Hydrodynamic Modelling of Coral Reefs: Ningaloo Reef-Western Australia

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Abstract
As with all coral reef systems, the ecology of Ningaloo Reef is closely linked to water circulation which transport and disperse key material such as nutrients and larvae. Circulation on coral reefs may be driven by a number of forcing mechanisms including waves, tides, wind, and buoyancy effects. Surface waves interacting with reefs have long been known to dominate the currents on many coral reefs. This forcing is provided by wave breaking on the forereef that causes a local increase in the mean sea level (the “setup”) that is responsible for driving the cross-reef flow. For this project, we are developing a coupled wave-circulation numerical model of Ningaloo Marine Park-located in northeast of Australia, using an extensive field data set collected from April-May 2006 in an ~5 km region around Sandy Bay, to validate its performance. The analysis of field data collected on the forereef, reef flat and in the channel revealed a strong correlation between the incident wave height and currents inside the reef lagoon and channel. A nearshore numerical wave model (SWAN) which simulates wave transformation due to the effects of shoaling, refraction, diffraction, and dissipation by both bottom friction and wave breaking was chosen to simulate waves across the system. The model uses a finely-resolved computational grid (~20 m resolution on the reef) and incorporates high resolution bathymetric data provided from hyperspectral imagery. The model is forced with offshore wave conditions measured during the 2006 field campaign and model output is compared with an array of wave gauges deployed along cross-reef transects from the forereef slope to the lagoon. Following successful validation, results from SWAN, particularly the 2D radiation stress gradients, are used by the circulation model to include the wave-driven circulation.

Keywords: Hydrodynamic modelling, Coral reef, Ningaloo.

1. Introduction

The Ningaloo Reef tract lies on the western coast of Australia between 21° and 24° S latitude and along 113° 30’ E longitude. The reef tract runs parallel to the coastline, for a distance of some 280 km, and consists of a barrier reef ~1-6 km offshore (average 2.5 km width), backed by a shallow, sedimentary lagoon (mean depth about 2m) with occasional patch and nearshore platform reefs (Hearn et al., 1986). Hearn and Parker (1988) used aerial photographs of the northern part of the reef to estimate that these gaps occupy about 15% of the...
length of the main reef under light swell conditions. They also estimated that the residence time of water within the lagoon system was on the order of hours, however, without applying a numerical model.

Fig. 1.a) Map illustrating the study area. The field study will focus on a stretch of reef located in the Sandy Bay region of Ningaloo Marine Park b) Bathymetry derived from hyperspectral imagery (adapted from Lowe et al., 2008).

2. Hydrodynamic Processes

Ocean currents operating near the reef front at Ningaloo have been previously studied by direct observation, aerial surveys (1990-92), and a current drogue (Taylor and Pearce, 1999). They demonstrate a predominant northward current along the reef front during late summer and early autumn. It was proposed that this current, of counter direction to the southward Leeuwin current further offshore at the shelf break, be termed the “Ningaloo Current” (Taylor and Pearce, 1999).

The Leeuwin and Ningaloo currents dominate the summer continental shelf dynamics between 22° and 24°S off the coastline of north-central Western Australia. The Leeuwin current is stronger and flows along the continental shelf break and slope, transporting warm, relatively fresh, tropical water poleward (Smith et al., 1991; Woo et al., 2006). The seasonal change in the Leeuwin Current is generally attributed to regional wind stress variability: in summer the Leeuwin current is weaker (~1.4×10^6 m^3/s) as it flows against maximum southerly (opposing) winds and flows strongly (~7×10^6 m^3/s) in winter in the absence of strong southerly winds (Godfrey and Ridgway 1985; Pearce 1991).

Based on records of cold water anomalies at Ningaloo coast recorded by Simpson and Masini (1986), Taylor and Pearce (1999) suggested the possibility of coastal upwelling at Ningaloo. This has now been confirmed by recent field data that indicated that the Ningaloo current, is also associated with upwelling and high primary productivity with distinct phytoplankton species (Hanson et al., 2005; Woo et al., 2006; Willis, 2007). It is therefore of vital importance that a full understanding of this regional circulation at Ningaloo be developed (Taylor and Pearce, 1999).
Circulation over shallow reefs can be driven by a number of forcing mechanisms including waves, tides, wind, and buoyancy effects (Andrews and Pickard, 1990). The relative importance of each mechanism varies among reefs and is a function of both the reef morphology and the hydrodynamic forcing at the site. The Ningaloo system has the typical morphology of many fringing reefs. The reefs are located between a few hundred meters to a maximum of 7 km offshore, and are separated from the shore by lagoons having mean depth 2-3 m (Taylor and Pearce, 1999). These reefs are broken every few kilometres alongshore by gaps, forming relatively deep channels through which a majority of the water exchanged between the lagoons and ocean is believed to occur. Relatively few studies have focused on the nearshore oceanography of the Ningaloo Reef system (e.g. Brinkman, 1998; Hearn et al., 1986), but these have shown that waves, tides and wind all contribute to driving the reef circulation, while the importance of buoyancy remains unknown.

The interaction between forcing mechanisms and reef circulation has been studied on coral reefs, in general, using a variety of different approaches. Conceptually, wave breaking can drive strong currents on coral reefs, due to the establishment of mean water level differences (termed “wave setup”) between the reef and lagoon (see Fig. 2). The first detailed investigation of the generation of wave setup on reefs was conducted by Gerritsen (1981). Using a laboratory physical model of a Hawaiian reef, he simulated the effects of waves approaching the reef shoreline at right angles. Wave setup and wave generated flow was subsequently investigated in several laboratory modelling study of coral reefs by (Gourlay, 1996a; and b; Gourlay and Colleter, 2005). Observations of wave and current over a natural reef and analytical solution for flow forced by wave breaking and modulation of energy spectrum of cross-reef currents at some harmonics was done by Symonds et al. (1995), although the morphology of the barrier reef they studied was different from fringing reef systems such as Ningaloo.

Unstratified (or barotropic) 3-D numerical modeling has been previously applied to reef-lagoon systems, but the morphology of the reefs studied and the forcing mechanisms responsible for driving circulation are very different from the Ningaloo fringing reef. Tartinville et al. (1997) developed a hydrodynamic/tracer transport model for Mururoa atoll lagoon, located in the tropical Pacific. They also did a sensitivity analysis of the circulation and computed how lagoon residence times scale with the tide and wind stress forcing mechanisms. They concluded that wind stress was the main driving force on the long-term circulation of Mururoa lagoon. So, according to the definitions of Atkinson et al. (1981) in their Marshall Islands atoll study, it is believed that the Mururoa lagoon belongs to the class of deep lagoons, as opposed to shallow lagoons, in which the circulation is overwhelmingly tidal, rather than wind-driven.

3. Methods

3.1. Field Experiment

An intensive field campaign during April - May 2006 focused on a stretch of reef (~5 km in length) located in the Sandy Bay region of Ningaloo Marine Park. The reef morphology in this region is fairly typical of the Ningaloo system, with a simple configuration of shore-parallel reef sections. The observational array included wave gauges and single point current meters deployed along cross-reef transects from the reef slope into the lagoons, and
current profilers deployed within the deep channels. A number of bottom mounted temperature loggers were also deployed within a reef channel to provide data on intrusions (upwelling) of cooler oceanic water and the development and destruction of thermal stratification. Aerial photograph of the area with the instruments represented by dots is shown in Fig. 3.

This extensive data set was used to investigate how the dominant circulation of Sandy Bay respond to different physical forcing mechanisms, as well as serving as the foundation for implementing and validating a regional- and lagoonal-scale model of the Ningaloo Coast.

The experiment captured a wide range of wave, tide and wind conditions. Offshore significant wave heights $H_s$ incident to the forereef ranged between 0.5 m and 2.1 m, averaging 1 m (Fig. 4a). The peak period $T_p$ of the incident waves ranged from ~5 s (i.e., due to short period wind waves) up to ~20 s associated with long period swell events (Fig. 4b). Throughout the experiment, waves were incident to the reef from a south-westerly direction (i.e., waves approaching normal to the reef would arrive from ~290 degrees; see Fig. 3).

The experiment captured three spring-neap tidal cycles (Fig. 4d) and three periods with fairly strong (>5 m/s) and continuous winds directed towards the north: these winds occurred in mid-April, toward the end of April, and mid-May (Fig. 4e). The wind speed slowed down and changed direction frequently from the end of April to mid-May, and wave heights were also relatively small ($H_s$ ~1 m) during this period.

3.2. Numerical Modeling

Numerical modelling of Sandy Bay commenced with a preliminary set of 6-week hourly simulations of waves in ~17 km alongshore x ~7 km cross-shore domain with 20 meter resolution domain. Based on the spectral wave action balance equation with sources and sinks, wave spectrum in the form of wave energy and radiation stress was derived for the area. Subsequently, the numerical circulation model
(coupled to the numerical wave model) will solve equations of conservation of mass and momentum numerically. Radiation stresses act as driving forces for the mean flow, and will be used to drive the wave-driven flows.

4. Results and Discussion

Analysis of the field data was conducted by processing raw data obtained from measurements and computing wave, water level and current time series. The current measurements show that cross-reef wave-driven currents measured at Sandy Bay are significantly weaker than expected from existing one-dimensional analytical models of reef circulation, likely due to the presence of considerable wave setup inside the shallow lagoon that is neglected in these approaches (Taebi et al., 2008). Results also indicate lagoonal flushing times of 5-8 hours under typical offshore wave conditions (Lowe et al., 2008).

Scatter plots of subtidal cross-reef currents (38 hour low-pass filtered) on reef flat and the possible forcing mechanisms, shows a strong correlation of currents with wave-setup while there is no clear correlation with wind speed (Fig. 5). Time series of current velocity in Fig. 6 confirms a strong correlation between current velocity and wave setup on the reef flat.

Circulation pattern in the reef-lagoon system is shown on Figure 7. The mean flows (arrows) measured by the ADV’s on the reef flat are directed onshore, while the channel flow is seaward. There is a tendency for the mean flow inside lagoon to rotate towards the channel in both northern and southern lagoons. There is relatively stronger flow in the channel, a mean of 0.2 m/s over 5 m depth, which discharges the incoming flow originating from the shallow reef. The standard deviation of flow time series in first and second axis forms the SD ellipses. The arrows that represent the average currents are always the same with or without tidal frequencies, although the standard deviations of the current velocities (ellipses) are smaller for the subtidal currents.

Fig. 5. Scatter diagrams of current and forcing mechanisms (a. wave setup, b. wind speed)

Fig 6. Wave setup and Current velocity in V3 on the reef flat
Fig. 7. Reef-channel circulation derived from the 6week experiment. Arrows are the time-averaged current velocities and the ellipses represent the standard deviation of the current velocities in 2 axis.

A power spectral density plot of tidal level and current velocity measured on the reef flat is shown on Fi. 8. For tidal level, the variability is dominated by the diurnal and semidiurnal components. However, variability in cross-shore current is distributed almost uniformly across a range of tidal harmonics.

Fig. 8. Power spectral density for tidal level and reef flat current velocity

A 2D wave numerical model was developed for the region surrounding Sandy Bay using the numerical wave model SWAN. The wave model was forced at the offshore boundary using directional wave conditions observed during the experiment, as measured by a Nortek AWAC deployed on the forereef. Figure 9 shows results from a typical simulation of significant wave height in the ~20 km alongshore domain.

Fig. 9. Simulated significant wave height at 18/05/06 10:00AM

The model was applied for different scenarios of bottom roughness (k_n) and wave breaking parameter...
and to investigate which parameter values produce the best agreement between the model and measurements. Results have been evaluated against measurements, with a particular emphasis on reef flat wave height (Fig. 10).

![Fig. 10. Significant Wave Height from modelling and measurement in V3 on the reef flat](image)

Agreement between model and field data was quantified by model skill which produces 0 in cases of no agreement and 1 for perfect agreement (Willmott et al., 1984).

\[
\text{Model Skill} = 1 - \frac{\sum (|X_{\text{model}} - X_{\text{obs}}|^2)}{\sum (|X_{\text{obs}}^2|)}
\]  

(eq.1)

Best agreement (Model skill = 98%) was achieved using knj=0.5 m and $\gamma=0.5$ as modelling parameters. Radiation stresses obtained from this wave model output will drive the coupled circulation model that is currently under development.

5. Conclusions

Recently released aerial photography and hyperspectral bathymetry shows Ningaloo Reef is broken several times in its 280 km length along the coast. This repeated pattern of reef-channel morphology enables us to look at Sandy Bay as a small unit of the entire reef tract. Hydrodynamic parameters of the region were recorded in a 6 week experiment in 2006. Scatter plots of current velocity and forcing mechanisms showed a strong correlation between current velocity on reef flat and wave setup, while there was no correlation between current velocity and wind speed.

Tidal frequencies in current velocity did not contribute to time average velocity; however they modulated currents at some harmonics.

Numerical wave modelling of Sandy Bay was completed with good agreement with the field observations, and model of circulation is now under development.

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