FINAL WAMSI PROJECT REPORT

Instructions for Use: Please complete each of the tables below and return to (insert Node Science Coordinator's name and email contact details).

Project Details

Project Number and Title:	6.2: Impact of tides and internal waves on offshore engineering
Node Leader:	Professor Greg Ivey, School Environmental Systems Engineering & UWA Oceans Institute, University Western Australia
Project Leader:	Professor Greg Ivey, School Environmental Systems Engineering & UWA Oceans Institute, University Western Australia
Project Team:	
Project Start Date:	1 July 2007
Project End Date:	30 June 2011
Due Date for Final Report:	1 July 2011
Project Team:	G.N. Ivey, N.L Jones, M.Rayson, C.E. Bluteau, P. van Gastel, M. Meuleners
Project Funding: WAMSI $ Additional Cash $ Additional In-Kind $ Total Funding $	

1. Project Objectives and Achievement Criteria

Confirmation of the project objectives and the delivery of milestones against the Key Performance Indicators:

Objectives:

Understand and quantify the mechanisms of tidally driven internal wave generation, propagation and dissipation at shelf break field sites near North Rankin A, representative of the southern portion of the North West Shelf (NWS).

Understand and quantify the mechanism of tidally driven internal wave generation, propagation and dissipation at field sites near Scott Reef and Browse Basin, representative of the northern portion of the North West Shelf (NWS).

Deliverables:

Physical oceanographic database from field measurement programs.

Hybrid suite of multi-scale, high-resolution numerical ocean circulation models for ocean modelling and forecasting.

Milestones and Reports:

Report 1

- Review literature, historical data from NRA - achieved
- Progress BLUElink/ROMS model output - achieved
- Refine research strategy – achieved

Report 2

- Completion of journal article on internal waves near NRA (output 1)- achieved

- Design and construction of IWAG field instrument - achieved
- Commence review of historical data from Browse Basin - achieved

Report 3

- Deploy IWAG off NRA and commence data analysis - achieved
- Commence numerical modelling at Browse Basin – achieved
- Journal article on internal waves near NRA submitted (output 2) - achieved

Report 4

- IWAG instrument at NRA data analysis - continuing
- Numerical modelling at Browse Basin – continuing
- Journal article describing ocean dynamics and role of internal waves in Browse Basin submitted (output 4) - achieved

Report 5

- IWAG instrument at NRA data analysis – almost complete
- Numerical modelling at Browse Basin (Scott Reef area) using SUNTANS – continuing
- Journal article describing results data analysis from IWAG instrument deployed at NRA submitted (output 3) – achieved.
- Deploy IWAG instruments within Browse Basin Array March 2010 to June 2010 – achieved.

Report 6

- IWAG instrument at NRA data analysis – almost complete
- Numerical modelling at Browse Basin (Scott Reef area) – continuing, using SUNTANS
- Deploy IWAG instruments within Browse Basin Array March 2010 to June 2010 – achieved.

Report 7

- Numerical modelling at Browse Basin (Scott Reef area) – completed.
- Journal article describing internal wave boundary layer dynamics on NWS submitted (output 5) - achieved

Report 8

- Journal article using SUNTANS Numerical modelling at Browse Basin submitted (Scott Reef area)
- Journal article describing mixing in bottom boundary layer submitted and attached (Bluteau et al 2011c).
- Journal article describing internal wave climatology and mixing in Browse Basin Bluteau, Jones and Ivey (2011d) attached (output 6).
- Final Project Report for 6.2 (current report) submitted – achieved.

In summary, all milestones met, all six outputs achieved. In fact two additional journal paper outputs were completed exceeding the original scope of outputs (see Section 4 for complete list).

2. Research Chapter(s)

a) Introduction

The project aim was to provide a comprehensive understanding and predictive capability of the tidal motions and tidally driven internal wave climatology on the Australian North West Shelf. This covers the generation, propagation and dissipation of internal waves and quantitative assessment of the intensity, spatial and temporal distribution of the currents and turbulence induced by these internal waves. The integration of field measurements, the development and application of hybrid numerical circulation models and some focussed laboratory experiments will accomplish these goals.

Industry has been actively making field measurements at many sites on the NWS for decades and this wealth of data and knowledge is an enormous resource that this project has drawn from and builds upon. This project effectively started in 2004 with funding from Woodside for a unique field experiment conducted in 125 m of water adjacent to the North Rankin A (NRA) oil and gas platform. Instrumentation supplied and deployed by MetOcean Engineers (MOE) was used to set up an intensive 'L-shaped' array of current meters extending over scales of order 3 km to intensively sample for the first time the intensity, spatial and directional characteristics of the vigorous internal wave field propagating through the region from March to June 2004. These data have provided an understanding of the seasonal variation of the large amplitude internal waves at this location. Work has focussed on the NRA location because of both the wealth of information there as well as it is a site of known extreme internal wave behaviour. However, an extensive field data sets was collected in the macro-tidal environment of the Browse Basin in the. Finally a third field data set was collected in the relatively small tidal environment offshore of Ningaloo Reef. Together these three data sets provide a comprehensive view of the tidally driven internal wave climate over the entire North West Shelf.

Concurrent with the field program, a numerical modelling program was conducted to model and predict the internal wave characteristics. The modelling approach is widely applicable. To model processes occurring over the vast range of physical scales on NWS, diverse numerical models are required and the focus has on the use of two complementary models: ROMS and SUNTANS. ROMS (**R**egional **O**cean **M**odelling **S**ystem) is an open source sigman coordinate hydrostatic numerical circulation model. SUNTANS (**S**tanford **UN**s**T**ructured **A**daptive **Na**vier Stokes **S**olver) is a fully non-hydrostatic model and is run in unstructured domains of approximately 100 km by 100 km with horizontal spatial resolution down to scales of 10 m. It is computationally intensive model requiring large parallel machine computations and is able to resolve the high-energy non-hydrostatic internal waves which are seen at some locations on the NWS. ROMS itself needs large-scale climatological ocean information and this was by using the BLUELink model. BLUELink is developed by BMRC/CSIRO and is a basin scale, data assimilating z-coordinate circulation model with spatial resolution of about 10 km on the NWS.

The combination of the field data program and the numerical program, augmented by laboratory and theoretical development, was the core approach adopted in Project 6.2.

b) Methodology - further details provided below in (3)

The work over the period 2004-7 has thus focussed on one specific site on the North West Shelf in vicinity of NRA. This is location where large amplitude internal waves are known to propagate, but the waves themselves form in much deeper water some 100 km away on the shelf break and evolve considerably before reaching NRA. Two further field sites are needed to capture the diverse character of internal waves on the NWS. Firstly, a deep-water site in approximately 500 m of water 100 km North West of North Rankin is the proposed site of a field program in early 2008 and 2009. While not an area of industry activity, this area appears a prime location for the generation of internal waves and an experiment to examine the benthic generation of internal waves is proposed at this location in 2008 and 2009. This experiment would involve fixed measurement arrays and flying ocean gliders from offshore and into shallow waters around North Rankin. The second proposed site would be near Scott Reef in the far north. This area is a site of current industry activity and the proposal is to augment this on-going measurement program in late 2008 with a specialist benthic array experiment to quantify and to fly ocean gliders in the vicinity at the time to obtain spatial pictures of the ocean conditions in the region. These three diverse experimental sites would provide high quality temporal and spatial information about the internal wave dynamics and this is essential for the development and testing of the numerical modelling aspect of the project.

In summary the objectives are to undertake field measurement arrays at physically diverse locations to determine characteristics of tides and internal waves in the energetic tidal-dominated environment of NW Western Australia

1) North Rankin measurement/modelling program.

2) Browse Basin and Scott Reef measurement/modelling program.

3) Ningaloo Reef measurement program.

ROMS (**R**egional **O**cean **M**odelling **S**ystem) is an open source hydrostatic numerical circulation model developed with funds from the National Science Foundation and available freely for research groups. In this application, ROMS is driven by the tidal model OTIS v2.1 and is applied to the North West Shelf with varying domain scales of up to approximately 2000 km by 800 km, and with horizontal spatial resolution down to scales of order 3 km and with 40 sigma layers in the vertical. ROMS is typically run on timescales of months and, in turn, drives SUNTANS. SUNTANS (**S**tanford **UN**s**T**ructured **A**daptive **Na**vier Stokes **S**olver) is a fully non-hydrostatic model and is run in unstructured domains of approximately 100 km by 100 km with horizontal spatial resolution down to scales of 10 m and with 120 z-layers in the vertical. It is computationally intensive requiring large parallel machine computations and is able to resolve the high-energy non-hydrostatic internal waves, which are seen on the NWS.

ROMS itself needs large-scale climatological ocean information and, starting in 2007, this process has begun with by using the BLUELink model. BLUELink is currently being developed by BMRC/CSIRO and is a basin scale, data assimilated z-coordinate circulation model with spatial resolution of about 10 km on the NWS has just become available in 2007. We are currently evaluating it and working to use the output of BLUELink to drive ROMS. The ultimate goal is to have a three component modelling system consisting of BLUELink/ROMS/SUNTANS which is tested, evaluated and developed against field measurements that can ultimately be used as a predictive tool.

c) Results - further details provided below in (4)

All goals of the project were accomplished. The results can be summarised as:

- Successful field measurement programs were conducted at three separate field sites: Offshore North Rankin A (NRA), Browse Basin, and offshore of Ningaloo Reef
- Field experiments involved measurement of both mean flow quantities and, for the first time ever on the NWS, direct measurements of turbulent mixing
- Completion of numerical modelling was successfully undertaken, using both the ROMS and SUNTANS numerical models, for the NRA area and the Browse Basin area
- Laboratory and theoretical modelling was completed to complement the field and numerical modelling activities described above
- Four PhD students from UWA have been involved in the project; the first two completing theses in 2010 and 2011, and two more will complete theses by November 2011.
- Four Final Year undergraduate Honours students have completed individual research theses over period 2007-2010.

- A total of 11 refereed journal and conference papers have been produced
- A total of 13 presentations have been given at national and international conferences

d) Discussion - further details provided below in (5)

The conditions for creating internal waves are met throughout the NWS and they must be considered in engineering design at any location. Internal waves are generated by the tide in depths ranging from 100 m to 1500 m, approximately. They induce both strong horizontal bottom velocities as well as transmit large amounts of energy from one location to another. The character and the strength of the internal waves vary dramatically from location to location, as well as seasonally as the density stratification varies. On the southern part of the Shelf, internal waves are much stronger in summer than winter, for example.

In the Browse Basin, the topography is very complex, internal waves propagate in all directions and there is evidence of standing internal waves being present (Rayson et al 2011). This is important as it makes the interpretation of measurements from a single mooring of the internal wave climate, for engineering design purposes for example, very difficult. Design must therefore be done with a combination of both direct measurements and numerical modelling to quantify the internal wave field.

Mixing and turbulence measurements, conducted for first time on the NWS, in this project revealed the intense nature of the turbulent mixing that can occur in the bottom boundary layer, an area of great importance for bottom pipeline stability and engineering infrastructure. Turbulence is generated by tidal motion moving density-stratified fluid up and down the bottom. The mixing is present throughout the tidal cycle although it varies in intensity during the up and down slope phase of the motion. The measurements in 400 m (Bluteau et al, 2011) showed that the traditional method of using mean velocity measurements to infer bottom stress by assuming the logarithmic boundary layer profile is not valid. Alternative means must be used to infer bottom stress and hence stability of the bottom surface.

e) Acknowledgements

WAMSI
Woodside and Chevron via the NASS JIP
Australian Research Council Discovery Grants Program
Australian Institute of Marine Science
UWA for in-kind salary support for investigators and for scholarships funds for some of the PhD students

f) References

Bluteau, C.E., Jones, N.L. and G.N. Ivey (2011). Turbulent mixing in a tidally forced stratified shear f1ow on the continental slope. *Journal of Geophysical Research, submitted*

Rayson, P., M. Meuleners, G.N. Ivey, N. Jones and G. Wake (2011) Field and numerical study of the internal tide dynamics in the Browse Basin, Australian North West Shelf. *J. Geophys. Res. Oceans,* 116: C01016.

3. Methodology

Summarise the method(s) utilised as part of the project and provide a listing of the sub-projects (if appropriate). Sub-project reports should be provided as annexures to this project report.

Project methods involved combination of direct field measurements and numerical modelling, and these were combined with laboratory and theoretical development, to realise the objectives of the project. Field measurement of tides and internal waves in the energetic tidal-dominated environment of NW Western Australia were conducted at three locations (see map):

1) North Rankin measurement/modelling program.

2) Browse Basin and Scott Reef measurement/modelling program.

3) Ningaloo Reef measurement/modelling program.

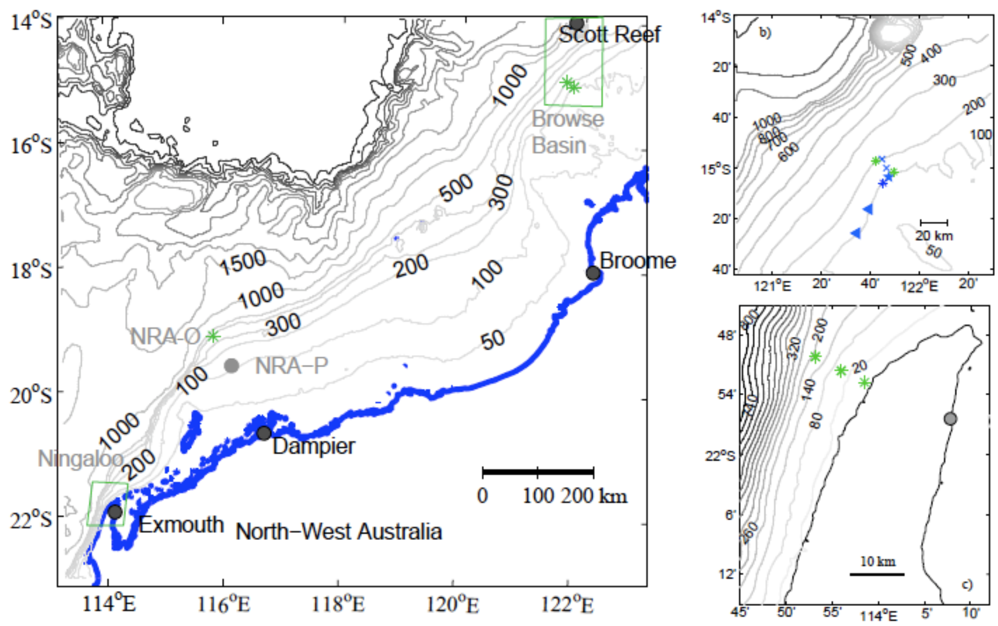

Fig 1 Location of field sites on the Australian NWS (b) Inset showing placement of the Browse moorings and (c) those at Ningaloo.

Field instrumentation was centred around the use of a novel high resolution turbulence resolving measurement program, augmented with background field data mainly collected by our industry partners and, in the case of the Ningaloo work, by AIMS. A schematic of this instrument as configured for the NRA-O deployment is shown below.

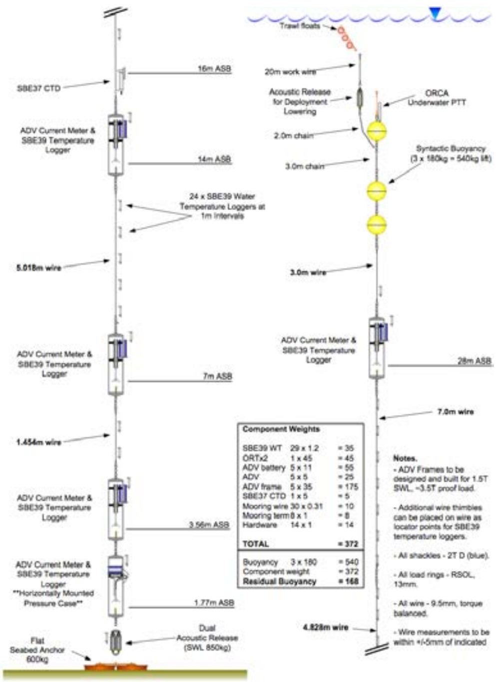

Fig 2 Field instrument system in configuration employed on NWS at NRA-O

Numerical models

ROMS (**R**egional **O**cean **M**odelling **S**ystem) is an open source hydrostatic numerical circulation model developed with funds from the National Science Foundation and available freely for research groups. In this application, ROMS is driven by the tidal model OTIS and is applied to the North West Shelf with varying domain scales of up to y 2000 km by 800 km, and with horizontal spatial resolution down to scales of order 2 km and with 50 sigma layers in the vertical. ROMS is typically run on timescales of months.

SUNTANS (**S**tanford **UN**s**T**ructured **A**daptive **Na**vier Stokes **S**olver) is a fully non-hydrostatic model and is run in unstructured domains of approximately 100 km by 100 km with horizontal spatial resolution down to scales of 10 m and with 120 z-layers in the vertical. It is computationally intensive requiring large parallel machine computations and is able to resolve the high-energy non-hydrostatic internal waves, which are seen on the NWS.

Field data is used to test and evaluate the performance of the models.

4. Results

Present the results of the project and attainment of scientific objectives. Assess the success of meeting each objective identified in the proposal, as initially approved or later modified. For each objective:

1. Re-state the objective,
2. Tell the degree to which it has been met, and
3. Describe the technical findings and conclusion in a paragraph or two. This language should be informative, not just indicative (i.e., don't say "a new process was developed," but rather "the XYZ method increases productivity by 20 %"). A sample statement might begin, "Objective 1 -- To increase survival of juvenile...by 50%. This objective has been met. Survival of……..was increased 67% by altering culture tanks in the following way. If an objective was not 100% complete at the end of a project, indicate why.

Objectives:

1) Understand and quantify the mechanisms of tidally-driven internal wave generation, propagation and dissipation at shelf break field sites near North Rankin A (NRA), representative of the southern portion of the North West Shelf (NWS).

This objective was 100% met. Internal waves observed at the North Rankin A oil and gas platform site were generated about 75 km north-west of NRA at local critical points on the continental slope in water depth of 400-600 m. Waves take approximately 36 hours to propagate to NRA and during this time the waves evolve considerable from linear to the highly non-linear forms observed at NRA. The largest waves seen at NRA were waves of depression seen in late summer with amplitude up to 85 m in depth, in 125 m of water. During winter, waves are mainly waves of elevation although with large amplitude.

Numerical modelling showed that the shoreward-propagating waves dissipated inshore of NRA in water depth of about 50 m, where the seasonal thermocline intersects the sloping bottom. The modelling also showed that both to the SW and the NE of this site, internal waves are also generated but, due to the complex bottom topography and orientation of the tidal ellipse, internal waves can travel offshore. Thus, contrary to some conceptions, it is not true to say internal waves propagate onshore and dissipate and mix in shallower water.

To further quantify generation dynamics, direct measurements were made at the 400 m site of the mean and turbulent flow in the bottom boundary layer region. These measurements are unique and a first for the NWS, and few comparable measurements have been made anywhere in the global ocean. They reveal that while mixing is quiet inefficient locally, the near-bottom turbulent intensities are very high – with mixing rates 100 times molecular – even at this deep site. The complex nature of the turbulent flow field in thesis near bottom region is a serious challenge to model within numerical models as this requires high spatial resolution in both the vertical and horizontal and, at least for some of the time, non-hydrostatic mixing is observed and this can only be captured by high resolution non-hydrostatic models like SUNTANS. Suggested parametizations of the turbulence in the region have been derived from the field experiments and these can be tested and incorporated into future numerical models.

2) Understand and quantify the mechanism of tidally-driven internal wave generation, propagation and dissipation at field sites near Scott Reef and Browse Basin, representative of the northern portion of the North West Shelf (NWS).

This objective was 100% met. Using the ROMS model, internal waves were generated at a number of discrete sites throughout the macro-tidal Browse Basin, mainly at locations along the inner shelf break (110 m to 250 m) and at the outer shelf break (600 m to 2000 m) as well as preferentially around complex 3-D structures, such as Scott Reef with its very steep sides. Low vertical mode waves were generated at the inner shelf, while high mode waves were seen emanating from the outer shelf. The waves leaving the inner and outer shelf interact and produce partly standing waves with large along-shelf energy fluxes. There was distinct seasonal variation in this behaviour. While standing waves were common over the year, the seasonal deepening of the thermocline in winter caused a shift in the pattern of the wave field. The most efficient conversion of energy from the barotropic tide to the internal tide (or wave) occurred around the outer shelf where the conversion efficiency was 74%. This energy can then radiate away and be responsible for mixing at sites far removed from the generation region.

High resolution non-hydrostatic numerical modelling around the important Scott Reef area examined the dynamics of the flow forced by the strong tide through the 500 m deep channel separating North and South Scott Reef. The ocean is strongly density stratified in the channel, and as the flow accelerates through the channel on the flood tide, it creates and internal hydraulic jump in the divergent section of the channel. This, in turn, promotes locally intense internal mixing. A similar but slightly weaker process is seen on the ebb phase of the tide as the flow exits the channel, so the mechanism appears an important process driving vertical mixing around Scott Reef. In turn, this is important for the vertical flux of nutrients from deep water up into the coral reef system of the lagoon at Scott Reef. The numerical modelling also examined the process of flushing of this lagoon system by the tidal process, showing a complex pumping process whereby water in the lagoon appears flushed on a time scale of about 1 week. This understanding of the physical processes is crucial to understanding the operation of the unique ecological systems of Scott Reef.

5. Discussion

Implications for Management and Advancement of the Field – Describe the key findings as they relate to the objectives and the management questions discussed at the outset of the project.

Tidally generated internal waves are created due to the combination of surface (or barotropic) tidal forcing, sloping bottom bathymetry and the presence of density-stratified water. Two additional criteria must be met for internal waves to be generated: firstly, the barotropic tidal forcing drives the fluid in a horizontally elliptical path, and this ellipse must be oriented so that some of the fluid is forced upslope/downslope; secondly, the most sensitive regions of the bottom slope occur at critical locations where the local bottom slope exactly matches the slope of a freely propagating internal wave ray.

These are a complex set of conditions, which must be met for internal waves to be generated. Our study site focussed on the Australian North West Shelf, home of the oil and gas industry in WA, and the main implications are:

These conditions are met throughout the NWS and internal waves are ubiquitous and must be considered in engineering design at any location. They induced both strong horizontal bottom velocities as well as transmit large amounts of energy from one location to another.

The character and the strength of the internal waves vary dramatically from location to location, as well as seasonally as the density stratification varies. On the southern part of the Shelf, internal waves are much stronger in summer than winter, for example.

While the magnitude of the barotropic tide is greater in the Browse Basin than it is for the southern part of the NWS, it does not follow that internal waves are stronger as one moves towards the north. In fact the largest amplitude waves were seen around the North Rankin area to the south. In this region velocities near bottom induced by the internal waves can exceed the magnitude of the velocities induced by the tidal motions. In the north they tend to be more comparable in magnitude. Internal waves are generated by the tide in depths ranging from 100 m to 1500 m, approximately. They do not simply propagate from offshore into shallower water. At both the NRA area and the Browse Basin, there is evidence they can propagate both onshore and offshore. Mixing and turbulence measurements, conducted for first time on the NWS, in this project revealed the intense nature of the turbulent mixing that can occur in the bottom boundary layer, an area of great importance for bottom pipeline stability and engineering infrastructure. The tidal motion moving density-stratified fluid up and down the bottom generates turbulence. The mixing is present throughout the tidal cycle although it varies in intensity during the up and down slope phase of the motion and the thickness of the bottom boundary layer is of order of 10-20 m. Mixing efficiencies are low but the turbulent diffusivities are more than 100 times molecular rates even in 400 m of water. The measurements in 400 m (Bluteau et al, 2011) showed that the traditional method of using mean velocity measurements to infer bottom stress by assuming the logarithmic boundary layer profile is not valid. Alternative means must be used to infer bottom stress and hence stability of the bottom surface. In the Browse Basin, the topography is very complex and three dimensional with changing shelf width and complex seamount structures such as Scott Reef. As a consequence, internal waves propagate in all directions and there is evidence of standing internal waves being present. This is important as it makes the interpretation of measurements from a single mooring of the internal wave climate for engineering design purposes, for example, very difficult. Design must therefore be done with a combination of both direct measurements and numerical modelling. Hydrostatic numerical models, such as ROMS, can be used very effectively to describe the internal wave generation, climate and the direction in which internal waves propagate and carry energy. Such models cannot be used to predict the extreme events and currents that exist under fully non-linear, non-hydrostatic waves and only models such the fully non-hydrostatic model SUNTANS can be used for this purpose.
Problems encountered (if any) – Describe any major problems/issues encountered during the study and how they were addressed.
No significant problems encountered.
New Research Directions (if any) – Identify new research directions pursued during the course of the project and reasons for modifying original research plans. Describe how the changed research agenda improved the project.
In order to give a more comprehensive picture of the range of behaviours to be found on the NWS, an additional field experiment was conducted offshore of Ningaloo in early 2010. This was not envisaged in the original project plan but, with the assistance of AIMS and the R/V Solander, was successfully completed. In the Kimberly area, our project had focussed on the tides and internal waves in the waters offshore where internal waves are present. In order to examine the tidal driven coastal ocean flow all the way to zero water depth, we were successful in winning and ARC Discovery Project to investigate the impact of tidal motions on the complex coastal areas of the Kimberley: G Ivey, N Jones, R Lowe, M Ghisalberti, M Meuleners, R. Brinkman and J Koseff (2010-2102) ARC Discovery Grant, Extreme tidal forcing of a topographically complex coastal region: the Kimberley, Western Australia

While tides are the dominant forcing process on the NWS, Cyclones are an intense but aperiodic occurrence in the summer months. We were successful in winning and ARC Linkage Project, with Woodside as the industry partner, to investigate the impact of cyclones:

G.Ivey, N. Jones, R.Lowe, G Wake, J McConchie (2011-2013), ARC Linkage Grant, Ocean response to tropical cyclone forcing on the Australian NWS

6. Overall Project Accomplishments

Students supported – Record the name of each student involved with the project. Indicate whether PhD or other (give details) and briefly describe their role.

Zed, M. (2007) Undergraduate honours theses using ROMS tool for hydrodynamic modelling tropical cyclones Monty.

Millar, E. (2007) Undergraduate honours theses using BlueLINK model output for Characterisation and variability of the alongshore mass fluxes on the Australian NWS

Costin, J. (2010) Undergraduate honours theses using field data to examine the circulation in the Lagoon of South Scott Reef

Taylor, J. (2010) Undergraduate honours theses using SWAN model to examine surface wave field developed under cyclonic forcing

Lim, K. (2006-2010) Used laboratory experiments to understand the process of generation of internal waves over continental shelf topography. PhD

Van Gastel, P. (2005-2010) Used field experiments and ROMS modelling to study Internal wave dynamics on the southern portion of the Australian North West Shelf. PhD

Bluteau, C. (2008-2011) Used field experiments to examine the benthic boundary layer dynamics and internal wave climatology, to be submitted November.nPhD

Rayson, M.(2007-2011) Used numerical models and field data to define the ocean circulation in the Browse Basin, to be submitted October. PhD

PhD theses, Dissertations and Student Placement – Please give complete citation for theses and dissertations (student's name, month and year completed or expected, level of degree, institution). Please provide a copy of the abstract of the thesis or dissertation when complete.

<u>PhD theses</u>

Lim, K. (2010) The generation of internal waves over continental shelf topography

Van Gastel, P. (2010) Internal wave dynamics on the Australian North West Shelf

Bluteau, C. (2011) Benthic boundary layer dynamics and internal wave climatology, to be submitted November.

Rayson, M.(2011) Ocean circulation Browse Basin, to be submitted October

<u>Honours theses:</u>

Zed, M. (2007) Hydrodynamic modelling of tropical cyclones Monty.

Millar, E. (2007) Characterisation and variability of the alongshore fluxes on the Australian NWS

Costin, J. (2010) The circulation in the Lagoon of south Scott Reef

Taylor, J. (2010) Surface wave modelling under cyclones

Publications - List in standard academic format the citations of literature produced during the reporting period. Include journal articles, book chapters, reports, etc. submitted, in press and printed. Please provide a paper and electronic version copy of each publication resulting from the project. If there is a link to the journal electronically, please also include this.

Bluteau**,** C**.**E, N.L. Jones and G.N. Ivey (2010) Bottom boundary layer dynamics in an internal wave generation zone, *17th Australasian Fluid Mechanics Conference, Auckland*, *New Zealand*, 5-9 December 2010, pp 4.

Bluteau, C.E., Jones, N.L. and G.N. Ivey (2011a) Estimating turbulent kinetic energy dissipation in boundary and stratified flows using the inertial dissipation method. *Limnology and Oceanography Methods, in press.*

Bluteau, C.E., Jones, N.L. and G.N. Ivey (2011b). Turbulent mixing in a tidally forced stratified shear f1ow on the continental slope. *Journal of Geophysical Research, submitted.*

Bluteau, C.E., Jones, N.L. and G.N. Ivey (2011c). Turbulent mixing efficiency at an energetic ocean site Geophysical Research Lettters*, submitted.*

Bluteau, C.E., N.L. Jones and G.N. Ivey (2011d) Observations of turbulent mixing regions in stratified bottom boundary layers forced by internal waves. Proceedings of the Seventh International Symposium on Stratified Flows, Rome, August 2011, to appear.

Ivey, G.N. (2011) Tides and internal waves on the continental shelf, Schiller, A. and G. B. Brassington (eds), *Operational Oceanography in the 21st Century*, *Springer*, Chapter 9: 225-238.

Lim, K., G.N. Ivey and N. Jones (2010) Experiments on the generation of internal waves over continental slope topography, *J. Fluid Mech*., 663:385-400

Rayson, P., M. Meuleners, G.N. Ivey, N. Jones and G. Wake (2011a) Field and numerical study of the internal tide dynamics in the Browse Basin, Australian North West Shelf. *J. Geophys. Res. Oceans,* 116: C01016.

Rayson, M, N. L. Jones, G.N. Ivey and O.B. Fringer (2011b) Internal hydraulic jump formation in a deep water, continuously stratified unsteady channel flow, Proceedings of the Seventh International Symposium on Stratified Flows, Rome, August 2011, to appear

Van Gastel, P., G.N. Ivey, M. Meuleners and O. Fringer (2009) The variability of the large-amplitude internal wave field on the Australian North West Shelf. *Cont. Shelf Res., 29:1373-1383*

Presentations - Cite any presentations resulting from the project, including conferences, symposiums, etc.

WAMSI Node 6 Symposium (2009) took place August 25, 2009 where six talks were presented under Project 6.2.

WAMSI Node 6 Symposium 2 took place Friday November 26', 2010 where five talks were presented under Project 6.2.

National and international conferences:

Ivey, G. (2009) Tidally generated internal waves and the role of turbulence (2009), 4th Warnemunde Turbulence Days Workshop, Vilm , Germany (invited).

Ivey, G (2009) Modelling the ocean dynamics on the Australian North West Shelf (2009), Geoscience Australia, Canberra.

Ivey, G. (2010) Oceanic Internal Waves – waves, boundaries and turbulence (2010), Coordinated mathematical modelling of internal waves, Banff International Research Station, Banff, Alberta, Canada (invited).

Ivey, G (2010) Internal waves on the Australian North West Shelf (2010), Woods Hole Oceanographic Institute, Woods Hole, and Massachusetts.

Ivey, G (2010) The generation of internal waves on the Australian North West Shelf (2010), 2nd Norway Scotland Symposium in Internal waves, Edinburgh, Scotland (invited)

Jones, N. (2010) Towards a comprehensive understanding of the internal wave dynamics of the Australian North West Shelf. Ocean Sciences Meeting, Portland, Oregon.

Bluteau, C.E (2010) Bottom Boundary layer dynamics in an internal wave generation region. s 17th Australasian Fluid Mechanics Conference, Auckland NZ, December 2010,

Bluteau, C. (2011a) Near-Bottom turbulent mixing regions of internal waves activity on the Australian North West Shelf, AMSA Conference, Fremantle, July 2011

Bluteau, C. (2011b) Observations of turbulent mixing regions in stratified bottom boundary layers forced by internal waves, Seventh International Symposium on Stratified Flows in Rome, August 2011

Ivey, G. Mixing and internal waves on the Australian North West Shelf, International Union of Geodesy and Geophysics Conference, Melbourne, July 2011 (invited)

N. Jones, N. (2011) Internal wave climatology at Ningaloo Reef, AMSA Conference, Fremantle, July 2011

M. Rayson, M. (2011a) Ocean dynamics of the Browse Basin and Scott Reef, AMSA Conference, Fremantle, July 2011

Rayson, M (2011b) Internal hydraulic jump formations in a deep water, continuously stratified unsteady channel flow Seventh International Symposium on Stratified Flows in Rome, August 2011

Other Communications Achievements - Interviews, press releases, etc.

Knock on opportunities created as a result of this project – new grants, top up funding, new opportunities, new staff and on-going opportunities as a result of this project.

2006-2008	ARC Discovery Grant	Tidal generation internal waves
2009-2011	ARC Discovery Grant	Transient coastal upwelling
2010-2012	ARC Discovery Grant	Coastal circulation in the Kimberley
2011-2013	ARC Linkage Grant	Ocean response to tropical cyclone forcing

7. **Implications for Science and Future Science:** Please note: Implications go beyond Results and Accomplishments to provide information on direct physical, environmental, economic or social gains realised as a result of a research project or outreach activity.

Discovery and Application of New Products and Processes (if applicable) - Describe any actual or anticipated products or processes discovered or developed in the project.
For the first time we have a comprehensive understanding of the physical oceanography of the Browse Basin in response to the macro-tidal forcing in the region. This is a necessary step before we can explain and understand the complex ecology of the region. Similarly, we have a comprehensive understanding of the physical oceanography in the southern part of the NWS in response to the moderate tidal forcing in the region.
Tools, Technologies and Information for Improved Ecosystem Management - Describe how project results are being (or will be) translated into sustainable use and management of coastal and ocean ecosystems. Tools might include benthic habitat maps or environmental sensitivity indicators. Technologies might include remote and bio-sensing, genetic markers, and culture systems. Information might include technical assistance, training and educational materials.
We have developed an instrument system and analysis method, which enables direct measurements in the bottom boundary layer (BBL) anywhere in the coastal ocean environment. The BBL region is of special importance to ecosystem management as it is the region controlling nutrient and tracer fluxes from the sediments into the water column and is the home diverse benthic communities
Forecasting for Natural Resource Management Decisions - Describe how results already are being used - or are expected to be used after project completion - by natural resource management to make decisions based on project forecasts. Forecasts may be due to field and laboratory studies and models. Examples include hypoxia forecast models, algal bloom alerts, forecasts of fishery harvest, and prediction of impacts from ecosystem stressors such as pollutants or invasive species.
The numerical ocean circulation models developed during the course of this project have been tested and developed using the process understanding obtained from the field measurement programs. These models are being used to forecast the ocean environment in regions where there are currently no measurements but the oil and gas industry is proposing current and future developments. The models describe physical processes, but are now ready to be coupled with biogeochemical models. With suitable measurements of key biogeochemical processes, this will provide tools for the long term modelling, forecasting and management of the ecosystems of the NWS. More generally, the models and methods developed here are not geographic specific but can be applied to any coastal ocean environment.
Impacts - Impacts are higher order, usually long-term results of a project's activities that have significant scientific, economic or social benefits. Impacts may involve behavioural, policy or economic changes. Describe impacts (anticipated or realized. These impacts may involve behavioural, policy or economic changes. Seminal contributions to science are considered impacts especially if the research findings lead to major progress in a particular field, implementation of new technologies or have a substantive bearing on an economic or societal issue.

The project has created a comprehensive and quantitative understanding of internal wave dynamics on the NWS which, in turn, is leading to a paradigm shift in the way the offshore oil and gas industry is undertaking engineering design for the natural hazards imposed by internal waves.

8. Project Metadata and Data Generated

These must be available at an open access repository/data centre/iVEC.

Project 6.2 metadata are available on iVEC, see:

http://waodn.ivec.org/geonetwork/srv/en/metadata.show?uuid=b6054a9e-6f45-45ea-8beb-bb2def618302

9. Linkages to Associated Projects – can be WAMSI and non-WAMSI

2006-2008	ARC Discovery Grant	Tidal generation internal waves
2009-2011	ARC Discovery Grant	Transient coastal upwelling
2010-2012	ARC Discovery Grant	Coastal circulation in the Kimberley
2011-2013	ARC Linkage Grant	Ocean response to tropical cyclones

WAMSI project 3.5

10. Other Comments and General Discussion

11. Annexures

- **Sub-project reports presented**
- **Additional attachments: 2**

  Abstract from PhD theses for K. Lim (2010) and P. van Gastel (2010)