13

*Dupouy-Douchement C., Oiry H., Le Bouteiller A. and M. Rodier. in :*
*I.S.F. Jones et al. (eds.), Satellite Remote Sensing of the Oceanic Environment, 408-420.*
*1993 Seibutsu Kenkyusha Publishers, Australia, Japan.*

# 12.3 Variability of the equatorial phytoplankton enrichment in the Western and Central Pacific Ocean

C. Dupouy-Douchement, H. Oiry, A. Le Bouteiller and M. Rodier

## *12.3.1 Introduction*

The equatorial Pacific Ocean is a huge productive region of the world ocean. During non El Niño conditions, the upwelling of nutrient-rich deep water (Wyrtki, 1981) in the euphotic layer enhances primary production. Chavez and Barber (1987) have estimated that the equatorial region would support half of the global primary production. We know relatively little about spatial extents of biomass and primary production in the equatorial Pacific. The map by Koblentz-Michtke et al. (1970) describes the phytoplankton enrichment as a tongue spreading westward from the eastern Peruvian coast to the date line. Sea surface chlorophyll variations were described at large scales with a specific method during a ship-of-opportunity program on three tracks crossing the equator in the Pacific (Dandonneau, 1992). Barber and Chavez (1991) showed that primary production, as well as nutrient concentrations and chlorophyll follow a decreasing zonal gradient from east to west. Recently, the ALIZE 2 transect showed that phytoplankton biomass was homogeneous all along the equator (Le Bouteiller and Blanchot, 1991). Seasonal variability has well been shown in the eastern tropical Pacific (Blackburn et al., 1970, Owen and Zeitschel, 1970). Interannual variability in productivity is well documented, with a good description of the warm/cool 1982/83 El Niño/La Niña episodes of the El Niño and Southern Oscillation (ENSO). In the eastern Pacific, the dramatic reduction of primary production during the warm El Niño 1982/83 event has well been shown by Barber and Chavez (1983, 1986) and Barber and Kogelschatz (1989). In the eastern and central Pacific, phytoplankton composition and production have been described during the last La Niña period by Chavez et al. (1990). In the western Pacific, Blanchot et al. (1989, 1992) have shown the effect of the two contrasted El Niño/La Niña 1988 events on biomass, primary production and phytoplankton composition.

Despite these efforts, the scarcity of observations, constrained by the limited coverage of research vessels and difficulties in intercalibration of methods (Le Bouteiller, 1993), do not allow a synoptic view of primary productivity in the equatorial enrichment, mainly in the *warm pool* (Lucas and Lindstrom, 1991) of the western Pacific. The best way to observe spatial and temporal variations of the phytoplankton field consists in using ocean color remote sensing. It has been widely shown that phytoplankton biomass can be assessed by the Coastal Zone Color Scanner on board Nimbus-7. Archive data have been processed over the world ocean (Feldman et al., 1989). The mean equatorial field for the 1978-1986 period has already been described by Feldman et al. (1992), but seasonal variations of the equatorial ocean color field have not been analysed in detail yet.

The objective of the FLUPAC (Flux of carbon in the Western Pacific) program, in accordance with the Joint Global Ocean Flux Study program, is to estimate the global carbon flux in the western Pacific (Le Borgne, 1992). To describe by remote sensing the mesoscale variability of the equatorial enrichment boundaries in the western ( and central Pacific) is one important point of study. ORSTOM has gathered a great amount of in-situ physical and biological data over the western tropical and equatorial regions during their field programs, which are useful for interpreting ocean color variations. CZCS ocean color data is used both as a test for future Seawifs and OCTS data and to answer two major questions:

1. can we determine the geographic boundaries of the phytoplankton enrichment in the equatorial Pacific ocean, and mainly its westernmost border?
2. can we convert the satellite pigment estimate to the euphotic layer pigment content?

The latter is a necessary step in the assessment of primary production. It has to be kept in mind that the deep chlorophyll maximum is a common feature in the western tropical Pacific (Le Bouteiller et al., 1992, Blanchot et al., 1992. Dandonneau, 1979), which is a rather unfavourable situation for ocean color applications.

### *12.3.2 Methods for pigment determination*

Data used in this study are individual orbit portions which were pre-processed and transformed to pigment and aerosols data, from the Coastal Zone Color Scanner archive maintained by the National Space Science and Data Center at NASA Goddard Space Flight Center (Feldman et al., 1989). To determine boundaries of the phytoplankton enrichment in the equatorial region of the Pacific, we needed to form global composites, with keeping the best resolution in space and time. The level 2 products consisting in pre-processed data : three visible marine radiances, attenuation coefficient, aerosols and pigment, at the resolution of 3.3 km (Feldman et al., 1989) were taken for this purpose. All approved individual level 2 scenes found within the studied area (15° N-15° S, 130° E-130° W) were selected. Only the two successive years 1981 and 1982 were processed in this paper. The characteristics of this data set is provided at Table 12.1.

**Table 12.1 CZCS level 2 scenes used for composites in the equatorial Pacific (15° N to 15° S, 30° E to 130° W) for quarters; January to March, April to June, July to September and October to December.**

| QUAR | Jan-Mar | Apr-Jun | July-Sept | Oct-Dec | TOTAL |
|---|---|---|---|---|---|
| 1981 | 0 | 14 | 27 | 103 | 147 |
| 1982 | 54 | 57 | 80 | 113 | 304 |

The single CZCS level 2 images were transformed to a squared-degree projection before compositing, by using a personal procedure (Oiry, 1992). For producing *cloud-free* global composites, we developed an automatic procedure (Oiry, 1992), which consisted in computing, for each pixel, the arithmetic mean and variance, avoiding pixels of clouds and land. Three mosaic fields were then generated: mean, variance and number of valid pixels. The initial image resolution of the level 2 product (one pixel sampled over four) was kept for the composite, allowing a better description of the mesoscale spatial variability. Isolated pixels corresponding to noise were eliminated. Remaining clouds and also lands were masked in white. The Feldman's transformation between numerical counts and total pigment concentration (chl a + pheo) was applied to the resulting mosaic images.

Due to both high cloud cover and a limited duty cycle in the western Pacific, the CZCS coverage was not spatially or temporally homogeneous during the period of study (Table 12.1), introducing large gaps when generating the composites. In order to obtain full chlorophyll fields over the equatorial region between 15° N and 15° S, 130° E and 130° W, we had to form composite means over a minimal period of three months. Monthly composites were also formed but contained large gaps. Annual composites were also computed, by averaging the four quarterly images, rather than averaging all valid pixels (in order to reduce the bias due to the irregular temporal CZCS sampling during a year). It was checked that pigment fields were not dependant of the CZCS sampling in space and time.

For that purpose, we compared mean pigment composites to equivalent maps of the number of sampled pixels. Since the maps did not present any correlation (as indicated by bi-dimensional histograms), we assumed that the field resulting from composites was not biased. It was also verified that CZCS-chlorophyll maps were not influenced by an atmospheric artefact. As a matter of fact, the Mexican volcano El Chichon produced a high level of aerosols in the upper atmosphere migrating southward to the equatorial region in late summer 1982 (Strong, 1986). This was done simply by comparing pigment maps and channel 6 composites at the same scales. Visual comparison of aerosol and chlorophyll distributions excluded the hypothesis of a contamination of the pigment composites by a heavy atmospheric charge at that date.

### *12.3.3 Oceanographic data*

For the calibration of our CZCS composites, we used data collected by ORSTOM between 1988 and 1991 in the western Pacific. This data set consisted in pigments and nutrients measurements obtained with high-sensitivity methods (Oudot and Montel, 1988) during four PROPPAC and six SURTROPAC transects along 165° E between 20° S and 6° N from 1988 to 1991 (Bonnet et al., 1990), and during the ALIZE 2 cruise along the equatorial Pacific from 90° E to 167° E in January-March 1991 (Reverdin et al., 1991).

From all these chlorophyll profiles (around 500), we computed *Cs* the optically *weighted* mean chlorophyll concentration within the surface layer *Zs* sensed by the CZCS (first penetration depth, Gordon and Clark, 1980), as the following. *Ze*, the depth of the euphotic zone, (i.e. depth at which the, photosynthetic available radiation is reduced to 1% of its sub-surface value) was computed from our chlorophyll profiles by using a correlation established between the attenuation coefficient of photosynthetic available radiation and chlorophyll concentrations below 20 m (based on 31 radiation profiles of PROPPAC long duration stations, Le Bouteiller, unpublished results). This relation was preferred to the one of Morel and Berthon (1989) which underestimated *Ze* in our oligotrophic waters. Then, according to these authors, the thickness of the *surface layer Zs*, was estimated as *Ze*/4.6. Estimated *Zs* varied from 11 m for our mesotrophic waters to 28m for our oligotrophic waters. Integrated chlorophyll contents *Ctot* and *Cze* were computed over the total column and the estimated euphotic depth, respectively. In these computations, chlorophyll values for surface samples containing Trichodesmium colonies (cyanobacteria detected by ocean color remote sensing, Dupouy, 1992) were eliminated, by a specific method based on the chlorophyll a/pheopigments ratio in fluorometer analyses (Le Bouteiller, unpublished).

### *12.3.4 The boundaries of the equatorial chlorophyll enrichment*

The Pacific between 15° N and 15° S has been identified as a region where phytoplankton biomass characteristics vary between an *oligotrophic* state at the tropics, to a mesotrophic state at the equator (in non El Niño conditions) (Blanchot et al., 1992). The biomass enrichment related to the equatorial upwelling is due to the increase of nutrient in the euphotic layer. Le Bouteiller et al. (1992) have shown that in the western Pacific, the 0.1 µM isoline in $NO_3$ concentration is the boundary at which size structure and phytoplankton concentration shift. In *nitrate-depleted* waters ($NO_3$ < 0.1 µM), pico-cyanobacteria (<1 µm) dominate and chlorophyll concentrations are low, while in *nitrate-rich* ones ($NO_3$ > 0.1 µM), pico-cyanobacteria and larger eucaryotic microalgae (> 1µm) are abundant and higher chlorophyll concentrations occur (Le Bouteiller et al., 1992, Le Bouteiller and Blanchot, 1991, Blanchot et al., 1992). In order to determine the chlorophyll concentration associated to this trophic shift (under or above 0.1 µM of nitrate), a statistical approach was made. Stations were separated into two groups, depending on the nitrate content of the surface water ($NO_3$ < 0.1 µM and $NO_3$ > 0.1 µM). Characteristics of chlorophyll averages, *Cs*, for these two groups are found in Table 12.2.

**Table 12.2 Optically weighted mean concentrations *Cs* on the region 6° N/20° S, 165° E (SURTROPAC, PROPPAC) and along the equator from 90° E to 167° E (ALIZE) between 1988 and 1991, for *nitrate-depleted* and *nitrate-rich* waters (limit: 0.1µM of $NO_3$).**

| Stations | TOTAL | $NO_3$ >0.1µM | $NO_3$<0.1 µM |
|---|---|---|---|
| Number | 493 | 161 | 332 |
| Avg Cs | .131 | .203 | .096 |
| Max Cs | - | 180 | .065 |
| Avg Ctot | 27 | 29.4 | 25.9 |
| Avg Cze | 13.7 | 16.4 | 12.6 |

*Cs* in mg $m^{-3}$, *Ctot* and *Cze* in mg $m^{-2}$.

Frequency histograms of the *Cs* values (normalised to the maximal frequency) were established for each group as shown on Fig. 12.5. We assumed that the *Cs* value obtained at the crossing of the two histograms could be used to determine the limits of the rich waters associated to the equatorial upwelling on the CZCS images. The C*s* value of 0.12 mg $m^{-3}$ was found by this method.

To verify that this threshold could be applied on the CZCS maps, we compared the C*s* values described in Table 12.2 to the remote sensed ones. For each period, the CZCS-pigment averages of the tropical (a) and of the strictly equatorial (b) bands were computed, the width of bands (a) and (b) being respectively taken arbitrarily as 15° N/15° S and 3° N/3° S.

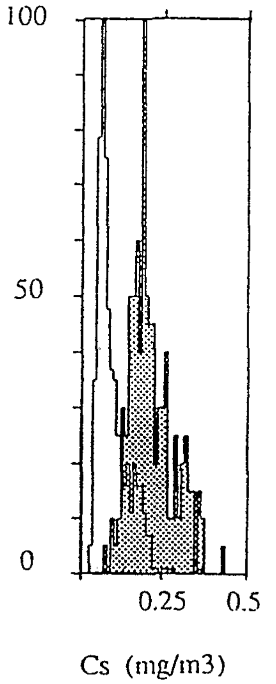


Fig. 12.5 Normalised frequency histograms of *Cs*, the optically weighted chlorophyll concentration, for $NO_3$-poor waters ($NO_3 <$ 0.1 µM) and $NO_3$-rich waters ($NO_3 >$ 0.1 µM), computed from extracted chlorophyll data obtained during SURTROPAC, PROPPAC and ALIZE 2 cruises. The *Cs* value at the crossing (0.12 mg $m^{-3}$) is considered as the boundary of rich equatorial waters.

When comparing Table 12.2 and Table 12.3, CZCS-pigment averages appear lower than the *Cs*. The highest quarterly CZCS-pigment mean of the equatorial band (0.16 mg $m^{-3}$, in July-September 1981) is lower than the *Cs* mean for $NO_3$-rich waters (0.203 mg $m^{-3}$). This discrepancy is even greater, when considering that the CZCS-pigment includes pheopigment concentrations, in the difference of the *Cs* (in our waters, total *pheopigment* (i.e. pheo a + chl b) represent about 35% of the total pigment, Le Bouteiller, personal communication). This indicates that CZCS-pigment are underestimated in our region of study. In this case, the 0.12 mg $m^{-3}$ threshold value must be applied with caution on the CZCS images. As an example of this underestimation, when forming binary composites by masking to 0 the chlorophyll values less than 0.12 mg $m^{-3}$, the equatorial enrichment did not appear in 1982, as CZCS-pigment were lower than this threshold even at the equator. So, for the representation of composites in the binary mode, Figures 12.5 and 12.6, a slightly lower limit of 0.10 mg $m^{-3}$ was taken and for the determination of the geographic limits of the rich area, the two values of 0.12 and 0.10 mg $m^{-3}$ were compared.

**Table 12.3 CZCS-pigment averages (in mg.$m^{-3}$) at quarterly interval in the Pacific Ocean in 1981 and 1982 for (a): *tropical band* : 15° N/15° S, 130° E/130° W, and (b): *equatorial band*: 3° N/3° S, 130° E/130° W.**

| QUAR | Jan-Mar | Apr-Jun | July-Sept | Oct-Dec | Annual |
|---|---|---|---|---|---|
| 1981(a) | - | .085 | .113 | .062 | .073 |
| 1982(a) | .068 | .109 | .122 | .077 | .089 |
| 1981(b) | - | .123 | .160 | .086 | .106 |
| 1982(b) | .080 | .145 | .150 | .064 | .098 |

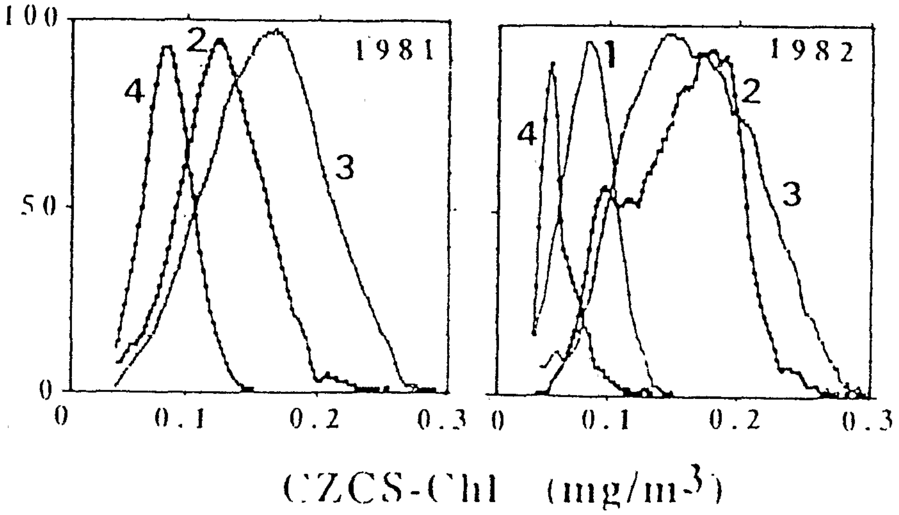


Fig. 12.6 Normalised histograms of pixels of the quarterly CZCS-pigment composites for the restricted equatorial belt (3° N-3° S/130° E-130° W). 1 : quarter 1 (January-March), 2 : quarter 2 (April-June), 3 : quarter 3 (July-September), and 4 : quarter 4 (October-December), in 1981 and 1982.

### *12.3.5 Results and discussion*

The histograms of CZCS-pigment concentrations of the equatorial band in Fig. 12.6, show distinct distributions for each quarter, with the lowest values for the first and fourth quarters, and the highest for the second and third ones. The seasonal variation ofthe CZCS-pigment concentration appears rather clearly, when looking at the quarterly composites on the black and white representation in Fig. 12.7 or in color Plates 12.7 and 12.8. For 1981, the April-June and July-September quarterly maps show high pigment values as indicated by a high density of black points in Fig. 12.7 and by yellow-orange colors in Plate 12.7, while the October-December one shows a minimum (January-March is not available at that year). For 1982 in Fig. 12.8 and Plate 12.8, the April-June and July-September quarterly maps present also high pigment values, while January-March and October-December present the minimum. The mean CZCS-pigment concentrations found at Table 12.3(b) are also indicative of show the strong seasonal variation with maximal quarterly values during southern fall and winter (April-June and July-September), for 1981 and 1982. This seasonal variation of CZCS-pigment was similar in 1981 and 1982, excluding any atmospheric artefact (case of El Chichon in 1982).

Spatial seasonal changes of the equatorial phytoplankton rich tongue as defined above are evidenced on the quarterly composites, for both 1981 and 1982 years, see Figures 12.7, and 12.8, and Color plates 12.7 and 12.8). The meridional section of CZCS-pigment equatorial enrichment which follows a Gaussian distribution with a maximum centred at the equator, varies seasonally in width (as demarcated by the 0.12 mg $m^{-3}$ boundary) from a minimum of about 4° (2° on both sides of the equator) in October-December 1981, to a maximum of 10° in July-September 1981 and 1982, see Table 12.4. The use of both 0.10-0.12 mg $m^{-3}$ thresholds change these zonal limits by about 1°.

**Table 12.4 Seasonal variation of the boundaries of the upwelling rich band (a): in latitude (in °N/°S), of the western limit (b): in longitude (in °E) of the equatorial phytoplankton enrichment by CZCS, as defined as Csat>0.10 $mg.m^{-3}$. Symbols: ? not enough data ; * undetermined for Cs= 0.12 mg.m; - no enrichment.**

| QUAR | Jan-Mar | Apr-Jun | July-Sept | Oct-Dec | Annual Average |
|---|---|---|---|---|---|
| 1981 (a) | ? | 5/5 | 5/5 | 2/2 | 3/3 |
| 1982 (a) | 5/2 | 6/6 | 5/6 | - | 3/3* |
| 1981 (b) | ? | 160 | 160 | 160 | 161 |
| 1982 (b) | 170* | 173 | ? | - | 178 |

In the period of maximal meridional extension of the equatorial enrichment, patches of high pigment concentration appear along the equator, at more or less regular interval. Poleward tongues of rich pigment are apparent in July-September 1981. One can think they correspond to the already observed cold jets extending poleward north and south to 5-7° between warm eddies along the equator. Wavelike pigment patterns are also clearly visible along the equator in April-June 1981 and 1982, and July-September 1982. These features are similar in shape and wavelength to those detected in the infra-red (Legeckis, 1986), and caused by a strong shear between zonal equatorial currents flowing in opposite directions.

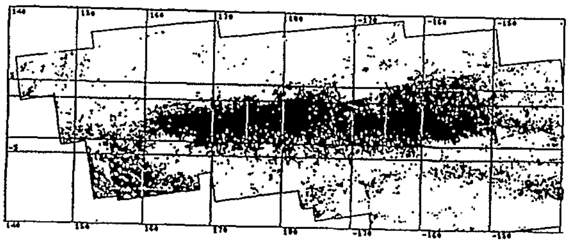
At the inverse of the meridional variations, the zonal variation of the western limit of the equatorial enrichment does not present clear seasonal variations (Table 12.4(b)). This western limit is influenced by monsoon winds and trades, which alternate with the position of the Inter Tropical Convergence and the South Pacific Convergence Zones. Our CZCS quarterly composites, though very gappy, suggest that the western extent of the chlorophyll enrichment is a constant through the year. The equatorial enrichment seems to extend further to the west in 1981 (161° E) than in 1982 (178° E) in Table 12.4, as shown on the east-west transects made on the CZCS composites in Fig. 12.9. CZCS composites show, despite large gaps, that the western extension of the upwelling rich tongue is not limited to the date line, at least for 1981 and 1982. It is also sometimes difficult, as in July-September 1982, to separate the equatorial enrichment from the coastal enrichment north of New Guinea.

### *12.3.6 Interpretation of pigment concentration data*

Which conjunction of physical, chemical or biological processes may induce such seasonal variations of the CZCS-pigment concentration and patterns. The meridional pattern of chlorophyll observed by CZCS, with a maximum associated to the maximal divergence is a classical pattern, as shown for example on transects made in the western Pacific by Blanchot et al. (1992), or in the central Pacific by Carr et al. (1992). It shows out in EOF #2 in the analyss of Dandonneau (1992). The seasonal variation of the width of the rich tongue may reflect a

*Satellite Remote Sensing of the Oceanic Environment*
*ed. Jones, Sugimori and Stewart, 1993*

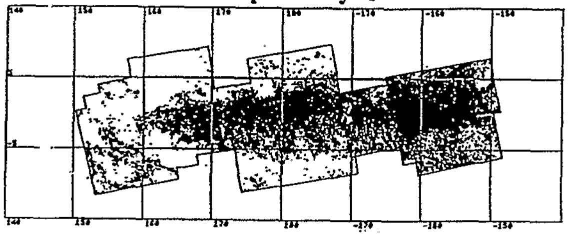
1981



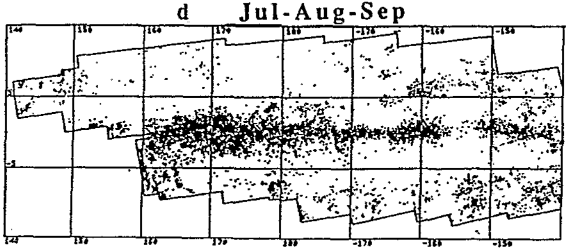
a Annual

b no data

c Apr-May-Jun



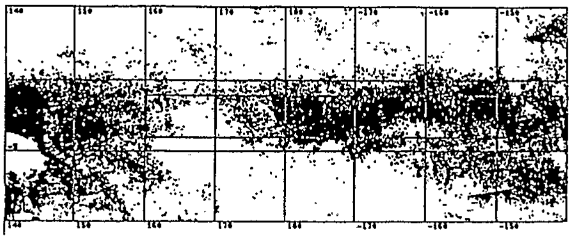
d Jul-Aug-Sep



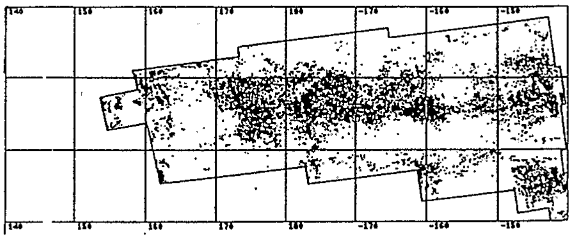
e Oct-Nov-Dec

Fig. 12.7 Binary maps of CZCS-pigment in the equatorial Pacific between 15° N and 15° S, 140° E and 140° W, for 1981. Black points represent CZCS-pigment values greater than 0.10 mg.m$^{-3}$. a) annual composite, b) quarter 1 (January-March), c) quarter 2 (April-June), d) quarter 3 (July-September), e) quarter 4 (October-December). Oversampling of 1 pixel over 2 for presentation (9.9 km). See also color plate 12.7.

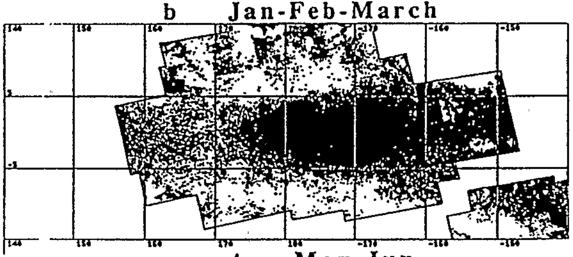
1982



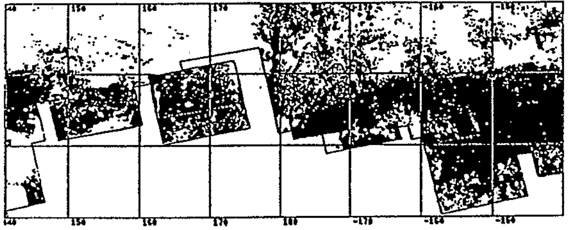
a Annual



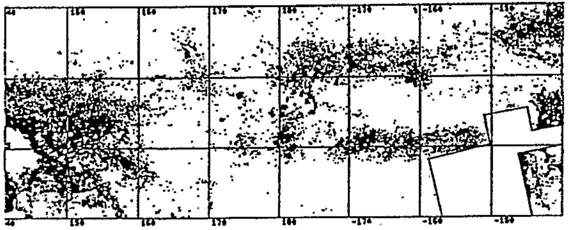
b Jan-Feb-March



c Apr-May-Jun



d Jul-Aug-Sep



e Oct Nov Dec

Fig 12.8 Binary maps of CZCS-pigment in the equatorial Pacific between 15° N and 15° S, 140° E and 140° W, for 1982. Black points represent CZCS-pigment values greater than 0.10 mg.m-3. a) annual composite, b) quarter 1 (January-March), c) quarter 2 (April-June), d) quarter 3 (July-September), e) quarter 4 (October-December). Oversampling of 1 pixel over 2 for presentation (9.9 km). See also color plate 12.8.

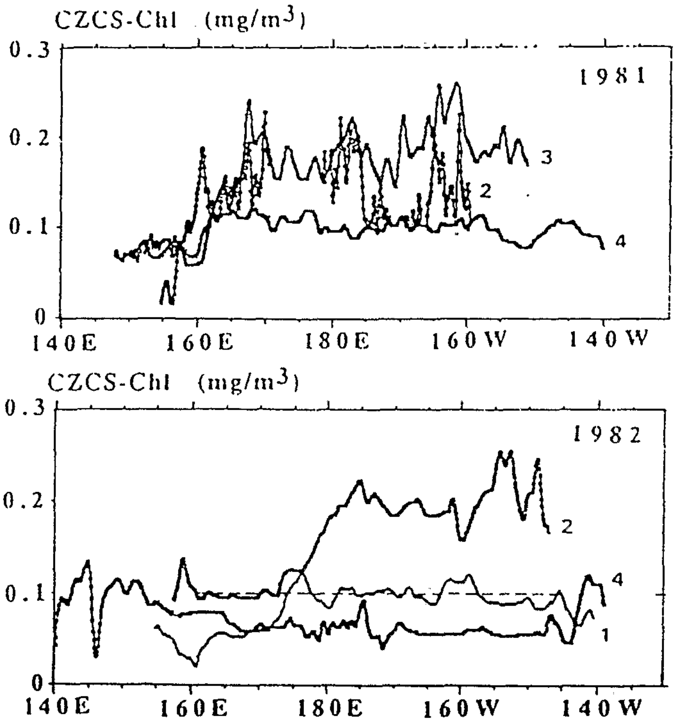


Fig 12.9 Zonal transects along the equator between 130° E and 130° W. 1: quarter 1 (January-March), 2: quarter 2 (April-June), 3: quarter 3 (July-September), and 4: quarter 4 (October-December), in 1981 and 1982. Are indicated the 0.12 and 0.10 mg.m$^{-3}$ thresholds determining the limit of the phytoplankton rich equatorial band.

variation in the strength of the equatorial divergence. The southeast trade winds at the equator, which influence the equatorial currents are intense in austral winter (July-August), when the Inter Tropical Convergence Zone (ITCZ) is farthest north (11° N), and weak in February and March when ITCZ is closer to the equator. As a result, the equatorial cool tongue is most pronounced from August to October and weakest in March-May (Wyrtki, 1981). This would be in accordance with our observations of a larger chlorophyll equatorial band in winter (July-September) and narrower in January-March. Blackburn et al (1970) and Owen and Zeitzschel (1970) showed that season has an effect on chlorophyll and day zooplankton standing stocks, with a maximum in April-September, and a minimum in October-January, differing by a factor of <2 in the eastern tropical Pacific. Merchant ship survey (Dandonneau, 1992) also suggests that the equatorial chlorophyll enrichment is more pronounced during southern winter, at least in 1981 and 1982, and only for the eastern and central Pacific. Dessier and Donguy (1985) showed that chlorophyll a and copepods biomass reach their maxima in austral winter between 4° N and 4° S in the eastern equatorial Pacific. Le Borgne (1991) also showed that zooplankton biomass is smaller in January than in July at 165°E, in the Western tropical Pacific. The seasonal variation of equatorial mean CZCS-pigment intensity is rather difficult to interpret. At the equator, high chlorophyll concentrations are associated to large nitrate concentrations. However, the equatorial upwelling zone west of the Galapagos Islands to about 150° W shows a generally low and uniform concentration of phytoplankton all year-round (0.2-0.4 mg $m^{-3}$) despite high concentrations of macronutrients (> 5 µM of $NO_3$). This point is confirmed by Chavez et al. (1991) and Le Bouteiller and Blanchot (1991). The equatorial upwelling region is one case of high nutrient-low chlorophyll situation (Minas and Minas, 1992). What limits primary production there has not been demonstrated yet, both hypotheses of iron or grazing being invoked (Cullen et al., 1992; Frost and Franzen, 1992). In this context, the seasonal variability of pigment concentrations as demonstrated by the CZCS is not really explained by the availability of nutrients.

### *12.3.7 Effect of the onset of the 1982/83 El Niño*

In the late quarter composite of 1982, CZCS pigment concentrations along the equator are very low compared to the map of the same period in 1981. In fact, the dramatic and sudden decrease of chlorophyll content along the equator is already detectable on the September 1982 CZCS monthly composite. This sharp decline contrasts with the long preceding period of high chlorophyll at the equator (from April to July 1982, no CZCS data in August 1982). Chlorophyll maxima are remaining at 10° N and 5° S.

On the Peru coast, the advection of warmer tropical waters coming from the north produced a sudden temperature increase in August 1982, as a result of the onset of El Niño 1982-1983. In the eastern Pacific, manifestations of the 1982-83 El Niño over temperature, nutrients, chlorophyll and primary production have been well described by Barber and Chavez (1983, 1986). Westerly anomalies in the wind, propagating from west to east in the Pacific were observed for the 1982/83 and 1986/87 El Niño events (Sadler and Kilonsky, 1983, Kousky and Leetma, 1989). Strong surface warming was detected by merchant ships (Tournier, 1989) by September 1982, in the western and central Pacific, and by NOAA satellites by August 1982 (Strong, 1986). Equatorial currents were modified, as the westward South Equatorial Current disappeared and was replaced by a strong eastward equatorial jet. Direct velocity measurements indicated the disappearance of the undercurrent from September 1982 to January 1983 at 159° W (Firing et al., 1983), and by late October and December 1982 (Meyers and Donguy, 1983). Barber and Kogelschatz (1989) suggested that the low biological productivity observed during El Niño in the eastern boundary was due to the deepening of the thermocline and nutricline, though the causal features lowering the primary production were not clear (in October 1982, at 110° W, the surface water was not nutrient-depleted, although all the physical and thermal criteria of El Niño were present, Barber et al. (1983)). Similarly, in the Western Pacific during the 86-87 El Niño event, the physical structure exhibited a strong downwelling at the equator at 165°E between July and September 1987 (Delcroix et al., 1992), and no nutrient and chlorophyll increases were observed in surface in September 1987 (Blanchot et al., 1992). With no doubt, the CZCS-pigment disappearance at the equator observed by CZCS from September to December 1982 was the early manifestation of the 1982/83 El Niño.

*Satellite Remote Sensing of the Oceanic Environment*
*ed. Jones, Sugimori and Stewart, 1993*

### *12.3.8 Estimation of integrated contents of chlorophyll from CZCS*

Our last objective is to compute production from the chlorophyll content of the euphotic layer (Morel, 1991, Platt and Sathyendranath, 1988, Balch et al., 1992) as determined from CZCS data. Primary production is largely determined by the chlorophyll content and vertical structure of phytoplankton biomass of the euphotic layer. All our chlorophyll profiles present a deep chlorophyll maximum well marked in tropical waters at depths as large as 120 m, or less sharp at the equator between 30 and 50m. The deep chlorophyll maximum is not sensed by the CZCS due to the physical limitations of the light penetration. Despite this unfavourable condition, added to the very narrow surface chlorophyll range of our study (0.05-0.40 mg $m^{-3}$), a relation between *Cze* and *Cs* was found:

$$Cze = 28.05\ Cs^{0.328}, \qquad r=0.75,\ n=493$$

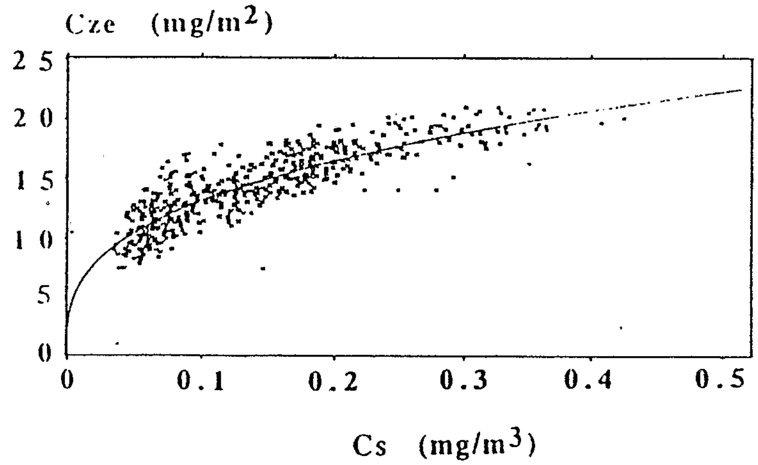


Fig. 12.10 Curve fitting of the chlorophyll content of the euphotic layer *Cze* (in mg.$m^{-2}$), vs optically weighted chlorophyll of the first penetration depth *Cs* (in mg.$m^{-3}$) for in situ data obtained during SURTROPAC (SURvey of the TROpical PACific) and PROPPAC (Pelagic PROduchion of the PACific) programs of the Centre ORSTOM de Noumen and during the ORSTOM-CNRS joint cruise ALIZE 2.

The fitting curve saturates to a maximal value, when the chlorophyll profiles tend to be homogeneous, in the case of well-mixed equatorial mesotrophic waters. In conclusion, in the studied waters, *Cs* gives a relatively good indication of *Cze*. The relation between *Ctot* and *Cs* is weaker, which is not surprising as in oligo- and mesotrophic waters, a significant amount of chlorophyll is found under the euphotic depth.

### *12.3.9 Summary*

The present study shows that, for the two successive years studied at the moment, (1981 and 1982), the CZCS is successful in determining, at the finest spatial scale, the geographical boundaries of the chlorophyll enriched zone due to the equatorial upwelling. The equatorial pigment enrichment boundary was defined from in situ measurements, as the chlorophyll limit between nitrate-poor and nitrate-rich surface waters. This value is not directly applicable to the CZCS data, due to a slight underestimation of pigment calibration by CZCS. The method remains useful for the definition of the upwelling enrichment boundaries with the future Seawifs data. Despite a reduced satellite coverage, a seasonal cycle in the chlorophyll content and the meridional boundaries of the equatorial phytoplankton enrichment clearly appears. From April to September, the enrichment is much larger and more intense, than between January and March, or October and December. The onset of El Niño 1982/1983 is responsible for the total disappearance of the equatorial enrichment from September to December 1982. These results are much clearer in the central part of the Pacific than in the western part. The westernmost limit shows an interannual variation rather than a seasonal one, and is further west in 1981 than in 1982. Such conclusions are preliminary, and must still be confirmed in other years. Nevertheless, the CZCS shows a high variability of the equatorial phytoplankton enrichment in the equatorial Pacific, variability which must be taken into account for an estimation of primary production and carbon flux in the region. Despite the fact that the chlorophyll concentration is confined most of the time in a deeper layer than the first penetration depth sensed by the CZCS, the chlorophyll content of the euphotic zone can be retrieved from *Cs* (and CZCS).

## *Aknowledgements.*

This research was supported by ORSTOM and the French "Programme National de Télédétection Spatiale" 1992. The authors thank Gene Feldman at NASA/GSFC for the CZCS data set, Norman Kuring and Jeff Whiting for providing rapidly the CZCS data. Helpful comments and encouragements were provided by R. Le Borgne, J. Blanchot, M.H. Radenac of the FLUPAC group. Thanks are for the LATICAL for assistance in image processing.

**Colour plates 12.5 - 12.6**

Satellite ocean colour images showing the distribution of phytoplankton pigments in the equatorial region of the Pacific, between 15°N and 15°S, 140°E and 140°W for 1981, 130°E and 140°W for 1982. These images are composite maps of pigments processed by the authors from level 2 data of the Coastal Zone Colour Scanner aboard NIMBUS-7 satellite kindly provided by Gene Feldman (GSFC-NASA). Images are colour-coded according to pigment concentration range. Regions of high concentrations (above 0.20 mg.m$^{-3}$) are in orange and red; intermediate levels, in yellow and green; lowest levels (< 0.05 mg.m$^{-3}$) in blue. Major islands in the Western Pacific (New Guinea and Salomon Islands) and clouds are masked in white. On the same plate are presented for each year : the annual composite in a), and the four quarterly composites in b) for January to March, in c) for April to June, in d) July to September, in e) October to December.

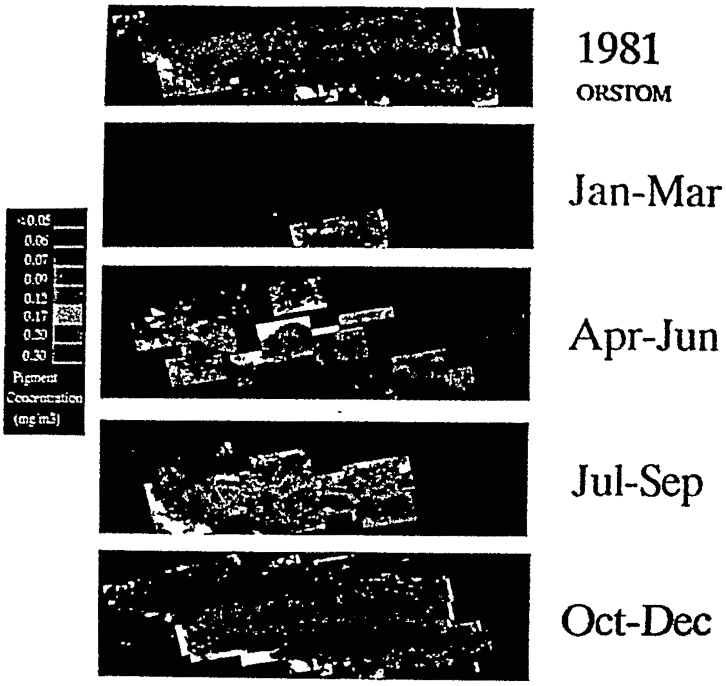


Plate 12.7 Satellite ocean colour images showing the distribution of phytoplankton pigments in the equatorial region of the Pacific, between 15°N and 15°S, 130°E and 130°W for 1981.

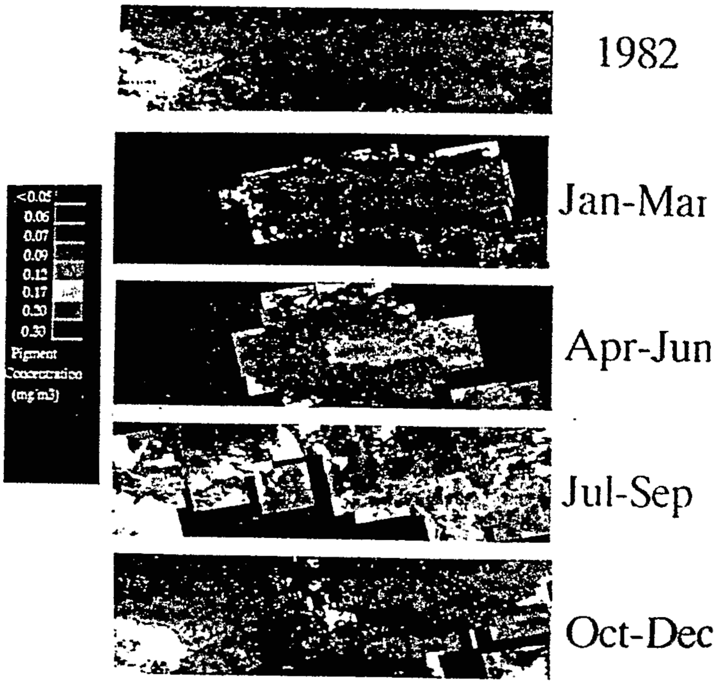


Plate 12.8 Same as Plate 12.7 but for 1982.

## *References (reported at the end of the book)*

Balch, W., Evans R., Brown, J., Feldman, G., McClain C., and W. Esaias (1992). The remote sensing of ocean primary productivity : use of a new data compilation to test satellite algorithms. J. Geophys. Res. 97, C2, 2279-2293.

Barber R.T. and F.P. Chavez (1983). Biological consequences of El Niño, Science, 222, 1203-1210.

Barber R.T., Zuta, S., Kogelschatz J. and F. Chavez (1983). Temperature and nutrient conditions in the eastern equatorial Pacific, October 1982. Tropical Ocean-Atmospheric Newsletter 16, 15-16.

Barber R.T., and F.P. Chavez (1986). Ocean variability in relation to living resources during the 1982-83 El Niño. Nature, 319, 6051, 279-285.

Barber R.T. and J.E. Kogelschatz (1989). Nutrients and productivity during the 1982/83 El Niño. Global Consequences of the 1982-1983 El Niño-Southern Oscillation. In P.W. Glynn (Ed), Elsevier Oceanography Series

Barber R.T. and F.P. Chavez (1991). Regulation of primary productivity rate in the equatorial Pacific. Limnol. Oceanogr. 36, 8, 1803-1815.

Blackburn, M., Laws, R.M., Owen, R.W. and B. Zeitzschel (1970). Seasonal and areal changes in standing stocks of phytoplankton, zooplankton and micronecton in the eastern tropical Pacific. Marine Biology, 7, 14-31.

Blanchot, J., Le Borgne, R., Le Bouteiller, A. and M. Rodier (1989). ENSO events and consequences on nutrient, planktonic biomass, and production in the western tropical Pacific Ocean. Proceedings of the western Pacific International Meeting and Workshop on TOGA COARE, pp 785-790

Blanchot J., Rodier M. and A. Le Bouteiller (1992). Effects of El Niño Southern Oscillation events on the distribution and abundance of phytoplankton in the Western Pacific Tropical ocean along 165°E. J. Plankton Res. 14, 137-156.

Bonnet S., Gérard, P., Le Borgne R., and M. Rodier (1991). Programme PROPPAC: Hydrologie, nutrients, chlorophylle et zooplancton des campagnes SURTROPAC 07 a 13 (1987-1989). Document de travail. Archives Sciences de la Mer, Océanographie n°3, ORSTOM, Noumea, New Caledonia, 103 pp.

Carr, M.H., Oakey, N.S., Jones, B. and M.R. Lewis (1992). Hydrographic patterns and vertical mixing in the Equatorial Pacific along 150°W. J. Geophys. Res. 97, C1, 611-626.

Chavez, F.P. and Barber R.T., 1987. An estimate of new production in the equatorial Pacific. Deep-Sea Res. 34, 7, 1229-1243.

Chavez, F.P., Buck, K.R., Coale, K.H., Martin, J.H., DiTullio, G.R., Welshmeyer, N.A., Jacobson, A.C., and R.T. Barber (1991). Growth rates, grazing, sinking, and iron limitation of equatorial Pacific phytoplankton. Limnol. Oceanogr. 36, 1816-1833.

Chavez, F.P., and R.C. Brusca (1992). The Galapagos Islands and their relation to oceanographic processes in the Tropical Pacific. In: Galapagos Marine Invertebrates. M. J. James (ed). Plenum Press, New York, pp. 9-33.

Chavez, F.P., Buck K.R., and R.T. Barber (1990). Phytoplankton taxa in relation to primary production in the equatorial Pacific. Deep-Sea Res. 37, 1733-1752.

Cullen, J., Lewis M.R., Davis, C.O. and R.T. Barber (1992). Photosynthetic characteristics and estimated growth rates indicate that grazing is the proximate control of primary production in the equatorial Pacific. J. Geophys. Res. 97, 639-654.

Dandonneau T., (1979). Concentrations en chlorophylle dans le Pacifique Sud Ouest: comparaison avec d'autres aires océaniques tropicales. Oceanol. Acta, vol 2, n°2, 133-142.

Dandonneau Y. (1992). Surface chlorophyll concentration in the Tropical Pacific ocean: an analysis of data collected by merchant ships from 1979 to 1989. J. Geophys. Res. 97, C3, 3581-3591.

Delcroix, T., Eldin, G., Radenac, M.H., Toole, J. and E. Firing (1992). Variation of the Western Equatorial Pacific Ocean, 1986-1988. J. Geophys. Res. 97, C4, 5423-5445.

Dessier, A. and J.R. Donguy (1985). Planktonic copepods and environmental properties of the eastern equatorial Pacific: seasonal and spatial variations. Deep-Sea Res. 32, 9, 1117-1133.

Dupouy, C. (1992). Discoloured waters in the Melanesian archipelago (New Caledonia and Vanuatu). The value of the NIMBUS-7 CZCS observations. in Ed Carpenter et al (Eds), Marine pelagic Cyanobacteria: *Trichodesmium* and other diazotrophs, Kluwer Academic Publishers, Netherlands, pp. 177-191.

Feldman G.C., Kuring N., Ng, C., Esaias W., McClain C., Elrod J., Maynard N., Endres D., Evans R., Brown J., Walsh S., Carle M., and G. Podesta (1989). Ocean color - availability of the global data set, EOS Trans., AGU, 70, n°23, 35-40.

Feldman G., Murray J. and M. Leinen (1992). EqPac planning: application of Pacific CZCS data. *Submitted* to Oceanography Magazine, J. Oceanogr. Soc.

Firing, E., Lukas, R., Sadler, J., and K. Wyrtki (1983). Equatorial undercurrent disappears during 1982-1983 El Niño, Science 222, 1121-1123.

Frost, B.W., and N.C. Franzen (1992). Grazing and iron limitation in the control of phytoplankton stock and nutrient concentration: a chemostat analogue of the Pacific equatorial upwelling zone. Mar. Ecol. Prog. Ser. 83, 291-303.

Gordon H.R. and D.K. Clark (1980). Remote sensing optical properties of a stratified ocean: an improved interpretation. Appl. Optics, 19 (20), 3428-3430.

Koblentz-Mischke, O.I., Volkovinsky, V.V. and J.G. Kabanova (1970). Plankton primary production of the world ocean. In : Scientific exploration of the South Pacific, W. Wooster (Ed), National Academy of Sciences, pp. 183-193.

Kousky, V.E. and A. Leetmaa (1989). The 1986-1987 Pacific warm episode: evolution of oceanic and atmospheric anomaly fields. J. of Climate, 2, 254-267.

Le Borgne, R., (1992). ORSTOM Noumea plans JGOFS study in Western Pacific. U.S. JGOFS News, vol 3, n°3, p. 11.

Le Borgne R. (1991). Effects of interannual variations of biological productivity in the tropical western Pacific ocean. In :"South Pacific environments: interactions with weather and climate", J.H. Hay (ed.), Univ. Auckland, 41-43.

Le Bouteiller A., Rodier M., and J. Blanchot (1992). Size distribution of phytoplankton in the Western Pacific: towards a generalization for the tropical open ocean. Deep-Sea Res. 39, 805-832.

Le Bouteiller A. and J. Blanchot (1991). Size distribution and abundance of phytoplankton in the Pacific equatorial upwelling. Colloque franco japonais d'océanographie, Tokyo, La Mer, 29: 175-179.

Le Bouteiller, A., (1993). Comparison of in-bottle measurements using 15N and 14C. ICES mar. Sci. Symp., 197 (in press)

Legeckis R, (1986). A satellite time series of sea surface temperatures in the eastern Equatorial Pacific Ocean, 1982-1986. J. Geophys.Res., 91, 12879-12886.

Lukas, R. and E. Lindstrom (1991). The mixed layer of the western equatorial Pacific Ocean. J. Geophys. Res. 96, 3343-3357.

Meyers, G. and J.R. Donguy (1983). Zonal topography of the equatorial thermocline during El Niño, 1982. Tropical Ocean Atmosphere Newsletter, n°21, 8-9.

Minas, H., and M. Minas (1992). Net community production in "High Nutrient-Low Chlorophyll" waters of the tropical and Antarctic oceans: grazing vs iron hypothesis. Oceanol. Acta, 15, n°2, 145-162.

Morel A., and J.F. Berthon (1989). Surface pigments, algal biomass profiles, and potential production of the euphotic layer: Relationships reinvestigated in view of remote-sensing applications. Limnol. Oceanogr. 34(8), 1545-1562

Morel A., (1991). Light and marine photosynthesis: a spectral model with geochemical and climatological implications. Prog. Oceanogr. 26, 263-306.

Oiry H., 1992. A. Automatic procedure for geometric transformation of level 2 CZCS images. B. CANVAS, an image processing tool. Techn. Doc., Centre ORSTOM de Noumea.

Oudot, C. and Y. Montel (1988). A high sensitivity method for the determination of nanomolar concentration of nitrate and nitrite in seawater with a Technicon AutoAnalyser II. Mar. Chem. 24, 239-252.

Owen, R.W. and B. Zeitzschel (1970). Phytoplankton production: seasonal change in the oceanic eastern tropical Pacific. Marine Biology, 7, 31-48.

Platt T., and S. Sathyendranath (1988). Oceanic primary production: estimation by remote sensing at local and regional scales. Science, 88, 1613-1629.

Reverdin, G., Morlière, A. and G. Eldin (1991). Campagne océanographique trans-Pacifique (janvier-mars 1991). Recueil des donnees. Rapp. Interne LODYC 91/13, CNRS/ORSTOM/Univ. Pierre et Marie Curie, Octobre 1991.

Sadler J.C. and B. Kilonsky (1983). Meteorological events during evolution of positive SST anomalies in the equatorial pacific in 1982. Tropical Atmosphere Ocean Letter, 16, 3-4.

Strong, A.E., (1986). Monitoring El Niño using satellite based sea surface temperatures. Ocean-Air Interactions, 1, 1, 11-28.

Tournier R., (1989). Variabilité de la structure thermique et des courants à l'ouest et au centre de l'océan Pacifique tropical de 1979 à 1985, Ph. D Thesis, Univ. de Paris VI, 154 pp, Centre ORSTOM de Noumea, New Caledonia.

Wyrtki K., (1981). An estimate of equatorial upwelling in the Pacific. J. Phys. Oceanogr. 11; 1205-1214.