INT. J. REMOTE SENSING, 1988, VOL. 9, NO. 3, 389–396

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

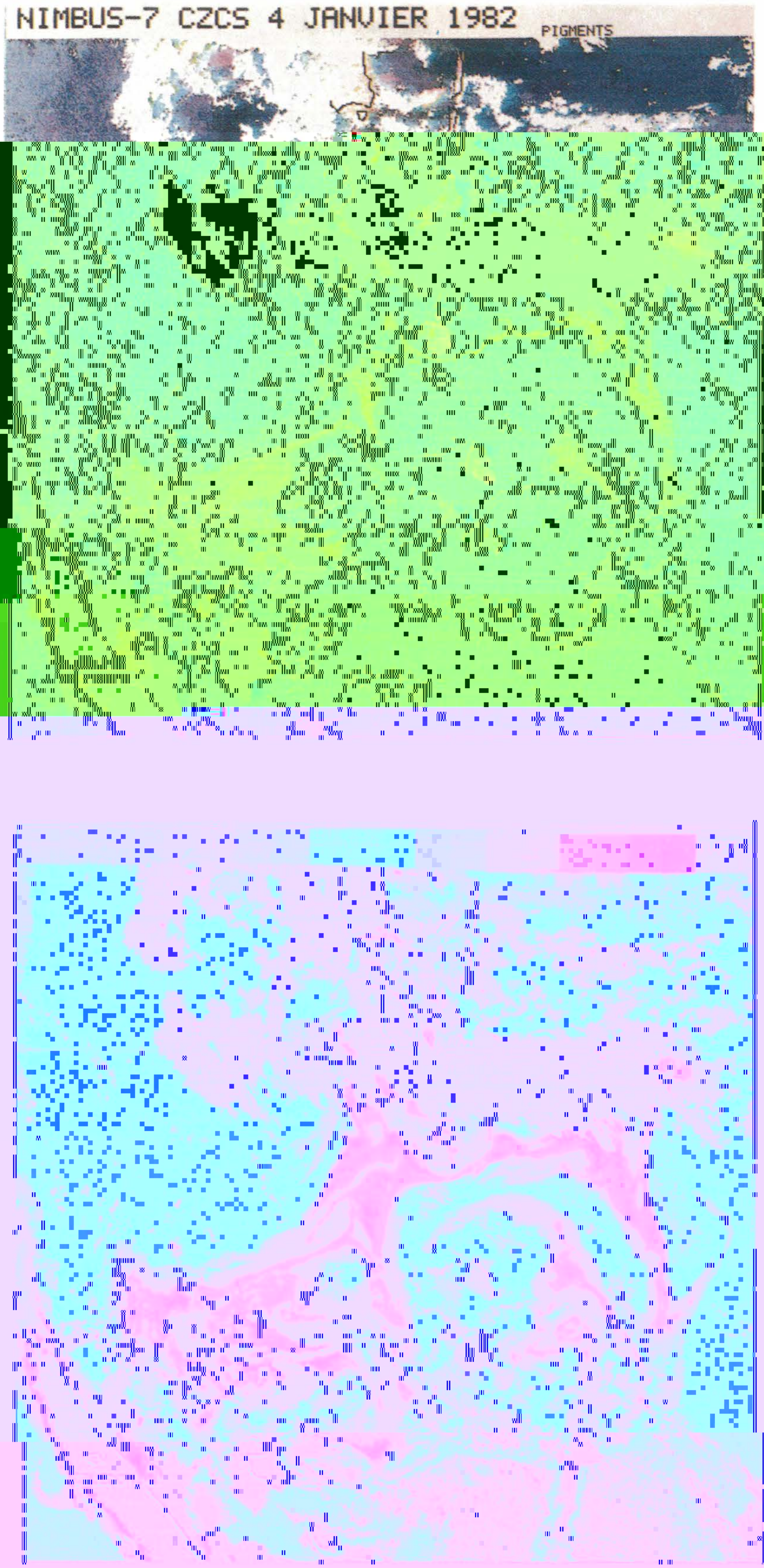
(Received 3 July 1987; in final form 29 September 1987)

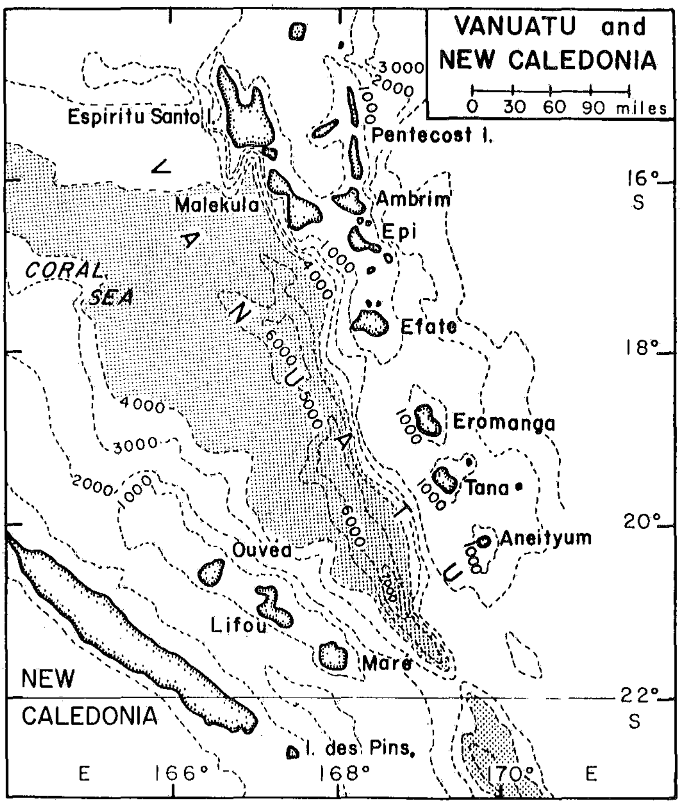
Abstract. Tropical seas are major sites for extensive cyanobacterial (= blue–green algal) developments. The oceanic nitrogen fixation caused by such blooms may be of relatively great importance in regard to the global nitrogen budget. A Nimbus-7 Coastal Zone Colour Scanner (CZCS) image on 4 January 1982 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


NIMBUS-7 CZCS 4 JANVIER 1982
PIGMENTS



(*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

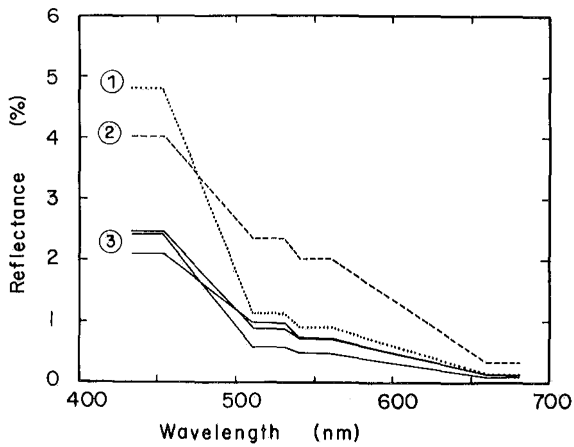


Figure 2. CZCS spectral signatures from three locations of the CZCS image for 4 January 1982. The reflectances in CZCS channels 1, 2 and 3 (440, 520 and 550 nm respectively) are corrected for atmospheric contribution. See §3.

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 $>0·05\,mg\,m^{-3}$, or 34 000 km^2 for C sat $>0·1\,mg\,m^{-3}$) 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 $1·17 \times 10^9$ g of N_2; the maximum being $3·6 \times 10^9$ 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.

Acknowledgments

Financial support was received from ORSTOM, CNRS and CNES. We wish to thank the following for advice and assistance during this work: A. Sournia for contribution to the text, M. Viollier for CZCS algorithms and marine signal calibration, L. Lemasson for his knowledge of the Coral Sea, Y. Blanchot for sea truth data and plankton determination, J. R. Donguy for his helpful advice and all our colleagues who provided helpful comments.

References

Baas-Becking, L. G. M., 1951, Notes on some Cyanobacteria of the Pacific Region. *Proceedings Koninklijke Nederlandse Akademie Van Wetenschappen* C, **54,** 213–214.

Capone, D. J., and Carpenter, E., 1982, Nitrogen fixation in the marine environment. *Science, New York,* **217,** 1140–1142.

Carpenter, E. J., 1983, Physiology and ecology of marine planktonic *Oscillatoria (Trichodesmium). Marine Biology Letters,* **4,** 69–85.

Carpenter, E. J., and Price, C. C., IV, 1976, Marine *Oscillatoria (Trichodesmium)*: explanation for aerobic nitrogen fixation without heterocysts. *Science, New York,* **191,** 1278–1280.

Carpenter, E. J. and Price, C. C., IV, 1977, Nitrogen fixation, distribution, and production of *Oscillatoria (Trichodesmium)* in the northwestern Atlantic Ocean and Caribbean Sea. *Limnology and Oceanography,* **22,** 60–72.

Dandonneau, Y., 1982, A method for the rapid determination of chlorophyll plus phaeopigments in samples collected by merchant ships. *Deep Sea Research,* **29,** 647–654.

Dandonneau, Y., and Gohin, F., 1984, Meridional and seasonal variations of the sea surface chlorophyll concentration in the southwestern tropical Pacific (14 to 32° S, 160 to 175° E). *Deep Sea Research,* **31,** 1377–1393.

DANDONNEAU, Y., and CHARPY, L., 1985, An empirical approach to the island mass effect in the south tropical Pacific based on sea surface chlorophyll concentrations. *Deep Sea Research,* **32,** 707–721.

DONGUY, J. R., OUDOT, C., and ROUGERIE, F., 1970, Circulation superficielle et subsuperficielle en Mer du Corail et à 170° E. *Cahiers ORSTOM, Série Océanographie,* **8,** 3–20.

GILMARTIN, N., and REVELANTE, N., 1974, The 'island mass' effect on the phytoplankton and primary production of the Hawaiian islands. *Journal of Experimental Marine Biology and Ecology,* **16,** 181–204.

GORDON, R., CLARK, D. K., MUELLER, J. L., and HOVIS, W. A., 1980, Phytoplankton pigments from the Nimbus-7 coastal zone color scanner: comparisons with surface measurements. *Science, New York,* **210,** 63–66.

HOVIS, W. A., CLARK, D. K., ANDERSON, F., AUSTIN, R. W., WILSON, W. H., BAKER, E. T., BALL, D., GORDON, H. R., MUELLER, J. L., EL-SAYED, S. Z., STURM, B., WRIGLEY, R. C., and YENTSCH, C. S., 1980, Nimbus-7 coastal zone colour scanner: system description and initial imagery. *Science, New York,* **210,** 60–63.

JONES, G. B., THOMAS, F. G., and BURDON-JONES, G., 1986, Influence of *Trichodesmium* blooms on cadmium and iron speciation in Great Barrier Reef lagoon waters. *Estuarine, Coastal and Shelf Science,* **23,** 387–401.

LE BORGNE, R., 1986, Programme PROCAL. III. Croisières 'Préfil' 3 à 10 (Zooplancton et micronecton) du N. O. Coriolis. Croisières 'Uitoe' 1 à 12, 'Maré' et 'Ondimar' du N. O. Vauban. Centre ORSTOM Nouméa.

LE BORGNE, R., DANDONNEAU, Y., and LEMASSON, L., 1985, The problem of the island mass effect on chlorophyll and zooplankton standing crops around Maré (Loyalty Islands) and New Caledonia. *Bulletin of Marine Science,* **37,** 450–459.

MAGUE, T. H., Mague, F. C., and HOLM-HANSEN, O., 1977, Physiology and chemical composition of nitrogen-fixing phytoplankton in the Central North Pacific Ocean. *Marine Biology,* **41,** 213–227.

MOREL, A., 1982, Télédétection dans le domaine visible. Couleur de l'océan et son interprétation. In *Space Oceanology,* CNES (Toulouse: CEPADUES), pp. 643–688.

OHKI, K., RUETER, J. G., and FUJITA, Y., 1986, Cultures of the pelagic cyanophytes *Trichodesmium erythreaum* and *T. thiebaudi* in synthetic medium. *Marine Biology,* **91,** 9–13.

PETIT, M., and GOHIN, F., 1982, Radiométrie aérienne et prospection thonière. Rapport (unpublished manuscript) ORSTOM, Nouméa.

PETIT, M., and HAZANE, P., 1983, Radiométrie aérienne et prospection thonière. Rapport (unpublished manuscript) ORSTOM, Nouméa.

PETIT, M., and HENIN, C., 1982, Aerial radiometry and tuna survey. Final report. Notes et Documents d'Océanographie (Port Vila, Vanuatu: ORSTOM) (unpublished manuscript).

SOURNIA, A., 1986, Atlas du Phytoplancton Marin. Volume 1: Introduction, cyanophycées. (Paris: CNRS).

SOURNIA, A., 1968, La cyanophycée *Oscillatoria (Trichodesmium)* dans le plancton marin: taxinomie et observations dans le Canal de Mozambique. *Nova Hedwiga,* **15,** 1–2.

SOURNIA, A., 1970, Les cyanophycées dans le phytoplancton marin. *L'Année Biologique,* **9,** 63–76.

ULBRICHT, K. A., 1983, Comparative experimental study on the use of original and compressed multispectral LANDSAT data for applied research. *International Journal of Remote Sensing,* **4,** 571–575.

VIOLLIER, M., TANRE, D., and DESCHAMPS, P. Y., 1980, An algorithm for remote sensing of water color from space. *Boundary Layer Meteorology,* **16,** 247–267.

VIOLLIER, M., 1982, Radiometric calibration of coastal zone color scanner on Nimbus-7. *Applied Optics,* **21,** 1142–1145.

VIOLLIER, M., 1984, Displaying CZCS data in 'true colour' mode. *Environmental Research Institute of Michigan Symposium held in Paris,* (Michigan: ERIM), pp. 1727–1729.

WOOD, E. J. F., 1955, *Marine Microbial Ecology* (London: Chapman and Hall. New York: Reinhold).