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Island mass effect in the Marquesas Islands: Time variation

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[1] Chlorophyll *a* in the Marquesas islands has been analyzed for the period 1997–2002 as well as simultaneous sea surface height anomaly, sea surface temperature, wind and rainfall. For the first time, the seasonality of phytoplankton blooms is shown around the Marquesas Islands. Clearly, the data show three types of blooms in this area: seasonal blooms, episodic ones, and La Niña (related bloom). Initiation of blooms is due to the island mass effect and has been explained by the dynamic interaction of the circulation and the topography. The island mass effect blooms are strongly correlated with the total (Ekman plus geostrophic) surface current and episodically correlated with the geostrophic current. Strong correlation is also observed with sea surface temperature. Analysis of rainfall data suggests that land drainage can enhance a bloom if the current dispersing the nutrients is sufficiently strong. **INDEX TERMS:** 4231 Oceanography: General: Equatorial oceanography; 4279 Oceanography: General: Upwelling and convergences; 4572 Oceanography: Physical: Upper ocean processes; 4520 Oceanography: Physical: Eddies and mesoscale processes; 4512 Oceanography: Physical: Currents. **Citation:** Martinez, E., and K. Maamaatuaiahutapu (2004), Island mass effect in the Marquesas Islands: Time variation, *Geophys. Res. Lett.*, **31**, L18307, doi:10.1029/2004GL020682.

1. Introduction

[2] Phytoplankton blooms occur predictably in some oceanic regions such as along eastern boundaries and the Equator. In oligotrophic ocean areas such as French Polynesia, large scale blooms are rare and are not fully understood. The Marquesas (218°E–222°E/8°S–11°S) are steep islands located in the north west of French Polynesia. Although located in the oligotrophic Subtropical Gyre of the South Pacific Ocean, these islands are associated with a significant phytoplankton production.

[3] Phytoplankton blooms occur when macronutrients and micronutrients are brought together to the ocean surface where light is sufficient to initiate the photosynthesis process. In an oligotrophic ocean, these conditions are met only around certain islands. Enhanced biological production in this case is known as the island mass effect [Doty and Oguri, 1956; Dandonneau and Charpy, 1985; Signorini *et al.*, 1999; Palacios, 2002].

[4] The island mass effect results from several mechanisms: input of macro and micronutrients from island runoff [Dandonneau and Charpy, 1985; Perissinotto *et al.*, 2000], contributions from benthic processes [Signorini *et al.*, 1999], lee eddies formed by flow disturbance or by Ekman

pumping [Heywood *et al.*, 1990; Coutis and Middleton, 1999; Barton *et al.*, 2000; Palacios, 2002; Signorini *et al.*, 1999].

[5] In the Marquesas, Dandonneau and Charpy [1985] and Signorini *et al.* [1999] reported a poor micronutrient - iron depleted - environment but a rich macronutrient environment [Levitus *et al.*, 1993], since a nitrate concentration of 2 μM is observed, a value too high to significantly limit growth rates. According to these authors, the micronutrients necessary for the enhancement of the local biomass are supplied by land drainage [Dandonneau and Charpy, 1985; Signorini *et al.*, 1999] and hydrothermal fluxes through old volcanic formations [Rougerie *et al.*, 1992; Signorini *et al.*, 1999]. A phytoplankton bloom then occurs when the micronutrients are mixed and dispersed westward following the interaction between the South Equatorial Current (SEC) (as deduced from geostrophy) and the topography. Signorini *et al.* [1999] suggest that strong and persistent westward flowing SEC is the major factor in dispersing iron enriched waters from the Marquesas downstream into the surrounding ocean. They base their results on one phytoplankton bloom which occurred during the period August–December 1998.

[6] In this paper, we revisit the bloom studied by Signorini *et al.* [1999], examine the time dependence of SeaWiFS chlorophyll in the Marquesas over 4.6 years, and attempt to verify the above hypothesis. In order to attempt to explain the origin of the blooms, simultaneous surface anomaly, wind field, sea surface temperature and rain data are used.

2. Data and Method

[7] We use satellite data from September 1997 to February 2002 around the Marquesas Islands. Weekly chlorophyll *a* concentration [Chl *a*] derived from ocean color data available on a 0.1° grid were produced by the SeaWiFS Project and distributed as a Level-3 Standard Mapped Image product. The Sea Surface Anomaly (SSA) data are on a 1/3° grid every 7 days provided as the AVISO-CLS TOPEX/POSEIDON (TP) and ERS-1/2 combined product [Ducret *et al.*, 2000]. SSA with the Levitus mean climatological dynamic height (S. Levitus, G. I. Monterey, and T. Boyer, Seasonal variability of dynamic height and its Fourier analysis, available at <http://www.nodc.noaa.gov/OC5/dyn.html>) referred to 1000 m depth are used to calculate the surface geostrophic currents (Figure 1a). The 1° gridded wind fields measured by the ERS scatterometers and provided by PODAAC (until January 2001) are used to estimate the surface Ekman velocity. Sea Surface Temperature (SST) provided by the NASA-NASDA TRMM Microwave Imager and available every day on a 0.25° grid are averaged to form a weekly map. Daily rainfall data available from twelve sites in the Marquesas islands

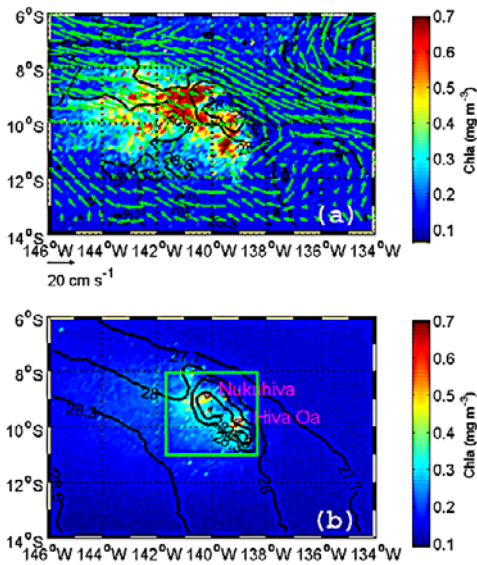


Figure 1. (a) Average Chl *a* (mg m^{-3}) for March 2000 observed by SeaWiFS. Corresponding geostrophic surface velocities derived from the combined T/P – ERS altimeter data and dynamic height climatology are superimposed. SST ($^{\circ}\text{C}$) contours are drawn in black. Islands are shown in gray. (b) Average Chl *a* (mg m^{-3}) over the 5 years of data observed by SeaWiFS. SST ($^{\circ}\text{C}$) contours are drawn in black. The green box delimits the region where data are spatially averaged.

provided by DIRPF-Meteo France are spatially and temporally averaged to correspond to the weekly satellite data. Rainfall is associated with land drainage. We do not have any river runoff data but it is well known that on islands maximum drainage occurs when it is raining and a strong correlation between land drainage and rainfall is assumed.

[8] Empirical orthogonal functions are calculated for the various data sets for the region 0° to 15°S and 130°W – 160°W . The results show large scale variations regarding the first three modes of SSA, SST and the wind field (zonal and meridian wind stress) while modes for [Chl *a*] show large variability centered on the Marquesas and around the Equator. The details of the EOF analysis are given by Martinez and Maamaatuaiahutapu [2003]. This analysis, along with the five year average [Chl *a*] map (Figure 1b) allows us to choose a restricted area around the Marquesas Islands ($[218^{\circ}\text{E}–222^{\circ}\text{E}]$ and $[8^{\circ}\text{S}–11^{\circ}\text{S}]$, box in Figure 1b) in which we further analyze the temporal variation of the various parameters. Spatial averages for each data set and correlations between them are calculated. These averages are then smoothed using a Gaussian window with a width of two months to show the seasonal variations.

3. Results and Discussion

[9] Figure 2 shows the variation of (from top to bottom) the [Chl *a*], sea surface temperature (SST), Geostrophic Surface Current (GSC), Total Surface Current (TSC) and precipitation for the period 1997–2002, spatially averaged over the region $8^{\circ}\text{S}–11^{\circ}\text{S}$ and $218^{\circ}–222^{\circ}\text{E}$. This period encompasses the 1997–1998 ENSO and La Niña events.

[10] Considering [Chl *a*], it is clear from Figure 2a that [Chl *a*] in the Marquesas is always higher than about 0.2 mg m^{-3} except during the El Niño event (end of 1997 to mid-1998) when the lowest value (0.07 mg m^{-3}) is measured. A seasonal bloom is observed every year during the second semester (peaks A, C, E, F). However, there is significant interannual variation in the cycle, to the extent that it is difficult to discern the actual seasonality. The seasonal peak value varies from year to year, the highest being about 0.37 mg m^{-3} in 2000 and the lowest being 0.25 mg m^{-3} in 2001. The seasonal bloom is a prominent feature for peaks A and E, and the peak A bloom is accentuated by the near absence of chlorophyll earlier in the year due to the strong

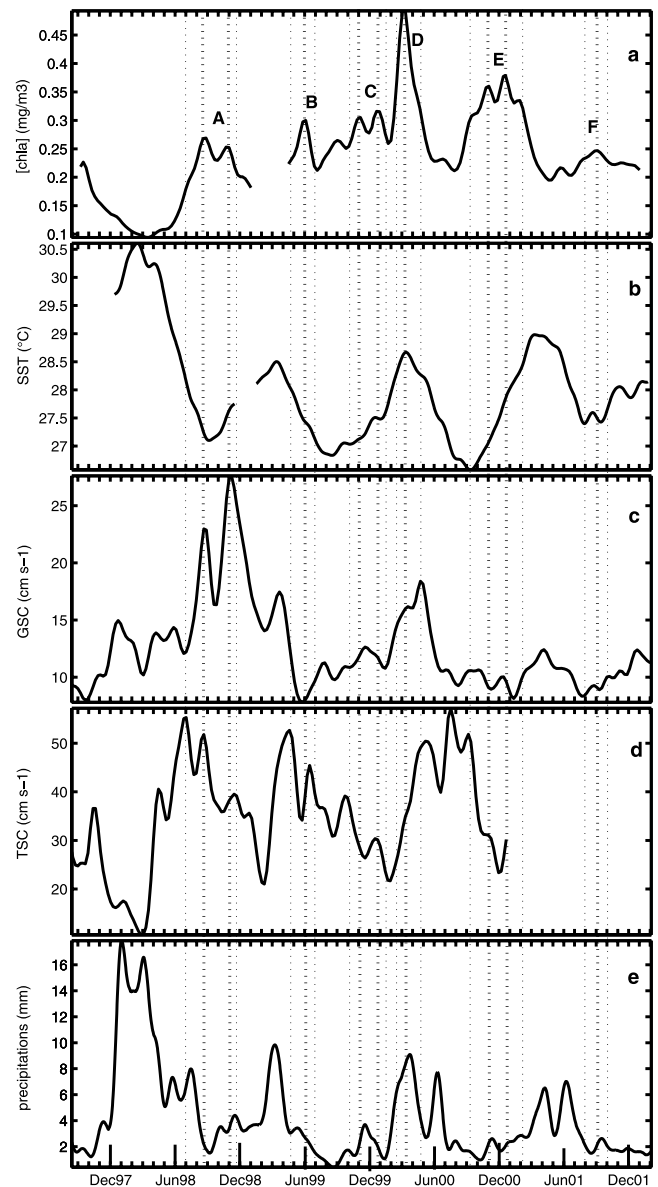


Figure 2. Time series of: (a) [Chl *a*]. (b) Sea Surface Temperature. (c) Magnitude of geostrophic surface velocities. (d) Magnitude of total surface current (geostrophic plus Ekman surface velocities). (e) Rainfall. Vertical dashed lines delimit the hypothetical start and end of the [Chl *a*] blooms. Vertical dotted and bold lines highlight peaks of [Chl *a*].

El Niño. *Signorini et al.* [1999] reported the existence of the bloom at peak A and discussed its possible origin. The F bloom in 2001 is also different from the other seasonal blooms in being very small, to the extent that it barely resembles a bloom. This virtual absence of a seasonal bloom in 2001 is probably due the background environmental conditions caused by the demise of La Niña, as can be seen by the warmer SST then, indicating a deeper thermocline and an associated reduction in upwelled nitrate. In addition to the seasonal [Chl a] peaks A, C, E and F, there are two exceptional blooms (peaks B and D) which do not appear to result from a seasonal process. Peak B occurs in June 1999 and peak D in March 2000. The [Chl a] value at peak D is the highest (0.5 mg m^{-3}) of the ~ 4.5 year period studied. The duration of blooms B and D is less than two months, which is shorter than that of the seasonal blooms (Figure 2a). The lack of data in January to March 1999 is due to cloud coverage in January and February and in March seems to result from technical problems given its regular geometric extent on the map.

[11] The seasonal trend is evident in the SST data (Figure 2b). Minima of SST are observed around October every year, and maxima in March. It is clear, except for [Chl a] peaks B and D, that high (low) SST is associated with low (high) [Chl a]. In other words, the colder the water, the higher the values of [Chl a]. The correlation coefficient for SST and [Chl a] is -0.7 . The seasonal trend is mostly due to the seasonal heating and cooling that affect SST. However, advection and/or local upwelling could influence the seasonal heating or cooling. The SST maximum (30.5°C) during the 1998 El Niño (March) is associated with the [Chl a] minimum as indicated earlier. Peaks B and D are not associated with the seasonal trend and occur respectively few months before the SST minimum and at the SST maximum. It is interesting to note from Figure 1a that peak D is associated with warm water, which argues against upwelling as a mechanism (we might expect cold water where upwelling occurs).

[12] Chlorophyll *a* blooms in the Marquesas islands have been associated with the island mass effect by *Signorini et al.* [1999]. These authors suggest that blooms are rather coherent with strong flow events past the islands since they found a high correlation (correlation coefficient $r = 0.83$) between geostrophic surface currents (GSC) derived from T/P altimeter data and [Chl a] for the period January–November 1998 corresponding to [Chl a] peak A in Figure 2a. In Figure 2c, we plot the magnitude of the surface geostrophic velocity for the period 1997–2002. Even though we perform our calculation on a smaller area, we do reproduce a strong correlation ($r = 0.71$) between GSC and [Chl a] for the period January–November 1998. According to *Signorini et al.*'s [1999] hypothesis, we should expect high correlations for all the peaks. Figure 2c shows that this is not the case ($r = -0.03$). Peaks in GSC are only found around peaks A and D, where GSC reaches 28 cm s^{-1} and 18 cm s^{-1} , respectively. It is clear from Figure 2 that blooms corresponding to peaks B, C, E and F are not associated with strong GSC.

[13] As mentioned above, low SST possibly suggests a local upwelling process. The upwelling process is generally associated with Ekman currents [e.g., *Dorman and Palmer*, 1981]. Using ERS wind data we calculate the magnitude of the Ekman surface currents (ESC) and derive the total

surface currents (GSC plus ESC). The magnitude of the total surface currents (TSC) is plotted in Figure 2d. A clear seasonal trend is visible in Figure 2d (although only ~ 3.5 years of data are available), with maxima around August. Overall, the TSC has a magnitude greater than 20 cm s^{-1} , showing that most of the time the Marquesas Islands are exposed to currents strong enough to generate turbulence and maintain a non negligible signal in phytoplankton as detected by SeaWiFS. Only during an El Niño event does the TSC become weak (10 cm s^{-1} around March 1998). The weakest TSC is coincident with the lowest values of [Chl a]. The maximum of TSC, observed one or two months prior to each peak of [Chl a] (except for peak D), corresponds to the start of the increase of [Chl a]. For peaks A, C and E, there is a double peak of [Chl a]. The second peak seems to be associated with an increase of TSC. Figure 2d shows a better correlation ($r = 0.3$) between TSC and [Chl a] than GSC and [Chl a]. The hypothesis of interaction of the South Equatorial Current and the chain of islands of the Marquesas as proposed by *Signorini et al.* [1999] seems acceptable if the ESC is considered. At any time, [Chl a] is detected around the Marquesas islands except when the magnitude of TSC is below 20 cm s^{-1} . Consequently, we assume that the mechanism at the origin of the bloom is the result of the interaction between the chain of islands and the mean flow but we are unable to distinguish between a wind driven upwelling process, like the ESC seems to suggest, and mixing due to friction. Further studies are needed to elucidate the relevant process(es).

[14] As mentioned previously the limiting factors in the Marquesas [Chl a] bloom is the availability of macronutrients from land drainage and hydrothermal fluxes. We can indirectly check the input of micronutrients to the area by land drainage by looking at the rainfall data. River drainage is generally negligible since the water has already washed the river bed while rain brings more sediments to the sea directly or to the river to be carried to the sea. We expect a high correlation between rainfall and sediment input, since around islands sediment is visible in the sea after one day of continuous rain. Figure 2e shows the time variation of the rainfall on the Marquesas islands. The seasonal trend is clear, with the rainfall peaks coincident with high SST around March (Figure 2b). Since macronutrients are not limited, we might expect an increase in [Chl a] every time it rains. Our results show that it is not the case except around March 2000 (peak D). This high peak seems to be explained by a large input of sediment but, surprisingly, this is the only one. Another explanation is that SeaWiFS, rather than measuring [Chl a], is detecting colored dissolved organic matter [*Siegel et al.*, 2002] which could be maintained at the surface by turbulent mixing (Y. Dandonneau, personal communication, 2004). In particular, heavy rain is observed from January to June 1998 but the smallest values of [Chl a] are found. However, during that period we expect the nitrate concentration to decrease because of the depression of the thermocline due to El Niño and the small values of the TSC (Figure 2d).

4. Conclusion

[15] We have investigated phytoplankton blooms in the Marquesas Islands over the period of SeaWiFS activity

September 1997 to February 2002. Simultaneous SST, geostrophic surface current, Ekman surface current and rainfall data were analyzed. Clearly, there are three types of blooms in this area: seasonal blooms (A,C,E and F), episodic ones (B and D), and La Niña related bloom (A, recovery from El Niño) with the latter occurring during the time period of the seasonal bloom. Normally, there are sufficient macronutrients except during El Niño. Micro-nutrients are available from the islands and are dispersed downstream by currents. Two blooms (A and D) are explained by the interaction of the geostrophic current with the chain of the Marquesas islands resulting in turbulent mixing and advection as reported by Signorini *et al.* [1999]. The total surface current (geostrophic plus Ekman drift) seems to explain the other blooms with blooms occurring one or two months after a TSC maximum.

[16] **Acknowledgments.** Comments by Y. Dandonneau and H. Todd were greatly appreciated. The authors would like to thank Joel Sudre from the LEGOS, for helping us with the SeaWiFS and the TMI data, Victoire Laurent from the Met Office (DIRPF-Météo France) and the PODAAC at NASA JPL for provision of altimeter and scatterometer data. E.M. is supported by a grant from the government of French Polynesia.

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