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Impact of cross-reef fluxes on the Ouano lagoon circulation.

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Abstract. In meso-tidal lagoons the coral reef barrier can be temporarily covered by water at high tide and emerged at low tide, inducing particular cross-reef dynamics. In order to understand the importance of cross-reef fluxes on lagoon dynamics a field survey had been conducted on Ouano Lagoon (New Caledonia). The lagoon water dynamics were analyzed and compared to a numerical model output. The main current was found to be northward during the flood, with inward flows through the ocean passes and through the south passage and outward flows through the north passage. During the ebb, currents are usually reversed. Concerning tidally averaged fluxes, they are mainly inward at the ocean passes and southward in passages.
Finally, numerical tests were performed to evaluate the impact of cross-reef fluxes on this circulation. The results of this study are, then, discussed.

Key words: tidal reef-lagoon; coral reef barrier; cross-reef fluxes; New Caledonia Lagoon.

Introduction

Water quality in tropical lagoons depends on water renewal time, which is regulated essentially by fluxes through passages and over the coral reef barriers (Pages and Andrefouet 2001; Andrefouet et al. 2001). The slightly or strongly submerged character of the reef barriers can reduce or enhance these ocean-lagoon hydrodynamic fluxes. In addition, reef structures surrounding tropical lagoons are particularly sensitive to the quality of the marine waters that bathe them. It appears therefore necessary to fully understand the hydrodynamic regulations exerted by these reef barriers in order to forecast the influence of climate change or anthropogenic activities on the lagoon resilience.

A number of studies have addressed specific hydrodynamics in the vicinity of reef barriers. Some authors have studied enriched upwelling generated along them (Leichter and Miller 1999, Henin and Cresswel 2005) while others have analysed wave driven flows over coral reefs, as reviewed by Monismith (2007). Some studies have also tried to evaluate the cross-reef fluxes induced by breaking waves above the reef flat (Kench 1998; Hearn 1999; Bonneton et al. 2007, Taeby et al., 2011) and the influence of these fluxes versus through-passage fluxes in micro-tidal lagoons (Atkinson, 1981, Lowe et al, 2009). Despite these studies, few have tried to evaluate the respective roles of through-passage versus cross-reef fluxes in coral reef lagoons. Studies addressing water exchanges between meso-tidal lagoons and the open sea often focus on fluxes through reef passages only, as described by Douillet (1998) and Douillet et al. (2001) for the Noumea lagoon in New Caledonia. Indeed, the ratio between passage size and reef-barrier length in large lagoons such as Noumea's induces primarily through-passage tidal exchanges with the ocean. The cross-reef fluxes are mainly attributable to swell breaking over the reef (Bonneton et al., 2007) and can modify inside lagoon current dynamics in their vicinity only. For some smaller meso-tidal lagoons with great reef-barrier length compared to the length of passages, vertical section cross passage can be similar to the one above the reef flat when it is submerged. Hence, at high tide, cross-reef fluxes can be, at least, as great as through-passage exchanges or even predominant (Angwenyi and Rydberg, 2005) in extreme cases such as when the lagoon is shallow with respect to the tide. Conversely, cross-reef fluxes become almost negligible at low tide when the reef barrier is slightly submerged or totally exposed.

Our aim is to determine the possible influence of cross-reef fluxes, in quite deep meso-tidal lagoons. We focus our study on the Ouano reef Lagoon, located in the southwest of New Caledonia Island. The current in passages has been acquired with ADCP at classical fixed moorings and our results allow us to develop a model of this lagoon. A detailed description of Ouano hydrodynamics functioning was obtained and tests were made on the impact of cross-reef fluxes on this circulation. Finally, we discuss the role of cross-reef fluxes on the lagoon circulation.

Material and Methods

Study site

The field observations were performed at the Ouano lagoon located at the north-west lagoon of New Caledonia. This lagoon, partially closed along the long reef, is approximately 30 km long, 10 km wide and 10 m deep. It is opened to the Pacific Ocean through two passes of about 1 km wide (Isie and Ouarai). Ouarai is the deeper with about 40m deep whereas Isie is only 10m deep. Furthermore, the lagoon is connected to northern and southern lagoons by two passages of 5 km wide. The north passage is the shallower (about 5m), the south passage being 10 m deep. At high water, the reef is submerged (2 m), whereas it is weakly immerged at low water. The incoming flow could be either of Pacific water (entering through the two passes and above the reef) or lagoon water from the lagoons situated at the south and north ends (entering through the south and north passages).

This lagoon is submitted to the semi-diurnal wave M2.

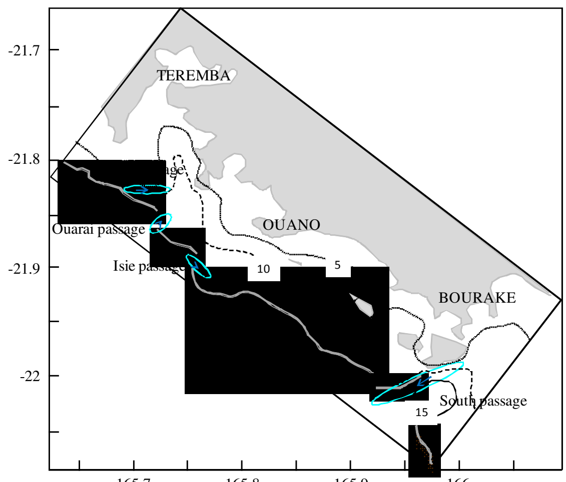

Figure 1: Ouano lagoon, its bathymetry. Scattered ellipse located on mooring position and mean current measured during the Ouano field campaign.

Sensor deployment

Our observations were performed from 2011, July 11th, to 2011, October 3th. Four moorings equipped with ADCP were deployed to gain insight into temporal variability of the velocity vertical profiles. The first is located in the Ouarai pass, the second in the Isie pass and the two latter in the north and south passages (Figure 1)

Model

The model employed is the Regional Oceanic Modeling System (ROMS) (Shchepetkin and McWilliams, 2005), a split-explicit, free-surface oceanic model discretized in coastline- and terrain-following curvilinear coordinates.

The horizontal mesh was 500 m and the 9 s-coordinate vertical levels are stretched toward the surface (Haidvogel and Beckmann, 1999). Bottom topography (h) is derived from SHOM data. To prevent the generation of pressure gradient errors, h is smoothed using a selective Shapiro filter in order to keep the topographic parameter (Haidvogel and Beckmann, 1999).

Tide is forced on boundaries by using the high resolution model developed by J. Lefevre.

Surface forcing is derived from the Comprehensive Ocean/Atmosphere Data Set (COADS) (Da Silva et al., 1994) monthly climatology. At the lateral boundaries, an active radiation condition connects the model solution to the surroundings (Marchesiello et al., 2001): in the case of inflow conditions, the solution is nudged toward data. World Ocean Atlas 2001 (WOA) (Conkright et al., 2002) mean-monthly climatology provides temperature and salinity. These data and COADS winds are combined to estimate geostrophic and Ekman velocity components for the boundaries. Model initialization is done by using WOA temperature and salinity and no flow.

The simulation was run for 3 months. Integrated properties show that after a spin-up of few days, the model has reached a statistical equilibrium (figure not shown). Results are then analyzed after this spin-up time.

To analyze the influence of the cross-reef fluxes on the lagoon circulation, three different reef parameterizations were developed. In the reference model, the reef is supposed to be an impervious wall. In the second one, the swell input due to the breaking waves on the reef is modelize by a water input along the reef. In the last model, the reef is immersed (1m) and let go through the tidal current.

Results

ADCP data

Tidal amplitude at moorings was approximately 0.8 m during the spring tide and 0.25 m during neap tides. The tide was mainly semi-diurnal with diurnal inequality. The sea level power spectrum estimated using a periodogram analysis (Bendat and Piersol 2000) confirms the prevalence of the semi-diurnal and diurnal tidal waves M2, S2 and K1 in the studied area. Tidal amplitude varied slightly inside the lagoon, and a weak phase lag of a few minutes appeared between stations (Table 1).

	M2		S2	
Mooring	Ampl	Phase	Ampl	Phase
North	38	270	16	302
Ouarai	40	269	16	302
Isie	41	269	18	304
South	39	268	17	300

Table 1: Main tidal waves of the water level variability: Amplitude (cm) and Phase (°).

The main current direction was mainly cross-passage in the north passage and followed isobaths in the Ouarai and Isie passes. This current reveals water exchanges with the studied lagoon and the ocean. Current measurements, also reveals a current mainly getting out of the bay through the south passage while the averaged current was mainly inward through the north passage. In Isie and Ouarai passes, the current was weak and rather in-flow. Therefore, the water of the Ouano lagoon seems to mainly come from the lagoon situated at the north of the studied one.

Data show an in- and out-flow oscillations linked to the tidal regime. Velocity was found to be relatively high at moorings in north and south passages, regularly up to 0.5 $m.s^{-1}$ and reaching 1 $m.s^{-1}$ in July due to a high residual current (around 0.5 $m.s^{-1}$). In Isie and Ouarai passes, this residual current is weaker and its measured velocity is regularly under 0.5 $m.s^{-1}$. Harmonic analysis (Foreman, 1978) of the velocity data confirms the predominance of the semi-diurnal tidal waves M2 and S2, and diurnal tidal waves O1 and K1 on the velocity signal. This analysis also reveals the presence of quarter-diurnal waves (M4, MS4) in the velocity signal. It is probably due to water exchanges across the reef as it occurs on Mayotte and Tulear Lagoons (2011).

The phase lag between the water level and the current ranges from 2 to 3 hours for the M2 wave in passages and in Isie pass. At the Ouarai pass, velocity and current are quite in phase (Table 2). Therefore, for the tidal wave M2, the water arrives during the flow, from the south passage and from the two passes but gets out from the north passage and reversely during the flow.

	M2		O1	
Mooring	Ampl	Phase	Ampl	Phase
North	105	344	39	42
Ouarai	45	75	8	227
Isie	83	197	37	260
South	413	155	34	212

Table 2: Main tidal waves of the velocity in the main direction Amplitude ($cm.s^{-1}$) and Phase (°). The velocity is positive when the current is getting out.

Model result

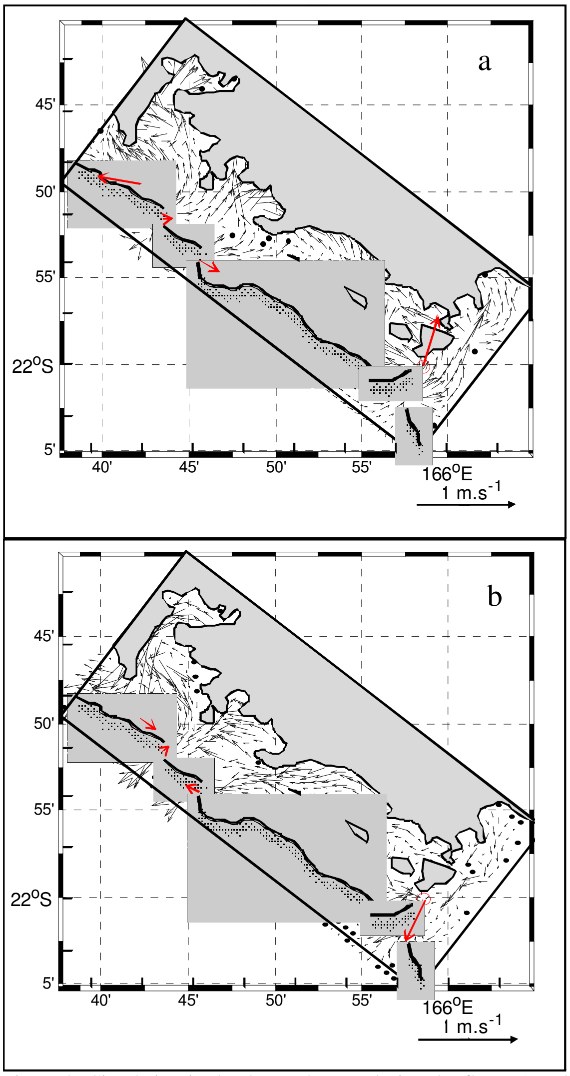

Figure 2: Circulation in the Ouano lagoon during the flow (a) and the ebb (b), on the 2012, July 16th. Reference model: the reef has been considered as an impervious wall. Red quivers correspond to measured velocities.

Despite its schematic characteristic, model qualitatively agrees with the field measurements. The general circulation dynamics seem to be well reproduced (figure 2). Amplitude and phase of the main tidal waves of the water level and the velocity are in the same order that those measured (for instance, see plots on figure 3). However, in this configuration, the variability of north passage residual current is not reproduced, notably due to the monthly-averaged climatology.

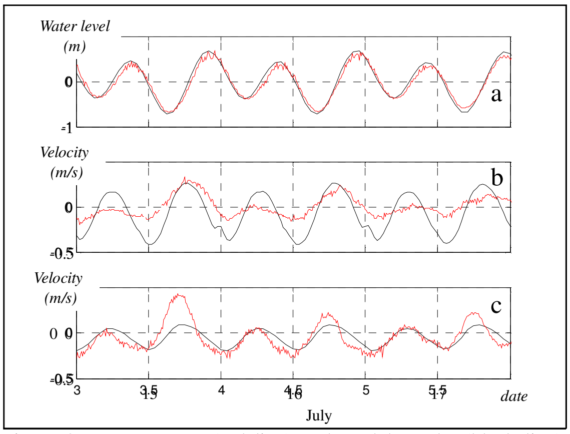

Figure 3: Measurement (red line) and model results (black line): water level in the north passage (a), tidal wave component of velocity in the main direction in the Isie pass (b) and in the north passage (c).

Discussion

The global circulation obtained with the three models is then analyzed.

In both simulations, the main characteristic of circulation is maintained. However, if this reef is immersed, we can notice that the circulation may be enhanced in some area near the reef whereas, the global circulation seems to be dampened. If a water input is parameterized at the reef, the intensity of circulation is slightly reduced during the flow but it is slightly enhanced during the ebb.

In contrast, the velocity in passes is strongly modified in the two cases. If the parameterization include a water cross-reef input, the out-flow in passes is enhanced. If the reef is immersed, the tidal variability of current in passes is reduced.

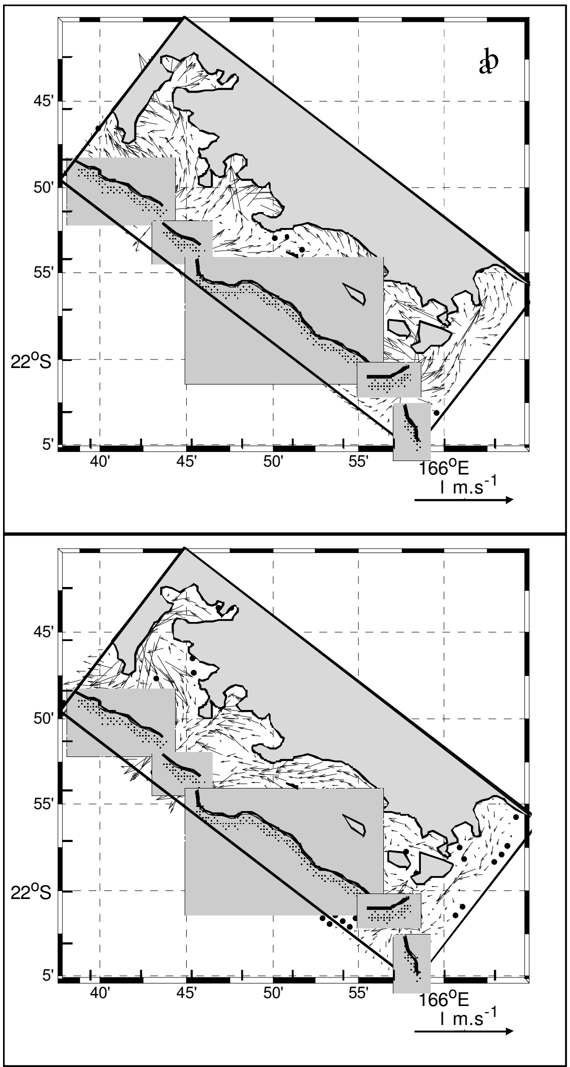

Figure 4: Circulation in the Ouano lagoon, on the 2012, July 16th, if a cross-reef in-flow is imposed: during the flood (a) and the ebb (b).

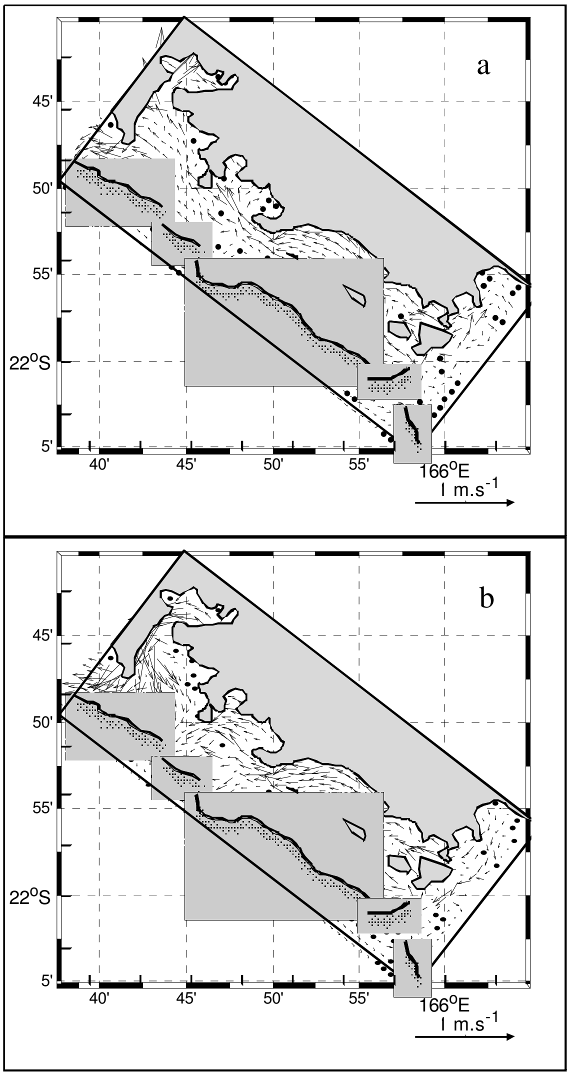

Figure 5: Circulation in the Ouano lagoon, on the 2012, July 16th, if the reef is immersed: during the flood (a) and the ebb (b).

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