western australian
marine science institution

Student Progress Reporting Form
WAMSI Top-up Scholarship

STUDENT:	Soheila Taebi	**DATE:**	NOVEMBER 2008
SUPERVISORS:	Charitha Pattiaratchi, Greg Ivey Ryan Lowe, Graham Symonds		

PROJECT TITLE:	Characterisation and modelling of oceanographic processes in Ningaloo Reef and adjacent waters
NODE LEADER:	Dr Chris Simpson
PROJECT NUMBER:	3.5

REPORTING REQUIREMENTS		
1		PROGRESS REPORT FROM SUPERVISOR [TO INCLUDE]
		Overall aims of research The overall aims of this project are to investigate and quantify the hydrodynamic processes of Ningaloo Reef in Western Australia by: 1. Identifying hydrodynamic processes in the reef lagoon system using field data, collected on a small (~5 km alongshore) section of Ningaloo at Sandy Bay. 2. Investigating the relative importance of the major hydrodynamic processes in the reef lagoon system using numerical techniques – evaluated against the measurements for Sandy Bay. 3. Applying a numerical model to investigate the hydrodynamic connectivity between the local reef-lagoon system and the whole of reef scale including the offshore ocean waters, thereby aiding in the improved management of the system.
		Progress made on the project The student, Soheila Taebi has been very good progress. She started in May 2008 and submitted her UWA research proposal within 4 months which has been accepted by the UWA Graduate School. UWA usually requires the submission of the research proposal within 6 months and Soheila is well advanced on this. She has also made significant progress on the data analysis and modelling. She has made 2 presentations at International conferences: AGU Western Geophysics Meeting in July and Kish Island workshop (Iran) at the end of November (see paper attached). She is currently preparing a paper for submission to a journal.
		Any major risk issues None
2		PROGRESS REPORT FROM STUDENT
		Summary of progress

REPORTING REQUIREMENTS		
		• Research proposal for PhD study has been submitted in September 2008 and it was accepted by UWA Graduate Research School in couple of weeks (attachment 1). • Up to date results of the research has been submitted in a paper to International Workshop on “Monitoring & Modelling of Marine Pollution”, December 2008, Kish-Iran (attachment 2).
		Summary of major findings to-date • There is a strong correlation between current velocity and wave setup on reef flat as a forcing mechanism, while there is no correlation between current velocity and another potential forcing mechanism (wind speed). As a result, dominant forcing mechanism for Ningaloo current is wave setup. • Tidal frequencies in current velocity do not contribute to time average velocity; however they modulate currents at some harmonics. • Numerical wave modelling of Sandy Bay has been completed with good agreement with the field observations, and circulation modelling is now under development.
		Presentations made at workshops & conferences • Oral Presentation by Soheila Taebi in American Geophysical Union, Western Pacific Meeting, July-August 2008, Cairns. • Oral Presentation by Charitha Pattiaratchi in Second Annual Ningaloo Research Symposium, May 2008, Perth.
		Final report N/A
3		OTHER REQUIREMENTS
		Major findings to be reported immediately
		Supervisor & student present at a minimum of one WAMSI organised event • Second Annual Ningaloo Research Symposium, May 2008, Perth
		Node Leader, supervisor and student to meet at a minimum of 2 times yearly • One meeting at UWA in 4th August 2008 since student enrolment in May 2008
		Final report to be placed on WAMSI website

A. Proposed Study

i. Title

Hydrodynamic Processes of Fringing Reef Systems: Ningaloo Reef, Western Australia

ii. Contribution to scholarship

The only major study of hydrodynamics on Ningaloo Reef was undertaken by Hearn et al. (1986). They believed that effective management of the Ningaloo Reef system, and coral reefs more generally, is dependent upon an understanding of the key ecological processes of the system, which ultimately relies upon a basic understanding of physical oceanographic processes. Therefore, they attempted to lay a foundation for future programme of physical studies by using knowledge of processes on coral reefs and applying this specifically to the Ningaloo Reef tract. Their report draws on regional oceanographic information about large-scale oceanography (stratification, tides, internal waves), and reef-lagoon oceanography (wave pumping, tidal currents, wind forcing, flushing time), much of which comes from oil and gas exploration and extraction described in reports by Meagher (1980), May et al. (1983), Simpson and Masini (1986), Simpson (1985). They have emphasised the general need to assemble a basic understanding of the physical processes which operates within the reef and lagoon. Hearn et al. (1986) at the end of their report recommended minimum data set of tides, current, wind, wave and bathymetry to be provided by oceanographers to be used in environmental resources management plan. Although the report was a good reference at that time, there are very limited measurements and no numerical modelling and hardly can get detailed information about physical processes of Ningaloo reef-lagoon system from it.

A special feature of the Ningaloo Reef tract is the existence of shallow, narrow, long coastal lagoon close to the shelf break. An ideal region would have a long length of unbroken reef with a major break towards its southern boundary and the report suggests a suitable study region can be centred on Sandy Bay and both field work and numerical modelling to be done for the area. It is interesting that the whole Ningaloo Reef is the body of several small reef-channel systems, therefore an efficient approach would be to find out the physical process in one small system through an extensive research and extend the study to the whole region.

The scientific contribution from this research will advance the understanding of oceanographic processes along the Ningaloo Reef in North West of Western Australia. There is not much known about oceanographic process of Ningaloo Reef in detail so far, and this research aims to fill this gap by developing tools that can be used to accurately predict the ocean circulation over this reef.

B. Research Plan

i. Literature review

The Ningaloo Reef tract lies on the western coast of Australia between 21° and 24° S latitude and along longitude 113° 30′ E. 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.

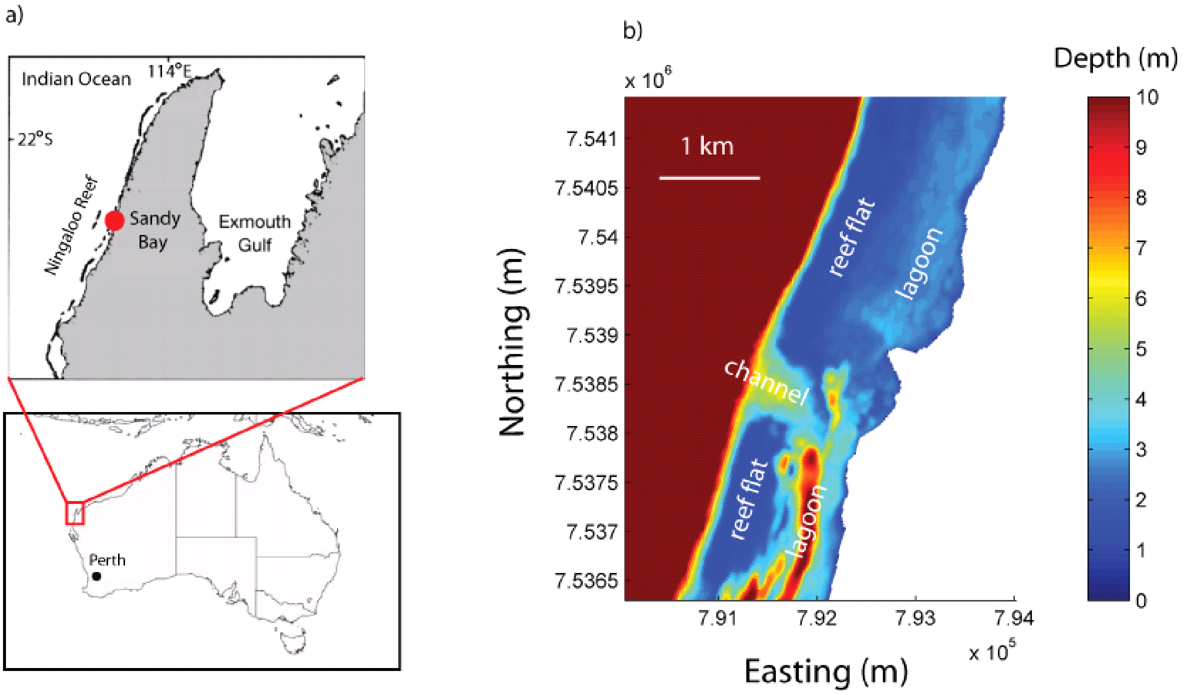

Figure 1.a) Map illustrating the study area. The field study will focus on a stretch of reef located in the Sandy Bay region of Ningaloo Marine Park b) Bathymetry derived from hyperspectral imagery (adapted from Lowe et al., 2008).

Ningaloo Reef is significant for both its size and ecological composition. The reef supports a high biodiversity of more than 500 fish species, over 200 species of coral, and 600 species of molluscs. The local coral communities contain both species typical of the tropical Indo-Western Pacific region as well as temperate species that are at the northern limit of their distribution in WA. Ningaloo Reef is rapidly gaining an international reputation for nature based tourism, due to easy access to the reef from shore and the unique wildlife present (Environment Australia, 2002). The Ningaloo Marine Park possesses a range of areas of natural and international significance. Its water has been divided into sanctuary zone, recreation zone and general use zone. Protection of the Ningaloo coral reef system is one important aspect in the regional strategy plan. The reef sits very close to the shoreline and any shore based development potentially may have more significant impact than the case of Great Barrier Reef (Ningaloo coast regional strategy, 2004).

Like all coral reefs, the ecology of the Ningaloo Reef system is closely linked to water motion, which transports and disperses vital material such as nutrients and larvae. For example, it has been shown that nutrient uptake by coral reefs is positively correlated to large-scale roughness and to excess wave height (above the breaking height) of incoming waves (Hearn et al., 2001).

i.1. Large scale 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 pole ward (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 (~1.4×106 m^3/s) as it flows against maximum southerly (opposing) winds and flows strongly (~7×106 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, which has similar water characteristics to the Leeuwin current, is also associated with upwelling and high primary productivity with distinct phytoplankton species (Hanson et al., 2005; Woo et al., 2006; Willis, 2007). The presence of the Ningaloo current and has major implications for various biological systems in the region. It is therefore of vital importance that a full understanding of this regional circulation at Ningaloo be developed (Taylor and Pearce, 1999).

i.2. Nearshore hydrodynamic processes

Circulation over shallow reefs can be driven by a number of forcing mechanisms including waves, tides, wind, and buoyancy effects (Andrews & Pickard, 1990). The relative importance of each mechanism varies among reefs and is a function of both a reef's morphology and the forcing conditions present 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 & 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; Gourlay, 1996b; 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.

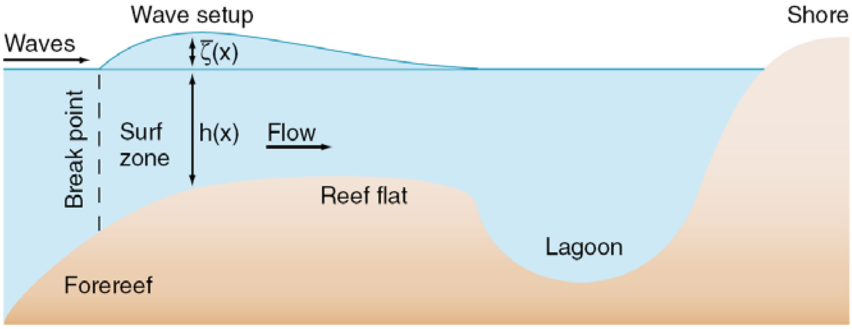

Figure 2. Definition sketch for wave-driven flow over a reef and into a lagoon (redrawn from Hearn 1999, courtesy of R. Lowe)

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.

ii. Project aim

The overall aims of this project are to investigate and quantify the hydrodynamic processes of Ningaloo Reef in Western Australia by:

1. Identifying hydrodynamic processes in the reef lagoon system using field data, collected on a small (~5 km alongshore) section of Ningaloo at Sandy Bay.

2. Investigating the relative importance of the major hydrodynamic processes in the reef lagoon system using numerical techniques – evaluated against the measurements for Sandy Bay.

3. Applying a numerical model to investigate the hydrodynamic connectivity between the local reef-lagoon system and the whole of reef scale including the offshore ocean waters, thereby aiding in the improved management of the system.

iii. Methodology

iii.1. Field study

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 subsequent analysis and interpretation of this existing data will be a key component of the proposed Ph.D. research. The reef morphology in this region is fairly typical of the Ningaloo system, with a simple configuration of shore-parallel reef sections. The six-week field campaign, undertaken as a joint collaboration between UWA, CSIRO and AIMS, measured key hydrodynamic variables at 25 sites spanning the lagoonal waters to the front reef slopes (Figure 3) and the role of UWA is to analyze the data obtained from campaign. 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.

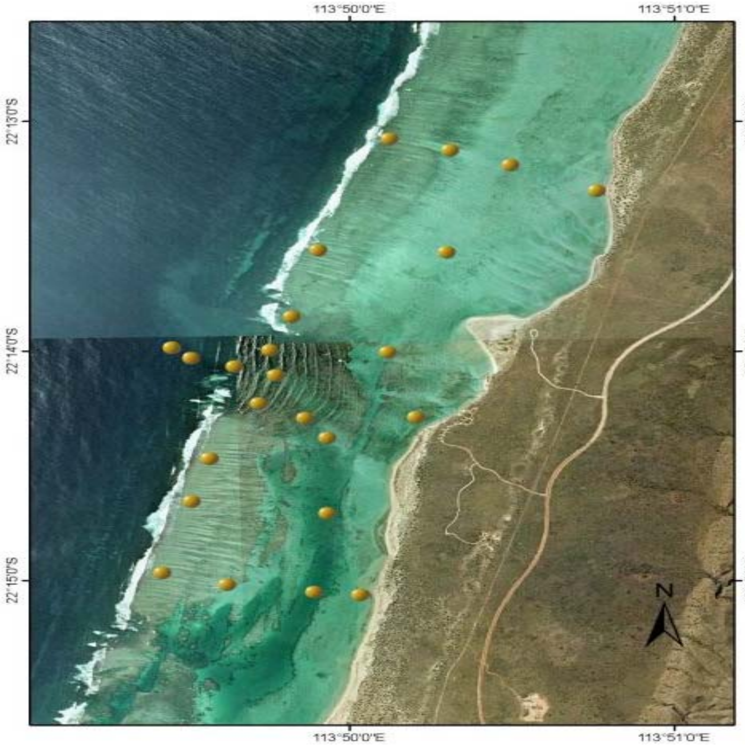

Figure 3. Aerial photograph of the site with the instrument locations

The data set includes hourly measurements of wave, current, mean water level and temperature at a number of sites on: (1) the forereef (10~15 meter depth), (2) the reef flat (1~2 meter depth) and (3) the northern and southern lagoon (respectively 2~4 meter and 5~8 meter depth). This extensive data set will be used to investigate how the dominant circulation of Sandy Bay responds 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.

iii.2. Numerical modeling

Numerical modeling of Sandy Bay has been started with a preliminary set of 6-week hourly simulations of waves in 20 meter resolution domain (Figure 1). Based on the wave action balance equation with sources and sinks, the deep wave model incorporates formulations for the processes of wave generation, dissipation and the quadruplet wave-wave interactions. In shallow water, these processes need to be supplemented with the dissipation due to bottom friction, triad wave-wave interactions and depth-induced breaking. All information about the sea surface is contained in the wave variance spectrum or energy density E (σ; θ), distributing wave energy over frequencies and propagation directions. Usually, wave models determine the evolution of the action density N(x; t; σ; θ) in space x and time t. The action density is defined as N = E/ σ and is conserved during propagation in the presence of an ambient current, whereas energy density E is not (Whitman, 1974). In brief, six processes contribute to total energy (S_{tot}) in shallow water:

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds;w} + S_{ds;b} + S_{ds;br} \qquad \text{(Eq. 1)}$$

These terms denote, respectively, wave growth by the wind, nonlinear transfer of wave energy through three-wave and four-wave interactions and wave decay due to whitecapping, bottom friction and depth-induced wave breaking. The last two terms, bottom friction and depth-induced wave breaking, are nearshore processes, where a bottom roughness (K_n) and wave breaking parameter (γ), respectively, are used to parameterize dissipation.

The numerical circulation model (coupled to the numerical wave model) will be based on the solution of the 3-D incompressible Reynolds averaged Navier-Stokes equations. Equations of conservation of mass and momentum will be solved numerically and the second order stresses due to breaking of short period waves will be included in the flow simulation. Radiation stress act as driving forces for the mean flow and will be used to calculate wave–driven flows. Currently we are evaluating two similar coupled wave-circulation models for this application: 1) the circulation model ROMS (Shchepetkin and McWilliams, 2005) forced by the numerical wave model SWAN (Booij et al., 1999), and 2) a coupled wave-circulation model based on DHI's MIKE21 modelling suite (DHI, 2008).

iii.3. Preliminary results

A preliminary analysis of this field data set has been conducted by processing raw data obtained from measurements and looking at wave, tide and current time series. Results of the first stages of current study shows 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 on reef flat and the possible forcing mechanisms, shows strong correlation of currents with wave-setup while there is no clear correlation with wind speed (Figure 4). Time series of current velocity in Figure 5 confirms a strong agreement between current velocity and wave setup in reef flat.

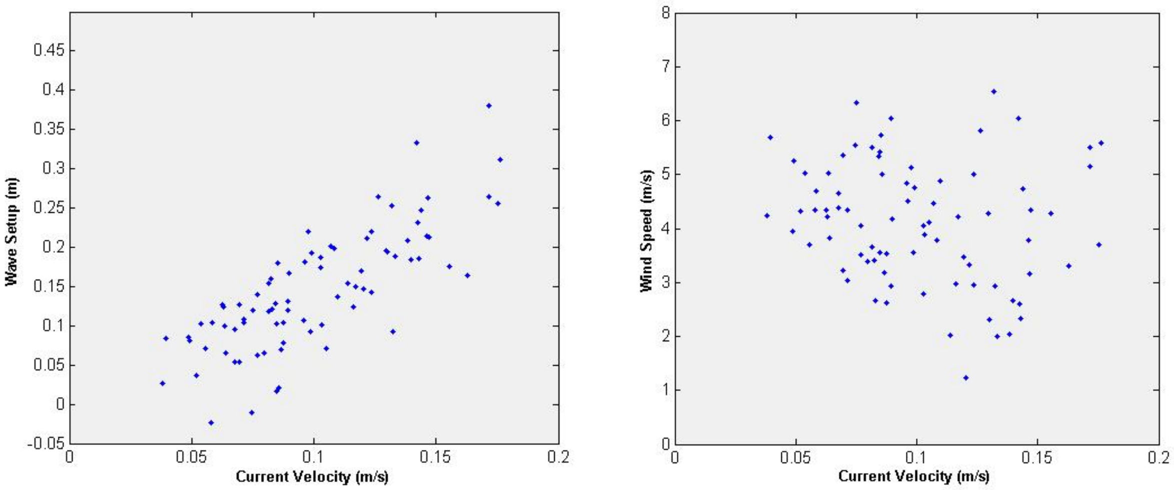

Figure 4. Scattering diagrams of current and forcing mechanisms (wave setup and wind)

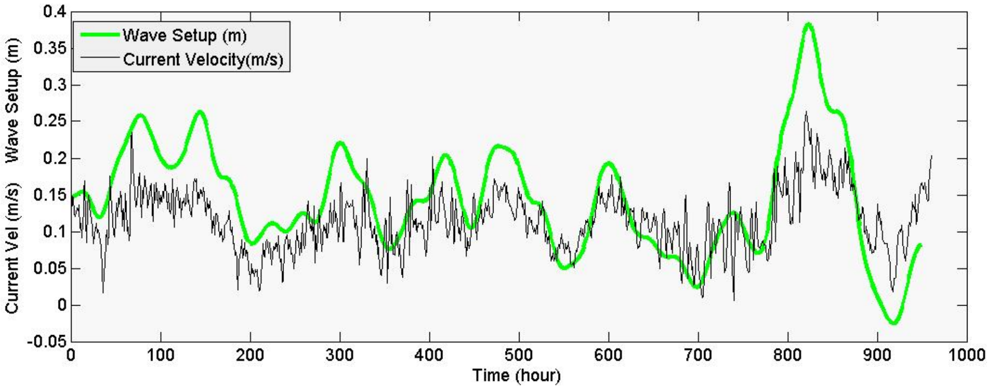

Figure 5. Wave setup and Current velocity in NTH_ADV1 station on top of the reef

A preliminary 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 6 shows typical simulation of significant wave height in ~20 km alongshore domain. Results have been evaluated against measurements, with a particular emphasis on reef flat wave height (Figure 7).

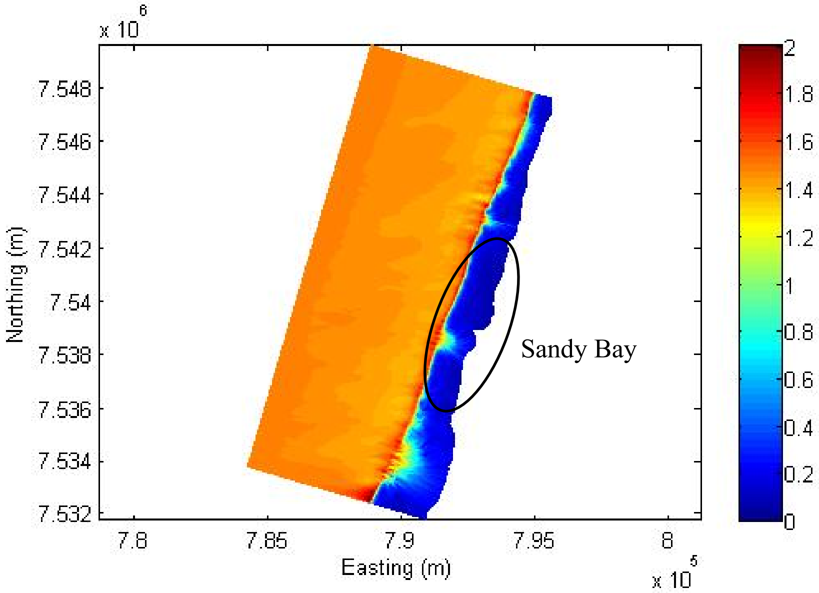

Figure 6. Simulated significant wave height at 18/05/06 10:00AM

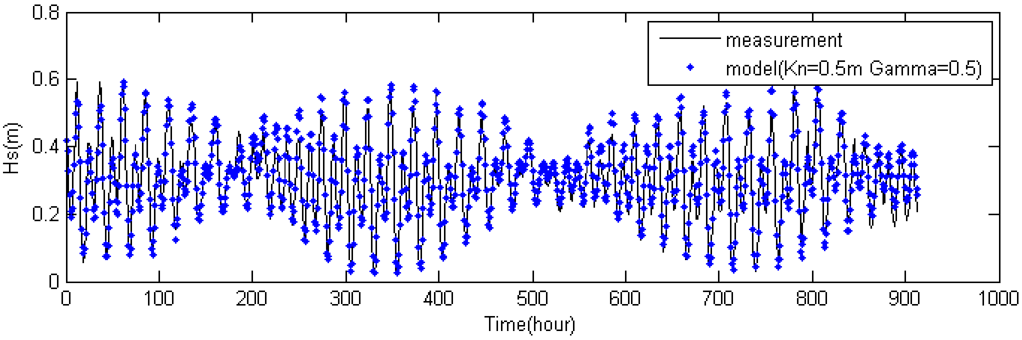

Figure 7. Significant Wave Height from modelling and measurement in NTH_ADV1 station on top of the reef

The expected outcomes of this research will be three scientific papers published in peer-reviewed international journals and a final thesis combining the three papers with additional subtopics relevant to PhD thesis requirements and standards. The proposed scientific papers and subject matter of each paper are as follow:

1- quantification of the dominant hydrodynamic processes in Ningaloo Reef through field observation
2- Prediction of circulation driven by wave, wind and tide within Sandy Bay-Ningaloo Reef through numerical modelling
3- Application of numerical model to quantify the hydrodynamics connectivity between different sections of Ningaloo reef

iv. Originality

In order to ensure that the proposed research does not duplicate work already done, an extensive literature search has been carried out to identify previous hydrodynamic studies on Ningaloo Reef and other related coral reef systems. A database of relevant journal papers and regional reports has been established in this study. Preliminary results of this study have already been presented in relevant conferences (Pattiaratchi 2008, Lowe et al. 2008, Taebi et al. 2007 and 2008) and has been discussed with many coral reef experts which ensures us the research is not duplicated or repeating any past or present research activities.

C. Scholars

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D. Bibliography

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E. Facilities

All software packages for conducting this research project (Matlab, ArcGIS, MIKE flow model and ROMS) are currently available at no cost to the project. We also have access to the IVEC supercomputing facility in WA for running simulations on multiple processors, as well as for data storage.

F. Estimated costs

The most expensive part of this research was the necessary field work at Ningaloo, however, this has already been completed (see section B.ii.1 and figure 3) through funding by Western Australian Marine Science Institute (WAMSI) for $500,000. This work was carried out by the School of Environmental Systems Engineering at UWA in collaboration with researchers Australian Institute of Marine Science (AIMS) and CSIRO. SESE has full access to the data and is the responsible party for analysing this dataset.
Importantly, this field work is not ongoing, so there won't be any further costs for field data collection. The current cost of this research will be photocopying, conference travel and miscellaneous expenses; this cost is estimated to be around $6,000 /year and will be covered by a WAMSI award to my supervisors.

G. Field work

This was already completed in 2006 - please see section B.ii.1 for more details.

H. Supervisors

Coordinating supervisor: Professor Charitha Pattiaratchi 40%
Co-supervisor: Professor Greg Ivey 20%
Co-supervisor: Dr. Ryan Lowe 30%
External supervisor: Dr. Graham Symonds (CSIRO) 10%

I. Confidentiality and intellectual properties

The thesis produced from this research is unlikely to contain any information of a confidential nature. There is no foreseeable intellectual property issue concerning this research.

J. Approvals

This project does not need any extra approvals.

APPENDIX 1 – Paper submitted for Kish Island Workshop

Hydrodynamic Modelling of Coral Reefs: Ningaloo Reef- Western Australia

Soheila Taebi[1], Ryan Lowe[1], Chari Pattiaratchi[1], Greg Ivey[1], Graham Symonds[2]
[1] School of Environmental Systems Engineering, University of Western Australia, Crawley, Western Australia
[2] Australian Commonwealth Scientific and Research Organization (CSIRO)

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.

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.

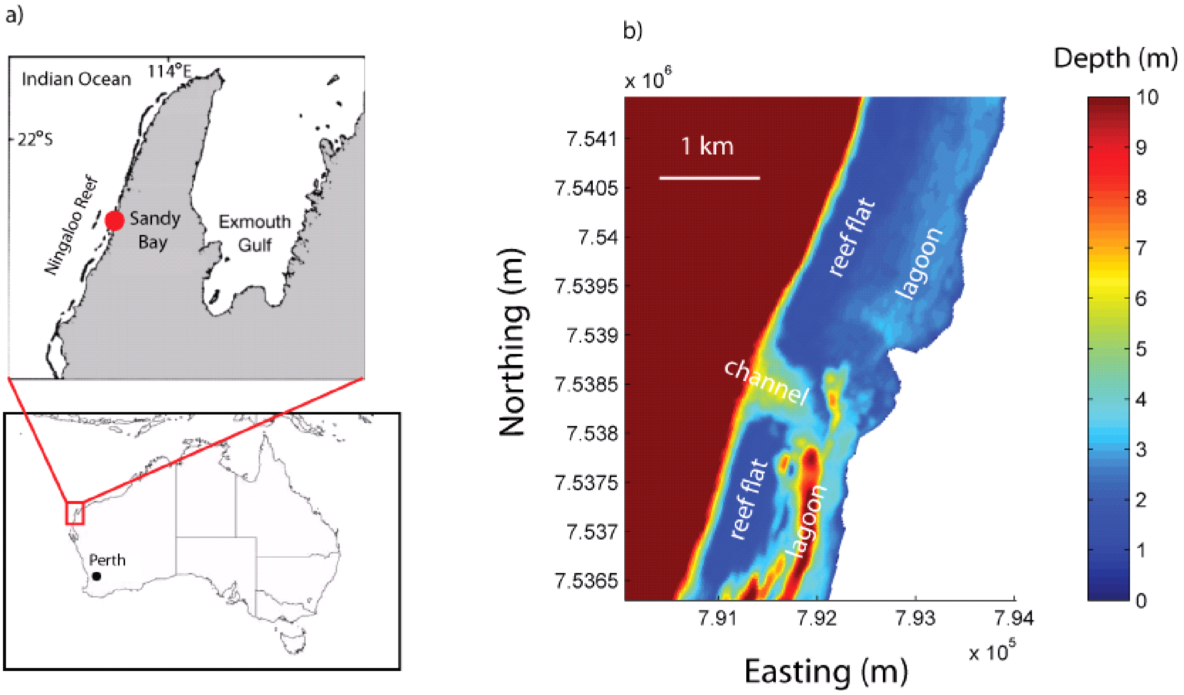


Figure 1.a) Map illustrating the study area. The field study will focus on a stretch of reef located in the Sandy Bay region of Ningaloo Marine Park b) Bathymetry derived from hyperspectral imagery (adapted from Lowe et al., 2008).

Hydrodynamic processes

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 & 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 & 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).

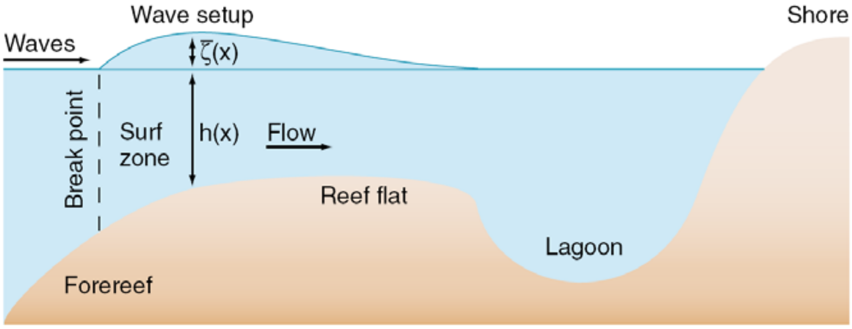


Figure 2. Definition sketch for wave-driven flow over a reef and into a lagoon (redrawn from Hearn 1999, courtesy of R. Lowe)

Methods

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 Figure 3.

Figure 3. Aerial photograph of the site with the instrument locations

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.

Numerical modelling

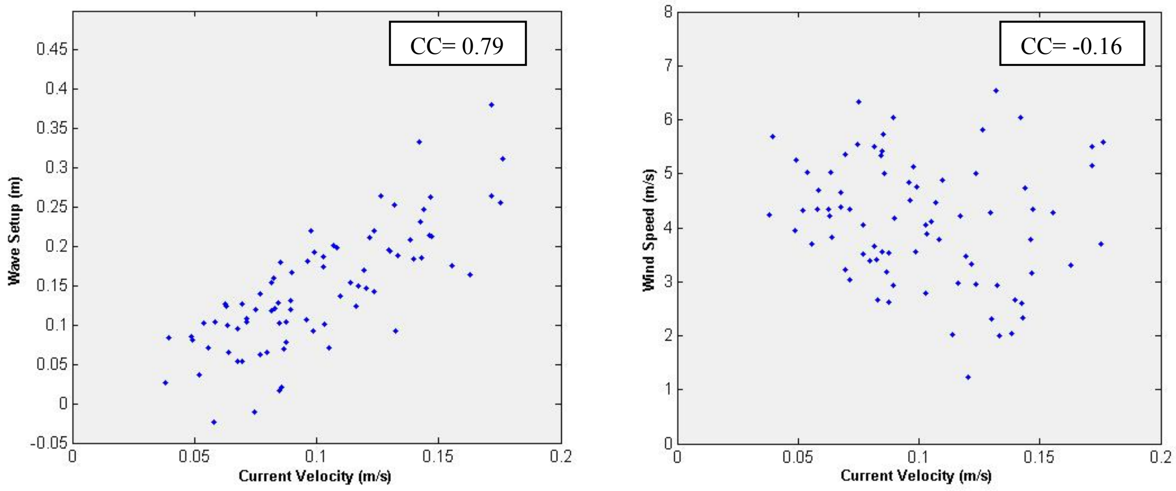
Numerical modelling of Sandy Bay commenced with a preliminary set of 6-week hourly simulations of waves in ~17 km alongshore x ~7 km cross-shore domain with 20 meter resolution domain. Based on the spectral wave action balance equation with sources and sinks, wave spectrum in the form of wave energy 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.

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 (Figure 4). Time series of current velocity in Figure 5 confirms a strong correlation between current velocity and wave setup on the reef flat.



(a) **(b)**

Figure 4. Scatter diagrams of current and forcing mechanisms (a. wave setup, b. wind speed)

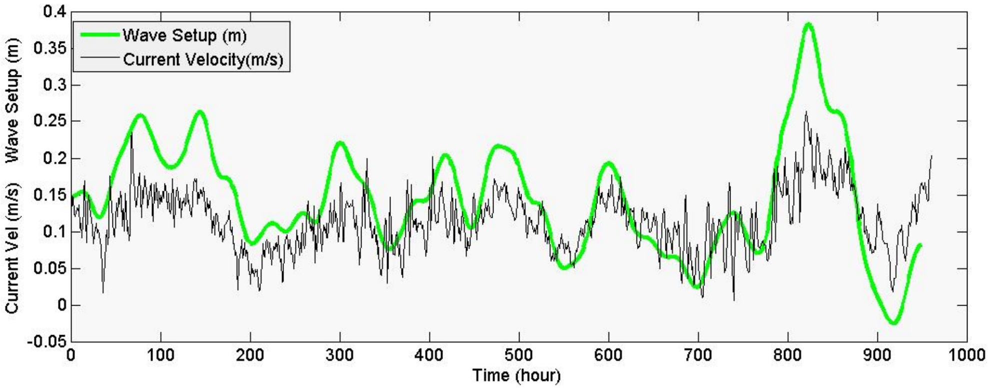


Figure 5. Wave setup and Current velocity in NTH_ADV1 station on top of the reef

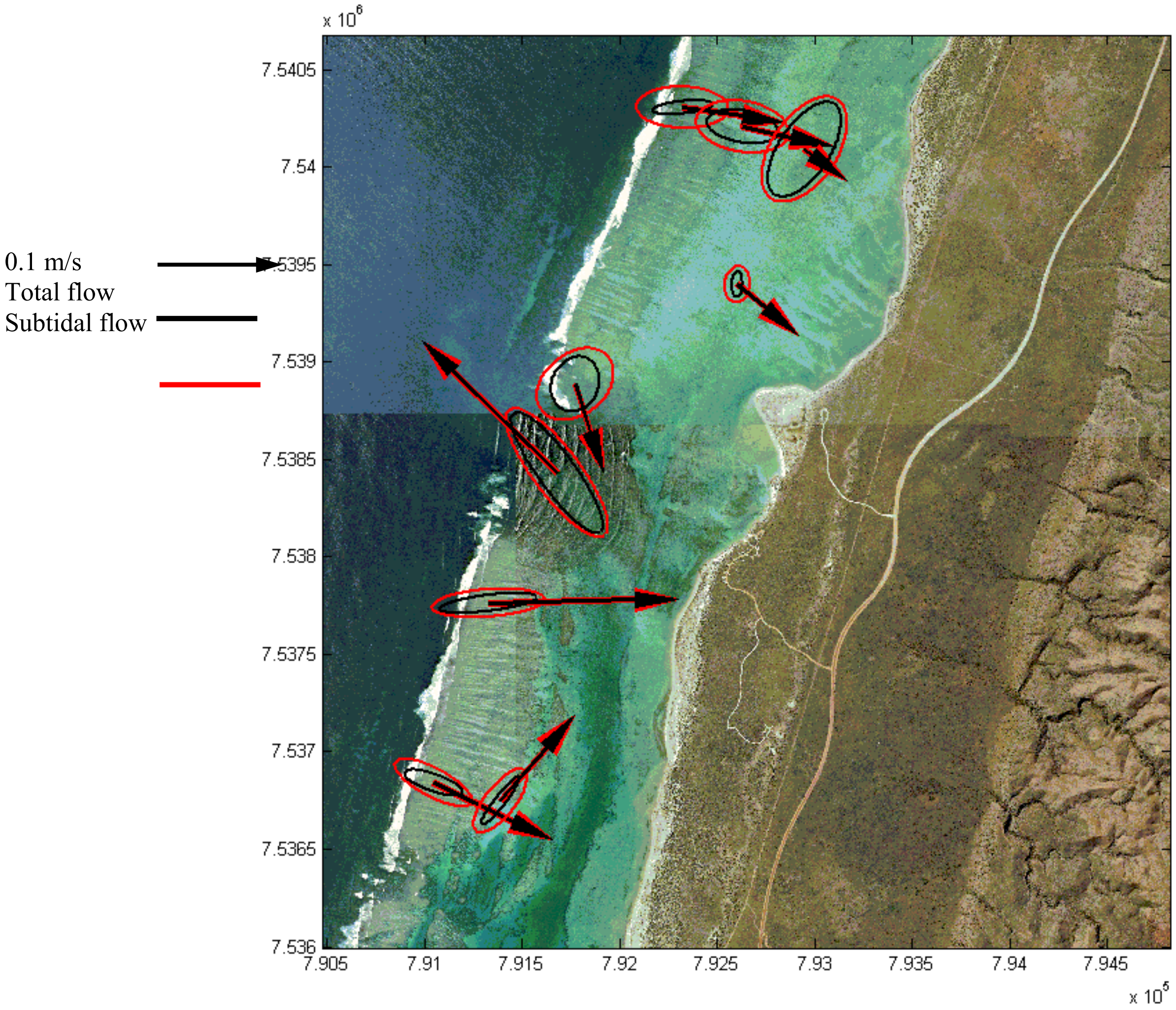


Figure 6. Reef-channel circulation derived from the 6week experiment. Arrows are the time-averaged current velocities and the ellipses represent the standard deviation of the current velocities in 2 axis

Circulation pattern in the reef-lagoon system is shown on Figure 6. 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.

A power spectral density plot of tidal level and current velocity measured on the reef flat is shown on Figure 7. 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.

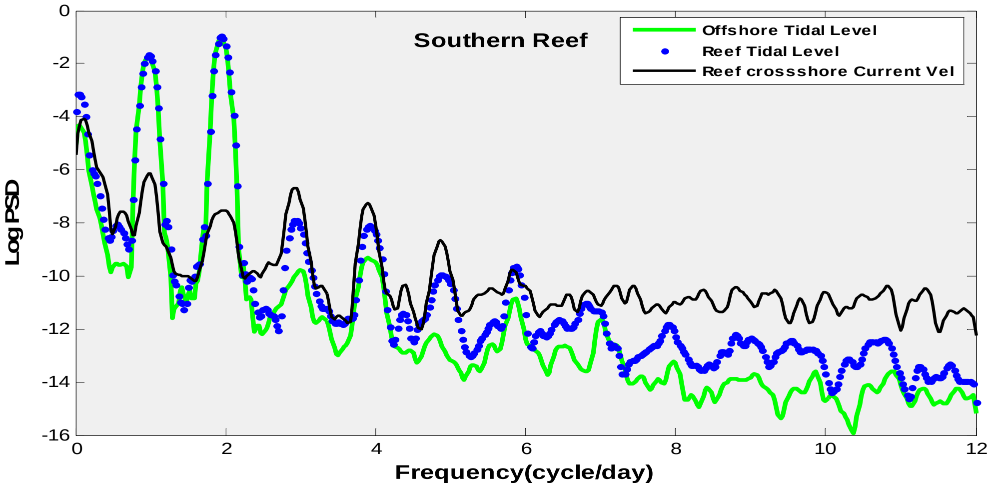


Figure 7. Power spectral density for tidal level and reef flat current velocity

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 8 shows results from a typical simulation of significant wave height in the ~20 km alongshore domain.

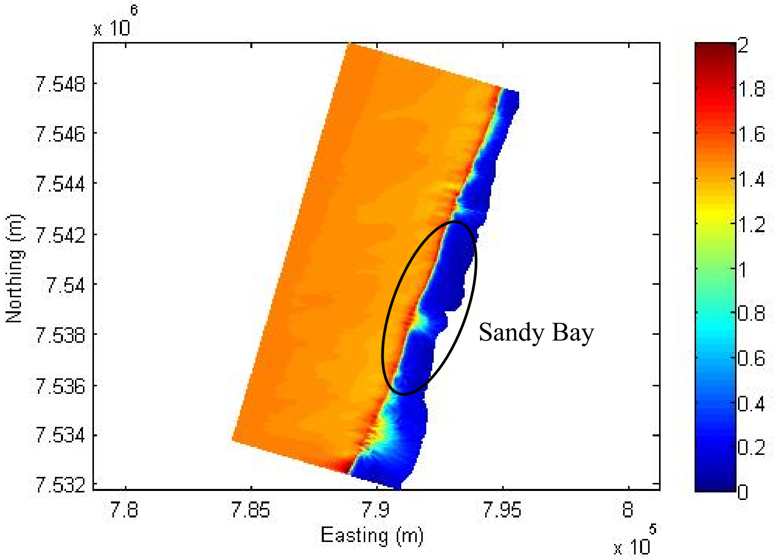


Figure 8. Simulated significant wave height at 18/05/06 10:00AM

The model was applied for different scenarios of bottom roughness (k_n) and wave breaking parameter (γ) 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 (Figure 9).

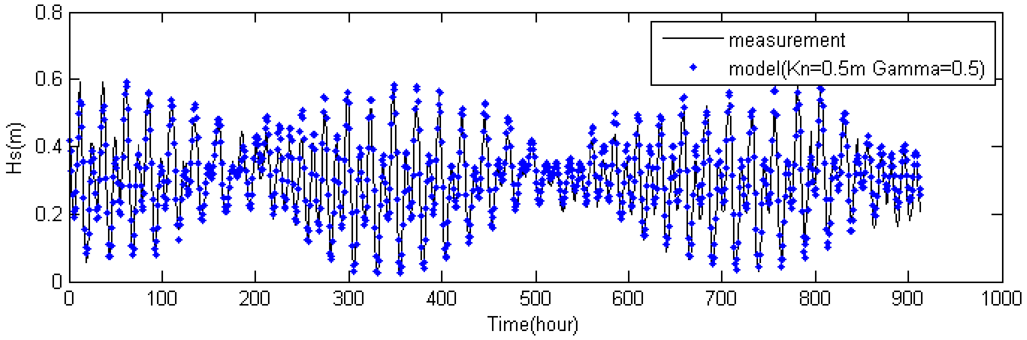


Figure 9. Significant Wave Height from modelling and measurement in NTH_ADV1 station on top of the reef

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).

$$Model\ Skill = 1 - \frac{\sum |X_{model} - X_{obs}|^2}{\sum \left(|X_{model} - \overline{X_{obs}}| + |X_{obs} - \overline{X_{obs}}|\right)^2} \qquad \text{(eq. 1)}$$

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

Summary and conclusion

Arial photography and hyperspectral bathymetry which is released recently 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 have been recorded in a 6 week experiment in 2006. Scatter plots of current velocity and forcing mechanisms show a strong correlation between current velocity on reef flat and wave setup, while there is no correlation between current velocity and wind speed.

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

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

Acknowledgement

We thank Wojciech Klonowski and Merv Lynch at Curtin University for providing access to preliminary hyperspectral bathymetry data. We also thank Richard Brinkman from Australian Institute of Marine Science for assisting with the collection of the field data.

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APPENDIX 2 – UWA PhD Proposal

A. Proposed Study

iii. Title

Hydrodynamic Processes of Fringing Reef Systems: Ningaloo Reef, Western Australia

iv. Contribution to scholarship

The only major study of hydrodynamics on Ningaloo Reef was undertaken by Hearn et al. (1986). They believed that effective management of the Ningaloo Reef system, and coral reefs more generally, is dependent upon an understanding of the key ecological processes of the system, which ultimately relies upon a basic understanding of physical oceanographic processes. Therefore, they attempted to lay a foundation for future programme of physical studies by using knowledge of processes on coral reefs and applying this specifically to the Ningaloo Reef tract. Their report draws on regional oceanographic information about large-scale oceanography (stratification, tides, internal waves), and reef-lagoon oceanography (wave pumping, tidal currents, wind forcing, flushing time), much of which comes from oil and gas exploration and extraction described in reports by Meagher (1980), May et al. (1983), Simpson and Masini (1986), Simpson (1985). They have emphasised the general need to assemble a basic understanding of the physical processes which operates within the reef and lagoon. Hearn et al. (1986) at the end of their report recommended minimum data set of tides, current, wind, wave and bathymetry to be provided by oceanographers to be used in environmental resources management plan. Although the report was a good reference at that time, there are very limited measurements and no numerical modelling and hardly can get detailed information about physical processes of Ningaloo reef-lagoon system from it.

A special feature of the Ningaloo Reef tract is the existence of shallow, narrow, long coastal lagoon close to the shelf break. An ideal region would have a long length of unbroken reef with a major break towards its southern boundary and the report suggests a suitable study region can be centred on Sandy Bay and both field work and numerical modelling to be done for the area. It is interesting that the whole Ningaloo Reef is the body of several small reef-channel systems, therefore an efficient approach would be to find out the physical process in one small system through an extensive research and extend the study to the whole region.

The scientific contribution from this research will advance the understanding of oceanographic processes along the Ningaloo Reef in North West of Western Australia. There is not much known about oceanographic process of Ningaloo Reef in detail so far, and this research aims to fill this gap by developing tools that can be used to accurately predict the ocean circulation over this reef.

B. Research Plan

v. Literature review

The Ningaloo Reef tract lies on the western coast of Australia between 21° and 24° S latitude and along longitude 113° 30′ E. 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.

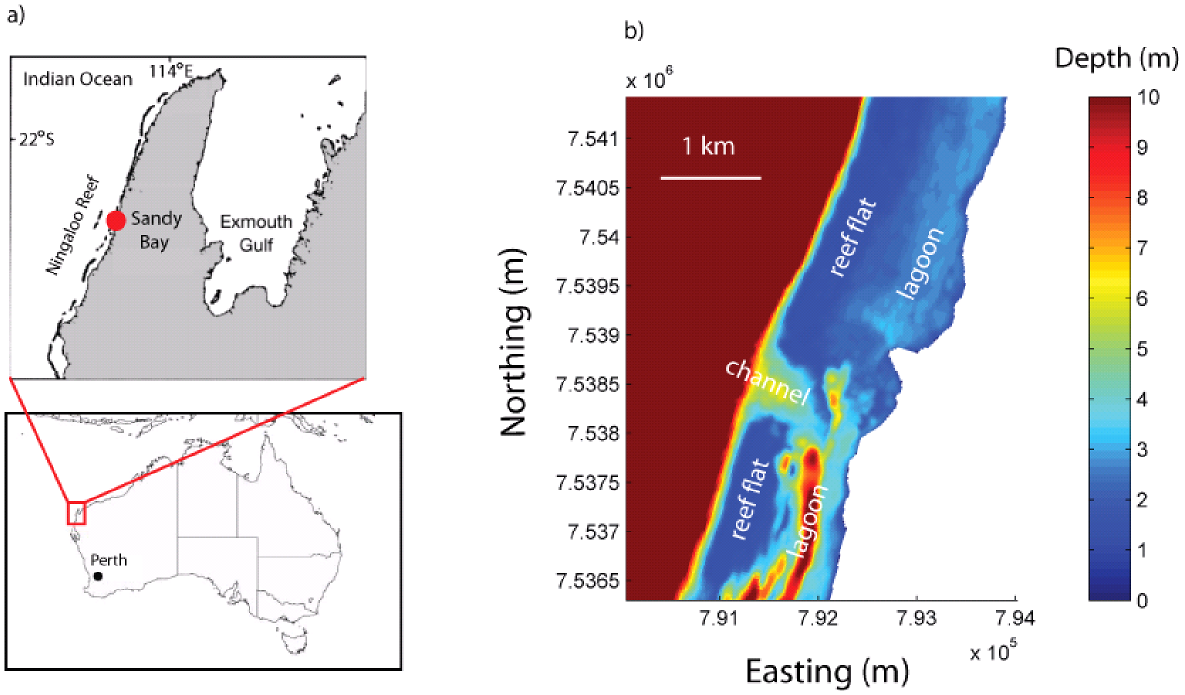

Figure 1.a) Map illustrating the study area. The field study will focus on a stretch of reef located in the Sandy Bay region of Ningaloo Marine Park b) Bathymetry derived from hyperspectral imagery (adapted from Lowe et al., 2008).

Ningaloo Reef is significant for both its size and ecological composition. The reef supports a high biodiversity of more than 500 fish species, over 200 species of coral, and 600 species of molluscs. The local coral communities contain both species typical of the tropical Indo-Western Pacific region as well as temperate species that are at the northern limit of their distribution in WA. Ningaloo Reef is rapidly gaining an international reputation for nature based tourism, due to easy access to the reef from shore and the unique wildlife present (Environment Australia, 2002). The Ningaloo Marine Park possesses a range of areas of natural and international significance. Its water has been divided into sanctuary zone, recreation zone and general use zone. Protection of the Ningaloo coral reef system is one important aspect in the regional strategy plan. The reef sits very close to the shoreline and any shore based development potentially may have more significant impact than the case of Great Barrier Reef (Ningaloo coast regional strategy, 2004).

Like all coral reefs, the ecology of the Ningaloo Reef system is closely linked to water motion, which transports and disperses vital material such as nutrients and larvae. For example, it has been shown that nutrient uptake by coral reefs is positively correlated to large-scale roughness and to excess wave height (above the breaking height) of incoming waves (Hearn et al., 2001).

i.1. Large scale 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 pole ward (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 (~1.4×106 m^3/s) as it flows against maximum southerly (opposing) winds and flows strongly (~7×106 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, which has similar water characteristics to the Leeuwin current, is also associated with upwelling and high primary productivity with distinct phytoplankton species (Hanson et al., 2005; Woo et al., 2006; Willis, 2007). The presence of the Ningaloo current and has major implications for various biological systems in the region. It is therefore of vital importance that a full understanding of this regional circulation at Ningaloo be developed (Taylor and Pearce, 1999).

i.2. Nearshore hydrodynamic processes

Circulation over shallow reefs can be driven by a number of forcing mechanisms including waves, tides, wind, and buoyancy effects (Andrews & Pickard, 1990). The relative importance of each mechanism varies among reefs and is a function of both a reef's morphology and the forcing conditions present 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 & 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; Gourlay, 1996b; 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.

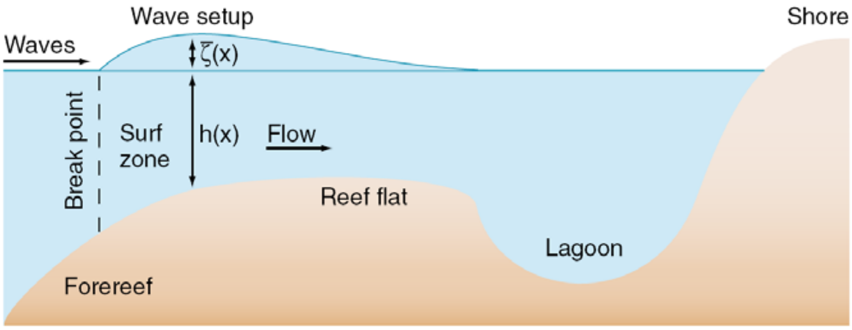

Figure 2. Definition sketch for wave-driven flow over a reef and into a lagoon (redrawn from Hearn 1999, courtesy of R. Lowe)

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.

vi. Project aim

The overall aims of this project are to investigate and quantify the hydrodynamic processes of Ningaloo Reef in Western Australia by:

1. Identifying hydrodynamic processes in the reef lagoon system using field data, collected on a small (~5 km alongshore) section of Ningaloo at Sandy Bay.

2. Investigating the relative importance of the major hydrodynamic processes in the reef lagoon system using numerical techniques – evaluated against the measurements for Sandy Bay.

3. Applying a numerical model to investigate the hydrodynamic connectivity between the local reef-lagoon system and the whole of reef scale including the offshore ocean waters, thereby aiding in the improved management of the system.

vii. Methodology

iii.1. Field study

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 subsequent analysis and interpretation of this existing data will be a key component of the proposed Ph.D. research. The reef morphology in this region is fairly typical of the Ningaloo system, with a simple configuration of shore-parallel reef sections. The six-week field campaign, undertaken as a joint collaboration between UWA, CSIRO and AIMS, measured key hydrodynamic variables at 25 sites spanning the lagoonal waters to the front reef slopes (Figure 3) and the role of UWA is to analyze the data obtained from campaign. 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.

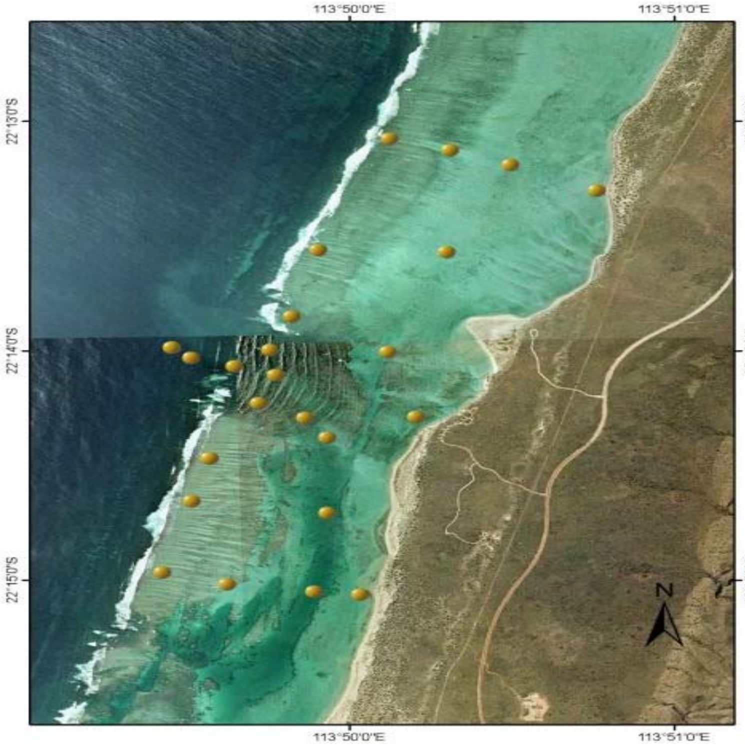

Figure 3. Aerial photograph of the site with the instrument locations

The data set includes hourly measurements of wave, current, mean water level and temperature at a number of sites on: (1) the forereef (10~15 meter depth), (2) the reef flat (1~2 meter depth) and (3) the northern and southern lagoon (respectively 2~4 meter and 5~8 meter depth). This extensive data set will be used to investigate how the dominant circulation of Sandy Bay responds 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.

iii.2. Numerical modeling

Numerical modeling of Sandy Bay has been started with a preliminary set of 6-week hourly simulations of waves in 20 meter resolution domain (Figure 1). Based on the wave action balance equation with sources and sinks, the deep wave model incorporates formulations for the processes of wave generation, dissipation and the quadruplet wave-wave interactions. In shallow water, these processes need to be supplemented with the dissipation due to bottom friction, triad wave-wave interactions and depth-induced breaking. All information about the sea surface is contained in the wave variance spectrum or energy density E (σ; θ), distributing wave energy over frequencies and propagation directions. Usually, wave models determine the evolution of the action density N(x; t; σ; θ) in space x and time t. The action density is defined as N = E/ σ and is conserved during propagation in the presence of an ambient current, whereas energy density E is not (Whitman, 1974). In brief, six processes contribute to total energy (S_{tot}) in shallow water:

$$S_{tot} = S_{in} + S_{nl3} + S_{nl4} + S_{ds;w} + S_{ds;b} + S_{ds;br} \qquad \text{(Eq. 1)}$$

These terms denote, respectively, wave growth by the wind, nonlinear transfer of wave energy through three-wave and four-wave interactions and wave decay due to whitecapping, bottom friction and depth-induced wave breaking. The last two terms, bottom friction and depth-induced wave breaking, are nearshore processes, where a bottom roughness (K_n) and wave breaking parameter (γ), respectively, are used to parameterize dissipation.

The numerical circulation model (coupled to the numerical wave model) will be based on the solution of the 3-D incompressible Reynolds averaged Navier-Stokes equations. Equations of conservation of mass and momentum will be solved numerically and the second order stresses due to breaking of short period waves will be included in the flow simulation. Radiation stress act as driving forces for the mean flow and will be used to calculate wave–driven flows. Currently we are evaluating two similar coupled wave-circulation models for this application: 1) the circulation model ROMS (Shchepetkin and McWilliams, 2005) forced by the numerical wave model SWAN (Booij et al., 1999), and 2) a coupled wave-circulation model based on DHI's MIKE21 modelling suite (DHI, 2008).

iii.3. Preliminary results

A preliminary analysis of this field data set has been conducted by processing raw data obtained from measurements and looking at wave, tide and current time series. Results of the first stages of current study shows 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 on reef flat and the possible forcing mechanisms, shows strong correlation of currents with wave-setup while there is no clear correlation with wind speed (Figure 4). Time series of current velocity in Figure 5 confirms a strong agreement between current velocity and wave setup in reef flat.

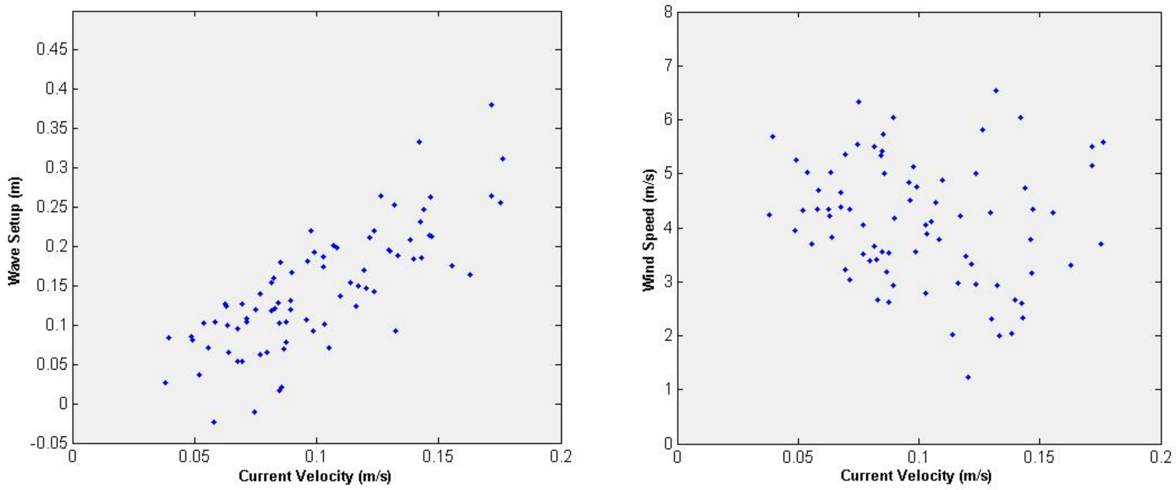

Figure 4. Scattering diagrams of current and forcing mechanisms (wave setup and wind)

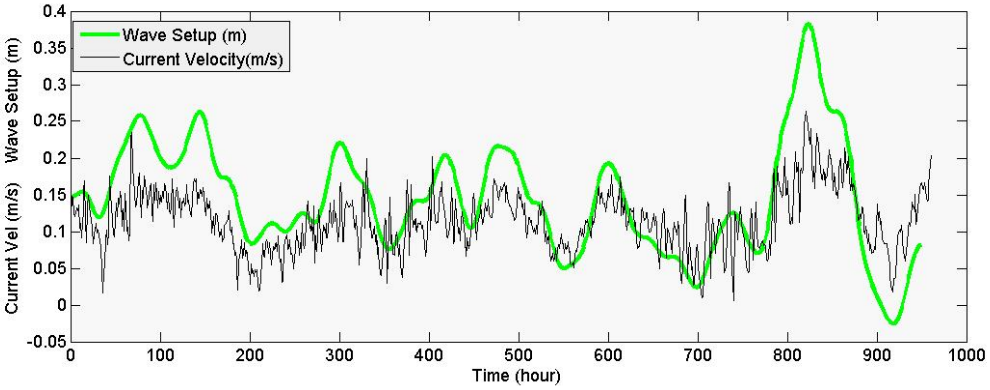

Figure 5. Wave setup and Current velocity in NTH_ADV1 station on top of the reef

A preliminary 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 6 shows typical simulation of significant wave height in ~20 km alongshore domain. Results have been evaluated against measurements, with a particular emphasis on reef flat wave height (Figure 7).

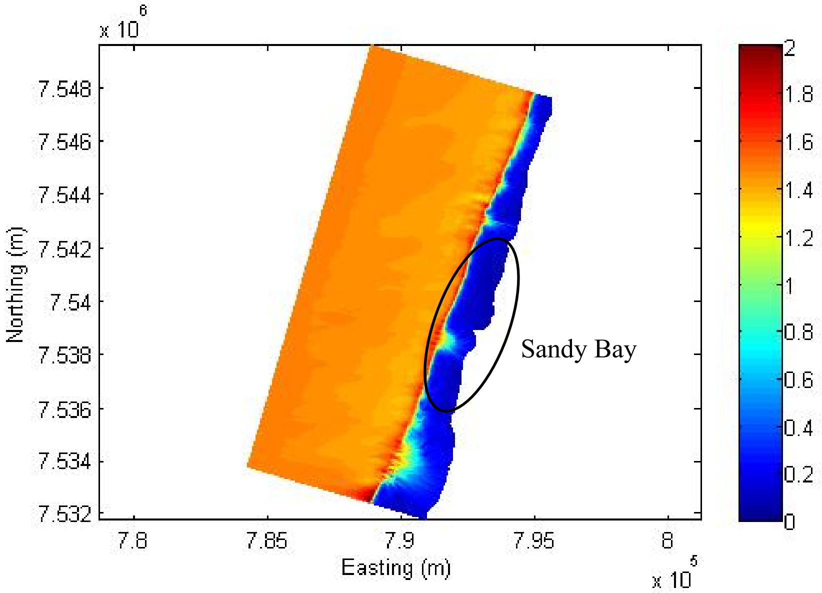

Figure 6. Simulated significant wave height at 18/05/06 10:00AM

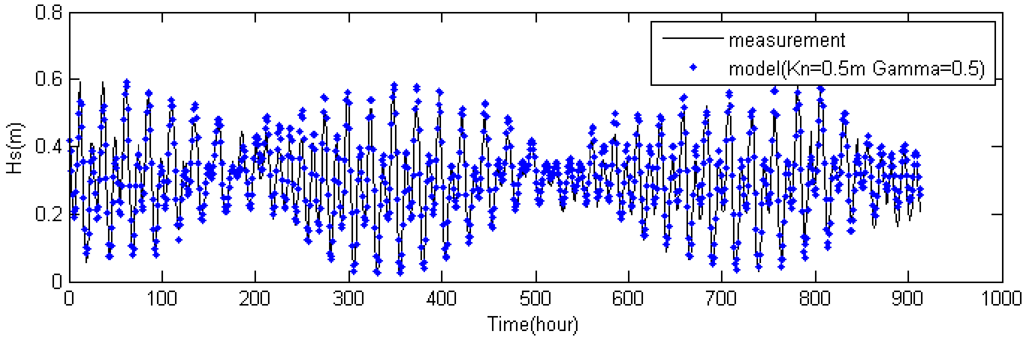

Figure 7. Significant Wave Height from modelling and measurement in NTH_ADV1 station on top of the reef

The expected outcomes of this research will be three scientific papers published in peer-reviewed international journals and a final thesis combining the three papers with additional subtopics relevant to PhD thesis requirements and standards. The proposed scientific papers and subject matter of each paper are as follow:

4- quantification of the dominant hydrodynamic processes in Ningaloo Reef through field observation
5- Prediction of circulation driven by wave, wind and tide within Sandy Bay-Ningaloo Reef through numerical modelling
6- Application of numerical model to quantify the hydrodynamics connectivity between different sections of Ningaloo reef

viii. Originality

In order to ensure that the proposed research does not duplicate work already done, an extensive literature search has been carried out to identify previous hydrodynamic studies on Ningaloo Reef and other related coral reef systems. A database of relevant journal papers and regional reports has been established in this study. Preliminary results of this study have already been presented in relevant conferences (Pattiaratchi 2008, Lowe et al. 2008, Taebi et al. 2007 and 2008) and has been discussed with many coral reef experts which ensures us the research is not duplicated or repeating any past or present research activities.

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E. Facilities

All software packages for conducting this research project (Matlab, ArcGIS, MIKE flow model and ROMS) are currently available at no cost to the project. We also have access to the IVEC supercomputing facility in WA for running simulations on multiple processors, as well as for data storage.

F. Estimated costs

The most expensive part of this research was the necessary field work at Ningaloo, however, this has already been completed (see section B.ii.1 and figure 3) through funding by Western Australian Marine Science Institute (WAMSI) for $500,000. This work was carried out by the School of Environmental Systems Engineering at UWA in collaboration with researchers Australian Institute of Marine Science (AIMS) and CSIRO. SESE has full access to the data and is the responsible party for analysing this dataset.
Importantly, this field work is not ongoing, so there won't be any further costs for field data collection. The current cost of this research will be photocopying, conference travel and miscellaneous expenses; this cost is estimated to be around $6,000 /year and will be covered by a WAMSI award to my supervisors.

G. Field work

This was already completed in 2006 - please see section B.ii.1 for more details.

H. Supervisors

Coordinating supervisor: Professor Charitha Pattiaratchi 40%
Co-supervisor: Professor Greg Ivey 20%
Co-supervisor: Dr. Ryan Lowe 30%
External supervisor: Dr. Graham Symonds (CSIRO) 10%

I. Confidentiality and intellectual properties

The thesis produced from this research is unlikely to contain any information of a confidential nature. There is no foreseeable intellectual property issue concerning this research.

J. Approvals

This project does not need any extra approvals.