvea (L. Lemasson 1987, personal communication).

4. Implication for global atmospheric nitrogen fixation

In conclusion, the large bloom of *Oscillatoria* is of great significance to the pelagic ecosystem of the Coral Sea in terms of phytoplanktonic productivity and nitrogen fixation. The carbon content integrated over the bloom surface seems high, though *in situ* productivity and implications for the food chain have not yet been determined. The main point is the ability of *Oscillatoria* to fix atmospheric nitrogen. Their proliferations constitute a source of nitrogen for the depleted tropical euphotic zone. The role of this oceanic input is supposed to be minor in comparison to other nitrogen sources (Capone and Carpenter 1983) such as remineralization and recycling, rainfall addition and island run-off. The nitrogen fixation rates measured *in situ* (Carpenter and Price

1977) in *Oscillatoria* rich waters range between 0·06 (Sargasso Sea) and 1·3 mg of $N_2\,m^{-2}\,d^{-1}$ (Caribbean Sea); the maximum value being 4 mg of $N_2\,m^{-2}\,d^{-1}$. These values apply to the euphotic zone (50 m), (100 m at PREFIL, cruises: Lemasson 1987, personal communication) though an *Oscillatoria* maximum is generally found at a depth of 5 to 20 m (Carpenter and Price 1976). Satellites measure chlorophyll content over one optical depth, which varies in this zone from 20 to 40 m (values related to low attenuation values). This optical depth presumably includes the depth of maximum concentration of *Oscillatoria*. Assuming a homogeneous horizontal distribution of the algae over the bloom surface (90 000 km^2 for C sat $>0{\cdot}05\,mg\,m^{-3}$, or 34 000 km^2 for C sat $>0{\cdot}1\,mg\,m^{-3}$) and using the two extremes of the nitrogen fixation rate given above, the total amount of nitrogen fixed by the bloom during 10 days ranges from 0·02 to $1{\cdot}17\times10^9$ g of N_2; the maximum being $3{\cdot}6\times10^9$ g N_2. If we choose the highest value and if we assume that only one *Oscillatoria* bloom of 10 days occurs per year and per 4° by 4° of longitude and latitude square, we can evaluate the total nitrogen fixation for the Southern Pacific (between 10° S and 25° S, 160° E and 140° W). This amount is 202 tonnes of N_2, which represents 60 per cent of the annual fixation estimation for the entire Pacific (337 tonnes of N_2, from Capone and Carpenter 1983). Therefore the nitrogen fixation evaluation from CZCS, with a high hypothesis for the fixation rate, but a low one for occurrence (one bloom per year) appears to be higher than previous estimations. Satellite images are probably the ideal tool to observe and evaluate the surfaces of patterns of phytoplankton biomass and moreover proliferations of *Oscillatoria* in the Pacific. The study of repetitivity of such blooms is a major challenge and one can suggest that a global survey by the future ocean colour sensors, combined with *in situ* classical measurements of fixation rates, will be helpful in determining the annual nitrogen fixation in the southern tropical oceans.

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