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Western Australian Marine Science Institution NODE 2

Climate processes, predictability and impacts in a warming Indian Ocean

SUMMARY REPORT

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Important Disclaimer

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NODE DETAILS

Name of Node: Climate processes, predictability and impacts in a warming Indian Ocean

Node Leader: Ming Feng (CSIRO)

Project 2.1: Dynamics and predictability of the Indo-Pacific Ocean as a global condition on marine climate impacts in Western Australia
Project Leader: Harry Hendon (BoM)

Project 2.2: Dynamics and impact of the Leeuwin Current on the marine environment off Western Australia
Project Leader: Ming Feng (CSIRO)

Project 2.3: Oceanic conditions at Ningaloo Reef—analysis of downscaling ocean climate into the Ningaloo Reef Tract
Project Leader: Richard Brinkman (AIMS)

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1. NODE KPIS

The objective of the Node is to understand and predict large scale variation and change of ocean-climate, its impact on the continental shelf, and to inform decision making in WA on vulnerability of marine environment to climate variation and change.

The overall outcomes of the Node are to address:

1.1. An understanding of the usefulness of seasonal forecasts of Leeuwin Current strength and structure, including downscaling to inshore areas that are affected by climate

Outputs from projects 2.1, 2.2, 2.3

1.2. Knowing the best we can expect (so called “potential predictability”) from seasonal climate forecasts of large scale ocean-climate, and possible applications in Western Australia

Outputs from project 2.1

1.3. An understanding of the usefulness of downscaling climate change to support planning and management of Leeuwin Current ecosystems

Outputs from projects 2.1, 2.2, 2.3

1.4. A solid scientific foundation and improved capacity to manage the Ningaloo Marine Park

Outputs from projects 2.1, 2.2, 2.3

2. RESEARCH PLAN

Understanding and predicting variation and change of ocean-climate off Western Australia, including the Leeuwin Current, requires knowledge of the tropical Indian and Pacific Oceans, present day capability to simulate variable circulation in those oceans, and documentation of the impact of an imperfect ocean observing system, particularly in the Indian Ocean, on ocean-forecasts. After the above assessments, experimental seasonal forecasting products will be tailored to the WA marine environment.

With a focus specifically on the Leeuwin Current region, analysis of the available observations and results from numerical models, will identify mechanisms of regional warming, multi-decadal trends and interannual variation of regional circulation. Development of a capability to downscale results from climate model projections will provide the capability for future climate change scenarios ranging from the Leeuwin Current system to the small scale of the Ningaloo Reef Tract. Validation of the performance of the downscaling model at each nested level will be carried out against in-situ observations and remotely sensed data. Validation of downscaling is an essential step toward uptake and use of climate change scenarios.

In order to bridge from physical understanding to biological impacts, which occur on a small spatial scale, ship-based process studies and numerical modelling will document the role of Leeuwin Current eddies in cross-shelf transport.

3. RESEARCH ACTIVITIES

Project 2.1 developed a predictive scheme for Fremantle sea level, a proxy index of the Leeuwin Current (Feng et al. 2003), based on historical forecasts (hindcasts) from the Bureau of Meteorology's coupled dynamical seasonal prediction system POAMA version 1.5b (The Predictive Ocean Atmosphere Model for Australia). The hindcasts were used to establish the accuracy of seasonal predictions for the large-scale marine environment off Western Australia. A statistical downscaling approach provides predictions of Fremantle Sea Level based on the POAMA system with lead times out to 9 months. The forecast scheme described by Hendon and Wang (2009) uses prediction of the Nino34 (tropical Pacific) sea surface temperature (SST) index from POAMA, prediction of heat content on the northwest shelf of Australia from POAMA, and the latest monthly mean observation of sea level at Fremantle for the initial forecast time. The output of their predictive scheme is a forecast of the Fremantle sea level anomaly (anomaly relative to the seasonal cycle) at lead times to 9 months.

Recognizing that the El Nino Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD) affect seasonal weather patterns off Western Australia, Project 2.1 also estimated the potential predictability of the IOD using POAMA and the interannual atmospheric conditions over WA during ENSO and IOD events.

The POAMA Ensemble Ocean Data Assimilation System (PEODAS) produced daily ocean-maps for the period from 1980 to 2006 using all available observations. After validation against independent data and comparison to similar products from other groups around the world, the project developed a characterisation of the upper ocean state associated with Madden Julian Oscillation (MJO, Wheeler and Hendon 2004) with particular focus on the near-shore variations of temperature and currents off Western Australia. Predictability of the regional marine and weather conditions associated with MJO was assessed**.**

Project 2.2 documented oceanography, multidecadal trends and quantitative heat budgets in the warming regions of the eastern Indian Ocean, including the equatorial and Leeuwin Current regions. Standard techniques of time series analyses and linear regression documented multi-decadal trends in surface and subsurface temperature, sea level, and weather variables, as well as the results from long term numerical model simulations forced by observed wind stress. The analysis used three fine scale ocean models (two from the BlueLink project and a fine scale model developed by French and German colleagues). The seasonal, interannual, and decadal variability of the Leeuwin Current and its heat balances were studied using these models. In addition, the Community Atmosphere Model version 3 (CAM3) (Collins et al., 2004) was used to assess the influences of the Indian Ocean Dipole sea surface temperature anomalies on wind patterns in the Leeuwin Current region.

In order to link physical oceanography and biology, the role of ocean eddies and other mesoscale structures in the ecosystem of the Leeuwin Current was identified using satellite-observed sea surface height and sea surface temperature (SST) and observations from a number of Southern Surveyor cruises. The goal was to understand the cross-shelf processes and their biological impacts. Field work was engaged through a PhD student project, which was an effective way to establish the necessary multidisciplinary team, investigate the cross-shelf transport and entrainment of larval fish during the formation of meso-scale eddies of the Leeuwin Current. The three-dimensional characterisation of the flow field in OFAM model permitted estimation the strength of two pathways of nutrient supply to the euphotic layer in the eddy: (1) nutrient supply from the shelf and (2) supply from the thermocline below the euphotic zone.

Downscaling model results is also required to make a link between physical oceanography and biology. We have taken the first steps to downscale the projected future changes in the Leeuwin Current system under the influence of global warming. Firstly, an assessment of Global Climate Models (GCM), including the CSIRO Mk3.5 model, which is the most accessible and familiar to Australian researchers. Secondly a downscaling run of a future climate scenario was carried out with OFAM nested in the future oceanic and atmospheric boundary conditions from the CSIRO Mk3. The downscaled ocean anomaly fields in the Leeuwin Current region are defined as changes between the decadal averaged temperature, salinity and velocity fields between 2060s and 1990s (Sun et al. 2011; Chamberlain et al. 2008).

Project 2.3 developed the capability to downscale the output of regional ocean models (both contemporary and future ocean conditions) to the very small scale (~0.5km x 0.5km) of the region encompassing Ningaloo Reef. This involved multiple nesting in the large scale model, using Sparse Hydrodynamic Ocean Code (SHOC; Herzfeld et al. 2007) and for the smallest scales Regional Ocean Modelling System (ROMS; Wilkin *et al.* 2005). The capability was demonstrated with downscaled model simulations of contemporary conditions from the OFAM and OceanMAPS. Output was used to analyse the frequency of upwelling favourable conditions for the period 2002-2008 in order to construct climatology for contemporary conditions.

Evaluation of the numerical model performance, at both levels of nesting, was undertaken using in-situ observations of vertical current profiles and water column temperature structure, provided from the AIMS long-term Ningaloo current meter and temperature moorings and a field campaign undertaken between September and November, 2011.

Future oceanic conditions were simulated using output from WAMSI Project 2.2, the downscaled climate in the decade of 2060 to 2069, following the “A1B” scenario of the Special Report of Emission Scenarios. OFAM downscaled projections of the regional circulation were used as boundary forcing for our regional downscaling and also to analyse changes to the general alongshore currents from contemporary conditions.

4. RESEARCH FINDINGS

4.1 Overall Research Findings [very high level]

The three projects in Node 2 have characterised the Western Australian marine environment from the largest scale of climate drivers spanning the Pacific and Indian Oceans, to the width and length of the Leeuwin Current, and down to a single reef (on the order of 0.5km). This characterisation involves description of the present day oceanographic conditions, capability to predict future conditions three seasons in advance, and capability to prepare regional scenarios of the impact of global warming at mid-century even at the scale of an individual reef. This work underpins future improvement of both the POAMA seasonal forecast system and the CSIRO Mk3.5 Global Climate Model by identifying the mechanisms that govern regional marine conditions and that must be correctly incorporated in ocean and climate models. The work also opens the way for more extensive uptake and application of the model results. A key insight, potentially important for all the scales that have been addressed, is finding evidence for natural, multi-decadal variation in the regional marine environment and basin-scale climate, which must occur in tandem with the slower development of impacts of climate change. This has to be taken into account in adaptation and mitigation of climate change.

4.2 Specific Research Findings/outputs [specific to the individual projects]

4.2.1 Project 2.1

- We found that the El Niño impacts on the West Australian marine environment occur through two distinct mechanisms: 1) an oceanic teleconnection that drives variations of the Leeuwin Current and 2) an atmospheric teleconnection that cause variations in winds and rainfall over the southern region. The atmospheric teleconnection occurs via the co-varying sea surface temperature (SST) and convection variations in the tropical Indian Ocean that excite an atmospheric Rossby wave. This mainly occurs associated with co-development of the Indian Ocean Dipole (IOD) during El Nino. However, the IOD is largely independent of the El Niño in austral winter, so there is very little impact of ENSO on the WA climate in winter. The Rossby wave associated with the positive IOD generates an equivalent baroptropic anticyclone over the Australian Bight region with resultant easterly wind anomalies across southern WA. The IOD, although strongly co-varying with ENSO in austral spring, does vary independently of ENSO and thus can be an important source of wind variability and rainfall in the WA marine environment.

- POAMA has good skill in predicting El Niño and its oceanic teleconnection of heat content off of the North West Shelf (HCNW; 15ºS-25ºS, 112ºE-120ºE). Because HCNW and El Niño (as monitored using the Nino3 SST index) co-vary tightly with the Leeuwin Current (as monitored by Fremantle sea level), the POAMA forecast of heat content and EL Niño can be used to make highly skilful forecasts of the variations of the Leeuwin Current with up to 9 month lead time.

- Because variations of the Leeuwin Current are associated with a broad scale variation of ocean surface temperatures along the entire WA coast, seasonal predictions of the variations of Leeuwin Current with up to 9 month lead time have many potential uses for management of resources in the WA marine environment.

- In observation, the IOD develops in austral winter, peaks in austral spring and rapidly decays in austral summer. About half of the variance of the IOD can be explained by its co-variation with ENSO. It shows that the seasonal phase locking of the development of the IOD is well depicted in the POAMA forecasts but the IOD's structure is distorted and its amplitude weakens with increasing forecast lead time.

- At longer lead time, the IOD is simulated in POAMA to become spuriously over-dependent on ENSO. This appears to stem partly from biases in the Pacific ENSO mode (i.e., the westward extension of the ENSO related SST anomalies in the Pacific) as a result of biases in the mean state of the Pacific cold tongue, thus causing the ENSO teleconnection into the Indian Ocean region to strengthen and shift westward at longer lead time.

- In light of these biases in the simulation of the IOD, skilful prediction of the IOD with the POAMA1.5b system is confined to forecasts that verify in September-November and that are initialized after June. Skill drops off rapidly for forecasts initialized before June and is much lower than the skill for predicting El Niño, reflecting both the more limited lifetime of the IOD as compared to ENSO but also the overall lower level of predictability in the equatorial Indian Ocean than in the equatorial Pacific.

- Forecast skill for the IOD appears to be primarily limited by the ability to predict SST variations in the eastern portion of the equatorial Indian Ocean (associated with coastal upwelling off of Java-Sumatra) as forecast skill in the western portion of the basin is comparable to (as a result of being driven by) forecast skill of ENSO in the Pacific (i.e., skill in the western pole extends beyond 9 month lead time for forecasts initiated in the June-January period).

4.2.2 Project 2.2

- Approximately half of the positive or negative IOD years occur when the ENSO phase is neutral (i.e. many positive and negative IOD events are independent of El Nino and La Nina.). They develop through an ocean-atmosphere instability that occurs within the Indian Ocean. Maps of rainfall over Australia in the various phases of IOD-ENSO were prepared.

- Analysing climate model simulations, the warming in the equatorial Indian Ocean in the recent decades was identified to be caused primarily by decreased cooling by the upwelling process, in contrast to the global averaged temperature which is governed by increased surface heat flux.

- A multi-decadal cooling trend in subsurface temperature of the western Pacific, along the northwest coast of Australia and in the Leeuwin Current region is consistent with the observed weakening of the trade winds in the Pacific from 1960 to early 1990's. The change in temperature and wind is also consistent with a 23% weakening of the Indonesian Throughflow after the 1976 climate regime shift.

- The tropical Pacific appears to be experiencing a reversal in trends since the early 1990's. All atmospheric reanalysis products corroborate the trend reversal of the trade winds and there has been a strengthening trend of the Pacific subtropical cells. The reversal of trends in strength of the Indonesian Throughflow and Leeuwin Current appear to be weak in model, due to model-drift and weak reversal in model forcing. However, a linear regression analysis between the interannual variations of the current transports and the equatorial

Pacific winds is able to derive a significant strengthening trend of the Indonesian Throughflow and the Leeuwin Current since early 1990's.

- The lower west coast of Australia has experienced a significant increase in near surface temperature which was confirmed using global SST products. SST in the region does not have a reversal of trend because it is directly, locally forced by the surface heat fluxes associated with the enhanced greenhouse effect, where as the Leeuwin Current variation is largely remotely forced by Pacific wind stress.

- There is a strong seasonal variation in the historic increases in temperature, with maximum rate of increase during May to August (a joint Nodes 2 and 4 study). The warming trend results in a change to the seasonal temperature cycle over the decades, with a delay in the peak in the temperature cycle during autumn between the 1950s and 2000s of about 10–20 days. The implications of change in seasonal cycle for fisheries and the marine ecosystem are assessed in WAMSI Node 4.

- A comparison of the CSIRO climate change model Mk3.5 to observed trends and simulations with ORCA025 leads to the conclusion that Mk3.5 cannot reproduce the strength of the Leeuwin Current, due to its low spatial resolution, and consequently it cannot capture the seasonal variation of the heat balance in the Leeuwin Current region. Thus, it is necessary to use nested modelling to downscale the climate change signals in the Leeuwin Current system.

- From Bluelink model and satellite altimeter data, the seasonal cycle in strength of the Leeuwin Current originates from an annual pulse of sea level generated in the North West Shelf that propagates around the Australian coastal waveguide. The sea level feature appears to be initiated due to an anomalous increase in heat flux to the northwest shelf region which is evident in sea surface temperature as well as seasonal changes of wind regime. Bluelink model is sensitive to physical parameterisations (e.g. tidal mixing); however, some parameterisations are able to simulate small scale structure such as the Holloway Current. Careful validation of the model and its sensitivity to parameterisation is necessary before using it for small scale studies.

- On both seasonal and interannual timescales, the mixed layer heat budget off the west coast of Australia is predominantly balanced between the variations of the Leeuwin Current heat advection and heat flux across the air-sea interface. Warming by heat advection of the Leeuwin Current is stronger during winter than summer and stronger during La Nina than El Nino. The heat gain by the atmosphere is latent heat, which implies a potential impact on coastal climate of in southern regions of WA. The analysis of the heat budget has shown that the interannual variation of the average February–April surface temperature off the west coast of Australia is mainly controlled by the Leeuwin Current heat advection as well as the conserved subsurface temperature from the previous austral winter, with the air-sea flux playing a buffering role. The surface temperature is an important factor in recruitment of western rock lobster.

- The teleconnections from IOD have been identified by our collaborators in WAMSI Project 2.1 and the anomaly off southwest Australia appears as an easterly wind blowing offshore. Sensitivity studies of the IOD teleconnection with the atmospheric model (CAM3) indicate that the wave train is a highly non-linear phenomenon. The poles of the wave train vary a lot in strength and location from event to event. This may account for the low statistical correlation between IOD and weather variables in the south western region of Australia.

- The physical and chemical structure of a developing anti-cyclonic eddy in the Leeuwin Current and its connection to cross-shelf exchange was documented during the eddy formation. Water mass within the eddy was mainly derived from the Leeuwin Current or modified water on the shelf. Near the centre of the eddy, high nitrate concentrations (up to 2 µmol $L^{-1)}$ were observed just below the mixed layer depth, and high silicate concentrations (up to 4 µmol $L^{-1)}$ were observed within the mixed layer. The cross shelf transport provided a pathway for the transport of shelf-origin biota to the eddy. Circulation of the Leeuwin Current was largely responsible for the observed patterns of horizontal distribution of fish larvae. The occurrence of neritic larvae of inshore reef-dwelling families such as the Tripterygiidae (Triple-fin blennies) within the eddy confirmed that the larvae of neritic fish species are subject to offshore transport and incorporation into eddies during eddy formation.

- A suite of tracers inserted in the model-flow field indicates that offshore export of nutrients starts with the formation of the eddies in April-May, continues well into the austral winter, reaches as far as several hundred of kilometres offshore and is sufficient to explain 70% of elevated chlorophyll a concentrations observed in anti-cyclonic eddies during the first seven months of their lifespan. Diapycnal transport (such as vertical entrainment) of thermocline waters high in nitrate is less important. The late austral autumn/early austral winter blooms off the west coast of WA are highly linked with enhanced horizontal mixing by mesoscale eddies in the region, as derived from the finite-size Lyapunov exponent (FSLE) of the surface geostrophic flow field derived from satellite altimeter data. The pathways of the cross-shelf exchanges, which are mostly driven by the mesoscale eddies, are revealed with coalescing the FSLE of the surface geostrophic flow field and the satellite chlorophyll *a* images.

- The GCM simulations of the zonal wind stress during the 1990's in most climate models show a weak to moderate bias toward strong easterly Trade Wind over the equator in the western Pacific. The GCM simulations of meridional wind stress show a bias toward stronger southerly wind over the Leeuwin Current in the GFDL and MPI models and bias toward weaker southerly wind in the CSIRO and UK Met Office models (not shown, see Sun *et al*. 2008). The wind-biases in the CSIRO model will generate a bias toward a strong Leeuwin Current. This bias appears in the simulation of sea level. The impact of bias needs to be considered in assessment of trends between the 1990's and 2060's. The trends in Pacific equatorial zonal wind stress between 1990's and 2060's due to human induced greenhouse forcing are increasing strength in the GFDL model, decreasing strength in the CSIRO model and little change in UKMO and MPI models. The GCM's also produce different trends in the meridional wind stress over the Leeuwin Current; however, the CSIRO model shows little change. The trends in the CSIRO model will force a weaker Leeuwin Current, with other forcing factors remaining unchanged.

- A conclusion of this study is that a range of GCM's will have to be downscaled to identify the range of possible future behaviours of the Leeuwin Current System. Only one GCM can be downscaled at this time due to limited resources in WAMSI. The CSIRO model was used because it is the most accessible and familiar to Australian researchers. However, the differences in bias and trend of alternative models need to be kept in mind when assessing results. A multi-GCM downscaling is recommended for the future.

- All the climate models simulate a Pacific-Indian Ocean Indonesian Throughflow (ITF), a broad poleward-flowing Leeuwin Current (LC) and an equatorward-flowing undercurrent adjacent to the WA coast. The models adequately simulate the mean seasonal cycle of ITF- and LC-transports. The MIROC3.2-HI simulates the most realistic LC in the sense that the core of the current is concentrated close to the coast. This could be in part due to the fact that it has the finest longitude resolution and is one of the few models to have a shelf like bathymetry along the west coast of Australia. This supports the need for dynamical downscaling to resolve a changing climate in the future more reliably.

- The correlation of Indonesian Throughflow and Leeuwin Current to forcing by Pacific wind was assessed for all available IPCC models. Significant correlations exist between the ITF transport and the equatorial Pacific zonal winds. With the exception of two outliers (the models with lowest and highest horizontal resolution), a similar relationship exists between the LC transport and both the ITF transport and equatorial Pacific zonal winds. Examination of future changes in the same variables revealed that the correlation between ITF transport and equatorial Pacific zonal winds was significant, however, there is more scattering among the climate models. The changes in future LC transport are weakly (but still significantly) related to ITF transport and equatorial Pacific zonal winds. CSIRO-MK3.5 model appears to represent close to the average of the climate models examined.

- The downscaling run produced oceanic structure relevant to narrow currents in a large region around Australia, including the Leeuwin Current, the East Australia Current and Southern Ocean fronts. While the product is realistic looking, it must be considered the first step toward having a reliable and useful capability to downscale future climate projections. Atmospheric forcing for the downscaled ocean model in 2060’s needs to take account of ocean-feedback on air-sea fluxes. This feedback was represented as a flux that tends to preserve the changes in SST and SSS in the GCM run. Trial downscaling runs with no feedback produced significant differences from the future GCM SST and SSS on a large scale around Australia. These differences were reduced but not eliminated by a range of feedback-strengths. Further research is needed to increase confidence that ocean-feedback on air-sea fluxes is realistically represented. The downscaled product produces realistic looking transport of currents around Australia, particularly the strongest currents, East Australia Current and streams in the Antarctic Circumpolar Current; The Leeuwin Current appears weaker than the EAC and ACC, but it appears clearly with a realistic width and strength if the map is telescoped to a regional scale. The current as well as the eddies and zonal jets connecting the Leeuwin Current to the offshore ocean interior are more realistic than circulation in the GCM; The downscaling projects a reduction in Leeuwin Current transport of ~15%.

4.2.3 Project 2.3

- Northward coastal currents along the Gascoyne and Ningaloo coasts develop on the inshore side of the Leeuwin Current under strong southerly winds (Taylor and Pearce, 1999). However, observational data and local modelling show that north-south reversals of the near-reef currents may not be solely a response to southerly winds stress. The strong offshore eddies adjacent to Ningaloo (Feng et al. 2005) also introduce significant variability to the near-shore currents adjacent to the reef. Understanding the combined action of southerly wind and eddies is important for understanding upwelling of nutrient rich water.

- When the Leeuwin Current moves toward the coast, the thermocline adjacent to Ningaloo Reef deepens. On reversal of the current near the coast under strong southerly wind, the thermocline shoals in response to offshore Ekman transport, rising by up to 50m at the continental slope and delivering cool nutrient rich water to near the surface, where it can mix and exchange with lagoon waters via tidal mixing and wave pumping. Our modelling has demonstrated that offshore eddies adjacent to Ningaloo can also contribute to this process.

- A climatology of the alongshore currents adjacent to the Ningaloo coast based on the BlueLink re-analysis (Oke *et al*. 2008) and downscaling, indicates strong seasonality in both the mean alongshore current and it’s standard deviation, with weakened southward flow during the austral summer months and in late winter. A climatology of wind based on data collected on the NW Cape at Milyering confirms seasonal variability in both wind speed and direction. Analysis of the Bluelink reanalysis and downscaled products indicates that winter flow reversals (upwelling) are strongly influenced by remotely forced regional circulation features such as eddies.

- A similar analysis of monthly mean alongshore flow and flow reversal events based on downscaling of CSIRO Mk3.5 model A1B future climate scenario indicates changes from the contemporary climatology based on the BlueLink reanalysis. In all future years, the mean monthly alongshore flow displays a peak in southerly flow in autumn/ early winter, but the weakening of the southerly flow, which occurs in August/September in contemporary conditions, does not have a similarly clear and repeated seasonality. It is unclear what processes are driving the divergence from contemporary conditions, and more analysis of the future scenario model output is underway to determine the appropriate approach for interpreting and using the OFAM future scenarios as forcing for the nested regional and coastal models.

4.3 Intra-Nodal Scientific Outcomes [across the projects]

There have been excellent interactions among the Node 2 projects over the last 5 years. Importantly, this has involved collaboration across the boundaries of three organisations—CMAR, BoM and AIMS—and should open the way to further collaboration in this area of research.

Project 2.1 provided large scale background of Indian Ocean climate variability for the regional study in project 2.2, such as on the interaction between the ENSO variability in the Pacific and the Indian Ocean Dipole in the Indian Ocean, and their potential influences in the offshore winds off southwest WA. Project 2.2 supported project 2.1 by providing regional oceanographic data to validate global numerical models, as well as insights into the Leeuwin Current dynamics.

Project 2.2 provided the future climate downscaling model outputs for the boundary current systems around WA for project 2.3 to understand and downscale the climate change impacts on the Ningaloo Reef, while project 2.3 supplied field data for the PhD student project in project 2.2 on the role of mesoscale circulation in the regional ecosystem.

Most of the intra-Nodal communications and collaborations are achieved through the annual science symposium and workshops, as well as project leaders meetings. The WAMSI science review has also been facilitating the intra-Nodal exchange among the Node 2 projects.

4.4 Inter-Nodal Scientific Outcomes [between this and another Node(s)]

Overall, Node 2 provided up-to-date climate information to the other Nodes, such as the status of ENSO and Indian Ocean Dipole, as well as the interannual and decadal variations of the Leeuwin Current systems over the years.

Project 2.1, together with it strong relationship to Project 2.2, has strong links to other non-WAMSI projects that are aimed at improving the capability to make seasonal climate predictions with the POAMA model. These include a suite of projects supported by the Managing Climate Variability Program of GRDC, whose main aim is to deliver improved climate predictions that have utility for agricultural application. The MCV projects supported improvement to the ocean data assimilation system, development of shorter time scale predictive capability, and application of the forecasts to specific agricultural problems. The South East Australian Climate Initiative has also supported research for improving climate predictions in SE Australia in support of improved management of water resources. This project has contributed to the development of the atmospheric initialization of the POAMA model and to analysis of forecasts in SE Australia. The WIRADA program supports the development of the POAMA system for application to hydrological prediction, and the developments and assessment in WAMSI 2.1 directly feed into the application of POAMA for hydrological prediction. The WAMSI project complimented these projects because WAMSI was primarily focused on the marine environment while the other projects were focused on improved prediction of climate over land.

Project 2.2 has strong links to other WAMSI Nodes, especially Nodes1, 3 and 4. Project 2.2 provided up-to-date climate information to the other Nodes, such as the status of ENSO and Indian Ocean Dipole, as well as the interannual and decadal variations of the Leeuwin Current systems, such that Node 2 scientists have been invited to co-organise the “marine heatwave” workshop with WA Department of Fisheries after the strong 2010/11 La Nina event which has many biological implications in the WA marine environment. Project 2.2 scientists also work with WA Department of Fisheries scientists in WAMSI project 4.2 to work on the impacts on WA fisheries of the past climate change. We have also participated in the writing group of the Australian climate Change Report Card on the past and future projections of climate change, which was published in 2009 and has great influences on climate adaptation research in the marine environment in WA and in Australia. The downscaling products from project 2.2 also have wide impacts on fisheries and marine protection research in WA and in Australia.

Project 2.3 has a close connection with WAMSI 3.5 on numerical modelling of Ningaloo Reef, and nearshore circulation, and with Australian IMOS program on sustained observations of the circulation adjacent to the Ningaloo Reef – now the site of a National Reference Station Mooring. It is also well connected with ANNiMS – Springboard project to augment long-term moorings offshore from Ningaloo with optical sensors to observe nutrient response to upwelling – and provide a contemporary perspective for understanding changes in upwelling driven productivity under future climate scenarios.

4.5 What wasn't addressed by the Node research, but is likely to be important from a scientific perspective?

Application of new tools and capabilities developed by WAMSI and other programs to understand climate impact on the coastal zone: With its teleconnections to the tropical Indian and Pacific Oceans, the marine environment off Western Australia is strongly modulated by large-scale modes of ocean and climate variability such as the El Nino Southern Oscillation (ENSO), the Indian Ocean Dipole (IOD) and the Southern Annular Mode (SAM). The impacts of year to year changes in the physical environment on recruitment to key fisheries is well known, as well as the harmful results of extreme events, such as the 2010/11 marine heat wave. However, the means to understand and predict the details of how large-scale forcers drive changes over the shelf and at the coast are still poorly developed. The work carried out in the past, by WAMSI and Indian Ocean Climate Initiative (IOCI), but also by other national research programs (both the Australian and Pacific Climate Change Science Programs and the Bluelink Project) as well as work being planned in these programs, now allow a set to tools to be brought to bear on this problem not available in the past. Along with the substantial investments made in observing system capability, both via the WA and Bluewater Nodes of the Integrated Marine Observing System, the prospect exists of making substantial progress in understanding and predicting the behaviour of shelf and coastal marine systems. Achieving this hinges on ensuring strong connections with the major national research efforts and deployment of a coordinated modelling and synthesis strategy.

Understanding extreme events generated by interannual and decadal variation: There is research need to focus on improving the level of understanding the dynamics of climate variability and change that are occurring across the full range of time scales (seasonal, annual, decadal and longer term) and appropriately related spatial scales (Leeuwin Current, Capes Current and spawning locations and habitats of key marine species), and how the multiple scales interact. Especially, there is a need to provide insight into the understanding of the internannual and decadal climate variability that drove the unprecedented “marine heat wave” during the summer of 2010/2011, which has brought wide-spread coral bleaching and fish kills off WA coast.

Multidisciplinary research to understand climate impacts on ecosystems, *including human impacts*. New climate research in WA needs to underpin our aspirations to forecast the biological, economic and social implications of climate variability and the potential mitigation strategies for impacts of climate change in these important WA coastal waters to enable the development of more flexible and adaptive management regimes. For example, when assessing effects of climate variability and change on fish stocks it is important to understand the changes occurring at appropriate time and spatial scale that affects the key life history stages of spawning, larval phase, juvenile and recruitment to the fishery. It is also important to provide a better understanding of the future changes in coastal sea levels and storm surges under the greenhouse forcing, which are crucial for coastal development planning in WA. A high resolution (2-3 km) numerical model to reanalyse the ocean circulation and physical and biochemical processes of WA coastal marine environment of the past 20 years is also crucial to underpin the marine impacts studies.

5. IMPLICATIONS FOR MANAGEMENT

a) What “management objectives” were being addressed by the research in this Node?

An objective of the State Departments responsible for fisheries, sustainable use of other marine resources and conservation of the marine environment is to develop a Climate Change Adaptation Strategy as well as manage climate impacts on a yearly basis, for example the impacts of El Nino. Node 2 has substantially enhanced our understanding of climate variability and climate change in the marine environment, which provides a foundation for evidence-based decision making. For example, finding that both global warming and natural, multi-decadal variation are influencing the marine environment has implications for management that are discussed further below. Beyond compiling evidence and knowledge, the Node has developed the proto-type of downscaling “tools” that will help management get specific information related to future seasonal climate forecasts and climate change scenarios.

What are the implications for management of the finding that natural multi-decadal variation as well as global warming affects the environment? Some aspects of a Climate Change Adaptation Strategy are independent of natural variation, because over a few decades the natural variation averages out. Global warming may be enhanced in one decade then diminished in another; but the impact of global warming emerges in the long term. Consequently, a long term strategy, such as the need to reduce carbon emissions, can be developed regardless of natural variation. On the other hand, a short term strategy, one that will be implemented over a decade or two, needs to take natural, multi-decadal variation into account. We think that examples of short term strategy could be changing the type of plants used in agriculture or setting decadal quotas for harvesting marine living resources, or taking extreme events of coastal flooding into account in building codes. Short term strategy will be highly dependent on a capability to predict natural, multi-decadal variation, which is now a focal point in the World Climate Research Programme.

We should mention here that the tools developed by Node 2 are proto-types, the first versions of developments that are technically and intellectually challenging. They are potentially useful for Western Australian industry, especially in the state fisheries and marine conservation, and can be used for first assessments of the likely impacts and risks of climate variability and change. Never-the-less further development and improvement of the tools is possible and should be a priority of future research.

b) Who are the key management agency “beneficiaries” of the work in this Node?

Department of Fisheries

Department of Environment and Conservation

c) What “management strategies” were being addressed by the research in this Node?

N/A

d) What “strategies and actions” are likely to be changed as a result of the research in this Node?

WA Climate Change Adaptation Strategy

e) Has the research in this Node improved “management effectiveness”?

N/A

f) Are the research findings “easily accessible” and in a format that allows for ease of interpretation and “take-up” by management agency staff? How has this “knowledge transfer” been facilitated to ensure the maximum value has been gained from the research?

Most the research findings are published in peer-reviewed journals, which are easily accessible by general public and state management agencies. Scientists in the Node communicate research results through seminars, workshops, symposium, and conferences held in WA. Some of the communication has been facilitated through WAMSI office, DEC and DoF staff.

g) Has the research in this Node improved the overall management of the marine/ coastal environment in WA? How and give examples.

While the Node research does not directly address marine management question, projects 2.1 and 2.2 together have developed tools to better understand and manage the response of marine resources to inter-annual climate variation. The research has demonstrated the accuracy of predictions of the large scale structure around the Leeuwin Current three seasons in advance. The quantitative assessment of accuracy is the basis for risk management approaches to decision making.

Projects 2.2 and 2.3 have taken the first steps toward a capability to downscale the Leeuwin Current and its biogeochemical environment from the output of global climate change models, in order to understand the future climate scenarios as a probability and to produce the information needed for risk analysis. The same tool can be used to downscale seasonal predictions of the marine environment up to three seasons in advance.

The Node scientists have responded quickly to management needs, such as to understand the environmental factors that influence the declining trend of the western rock lobster puerulus settlements, and the "marine heat wave" impacts on marine life during an unprecedented La Nina event in 2011.

h) What are the longer-term likely impacts of the research for the State?

The likely impacts of this research will involve, firstly, uptake and application of new knowledge, and secondly, application and improvement of tools that Node 2 produced.

We think the most important new knowledge is:

- Identification of global warming trends combined with natural, multi-decadal variation in the Leeuwin Current region—the impact will be in developing strategies to manage climate variability and change. It is strongly recommended that State Departments become engaged in (at least knowledgeable of) international programs to improve capability for multi-decadal climate prediction.

- Identification of the Indian Ocean pathway for El Nino impacts on southern Australia—the impact will be in management of agriculture in Western Australia and the marine environment and resources. This understanding is likely to lead to improved seasonal climate prediction for the Indian Ocean region by the Bureau of Meteorology's POAMA system. The predictions are already widely used in agriculture but there needs to be some thought on how to use the prediction for the marine environment.

- Identification of physical processes (e.g. off-shore currents) associated with dispersal of larvae and recruitment—the impact is likely to be in management of western rock lobster, particularly with regard to strategies to protect the industry in the face of global warming and multi-decadal variation.

The tools developed by Node 2 will have an impact on future research as well capability in State Departments that manage the marine environment. The key tools are:

- Downscaling models linked to Global Climate Models and the Bluelink re-analysis—this capability will allow research on coastal climate impacts that was not possible before; it will allow State Departments to address climate issues that were intractable before.

- The seasonal prediction system POAMA and its ocean analysis system PEODAS—the impacts on research are the availability of good ocean data sets covering the period 1960-2010 (the severe limitation of historical ocean data is probably not well know outside of oceanography circles) and the international recognition of Australia's contribution to world class climate research. The impact on management will be improved accuracy of seasonal predictions.

6. CAPACITY BUILDING

The research Node has recruited one regional ocean modeler to WA, which has strengthened our capability to predict climate impacts on WA marine environment. The Node has also provided effective training for three postdoctoral research fellows in climate research and modeling areas, as well as two PhD students on biophysical coupling studies on fish larvae and coral reef.

7. DATA MANAGEMENT

The complete POAMA hindcasts 1980-2008 in project 2.1 are available publicly at http://poama.bom.gov.au/dataserver/index.htm. The metadata for the hindcasts has been provided to iVEC.

Project 2.2 downscaled climate change products are now available on an openDAP server hosted by IVEC facility.

Project 2.3 current house the metadata describing field observations entered in AIMS metadata system

8. MODELING

Project 2.1 demonstrated the strengths and weaknesses of the POAMA seasonal forecast model for predicting interannual variations of the WA marine environment. POAMA forecast products of relevance to the WA marine environment are available at the BoM POAMA web pages. These include predictions of Indian-Pacific Ocean SSTs, the El Niño indices, the IOD indices, and global and regional Australia rainfall forecasts from lead times 1-9 months. The hindcast archive is also assessable so that past forecasts can be examined. Forecast skill, as measured by correlation and hit rate, is also available. Access to the raw forecast model fields is also available for any researchers who want to directly use the ensemble of forecast from POAMA. Fields include surface winds and temperatures, rainfall, and sub surface ocean temperatures. These forecast fields have the potential to be used in application models, such as for estimating crop yield and for driving higher resolution models of the coastal environment, for example to simulate high resolution variations of the Leeuwin Current. Resource managers in WA need to position themselves to take advantage of this enormous resource provided by the POAMA seasonal prediction system.

Additionally, a key product developed in Project 2.1 was a calibrated, downscaled seasonal prediction product for the sea level anomaly at Fremantle, which is a good proxy for the overall strength of the Leeuwin Current. This prediction is run operationally at the BoM and is available publicly via the BoM POAMA web page. Uptake and usage of this product is unknown because this product has only just become available in May 2011. Its usage will be monitored via web page hits and any feedback from users will be incorporated into future revision of the forecast product and its web page delivery. It has potential use for management of the some coastal ecosystems, so its availability will be brought to the attention of the WA Fisheries. Follow-on studies that explore the utility of the POAMA hindcasts for management of the WA Fisheries should be encouraged.

In project 2.2, the use of the Ocean Forecasting for Australia (OFAM)/BLUElink model, to downscale climate change scenarios in regional oceans is an unprecedented effort in climate research and will have a great impact on the Australian and international research communities. The results are unique because of the unique characteristics of OFAM. It has a global grid and does not require any artificial open ocean boundary condition; while the grid is eddy resolving around Australia and Southeast Asia. This unique structure is achieved by telescoping the grid from 200 Km spacing far away (e.g. the Atlantic Ocean) to 10 Km around Australia. The downscaling products will not only underpin the climate impact downscaling research in the Ningaloo Reef in WAMSI project 2.3, it will also develop the basis for future climate change research along the western coast, e.g. the climate change adaptation research on fisheries in Western Australia, an FRDC project co-funded by the National Climate Change Adaptation Research Facility, and potentially future WAMSI work off the Kimberley Coast.

While it is important to make the downscaling products available, it should also be emphasized that the model data at this stage should be only used for research purposes.

The dynamic downscaling methodology developed and applied in this Node represent significant contributions to understanding how future climate scenarios, as predicted using couple atmospheric and ocean models, may impact the marine environment. The OFAM ocean model presents an ideal tool on which to base the downcaling methodology due to the whole-of-ocean simulation, without the potential corrupting influence of prescribed boundary conditions. However, downscaling to finer spatial scales using this product also propagates any errors that may be present in the global simulations, and interpretation of finer downscaled modelling results should appreciate the potential errors in the forcing data provided by the OFAM future model scenarios. Furthermore, the same downscaling techniques should be applied to a range of global circulation model predictions to assess the variability between models for a given scenario(s).

9. SOCIETAL BENEFITS

At the beginning of WAMSI we had a preliminary understanding of climate variation in the marine environment off Western Australia. An ENSO signal had been identified in the Leeuwin Current and it was known to have an impact on recruitment of western rock lobster. The Indian Ocean Dipole (IOD) had recently been discovered and there was a great debate in the research community (much of it arm-waving) on how it was or was not related to ENSO. A trend in the equatorial Pacific SST and wind toward a state favorable to El Nino had been identified, and was interpreted by some researchers as an impact of global warming. The Indian Ocean warming was recognized as one of the fastest in the world. This understanding was the basis for a hypothesis that the marine environment off Western Australia was influenced by multiple cross-scale interactions ranging from the entire tropical Indo-Pacific Ocean, to the scale of boundary currents such as Indonesian Throughflow and Leeuwin Current and down to the scale of coastal larval recruitment. The oceanographic, physical mechanisms that control the scale-interactions were not known. More importantly description of the oceanic structure across the range of spatial and temporal scales was spotty at best, largely because suitable oceanographic data was lacking.

Now there is an understanding of how ENSO relates to the Leeuwin Current, the role of Indonesian Throughflow in this link, how and why the trend in ENSO observed before WAMSI reversed, when the IOD is and is not independent of ENSO and how the IOD influences climatic conditions over Western Australia. There is the beginning of an understanding of the physical mechanisms behind all of these interactions. Importantly, there is the beginning of an understanding of the mechanisms that link variation in the Leeuwin Current to larval dispersal in the marine environment and to recruitment and settlement of western rock lobster. Of all the accomplishments of Node 2, probably the one that will be most important in the long term is the preparation and access to well organized, mapped oceanographic data from observations and models (e.g. PEODAS and downscaling products with BlueLink, among others) which will provide the basis for a great range of future research and products useful for management of the marine environment.

Forecasting for Natural Resource Management Decisions

Node 2 made substantial contributions to the 2009 Report Card on Marine Climate Change in Australia, a document widely used in State and Federal Departments responsible for managing the impacts of climate change. Node 2 provided much of the information on El Nino and the Leeuwin Current.

Node 2 provided modelling-tools that characterise the marine environment across the range of scales from the tropical Indo-Pacific Ocean, to the length and width of the Leeuwin Current and down to an individual reef near the coast. An add-on for seabed morphological changes is available. The main tools include the improved POAMA seasonal forecast system, the Bluelink downscaling tool for climate change scenarios and the local (0.5km grid) downscaling tool for coastal assessments. These tools are either run operationally or can be run for special circumstances as required by State Departments for management of ENSO or climate change impacts.

Node 2 made substantial progress in characterising interannual variability and multi-decadal trends associated with the key environmental factors that influence the western rock lobster fishery. This provides the information necessary to design an improved system for monitoring settlement and recruitment in the fishery.

Impacts—long-term results of the project's activities

As mentioned above providing access to well organized oceanographic data relevant to the marine environment of Western Australia is a major accomplishment of Node 2. The key data sets include the ocean reanalysis by PEODAS that come out of the POAMA seasonal forecast system, the data sets mapped by the BlueLink downscaling tool for Global Climate models and the local modelling of circulation and ocean structure near Ningaloo Reef. The new data base open the way for a broad range of future research and provides information that will increasingly be useful for State Departments.

Discovery of the Indian Ocean pathway for El Nino impacts on southern Australia is an exciting insight. As this link from the Pacific Ocean to the Indian Ocean and on to Australia is explored further we expect the climate-links of both past and future events in Western Australia to be brought into clearer focus. Getting this link right in global climate models—for forecasting seasonal climate and/or climate change—is highly likely to improve the accuracy of forecasts.

Discovery of the reversal of multi-decadal trends in the ENSO region and the Leeuwin Current may have far reaching implications. Predicting the natural and human induced trends over one to two decades is now a major activity in the World Climate Research Programme. When and if this capability is accurate enough it will provide invaluable information for management of the marine environment, with particular relevance to the western rock lobster fishery.

There was substantial progress in understanding the mechanisms that influence the larval stages of fish and invertebrates in the Leeuwin Current region. This is likely to prove useful in understanding the recent decline in settlement of lobster-larvae and future management of the fishery.

10. FUTURE RESEARCH

The WAMSI 2.2 papers on the reversal of trends in the Indo-Pacific Ocean are an important contribution to planning for decadal predictions that will take into account both natural and human induced climate variation and change. The World Climate Research Programme is coordinating a very large international effort to model and predict the combined effect of human-induced and natural variation in the climate system. Future research in Western Australia needs to position itself to take advantage of advances in understanding and predictability as they emerge.

Development of the ocean downscaling model is an important contribution to the international effort to produce climate scenarios at a local level in the marine environment. Downscaling with BlueLink is unique because it avoids artificial open boundary conditions. However, the large domain introduces imbalances in air-sea fluxes that are not yet resolved. The next version of OFAM/BlueLink will integrally include wave and littoral processes. This will provide an improved tool for future research aimed at a more realistic simulation of the future seabed off Western Australia.

Feng and Wild-Allen (2010) determined from a simple nitrogen budget that the benthic input provides a significant portion of the nitrogen required to support the annual primary production on the continental shelf. The benthic re-supply of nutrient to the water column is driven by storms and swells, which is coincident with strong onshore winds during the austral autumn-winter. This process is likely to be affected by future climate change. As noted above, the next version of OFAM/BlueLink will integrally include wave and littoral processes and will provide a better tool for future research to improve understanding of the benthic-pelagic coupling.

The potential impacts of climate change on the regional ecosystem will depend on a complex interaction of the processes listed above. The qualitative analysis by Feng, Waite and Thompson of the results of WAMSI Node 2 and future climate from model-projections suggests that nutrient input will increase north of the Abrolhos Islands and decrease south of the Abrolhos Islands. They concluded that future research to accurately predict ecosystem impacts will require a combined assessment of the effects of the global warming, changes in regional circulation, and changes in the regional air-sea heat fluxes. This will be achieved through long-term monitoring of the shelf environment and improved climate model downscaling for the Leeuwin Current system. WAMSI Node 2 has enhanced the capability for further research on the biogeochemical responses of the system by developing the OFAM/BlueLink based downscaling tool that includes the biogeochemical processes. Further research on climate variability and climate change in the Leeuwin Current ecosystem is necessary to underpin the long term management of the marine resources in this region.

Assuming that major international and national programs will address the major challenges of climate modelling and prediction, the research gaps that should be address in Western Australia are identified as:

- Improved regional downscaling to increase resolution of the Leeuwin Current, shelf circulation, mesoscale dynamics and biogeochemical interactions in climate projections;
- Downscaling techniques should be applied to a range of global circulation model predictions to assess the variability between models for a given scenario(s).
- Establish time series of the Leeuwin Current volume and heat transports, and near-shore ocean circulation using observation programs such as Integrated Marine Observing System;
- Establish/extend time series of the Indonesian Throughflow volume and heat transports using observation programs such as Integrated Marine Observing System; as well as sea surface salinity to infer the hydrological cycle of the

climate system which could potentially be important for the regional ocean circulation;

- Establish/extend programs to measure biogeochemical properties of marine systems off the WA coasts;

- Improved understanding of the nature of decadal and multi-decadal variations of the climate systems in the tropical Pacific, Indian Ocean, and Southern Ocean and the interplay of human induced climate change and natural climate variation.

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ANNEXURE 1: A LISTING OF THE PROJECTS AND PROJECT LEADERS AND THEIR PROJECT STAFF, INCLUDING STUDENTS

Project 2.1 Leader

Harry Hendon, Senior Principal Research Scientist, BoM CAWCR

Project Team

Oscar Alves, PRS BoM CAWCR

Guomin Wang SPOB BoM CAWCR

Maggie Zhao Post Doctoral Researchers, SPOC BoM CAWCR

Guo Liu SITOC BoM CAWCR

Yonghong Yin PO2 BoM CAWCR

Project 2.2 Leader

Ming Feng, Principal Research Scientist, CSIRO

Project Team

Gary Meyers, Senior Principal Research Scientist, CSIRO (Node Leader, 2006–2007)

Bryson Bates, Senior Principal Research Scientist, CSIRO (Node Leader, 2007–2008)

Gael Alory, Postdoctoral fellow, CSIRO (2006-2008)

Matthew Chamberlain, Ocean Modeller, CSIRO (2008–2010)

Richard Matear, Principal Research Scientist, CSIRO (2008–2010)

Ken Ridgway, Principal Research Scientist, CSIRO (2008–2011)

Dirk Slawinski, Data Analyst, CSIRO (2006–2011)

Chaojiao Sun, Research Scientist, CSIRO (2008–2011)

Evan Weller, Postdoctoral fellow, CSIRO (2008-2011)

David Holliday, PhD student, Murdoch University (2006-2010)

Saskia Henrichs, PhD student, UWA (2009-2011)

Project 2.3 Leader

Richard Brinkman, Senior Research Scientist, AIMS (2006-2011)

Project Team:

Richard Brinkman, Senior Research Scientist, AIMS (2006-2011)

Simon Spagnol, Experimental Scientist, AIMS (2007-2011)

Craig Steinberg, Experimental Scientist, AIMS (2010 field campaign)

Field support technician, AIMS (2010)

ANNEXURE 2: THE APPROVED *SCIENCE PLAN* FOR THE NODE [2006 OR 2007]

Attached

ANNEXURE 3: THE FINAL *PROJECT REPORTS* FOR THE NODE

Attached

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