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MONITORING THE SEA SURFACE CHLOROPHYLL CONCENTRATION IN THE TROPICAL PACIFIC: CONSEQUENCES OF THE 1982-83 EL NIÑO

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ABSTRACT

The sea surface chlorophyll concentration (SSCC) is routinely measured in the tropical Pacific using filtrations made aboard merchant ships that sail from New Caledonia to Japan, North America, Panama, New Zealand, and Australia. About 4,000 measurements are collected every year, allowing a tentative monitoring of SSCC in the Pacific. Heavy smoothing made it possible to map quarterly charts of SSCC which cover the 1982-83 El Niño episode. The usually enriched belt which corresponds to the equatorial upwelling vanished after September 1982, except for a reduced zone east of long. 120°W, where a moderate enrichment persisted throughout the warm event. It recovered after July 1983, spreading westwards to long. 170°E. During the mature phase of El Niño (October 1982-June 1983), an enriched zone appeared in the western Pacific, centered at about lat. 7°N, consistent with a rise of the thermocline in this region. An examination of oceanographic data collected in this region since 1970 shows that nutrients from below the thermocline are consumed by the phytoplankton during each El Niño. This western Pacific enrichment was weakened with time, and the period from April to June 1983 was characterized by low SSCC values over most of the tropical Pacific. Unusually high SSCC values are reported in subtropical zones, during the austral winters of 1982 and 1983 in the southwestern Pacific and during the 1982 autumn in the northeastern Pacific, which may be due to advection of rich water from higher latitudes and to intensified vertical mixing by strong westerly winds, respectively.

El Niño was first observed and experienced in Peru, where it was given its name and became a familiar part of Peruvian life. Although the southern oscillation was identified more than 60 yr ago (Walker 1924), the relation between the El Niño phenomenon and ocean-scale features was only established after the 1957-58 event by Bjerknes (1966). It is now well established that El Niño is simply the most obvious consequence of important oceanographic and meteorological changes in the Pacific Ocean (Donguy and Henin 1976; Quinn et al. 1978; Cane 1983). One would expect biological changes at the same scale. These, however, have only been studied in the eastern Pacific (Walsh 1981; Chelton et al. 1982; Barber and Chavez 1983) where a pronounced decrease in phytoplankton biomass and primary production is observed. Farther west in the equatorial zone, the decrease in primary productivity has been shown only by indirect observations on marine birds (Schreiber and Schreiber 1984) and on abnormal distributions of some fishing grounds in relation to changes of water mass (Donguy et al. 1978; Yamanaka 1984). The difficult problem of monitoring the intensity of primary production on a large scale is usually reserved for satellite-borne sensors. A modest attempt, however, is in progress, as a part of the SURTROPAC program (ORSTOM, Nouméa) based upon chlorophyll samples taken by voluntary observers on ships of opportunity. Each year about 4,000 sea surface chlorophyll concentrations (SSCC) are collected in this way, distributed along maritime lanes from the Tasman Sea to Panama, North America, or Japan. These data cover the tropical Pacific from lat. 30°S to 30°N, and from long. 140°E to 80°W. There are large gaps both in space, between the main lanes, and in time, between consecutive crossings. But, on a quarterly basis, the SSCC data are numerous enough to allow a crude view of the whole tropical Pacific Ocean, with the advantage of using a single methodology. The consequences of the 1982-83 El Niño can thus be examined, and most of the attention will be directed towards the central and western Pacific, where present knowledge is very incomplete.

METHODS

Chlorophyll Measurements

SSCC measurements are made according to a nonextractive method (Dandonneau 1982). Twenty milli-

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liters of seawater are filtered on 13 mm HAWP Millipore filters, using a syringe and Swinnex type filtering cartridges. The filters are then stored in a dark place at ambient temperature. When the observing ship reaches Nouméa, the filters are taken to the laboratory for fluorescence measurements. A 3-wk minimum time lag is needed between filtration and measurement, after which degradation processes lead to stable fluorescent chlorophyll byproducts on the filters. The fluorescence (Ff) of the filters is then measured without extraction, using a specially adapted sample holder.

The measurement error e is proportional to the chlorophyll concentration C and can be expressed as $e = |\text{SSCC}-C|/C$ where SSCC is measured by the non-extractive method while C is obtained by a more conventional technique (Holm-Hansen et al. 1965). Ninety-five percent of e values are <0.6 (Dandonneau 1982, and confirmed by later tests). This value is probably an overestimate of e since it results both from the error on SSCC and from the unknown error on C. Different phytoplankton populations can also result in different fluorescence to chlorophyll ratios for the dry filters. This ratio has shown no significant change between winter and summer conditions around New Caledonia where a mixed regime alternates with a stratified one (Dandonneau and Gohin 1984). The risk of a variation of the ratio in other environments has not been examined, and must be kept in mind. The few SSCC data points at latitudes higher than 30° were not taken into account for this reason.

Calibrations

SSCC is estimated using $\text{SSCC} = k\,Ff$ where k is a calibration coefficient that must be corrected from time to time. Twenty milliliters from a seawater sample are filtered giving a fluorescence Ff_0 after 21 d of storage. A larger volume V from the same sample is filtered on a glass fiber filter, ground, and extracted by a volume v of 90% acetone. The fluorescence of the extract is Fe_0. Knowing the fluorescence to chlorophyll ratio of the fluorometer, R_0, determined from a known solution of pure chlorophyll a, we can estimate the following chlorophyll concentration of the seawater sample:

$$C_0 = (Fe_0 \times v)/(R_0 \times V);$$

we obtain then $k_0 = Ff_0/C_0$.

k_0 is sensitive to detrital material in turbid coastal waters, so these main calibrations are made during offshore oceanographic cruises. As such opportunities are infrequent, secondary calibrations are made more frequently with known solutions of pure chlorophyll a, giving R_i instead of R_0. We then assume that $k_i = k_0 \times R_i/R_0$. This procedure does not consider correction for chlorophylls b and c, nor does it consider correction for phaeopigments, which has recently proven to be uncertain when the fluorometer is fitted with a commonly supplied blue excitation lamp (Baker et al. 1983). Although the SSCC data presented in this work are expressed in milligrams of chlorophyll a, they should be considered only as indices of phytoplankton abundance.

Data Rejection

The crew members who take the seawater samples and make the filtrations are voluntary observers. Errors may occur which are difficult to detect because, unlike temperature or salinity, 1) any SSCC value in the interval 0-1 $\text{mg} \cdot \text{m}^{-3}$, which covers almost the whole data set, is a possible one anywhere in the tropical Pacific, and 2) the autocorrelation of SSCC decreases very quickly with time or space, so that surrounding data cannot help in error detection. Therefore, all the data are accepted, unless the filter exhibits an obvious fault (i.e., breaking, stain, extraneous material). Occasionally, all the data from a ship's voyage were evidently too high, by a factor 3 or 5. Contamination by a polluted sampling bucket was the cause, and the data from the entire voyage were rejected.

Other possible errors are more insidious, such as insufficient care in keeping the filters out of light, or using an oxidized sampling bucket. These errors result in slightly lowered values, but there is no way to correct them and, in most cases, no way to even detect these biases. Such data are entered in the data bank. As a resulting constraint, any estimate from this SSCC data set must be developed from many data, in order to minimize the effect of a few possibly biased values.

Mapping Techniques

In a previous work (Dandonneau and Gohin 1984) the principles of objective analysis were applied to compute best estimates of SSCC at a given place and time in the southwestern tropical Pacific. The studied area in the current study is much larger and more complex, and the density of data is not high enough to allow good estimates of the statistics of the field. Hence, the use of an objective analysis of the SSCC data has been excluded. The SSCC mapped here on Figure 1 have been estimated using

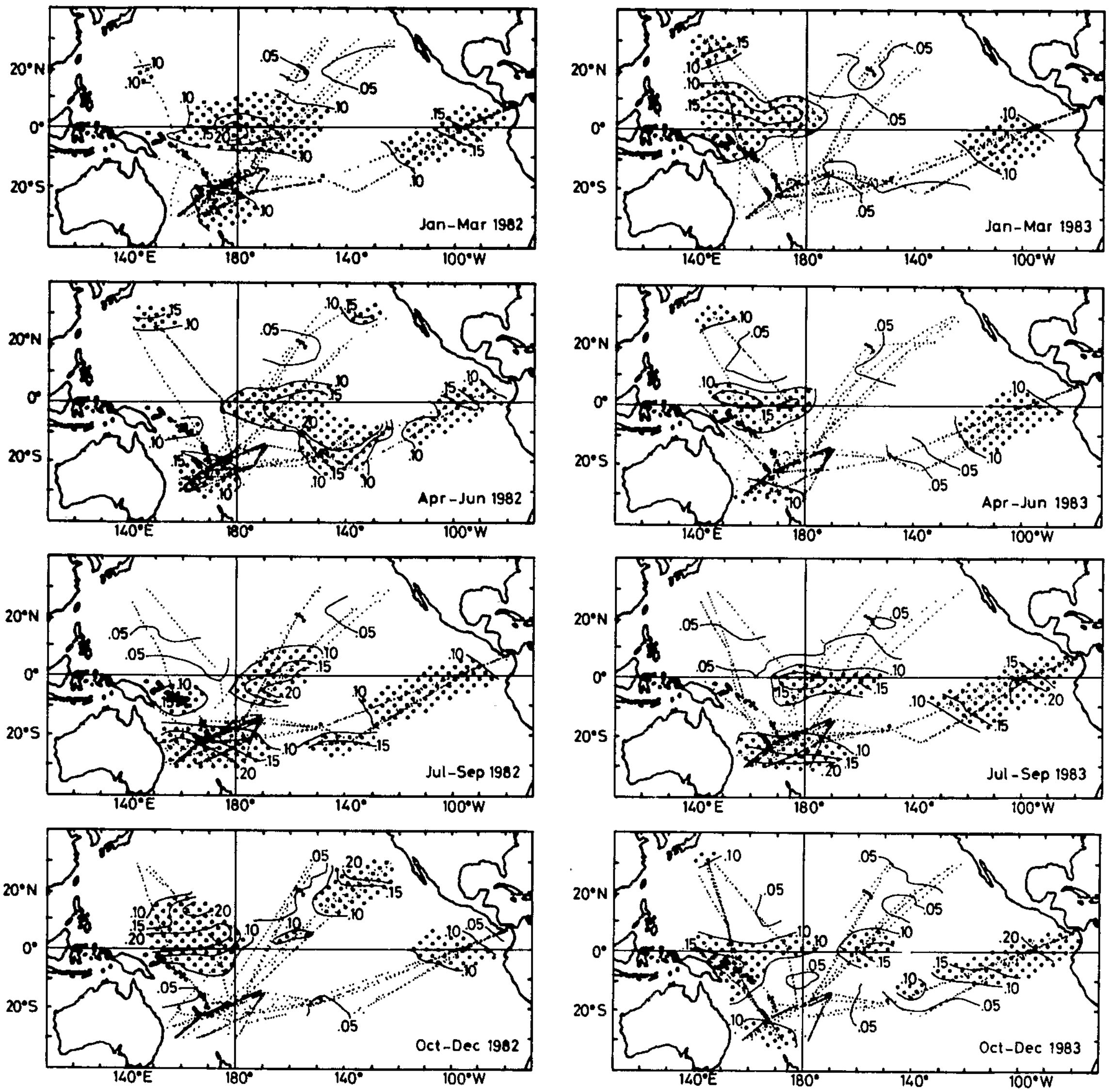

FIGURE 1.—Quarterly charts of SSCC (sea surface chlorophyll concentrations) in the tropical Pacific from January 1, 1982 to December 31, 1983. Areas where SSCC is >0.10 mg·m^{-3} are shaded with large dots. Smaller dots represent the data points.

$$\tilde{t}_j = \sum_{i=1}^{n_j} p_{ij} t_i / \sum_{i=1}^{n_j} p_{ij}$$

where $\tilde{t}_j$ is the SSCC estimate at longitude x_j and latitude y_j, and p_{ij} is the weight given to observation t_i for the estimation $\tilde{t}_j$. p_{ij} is given by

$$p_{ij} = [R^2 + (x_i - x_j)^2 + a^2 (y_i - y_j)^2]^{-1}$$

where a accounts for anisotropy of the SSCC variations in space. We used $a = 2$, so that observations at a distance Δy in latitude are given the same weight as observations at a distance $\Delta x = 2\Delta y$ in longitude. p_{ij} was set to zero when $(x_i - x_j)^2 + a^2 (y_i - y_j)^2$ was >160, so that the observations were considered as "non useful" when outside an ellipse centered at (x_j, y_j) with a principal axis equal to about 25° longitude, and a small axis equal to about 13° latitude. In order to avoid hazardous estimates at the margin of the contoured area, t_j has not been estimated when n_j (the number of useful observations) was <12.

$R = 0$ would give an infinite weight to an observation k available at $x_k = x_j$ and $y_k = y_j$. We would then obtain $t_j = t_k$ regardless of the other observations. This is acceptable only if the instrumental and sampling errors on t_k were null, which is not the case. Thus, R accounts for the errors on the observations. We choose $R^2 = 25$, which, together with $a = 2$ and $p_{ij} > (25 + 160)^{-1}$, performed an efficient smoothing and preserved the large-scale information.

RESULTS

The sequence of quarterly mean SSCC for 1982 and 1983 is presented in Figure 1, together with the positions of the data. The western part, north of lat. 20°N, is poorly sampled. The data range between 0.05 and 0.20 mg·m^{-3}. The highest values are found during the northern spring of 1982, and the northern winter of 1983. The 1982 winter, and the spring and fall of 1983 exhibit a few values >0.10 mg·m^{-3}. The 1982 winter and fall show low SSCC, like the summer of both years, below 0.10 mg·m^{-3}.

The eastern part, north of lat. 10°N, has generally low SSCC values, often below 0.05 mg·m^{-3}. Exceptions are the spring of 1982 at the extreme north, and, mainly, the fall of 1982 during which the mean values exceeded 0.20 mg·m^{-3} off California.

Low SSCC values are observed in the western part between the Equator and lat. 20°N until the summer of 1982. They are abruptly replaced at the end of 1982 by high values which persist until March 1983. Later, low values, generally below 0.05 mg·m^{-3}, dominate again between lat. 5°N and 20°N, while SSCC >0.10 mg·m^{-3} shift back southward to the Equator.

The equatorial zone shows high SSCC in January-March 1982, between America and long. 160°E. Values higher than 0.10 mg·m^{-3} spread from lat. 10°N and 10°S in the central Pacific, and to 15°S at 120°W. From April to June 1982, the enriched zone shifts eastwards and southwards. The eastwards shift continues between July and September and is accompanied by a decrease of SSCC in the eastern Pacific, with mean values <0.15 mg·m^{-3}. From October 1982 to June 1983, a narrow band with SSCC between 0.10 and 0.15 mg·m^{-3} in the eastern Pacific is the only remnant of the equatorial enrichment. A normal situation returned after the El Niño, in July-September 1983, with SSCC values >0.15 mg·m^{-3} spreading westwards to long. 170°E. In October-December 1983, SSCC >0.10 mg·m^{-3} are seen all along the Equator.

South of lat. 20°S, an SSCC increase is observed during the austral winter. The increase started in April-June in 1982, the maximum was reached in July-September, with SSCC >0.20 mg·m^{-3} spreading northward to 22°S, and low values were seen again in October-December. The increase during the austral winter of 1983 was of a lesser extent, being well developed only during July-September, with SSCC >0.20 mg·m^{-3} limited to the south of 28°S.

The intermediate zone, from lat. 10°S to 20°S, between the equatorial upwelling and higher latitudes where a winter increase is observed, generally has low chlorophyll concentrations, below 0.10 mg·m^{-3}. The lowest concentrations are seen in austral summer, from October 1982 to June 1983, and in October-December 1983. The highest concentrations are associated with a strengthening of the equatorial upwelling (around long. 140°W in April-June 1982; westwards spreading of richer waters from the eastern Pacific in July-September 1982 and 1983).

When looking at the whole series of maps, the most striking feature is the reduction of the equatorial upwelling enriched area after the onset of El Niño. The most pronounced stage was in April-June 1983, with poor waters over most of the tropical Pacific. On the contrary, a zone centered at lat. 10°N, west of the dateline, which is usually occupied by chlorophyll-poor waters, had higher SSCC during the 1982-83 El Niño.

DISCUSSION

Equatorial Upwelling

The collapse of the equatorial upwelling after the onset of El Niño, when westerlies have replaced the trade winds at the Equator, consistently results in a decrease in SSCC. This decrease has already been documented for the eastern Pacific in the Galapagos Islands region by Feldman et al. (1984) using sea color satellite images. It corresponds to a decrease in primary production of the whole photic layer (Barber and Chavez 1983). The data presented here show that the equatorial zone was impoverished westwards to nearly 180°. This is in agreement with the reproductive failure and disappearance of seabird communities at Christmas Atoll (lat. 2°N, long. 157°W) in November 1982; Schreiber and Schreiber (1984) attributed these events to the establishment of an oligotrophic oceanic ecosystem instead of a productive one. Successful reproduction started again for some birds species in June 1983, and hatching occurred in July-September 1983, when SSCC higher than 0.15 $mg \cdot m^{-3}$ reappeared at the Equator (Fig.1).

Western Pacific Around Lat. 7°N.

Under normal conditions (see Figure 1: January to March 1982, July to December 1983) the equatorial upwelling also drives a chlorophyll-rich zone west of 180°. This does not appear on the map of Koblentz-Mishke et al. (1970) on the primary production in the world ocean, but is described as an episodic feature by Oudot and Wauthy (1976). The area with SSCC >0.15 $mg \cdot m^{-3}$ which appears north of the Equator, centered at about 7°N from October 1982 to March 1983 (Fig. 1) has nothing to do with the equatorial upwelling. Based on approximately 100 SSCC data points obtained by three different merchant ships, this chlorophyll-rich area can hardly be thought to result from measurement errors. It rather may be related to the eastward draining of warm water from the western tropical Pacific and consequent thinning of the surface mixed layer and drop of the sea level (Wyrtki 1985). A simultaneous cooling of the sea surface by 1°C occurred in this region during El Niño, which can be explained by advection of cooler water, and also by other potentially important processes which are more difficult to quantify (Meyers and Donguy 1984). The observed SSCC increase supports the hypothesis that vertical mixing of cooler nutrient-rich deep water might be one of these processes. Even if vertical mixing is unlikely, the 50 m rise of the thermocline which has been observed at lat. 7°N between January 1982 and January 1983 (Meyers and Donguy 1984) allows more light to penetrate to the deep chlorophyll maximum. This hypothesis is supported by the shift which occurred between January 1982 and January 1983 in the nitrate-temperature relationship (Fig. 2; data collected by the Japan Meteorological Agency along long. 137°E aboard RV *Ryofu Maru*; Anonymous 1972-84). The nitrate concentration at a given temperature (which we assume to represent a given water mass) dropped by about 2 $\mu moles \cdot L^{-1}$. Shifts in the nitrate-temperature relationship provide information on the consumption of nitrate by the phyto-

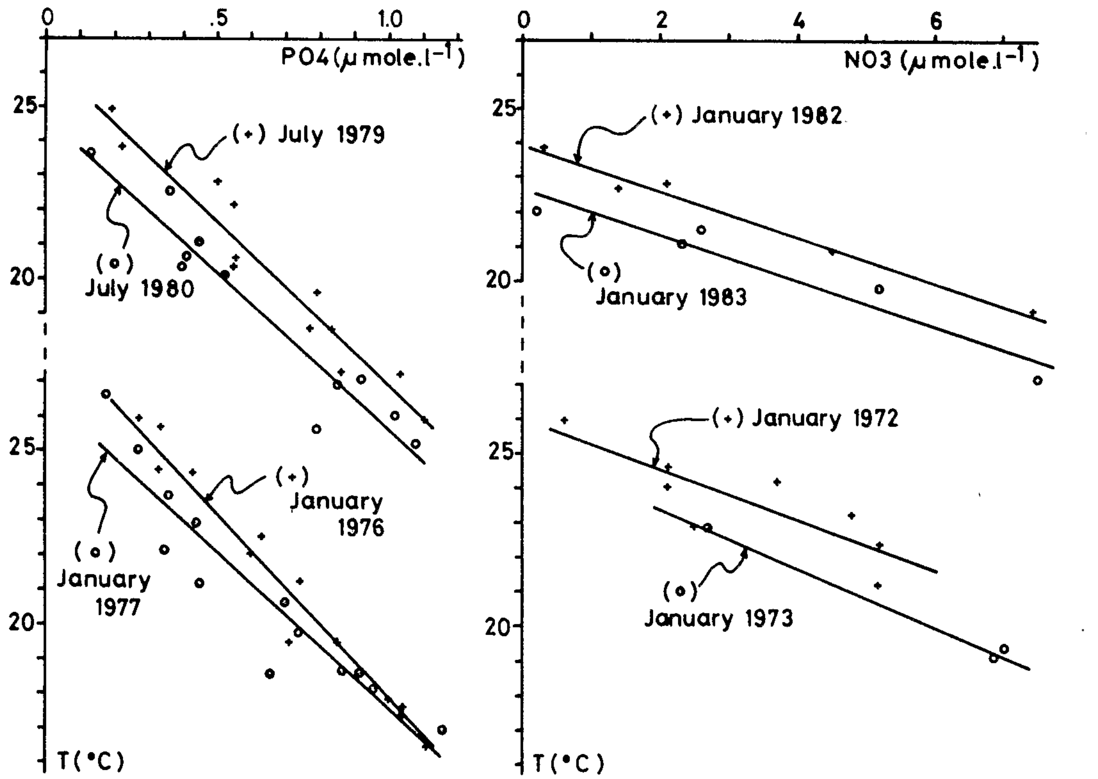

FIGURE 2.—Nutrient-temperature relationships between lat. 6°N and 9°N. Crosses: observations before an El Niño; open circles: observations after an El Niño. (Data from the RV *Ryofu Maru* cruises at long. 137°E, Anonymous 1972 to 1984).

plankton (Voituriez and Herbland 1984). We can then suggest that new nitrates have been assimilated during El Niño in the western Pacific at lat. 6-9°N. The 2 μmoles$\cdot$L^{-1} drop in nitrate concentration is observed in the interval 17°-22°C, corresponding to a 35 m thick water layer (Anonymous 1972-84), so that the amount of new nitrates used by photosynthesis is 70 μmoles$\cdot$m^{-2}, or 980 mg$\cdot$m^{-2}. If C/N = 9.01 and C/Chl = 114 in surface waters of the oligotrophic central North Pacific (Sharp et al. 1980), this amount of nitrogen corresponds to 77 mg Chl a$\cdot$m^{-2}. It represents an important supply in an ecosystem where the chlorophyll concentration is usually low.

Figure 3 shows the variations of integrated chlorophyll (0-200 m) between lat. 6°N and 9°N at long. 137°E, obtained from the *Ryofu Maru* data (Anonymous 1972-84). Values during the 1982-83 El Niño are similar to those since July 1981, i.e., below 50 mg$\cdot$m^{-2}. SSCC from the same data set also shows low values during the 1982-83 El Niño, conflicting with the results mapped on Figure 1. Recent El Niño events in 1972 and 1976 resulted in a drop of the sea level in the western Pacific (Meyers 1982). Low sea level was also recorded during an El Niño like event in the western Pacific in 1979-80 (Donguy and Dessier 1983). These low sea level episodes during which the thermocline is shallow (Wyrtki 1978), yet do not correspond to high SSCC or high integrated chlorophyll values in the *Ryofu Maru* results (Fig. 3). It seems however that the nutricline depth is shallower during these four episodes (Fig. 3). All of them are moreover characterized by a shift in the nutrient-temperature relationship (Fig. 2) indicating a consumption of new nutrients. We are dealing with an SSCC enrichment in the northwestern tropical Pacific which persists for several months (October 1982-March 1983) and is consistent with an input of new nutrients from below, but which does not appear in the chlorophyll concentrations measured every 6 mo on the *Ryofu Maru*. Both data sources have weaknesses. The SSCC monitoring does not measure what occurs below the surface. A significant correlation exists between SSCC and integrated chlorophyll on broad data sets (Lorenzen 1970; Platt and Herman 1983), but oligotrophic ecosystems often show no relationship or, sometimes, inverse relationships (Hayward and Venrick 1982). The *Ryofu Maru* data at 137°E between 6°N and 9°N allow a look at this problem (Fig. 4): the correlation between SSCC and integrated chlorophyll is significant at the 1% level. The value r = 0.52 obtained with individual stations increases to r = 0.70 when enlarging the spatial scale (i.e., taking mean values between 6°N and 9°N instead of individual stations); a further improvement would probably be obtained by enlarging the time scale, but appropriate time series do not exist

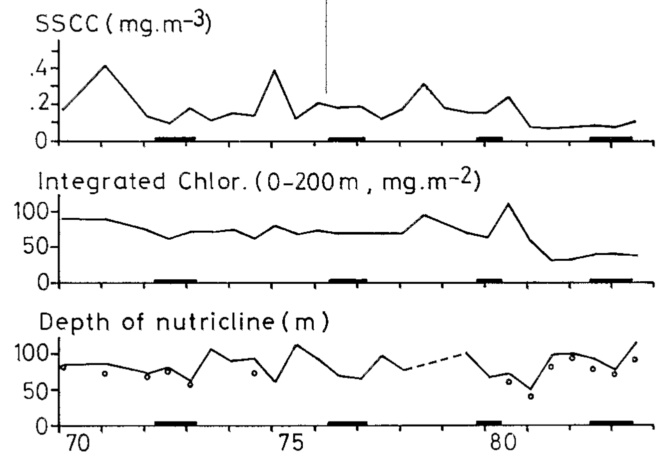

FIGURE 3.—Long-term evolution of lat. 6°N-9°N averaged parameters related to the primary production (data from the RV *Ryofu Maru* cruises at long. 137°E, Anonymous 1972 to 1984). Upper and middle panels: the chlorophyll concentrations primarily expressed in active chlorophyll a and pheophytin have been converted into chlorophyll a equivalents (Dandonneau 1979). Lower panel: the continuous line joins the depth of PO_4 = 0.35 μmole$\cdot$L^{-1}; open circles represent the depths of NO_3 = 1 μmole$\cdot$L^{-1}. Thickened marks on the horizontal axis indicate the low sea level episodes in the western tropical Pacific.

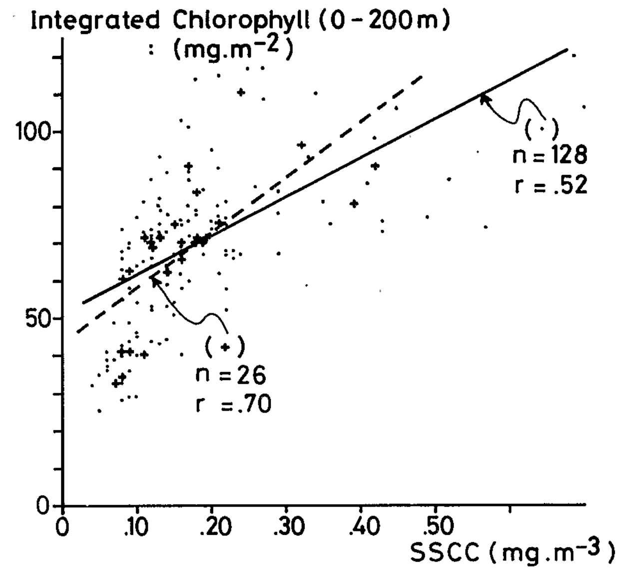

FIGURE 4.—Integrated chlorophyll (0-200 m)/SSCC relationship between lat. 6°N and 9°N (data from the RV *Ryofu Maru* cruises at long. 137°E, Anonymous 1972 to 1984). Points and continuous line: individual stations. Crosses and dashed line: averaged values for each cruise.

in this region. We can thus conclude that SSCC is a reasonable index of the chlorophyll content in the photic layer. The weakness of the *Ryofu Maru* data series is that only 4-6 stations within 3 d are available for each El Niño episode. This sampling pattern can describe the vertical structure of the ocean, but it is not helpful in large-scale studies based on chlorophyll, in which the signal to noise ratio is very low (Dandonneau and Gohin 1984).

Subtropical Zones

At the start of the 1982-83 El Niño (and a possible cause of it?) strong southerly winds were recorded east of Australia in June and July 1982 (Harrison and Cane 1984). In the Coral and Tasman Seas, a chlorophyll enrichment occurs in austral winter between 22°S and higher latitudes (Dandonneau and Gohin 1984). This chlorophyll enrichment can be seen in austral autumn and winter of 1982 (Fig. 1), while it only appears in winter in 1983. Moreover, SSCC higher than 0.15 mg·m^{-3} spread northward to lat. 20°S in July-September 1982 around long. 160°E, but only to 24°S in July-September 1983 at the same longitude. The long and intense SSCC winter increase in this area in 1982 may be the result of advection of richer water from the south after the strong wind anomaly. In the Northern Hemisphere, a zone with high SSCC values is observed off North America during the fall of 1982 (Fig. 1); this feature is especially noteworthy since most regions of the Pacific (even those from the same merchant ship voyage) show low SSCC values. Like other El Niños, the 1982-83 one resulted in temperatures and sea levels higher than normal along the California coast, and strong westerly winds at about 30°N. One would not expect increased chlorophyll concentrations with higher temperatures, and according to Chelton et al. (1982), El Niño episodes are likely to diminish advection of water from the north which generates a higher biomass. However, our data points corresponding to the enriched zone were far offshore (Fig. 1) and the thermal anomaly there did not greatly differ from zero. The high SSCC values off North America during the fall of 1982 might then be related to the severe wind conditions which prevailed during this time, and probably induced vertical mixing of deep nutrients.

A few more features which appear on Figure 1 would be worthy of discussion, but conclusion is hindered by the lack of accordance with a poorly known field of oceanic properties and by the risk of sampling or instrumental errors in SSCC measurements. For instance the shape of the area with SSCC >0.15 mg·m^{-3} centered slightly south of the Equator at 165°W in July-September 1982 (Fig. 1), while the upwelling was collapsing, is surprisingly similar to the shape of the maximum of cloudiness in September 1982, derived from satellite measurements of outgoing long wave radiation (Gill and Rasmusson 1983). Similarity might be causal, i.e., high SSCC values might result from a response of the phytoplankton to attenuation of light by the clouds, or from enhanced phytoplankton growth caused by precipitation of dust and aerosols by the rain (Menzel and Spaeth 1962). It may also result, at least partly, from sampling artifacts.

The major features shown by this SSCC monitoring experiment are in agreement with the large-scale processes that affect the tropical Pacific during El Niño episodes. The collapse of the equatorial upwelling in October 1982 resulted in a nearly complete disappearance of the chlorophyll-rich area which is usually located across the Equator. A moderate enrichment persisted, however, east of long. 120°W. In the northwestern tropical Pacific, the eastward drift of the warmwater pool was followed by conditions which stimulated photosynthesis: a shallower thermocline, and more light penetrating to the nutrients gave rise to unusually high chlorophyll concentrations west of 180° from October 1982 to March 1983. In April-June 1983, the equatorial upwelling in the eastern Pacific was still reduced by the El Niño conditions, and the enrichment in the northwestern tropical Pacific was less intense; during this period, low chlorophyll concentrations prevailed over most of the tropical Pacific.

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