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WAMSI NODE 1 PROJECT 1
FINAL REPORT - OVERVIEW

Southwest Australian Coastal Biogeochemistry

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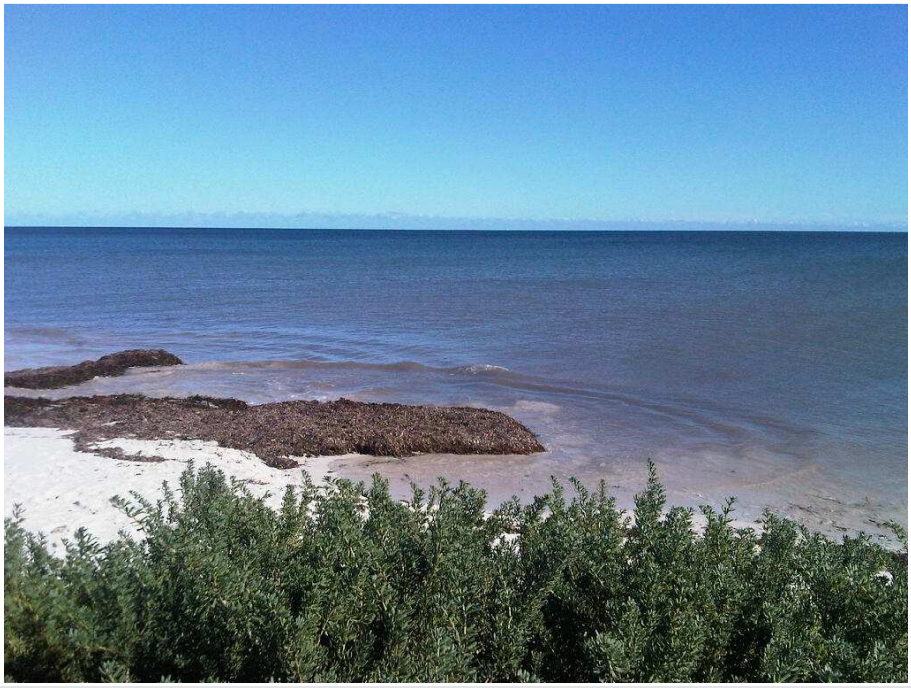

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Important Disclaimer

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Benthic ecosystem characterisation, biogeochemistry, biology and ecology

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1. PROJECT OBJECTIVES

The project objective was as follows:

To better characterise the south west Australian marine coastal and shelf ecosystem structure and function, and enhance our shared capacity to understand, predict and assess ecosystem response to anthropogenic and natural pressures by producing:

1. Downscaled hydrodynamic models to explore influences on benthic habitat, and the cross-shore and longshore exchange of water, nutrients and particles between the lagoon and shelf regions;

2. Coupled hydrodynamic and biogeochemical models and a quantitative nutrient budget for coastal waters at shelf and lagoon scales;

3. Improved descriptions and conceptual biogeochemical models for shelf and lagoon waters incorporating seasonal and interannual variability and improved representation of benthic primary production and bentho-pelagic coupling; and

4. Simple models for assessing and predicting impacts of physical forcing factors, primarily nutrients, on key benthic functional groups/habitats informed by experiments and observations conducted across a range of naturally varying and anthropogenically altered gradients related to nutrient enrichment.

Each component of the project objective had a series of milestones in the form of tasks or timelines which were developed to help plan and track progress of the project. Progress against each of these tasks and timelines was reported in a series of seven Biannual Reports. All of the milestones were met either in original or, in one case, a revised and approved form, and all Biannual Reports were delivered.

In this Final Report, we present the findings of the research in four integrated chapters (see Section 2) which address each of the four components of the project objective above.

A summary of the key findings and components delivered against objective is given in Section 4 below.

2. RESEARCH CHAPTER(S)

Please see the attached Project Final Report – Research Chapters (Annexure A) which comprises four chapters documenting the research undertaken towards each of the four objectives for this project. This Project Final Report – Research Chapters is the basis for information presented in this overview.

3. METHODOLOGY

This is a large multidisciplinary research project. A wide array of physical, biogeochemical and ecological approaches were taken to collecting data and a similarly wide range of analytical, statistical and modelling approaches were taken to analyse the data. The methodologies used are provided within each of the main chapters which comprise the Project Final Report – Research Chapters (Annexure A).

4. RESULTS

4.1 Downscaled hydrodynamic models to explore influences on benthic habitat, and the cross-shore and longshore exchange of water, nutrients and particles between the lagoon and shelf regions;

This objective has been met by examining the dynamics at the scales of the eastern Indian Ocean, the continental shelf, and the Marmion lagoon.

4.1.1 Eastern Indian Ocean Scale

By modelling the connectivity among regions of the WA coast we have identified key source and sink areas for the larvae of commercial and recreationally important species of finfish, lobster and scallops. Connectivity varies with season and is also influenced by factors such as ocean swells and larval behaviour.

Numerical models are key tools for our understanding of hydrodynamics of the ocean boundary current systems and their impacts on marine ecosystems. In this study, the primary source of large-scale and regional ocean circulation information is a global ocean model, OFAM (Ocean Forecasting Australia Model), which has 0.1 degree (~10 km) resolution in the Australasian region. OFAM was developed as part of the BLUElink partnership between CSIRO, the Bureau of Meteorology, and the Royal Australian Navy. To prove the accuracy of the model in simulating the Leeuwin Current along the shelf break of the WA coast, we have validated the BLUElink Reanalysis (BRAN) product of OFAM with field data. The validation against observations from research vessels and shelf moorings suggests that the BRAN product provides good qualitative representation of the Leeuwin Current and its associated eddies. This comparison gives confidence for nested ocean modelling, biophysical investigations, and ocean connectivity analysis, based on the BRAN product, in this WAMSI project as well as in other projects in Node 2 and Node 4.

The BRAN model output has been used to assess the seasonal variations of the Leeuwin Current and its eddy field. It has confirmed the two pathways for tropical waters entering the southward Leeuwin Current during the autumn and winter seasons.

The study has developed particle-tracking based on the BRAN model output that can be used to track the movements of passive particles representing fish and invertebrate larvae, as well as marine pollutants. The retention and connectivity of shelf waters off the west coast of WA have been

assessed using the particle tracking, to provide indication of fisheries recruitment processes. The shelf regions off the west coast of WA can be classified into several sections of alternating low and high retention, to a large extent determined by the magnitude of alongshore velocity. Shelf regions identified to have significantly higher retention rates than their standard deviations were: Carnarvon (24º-25.5ºS), the broad Abrolhos region (26.5º-29.5ºS), between Perth and Geographe Bay (32-33.5°S), and south of Cape Leeuwin (34.5-35ºS). In addition to North West Cape, low retention shelf regions were identified off Shark Bay (~26°S), near Jurien Bay (30-31°S), and off Cape Leeuwin (~34ºS). With the exception of the Shark Bay scallop fishery (which occurs inside the shelter of an almost continuous island chain), the shelf areas with sufficient scallop populations to support commercial saucer scallop fisheries occur in close association with regions with high levels of particle retention rates.

Particle tracking suggests that alongshore dispersal is dominantly southward in April-June when the Leeuwin Current is strong, but more north-south symmetrical in October to December. Thus, the direction of fish larval transport along the coast will depend on the spawning season.

From the particle modelling, larval behaviour has been found to be important in determining eventual recruitment. For example, the open-ocean swells have been found to be critical in transporting and retaining biological particles, especially the western rock lobster puerulus off the west coast of Australia. Since the puerulus are slightly buoyant, they are pushed by the swell (in a process called Stokes drift) towards the shore. This conclusion has been successfully developed in an associated FRDC western rock lobster recruitment project.

4.1.2 Western Australian Continental Shelf Scale

The objective was to develop an intermediate scale model capable of resolving sub-mesoscale processes on time scales ranging from hours/days to seasonal cycles, with resolution down to around 2 km, centred on Perth and extending from the coast to the continental slope and nested within the regional scale model.

The Regional Ocean Modelling System (ROMS) was implemented on a domain extending from the coast offshore to 108°E and from 35°S (Cape Leeuwin) to 21°S (North West Cape). ROMS is a widely-used open-source model (developed at Rutgers University) that has also been implemented in WAMSI Nodes 3 and 6. On this southwestern domain, the horizontal resolution in cross-shore direction varies between 2 km and 4 km from the coast to the 1000 m isobath and then increases to 8 km at the oceanic boundary. The alongshore resolution varies from 3 km to 8 km. This horizontal resolution is considerably higher than the uniform 10 km used in previous (SRFME) studies, and in BLUElink (BRAN). In the vertical, there are 30 levels with refinement in the top 200 m. The model was driven by the same air-sea flux forcing as the BLUElink model and was one-way nested into BRAN at the open boundaries. This nesting ensures that the consequences of large-scale forcing, including the Leeuwin Current itself, are captured by the model.

The model was integrated for 4 years from January 2000 to December 2003 and the solution for 2003 is selected to represent "typical" (i.e. neither El Nino nor La Nina) conditions for the region. The model reproduces defining features of the Leeuwin Current System, including the seasonal variability seen in BRAN and satellite observations, but the finer-scale features such as eddies are better represented in ROMS. For example, ROMS produces a much stronger northward Capes Current than BRAN, and the Leeuwin Current is also significantly stronger. Both models reveal a seasonal cycle of eddy kinetic energy (EKE), with higher EKE in austral winter and lower EKE in austral summer, but

EKE is higher in ROMS than in BRAN due to the improved eddy resolution. The shelf-scale hydrodynamic model was developed primarily to examine the nutrient balance and primary productivity of the region (see below). The higher resolution of the model addresses the underestimation of velocities (including cross-shore fluxes) in the 10 km models like BRAN. This is obviously critical to the biogeochemical balances over the shelf, which are driven by physical processes, including eddies, as discussed below.

4.1.3 Lagoon Scale (Marmion Lagoon)

The first objective was to develop a model with horizontal resolution of order 100m for the Marmion lagoon region in an area of order 10km x 10km. Time scales of interest vary from seconds to weeks and the model should ideally incorporate the influence of surface waves.

At the lagoon-scale, wave driven currents were incorporated (for the first time) in a very high resolution (30 m) hydrodynamic model of the WA coast, leading to significant improvements in accuracy. This will enable much more accurate predictions of processes such as dispersal, mixing, and connectivity of these reef and lagoonal systems.

The numerical model XBeach was used to simulate the depth-averaged wind and wave-driven circulation. The wave field is obtained using a simplified time-dependent wave-action balance that includes wave refraction, shoaling, current refraction, bottom friction and wave breaking. The model is forced at the offshore boundary with observed significant wave height, wave period and direction. The model domain is 13 km alongshore and 8 km across-shore, covering the Southern portion of the Marmion Marine Park with a grid size of 30x30 m. The wave model provides the spatial distribution of wave action, and therefore wave energy, which is then used to evaluate the radiation stress terms in the depth-averaged, shallow water equations for the mean flows.

Comparison of observed and modelled time-series of currents showed good quantitative agreement at some locations but at other locations the model failed to capture the stronger currents seen in the observations. Numerical results for the case with a significant wave height of 2.2m revealed the high spatial variability in the currents in the vicinity of the reefs due to the spatial variability in forcing associated with wave breaking on the reefs. Examination of the dominant terms in the momentum balance showed that, through the surf zone over the reef crest, the radiation stress gradient opposes the pressure gradient. The cross-reef current is forced by the combination of radiation-stress gradient and pressure gradient. In the lagoon behind the reefs radiation-stress gradients were small and the flow is governed by a balance between the pressure gradient and bottom friction.

The second objective was to undertake a field measurement program with the following aims:

(i) to provide data to help tune the numerical model
(ii) to examine the linkages between the hydrodynamic and biological environments

In situ measurements of coastal hydrodynamics provided insight into the interactions of physical and biological processes at a range of spatial scales validating predictions of the lagoon scale model, as well as revealing how algal canopies influence fine scale turbulence and mixing.

Under part one of this objective, in situ waves and currents at 11 sites across Marmion lagoon were measured by a variety of point current meters, acoustic doppler current profilers (ADCP) and wave gauges. Bio-fouling is a major problem in these shallow waters and, to ensure the highest quality data,

the array was deployed for approximately 6-8 weeks and then recovered to download data, replace batteries and clean sensors and mooring frames. The array was deployed four times during the course of the year. Additional data on water quality, temperature, salinity and nutrient distributions were also collected. The observations show primarily wind-forced alongshore currents shorewards and seawards of the reefs during periods of low waves. This result is consistent with earlier studies in a region just a few kilometres north of the current work. However, during high wave events, currents in the vicinity of the reefs and at sites several kilometres removed from the reefs are correlated with offshore wave height. During periods of high waves the observations showed onshore flow over the reefs, offshore flow through gaps between reefs, and alongshore flow in the lagoon behind the reefs. The strongest currents were observed during periods of high waves, sometimes even with opposing, or light winds.

Under part two of this objective, UWA PhD student, Eloise Brown, completed a study of boundary-layer hydrodynamics in submerged canopies. With an array of 4 acoustic Doppler velocimeters (ADV), sampling at 8 Hz, and an acoustic wave and current profiler, water velocities were measured in the field at fixed heights through the kelp canopy and on bare reef over a 3-week period spanning several winter storms. Flows through the canopy were also examined in the laboratory using a synthetic canopy of varying density. Turbulent Kinetic Energy (TKE) was parameterized as a function of reef roughness, canopy density and distance from the canopy edge. Profiles of the flow field were measured with paired ADVs sampling at 25 Hz over bare reef, over five densities of model kelp canopy, and at five distances away from the edge of the model canopy. The results are to be reported in the thesis.

4.2 Coupled hydrodynamic and biogeochemical models and a quantitative nutrient budget for coastal waters at shelf and lagoon scales;

4.2.1 Continental Shelf Scale

Primary productivity over the southern western WA continental shelf, particularly as viewed in satellite ocean colour, shows variability on space scales of km, and time scales of days. The variability is caused mainly by the underlying physical dynamics. The main source of nutrients to support the productivity appears to be the deep nutrients off the shelf, but the biological dynamics on the shelf itself appear to be largely self-sustaining. In this component of the program, the observations are explained with coupled physical-biological models that improve understanding of the shelf biogeochemical dynamics, and quantify both the fluxes of nitrogen onto and off the shelf, and the patterns of primary production and chlorophyll biomass over the shelf. Four separate model studies contributed to meeting this objective.

First, a nitrogen box-model was constructed for the Western Australian shelf from Shark Bay to Cape Leeuwin based on a range of observations throughout the region. The budget shows that terrestrial and atmospheric inputs to the continental shelf off western WA are small (<1%) compared to preliminary estimates of nitrogen derived from Leeuwin Current advection and eddy activity (8%) and seasonal upwelling along the shelf (7%). By closure, the budget suggests that 84% of primary production is recycled on the shelf, including a large contribution from the sediment.

Second, the seasonal evolution of chlorophyll *a* at the continental shelf break was investigated using a one-dimensional (vertical) model. The model suggest that in years of high Leeuwin Current flow vertical mixing associated with the current could support the increase in chlorophyll a concentration at the shelf break. In addition, inter-annual variation in the timing and magnitude of the winter increase is shown to relate to the strength of the Leeuwin Current. In years when the Leeuwin Current flow is weak surface cooling and convective mixing could explain the winter increase in chlorophyll *a*.

Third, the relative influence of temperature and passing surface-waves on the seasonality of the sediment nutrient flux was examined using a one-dimensional coupled pelagic-benthic biogeochemical model. The results suggest that enhanced sediment pore-water flow associated with large amplitude surface waves during the winter increases the sedimentary mineralisation rate of nitrogen in the sediment, which releases dissolved nitrogen to the overlying water column. The seasonal increase in sediment nitrogen flux is shown to drive pelagic phytoplankton production, accounting for an observed correlation between chlorophyll *a* concentration and surface-wave height. During the summer months the sediment mineralisation lowers again, allowing organic matter to accumulate in the sediment balancing the annual sediment nitrogen budget.

Fourth, a high-resolution coupled hydrodynamic-biogeochemical model was configured for the continental shelf from North-West Cape to Cape Leeuwin, and used to construct a seasonal nutrient budget for the shelf. The model has provided information for the first time about the likely spatial extent and temporal nature of both the deep-chlorophyll maximum, and the biological response to wind-driven upwelling along this coast during the summer. Although the region has its lowest standing stock of chlorophyll *a* during summer numerous small upwelling events were predicted by the model along the shelf between Shark Bay and Cape Leeuwin. These predicted upwelling events during summer were short-lived and associated with model predictions of increased chlorophyll in surface waters along the shelf-break and coast. The model also confirmed the role of anti-cyclonic eddies in the entrainment and export of phytoplankton from the shelf during autumn months, and the potential importance of the sediment nutrient flux in shaping the seasonal variation in chlorophyll biomass on the shelf. An annual nitrogen budget constructed for the model showed that particulate nitrogen production on the shelf was largely fuelled by nutrients released from the seafloor (~90%), with offshore supply of nutrients (via upwelling and advection) supporting the remaining 10%. Deposition of particulate nitrogen on the shelf was underestimated by the model, with about 60% of the particulate nitrogen produced on the shelf exported offshore.

4.2.2 Lagoon Scale (Marmion Lagoon)

Persistent high nitrate concentrations were discovered in the vicinity of limestone reef during the biophysical sampling of the Marmion Lagoon. The main objective of this part of the project was to identify the source of the nitrate, and explain the spatial and temporal variability in the measured distributions. The objective was met by conducting a series of simulated dye release experiments using a high resolution three-dimensional model, and constructing a simple box model of the reef.

The results of the dye release experiments indicated that the observed nitrate distributions in Marmion Lagoon could be reproduced by the release of nitrate from two separate locations on the seabed. In addition, rapid change in the modelled surface dye fields, in response to changes in circulation, provided evidence that the observed nitrate fields were highly transient features, and the spatial variation between observations was largely due to changes in the hydrodynamic conditions. The model was unable to identify the mechanism responsible for the release of nitrate at the seabed.

Bacterial nitrification associated with sponges, and the infiltration of nitrate-rich groundwater are suggested as two possible explanations.

Published rates of sponge mediated nitrification (from elsewhere) are an order of magnitude smaller than the two point sources used in the model experiments. However, it is estimated that a reef area of 50,000 m^2 could potentially supply the required amount of nitrate. Box-model calculations showed that the nitrate results could be explained by a groundwater infiltration velocity of 5×10^{-6} ms^{-1} and a groundwater nitrate concentration of 200 mmol N m^{-3} similar to values previously reported for Marmion. The calculations also show that the flow rate is small enough to explain why a salinity signal was not identified.

4.3 Improved descriptions and conceptual biogeochemical models for shelf and lagoon waters incorporating seasonal and interannual variability and improved representation of benthic primary production and bentho-pelagic coupling;

4.3.1 Lagoon Scale (Marmion Lagoon)

Research at the lagoon scale resulted in greatly improved understanding of the principal environmental influences on variability in nutrients, primary and secondary production. The research also resulted in improved representation of benthic primary production and bentho-pelagic coupling. Wave climate variability at scales of hours to days was shown to be a key driver of nutrient concentrations in the coastal lagoon. This observation is particularly important in the context of laboratory studies which revealed that nutrients were rapidly consumed – likely by sediment biota including benthic microalgae. Laboratory studies of production by benthic microalgae and by different species of macroalgae revealed that the highest rates of mass-specific production (i.e. production per unit biomass) were yielded by several species of relatively small red macroalgae, but despite the relatively high rates of production by these species, the biomass of benthic autotrophs in Marmion Lagoon is dominated by kelp *Ecklonia radiata*, and this dominance means that benthic production is also very likely dominated by this single species. Field studies of production by *E. radiata* showed that production was highest when water temperatures were coolest and water clarity was highest.

The biomass and the identity of benthic fauna were quite different among habitats for the benthic invertebrate groups studied. In general, reefs supported much higher biomasses than seagrass beds, which in turn supported higher biomasses than unvegetated sand. Patterns in growth and nutrition of mussels were consistent with a model of high contribution by detritus of benthic origin. The high biomasses of filter feeders on reefs and in seagrass beds, the high growth rates we observed inshore, and the high rates of filtration all indicate that suspension feeders are very likely play a key role in detrital food webs and nitrogen cycling in nearshore ecosystems in Western Australia. The likely importance of this recycling by filter feeders on nutrient budgets is highlighted in section 4.2.2 above.

4.3.2 Continental Shelf Scale (Pelagic)

The objective was to improve our descriptions and conceptual models for shelf waters including understanding of seasonal and interannual variability.

In the pelagic realm WAMSI has provided the glue to bring together scientists from many institutions including local (especially UWA and Murdoch Universities) and international scientists, post doctoral fellows and PhD students to achieve this objective. Between them they attracted millions of dollars in ship time and support from other agencies (e.g. ARC). The results have been impressive with many publications on the physical, chemical and biological oceanography of the region. The general approach been to describe and understand the spatial and temporal variation in physics, chemistry and biology so that our natural resources can be managed in an environmentally sustainable manner that considers all aspects of the pelagic ecology. The data collected on the two Marine National Facility cruises in 2006 and 2007 have supported many other studies not reported on here including topics as diverse as larval fish dispersal, rock lobster genetics and microzooplankton grazing. The focus within CSIRO has been on understanding the source of nutrients to support pelagic primary production and how this is manifest at higher trophic levels. The sum of this research exceeds the requirements of the objective.

A simple empirical model described 74% of the variation in chlorophyll *a* as a function of seasonality. The residual anomalies were found to be a function of the Southern Oscillation Index (65%) and wind (11%).

Long term trends in the marine environment have been observed at the Rottnest Island Station over the last ~ 40 years including a warming trend of 1.23°C century^{-1}, a rise in salinity of ~ 0.41 parts per thousand century^{-1}, a fall in dissolved oxygen (-49 µM century^{-1}), and a rise in nitrate (0.4 µM century^{-1}) and phosphate (0.3 µM century^{-1}).

The dominant phytoplankton have been identified and their abundance quantified using a range of methods. We now know that 67% of the biomass is < 2 µm cells, primarily *Synechococcus* and *Prochlorococcus* with their dominance decreasing with latitude and proximity to shore. This represents a considerable change in the previously reported phytoplankton communities in this region.

Regions of high primary production along the west coast of Australia are associated with features of the Leeuwin Current such as a productive eddy-forming meanders, thin and shallow layers of high nitrate offshore at ~ 22 to 24°S and the LC transport and entrainment of this thin layer into the photic zone at latitudes > 28°S.

In the first large scale survey of zooplankton along the west coast of Australia they were found to be > 5 times more abundant nearshore providing a relatively rich coastal environment for the growth of planktonic carnivores such as larval fish.

Regions of high productivity had a more diatom based food web but the majority of zooplankton feed in the microbial food web where heterotrophic dinoflagellates are the keystone species.

The growth of zooplankton was measured for the first time and found to be associated with mesoscale features of the Leeuwin Current such as eddies and edges.

During the autumn of 2007 the greatest abundance of larval fishes was found at the continental shelf

break where the fast moving surface layer of the Leeuwin Current delivers a flow of phytoplankton and zooplankton. Successful recruitment of neritic larvae to the location of spawn probably requires behaviours such as vertical migration out of the surface current.

New technology made it possible to observe thin layers of high nitrate water being advected south in the Leeuwin Current. Given the extreme nitrogen limitation (factor 10) for the pelagic ecosystem and the estimated magnitude of this source the shelf wide phytoplankton bloom that occurs each winter appears to depend largely this source.

4.3.3 Continental Shelf Scale (Benthic)

The importance of bentho-pelagic coupling to the ecology of west coast pelagic and benthic ecosystems was highlighted by a combination of empirical and modelling approaches. The presence of extensive primary producer habitats across the shelf out to depths of >70m and rapid nutrient uptake at the benthic boundary layer was shown by modelling to have the potential to maintain low nutrients in the water column.

The project has provided a description of the shelf habitats by categorising the range of benthic habitats encountered and their relative coverage of the shelf region from 20-200 m. Improved methods of analysing acoustic backscatter data to more rapidly characterise benthic habitat types were developed as part of the project. We also describe the distribution of animal and plant abundance and biomass on the shelf and their association with particular habitat types.

We provide models which enable estimates of benthic primary production by depth, benthic irradiance by depth and model which highlights the importance of bentho-pelagic coupling to ecosystem function and resilience and the potential impacts of human impacts such as increased nutrients and associated consequences such as increased light attenuation. Lastly we provide spatial estimates of biomass, carbon and nitrogen distribution and of primary production on the shelf out to 200 m deep off the Marmion coastline. In this region we estimate primary production rates of 122.9 gC per m^2 per year of which benthic primary production comprises 42.7 gC per m^2 per year. This is much higher than previous estimates of benthic primary production in this region and thus has important implications for nitrogen budgets. In revising these budgets we confirmed the importance of benthic resupply of nitrogen to productivity of shelf waters and our model estimates a requirement for a benthic nitrification flux of 9.53 gN per m^2 per year. This is higher than other estimates made for the entire shelf region south of Northwest Cape in WAMSI (6.24 gN per m^2 , see Chapter 1 of Annexure A) but is similar to the flux of 10.9 gN per m^2 per year measured at Marmion in other parts of the WAMSI study (see Chapter 1 of Annexure A) .

4.4 Simple models for assessing and predicting impacts of physical forcing factors, primarily nutrients, on key benthic functional groups/habitats informed by experiments and observations conducted across a range of naturally varying and anthropogenically altered gradients related to nutrient enrichment.

We aimed to develop a conceptual understanding of ecosystem responses to forcing factors (primarily anthropogenic nutrient load) with the ultimate aim of improving our capacity to predict the impacts of anthropogenic activities which alter the physical dynamics and level of nutrients in nearshore systems. We focussed on an existing gradient of sediment nutrient content as a proxy for nutrient enrichment. We believe sediment nutrient content is a useful indicator because it integrates over time probably best reflecting the nutrient loading at each site much better than water column nutrient loading which can be highly variable in time.

The research was conducted at multiple sites in Marmion lagoon and Cockburn Sound and in between these two locations. This design presented a gradient of sediment nutrient enrichment in nearshore soft sediment habitats from low (Marmion) to high (Cockburn Sound) and gradients from sheltered (nearshore) to exposed (offshore) to determine the importance of wave induced seabed forcing in mediating the impact of sediment nutrient enrichment.

We measured a wide range of physical and biogeochemical parameters and a series of ecological and physiological responses across these gradients. Sediment carbon and nitrogen content were the most significant factors controlling benthic chlorophyll distribution and infaunal and macrofaunal biomass. These findings confirmed our view that sediment nutrient levels were an important driver of the physiological, biological and ecological dynamics of soft bottom benthic habitats.

The sediments of Jurien Bay and the mid and outer sites in the Marmion lagoon had the lowest sediment nutrient levels and those of Northern Harbour, Southern Flats and Jervoise Bank in Cockburn Sound and the Swan River had the highest. Of these the Northern Harbour site was significantly degraded. Primary producer and heterotrophy biomass and diversity was greater at many of the sediment-enriched sites when compared to low sediment nutrient sites in both Marmion lagoon and in Cockburn Sound. However the enriched sites in Cockburn Sound had the highest respiration rates and high counts of heterotrophic bacteria and the results suggest that if soft sediment habitats become overly enriched such as we observed at Northern Harbour then they become highly degraded with low levels of benthic primary production, high levels of heterotrophic bacteria and sediment community respiration and low levels of infaunal and macrofaunal biomass and diversity.

The roughly equivalent measures of microphytobenthos production, Pmax adjusted for differences in biomass (measured by oxygen evolution) and ETRmax (measured by PAM flourometry) tend to be higher outside Cockburn Sound than within and the was an ETRmax gradient across a series of stations distributed along a transect between an “impacted” (Northern Harbour) and offshore (Carnac Island) station suggesting that production efficiency is suppressed in Cockburn Sound possibly due to poor water quality or lower light penetration in the sound. The majority of mean nutrient fluxes (in both illuminated and dark treatments) encountered outside Cockburn Sound were negative suggesting that consumption of nutrients by microphytobenthos dominates the nutrient dynamics in these sediments. Inside the Sound there was pronounced summer time ammonium release from sediments in the dark treatments suggesting that higher respiration and remineralisation of organic matter during summer releases more nutrients than dark uptake by MPB can consume. A large overall efflux of

ammonia relative to nitrate suggests nitrification may have been inhibited (possibly by low dissolved oxygen) or that nitrate generated by nitrification may be lost via coupled denitrification or anammox. The ammonia oxidising bacteria and ammonia oxidising archaea are more numerous and form a larger percentage of the total DNA in winter than summer. The higher abundance of nitrifiers in winter compared to summer coincides with lower efflux of ammonia at the corresponding sites, suggesting that this winter increase in nitrifier biomass may also generate an increase in nitrification rate.

5. DISCUSSION

5.1 Downscaled hydrodynamic models to explore influences on benthic habitat, and the cross-shore and longshore exchange of water, nutrients and particles between the lagoon and shelf regions;

5.1.1 Eastern Indian Ocean Scale

This project has established a model-based description of retention and dispersal patterns of biota along the coast of WA, with results that can be readily applied to larval transport, fisheries recruitment, invasive species, and other ecological studies off the coasts. The study has demonstrated the importance of ocean dynamics in shelf-water transport and retention. Off the west coast, interaction between the ocean boundary-current and coastal geometry was found to be important for the spatial heterogeneity of retention and dispersal patterns. Low-retention shelf regions tend to experience high alongshore currents, owing to the nearshore influence of the Leeuwin Current (narrow shelf), protruding coastal geography, or formation of mesoscale eddies, whereas high-retention regions were sheltered by coastal geographic features from the direct influence of the Leeuwin Current. This information is crucial for the management of marine species, particularly those that have a larval phase.

Further, ocean swell has also been shown to be important for buoyant larvae, providing a mechanism for returning larvae to shore. These results have already been applied in a (FRDC-funded) extension of this project, applied to western rock lobster.

The study has shown the value, for WA marine management, of a global model like BRAN, which takes into account the large-scale ocean features, such as the Indonesian Throughflow that have a significant impact on the currents and temperature, and thus on the health and distribution of biota.

5.1.2 Western Australian Continental Shelf Scale

Ocean models provide information on spatial and temporal variability that cannot be determined from measurements. Ocean-physics models are coupled to biogeochemical and connectivity models, to describe the advection of nutrients, phytoplankton and larvae, and thus determine the strength and distribution of productivity along the WA shelf region. ROMS, downscaled to resolutions of 2 km inshore, produces stronger and more realistic currents than the coarser (10 km) BRAN model in which

it is nested. Based on the present comparisons with data, ROMS reproduces more faithfully the spatial structure and seasonal variability of the hydrodynamics, particularly of the Leeuwin Current, its eddies, and the inshore wind-driven currents. The implications of these dynamics on shelf productivity are explained in following sections.

The hydrodynamic model is a tool for determining the distribution of nutrients and biota (and potentially also pollutants) over the shelf, and for examining the influence and impacts of coastal development and of climate variability and change.

Problems encountered: the start of this part of the project was delayed by difficulties appointing a suitably qualified modeller. Initial milestones were delayed, but the study ultimately delivered on all milestones.

5.1.3 Lagoon Scale (Marmion Lagoon)

The limestone reefs offshore from Perth sustain high macroalgal biomass, while the reef lagoons support temperate sea-grass beds. These systems provide critical nearshore habitat for marine fauna, and yet the source of their productivity is not fully understood, given the low nutrient levels in the water. Field measurements show that currents and dissolved nutrients vary in the lagoonal systems on horizontal scales of tens of metres. Macroalgae thrive under wave conditions on the reefs, while seagrasses require the shelter of the lagoons. As at larger scales, the distribution of nutrients and biological connectivity of reefs and lagoons is determined by the current systems.

The present study, featuring both measurement and modelling components, demonstrated the importance of waves on the circulation over the reef and in the lagoon. The study has shown that models used both to understand nearshore nutrient and productivity distributions in, and to predict the impacts of climate change and coastal development on inshore waters need to incorporate coupling between waves and currents.

Problems encountered: A current meter was severely damaged, and generated significant costs in a "search and rescue" mission when it was buried during the first deployment by presumed fluidisation of sand on the reef top. Original research plans were not modified.

5.2 Coupled hydrodynamic and biogeochemical models and a quantitative nutrient budget for coastal waters at shelf and lagoon scales

5.2.1 Continental Shelf Scale

a. Implications for Management and Advancement of the Field

This work has provided improved understanding of the influence of offshore/onshore exchange, long-shore transport and upper-ocean physical processes on the nutrient supply to the shelf. This has included new information about the influence of vertical mixing, Leeuwin Current transport, ocean

swell, wind-driven upwelling, and cross-shelf transport by meso-scale eddies, on the biological oceanography of the region. The existence of links between these physical processes and phytoplankton production has important implications for the response of the WA ecosystem to climate change. This work has emphasised the importance of surface sediments in the seasonal nitrogen balance of the mid- and inner-shelf ecosystem, highlighting the potential sensitivity of the ecosystem to future dredging operations.

b. Problems encountered

No major problems were encountered

c. New Research Directions

Original research plans were not modified

5.2.2 Lagoon Scale (Marmion Lagoon)

a. Implications for Management and Advancement of the Field

This work provides new evidence that elevated levels of nitrate in the vicinity of Marmion reefs originate from multiple locations on the seabed. Likely sources are biologically mediated nitrification of organic matter and/or the infiltration of nitrate-rich groundwater. Both possibilities have implications for management. For example, damage to reef organisms, such as sponges, involved in biological nitrification, and/or increased inland removal of groundwater could result in a drop in overall biological productivity. Conversely, since such organisms are more abundant in open-gap habitats, their contribution of nutrients may provide a negative feedback on processes such as wave disturbance, that can reduce macroalgal canopies, thereby stabilising the composition of temperate reef ecosystems.

b. Problems encountered

No major problems were encountered.

c. New Research Directions

Original research plans were not modified

5.3 Improved descriptions and conceptual biogeochemical models for shelf and lagoon waters incorporating seasonal and interannual variability and improved representation of benthic primary production and bentho-pelagic coupling

5.3.1 Lagoon Scale (Marmion Lagoon)

a. Implications for Management and Advancement of the Field

Nearshore ecosystems along the coast of Western Australia support very high benthic primary productivity from macroalgae, seagrasses and microalgae, despite typically low nutrient concentrations. Our results suggest that this high production is facilitated by episodic release of nutrients from the benthos (probably due to the action of waves), and favourable light and temperature environments. In addition, our research suggests that food webs are supported by this primary production through detrital food chains rather than grazing food chains. Benthic suspension feeders likely play a key role in cycling the detritus and making the production available to higher trophic levels. The key implications for management are therefore that actions that substantially change the nutrient, light, temperature or wave climate will likely change the rates of benthic primary production, and that such changes would propagate through nearshore food webs.

b. Problems encountered

No major problems were encountered.

c. New Research Directions

The original research plan included investment of effort into measuring secondary production by methods that invoke production-biomass relationships for different size fractions. However, following early advice during the Node 1 review process, we re-focussed our efforts on improved estimates of other parameters, and direct measurements of growth. We did however attempt to measure secondary production rates of sediment infauna.

5.3.2 Continental Shelf Scale (Pelagic)

a. Implications for Management and Advancement of the Field

Processes that introduce nutrients into the euphotic zone determine the overall productivity of ecosystems. In this research we resolved a long standing (> 40 years) question about why the west coast of Australia is productive when there is no upwelling or obvious nutrient sources (e.g. significant river runoff). This new understanding makes it possible to have a mechanistic, rather than

empirical, relationship between physical forcing factors (e.g. Leeuwin Current flow) and biological responses (e.g. primary production). Future biogeochemical models will be able to include significant nutrient input from the Leeuwin Current and should be substantially better at predicting ecological responses. This will be especially valuable to future predictions of productivity along the west coast in response to forcings such as the Southern Oscillation Index and the Indian Ocean dipole.

The improved descriptions of biological oceanography on the west coast are the most comprehensive to be found anywhere around Australia. They provide the fundamental understanding to underpin pelagic ecosystem based management and improve our capacity to manage our aquatic resources in a sustainable manner. We link from physical attributes of the Leeuwin Current through to changes in phytoplankton community composition, to increases in primary production and standing stock through greater zooplankton and larval fish. The abundance of small phytoplankton cells and the fatty acid profiles of zooplankton suggest that most of the carbon cycles through the microbial pathway with heterotrophic dinoflagellates as a key species.

b. Problems encountered

All problems that were encountered were successfully resolved.

c. New Research Directions

Early in WAMSI the proposed nutrient budget for the shelf was developed by Feng and Wild-Allen. This budget challenged pelagic scientists to investigate all the possible mechanisms that could deliver nutrients to the euphotic zone and increased our emphasis on understanding nutrient recycling and benthic-pelagic cycling on the shelf. This refocus on benthic-pelagic coupling resulting in CSIRO seeking permission from the Marine National Facility to refocus part of an already reviewed and funded cruise proposal to include a more benthic component. The Steering Committee of the MNF accepted the rationale and these results are reported in Chapter 3 section 3.3 (below) and have yielded new insights into nutrient cycling for WA.

Given the discovery that the Leeuwin Current carries significant nitrate south it would be appropriate to rerun and recalibrate the biogeochemical budget and model for the SW domain.

The source of the nitrate that is advected south in the Leeuwin Current is not known. It will be necessary to investigate this source and measure some of the dynamics of N cycling if new understanding is to be fully utilized to improve modelling and predictions of future trends.

5.3.3 Continental Shelf Scale (benthic)

a. Implications for Management and Advancement of the Field

The project has made an important contribution to between understanding a key component of the south-west Australian ecosystem that has largely been ignored. Habitats in this region out to about 20m depth have been fairly well described, but the focus for this part of the study has been to describe the habitat out to 200m which is usually regarded as the continental shelf break. To emphasise the

importance of this region consider that the shallow areas to 20m only account for about 15% of the seabed in the photic zone.

In particular the study has highlighted the ecological importance of the extensive region of the shelf between about 20 and 50 m where significant amounts of the total benthic primary production on the shelf occur. We have discovered significant deepwater kelp beds to about 60m and we have found that deepwater brown and red algae have high levels of photosynthetic efficiency. Kelp comprises the biggest single store (34%) of organic carbon on the shelf 90% of it in the shallow 0 – 20 m zone.

The study also highlighted the importance of sediment habitats on the shelf. In particular those in the photic zone because they provide about 30% of total primary production on the shelf and store about 25%of carbon and 46% nitrogen on the shelf. Elsewhere in this study we have shown that these sediments play a critical role in the resupply of nitrogen for pelagic primary production which still comprises 65% of all production on the shelf. In the past these habitats have largely been regarded as lifeless and unimportant, in particular they are dismissed when considering the impacts of coastal development. However this part of the study has shown their importance and our modelling reveals the importance of healthy sediment habitats to healthy ecosystems.

The study has shown the great importance of sponge, ascidian and other filter feeders to the function of the shelf ecosystem. These animals make up 50% of all animal and plant biomass deeper than 20m and are likely to play a key role in storing and recycling the products of phytoplankton photosynthesis on the shelf. We made the first record of deepwater photosynthetic sponges anywhere in the world and future research may yet show that sponges are important primary producers in mesotrophic habitats. Indeed our study highlights the importance of and lack of knowledge about mesotrophic habitats off south-western Australia. It is worth noting that these habitats provide the majority of the catches of rock lobsters in Western Australia.

Lastly this study provides a significant re-assessment of the nitrogen budget for the shelf by incorporating the high levels of benthic primary production we measured in this study into our model which confirmed that about 90% of nitrogen used in primary production is recycled on the shelf and that to achieve this high levels of nutrient resupply from nitrification at the benthos are required. This again underscores the importance of the sediment microbial communities and those associated with sponges in maintaining a productive southwest Australian shelf ecosystem.

b. Problems encountered

No major problems were encountered.

c. New Research Directions

No significant change in research direction was taken.

5.4 Simple models for assessing and predicting impacts of physical forcing factors, primarily nutrients, on key benthic functional groups/habitats informed by experiments and observations conducted across a range of naturally varying and anthropogenically altered gradients related to nutrient enrichment.

a. Implications for Management and Advancement of the Field

The motive for the research contained within this part of the study was to develop a conceptual understanding of ecosystem responses to forcing factors (primarily sediment nutrient load) with the ultimate aim of improving our capacity of scientists and managers to predict the impacts of sediment nutrient enrichment. The wide range of parameters measured in this study across a gradient of nutrient enrichment together with studies of the biogeochemical processes have provided an insight in the function of these habitats and their response to nutrient enrichment. A number of simple regression models are used to describe these responses and a conceptual model of transition states for soft sediment habitats subject to nutrient enrichment is provided as an aid to monitoring and managing impacts to these habitats. This project has also demonstrated the utility of measuring variations in the physiology of the organisms (i.e. the photosynthetic performance of microphytobenthos). A change in photosynthetic performance will be reflected in the shape of the production versus irradiance relationship and factors such as Pmax, alpha and Ik may prove useful for management agencies looking for indications of photosynthetic stress resulting from coastal development or climate change.

b. Problems encountered

As a result of ambiguous outcomes from a pilot study to artificially manipulate nutrients *in situ*, we felt that the part of the original project endeavouring to conduct artificial nutrient enrichment of benthic communities was a high risk strategy. Professor Kendrick (Node 1 reviewer) agreed and made valuable suggestions for a revised project. The revised project represents a better investment of significant research funds and we have made significant advances in our understanding of MPB dynamics through these variations. Variations include: A detailed assessment of the photosynthetic members of the BMA community using advanced pigment analysis and of both the photosynthetic and non-photosynthetic members using molecular (DNA) analysis. Whole community respiration and biological oxygen demand were measured across the nutrient gradient. Carbon assimilation by photosynthetic members of the BMA was measured across the nutrient gradient in summer and winter. We applied novel molecular probes which target nitrifying and denitrifying genes across a range of taxa to samples collected across the nutrient gradient.

c. New Research Directions

The novel molecular probes which target nitrifying and denitrifying genes across a range of taxa are a significant new research capability that has been applied in this project. These probes are a powerful new tool for understanding the biological pathways of N cycling in the sediments. These technologies have been created from a substantial R&D effort by CMAR in Hobart and are new to WA.

6. OVERALL PROJECT ACCOMPLISHMENTS

6.1 Students supported

Adam Gartner (ECU) was awarded a WAMSI PhD top up scholarship and completed his PhD in 2010. Adam is now an associate at Oceanica. His project was entitled: Trophic implications of light reductions for *Amphibolis griffithii* seagrass fauna which is linked to the third project objective. Adam was supervised By Professor Paul Lavery (ECU).

Cecile Rousseaux (UWA) was awarded a WAMSI PhD top up scholarship and completed her PhD in 2010. Her project was entitled: Oceanographic forcing of phytoplankton dynamics in the waters off north Western Australia which is linked to the third project objective. Cecile was supervised By Professor Anya Waite (UWA) and Dr Peter Thompson (CSIRO).

Eloise Brown (UWA) was awarded a Wealth from Oceans PhD top up scholarship. She is undertaking a project titled "Hydrodynamics of submerged *Ecklonia radiata* kelp canopy in a subtidal reef ecosystem" and is linked to objective 1.3.ii, to examine the linkages between the hydrodynamic and biological environments. Eloise is supervised by Carolyn Oldham (UWA), Graham Symonds (CSIRO) and Euan Harvey (UWA).

Sharon Yeo (Murdoch) was awarded a WAMSI PhD top up scholarship. She is undertaking a project entitled Population Biology of the sand dollar, *Peronella lesueuri*, Cockburn Sound which is linked to the fourth project objective. Sharon is supervised by Dr. Mike Van Keulen (Murdoch) and Dr. John Keesing (CSIRO),

Thisara Wilhena (UWA) was awarded a WAMSI PhD top up scholarship. He is undertaking a project entitled: Dense water formation and cross-shelf exchange on the Rottnest Continental Shelf in south-western Australia, which is linked to the first project objective. Thisara is supervised by Professor Chari Pattiaratchi (UWA) and Dr Ming Feng (CSIRO)

Thibaut de Bettignies (ECU) was awarded a WAMSI PhD top up scholarship he is undertaking a project entitled: Spatial subsidies provided by organic matter export from kelp forests: importance of storm-driven pulses versus chronic export which is linked to the third project objective. Thibaut is supervised By Professor Paul Lavery (ECU), Dr Thomas Wernberg (UWA) and Dr Mat Vanderklift (CSIRO).

Charulata Singh (ECU) was awarded a WAMSI PhD top up scholarship he is undertaking a project entitled: Assessing the trophic subsidy provided by kelp wrack in seagrass ecosystems which is linked to the third project objective. Charulata is supervised by Professor Paul Lavery, Assoc. Prof Glenn Hyndes and Dr Mat Vanderklift. At this stage, Ms Singh has taken leave from the project for medical reasons and her research will recommence in 2012.

Natalie Millar (Murdoch) was awarded a WAMSI Honours scholarship to undertake a project entitled Larval Fish Assemblages in the Leeuwin current system, Western Australia which is linked to the 3rd objective. Natalie was supervised by Professor Lynnath E. Beckley from Murdoch University. Natalie successfully completed her thesis in 2009.

6.2 PhD theses, Dissertations and Student Placement

This section provides WAMSI PhD and Honours student theses titles and Abstracts (where PhD is complete) or Summaries (where PhD is incomplete at time of reporting)

Gartner, A. (2010). Trophic implications of light reductions for *Amphibolis griffithii* seagrass fauna. PhD thesis. Edith Cowan University 202pp.

Thesis Abstract

The ongoing threat of seagrass loss from reduced light availability, coupled with our lack of knowledge of associated trophic responses has motivated this characterization of the flow-on effects of light reductions to *Amphibolis griffithii* seagrass fauna. Recently, field manipulations of varying light reductions, induced disturbances in a *A. griffithii* seagrass meadow that have been shown to effect potential food resources and the structural complexity of seagrass habitats for macroinvertebrates. This offered the opportunity to assess the flow-on effects to seagrass for fauna, a topic that has seldom been examined. This study investigated the effects of different light reduction intensity (high: ~92% reduction; moderate: ~84% reduction), duration (3, 6 and 9 mo) and timing (post-winter and post-summer) on the density, biomass and community composition of macroinvertebrate epifauna within an *A. griffithii* seagrass ecosystem (Western Australia). Shade structures, placed within a healthy *A. griffithii* meadow, were used to create the light reduction treatments. Following shading, there were significant interactions between all three light reduction factors, and generally there was decline in the density and biomass of fauna (between 38% and 89% in density) and the number of families with increasing duration and intensity of light reduction (between 11 and 53% fewer families in light reduction treatments). There was also an effect of time, with taxa abundance and family composition Post-summer differing to Post-winter. However, not all fauna responded consistently, with gastropods appearing to be most sensitive to the shading treatments, while bivalves the least. Ten months after the removal of the light reduction treatments, plots shaded for three months were re-examined to test the resilience of the macroinvertebrate assemblage (in terms of their densities and biomass). No differences were detected among the impacted and control treatments, suggesting where moderate impacts occur in seagrasses, macroinvertebrate fauna have the capacity for recovery. Changes in the epifaunal assemblage were largely associated with declines in algal biomass, leaf variables and stem biomass, indicating food and habitat limitations. To better understand the underlying processes driving these changes, we also tested (using artificial seagrass units) whether the importance of the different structural components of seagrasses for macroinvertebrate fauna was consistent between types of seagrass meadows with naturally different complexity (*A. griffithii*, *Posidonia sinuosa, Cymodocea nodosa*). We concluded from these experiments that the effect of highly complex structural components of the seagrass canopy (for example, that provided by algal epiphytes) is more important than overall seagrass form, however, this effect is likely moderated by available seagrass canopy surface area, which when limited, may result in structural complexity having lower effect than seagrass species with high surface area available. Unfortunately, our ability to predict the effects of the complex interactions of light reductions on higher trophic orders is considerably limited (due to experimental constraints). Qualitative and quantitative modelling techniques, however, offer an effective alternative approach. We used Loop analysis and Ecopath with Ecosim to estimate the flow-on effects of reduced primary productivity of *A. griffithii* seagrass meadow on macrograzers, omnivores, invertivores and piscivorous fish. The results of modelling predict that there will be a lower overall net biomass in these fish taxa with increasing duration and intensity of disturbance. However, the effect of disturbances on piscivores is likely to lag for approximately 2 years, but once their population biomass declines, they would be unlikely recover.

Rousseaux, C. (2010) Oceanographic forcing of phytoplankton dynamics in the waters off north Western Australia. PhD Theses. University of Western Australia.

Thesis Abstract
Recent studies have shown that coral reefs can rely heavily on the delivery of offshore particulate matter as nutrient sources to sustain their high productivity. Off northwest Australia, the Leeuwin Current, an anomalous poleward flowing eastern boundary current, flows adjacent to Ningaloo Reef, Australia's longest fringing coral reef. Using chlorophyll *a* estimated from satellite-derived ocean colour and *in situ* field observations we identified the existence of a autumn phytoplankton bloom in the waters off northwest Australia. In autumn, a combination of the accelerating Leeuwin Current and net surface cooling lead to a significant deepening of the mixed layer depth down to ~100 m. This deepening also coincided with increased nutrient and chlorophyll *a* concentrations in the euphotic zone. We conclude that the MLD deepening is the mechanism driving the phytoplankton dynamics in the waters off Ningaloo Reef through the replenishment of nutrients in the surface waters autumn. In both spring and autumn the size-fractionated phytoplankton concentrations and community diversity, as well as nutrient uptake rates, were quantified. In autumn, the concentration of large-sized phytoplankton increased. Ammonium uptake was always greater than nitrate uptake. In autumn, nitrate uptake was relatively great at 30 % of the total dissolved inorganic nitrogen uptake. For a bloom to develop nutrients must be available at sufficient concentrations; however, grazing by predators can also control phytoplankton populations suppressing the development of a bloom. Theory suggests that a deepening mixed layer may result in a reduction in grazing pressure through dilution. The findings of this study showed that grazing rates did not decrease with the deepening of the mixed layer depth and therefore this theory did not hold for the waters off Western Australia. Instead growth rates were positively correlated with the mixed layer depth which further suggests that the mixed layer depth deepening is the key mechanism allowing net phytoplankton growth. The findings of this study show that there is likely to be substantial seasonal variation in the net production of offshore particulate matter and that this is likely to impact on the productivity of Ningaloo Reef itself.

Population Biology of the sand dollar, *Peronella lesueuri*, Cockburn Sound
Sharon Yeo (Murdoch University)

Peronella lesueuri is a sand dollar commonly encountered in Cockburn Sound, Western Australia and this species has been found throughout the wider Indo-West Pacific region. The intention of this study is to describe population size frequency distribution, growth rate, reproductive periodicity, effects on natural and transplanted seagrasses.

Studies of its population parameters, reproductive periodicity and burrowing effects on seagrass transplants are currently ongoing at sites within Cockburn Sound. The study of the seasonal variation of diurnal movement has been completed and the data is being analyzed.

Monthly sampling at Jervoise Bank in Cockburn Sound started in March 2009 and is due to finish in April 2011. Samples of *P. lesueuri* are collected by towing an epibenthic sled from a boat. The data to date shows a constant group of individuals with a size range of 125 -160mm. The data also suggests that a significant recruitment event occurred from August -December 2009, when a large cohort (>50 individuals) of small individuals (<2cm) first appeared in the samples. The size frequency graph for spring 2010 did not show a corresponding recruitment, though there were a consistently low numbers of small individuals appearing throughout the sampling period after May 2009. A large decrease was

observed in the proportion of small individuals (<2cm) collected in January 2010, indicating newly recruited juveniles may have a high mortality rate. Growth of a sample population of *P. lesueuri* is currently being monitored at a site west of Jervoise Bank. Length and width measurements of a caged sample population continue to be taken bimonthly to determine growth rate. This study is due to be completed in September 2011.The reproductive cycle periodicity of *P. lesueuri* will be determined through histological analyses on mature individuals from the monthly samples from a proposed two-year study to be completed in April 2011. Histological preparations and analyses are still ongoing, but preliminary data suggests an annual cycle, with general synchrony within the population and minor variations from year to year. The data to date also suggests an autumn spawning period with gamete maturation over spring and summer. The study of seasonal variability of diurnal movement rates of *P. lesueuri* has been completed and the dataset is being analyzed. The dataset for winter was collected in July 2010 and the summer dataset was collected in January 2011. Data analysis has yet to be completed but initial comparisons of means movement rates seems to indicate that *P. lesueuri* are more active in daylight and far more active in Summer, when water temperatures are warmer. An ecological study to investigate the impact of burrowing behavior of sand dollars on the success of natural and transplanted seagrass on Southern flats in Cockburn Sound is underway. Cages enclosing *P. lesueuri* at their natural density and new transplants at the same densities as used in seagrass rehabilitation are being used to determine the effect of the burrowing behavior of the sand dollar on transplant success. The cages will be monitored every two months until the end of the experiment in September 2011. The outcome of this PhD project will shed some light on various critical elements of population dynamics, and the biological and ecological aspects of a common, but thus far little-known species, *Peronella lesueuri.*

Hydrodynamics of submerged *Ecklonia radiata* kelp canopy in a subtidal reef ecosystem

Eloise Brown, School of Plant Biology, School of Environmental Systems Engineering, University of Western Australia

Boundary layer dynamics in submerged canopies and complex reef habitat are generally not well understood, yet have the potential to shape benthic ecology by controlling the fate of suspended matter and nutrients in these systems. This research examined wave-driven hydrodynamics and turbulence in Western Australian fringing limestone reefs with *Ecklonia radiata* kelp canopy. The experimental approach involved a field study and a physical model of reef with 1:10 scaled-down kelp. Using an array of 4 acoustic Doppler velocimeters (ADV) sampling at 8 Hz and an acoustic wave and current profiler, water velocities were measured in the field at fixed heights through the kelp canopy and on bare reef over a 3 week period spanning several winter storms. Spectral analysis showed a wave peak at 12.5 Hz and a clear inertial subrange between 0.5 - 3 Hz, indicating that there was a fully developed turbulent boundary layer. A significant vertical intensification of turbulent kinetic energy (TKE) dissipation rate (ε) occurred within the kelp canopy. However, comparisons between bare reef and kelp canopy suggest that the removal of kelp canopy had no impact on ε. This was further examined in the laboratory, where TKE was parameterized as a function of reef roughness, canopy density and distance from the canopy edge. Profiles of the flow field were measured with paired ADVs sampling at 25 Hz over bare reef, over five densities of model kelp canopy, and at five distances away from the edge of the model canopy. TKE decreased with canopy density and with distance away from the canopy edge, suggesting that, even at significant distances away from the canopy edge, kelp canopy in the presence of wave-orbital velocities exerts a strong influence on local hydrodynamics. This has important implications for the ecology of understory algal and invertebrate communities in these kelp forest ecosystems.

Dense water formation and cross-shelf exchange on the Rottnest Continental Shelf in south-western Australia.

Thisara Wilhena (UWA)

Introduction

Cross-shelf processes on the RCS is of concern due to rapidly growing population in the Perth Metropolitan, numbers are over 1.5 million, many of whom live close to the ocean leading to a growth of demands in social and economic benefits in the coastal zone as well as in the deeper ocean. These include coastal developments, shipping, ports, petroleum exploration and production, defence, recreational activities, tourism, fishing and naval activities. Thus increase of human activities may lead to negative impacts on the environment such as disposal of waste water, matter into ocean and influencing the sediment circulation in shallow waters.

Hence this study is focused on interpreting physical mechanisms which drive the cross-shelf circulation in the shallow bathymetric terrace of the RCS (Figure 1.b). First part of the study will consider the analysis of different data sources in order to reveal various driving forces of cross-shelf processes and their seasonal variability. Latter part of the research will focus on use numerical simulations to interpret the interconnectivity of different driving forces on cross-shelf processes via idealized scenarios.

Objectives

Dense shelf water is formed when the density of the inner shelf water is increased either due to a decrease in temperature through cooling and/or an increase in salinity due to either evaporation or ice formation. This water is transported as a near-bed gravity current across the continental shelf. Formation and propagation of this buoyancy driven current, known as dense shelf water cascade (DSWC). Recent field measurements, using ocean gliders, have identified the presence of DSWC on the Rottnest continental shelf and thus the objectives of this study are to:

(i) Identify the main mechanisms and seasonality of dense shelf water formation and transport along the Two Rocks transect

(ii) Investigate the role of Rottnest canyon as a conduit for offshore transport of dense water

(iii) Identify the relative importance of the physical processes that control cross-shelf transport.

Geographic extent of the research

Context of this research is the shallow bathymetric terrace of the RCS, lying between 31.2^{o}S - 32.2^{o}S and 115.0^{o}E - 115.7^{o}E in alongshore and 40-45 km in cross-shore (terminating around 160m isobath). Shelf region in this area has a unique bathymetric shape, a shallow (average depth of 40m) and wider terrace spanning northward over 100 km along the coast (Figure 1.a). Further, the inshore region of the shelf can be defined as a coastal lagoon because of discontinuous submerged limestone reef located around 5-10 km offshore. A sharp steepening of the RCS can be found around 160m isobath, which is approximately 40km offshore.

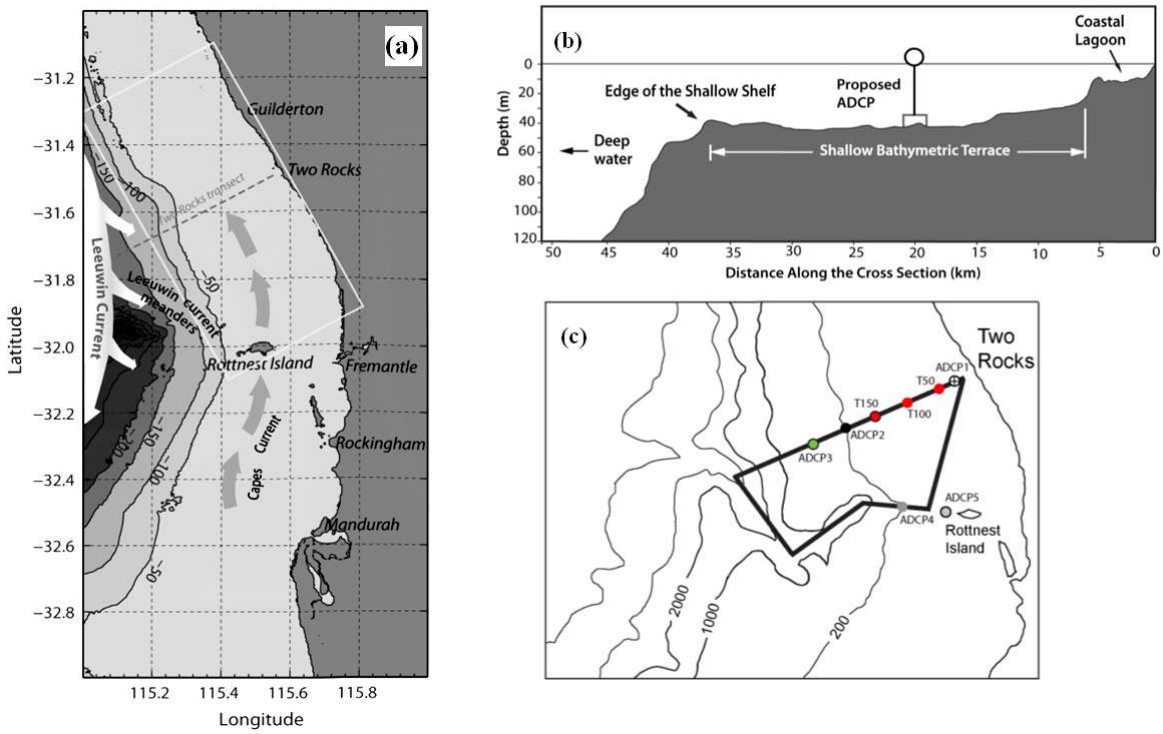

Figure 1: (a) Geographic extent of the study area on RCS (b) Cross sectional view of Two Rocks transect showing the Shallow Bathymetric Terrace; and, (c) Location of WAIMOS mooring along the Rottnest continental shelf and Perth canyon. ADCP1 is location of the additional mooring as part of this study.

Methodology

This research will be carried out by analysis of physical properties of ocean data obtained through different field observation techniques and use of numerical simulations to find out detailed processes driving the cross-shelf transport around Two-Rocks transect and Perth canyon. In addition to the field experiments, meteorological data, already recorded by the Bureau of Meteorology, Australia will also be used.

Field experiments are focused on gathering surface and subsurface physical properties, flow properties of shallow waters on the RCS around Two-Rocks transect. Subsurface data will be measured by Ocean gliders, ship observations and moorings.

This report will be based on the analysis carried out by the data collected by Ocean gliders.

Ocean Gliders

Ocean Gliders (gliders) are underwater instrument platforms used to monitor the subsurface temperature, salinity, and depth average currents on a particular area of a shelf. These are buoyancy driven self-propelled devices, designed to operate up to 200m in the water column. Glider is equipped with different types of sensors: global positioning system (GPS), conductivity sensor, temperature sensor, depth (CTD) sensor, dissolved oxygen sensor, turbidity, fluorescence, and dissolved organic matter (CDOM) sensors (Figure 2).

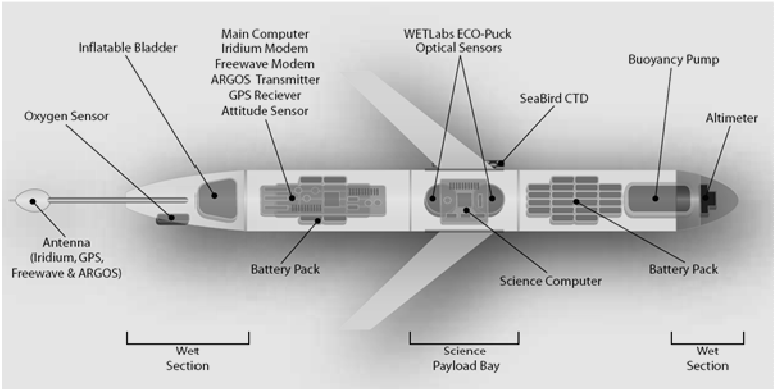

Figure 2: Slocum glider and its sensors

Data (temperature, salinity, mean current speed, etc.) obtained via gliders are processed in several stages. Firstly, quality controlling is done for filtering out any observational or instrumental errors. Next, data is categorised according to their temporal and spatial variability for screening the most appropriate set of data which represent the water properties along the Two-Rocks transect. Once selected, data is re-filtered, interpolated across depth-length and projected over the Two-Rocks transect. These processed data is analysed for finding various cross-shelf processes, cross-shelf density gradients, seasonality of these cross-shelf processes and buoyancy fluxes.

Findings: Dense Shelf Water Cascading (DSWC)

In sub tropical climatic conditions, dense water masses can be formed due to evaporation in summer and subsequent cooling in winter. These dense water masses can either flow along the bottom boundary of the shelf or form an isolated filament with a front, which flow towards deep water. Formation and propagation of these buoyancy driven currents have been documented as DSWC and having a significant impact on the thermohaline circulation and even formation of major water masses around the world such as Antarctic Bottom Water. In oceanographic point of view DSWC provides an effective mechanism for the exchange of water, heat, salt, phytoplankton, nutrients and pollutants between shallow coastal regions and the deep ocean. This phenomenon has been already evident in several places around the Australia locating in Great Australian Bight, Spencer Gulf and Northwest Australian Shelf.

However after the glider observations along Two-Rocks transect, Perth, it was found out that there is clearly a formation and segmentation of dense water masses towards the shallower end of the RCS. This gave an indication of an occurrence of DSWC even under sub tropical climatic conditions in Australia.

Figure 3 and 4 show the variation of density along the Two-Rocks transect during 2009 and early 2010 (bother winter and summer) based on the temperature and salinity data observed by shallow water gliders. From these figures, it can be clearly seen that formation and propagation of high dense water masses across the shelf towards the end of summer and beginning of winter (Figure 3.a & 3.b). These high dense water masses flow towards deep waters along the bottom boundary of the shelf, thus allowing buoyant water to flow towards onshore at surface. However this process was not prominent during the peak of the austral summer due to the action of strong sea breeze, which disturbs the water column by turbulent mixing thus depleting the segmented water masses.

During summer southerly winds are at maximum and energising the CC for extending further north of Rottnest Island. CC combined with wind generates a strong upwelling at the edge of the shelf break, resulting in an onshore flow at the bottom of the shelf. This was clearly observed during the period

from January to February in 2010 (Figure 3.c & 3.d).

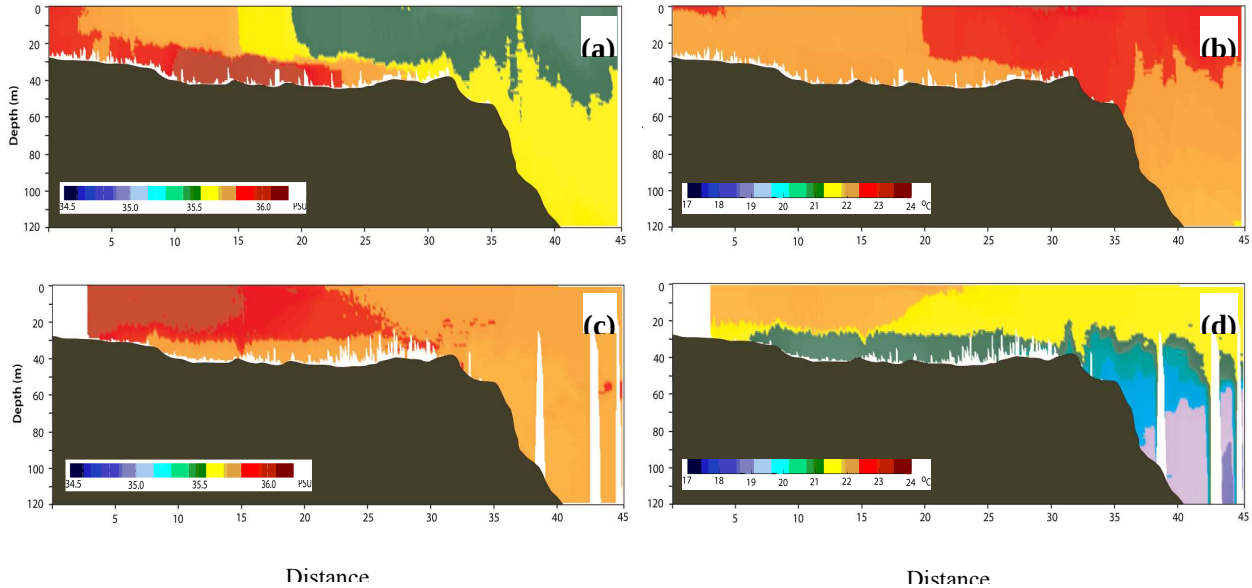

Figure 3: Oceanic Response in summer (a) Salinity distribution in March 2009 indicating formation of high dense water masses (b) Temperature distribution in March 2009 (c) Salinity distribution in January 2010 (d) Temperature distribution in March 2010 showing strong upwelling.

However, results obtained in winter noted that variations of density of water were not that intense compared to the summer. Hence stronger density gradients formed during late in summer started to decay and became weaker when winter was started. But still high dense water masses continued to cascade at a lesser intensity though there were not many contributions of salinity variations (Figure 4.a & 4.b). During mid of winter, when LC flows at its maximum, effect of warm low saline LC meanders were clearly visible at the shelf break (Figure 4.c & 4.d).

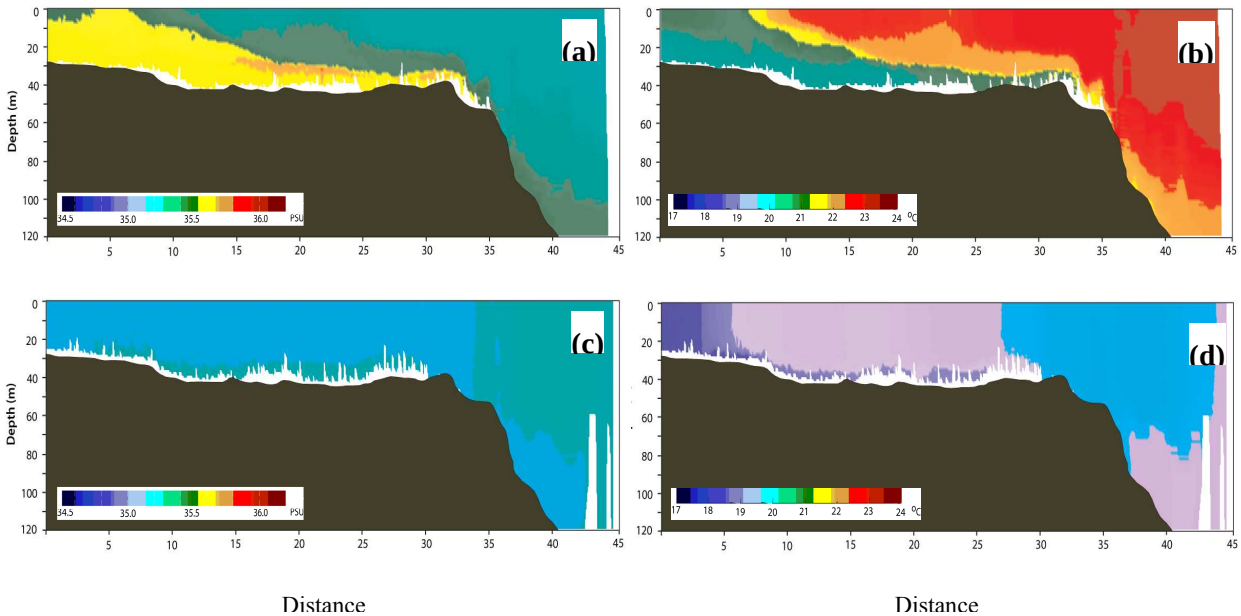

Figure 4: Oceanic Response in winter (a) Salinity distribution in May 2009 (b) Temperature distribution in May 2009 (c) Salinity distribution in August 2009 (d) Temperature distribution in August 2009.

Further analysis of the seasonal density variations showed cross-shelf density gradients are responsible for driving the density currents. Hence derived cross-shelf density currents based on density gradients show that there is a considerable cross-shelf flow (2 cm/sec) in autumn (March to May) compared to that of winter (July to Oct) where as velocities are less than 1 cm/sec (Figure 5). Therefore it is clear that cross-shelf density gradients are important DSWC rather mean density of the entire water mass. Further it can be explained cross-shelf density gradients can be influenced by advection due to shelf currents and wind induced turbulent mixing. However it is significant that DSWC is definitely taking place on RCS at different degrees of intensities under different driving forces.

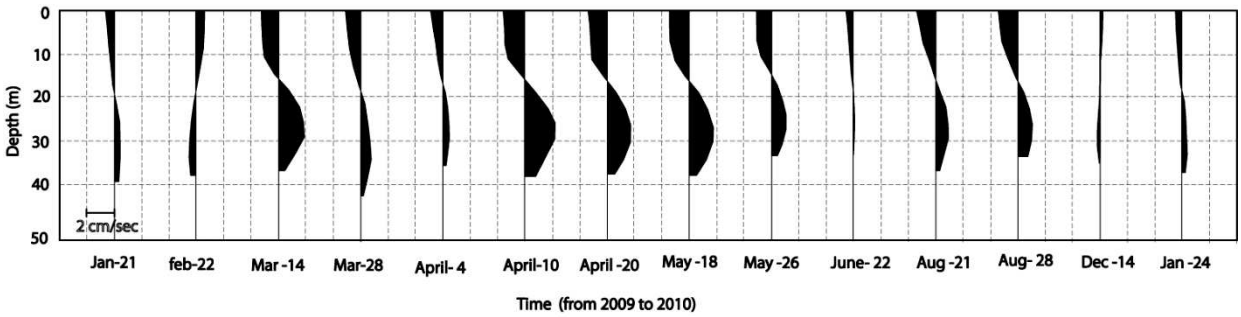

Figure.5: Cross-shelf depth averaged density currents. Values to right from centre represent directions toward off shore and vice versa

Spatial subsidies provided by organic matter export from kelp forests: importance of storm-driven pulses versus chronic export

Thibaut de Bettignies (Edith Cowan University)

This research is providing new quantitative insights into habitat connectivity and, more broadly, coastal ecology. The coastal zone is a highly dynamic system which relies on the movement of nutrient, detritus and consumers between habitats as a key component of its functioning. Kelp forest is a highly productive habitat, demonstrated to provide nutrient supply to adjacent, less productivity habitats through export of full thalli or kelp fragments. However questions remain about "How, Where and When" this material is ripped from the reef. Identifying the sources, pathway and conditions of this loss of organic matter from kelp forest is crucial for a better understanding of coastal system ecology.

The results indicated that significant storms drive the dislodgment of kelp as a pulse but, surprisingly, they were not driving a significant biomass loss from reefs. Indeed, the dislodgment of kelp was a more chronic process occurring throughout the year, with dislodgment rates during winter equivalent to other time of the year. To investigate further, a biomechanistic model was developed which suggested that kelp can withstand severe storms and that the post-storm wrack accumulating on the shores was likely the consequence of storm-driven transport of previously dislodged kelp rather than direct dislodgment. These findings go against important assumptions about the significant role of

storms that have emerged from previous research on temperate reefs.

Contrary to our expectations, the "erosion" pathway was far most important than whole kelp dislodgment as a fate for kelp production accounting for up to 15 times more biomass loss during the peak period (Autumn) and resulting in a loss of 40% of the standing biomass and 20% of the annual production. Mechanistically, this phenomenon is similar to the First Flush Theory, providing a massive pulse of material (small fragments of kelp) into the system in a short period of time. The subsequent reduction in kelp thallus size made them less susceptible to severe drag forces generated by subsequent winter storms (June to August). These findings will help to shape new paradigms for reefs and coastal ecology about the importance of this export and connectivity in the coastal zone.

Assessing the trophic subsidy provided by kelp wrack in seagrass ecosystems

Charulata Singh (Edith Cowan University)

The movement of material from one habitat to another, where it promotes increased productivity is a well-established process in coastal ecosystems. These 'trophic subsidies' have important implications for fisheries management and for the spatial management of marine habitats, such as the sizing and boundary determination in Marine Protected Areas. In many temperate regions of the World, the delivery of algal wrack from reefs to adjacent seagrass and sand habitats provides a *potential* subsidy. The subsidy provided by wrack could be in the form of particulate material directly ingested by consumers, or leaching of dissolved material that supports bacterial or primary production.

In Western Australia, kelp (*Ecklonia radiata*) wrack is ubiquitous and, at times of year, abundant. Studies have shown that kelp material is readily incorporated into the foodwebs of recipient habitats, more so than many other types of wrack. These differences in the degree of incorporation of wrack may be affected by the nature of the wrack, the consumer assemblage and its degradation and palatability. However, the significance of kelp wrack in actually driving productivity in adjacent habitat remains to be quantified.

This project is examining the temporal variability in kelp wrack availability and its importance in driving production in seagrass ecosystems. Areas of particular interest include: the role of microbial activity, grazing and physical abrasion in degrading wrack; the leaching of bio-available materials and how this alters with time; and how these affect the incorporation of wrack into seagrasses, epiphytic algae and consumers. The project is a companion project to a second WAMSI postgraduate project being undertaken by Mr Thibaut de Bettignies. That project is documenting the processes that lead to the export of kelp from reefs, while this project examines the consequences of that material for recipient habitats.

Pilot research has commenced in seagrass habitats in the Marmion Marine Park and Shoalwater Islands Marine Park. Seasonal surveys of wrack mass and composition have commenced and show significant differences in wrack abundance with time. Wrack traps (Figure 6) have been deployed to provide estimates of the net import, export and retention of wrack into seagrass meadows at different times of year and for different types of seagrass habitat. Initial results are showing low levels of import during autumn; winter sampling is expected to show higher rates of import associated with storm events. Other work has used natural isotope labelling to demonstrate the transfer of kelp nitrogen from drift wrack to both primary producers and consumers in *Posidonia* meadows. The transfer of kelp-derived nitrogen to seagrasses occurs within hours and is most likely due to the direct uptake of nitrogen leached from kelp, either as dissolved inorganic nitrogen or smaller molecular weight dissolved organic nitrogen. This is the first time this pathway of subsidy has been

demonstrated. Consumers take up kelp-derive nitrogen over a period of weeks. Ongoing work will quantify the effect of that kelp-derive nitrogen on primary producers and consumer assemblages.

Figure 6. Wrack trap placed on the landward edge of a seagrass meadow in Marmion Marine Park.

Millar, N. (2009) Larval Fish Assemblages in the Leeuwin current system, Western Australia. BSc (Hons) Thesis, Murdoch University, 73 pages.

Abstract

The dynamics of the Leeuwin Current and larval fishes were investigated in peak flow conditions in May 2007. Larval fish samples were taken at every degree of latitude from 22°S to 28°S at three depth stations, oceanic (2000m), shelf break (300m) and shelf (50m). In conjunction, physical oceanographic measurements were taken along the cruise track. A total of 6582 larval fishes were identified from 104 families and 188 taxa. Larvae of mesopelagic families in particular, Myctophidae and Phosichthyidae, dominated oceanic and shelf break assemblages. Shelf stations were distinctively different with Engraulidae, Bregmacerotidae and Gobiidae the most abundant families. Water mass characteristics of the Leeuwin Current were well mixed in the north becoming more variable in the southern latitudes with mesoscale features present, evident from satellite derived sea surface temperature images. This was reflected in the larval fish assemblages. The presence of neritic larvae at oceanic and shelf break stations was evidence of cross-shelf exchange. Where mesoscale features were present the occurrence and concentration of neritic larvae increased particularly that of Engraulidae (species *Engraulis australis*) at 27°S. MDS showed that shelf stations appeared to be gradational from north to south and was attributed to the biogeographical range of adult spawners. The hypothesis that tropical taxa would occur in the north with a gradational decline in abundance

and occurrence south was not realised. This was most likely due to the difficulty of identifying taxa, especially neritic taxa, to species level. Another contributing factor may have been that from one latitude to the next the assemblages were markedly different. Using BIOENV it was found that environmental parameters showed no correlation to larval fish assemblages. Conclusions drawn from these results were that due to the widespread nature of the Leeuwin Current in the north, water mass across stations was not distinct and thus other factors were driving assemblage patterns, such as the spawning mode of adults, biogeographical range of adults and cross-shelf exchange due to Leeuwin Current eddies and meanders.

6.3 Publications

Copies of Journal Publications listed below are given in Annexure B (WAMSI Node 1 Publications and Presentations). Published and Unpublished Reports have previously been provided to WAMSI.

Journal Publications

Caputi, N., R. Melville-Smith, S. de Lestang A. Pearce and, M. Feng (2010). The effect of climate change on the western rock lobster (*Panulirus cygnus*) fishery of Western Australia. *Canadian Journal of Fisheries & Aquatic Sciences* 67:85-96.

Caputi, N., S. de Lestang, M. Feng and A.F. Pearce (2009). Seasonal variation in the long-term warming trend in water temperature off the Western Australian coast. *Marine and Freshwater Research* 60: 129-139.

Feng, M. D. Slawinski, L. Beckley, J. Keesing (2010) Retention and dispersal of shelf waters influenced by interactions of ocean boundary current and coastal geography. *Marine and Freshwater Research* 61: 1259–1267.

Feng, M. and K. Wild-Allen (2010). The Leeuwin Current. P197-210. In: K-K. Liu, L. Atkinson, R. Quinones and L. Talaue-McManus (Eds.) *Carbon and Nutrient Fluxes in Continental Margins: A Global Synthesis*. IGBP Book Series. Springer, Berlin. 744 pp.

Feng, M. (2009). Eddy induced cross-shelf phytoplankton transport along the downwelling coast off Western Australia. *Journal of Tropical Oceanography* 28(5): 6-10.

Feng, M., A.M. Waite and P.A. Thompson (2009). Climate variability and ocean production in the Leeuwin Current system off the west coast of Western Australia. *Journal of the Royal Society of Western Australia* 92: 67-81.

Feng, M., A. Biastoch, C. Böning, N. Caputi and G. Meyers (2008). Seasonal and interannual variations of upper ocean heat balance off the west coast of Australia. *J. Geophys. Res.* 113: C12025, doi:10.1029/2008JC004908.

Forehead, H.I., P.A. Thompson, (2010). Microbial communities of subtidal shallow sandy sediments change with depth and wave disturbance, but nutrient exchanges remain similar. *Marine Ecology Progress Series* Vol. 414: 11-26.

Gartner, A., P. S. Lavery, K. McMahon, A. Brearley, H. Barwick (2010). Light reductions drive macroinvertebrate changes in *Amphibolis griffithii* seagrass habitat. *Marine Ecology Progress Series* Vol. 401: 87–100.

Greenwood, J. (2010). Evidence that increased nitrogen efflux from wave-influenced marine sediment enhances pelagic phytoplankton production on the inner continental shelf of Western Australia. *Marine and Freshwater Research*. 61, 625-632.

Greenwood, J. (2009). Shallow water dissolution of settling calcite at station ALOHA. *Limnology and Oceanography*, 54 (5), 1420-1424.

Greenwood, J. and K. Soetaert (2008). Interannual variability in the seasonal cycle of chlorophyll in the Leeuwin Current off the southwest Western Australian coast. *Journal of Marine Research* 66(3): 373-390.

Hanson, C.E., M.J. McLaughlin, G.A. Hyndes and J. Strzelecki (2009). Selective uptake of prokaryotic picoplankton by a marine sponge (*Callyspongia* sp.) within an oligotrophic coastal system. *Estuarine, Coastal and Shelf Science* 84: 289-297.

Hassler, C.S., J.R. Djajadikarta, M.A. Doblin, J.D. Everett, P.A. Thompson (2011). Characterisation of water masses and phytoplankton nutrient limitation in the East Australian Current separation zone during spring 2008. *Deep-Sea Research II* 58: 664-677.

Irvine, T., J. Keesing, N. D'Adamo, M.C. Aquarone and S. Adams (2008). West-Central Australian Shelf LME. In: K. Sherman and G. Hempel (Eds.) *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies No. 182. United Nations Environment Programme. Nairobi, Kenya. p 321-336.

Irvine, T., J. Keesing, N. D'Adamo, M.C. Aquarone and S. Adams (2008). Southwest Australian Shelf LME. In: K. Sherman and G. Hempel (Eds.) *The UNEP Large Marine Ecosystem Report: A perspective on changing conditions in LMEs of the world's Regional Seas*. UNEP Regional Seas Report and Studies No. 182. United Nations Environment Programme. Nairobi, Kenya. p 839-852.

Keesing, J.K, Graham F., Irvine, T. and Crossing, R. (2011) Synchronous aggregated pseudocopulation of the sea star *Archaster angulatus* Muller and Troschel, 1842 (Echinodermata: Asteroidea) and its reproductive cycle in south-western Australia. Marine Biology 158: 1163-1173.

Lawrence, J.M., J.K. Keesing and T.R. Irvine (in press). Population characteristics and biology of two populations of *Archaster angulatus* (Echinodermata: Asteroidea) in different habitats off the central-western Australian coast. *Journal of the Marine Biological Association* UK Doi:10.1017/s0025315410000871.

Li, F., C. M. Griffiths, C. P. Dyt, P. Weill, M. Feng and C. Jenkins (2009). Multigrain seabed sediment transport modelling for the southwest Australian Shelf. *Marine and Freshwater Research* 60: 774-785.

Limbourn, A.J., R.C. Babcock, D.J. Johnston, P.D. Nichols and B. Knott (2009). Spatial and temporal variation in lipid and fatty acid profiles of western rock lobster pueruli at first settlement: Biochemical indicators of diet and nutritional status. *Marine and Freshwater Research*. 60:810-823.

Lourey M.J. and H. Kirkman (2009). Short lived dissolved nitrate pulses in a shallow Western Australian coastal lagoon. *Marine and Freshwater Research* 60: 1068-1080.

Paterson, H. L., M. Feng, A.M. Waite, D. Gomis, L.E. Beckley, D. Holliday, and P.A. Thompson (2008). Physical and chemical signatures of a developing anti-cyclonic eddy in the Leeuwin Current, Eastern Indian Ocean. *Journal of Geophysical Research* 113: C07049.

Rousseaux, C., P. Thompson, J. Greenwood, and J.-P. Descy (submitted). Diel vertical migration of dinoflagellates as a mechanism to decrease the impact of microzooplankton grazing. *Marine and Ecology Progress Series*.

Symonds, G., L. Zhong and N. Mortimer (in press). Effects of wave exposure on circulation in a temperate reef environment. *Journal of Geophysical Research*.

Thompson, P.A., Wild-Allen, K., Lourey, M., Rousseaux, C., Waite, A.M., Feng, M., Beckley, L.E. (in press 2011). Nutrients in an oligotrophic boundary current: Evidence of a new role for the Leeuwin Current. *Progress in Oceanography*, doi: 10.1016/j.pocean.

Thompson, P.A., P. Bonham, A.M. Waite, L.A. Clementson, N. Cherukuru, C. Hassler, M.A. Doblin (2011). Contrasting oceanographic conditions and phytoplankton communities on the east and west coasts of Australia. *Deep-Sea Research II* 58: 645–663.

Thompson, P.A., I. Jameson, S.I. Blackburn (2009). The influence of light quality on akinete formation and germination in the toxic cyanobacterium *Anabaena circinalis*. *Harmful Algae* 8: 504–512.

Thompson, P.A., M.E. Baird, T. Ingleton and M.A. Doblin (2009). Long-term changes in temperate Australian coastal waters and implications for phytoplankton. *Marine Ecology Progress Series* 394: 1-19.

Vanderklift M.A. and T. Wernberg T. (2010). Stable isotopes reveal a consistent consumer-diet relationship across hundreds of kilometres. *Marine Ecology Progress Series* 403: 53-61.

Vanderklift, M.A., P.S. Lavery and K.I. Waddington (2009). Intensity of herbivory on kelp by fish and sea urchins varies between inshore and offshore reefs. *Marine Ecology Progress Series.* 376: 203-211.

Published and Unpublished Reports

Irvine, T., F. Parker, J. Strzelecki, M. Vanderklift, J. Keesing, D. Bearham, D. Thomson and R. Downie (2009). *Shelf and Lagoon Biomass and Ecological Sampling Data Report* (WAMSI Node 1 Project 1: Southwest Australian Coastal Biogeochemistry) CSIRO, Australia. 63 pp.

Symonds, G. and N. Mortimer (2009). *Marmion lagoon Measurement Program, July 2007 to May 2008*. WAMSI Node 1 Project 1, Southwest Australian Coastal Biogeochemistry, CSIRO Marine and Atmospheric Research Paper 27, 58pp.

6.4 Presentations

Bearham, D. and M. Vanderklift (2010). The influence of light intensity, temperature and water movement on changes in growth of *Ecklonia radiata* in Marmion Lagoon, Western Australia. *Australasian Society for Phycology and Aquatic Botany*. Rottnest Island, Australia, November 17, 2010

Campbell, N.A, T. Irvine, J. Keesing, G. Keith and P. Kennedy (2010). Canonical variate plots for categorising benthic classes using EM300 multibeam data. *Geohab 2010*. Wellington, NZ, May

4-7, 2010.

Campbell, N.A., J. Keesing, T. Irvine, G. Keith and P. Kennedy (2010). Distinguishing between benthic Classes - full-ping vs moving-window separation. *Geohab 2010*. Wellington, NZ, May 4-7, 2010.

Campbell, N.A., T. Irvine, J. Keesing, P. Kennedy and G. Keith (2009). Canonical variate index plots for categorising marine benthic classes using Simrad EM300 multibeam data. *Femme 09*. Lisbon, Portugal, April 21-24, 2009.

Campbell, N.A., J. Keesing and T. Irvine (2009). Canonical variate analysis using contiguous segments of multibeam data, *Femme 09*. Lisbon, Portugal, April 21-24, 2009.

Campbell, N.A., I. Parnum, J. Keesing, T. Irvine, G. Keith and P. Kennedy (2009). Whole-of-ping vs moving-window separation of seabed classes using EM300 multibeam data. *Femme 09*. Lisbon, Portugal, April 21-24, 2009.

Campbell, N.A., P.A. Caccetta, J. O'Connell, P. Kennedy, I. Parnum, J. Keesing and T. Irvine (2009). Posterior probabilities images incorporating the backscatter angular response for multibeam data. *Femme 09*. Lisbon, Portugal, April 21-24, 2009.

Craig, P.D. (2007). Regional application of Australia's GODAE outcomes. *Global Ocean Data Assimilation Experiment Coastal Workshop*. Liverpool, UK, October 10-11, 2007.

Feng, M. (2009). Modelling the influence of the Leeuwin Current on retention & alongshore connectivity off the west coast of Australia. *WAMSI Node 1: 2nd Symposium.* Perth, Australia, July 30, 2009.

Feng, M. (2009). Long term changes in the Leeuwin Current system in the southeast Indian Ocean. *Greenhouse 2009*. Perth, Australia, March 23-26, 2009.

Feng, M. (2008). Long term changes of the Leeuwin Current derived from an eddy-resolving numerical model. *WPGM*. Cairns, Australia, July 29 – August 1, 2008.

Feng, M. (2008). Physical and chemical signatures of a developing anti-cyclonic eddy in the Leeuwin Current, *PORSEC* Guangzhou, China, December 2-6, 2008.

Feng, M. (2008). The temperature trends in the tropical Pacific and Indian Ocean. *AMOS Annual conference*. Geelong, Australia, January 29 – February 1, 2008.

Feng, M. (2008). A high resolution physical description of the Leeuwin Current. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Feng, M., Biastoch, A., Boning, C., Caputi, N. and Meyers, G. (2008). Variability and trend of the heat balance in the southeast Indian Ocean. *International Symposium on Effects of Climate Change on the World's Oceans*. Gijon, Spain, May 19-23, 2008.

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Feng, M. (2007). Decadal variations and long-term trends in the southeast Indian Ocean. *IUGG*. Perugia, Italy, July 2-13, 2007.

Feng, M. (2007). Nitrogen budget on the continental shelf off the west coast of Western Australia. *IUGG*. Perugia, Italy, July 2-13, 2007.

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Feng, M., K. Wild-Allen and J. Keesing (2007). Climate Variability and the Marine Ecosystem in the Leeuwin Current off Western Australia. *Continental Margins Open Science Conference: Impacts of global, local and human forcings on biogeochemical cycles and ecosystems*. Shanghai, China, September 17-21, 2007.

Gartner, A. (2008). Trophic implications of seagrass habitat disturbance from reduced light. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Greenwood, J. (2010). 4-d bio-physical modeling at shelf and lagoon scale. *WAMSI Node 1 : 3rd Symposium.* Perth, Australia, June 29, 2010.

Greenwood, J. (2009). Chlorophyll dynamics on the continental shelf. *Catchment to Coasts Workshop*, Brisbane, Australia, May 20-21, 2009.

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Greenwood, J. (2008). The underwater light climate off WA. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

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Greenwood, J. (2007). Linking waves and nearshore chlorophyll biomass via sediment nutrient recycling. *International Symposium for the Interaction of Sediments and Waters*. Esperance, Australia, February 17-22, 2008**.**

Gusmão, L.F.M, J. Strzelecki and D. McKinnon (2009). The use of Aminoacyl-tRNA synthetases (AARS) activity as an index of mesozooplankton growth off Western Australian coast. *Australian Marine Science Conference.* Adelaide, Australia, July 5-9, 2009.

Gusmão, F., J. Strzelecki and A. David McKinnon (2011). Mesozooplankton growth as measured by enzymatic activity off the Western Australia coast. *5th International Zooplankton Production Symposium*. Pucon, Chile, March 14-18, 2011

Hanson, C., J. McLaughlin, G. Hyndes, and J. Strzelecki (2009). Connecting the benthic and pelagic: picoplankton uptake by a demosponge (Callyspongia sp.). *Australian Marine Science Conference.* Adelaide, Australia, July 5-9, 2009.

Holliday, D. (2008). Larval fish, eddies and the Leeuwin Current. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Irvine, T. (2008). Shelf scale benthic habitat characterisation by video analysis. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Keesing, J.K. (2010). WAMSI Node1: Strategic Research on Western Australian Marine Ecosystems. Marine *Science in Western Australia. Joint Symposium by WAMSI and AMSA*. Fremantle, Australia, February 9, 2010.

Keesing, J.K. (2010). Node 1 Overview. *WAMSI Node 1: 3rd Symposium.* Perth, Australia, June 29, 2010.

Keesing, J.K. (2010). Understanding the Leeuwin Current Coastal Marine Ecosystem Dynamics. Invited Presentation. *Society for Underwater Technology*. Perth, Australia, August 11, 2010

Keesing, J.K., D. Bearham and T.R. Irvine (2010). Influence of grazing intensity by the sand dollar *Peronella lesueuri* on microphytobenthos and sediment biogeochemistry in a south-western Australian embayment. *7th European Conference on Echinoderms*. Gottingen, Germany,

October 2-9, 2010.

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Keesing, J.K. (2008). Node 1 Overview. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

Keesing, J.K. (2008). SS 2007/04 Shelf scale benthic processes and benthic pelagic coupling – overview of rationale, objectives and operations. *WAMSI Node 1: 1st Symposium.* Perth, Australia, February 27, 2008.

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Keesing, J.K. (2008). Biological Responses to Physical Forcing in Western Australia's Unique Marine Environment. Invited Presentation to His Excellency Ken Michael, Governor of Western Australia, Government House, Perth, Australia, October 9, 2008.

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Lawrence, J.M., J. Keesing and T.R. Irvine (2010). Population characteristics and biology of two populations of *Archaster angulatus* (Echinodermata: Asteroidea) in different habitats off the central-western Australian coast. *7th European Conference on Echinoderms*. Gottingen, Germany, October 2-9, 2010. Echinoderm Research 2010, Abstracts p64-65. (Poster presentation)

Lourey, M., McLaughlin, M.J., Thompson, P, and Keesing, J.K. (2010). Production by Benthic Microalgae. *WAMSI Node 1: 3rd Symposium.* Perth, Australia, June 29, 2010.

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7. OVERALL PROJECT BENEFITS

7.1 Downscaled hydrodynamic models to explore influences on benthic habitat, and the cross-shore and longshore exchange of water, nutrients and particles between the lagoon and shelf regions;

7.1.1 Continental Shelf and Lagoon scales

a. Discovery and Application of New Products and Processes

Not applicable

b. Tools, Technologies and Information for Improved Ecosystem Management

This project has explored the use of models as tools for environmental understanding and prediction. At the full scale of the continental shelf, the project investigated larval advection along the shelf using the BLUElink reanalysis BRAN. Larval retention rates and early stage larval dispersal by ocean currents are pivotal to population dynamics, genetic structure, and biogeography of many coastal species, especially in the very dynamical and variable marine environment off the west coast of WA. There is observational evidence that fish larvae are transported by the Leeuwin Current and its eddies in and out of their hatching ground and inshore habitats. In this project, we have identified close association between the shelf retention rate and scallop fisheries off the west coast, demonstrating the strong oceanographic influence on fisheries recruitment. Further, we have shown that persistent southwestern swell from the Indian Ocean helps to move buoyant organisms, such as rock lobster puerulis, back towards the shore. In addition, in WAMSI Node 1 Project 2, oceanographers and geneticists worked together using the BRAN product and particle tracking to strengthen understanding of the connectivity of benthic communities off the coast of WA (see the Project 2 report).

BRAN is a multi-year archive of global model results with 10 km resolution, improved by data assimilation. While it demonstrates the features of the circulation off the west coast, it is too coarse to fully represent the fine detail of the Leeuwin Current and its eddies. The second tool used in these studies is a finer-resolution model nested inside BRAN. This is an implementation of the ROMS model, with resolution down to 2 km inshore. At this higher resolution, the modelled currents are considerably more energetic. The model was developed specifically to drive a further model of primary productivity (biogeochemistry) over the shelf. Its primary role in management comes through this application, which is described in the following section.

The third tool is a very high (30 m) resolution model of the Marmion lagoon. In this case, the model is Delft University's XBeach, which predicts both waves and currents, and the coupling between them. The modelling and the accompanying field work demonstrate that, when waves (swell) are high enough to break over the reef, this drives the currents inside the lagoon, with outflow to the north and south, and through gaps in the reef. The productivity of the lagoonal system is very dependent on the

wave and current dynamics. While waves appear to enhance access of reef macroalgae to nutrients, seagrasses thrive in the protection of the lagoon. Winter storms break off plant material that becomes wrack, and apparently leads to the recycling of nutrients. There is evidence (see below) that groundwater also introduces nutrients into the lagoonal system. The currents are responsible for distributing nutrients that are resupplied from nitrification in sediments, as well as propagules, through, and beyond the system.

At each of the three scales, eastern Indian Ocean, shelf and lagoon, the models show the importance of physical dynamics to the health and distribution of biological systems. At all scales, the exposed coastal waters of Western Australia show clear responses to climate variability, on time scales of years, and climate change on scales of decades. The physical manifestations of climate change may include changes in: the frequency and intensity of the El Nino-Southern Oscillation (ENSO) cycle; the frequency and intensity of both local storms and distant storms that generate swell; the currents associated with the Leeuwin Current; water temperature; and sea-surface height. Further, coastal waters are affected by coastal population growth and development. Coastal development can change both the physical nature (e.g. through construction) and chemical composition (e.g. through the release of nutrients) of the water. Models provide a mechanism for managing all of these phenomena. They allow cause and effect relationships to be evaluated (e.g. in separating natural and anthropogenic effects), time scales to be separated (e.g. between climate change and variability), and future scenarios to be simulated. Further, through coupling to biological models (see below), they allow quantitative investigation of ecosystem responses to the physical forcing.

7.2 Coupled hydrodynamic and biogeochemical models and a quantitative nutrient budget for coastal waters at shelf and lagoon scales

7.2.1 Continental Shelf Scale

a. Discovery and Application of New Products and Processes

Not applicable

b. Tools, Technologies and Information for Improved Ecosystem Management

The shelf-scale biogeochemical model developed, together with the hydrodynamic model, during this project represents a valuable tool for on-going investigation of the biogeochemical dynamics of the WA shelf. For example, tracer experiments are already underway to investigate the supply of deep-water nitrate to the shelf. The model shows that wind-driven upwelling of nitrate and eddy export of phytoplankton are significant processes in the supply and removal of nitrogen from the shelf. For much of the time, the presence of the Leeuwin Current at the shelf-break suppresses the upwelling. Further, large Indian Ocean swell appears to drive recycling of nutrients through the sediments. Most of the nutrients on the shelf appear to be recycled, rather than renewed from offshore (or inshore).

As noted above, all of these physical phenomena – upwelling, the Leeuwin Current and its eddies, and Indian Ocean Swell – are likely to be affected by climate change, and are affected by climate variability. There is clear interannual variability, and significant spatial structure, in the surface-water productivity across and along the shelf, as observed by satellite imagery. The model will enable climate variability in the primary production to be explained, and the impacts of climate change to be assessed. Further, although there are local sources of nutrients inshore, much of the nutrient supply to the coastal zone is likely to come from offshore. The model will be the only tool to allow a regional assessment of the offshore impacts of climate change on inshore (reef and lagoonal) productivity.

7.2.2 Lagoon Scale (Marmion Lagoon)

a. Discovery and Application of New Products and Processes

Not applicable

b. Tools, Technologies and Information for Improved Ecosystem Management

Measurement of nutrients in the Marmion lagoon throughout the year suggested groundwater seeps of nutrient-rich water into the reef system. Modelling shows that the plume-like distribution of nutrients in the water is consistent with relatively small-area seeps. However, seeps are yet to be definitively identified in field measurements, and other influences, such as the draw-down of phytoplankton by filter-feeding sponges, may contribute to the structure of the nutrient distribution. The modelling is preliminary at this stage, but indicates that ground-water management may contribute to the health of the reef system. Meanwhile, the lagoon-scale coupled physical-biological model developed during this project is a valuable tool for future understanding of the nearshore biogeochemical dynamics at Marmion and elsewhere along the coast. The model incorporates benthic macroalgal and sea-grass production, although this has not been run seriously because of uncertainties about the lagoonal nutrient balance. There will be major challenges in the modelling, for example, in capturing the wrack cycle, and the dependence of the macroalgae on the wave environment. It will also be challenging to deliver the observations required to calibrate and validate the model. However, the model will be a critical tool for understanding, predicting and managing the impacts of both climate change and the various human activities along the coast on the rich near-shore ecosystem.

7.3 Improved descriptions and conceptual biogeochemical models for shelf and lagoon waters incorporating seasonal and interannual variability and improved representation of benthic primary production and bentho-pelagic coupling;

7.3.1 Lagoon Scale (Marmion Lagoon)

a. Discovery and Application of New Products and Processes

Not applicable

b. Tools, Technologies and Information for Improved Ecosystem Management

Information for improved ecosystem based management was provided in the quantitative understanding that actions which substantially change the nutrient, light, temperature or wave climate will likely change the rates of benthic primary production, and that such changes would propagate through nearshore food webs.

7.3.2 Continental Shelf Scale (Pelagic)

a. Discovery and Application of New Products and Processes

The focus for this component of the WAMSI Node 1 project was not the production of products other than the improvement of our conceptual understanding of nutrient cycling on the shelf. This 'product' is encapsulated in Figure 7 below, published in Progress in Oceanography 2011.

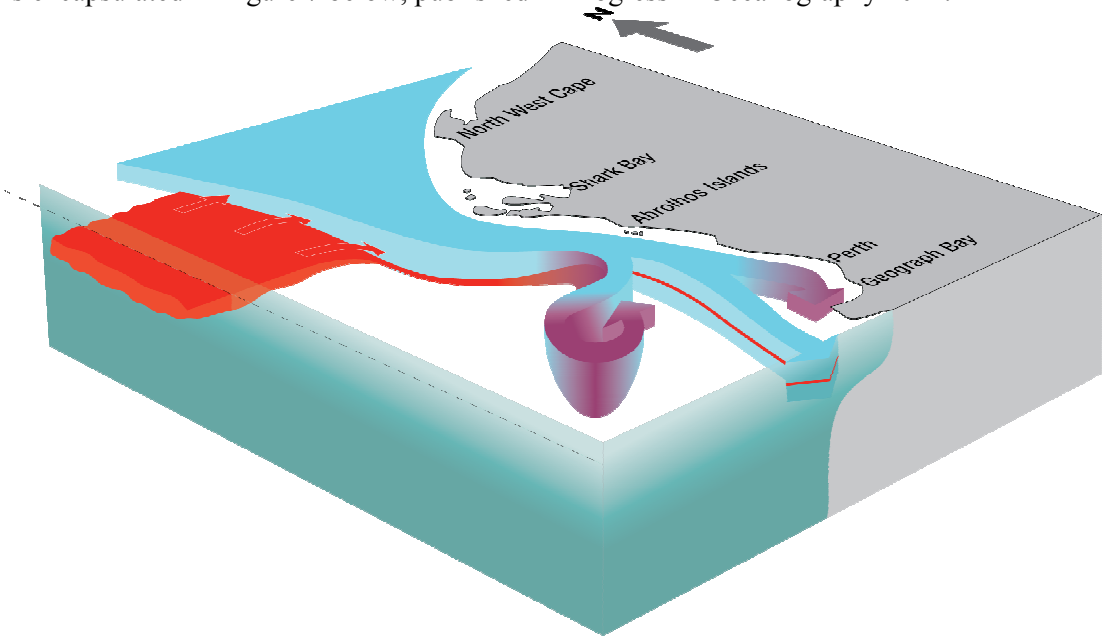

Figure 7. A conceptual model for the source of low dissolved oxygen and high nitrate being entrained into the Leeuwin Current during autumn. Red colour = nitrate, light blue = Leeuwin Current.

b. Tools, Technologies and Information for Improved Ecosystem Management

A great deal of data was collected and analysed as part of this component of the Node project. A great deal of this has been published and its existence in the public domain helps to assure sustained use of the data and the concepts. One publication provided extensive maps of phytoplankton distributions from 22° to 34°S. The entire physical data set is archived with CSIRO (as below), WAMSI and IMOS and is available to the public through easy to use web based tools. The majority of the biological data is similarly archived and those components collected by CSIRO have been transferred to publically accessible data bases at CSIRO and IMOS. As documented elsewhere a number of students used the research voyages to collect data and CSIRO personnel to assist with interpretation. All pigment data has been supplied to Australian researchers working on remote sensing and also will be supplied to American and European Space agencies.

7.3.3 Continental Shelf Scale (benthic)

a. Discovery and Application of New Products and Processes

Improved methods of analysis of acoustic backscatter data were developed and applied enabling greater discrimination between different classes of benthic habitats from swath mapping surveys.

b. Tools, Technologies and Information for Improved Ecosystem Management

The data and models produced in this part of the study have shown the importance of benthic habitats on the continental shelf and in particular shown that the importance of the very spatially extensive and deeper benthic habitats has been underestimated. Similarly the importance of soft sediment habitats has been underestimated in the past. As such the results have important implications for ecosystem based management of fisheries resources and implications for ecosystem and primary producer habitat protection, with habitats previously regarded as being of low environmental importance now evidently warranting greater protection. It is also clear that our study has demonstrated the need for more extensive studies on the processes which are important in structuring these deepwater habitats and the role they play in primary production and nutrient recycling and resupply, In particular we suggest that the deep water kelp communities warrant study they can tell us about kelp resilience and how to protect kelp resources in shallower eaters in the face of climate change, the role of sponges as nitrifiers and the extent of autotrophy and improved quantification of the contribution of soft sediment habitats to primary production and nutrient resupply functions in southwest Australian ecosystems. Lastly, this study has only looked at a very small section of the western Australian shelf and many of the conclusions are underpinned by assumptions and make use of literature values that should be tested and warrant verifying by targeted investigations. Thus much new work is warranted to quantify the importance of mesotrophic habitats to southwest Australian ecosystems.

7.4 Simple models for assessing and predicting impacts of physical forcing factors, primarily nutrients, on key benthic functional groups/habitats informed by experiments and observations conducted across a range of naturally varying and anthropogenically altered gradients related to nutrient enrichment.

7.4.1 Anthropogenically altered gradients of nutrient enrichment

a. Discovery and Application of New Products and Processes

We have applied novel molecular probes that target nitrifying and denitrifying genes across a range of microbial taxa. These probes are a cost effective tool for identifying the presence and biomass of particular organisms responsible for some of the most important microbial nutrient modification processes. These molecular probes are a powerful new tool for understanding the biological pathways of N cycling in the sediment and we anticipate their ongoing refinement and use will continue to give new insights into N cycling in the Western Australian marine environment. In addition we applied molecular probes for polychaete indicators of sediment nutrient enrichment which show promise of delivering rapid assessment of sediment health and anthropogenic enrichment.

b. Tools, Technologies and Information for Improved Ecosystem Management

A conceptual model of soft sediment habitat condition or state is proposed based on the large range of physical, biogeochemical and ecological parameters we measured. It suggests that biogeochemical and ecological attributes of sediments can reveal the degree of alteration of sediments between a base state of “typical” or “healthy” sediment habitats and the degraded condition state. Some aspects of the model are simplistic and require qualification but it does present a practical approach to assessing habitats, designing and carrying out monitoring and for predicting the trajectory of sediment habitats where there is concern about the potential for anthropogenic enrichment. The simple relationships derived for production versus irradiance (P versus I) have potential beyond the direct results of this project. These relationships form a baseline of photosynthetic performance for comparison with other regions and if repeated over time could reveal a response to changing climate.

8. PROJECT METADATA AND DATA GENERATED

The WAMSI program has generated data from a wide range of sources, disciplines and organisations that has resulted in the assembly of a multitude of data formats and data types.

To manage these datasets, a version controlled data repository was established that served as a central data distribution point and is supported by a repository website (http://www.marine.csiro.au/datacentre/SRFMEandWAMSI/) and a publicly accessible metadata tool called MarLIN (http://www.marine.csiro.au/marlin). MarLIN is linked to both the Australian Spatial Data Directory and the Australian Ocean Data Network (AODN). Both these external metadata search services provide international online access to WAMSI metadata records.

Metadata records are published in the public domain, while access to datasets in the data repository is provided via the data repository website.

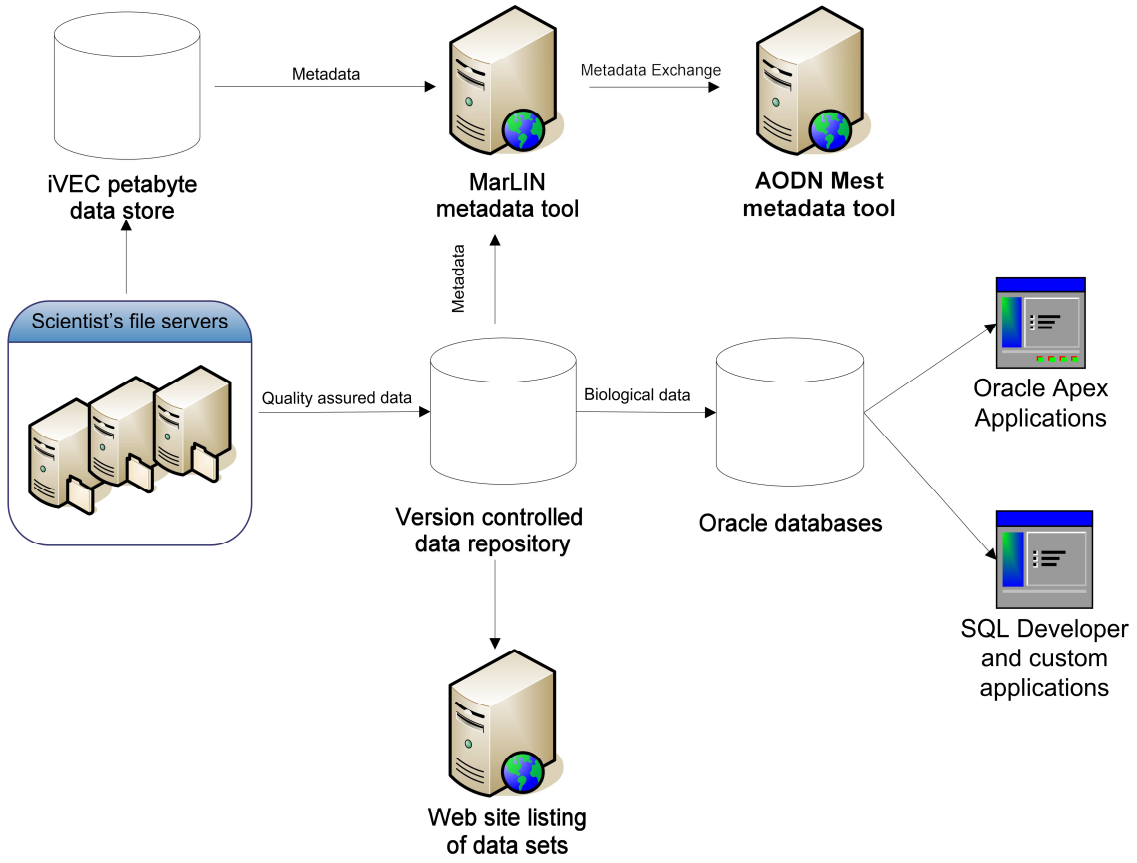

Figure 8. WAMSI Data Repository architecture

The data repository is mounted on a CSIRO computer with appropriate file restrictions to limit access to CSIRO WAMSI participants only. The repository consists of a directory structure that mirrors the major project components of the WAMSI program.

To maintain the integrity of data, only data that has been quality assured by scientific staff is included in the repository. Quality standards are maintained by, and are the responsibility of individual projects.

8.1 Version control

To maintain the currency of data exposed via the WAMSI data repository website, the data repository was placed under an "Apache Subversion" (SVN) version control system. SVN was chosen because of its simplicity and ability to support the needs of a wide variety of users and projects.

8.2 Biological data

Most biological data was provided in the form of Microsoft Excel® spreadsheets, the format of which reflected a wide range of datasets, experiments and data manipulation processes. These spreadsheets have been placed directly into the data repository.

Quality assured raw data was also entered into an Oracle database so that common attributes such as temporal and spatial information could be merged for different datasets, such as algae, invertebrate, fish species, coral, habitat and substrate datasets. A variety of tools were then used by scientists to further process data. At the time of writing, the data base contained 39,160 biological data items in 1,018 data sets and 11,973 transect images.

8.3 Large data sets

Where large data sets of terabyte size would have placed an excessive burden on the data repository and its associated infrastructure, this data was placed in the iVEC petabyte data store.

9. LINKAGES TO ASSOCIATED PROJECTS

Working with the Department of Fisheries, the BRAN product and particle tracking method are being applied to understand the recruitment of the western rock lobster recruitment in one of our FRDC related projects.

In another FRDC project, we plan to use the method to guide field work to sample the dhufish larvae off the lower west coast.

Methods and capability developed in WAMSI have been shared with FRDC project 2010/47 (Biological Oceanography of Western Rock Lobster Larvae - PI Professor Anya Waite, UWA) and applied in CSIRO and MNF funded research in the Kimberley region during 2010.

10. ANNEXURES

Annexure A: Project Final Report – Research Chapters comprising the research chapters for this project

Annexure B: Printed copies of Publications

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