Proceedings of the 11th International Coral Reef Symposium, Ft. Lauderdale, Florida, 7-11 July 2008
Session number 15

Experimental characterization of the water exchanges with ocean in a macro-tidal intermittently open lagoon bounded by semi-submerged coral reef

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Abstract. In the macro-tidal lagoons, of the Indian Ocean, coral reefs can be momentarily submerged by water at high tide and partially emerged at low tide. This process contributes to lagoon and open sea exchanges, although the reefs are often considered as impervious and the water fluxes assumed to occur only through the passes. To gain insight in spatial variability of fluxes at a reasonable cost that moorings alone cannot be able to provide, we develop an original experimental approach combining small ship side mounted ADCP measurement following transects thru passes and near reefs, with more classical high resolution ADCP moorings. This new strategy of measurement is exemplified at the occasion of an experimental campaign on the Mayotte lagoon and used after in Tulear lagoon. The results of this experiment are presented. Particularly, first, it is shown how the mounted ADCP data are made. A specific tidal analysis methodology is then proposed to get the spatial variability of the tidal component of the current thru the passes and above the reef. Then, all these analysis allow us to estimate the tidal induced fluxes thru the passes and above the reefs and to evaluate their respective part in water lagoon renewal.

Key words: measurement, tidal current, side mounted ADCP

Introduction

Tropical lagoons are impacted by climatic changes but also by direct anthropogenic activities. Water quality is directly related to water renewal time, which is regulated by passes and by the coral reef barrier. Possible reef modification (anthropic or intense climatic phenomena induced destruction, sudden stop of the suited general conditions for their edification, water level increase) could have major consequences on the functioning of reef-lagoon. To be able to forecast the reef tolerance versus modifications of the lagoon functioning conditions, it is needed to understand the hydrodynamic regulation induced by these reef barriers and the possible evolution of their regulating effects.

At some meso or macro tidal lagoons of the Indian Ocean, the water that is over running above the reef strongly tidally modulates fluxes through passes. The Mayotte lagoon and the Tulear lagoon, situated in the Mozambique Channel, are examples of meso-tidal reef lagoons. The pronounced tidal character of these lagoons generates peculiar hydrodynamics, which depend upon the tidal cycle.

In this study, it has been decided to focus on the cross reef tidal fluxes on the Mayotte lagoon and the Tulear lagoon. Our aim is to know the influence of the reef hydrodynamic control on the open seawater exchanges and on the lagoon dynamics, as well as to compare flux above coral reef and through passes.

In order to gain insight into spatial and temporal variability of fluxes at a reasonable cost that moorings alone are not able to provide, we have developed an original experimental approach. This approach combines small shipside mounted ADCP measurement following transects with more classical high-resolution ADCP moorings. This experimental strategy will be first presented, and then the specific analysis methodology will be described. In the third part, results will be presented and discussed, mainly, the tidal induced fluxes through passes and above reefs, as well as their respective part in water lagoon renewal.

Field experiment

Study site

The field observations were performed at the Tulear lagoon and at the north-east lagoon of Mayotte located in the Mozambique Channel. The north-east lagoon of Mayotte constitutes the north-eastern part of a wider lagoon extended to the south. These two lagoons that are located in same broad geographical area, are submitted to a quite similar external tide, dominated by the semi-diurnal wave M2.

Even if their orientation is opposite, their morphology is similar. They are about a 10nm long and 1nm to 5nm wide, opened at two passes of about 1 to 2nm. The north pass of the Mayotte lagoon and the south pass of the Tulear lagoon are the less wide (1nm) and the deeper ones (50m at the Mayotte lagoon; 20m at the Tulear lagoon). These lagoons are partially closed to the Mozambique Channel along the long reef. The Mayotte reef is a well-developed fringing reef whereas the Tulear reef is mainly a sand and mud covered, dead reef. Its topography is broken with crest and moat. Even if the geological origins of this reef, the external aspect or the width are different, their influence in the flow control seems to be the same. At high water, the reef is submerged (2-3m at the Mayotte lagoon), whereas the reef is weakly immerged (50 cm at the Mayotte lagoon) or emerged (at the Tulear lagoon) at low water.

However, the Mayotte lagoon is deeper (about 20m) than the Tulear one (about 10m), and the nature of entrance water varies with lagoon. At the Tulear lagoon, the incoming flow is usually constituted by water from the Mozambique Channel, but sometimes, due to external condition such as wind, a weak quantity of fresh water from Fiherena and Onilahy Rivers could enter. At the Mayotte lagoon, the incoming water could be either Mozambique Cannel water (entering through the north pass and above the reef) or lagoon water from the south lagoon (entering through the south pass).

Sensor deployment

Our observations were performed from 2006, November 9th, to 2006, November 24th, at the Mayotte lagoon and from 2007, September 9th to October 12th at the Tulear lagoon. To obtain spatial and temporal variability of hydrodynamics, we deployed moorings on which ADCP were installed and associated hull-mounted ADCP measurements. To investigate the flow through the pass and above the reef, we conducted a field survey along pass and along the reef.

Moorings deployment:

At the Mayotte lagoon, the north pass is divided in two channels. One ADCP was moored in each channel. The third was moored in the south pass and the last one, along the reef. At the Tulear lagoon, the south pass is divided in two channels as well. One ADCP was moored in each of them, the third one in the north pass. Because of technical problem, the last one was not moored along the reef, but in the middle of the lagoon. Finally, in each lagoon and during each campaign, four ADCP were deployed at locations indicated in Fig 1. In order to compare the velocity measured with moored ADCP and with side mounted ADCP, the cell had been set to 1m. About ten cells were obtained for each ADCP.

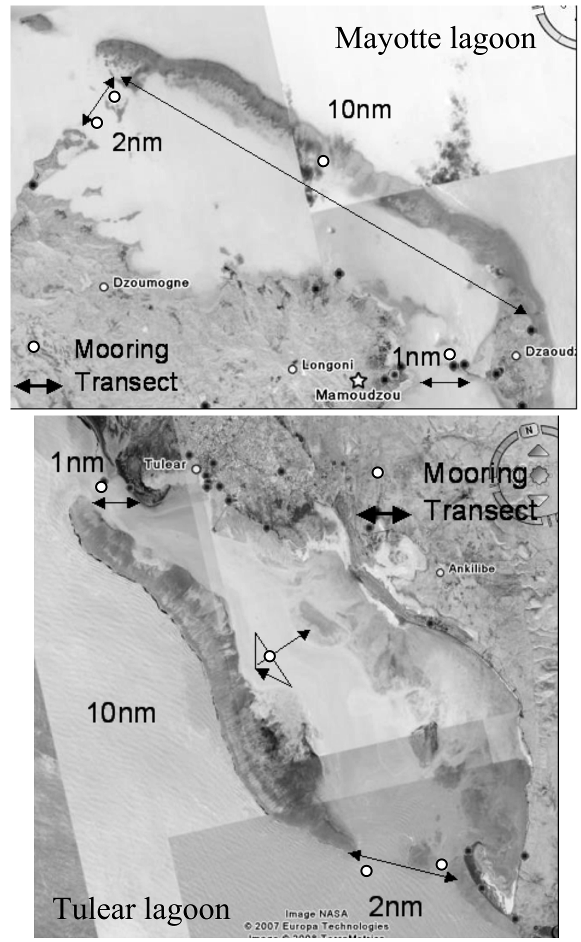

Figure 1: Study site (Mayotte lagoon and Tulear lagoon) and sensor deployment

In order to lighten the ADCP deployment field, the ADCP was fixed into a red plastic box weighted with concrete bloc. With only two divers and a small boat as a zodiac, this mooring can be deployed. Even with this rudimentary aspect and with velocity able to reach 2m/s, these moorings had been stable and a mooring set for tests did not move for more than 6 months.

Description of transect:

As is usually done to measure currents in rivers, the ADCP was set up on a boat with a tubular stainless steel frame along the inflatable fender. In low waves and with a boat velocity of about 3 knots, measurements were in good agreement with measured velocity mooring. Then, to associated data from the side mounted ADCP with those from mooring and to quantify fluxes, transects were made near moorings, along passes and along the reef barrier (at the Mayotte lagoon) or in the middle of the lagoon (at the Tulear lagoon) as presented in Fig 1.

Data description

The tide is mainly semidiurnal with a fluctuation spring and neap tide. The campaign duration was chosen to measure this variability. In Mayotte, the tidal amplitude is about 2m during the spring tide and 0.5m during the neap tide. In Tulear, the tidal amplitude is weaker, about 1.50m during the spring tide and 0.25m during the neap tide.

Velocity at moorings was obtained in the two lagoons. The Mayotte campaign was quite short in time and measurements were only performed during 10 days. But, the Tulear campaign was much more optimized and moored measurements were far longer (until 50 days). During the November Mayotte campaign, at the end of the rainy season, the sea was quite calm, while, during the October Tulear campaign, the sea was rougher, but transects could be performed. Then, velocity-measurements along transect were successful, but due to technical problems some data had not been acquired.

Velocities are quasi-barotropi*c*; their main direction is cross-pass or cross-reef at the boundaries and along-shore in the middle of the lagoon. Velocities are correlated to the tide. Periodograms can reveal the mean periodic waves. The main water level tidal waves are M2, S2 and K2 in Mayotte and mainly M2 and K2 in Tulear. The velocities are modulated by these waves, but other harmonics of M2 or S2 can be observed (notably, waves with a period of 6h).

The side mounted ADCP gives spatial information about the velocity along the pass. These measurements reveal variability due to the topography of the bottom.

Data processing.

The side mounted ADCP gives a spatial information velocity, however not synoptically. Indeed, the transect duration can take 1 hour. Notably, due to the tide effect, the velocity varies during this hour. Then, it is hard to compare velocity measured at the beginning of transect with the one measured at the end without treatment. So to treat this spatial information, the velocities have to be estimated for the same time for each transect. For this purpose, the temporal information of the mooring can be used to obtain temporal information at each point all along the transect.

Spectral analysis of mooring data

At the mooring station, named M_0, the measured velocity, is not the real velocity, but an approximation: $\hat{u}(M_0) = u(M_0) + \varepsilon(M_0)$, with ε, the measurement error with a blank noise and u(M_0), the complex representation of the velocity: $u(M_0) = \|\vec{u}(M_0)\| e^{i\theta(M_0)}$. Supposing a linear decomposition, the velocity can be decomposed into a periodic signal, u_{tide}, mainly linked to the tide and a non-periodic signal, $u_{res}(M_0)$:

$$u(M_0) = u_{tide}(M_0) + u_{res}(M_0).$$

The main frequencies of velocity waves can be deduced from the periodogram. Then, a classical harmonic analysis can allow reconstructing the tidal signal of this velocity.

$$u_{tide}(M_0) = \sum_{k=1}^{N} A_{M_0}(\omega_k) e^{i\omega_k t + \varphi_k}$$

with ω_k , $\varphi_k(M_0)$ and $A_{M_0}(\omega_k)$ the pulsation, the phase and the amplitudes for wave *k* and N the number of waves which depends on the tidal dynamics of area studied.

Wave amplitudes can be approximated by $A^*_{M_0}(\omega_k)$ with minimizing, by the least square sense, the equation:

$$u(M_0) - \sum_{k=1}^{N} A_{M_0}(\omega_k) e^{i\omega_k t + \varphi_k}$$

Hence, the approximated tidal velocity at M_0 location, $u^*_{tide}(M_0)$, and the approximated "residual velocity", $u^*_{res}(M_0)$, are written:

$$u^*_{tide}(M_0) = \sum_{k=1}^{N} A_{M_0}(\omega_k) e^{i\omega_k t + \varphi_k}$$

$$\text{and } u^*_{res}(M_0) = u(M_0) - u^*_{tide}(M_0)$$

$u^*_{res}(M_0)$ represents not only the measurement errors or harmonic analysis approximation, but also all velocity component not represented with the harmonic analysis as velocity due to wind effect or non-represented tidal wave, for example. Hence, the approximated velocity at M_0 is:

$$u^*(M_0) = u^*_{tide}(M_0) + u^*_{res}(M_0)$$

Temporal and spatial data processing

As identical transect were repeated along the campaign, many instantaneous data can be obtained in one location. The method proposed here is an expanded version of Candela et al. 1992 and Garcia-Gorriz et al., 2003. The main difference being that their method was developed in meso-scale region and not in coastal region and contrary to the both technical; our strategy uses a reference mooring. As for the velocity at the mooring, velocity at each point of the transect, named M, is assumed to be expanded in two types of components: time periodic and non-periodic component. Both are spatially variable. Then, equations analogous to the equation for the velocity at mooring, can be written at each transect location, M. Hence:

$$\hat{u}(M) = u(M) + \varepsilon(M),$$

with $\hat{u}(M)$ the measured velocity in M location, $\varepsilon(M)$ the measurement error estimated to about 5cm/s and $u(M)$ the real velocity. Then, the velocity is decomposed as tide-induced velocity, $u_{tide}(M)$, and "residual velocity", $u_{res}(M)$:

$$u(M) = u_{tide}(M) + u_{res}(M).$$

The aim is to estimate the tide-induced velocity and the "residual velocity". For that, as Candela et al, 1992 and Garcia-Gorriz et al, 2003, we assume that the time-periodic part of the equation can be expressed as the product of amplitude, and a sinusoidal function of time.

$$u_{\text{tide}}(M) = \sum_{k=1}^{N} A_M(\omega_k) e^{i\omega_k t + \varphi_k(M)},$$

with $\varphi_k(M)$ and $A_M(\omega_k)$ the phase and the amplitudes for the wave *k* at the location M. N is the number of waves which depends on the tidal dynamics of area studied and which is the same as for the velocity at the mooring.

$A_M(\omega_k)$ and $u_{res}(M)$ are functions depending on the location of M. Here, *s,* the distance from the mooring, characterizes the location: Candela et al, 1990 show that the quality of the fit was not strongly dependent on the choice of the function. Thus, the horizontal functions $A_M(\omega_k)$ and $u_{res}(M)$ are prescribed and we chose them to be polynomials. They are based in both velocity at the mooring location and along transect with no other dynamical assumption involved, and are expanded as

$$A_M(\omega_k) = A^*_{M_0}(\omega_k).P_k^{(n)}(s)$$

$$\text{and } u_{res}(M) = u^*_{res}(M_0).Q^{(m)}(s)$$

with $P_k^{(n)}(s)$ and $Q^{(m)}(s)$ polynomial expressed as:

$$P_k^{(n)}(s) = \sum_{p=1}^{n} \alpha_{p,k} s^p$$

$$\text{and } Q^{(m)}(s) = \sum_{p=1}^{m} \beta_p s^p,$$

where $\alpha_{p,k}$ and β_p are the constants to be fitted to the observations and n and m the degree of the polynomials.

Setting,

$$J(\alpha_{p,k}, \beta_p) = \left\| \sum_{k=1}^{N} A^*_{M_0}(\omega_k).\left(\sum_{p=1}^{n} \alpha_{p,k} s^p \right) e^{i\omega_k t + \varphi_k(M)} + u^*_{res}(M_0). \sum_{p=1}^{m} \beta_p s^p - \hat{u}(M, t) \right\|^2$$

$\alpha^*_{p,k}$ and β^*_p are defined as the values minimizing J.

Then, the approximated tidal and residual velocity at M location, ($u^*_{\text{tide}}(M)$ and $u^*_{res}(M)$), are written:

$$u^*_{\text{tide}}(M) = \sum_{k=1}^{N} A^*_{M_0}(\omega_k).\left(\sum_{p=1}^{n} \alpha^*_{p,k} s^p \right) e^{i\omega_k t + \varphi_k(M)}$$

$$\text{and } u^*_{res}(M) = u^*_{res}(M_0).\sum_{p=1}^{m} \beta^*_p s^p$$

Hence, the approximated velocity at M is:

$$u^*(M) = u^*_{tide}(M) + u^*_{res}(M)$$

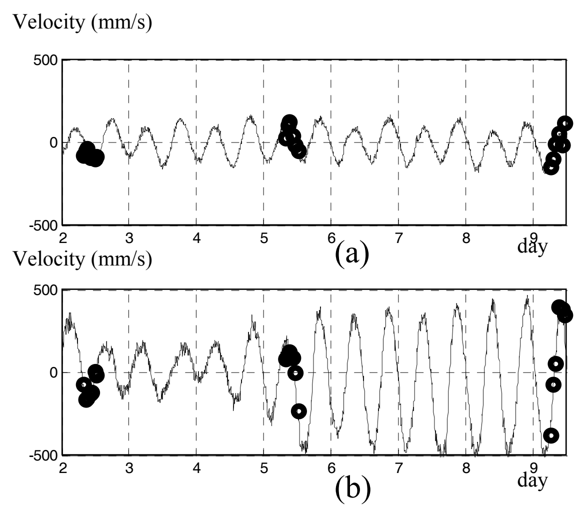

Figure 2: Measured velocity (black points) and calculated velocity (black line) in the middle of the south pass of Tulear lagoon. (a) represents the east component and (b) the north component.

As Garcia-Gorriz and al (2003), a systematic criterion was used to select the degrees of the polynomial. This test computes the error and the correlation when increasing the degree of polynomial functions. Hence, sequential tests with increasing polynomial degree values are run and the choice is made at the step when correlation tends towards 1 and errors displays small variation for higher degrees. The degree of the polynomial functions in the equation depends on the circulation in the studied area. Moreover, if M_0 is located on transect, $\alpha^*_{0,k}$ and β^*_0 are set to 1. Fig. 2 illustrates the reconstituted velocity in one point with the mooring velocity and in-situ data.

Results and discussion

Velocity

The resulting velocities are in accordance with measurement. The correlations with data are quite good (around to 0.9) and the error is weak (between 3 and 4 cm/s). The resulting velocity provides the main features of the velocity in passes. In the Tulear lagoon, the velocity is almost homogenous and follows the bathymetry. Contrarily, at the south pass of the Mayotte lagoon, the velocity is much more complex and this data process can point out the eddy in front of the north pass (Gourbesville and Thomassin, 2000). Fig. 3 illustrates the velocity at the Mayotte lagoon and the Tulear lagoon.

Flux

Spatial and temporal informations of velocity allow calculating fluxes. During the tidal campaign, in Mayotte, a mean flux of about 3000m^3/s entranced from the north pass whereas a flux of 2000m^3/s above the reef and of 1500 m^3/s through pass went out from the lagoon. At the Tulear lagoon, the flux went out through pass with a quantity of 1000 m^3/s and 2000 m^3/s. Hence, the water renewal times were respectively 7 and 4 days.

Conclusion:

A new strategy of data acquisition and a new data processing development to obtain spatial and temporal variations of current was developed. This methodology can provide spatial and temporal hydrodynamics information at reasonable cost. This data processing associates mooring and side mounted ADCP and evaluates the through-pass velocity with polynomial functions whose coefficient depends on the velocity at the mooring. Then, results can be extrapolated without any transect and the presented measurements allow calculating entrance lagoon flux. Moreover this boundary description allows the building of a numerical model that will be used to compute the residence time of water masses.

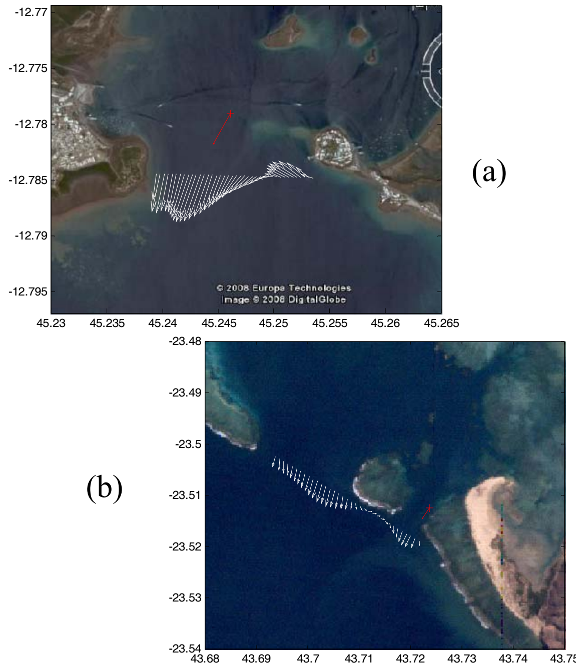

Figure 3: Reconstituted velocity in the south pass of Mayotte (a) and Tulear (b) lagoons.

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