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Modelling alongshore flow in a semi-enclosed lagoon strongly forced by tides and waves

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ABSTRACT

Alongshore flows strongly driven by tides and waves is studied in the context of a one-dimensional numerical model. Observations from field surveys performed in a semi-enclosed lagoon (1.7 km×0.2 km) outside Xai-Xai, Mozambique, are used to validate the model results. The model is able to capture most of the observed temporal variability of the current, but sea surface height tends to be overestimated at high tide, especially during high wave events. Inside the lagoon we observed a mainly uni-directional alongshore current, with speeds up to 1 ms^{-1}. The current varies primarily with the tide, being close to zero near low tide, generally increasing during flood and decreasing during ebb. The observations revealed a local minimum in the alongshore flow at high tide, which the model was successful in reproducing. Residence times in the lagoon were calculated to be less than one hour with wave forcing dominating the flushing. At this beach a high number of drowning casualties have occurred, but no connection was found between them and strong current events in a simulation covering the period 2011–2012.

1. Introduction

Reefs are common features along the coasts of the tropical oceans and often define semi-enclosed areas that can be densely populated. This is because such lagoons define particular ecosystems subject to fisheries, development of tourist industries, and in recent years also fish-farming. Therefore it is of interest to know the circulation in such areas to secure that the water quality may sustain the increased sewage discharges from growing settlements, the environmental impact of near-shore constructions and increased industrial activities. Coastal erosion is also of major concern, so it is important to study ocean currents, tides, waves and wind influencing erosion processes. An illustrative example is the study of Sandy Bay, Australia (Taebi et al., 2011).

In this paper we investigate the current dynamics at the beach of Xai-Xai, southern Mozambique. At Xai-Xai there is a fringing reef running parallel to the coast defining a lagoon about 1.7 km long and up to 200 m wide, see Fig. 1. The lagoon is almost closed in the west, and the major openings are found in the eastern end. The reef itself is only about 20 m wide and very regularly shaped, resembling the remains of a man made jetty. The tidal amplitudes in the area range from 0.5 m during neap and up to 1.5 m at spring tide (Sete et al., 2002). The uppermost level of the reef has a more or less constant height and is always submerged during high tides. At low tide the reef is always above sea-level. Waves may induce a mass flux across the reef even when the water level is below the top of the reef (Sibul, 1955). The water exits the lagoon mainly through the gaps in the eastern end.

Several studies of wave driven flow across reefs and wave driven circulation have been made. Early work includes Munk and Sargent (1954), who looked at circulation within a Pacific atoll. Gourlay (1996) performed laboratory experiments, seeking dimensionless parameters relating wave set-up on the reef and wave driven flow across the reef, which Kirugara et al. (1998) applied to develop analytical models for the Bamburi Lagoon, Kenya, see also

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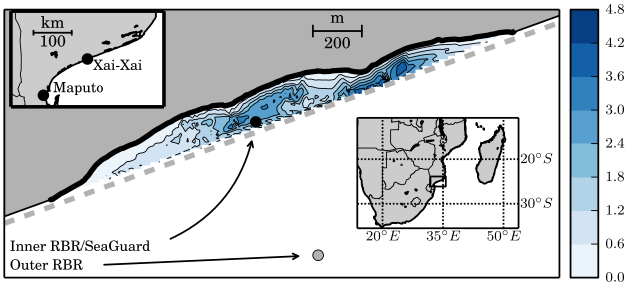

Fig. 1. Map showing a GPS track along the shoreline (thick black line) from October 2013, and bathymetry measured by echo sounder in October 2011. Instrument positions from survey in October 2012 are indicated. The dashed grey line indicates the approximate position of the reef. The insets show the location of Xai-Xai in southern Africa.

Angwenyi and Rydberg (2005). Lowe et al. (2009) defined an idealised model for a system with a reef and a lagoon, applying it to Kanehoe Bay, Hawaii. They related cross-reef flow to wave setup on the reef. Based on field experiments (Taebi et al., 2011) a two-way coupled circulation and wave model, investigating the circulation in a fringing reef, was developed by Taebi et al. (2012). Field studies at Bora Bay, Miyako Island by Kraines et al. (1998) showed that the cross-reef flow did not follow the tidal cycle, but was low at low tide and also had a local minimum at high tide. They explained the minimum at low tide by a blocking effect by the reef, and the corresponding minimum at high tide was found to be related to a reduced radiation stress gradient due to less wave breaking when the water level at the reef was high. Taebi et al. (2011) found the same sub-tidal oscillation of the current system at Sandy Bay, Australia. The importance of wave setup has been addressed by several of the above mentioned studies, see also Lowe et al. (2010). Antuono et al. (2007) developed 2D analytical models for alongshore circulation due to waves at a beach, while Stockdon et al. (2006) performed 10 field experiments to study wave setup, swash and run-up under various conditions.

The model efforts mentioned above all concentrate on the dynamics of wave and tide induced transports across the reefs which typically are several hundred metres wide. At Xai-Xai the reef is only about 20 m wide, and we have formulated the transports across the reef as functions of the offshore wave state and water level. We have developed a 1D model for the alongshore flow inside the lagoon. Our goal was to identify the main driving forces determining the time development of the current, as well as the alongshore variability. The intention here was to investigate if a model based on simple conservation laws could reproduce the main observed dynamics. We present also a few short (~1 day) observation series of current, water level and waves in the area.

This study was also motivated to see if there were any connections between strong current events and the large number of casualties due to drowning reported at this beach. A two years long model simulation is performed and the results are compared with data of drowning incidents.

In Section 2 we describe the field experiments at Xai-Xai beach. The model is developed in Section 3, and in Section 4 we present the measurements and a model run with idealised forcing. In Section 5 we force the model with realistic parameters, measured and modelled, and the output of the model is compared with observations. Section 6 contains some concluding remarks.

2. Field experiments

Field experiments were designed to obtain measurements of the parameters believed to be essential for the lagoon dynamics, such as sea level and waves inside and outside the lagoon, currents and bathymetry inside the lagoon. During a field survey in Xai-Xai in October 2011 bathymetric data inside the lagoon was collected, using a Garmin echo sounder. As the depth soundings were done over three days, at various times of the day, we adjusted the values by subtracting a modelled tidal amplitude from the TPXO.7 tidal model (Egbert and Erofeeva, 2002). The adjustments made were up to ± 0.4 m. A GPS track along the beach (thick black line in Fig. 1) that was recorded in October 2013 was used to define the land side of the lagoon, where the depth is zero. The GPS track and echo depths were interpolated to a regular and rectangular grid, to get the bathymetry shown in Fig. 1.

A second field survey was performed in Xai-Xai in October 2012 close to spring tide (Christensen et al., 2013). Point measurements of current velocity inside the lagoon (Fig. 1) were obtained using an Aanderaa SeaGuard moored at a depth of about 1 m below surface. The instrument contains a Doppler Current Sensor with high accuracy (0.15 cm s^{-1}).

We used two TWR-2050 pressure sensors from RBR to measure both the varying sea surface height due to tides, as well as wave parameters. Waves were measured in ‘bursts’, with the instrument recording 2048 samples at 2 Hz, repeating this procedure every 20 min. Tidal averaging was done every five minutes. The accuracy of the pressure sensor is 0.05% of the full scale, which in our case corresponds to about 1 cm of water. We mounted one sensor inside the lagoon, on the same mooring that held the current meter (‘inner RBR’, black dot in Fig. 1), while the other was mounted about 600 m outside the reef (‘outer RBR’, grey dot in Fig. 1).

A Lagrangian drifter buoy with a GPS unit was used to measure surface currents. The drifter was equipped with a Garmin DC40 transducer, and a handheld Garmin Astro 440 was used to log the position of buoy. The transducer was set to measure every five seconds, but several data points were not logged, possibly due to communication issues between transducer and the handheld unit, giving an irregular sampling interval.

In addition to the field observations, wave data from the ERA-Interim reanalysis (Dee et al., 2011) for January 1, 2011 to December 31, 2012 was obtained for a location about 50 km east of Xai-Xai. The TPXO.7 tidal model was run for the same location, creating a simulated time series of sea surface height for the same period, 2011–2012.

Comparisons between modelled data from ERA-I and TPX and data from the outer RBR generally show a good agreement, indicating that the modelled data is representative for Xai-Xai, cf. Fig. 2.

3. Model

A simplified model for the circulation in the lagoon at Xai-Xai is defined, where constant density is assumed and Coriolis forces are neglected. Fig. 3 shows a schematic of the system. The x-axis is placed parallel to the reef, with positive direction east-northeast (cf. Fig. 1). The model domain is closed on the left end, has a length of 1700 m and a width B varying in the range 80–200 m. The reef is about 20 m wide and defines a straight line. Inside the reef is an alongshore current $u(x,t)$ and sea surface height $\zeta(x,t)$. Forcing the system inside the lagoon is the sea surface height outside the lagoon $\eta(t)$ and a transport of water across the reef $V(x,t)$, caused by wave and a pressure gradient due to cross-reef sea level differences. Inside the lagoon, most waves have dissipated, and we ignore second-order wave effects, that is, setup/setdown inside and outside of the lagoon, or the excitation of low frequency (infragravity) waves (e.g., edge waves). Fig. 3b shows a cross section of the model lagoon. Sea surface heights are given as the deviation from a mean sea level. Table 1 contains a list of the parameters used in the model.