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An empirical approach to the island mass effect in the south tropical Pacific based on sea surface chlorophyll concentrations

Yves Dandonneau* and Loïc Charpy†

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Abstract—The island mass effect is defined here as the relationship between sea surface chlorophyll concentration (SSCC) and distance to the nearest island (DNI), assuming that SSCC is an index of biomass in the entire photic layer and that variable currents in this region result in evenness of effects around islands. The study uses about 8500 SSCC randomly sampled by ships of opportunity in the tropical Pacific from 0° to 25°S between 160°E and 130°W, and determination of DNI for each sample.

At each place of the field, the mean SSCC value and the SSCC–DNI correlation and regression slope have been computed using all SSCC–DNI pairs available at a distance of <240 nmi from that place. The highest mean SSCC values are found near the equator and originate from upwelling; south of 20°S, relatively high SSCC mean values are found in the western part corresponding to winter enrichment. These large-scale climatic features give more variance than presence or absence of islands, biasing the SSCC–DNI correlation in transition zones; significantly negative correlations (i.e., SSCC increase when approaching islands) are found mainly in a large patch between 13° and 20°S, including Vanuatu, Fiji, Tonga, and Samoa islands. Since these islands have rivers and no closed lagoon, the island mass effect is supposed to result mostly from land drainage. Positive correlations for the Tuamotu Archipelago (low atolls) suggest that the dominant effect could be predation by the coral reef benthic communities. Involving opposite phenomena, island mass effects are weak in the south tropical Pacific and, on the average, SSCC generally does not increase by more than 10% in 40 mi.

INTRODUCTION

Many changes occur in the ocean near islands. They are especially noticeable in tropical regions, where fishes, even pelagic species, are found in greater abundance in the vicinity of islands (Blackburn, 1965; Sund *et al.*, 1981). The "island mass effect" was introduced by Doty and Oguri (1956) for the shoreward increase in phytoplankton productivity which they believed explained, in part, the increased concentration of grazers and predators. Gilmartin and Revelante (1974), using more data, found a similar trend in the chlorophyll distribution. The distributions of biomass and productivity around an island, however, are extremely variable, and a regular shoreward increase is not an absolute rule (Bennett and Schaefer, 1960; Jones, 1962; Ricard and Delesalle, 1982). Among other factors that can generate irregular patterns, an obvious source of heterogeneity is the dispersion of enrichment products by currents whose direction and strength vary with time. A time varying velocity field, combined with the time lag of biological responses, complicate the concept of

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* Groupe SURTROPAC, Centre ORSTOM, B.P. A5 – Nouméa, New Caledonia.
† Centre ORSTOM, B.P. 529 – Papeete, French Polynesia.

'upstream' and 'downstream', so that new strategies must be applied for mesoscale studies of island mass effects.

The present study is based on determination of more than 8500 sea surface chlorophyll concentrations (SSCC). Surface seawater samples were collected in the South Pacific during a five-year period (1978 to 1982) as a part of the SURTROPAC program at the Centre ORSTOM de Nouméa. The extremely large data set and the multitude of islands in the region (Fig. 1) allow an empirical approach to the "island mass effect" based on SSCC.

MATERIAL AND METHODS

Sampling program

Crews of cooperating ships of opportunity sailing from New Caledonia to California or Panama sampled the sea surface in regions strewn with islands or in the open ocean. The data are distributed mostly along tracks from New Caledonia–the Solomon Islands–Vanuatu to Fiji and Hawaii or to the Society Islands and Panama, with or without passing through the southern Tuamotu Archipelago. The maximum density of data is found between New Caledonia and the Samoa Islands.

SSCC estimation

The method of Dandonneau (1982) for the determination of SSCC in samples collected by merchant ships was used. Samples (20 ml) are filtered by the crew using Millipore filters HA type, 13 mm in diameter; the filters are stored in the dark until it is possible to measure fluorescence in the laboratory, which is done without extraction. Long-term storage at ambient temperature causes a degradation of active chlorophyll *a* during the first two or three weeks; however, measurements have shown that thereafter fluorescence does not vary for months. The results are expressed as chlorophyll + phaeopigments.

Relationship of SSCC and island mass effects

Since island mass effects are likely to develop downstream, a previous knowledge of the currents in the South Pacific would be useful for this study. However, they are not well known, but there are many indications that the flows are extremely variable in the south tropical Pacific (Eldin, 1983). Consequently, no prevailing direction could be assumed and the distance to the nearest island (DNI) was used for each SSCC value. Figure 2 shows the SSCC–DNI relationship at Vanuatu and Tuamotu, areas where many and relatively few samples, respectively, were collected. Previously, Doty and Oguri (1956) related ^{14}C fixation to the distance from shore. As a sufficiently complete computerized coastline is not available for the South Pacific, information has been drawn from marine charts and processed as follows. A matrix A, 125 lines × 350 rows, in which each element represents a 12′ × 12′ square has been opened. Thus the matrix represents 25° in latitude × 70° in longitude, corresponding to the study area. The matrix was first set to zero, then the value 1 was assigned to the elements where an island (or part of an island or a reef) was present (Fig. 1).

Each of the 8565 SSCC values can be positioned in matrix A at coordinates X_0 and Y_0. The space around (X_0, Y_0) is then thoroughly explored farther and farther until an element of A is found equal to unity, i.e. until the nearest island is encountered. The distance between the observation and the nearest island is then given in nautical miles by $\text{DNI} = 12\,((X_0 - X_i)^2 + (Y_0 - Y_i)^2 \cos^2\Phi)^{1/2}$, where Φ is the latitude of the observation and X_i and Y_i are the coordinates of the nearest island in matrix A.

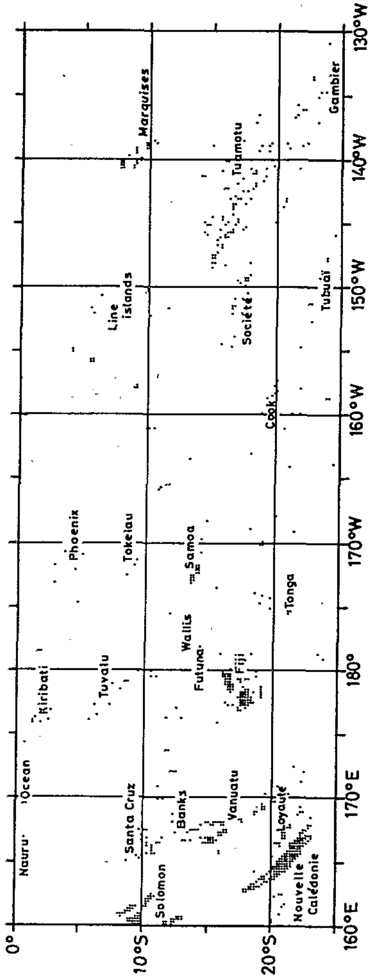

Fig. 1. Study area, showing position of islands (presence or absence of islands or banks in 12′ squares).

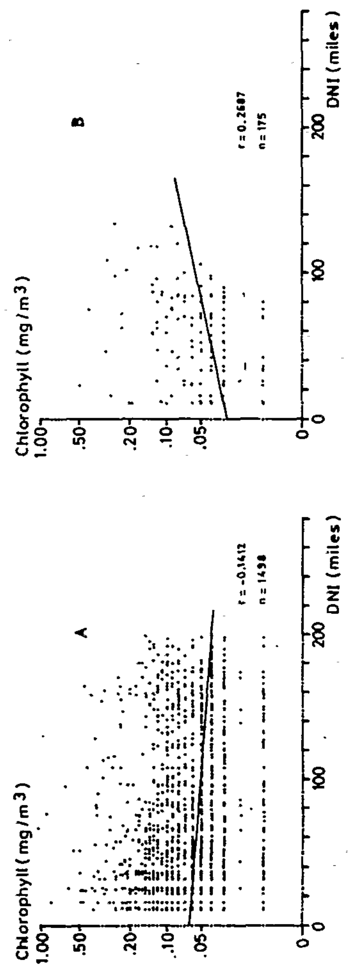

Fig. 2. SSCC–DNI relationships at points A (Vanuatu) and B (Tuamotu). The positions of A and B are shown in Figs 3 to 7.

Thus DNI is defined as 12 mi due to the grid adopted for matrix A. This definition is coarse compared to the studies of DOTY and OGURI (1956) and GILMARTIN and REVELANTE (1974) where DNI was within 16 or 22 mi, respectively. However, the range of distances we can examine is much wider (Fig. 2) and the poor precision associated with the 12′ × 12′ grid is unimportant for the present large-scale study.

RESULTS

To map statistical properties of the field [mean SSCC, correlation and regression slope between Log (1 + SSCC) and DNI], the estimate at a place (X, Y) of the ocean has been computed using all the available observations taken from a circle with its center at (X, Y) and a radius R (Fig. 3). These statistical properties may vary according to R, and a convenient scale must then be adopted. Results corresponding to various R values are shown in Table 1; they have been obtained at three places: point A is at 20°S, 171°E, east of the Vanuatu Islands; point B is at 15°S, 142°W, north of the Tuamotu Archipelago (A and B are representative of two wide areas with opposite properties). The third point is at 16°S, 180°, close by Vanua Levu (a large island of the Fiji Islands), allowing a relatively small-scale study focused on a single island.

The statistics estimated from <100 observations are generally not significant (Table 1). The lower limit of R is then a function of the density of observations (Fig. 3). At point A, $R = 36$ nmi gives the best correlation and the strongest slope, suggesting that small-scale phenomena are dominant. However, this scale does not give significant results in the Fiji or in Tuamotu islands, where data are scarce. Enlarging the scale up to 400 mi does not improve the results at any of the three points; large-scale geographical trends in SSCC probably tend to dominate island mass effects. A radius equal to 240 nmi has been adopted since it appears that this distance gives both significant correlations and strong regression slopes (Table 1). Furthermore, it allows statistical estimates with more than 50 SSCC–DNI pairs over a large part of the studied area (Fig. 3). The areas where fewer than 50 observations are available within 240 nmi of an island exhibit unstable and unreliable correlation coefficients and will be ignored hereafter.

The mean SSCC values that cover 5 years (1978 to 1982) are shown in Fig. 4. The areas where SSCC is lower than 0.06 mg m^{-3} spread in a basin between the Fiji and Tokelau islands and east of 170°W where they include the Cook and Tuamotu islands. The south edge of the studied zone exhibits SSCC mean values higher than 0.08 mg m^{-3} west of 170°W, corresponding to an area where winter vertical mixing alternates with oligotrophic summer conditions (DANDONNEAU and GOHIN, 1984). Equatorial upwelling results in SSCC higher than 0.10 mg m^{-3} north of the Marquesas Islands (10°S) in the east, north of the Tokelau Islands (6°S) in the central part, and north of the Solomon Islands (12°S) in the west, where doming mechanisms may also interfere (OUDOT and WAUTHY, 1976).

Positive and negative correlation coefficients between Log (1 + SSCC) and DNI are equally abundant (Fig. 5). The correlation coefficient for all 8565 data points is $r = 0.051$. Negative correlations (i.e., increasing SSCC when approaching islands) dominate between the Vanuatu and Samoa islands and around the Society Islands, in regions where the density of data is highest (point A, Fig. 2). Areas with negative correlations also are seen in the Coral Sea, around the Solomon Islands, to the equator at 165°W, and south of the Tuamotu Archipelago, in regions where the density of data is relatively low. Positive correlations (i.e., an inverse island mass effect!) are seen west and north of Vanuatu, west of the Tuvalu

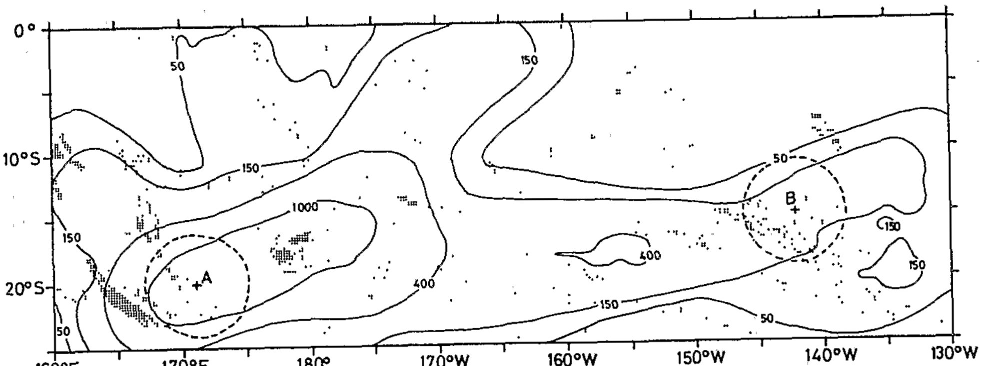

Fig. 3. Density of data (numbers correspond to the amount of SSCC data within 240 nmi). + indicates center of circle with radius of 240 nmi for (A) Vanuatu Islands, (B) Tuamotu Archipelago.

Table 1. Effect of varying scale

		Radius of the circle in which observations are taken into account (nmi)							
		400	320	240	180	120	90	60	36
	n	2534	2045	1498	907	430	285	146	37
A: Vanuatu	*r*	–0.13	–0.16	–0.14	–0.11	–0.13	–0.08	–0.16	–0.37
Islands	*b*	-0.18×10^{-2}	-0.21×10^{-2}	-0.18×10^{-2}	-0.16×10^{-2}	-0.26×10^{-2}	-0.18×10^{-2}	-0.53×10^{-2}	-3.19×10^{-2}
20°S, 171°E	*P*	2×10^{-9}	2×10^{-10}	7×10^{-8}	1×10^{-3}	6×10^{-3}	18×10^{-2}	5.3×10^{-2}	2.5×10^{-2}
	n	405	270	175	130	77	55	32	15
B: Tuamotu	*r*	0.22	0.33	0.29	0.19	0.02	0.03	–0.11	0.15
Archipelago	*b*	0.40×10^{-2}	0.68×10^{-2}	0.67×10^{-2}	0.48×10^{-2}	0.05×10^{-2}	0.08×10^{-2}	-0.36×10^{-2}	0.97×10^{-2}
15°S, 142°W	*P*	7×10^{-6}	2×10^{-8}	1×10^{-4}	2.9×10^{-2}	89×10^{-2}	84×10^{-2}	55×10^{-2}	59×10^{-2}
	n	2566	1796	1230	876	523	340	135	40
Fiji Islands	*r*	–0.02	–0.10	–0.16	–0.16	–0.15	–0.10	–0.21	–0.09
	b	-0.03×10^{-2}	-0.21×10^{-2}	-0.35×10^{-2}	-0.39×10^{-2}	-0.39×10^{-2}	-0.33×10^{-2}	-0.76×10^{-2}	-0.51×10^{-2}
16°S, 180°	*P*	33×10^{-2}	2×10^{-5}	3×10^{-8}	4×10^{-6}	8×10^{-4}	6.5×10^{-2}	2×10^{-2}	57×10^{-2}

n, Number of observations; *r*, correlation coefficient between Log (1 + SSCC) and DNI; *b*, regression slope of Log (1 + SSCC) on DNI; and *P*, probability of the null hypothesis.

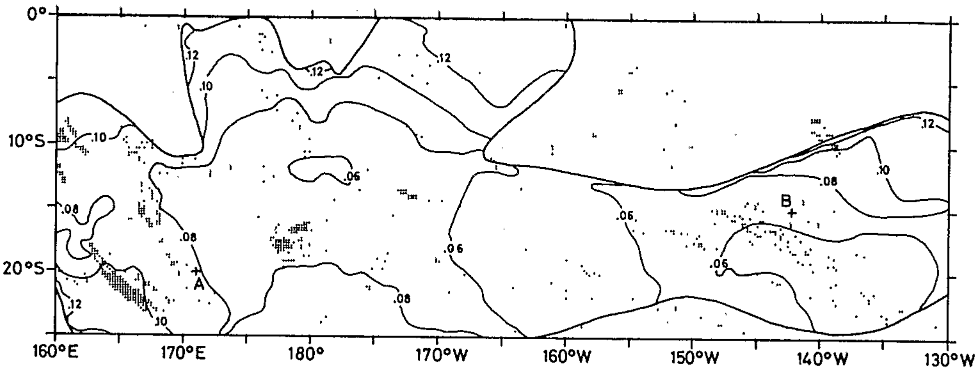

Fig. 4. Mean SSCC estimated from observations within 240 nmi.

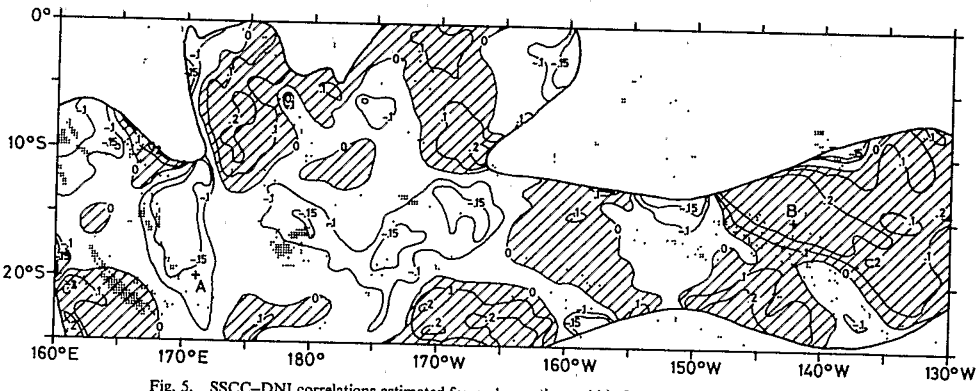

Fig. 5. SSCC–DNI correlations estimated from observations within 240 nmi. Positive correlations (hatched) indicate decreasing SSCC when approaching islands.

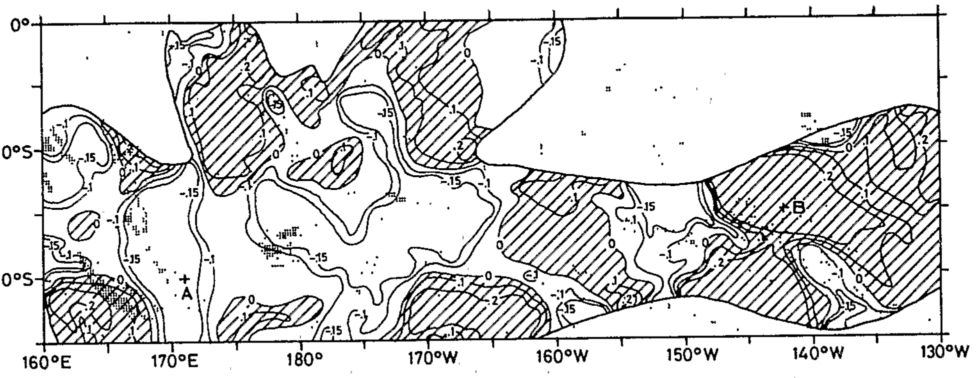

Fig. 6. Regression slopes of SSCC on DNI estimated from observations within 240 nmi. Positive regressions (hatched) indicate decreasing SSCC when approaching islands.

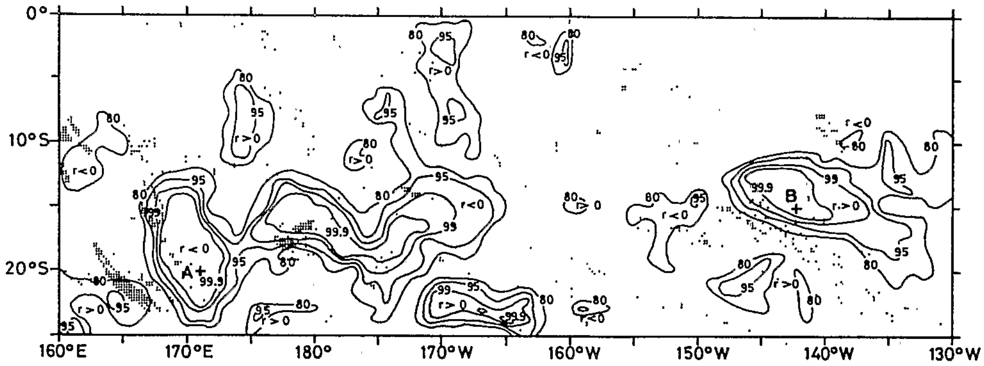

Fig. 7. Probability of positive or negative correlations (in percent) = probability of $t < |r|((n-2)/(1-r^2))^{1/2}$, computed using series expansions (ABRAMOWITZ and SEGUN, 1965).

Islands, east of the Tokelau and Phoenix islands, south of the Fiji and Tonga islands, around the Cook Islands and east and south of the Tuamotu Archipelago (point B, Fig. 2). Only around New Caledonia, north of Wallis and Futuna, south of Fiji, and north of the Cook Islands are positive correlations encountered corresponding to more than 400 available data points (Figs 3 and 5). Regression slopes follow a similar pattern (Fig. 6). The significance of the correlation coefficients between Log (1 + SSCC) and DNI mapped on Fig. 5 cannot be estimated in a simple way. For each estimate r of the correlation coefficient, we know the number of observations n, and we can compute the probability P of $t > |r|\,(n-2)^{1/2}\,(1-r^2)^{-1/2}$ under the null hypothesis of no relationship. The probability varies according to the scale of study (Table 1). It is obvious too that neighbouring r estimates are not independent, since the data used for each r determination partly overlap; in this bearing, the significance of a correlation coefficient obtained at one locality is improved if similar r values are found nearby. The significance levels $(1-P)$ that are mapped therefore are indices for the comparison of the computed correlations rather than exact levels of significance. Since most tables of Student's t are not convenient for small r values and large numbers of observations (Figs 3 and 5), P has been computed using series expansions (ABRAMOWITZ and SEGUN, 1965). Significance levels $(1-P)$ better than 95% are mainly found in two wide areas: between the Vanuatu and Samoa islands, corresponding to negative r values, and northeast of the Tuamotu Archipelago, where r is positive, implying a significant SSCC decrease when approaching islands. Smaller areas where $1-P$ is >95% appear at the periphery; they mostly correspond to positive SSCC–DNI correlations (Fig. 7).

DISCUSSION

Primary production results from processes in the whole photic layer and the role of the subsurface chlorophyll maximum has often been emphasized (e.g., VENRICK *et al.*, 1973; HERBLAND and VOITURIEZ, 1979). A close relationship between SSCC and integrated primary production has been shown by LORENZEN (1970), but HAYWARD and VENRICK (1982) warn against an excessive use of this relationship, especially in oligotrophic zones where the compensation depth and nutrient-rich waters are very deep. Most of the south tropical Pacific relates to oligotrophic conditions (MCGOWAN, 1974), so that the conclusions of this study might be limited. However, a positive relation between SSCC and integrated primary production can reasonably be expected, mainly because, due to specific aspects of the sampling by ships of opportunity, our SSCC observations in all parts of the studied area are evenly distributed throughout the five-year period. On such a time scale, either an inverse relation, or no relation, between SSCC and integrated primary production is unlikely.

The modifications to the oceanic environment due to an island are relevant to three categories of factors (SANDER, 1981). The first is land drainage from river outflows, human wastes, or springs of underground waters; the effects differ whether large communities are present or not, whether agriculture is developed and fertilizers are used, and whether a barrier reef maintains most of the enrichment in a lagoon. Whatever the specific conditions are, an SSCC increase is expected. The second category is relevant to benthos–water interactions; animals are especially abundant on the slopes of the Pacific islands where corals and associated species are adapted for feeding on plankton biomass and on seston. These forms would clear up the sea water if they were not simultaneously excreting; thus, an immediate effect of the coral reef benthos is a decrease in the phytoplankton biomass, while further utilization of regenerated nutrients can lead to an increase downstream at remote distances. The third category, internal waves, was identified by SANDER (1981) as a dominant phenomenon allowing vertical mixing and input of new nutrients from deeper waters into the surface mixed layer. Turbulence generated in a current by an island (BARKLEY, 1972) may also favour vertical mixing or divergent eddies. An SSCC increase is expected to result from this category of factors, the effects of which will vary in intensity, place, and time according to the variability of the currents. To summarize, only if predation by benthic animals is very important will SSCC decrease when approaching an island. The other island mass effects are expected to produce an SSCC increase when DNI decreases, and thus is a negative correlation.

The correlation coefficients shown on Fig. 5 are low and their significance at the 5% level is only obtained on a small part of the studied area (Fig. 7). The large patch between the Vanuatu and Samoa islands with significant negative correlations also corresponds to the zone where sampling density is maximum (Fig. 3). In most places, data are not abundant enough to draw any conclusions. The patches with significant positive correlations bring up a problem; in these patches, SSCC decreases with DNI, which, if related to island mass effects, could only be explained by the dominance of grazing close to the islands. The patch with significantly positive SSCC–DNI correlations between Tuvalu and the Santa Cruz islands covers a region where SSCC is relatively high due to equatorial upwelling (Fig. 4) and where few islands are present (Fig. 1). Thus, the selection of SSCC–DNI pairs within 240 mi, which initiates the statistical computations, brings in many pairs with large DNI (due to the scarcity of islands) and large SSCC (due to equatorial upwelling). In this patch, positive correlations result from the repartition of islands and from the existence of an enrichment phenomenon that dominates the island mass effect. This is also true for the patches with significantly positive correlations south of the Fiji Islands, and south of New Caledonia. Higher SSCC to the south (Fig. 4) result from a winter enrichment due to enhanced vertical mixing (DANDONNEAU and GOHIN, 1984) and, in addition, islands are scarce. Consequently, at 22°S, 164°E, for instance, the correlation coefficient ($r = +\,0.10$ for 410 observations) is equal to -0.03 for 213 observations (non significant), when winter data (May to October) are ignored.

The large patch with r significantly positive northeast of the Tuamotu Archipelago perhaps requires more attention. It corresponds to a transition zone between oligotrophic waters in the southwestern part and northeastern waters coming from the rich equatorial and eastern Pacific; the SSCC gradient northeast of the Tuamotu Islands (Fig. 4) results from this transition. However, when the effects of the gradient are partly reduced, by using smaller scales of study, significance is lost, but r is still positive (Table 1). This archipelago spreads in a region with a poorly known but apparently uniform physical environment; the contours of most properties reveal weak horizontal gradients (BARKLEY, 1968), and XBT data from ships of opportunity sailing from Tahiti to Panama show that the thermocline topography is flat in the Tuamotu area. At the latitude of the Tuamotu Archipelago, the South Equatorial Current flows westwards (ELDIN, 1983) through the thick and widespread island network. The benthic filter feeder communities of these coral islands seem able to exert an important grazing pressure on the passing plankton populations, thereby reducing the phytoplankton and zooplankton biomasses. It seems unlikely that the resulting decrease in grazing by zooplankton would be sufficient for an enhanced phytoplankton growth, because the mixed layer is nutrient depleted and the nutricline is very deep in this region. Furthermore the Tuamotu Archipelago consists of atolls, so that land drainage is reduced and mostly benefits the closed lagoon. Thus, a grazing effect by the benthic communities of the Tuamotu Archipelago may contribute to the positive SSCC–DNI correlation in this region.

It is noteworthy that the islands in the largest patch with significantly negative correlations

(Fig. 7) are high islands without closed lagoons (Vanuatu, Fiji, Tonga, and Samoa). Such configurations are favorable for land drainage and input of terrigeneous nutrients to the sea. New Caledonia is also a high island but is surrounded by a lagoon which retains most of the inputs from land, resulting in positive or non significant SSCC–DNI correlations.

The regression slopes of Log (1 + SSCC) on DNI mapped in Fig. 6 are very low. Absolute values generally are <0.0025, corresponding to a 11% variation in 40 mi. The slopes do not describe a phenomenon developing in a few determined directions from an island, but rather an empirical relation observed on the entire circumference. Hence, our observations are more accountable for presumably unaffected large sectors than for narrow sectors where an island mass effect can be expected to develop. The resulting confusion is partly responsible for the low regression slopes. As a comparison, similar data processing has been applied to the results from a cruise around the Scilly Islands, where an island mass effect on SSCC was observed in two main directions, due to vertical mixing of nutrients (Simpson *et al.*, 1982). For SSCC–DNI pairs we found that r is equal to -0.67 and slope b is equal to -0.037, with DNI ranging from a few miles to 40. The slope is one order of magnitude larger than those found during the present work, in spite of a similar empirical approach. Hence, it seems that the island mass effect on SSCC is weak in the south tropical Pacific, if compared to temperate seas where shallow nutrients can be brought to the surface by island-induced turbulence. In the South Pacific, weak currents (Eldin, 1983) and a deep nutricline make such mixing difficult; land drainage and benthos–sea interactions are weak but probably dominate island mass effects.

CONCLUSIONS

In a previous work (Dandonneau, 1979), island mass effects were suggested as an explanation for the relatively high chlorophyll concentrations in the southwestern tropical Pacific. The present study indicates that this opinion probably must be moderated since the mean SSCC values (Fig. 4) from a larger data set are distributed in agreement with large-scale climatic factors and the vicinity of islands apparently has only a slight effect on SSCC. A significant negative SSCC–DNI correlation is mainly found from Vanuatu to Samoa, where high islands lack closed peripheral lagoons so that water from land drainage enriches the ocean. Low islands or atolls of the central South Pacific have no rivers and the relation between SSCC and DNI is uncertain. A SSCC decrease when approaching islands in the Tuamotu area even suggests that grazing by the rich coral reef communities dominates other island mass effects; then, the mature reef ecosystem would exploit the pelagic one, as often observed at interfaces between two ecosystems (Frontier, 1978). This scheme is a possible explanation for the discrepancy between well-known fish concentrations around islands and the uncertainty of an enrichment at the primary production level. Exploitation of planktonic living forms by the coral reef communities realizes a short cut between primary producers and pelagic fishes, with loops as complex as ammonium excretion by fishes benefiting coral ecosystems (Meyer *et al.*, 1983). Turbulent vertical mixing of nutrients could not be identified here as an important mechanism for inducing phytoplankton growth. This is probably due to slow currents and deep nutricline (below 200 m in the central South Pacific).

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