Journal of Coastal Research	16	3	776–781	West Palm Beach, Florida	Summer 2000

Wave-induced Flow over Mururoa Atoll Reef

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ABSTRACT

TARTINVILLE, B., 2000. Wave-induced flow over Mururoa atoll reef. *Journal of Coastal Research,* 16(3), 776–781. West Palm Beach (Florida), ISSN 0749-0208.

A unique long-term timeseries of current over Mururoa atoll reef is presented here. Comparison with TOPEX/POSEIDON satellite altimeter data reveals that the daily-averaged cross-reef current is wave-driven and varies at the synoptic time scale. This current also exhibits variations at or near the tidal frequency. In order to understand this evolution, a previously published analytical model of the wave-induced flow over a reef flat is used (Symonds *et al.,* 1995). Forced by the altimeter data and the tide, it gives results which agree well with field data. It appears that the model is able to reproduce the observed long-term variations of the inward current and also its variations at tidal frequency. Furthermore, the model gives an explanation of the observed six-hour period signal. It reveals that the response of the cross-reef current to the tidal forcing highly depends on the reef geometry and particularly on the water depth over the reef flat. This confirms that the response of the current over a reef flat at or near the tidal frequency is site-specific.

ADDITIONAL INDEX WORDS: *Coral reef, wave, hydrodynamic, satellite altimeter data, wave set-up.*

INTRODUCTION

Barrier reefs and atolls are carbonate structures found in the tropical regions. Their summit is located near the sea surface and they form an abrupt barrier which separates the deep open ocean from an almost enclosed and shallow coastal sea or lagoon. Oceanic waves could break over the reef, losing a large part of their energy and producing a water flux directed from the deep ocean towards the shallow region. This oceanic water flux is an important process driving the circulation in the backreef. An excess filling of a semi or totally enclosed lagoon could produce a transient reverse current over the reef. Such an exceptional reverse flow is beyond the scope of the present study.

Since the inward flow due to wave breaking could transport substances from the ocean into a lagoon, it may have some importance for the organic and inorganic matters budget of the coral reef ecosystem. As suggested by Rougerie *et al.* (1992) and Wolanski and Delesalle (1995), this inflow could produce a significant nutrient enrichment and could be an element to the solution to the reef nutrient paradox. According to Atkinson (1992) there is no nutrient paradox and phosphate uptake is greatly enhanced by the water velocity over the reef flat. This inflow has also an impact on the recruitment of fish larvae for a totally enclosed atoll lagoon (Leis *et al.,* 1998). Due to wave breaking, this oceanic water is supersaturated with oxygen. The presence of large dissolved oxygen concentration has an impact on phytoplanktonic species encountered in the immediate backreef (Michel, 1969). Furthermore, providing a new entrance to an atoll lagoon, this additional oceanic water entry has an impact on its turnover time (Wolanski *et al.,* 1994; Tartinville *et al.,* 1997). Therefore, it seems interesting to understand the physical processes driving this flux in order to evaluate its implications for the coral reef ecosystem (Hatcher 1997).

The spectral window of those processes is very large. Their temporal scale varies from seconds to several days or weeks. The flow over the reef changes at the period of the incident waves, the tidal period and the period of atmospheric synoptic disturbances. Most of the waves energy is contained in the high-frequencies, from 0.05 to 1. Hz. At this time scale, the inflow is driven by the periodic breaking of the oceanic surface waves. Roberts and Suhayada (1983) have shown that the flow over Cana Reef (Nicaragua) varies at the frequency of the incident waves. The tide has an impact on the position of the sea surface relative to the summit of the coral reef. Thus it should influence the inflow at the tidal periods. However, it seems that the response of the inflow to this forcing is site-specific. According to Munk and Sargent (1954), there is no relation between the tide height and the flow over the reef at Bikini atoll, whereas Roberts and Suhayada (1983) have found that the flow over Cana Reef depends on the tide. It is maximum at low tide and minimum at high tide. The energy spectrum of the cross-reef current over John

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98232 received 30 September 1998; accepted in revision 29 August 1999.

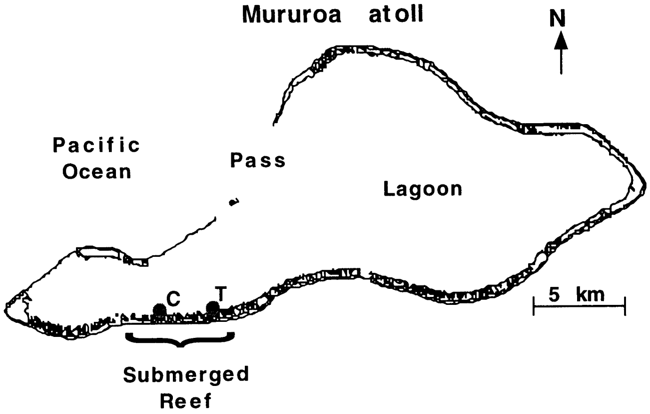

Figure 1. Map of Mururoa atoll. The letters C and T indicate the location of the current meter and the tidal gauge, respectively.

Brewer Reef (Great Barrier Reef) exhibits a significant peak at twice the semi-diurnal tidal frequency (SYMONDS *et al.*, 1995). Waves are created by the wind stress at the sea surface. Their significant wave height increases with the wind duration and the fetch. Therefore, the inflow also varies at low-frequencies, the periods of which are close to the periods of the atmospheric synoptic disturbances—from three to twenty days (WALLACE and CHANG, 1969). SYMONDS *et al.* (1995) have illustrated a correlation between the cross-reef current over John Brewer Reef and the offshore wave height which is forced by those synoptic disturbances.

Whereas the response of the flow over the reef at high and low-frequencies seems to be clearly established, the impact of the tide is more confused. Therefore, a detailed study of the variations of the inflow at or near the tidal frequency should be carried out. To do so, ROBERTS and SUHAYADA (1983) proposed to conduct various field studies on many reefs with different geometry. Such an amount of data is not available yet and will certainly not encompass all the aspects of the physical processes involved in this inflow. Here, we propose to use a somewhat different and more pragmatic approach based on the use of a mathematical model in order to simulate this inflow. The model, initially presented by SYMONDS *et al.* (1995), depends on parameters which are directly related to the reef geometry. It has first successfully been applied to John Brewer Reef. In order to verify this model for a different geometry, it is now applied to the south-western reef of Mururoa atoll where currents have been measured for about two months.

The long-term timeseries of current measured over the reef at Mururoa atoll is presented in the next section. Since direct measurements of the wave height in the vicinity of this atoll are not available for the same period, this timeseries will be compared to the significant wave height (SWH) derived from the TOPEX/POSEIDON satellite measurements. The mathematical model of the cross-reef current, similar to that presented in SYMONDS *et al.* (1995) and forced by the CNES/NASA TOPEX/POSEIDON data and the tide, is described in the next section. Its results will be compared to observed currents and it will provide an explanation to the observed variations of the inflow at or near the tidal period and at lower frequencies.

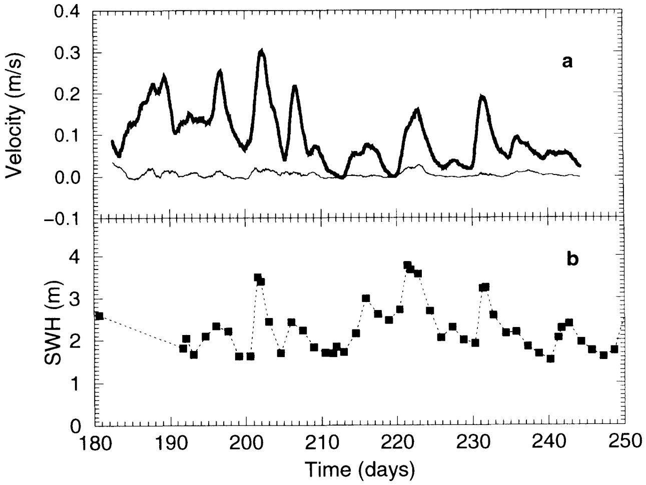

Figure 2. (a) Daily running averaged cross-reef (bold line) and along-reef (normal line) currents measured at C; (b) significant wave height measured in the vicinity of Mururoa atoll by the TOPEX/POSEIDON altimeter.

DATA ANALYSIS

Current Over the Reef

Mururoa atoll (French Polynesia) is located in the tropical Pacific Ocean. It has been one of the French nuclear test sites from 1966 until 1996. The atoll rim separates the open ocean from a 30 m-deep semi-enclosed atoll lagoon which is continuously connected with the surrounding ocean through a shallow pass (Figure 1). Occasionally, waves coming from the south could break over the approximately 100 m-wide reef flat and induce a significant inflow in the southern region of the atoll rim. This oceanic water, flushing over the reef, is transported towards the lagoon through reef flat spillways (also called hoa) (BATTISTINI *et al.*, 1975). In the south-western part of the atoll rim, because of the mechanical compression due to the past underground nuclear tests, the reef is totally submerged and the top of the reef flat lies about 60 cm below the sea surface (BOUCHEZ and LECOMTE, 1995).

In order to investigate the variations of the inflow over the submerged reef flat at different time scales, a SUBER rotor current meter has been installed from July to September 1995, inside a hoa, at C, near the southern inner reef slope. Current is measured 50 cm above the bottom every 15 min, averaged over 1 min (current is measured 100 times during this minute). Its detection limit is of 2.10^{-2} m.s^{-1}. During the same period, a tide gauge was moored in the lagoon, at T, close to the current meter. Sea surface elevation derives from pressure data recorded every 30 min.

Figure 2(a) represents the variations of the daily running averaged cross-reef and along-reef currents measured at C (reference date is the first of January 1995). Cross-reef current is an order of magnitude greater than its along-reef component. The daily-averaged flow is always inward and almost

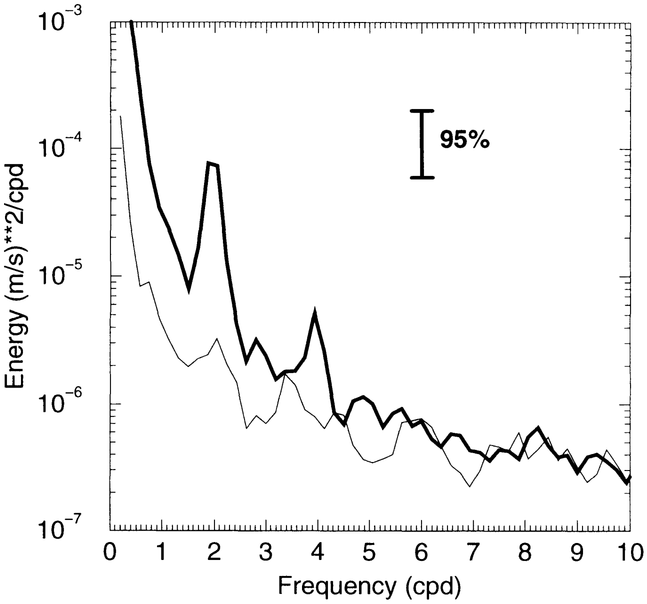

Figure 3. Power spectrum of the cross-reef (bold line) and along-reef (normal line) currents measured at C.

perpendicular to the reef flat. It varies at synoptic time scale with an approximate period of five days and a peak velocity of about 0.3 m.s^{-1}. This confirms that the flow over the reef is highly variable in time. Further measurements have also shown a significant spatial variability that should be due to the local variations on the reef geometry.

The sea surface elevation measured at T shows that M2 (principal lunar) is the major tidal constituent. Its period is 12.4 hours and its amplitude about 0.3 m. Figure 3 displays the power spectrums of the unfiltered cross-reef and along-reef currents. The 95% confidence interval is also displayed on this figure. The cross-reef current exhibits an important semi-diurnal signal related to the M2 tide. In order to illustrate the semi-diurnal variation of the inflow, Figure 4 depicts the unfiltered cross-reef current measured at point C from day 235 to day 239. It appears that the cross-reef current varies with the tide. The current is maximum at low tide, when the water depth over the reef flat is minimum, and it is minimum at high tide, when the water depth over the reef flat is maximum. This is similar to previous observations made by ROBERTS and SUHAYADA (1983) over Cana Reef. This result could be somewhat surprising, however it will be explained in the next discussion. Cross-reef current also exhibits a peak at twice the tidal frequency (4 cpd). A similar peak has been observed over John Brewer Reef (SYMONDS *et al.,* 1995). Since the sea surface record does not produce a similar peak, it seems to be due to an interaction between the tidal elevation and the oceanic wave height. The frequency spectrum of the along-reef current does not exhibit any significant peak at 2 and 4 cpd.

Variations of the inflow at higher frequencies have not been studied as yet, but visual observations reveal that the inflow is highly modulated by the period of the swell, *i.e.* between 6 and 9 s.

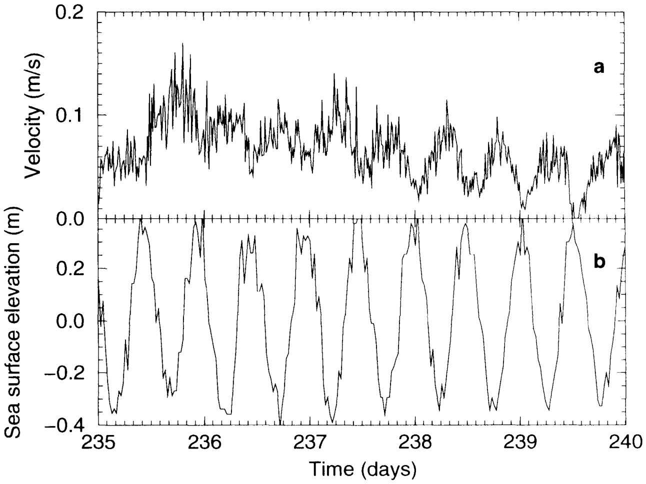

Figure 4. (a) Cross-reef current and (b) sea surface elevation measured at C and T, respectively.

Satellite Significant Wave Height

In situ wave data are not available in the vicinity of Mururoa atoll during the period of the experiment. Therefore, in order to investigate the variations of the inflow at the synoptic time scale, the SWH measured by the TOPEX/POSEIDON satellite is used. Since 1992, its three altimeters routinely measure the SWH (FU *et al.,* 1994) which is defined as four time the standard deviation of the sea surface elevation (CHELTON *et al.,* 1989). Only results from the TOPEX Ku band (13.65 GHz) are considered here. Those measurements have been successfully compared with buoy data (COTTON and CARTER, 1994; GOWER, 1996) and are highly accurate—the rms error is estimated at about 0.03 m for wave height of 2 m. Data used in the present study are extracted from the wind/wave product distributed by CLS (Collecte Localisation Satellites, France). Selection rules similar to those proposed by COTTON and CARTER (1994) are applied in order to suppress bad SWH or values contaminated by land or heavy rain. Furthermore, in order to avoid a slight underestimation at high SWH and an overestimation at low SWH, TOPEX data are corrected according to relation (4) of COTTON and CARTER (1994).

The orbit of the satellite, which has a 10-day repeat period, is made of a series of ascending and descending paths which are separated by approximately 316 km at the Equator. The minimum distance between Mururoa atoll and the satellite track is 86 km (path number 195). Only selecting the SWH at this closest point will produce single data every 10 days. This is more than the observed period of the variations of the flow over the reef. Therefore, it is necessary to find a method in order to select data close enough to the atoll but with a sufficiently small time step. This is made by averaging the SWH over a 500 km radius circular domain centred on Mururoa atoll. This length scale is of the order of the atmospheric synoptic disturbances. Only paths number 006, 017, 082, 119, 158, 195 are relevant. The averaging procedure is used for each path. This method computes approximately one data every 1.3 days. By increasing the radius of the domain, the averaged SWH will be less relevant to the situation around Mururoa atoll and the decrease of the time step will not be significant. As an example, the time step is 0.8 day for a 1,000 km radius domain. Therefore, it is assumed that a 500 km radius is an adequate compromise between time stepping and accuracy.

It is further assumed that oceanic waves are created by high latitude low pressures and are directed towards the north. This is confirmed by wave monthly mean data archives provided by the European Centre for Medium-Range Weather Forecasts (United Kingdom). Those northward waves have an impact on the flow over the south-western reef of Mururoa atoll.

The measured SWH (Figure 2(b)) displays low-frequency variations at a synoptic time scale corresponding to the variations of the daily averaged cross-reef current. Maximum velocities, at days 202, 222 and 231, are related to measured peak SWH. On the other hand, during period of small SWH, from day 208 to day 213 for example, the cross-reef current is weak. Probably due to the scarcity of SWH data and to the averaging procedure, cross-reef current exhibits peaks at days 189, 196 and 207 which do not appear on the SWH record. In spite of these shortcomings, the correlation coefficient between those two data set is 0.53. This tends to confirm that the daily averaged cross-reef current over Mururoa atoll reef is linearly related to the offshore SWH.

MODEL

If the daily averaged cross-reef current seems to be clearly related to the incident wave height, and therefore varies at the period of the atmospheric synoptic disturbances, it is more difficult to explain the observed variations of this current at semi or fourth-diurnal frequencies. SYMONDS *et al.* (1995) proposed a mathematical model of the inflow over a shallow reef. Those authors produced a physical explanation to the observed variations of the velocity over John Brewer Reef at semi and fourth-diurnal frequencies. However, no direct comparison of the measured and calculated velocities at this time scale was depicted in their article. Here, it is proposed to test if their model could be applied to Mururoa atoll reef and to compare the observed and calculated variations of the inflow at or near the tidal frequency.

The model of SYMONDS *et al.* (1995) is derived from the balance between the pressure gradient, a linear bottom friction and the gradient of the radiation stress due to wave action. Wave breaking induces a set-up at the seaward edge of the reef flat which drives the cross-reef current (see LONGUET-HIGGINS and STEWART (1962) for a theoretical approach). For a schematic reef (Figure 5), it provides a simple analytical formulation to the velocity over the reef flat. Assuming that the cross-reef velocity at point C, u, is proportional to the latter, this velocity may be written:

$$u = \frac{KH}{H + D}(h_b - H) \quad \text{if } H < h_b \tag{1a}$$

$$u = 0 \quad \text{if } H \geq h_b, \tag{1b}$$

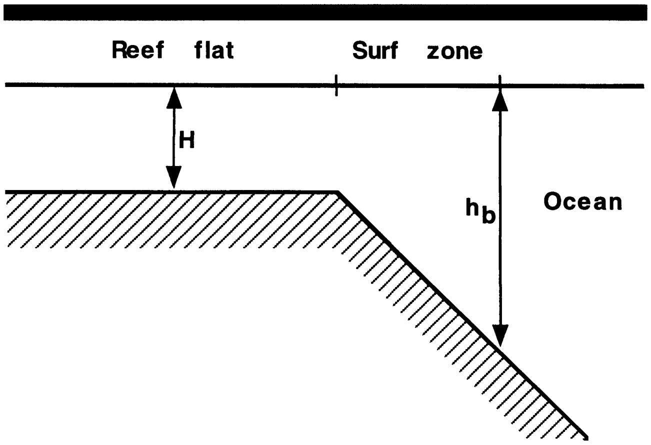

Figure 5. Schematic reef as proposed by SYMONDS *et al.* (1995).

where H is the water depth over the reef flat, h_b denotes the total water depth at the break point, K and D are parameters related the reef geometry. Relation (1b) denotes that if H is greater than h_b then the incident waves are not breaking and the cross-reef current is null. Assuming that D is much greater than H (which is an acceptable assumption since D is of the order of the width of the reef flat), equations (1a) and (1b) become:

$$u = \beta H(h_b - H) \quad \text{if } H < h_b \tag{2a}$$

$$u = 0 \quad \text{if } H \geq h_b, \tag{2b}$$

where $\beta = K/D$. Relation (2a) gives a very simple linear relation between the cross-reef current and the total water depth at the break point. It should be noted that u varies as a quadratic function of H. As suggested by numerous authors (BOWEN *et al.*, 1968; TAIT, 1972; GUZA and THORNTON, 1981; HARDY and YOUNG, 1996), h_b is proportional to the incident wave height. Therefore, h_b is calculated according to:

$$h_b = \frac{SWH}{\gamma}, \tag{3}$$

where $\gamma = 0.35$ (SYMONDS *et al.*, 1995).

The total water depth over the reef flat is a function of the average water depth, $H_0 = 0.6$ m, and of the tidal elevation. For the purpose of the model, oceanic tidal elevation is computed thanks to the eight major tidal constituents at Mururoa provided by the Service Hydrographique et Océanographique de la Marine (France). The computed sea surface elevation is similar to the one measured at T but less noisy and more relevant to the offshore tidal height. Therefore, it is advocated that the former should be used in order to calculate H. SWH is calculated from TOPEX data at the same temporal resolution as the current by means of a natural cubic spline interpolation procedure. Since β depends on the geometry of the reef—*i.e.* the outer reef slope, the width of the reef flat and the friction coefficient over the reef flat—this parameter is very difficult to evaluate. For our purpose and in order to give a best fit between model and data, it is set to 0.5.

Because of the low temporal resolution of altimeter data,

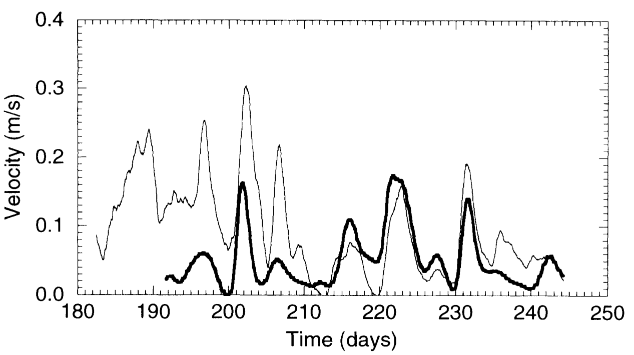

Figure 6. Daily averaged measured (normal line) and calculated (bold line) cross-reef currents.

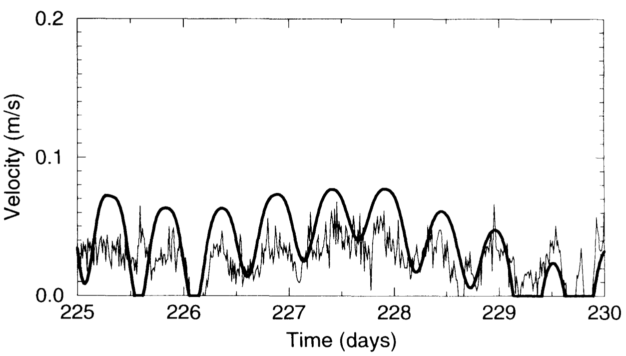

Figure 7. Comparison of measured (normal line) and calculated (bold line) cross-reef currents from day 225 to day 229.

the model is not integrated before day 191. Comparison of the daily averaged computed and measured cross-reef currents reveals that the model is able to reproduce long term variations of the inflow (Figure 6). However, several external parameters could affect the ability of the model to reproduce the observed inflow. Those are the scarcity of wave data, their relevance, the averaging procedure, the direction of the incident waves relative to the reef flat, the presence of coastal trapped waves, and the wind forcing. Nevertheless, results are close to observations from day 210 to day 245. For this time period the correlation coefficient between the two sets is 0.73.

Since the water depth over the reef flat is a function of the tidal elevation, the model is able to reproduce the semi-diurnal signal. It is useless to compare the short-term variations of the current if the long-term current is not well reproduced. Therefore, direct comparison between model results and data is depicted only during a time period for which the model produces results similar to the daily averaged cross-reef current. This is the case from day 225 to day 229 (Figure 7). It appears that the model results are very close to the observed semi-diurnal variations of the current. The calculated amplitude of the signal is similar to the observed one, *i.e.* about 3 $cm.s^{-1}$. The model also reproduces periods without any current as at the beginning of day 226. It has to be noted that the direct comparison leads to very poor results before day 210, *i.e.* when model and wave data are unable to accurately reproduce the observed daily averaged cross-reef current.

DISCUSSION

Model and data do not represent the variations of the inflow at the frequency of the incident waves breaking. Therefore, the discussion only deals with longer time scales.

Most of the incident wave energy is dissipated during breaking. However it induces a sea surface set-up at the seaward edge of the reef flat. According to the model of SYMONDS *et al.* (1995) this rise in sea level creates a horizontal pressure gradient across the reef flat which drives the cross-reef current. On the one hand, if H is much smaller than h_b, the set-up is close to its maximum and slightly depends on H. Therefore, the cross-reef current increases with the water depth over the reef flat. As H tends towards zero the solution converges to the plane beach solution and the velocity across the reef flat becomes null. On the other hand, if H becomes of the order of h_b, the set-up decreases as H increases. The cross-reef current remains proportional to the product of the set-up and the water depth over the reef flat. As H becomes greater than a critical value, $h_b/2$, the cross-reef current decreases as H increases. As h_b becomes smaller than H, no more waves break over the reef flat and the cross-reef current is again null. Therefore, the cross-reef current could be in phase with the tide or with a phase lag of π radian. The phase lag depends mainly on the water depth over the reef flat and is site-specific. This could explain the observed discrepancies in the response of the cross-reef current to the tidal forcing. For a very shallow reef flat the cross-reef current is in phase with the tide whereas, for a deeper reef flat, the cross-reef current is maximum at low tide and minimum at high tide (Figure 4).

Since H varies with the tide, it could reach the critical value $h_b/2$ twice during the tidal period. Therefore, the cross-reef current is maximum during flood and ebb and is minimum at low and high tides. It induces a variation of the cross-reef current at twice the tidal frequency as observed at Mururoa (Figure 3).

As phosphate uptake into a coral reef flat community is related to the cross-reef velocity and as that relation is not linear (ATKINSON, 1992), the variations of this velocity caused by the tide could have an impact on the total daily nutrient uptake and therefore on the productivity of the reef flat. Coupling the P-uptake model of ATKINSON (1992) with the model presented in SYMONDS *et al.* (1995) is beyond the scope of the present study.

For the purpose of our discussion it has been previously assumed that h_b is a constant. If we suppose now that the SWH could vary with time, it appears that, for an important SWH, the cross-reef current increases with the sea level. Conversely, for a smaller value of the SWH, the cross-reef current increases as the sea level decreases. Furthermore, if $h_b/2$ lies between the maximum and minimum water depths over the reef flat, the cross-reef current varies at twice the tidal frequency.

Insofar as the cross-reef transport is the product of the cross-reef velocity and the water depth over the reef flat, it also depends on the tide. Its variations are similar to those of the current but the critical water depth, for which the transport is maximum, is equal to $2h_b/3$. Since it transports substances from the deep ocean towards a shallow lagoon, its variations have an impact on the flow of materials. The maximum import depends not only on the wave height and the water depth but also on the tide.

From current measurements it appears that the velocity over the reef flat is related to the offshore incident wave height. Therefore, it varies at the period of the atmospheric synoptic disturbances. It is more than likely that the inflow has also a seasonal variability. But a longer timeseries is needed in order to verify this assertion.

CONCLUSION

This article deals with the response of the current over Mururoa atoll reef flat to the wave and the tidal forcing. From field observations, it appears that the flow is predominantly inward, perpendicular to the reef and that the incident wave is the major forcing driving the cross-reef current. In spite of the scarcity of TOPEX/POSEIDON altimeter data, a clear linear relation is established between the SWH and the daily averaged cross-reef current. Variations of the current at tidal and twice the tidal frequencies are superimposed on this long-term pattern.

A mathematical model of this inflow was proposed by Symonds *et al.* (1995). It reproduces the observed response of the current to the tidal forcing. This response is highly variable and depends on the reef geometry. Furthermore, the model is able to explain the observed variations of the current at twice the tidal frequency.

Those encouraging results have shown that it is possible to use satellite altimeter data for local studies, even with low spatial and temporal resolutions. Furthermore, since the model has been tested on two different reef sites, it provides an extra verification to the mathematical model of Symonds *et al.* (1995). This model seems to encompass the major physical processes driving the flow over a submerged reef. An additional verification should be carried out for a shallower reef flat.

However, this is a first step towards a more complex approach of the cross-reef transport problem. Since this inflow could play a significant role for the reef ecosystem, it is advocated that a more detailed field study, including long-term timeseries from numerous current meters, wave rider buoys and biological measurements, should be carried out in the near future.

ACKNOWLEDGEMENTS

The authors would like to thank CLS for providing CNES/NASA TOPEX/POSEIDON altimeter data. E. Deleersnijder, S. Andréfouët, and H. Goosse are also acknowledged for their helpful comments on this manuscript.

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