WAMSI PROJECT FINAL REPORT

Oceanic conditions at Ningaloo Reef—analysis of downscaling ocean climate into the Ningaloo Reef Tract

Richard Brinkman

Project Details

Project Number and Title:

2.3 Oceanic conditions at Ningaloo Reef—analysis of downscaling ocean climate into the Ningaloo Reef Tract

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Project Start Date: 28 March 2007

Project End Date: 30 June 2011

Due Date for Final Report: 30 June 2011

Project Objectives and Achievement Criteria

Project 2.3 has the objective to understand and predict large scale variation and change of ocean-climate, it's impact with the continental shelf and to inform decision making in WA agencies that have to address vulnerability to climate variation and change: This project addressed these objectives by providing:

1. Development and interpretation of products to downscale global models of future climate change scenarios to the Ningaloo Reef Tract.
2. Validation of the performance of the downscaling model at each nested level against in-situ and remotely sensed data.
3. Assessment of impacts of projected climate change upon the Ningaloo Reef Tract using the downscaling model, with a focus on sea temperatures in the coastal zone

Project 2.3 has delivered 4 milestone reports against these three objectives.

This project has investigated the ocean current dynamics that influence the Ningaloo Reef tract, using both field observations and a suite of numerical models to downscale coarsely resolved global ocean circulation models. Offshore from Ningaloo, the Leeuwin Current gains definition at North West Cape, and flows southwards along the continental slope transporting warm low-salinity tropical water. Closer inshore, southerly winds create the seasonal Ningaloo Current; an intermittent coastal counter current inserted between the poleward flow of the Leeuwin Current and the fringing reef front. This project has investigated how the interaction of these two currents control the thermocline depth and upwelling along Ningaloo Reef under contemporary and future ocean conditions, by using future predictions from a global ocean circulation models. This work has increased our understanding of the local ocean dynamics along Ningaloo Reef, and provided an indication of how these dynamics may change in the future.

Research Chapter

Introduction

Ningaloo Reef Tract (NRT) is the second largest coral reef ecosystem in Australia after the Great Barrier Reef and one of the largest fringing barrier reef systems in the World, straddling almost 300km of the Western Australia coastline south from North West Cape. Tourism in the region is estimated to contribute >$100 million per annum to the regional and State economies. Tourists are attracted by the rich coral reefs and productive recreational fishing that can be accessed from shore (unlike the GBR) given the close proximity of the barrier reef in many locations, and the relative ease of meeting migratory whale sharks outside the Reef. Climate change resulting in warmer sea temperatures is likely to impact on the socio-economic values of the region as well producing other changes in the structure and function of this important ecosystem. Like all coral reefs, Ningaloo is a constantly eroding biogenic structure that depends ultimately upon continuous coral regrowth (i.e. net calcium deposition) for its long-term existence. The thin veneer of living corals is a strong stimulus of marine tourism but also provides essential habitat for the rich biodiversity of small invertebrates found in healthy coral reef environments. Climate change, in the form of higher sea temperatures, is the greatest threat facing coral reefs in developed countries. This is because reef-building corals depend upon a symbiosis with internal micro-algae (zooxanthellae) that is very sensitive to temperature. Wherever it has been studied, the symbiosis breaks down (signified by coral bleaching) when the ambient temperature remains 1-1.5^{O}C higher than the long-term seasonal average for more than a few weeks.

Unlike the equatorward flowing eastern boundary currents that exists in other ocean basins, the Leeuwin current drives warm, low-salinity water of tropical origins southwards along the coast of Western Australia, limiting upwelling and resulting in sea surface temperatures along the WA coast that are several degrees warmer than other eastern boundary current systems at similar latitudes (Feng and Wild-Allen, 2008). However, during summer months when southerly wind-stress increases, the Leeuwin current can be forced offshore by a wind-driven northwards coastal current (Woo et al., 2006). At Ningaloo, this northwards flowing current is referred to as the Ningaloo Current (Taylor and Pearce 1999). The seasonal Ningaloo Current drives transient upwelling along the continental slope adjacent to Ningaloo Reef that impacts the ecology of the region through increased nutrient delivery and the lowering of water temperatures bordering the reef by several degrees relative to waters of the Leeuwin Current (Taylor and Pearce 1999; Woo et al. 2006).

In a warming ocean, coral bleaching is expected to become more frequent and severe as a result of global climate change (e.g., Hoegh-Guldberg et al. 2007). However, while mass coral bleaching events have severely impacted many coral reef systems worldwide, significant bleaching events have yet to be observed at Ningaloo Reef suggesting it may be less vulnerable to impacts for global warming. It is logical to suggest that the cooling effect of upwelling associated with the Ningaloo Current may increase the resilience of Ningaloo Reef to climate induced coral bleaching. However, there may be other mechanisms driving the alongshore currents that produce upwelling favourable conditions or otherwise influence the local water temperature along Ningaloo Reef. This project has investigated how the local current interactions control the thermocline depth and upwelling along Ningaloo Reef under contemporary and future ocean conditions, by using future predictions from a global ocean circulation models.

Methodology

The project has applied and validated a regional and local circulation models to the region encompassing Ningaloo Reef, as a means to downscale global ocean simulation of both contemporary and future ocean conditions. The circulation model SHOC (Sparse Hydrodynamic Ocean Code) was employed to simulate the 3-dimensional baroclinic hydrodynamics and regional circulation influencing Ningaloo Reef. SHOC is based on the three dimensional equations of momentum, continuity and conservation of heat and salt, employing the hydrostatic and Boussinesq assumptions, and uses a curvilinear orthogonal grid in the horizontal and a choice of fixed 'z' coordinates or terrain following σ coordinates in the vertical (Herzfeld et al. 2007). The 'z' co-ordinate system is employed for the application to Ningaloo Reef in order to adequately resolve the vertical structure and large depth range in this regional domain. Outputs from the model include three-dimensional distributions of velocity, temperature, salinity, density, passive tracers, mixing coefficients and sea-level.

Physical forcing processes required by SHOC include wind, atmospheric pressure gradients, surface heat and water fluxes, and open boundary conditions for temperature, salinity, sea-surface elevation and regional circulation. Model forcing for spatially and temporally resolved sea-surface elevation, temperature, salinity and low frequency (non-tidal) meridional and zonal currents along the model boundaries were interpolated from global circulation hindcasts produced by the Ocean Forecast Australia Model (OFAM: Schiller et al. 2008), or the Bureau of Meteorology's operational ocean prediction system, OceanMAPS (which is based on OFAM) . OFAM has a horizontal resolution of $1/10^{\circ}$ x $1/10^{\circ}$ (approximately 10km x 10km) in the Asian-Australian region (90E-180E, 75S-16N) and is suitable for simulation of eddy-resolving circulation. OFAM also assimilates remotely sensed ocean surface temperatures and ocen surface altimetry, The vertical grid has 47 levels with uniform resolution of 10m over the surface 200m and gradually coarsens to a maximum depth of 5000m (Brassington et al, 2005). In addition to the forcing provided by OFAM, regional model boundaries are forced by tidal elevation, superimposed using the global tide model of Cartwright and Ray (1990). Atmospheric forcing products are consistent to that applied to the OFAM model, and originate from the MesoLAPS atmospheric model. This modelled product is preferable to spatially interpolated meteorological data supplied by BoM (Bureau of Meteorology) weather stations for surface forcing, since its spatial detail is superior. The regional model grid at Ningaloo has a rectilinear spatial resolution of approximately 2.3 km, with 100 x 110 surface elements and 44 vertical layers non-uniformly space with 5 layers in the surface 10 m. Bathymetric information utilised in the model grid is from the current version of the Geosciences Australia national bathymetric grid. The model domain of the regional implementation of SHOC model is shown in Figure 1.

A second hydrodynamic model was nested within the SHOC model grid, to further refine the spatial resolution of our simulations. The Regional Ocean Modelling System (ROMS; Wilkin *et al.* 2005) was implemented as a fine-scale coastal application nested within the regional SHOC model. The fine-scale application of the model has a curvilinear grid of resolution of ~0.5km x 0.5km in the horizontal, with 16 z-layers. The coastal application of ROMS was forced by boundary data generated as output from the regional application of SHOC. Bathymetry underlying this grid was sourced from Geoscience Australia 2009 National Bathymetry Grid merged with the HyVista Multispectral Bathymetry product produced for Ningaloo. The domain of the coastal implementation of ROMS is shown in Figure 2.

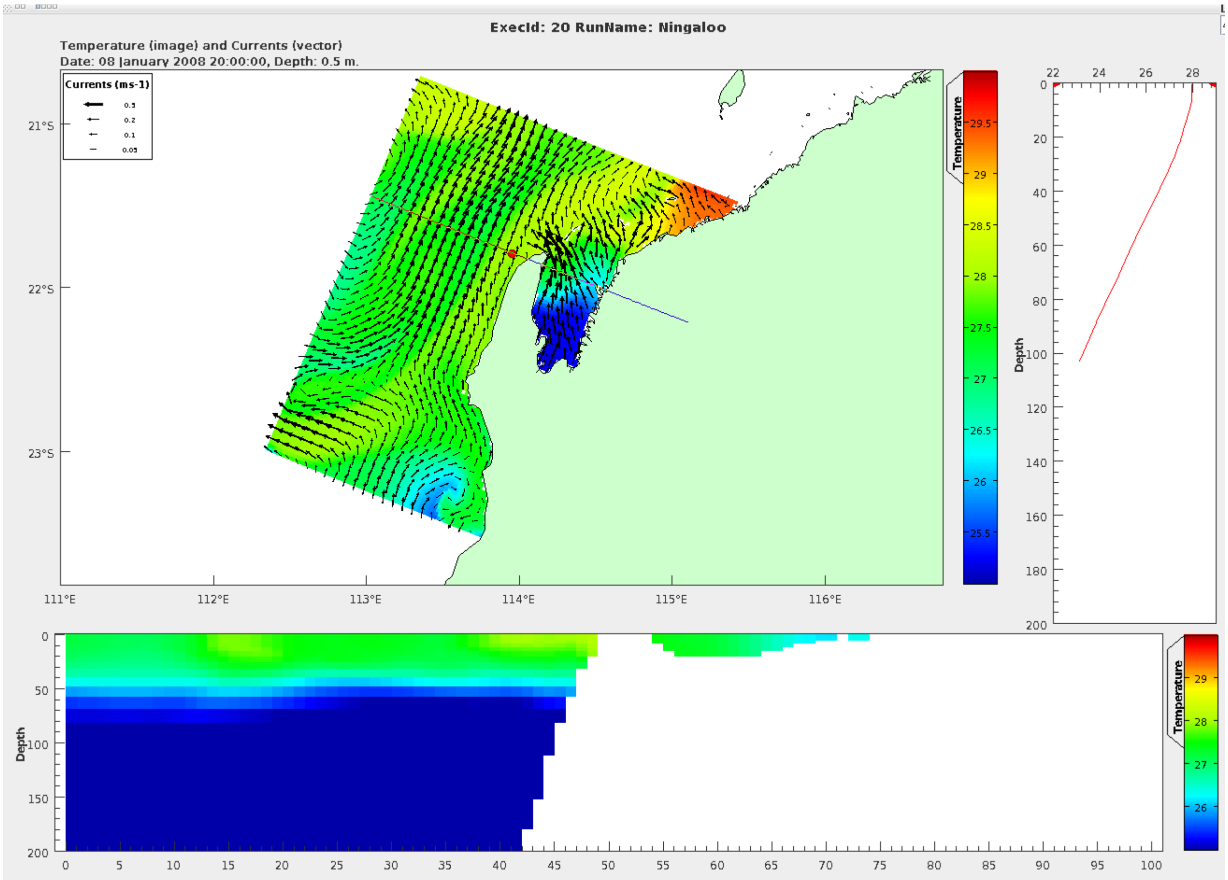

Figure 1. Model domain established for regional implementation of SHOC (top left). Predicted temperature profile (top left) at location shown by red dot in plan view. Section through model grid (bottom) showing across shelf temperature structure.

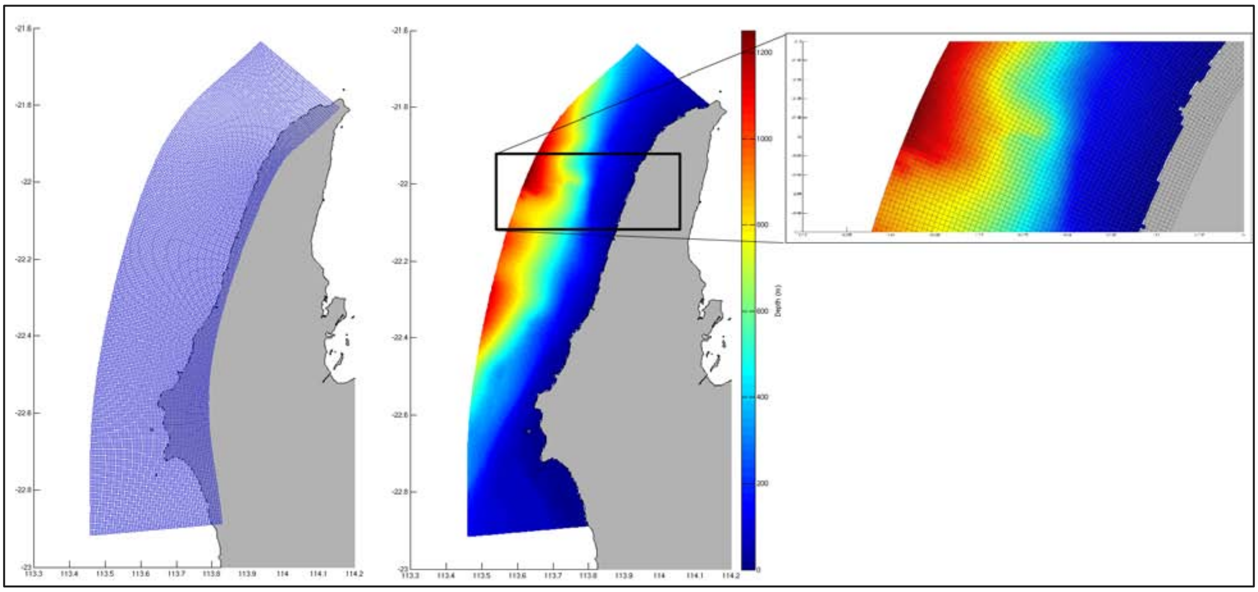

Figure 2. Curvilinear grid establiashed for the coastal implementation of ROMS. Grid has resolution of ~0.5km x 0.5km.

Downscaled model simulations of contemporary conditions were undertaken using forcing data either from the OFAM archive or from OceanMAPS (for most recent activities). These model data sets were used to both force the nested suite of models, and to aid in the interpretation of our analysis of alongshore currents in the region. In particular, OFAM output was used to analyse the frequency of upwelling favourable conditions for the period 2002-2008 in order to construct a 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. These moorings have been maintained contiguously since 1999 offshore from Ningaloo Reef at Tantabiddi, in water depths of 50m and 100m at locations chosen to enable monitoring of the Leeuwin and Ningaloo currents. A second validation data set with increased spatial coverage was collected during a field campaign undertaken between September and November, 2011. This recent data set consisted of current and temperature data from 4 moorings spanning 60km of the Marine Park during: three ADCP and temperature logger moorings were deployed along the 100m isobath to observe the spatial variability in alongshore flow along the Ningaloo coast; one ADCP and temperature mooring was deployed in 150m water depth directly offshore from Sandy Bay to observe the offshore prevailing flow.

Future oceanic conditions were simulated using output from WAMSI Project 2.2 subproject 5 “Projected future changes in the Leeuwin Current system”. Project 2.2 used OFAM version 1 (Schiller et al. 2008), to dynamically downscale the CSIRO Mk3.5 Global Climate Model (Gordon et al., 2002), for the projected climate in the decade of 2060 to 2069, following the the “A1b” scenario of the Special Report of Emission Scenarios (Nakicenovic et al., 2000). OFAM predictions of the regional circulation were used as boundary forcing for our regional downscaling and also analysed for changes to the general alongshore currents from contemporary conditions.

4. Results

Contemporary conditions: observations and model results

Observational data and results of the regional modelling have indicated that there exists rich complexity in the current field offshore from Ningaloo Reef (Figure 3), and the underlying process responsible for the reversal of the near-reef currents may not be solely related to a response to southerly winds stress (Figure 4). Indeed the Leeuwin Current generates the strongest eddy kinetic energy of any eastern boundary current system (Feng et al. 2005) and during summer months, when southerly winds are strong enough to oppose it, the Leeuwin Current can be pushed offshore often leading to the formation of northward wind-driven coastal currents inshore along the Gascoyne and Ningaloo coasts (Taylor and Pearce, 1999; Woo et al. 2006). Simulated surface circulation and temperature from OFAM and downscaled models show that offshore eddies adjacent to Ningaloo introduces significant variability to the near-shore currents adjacent to Ningaloo reef.

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. Initial validation of the regional and coastal models for the 2007/2008 summer demonstrated that the models captured the sub-surface temperature variability observed at the AIMS mooring sites (Figure 5 and Figure 6). Inter-comparison of model performance in simulating velocities is shown in Figure 7.

Model simulations qualitatively resolve the opposing Leeuwin and Ningaloo currents and the anti-cyclonic circulation pattern south of Point Cloates, and provide insight into the response of the vertical thermohaline structure associated with these large circulation features. Under south-easterly flow associated with a well defined near-shore Leeuwin current, the thermocline adjacent to Ningaloo Reef deepens towards the continental margin. On reversal of this coastal current, the thermocline relaxes in response to offshore Ekman transport, rising by up to 50m at the continental slope and delivering cool water to near the surface, where it can mix and exchange with lagoon waters via tidal mixing and wave pumping (Figure 8). This behaviour has been previously described and attributed to a coastal current response to strong south-easterly winds. However, our modelling is demonstrating that offshore eddies adjacent to Ningaloo introduces significant variability to the near-shore currents adjacent to Ningaloo Reef.

Analysis of the alongshore currents adjacent to the Ningaloo coast, based on output from the OFAM re-analysis products (Oke *et al*. 2008), indicates strong seasonality in both the mean alongshore current and it's standard deviation (Figure 9), with expected reductions in alongshore southerly flow during the austral summer months in response to opposing southerly winds (Figure 10). There exists however, a second peak in the relaxation of southerly flow centred around August. Analysis of historical wind data collected on the NW Cape at Milyering (Figure 10), confirms significant seasonal variability in both wind speed and direction at the site. Mean alongshore winds display strong seasonality, with upwelling favourable (from the southwest) winds reaching a maximum between November and January, with a minimum close to zero around June. The highest variability in the along-shore current occurs in June (Figure 9) when the mean alongshore wind diminishes, suggesting that there may be strong eddy induced variability in the near-coast flows during this period.

A histogram of northward flow events (flow reversals) based on the OFAM re-analysis clearly shows a peak in summer in response to the upwelling favourable winds, and a second peak between June and September. The high variability in the along-shore current in June (Figure 9) and the corresponding peak in flow reversal events (Figure 11) occur when the mean alongshore wind diminishes, again suggesting that winter flow reversals (upwelling) are strongly influenced by remotely forced regional circulation features such as eddies that can reverse the coastal flows.

Future conditions : OFAM

A similar analysis of monthly mean alongshore flow and flow reversal events has been performed on the results of the downscaling of CSIRO Mk3.5 model A1B future climate scenario using OFAM from WAMSI project 2.2 (Figure 12). Mean monthly alongshore flows and the number and seasonal characteristics of northwards flow events from the future scenarios show large variation between the years examined, and only limited qualitative agreement with the results of analysis of the contemporary OFAM re-analysis. 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. The magnitudes of the along shore flows are not significantly different to those of contemporary conditions (Figure 13). 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.

The OFAM downscaling results suggest a decrease in the strength of the Leeuwin Current (results from Project 2.2). This would suggest that if the strong upwelling favourable winds persist (as under current conditions), then episodes of upwelling favourable northwards flow along the shelf edge may increase. However, this will not necessarily be linked to an increase in the frequency of coolwater upwelling along the reef front, as the OFAM future scenarios also indicate a deepening of isotherms (Figure 14) and an increase in the strength of stratification.

Future conditions: Dynamic downscaling with nested models

The nested suite of SHOC and ROMS models were forced by the OFAM downscaling of CSIRO Mk3.5 model A1B future climate scenario. The downscaling runs produced realistic ocean features for the region, showing, at times, a well defined Leeuwin Current close to the shelf, and a recirculation feature south of Pt Cloates (Figure 15). Vertical temperature structure shows a deepening of the thermocline depth and significant warming in the surface 200m (Figure 16). As with the results from the OFAM downscaling from GCMs, these locally downscaled simulations must be considered the first step toward having a reliable and useful capability to downscale future climate projections to local scales.

One manuscript describing *the observed seasonal flow variability and transient upwelling along the North West Cape of Australia* has been submitted.

> Lowe RJ, Ivey G, Brinkman RM and Jones NL (Submitted) Seasonal circulation and temperature variability near the North West Cape of Australia. Journal of Geophysical Research

One manuscript in draft form describes *the dynamics of the flow variability along Ningaloo Reef using numerical downscaling*.

One manuscript describing the inshore/reef circulation has been published.

> Taebi S, Lowe RJ, Pattiaratchi C, Ivey G, Symonds G and Brinkman RM (2011) Nearshore circulation in a tropical fringing reef system. Journal of Geophysical Research 116:C02016.

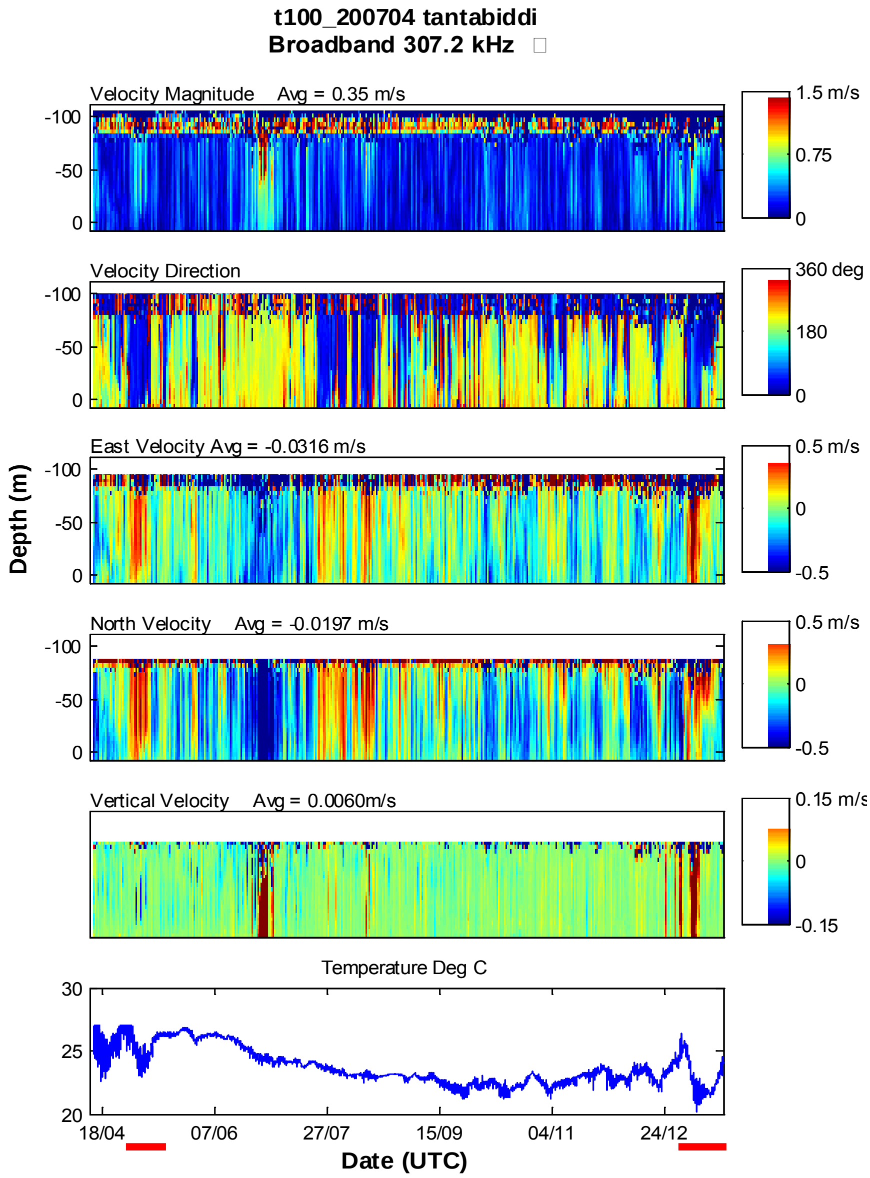

Figure 3. Current profile and temperature time series from ADCP mooring in 100m water depth of shore from Ningaloo. Note periods of strong current reversal (shown by red bars on date axis) and associated drops in near bottom temperature. Date is shown as day/month of year 2007.

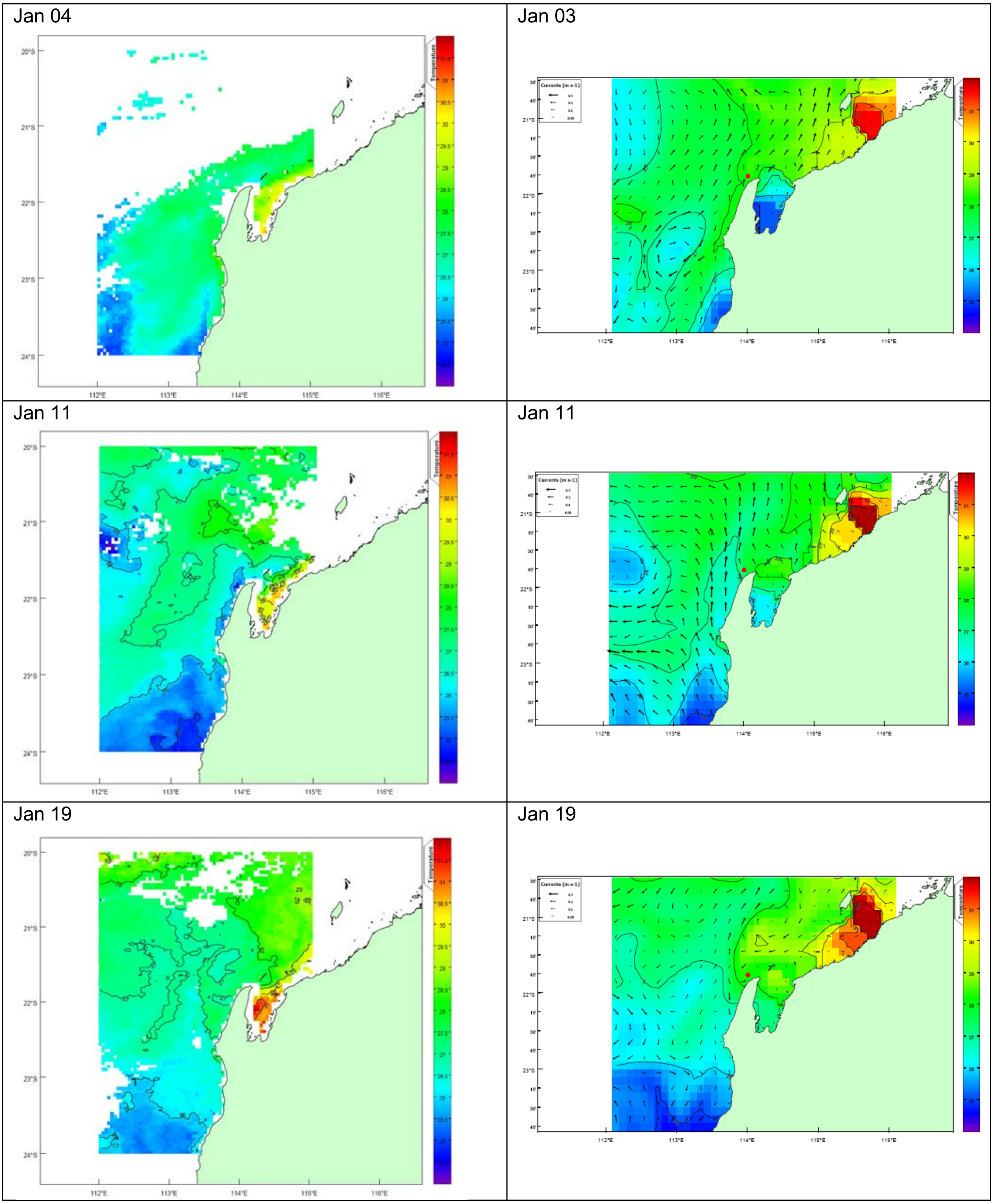

Figure 4. Sea surface temperature as observed by MODIS AVHRR (left) and as simulated by OFAM (right) during a January 2008 Ningaloo cooling event.

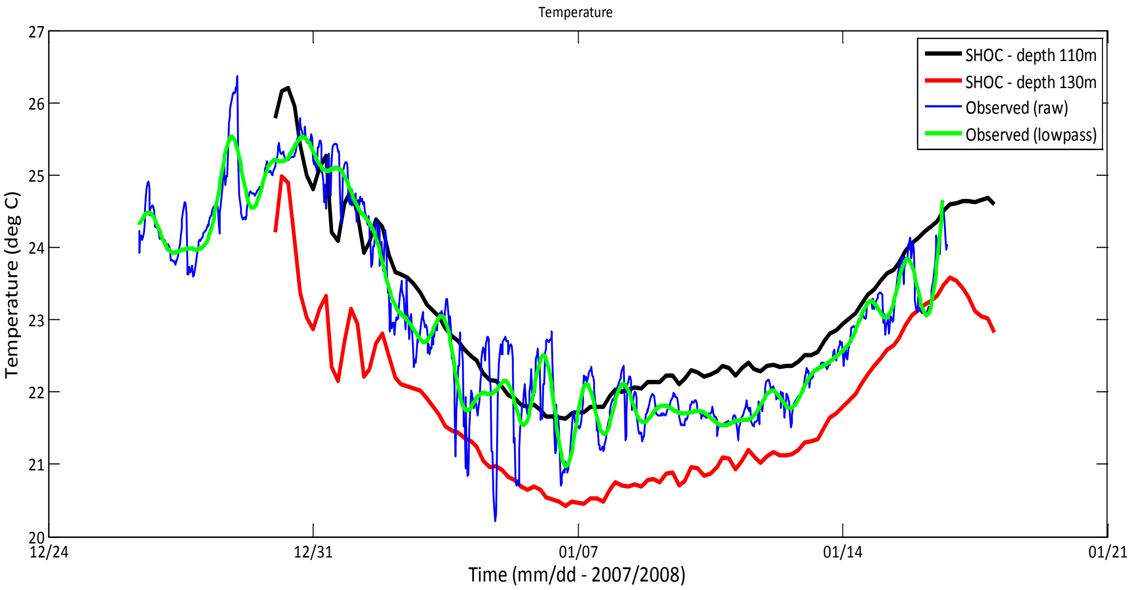

Figure 5. Comparison of predicted and observed temperature at ~100 m water depth at the Tantabiddi mooring site. Predicted temperatures from regional SHOC are shown for model layer depths of 110 m and 130 m.

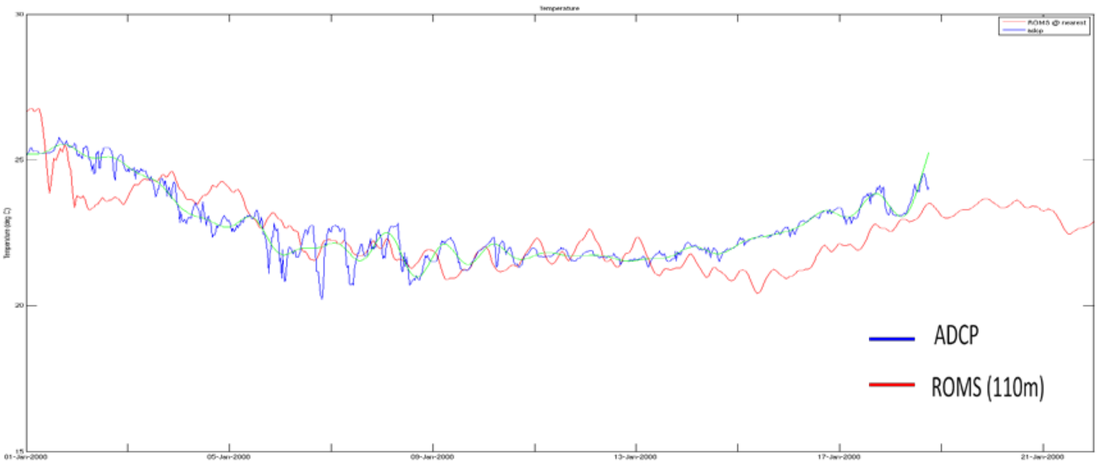

Figure 6. Comparison of predicted and observed temperature at ~100 m water depth at the Tantabiddi mooring site. Predicted temperatures from coastal ROMS model are shown for model layer depth of 110 m.

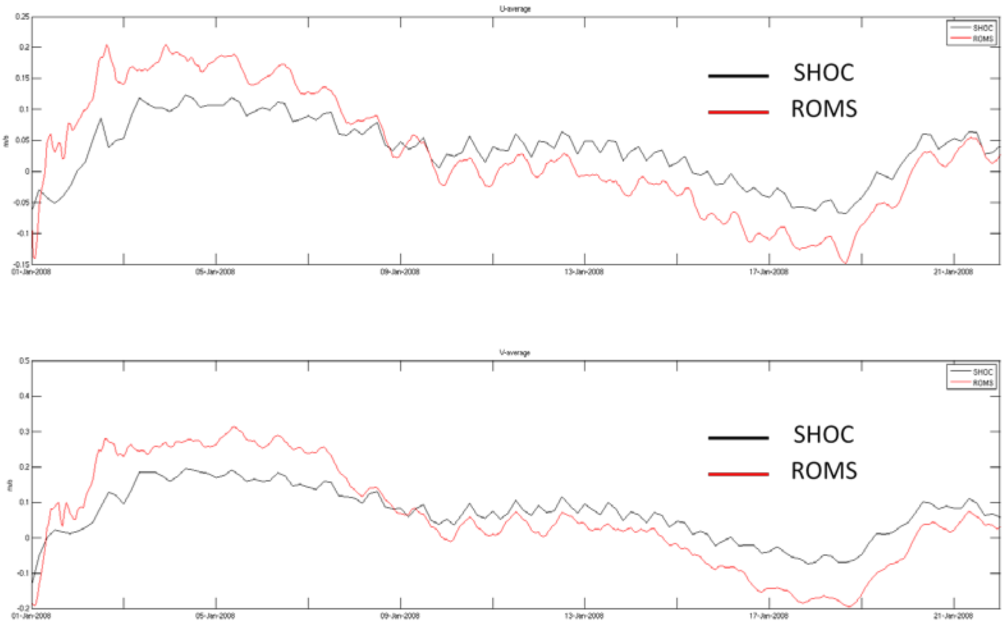

Figure 7. Inter-comparison of depth averaged east (top) and north (bottom) velocities for regional SHOC and nested coastal ROMS models.

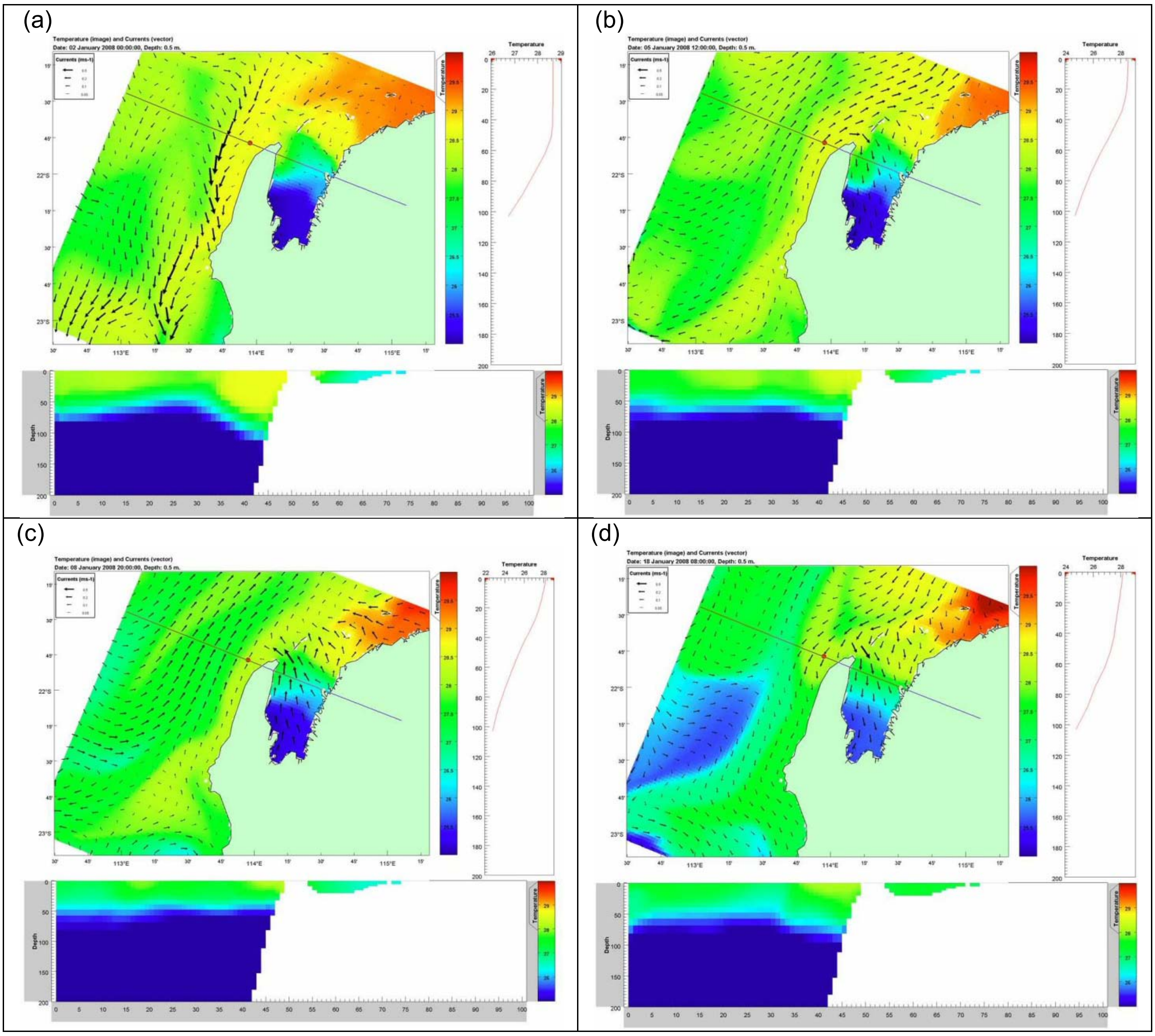

Figure 8. Snapshots of surface circulation, vertical temperature profiles and cross shelf temperature transects from the SHOC regional model for 02 January 2008 (A), 05 January (B), 08 January (C) and 18 January (D). Vertical temperature profile (left plot in each panel) is from the location marked with a red dot. Cross-shelf transect (bottom plot in each panel) is shown along the line indicated in the plan-view plots. In all panels, colour shows sea surface temperature.

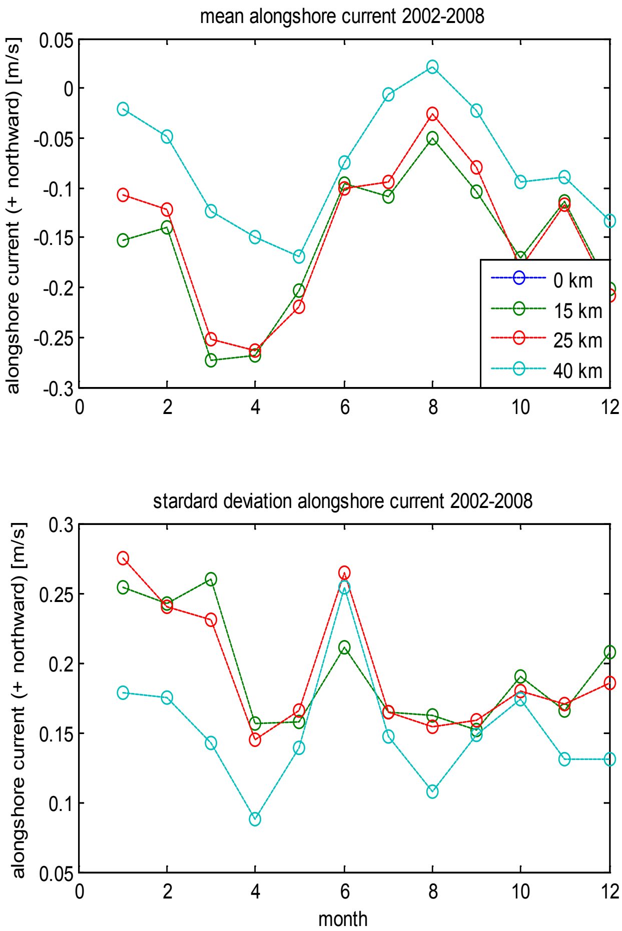

Figure 9. Analysis of OFAM re-analysis data from 2002-2008. Transect off Tantabiddi normal to coast (coastline at 35 deg). Alongshore current below is depth averaged over top 100 m of water column. Different coloured

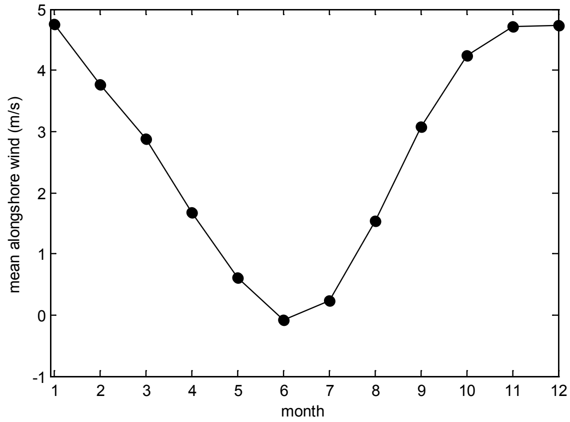

Figure 10. Monthly mean seasonal alongshore component of the wind velocity for period 2002-2008, from observations at Milyering on the NW Cape. Positive is towards the north.

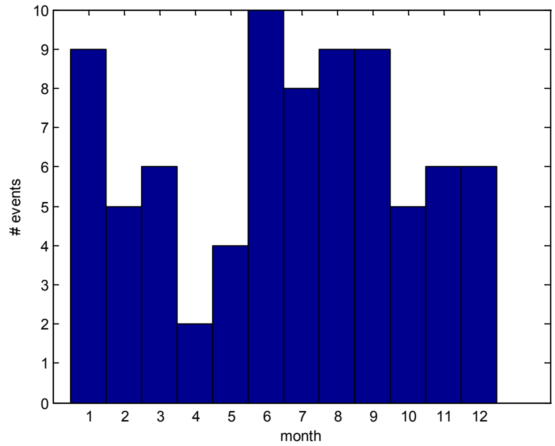

Figure 11. Analysis of OFAM re-analysis data from 2002-2008. Histogram of number of events lasting longer than 2 days where alongshore flow reverses.

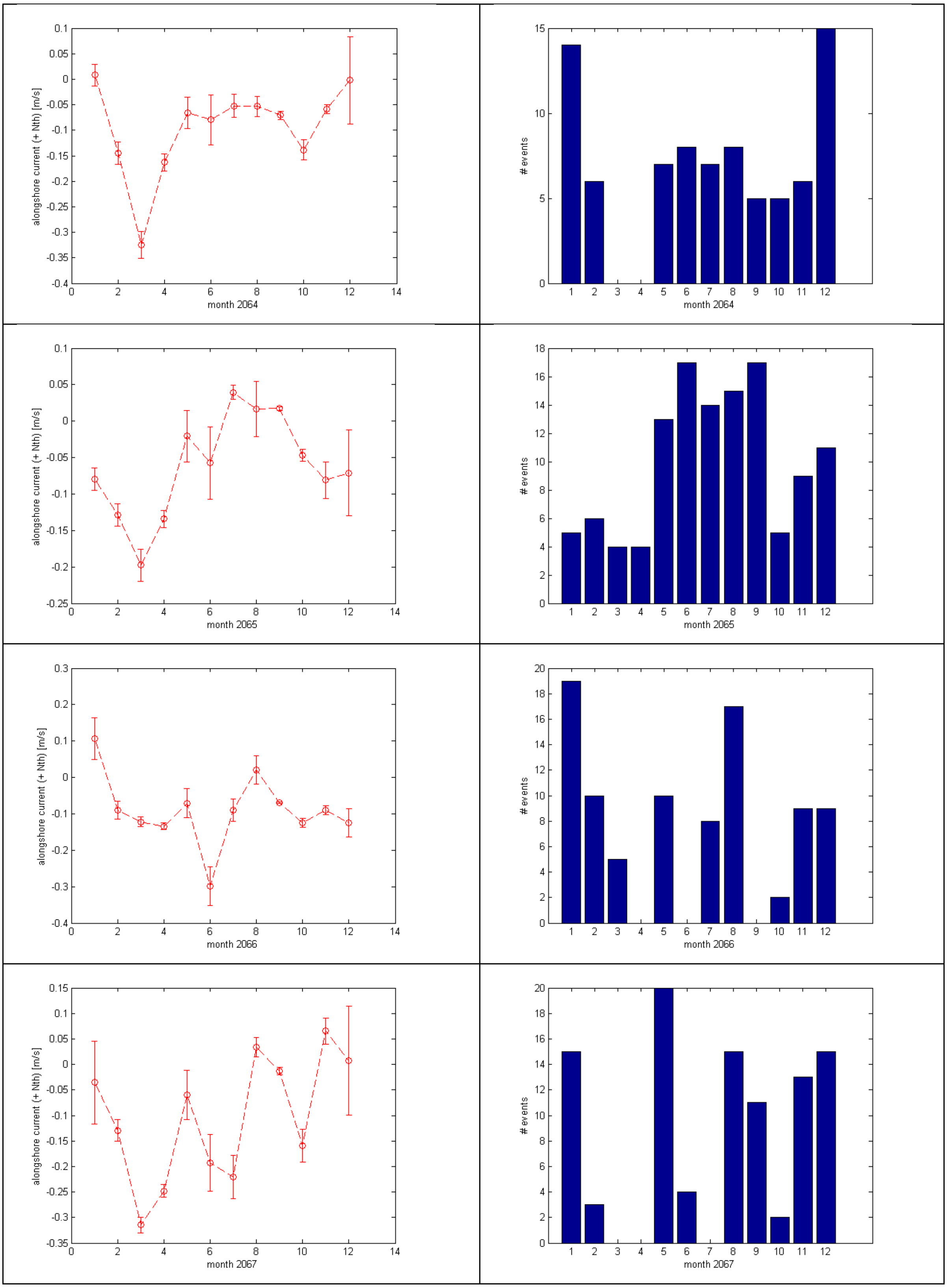

Figure 12. Analysis of OFAM Downscaling Mk3.5 A1B. Monthly mean alongshore current (left) and Histogram of number of events lasting longer than 2 days where flow reverses for years 2064 to 2067.

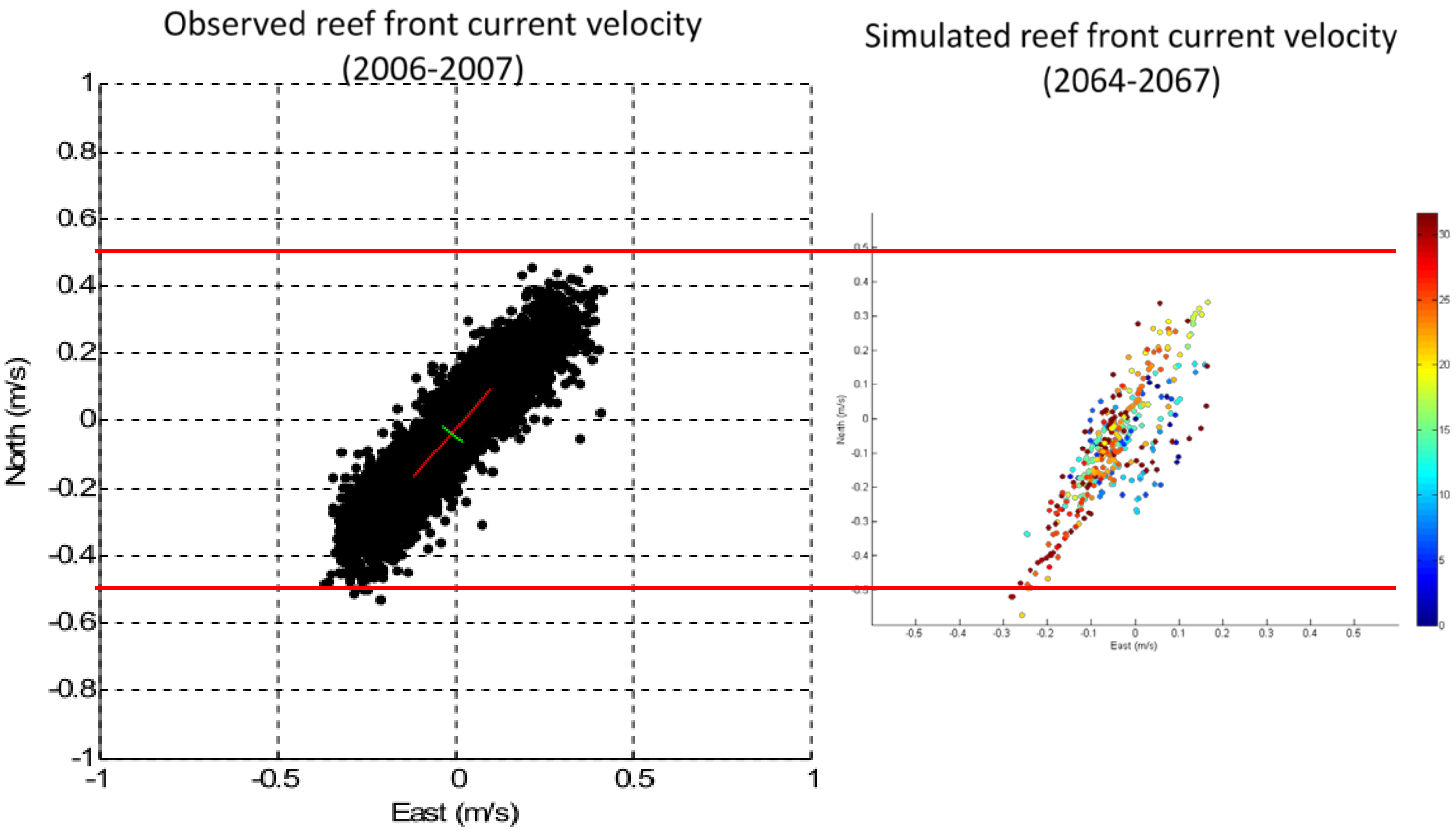

Figure 13. Alongshore current velocity as observed (2006-2007) and as simulated (2064-2067). Red lines show ±0.5 m/s (north +ve) as reference.

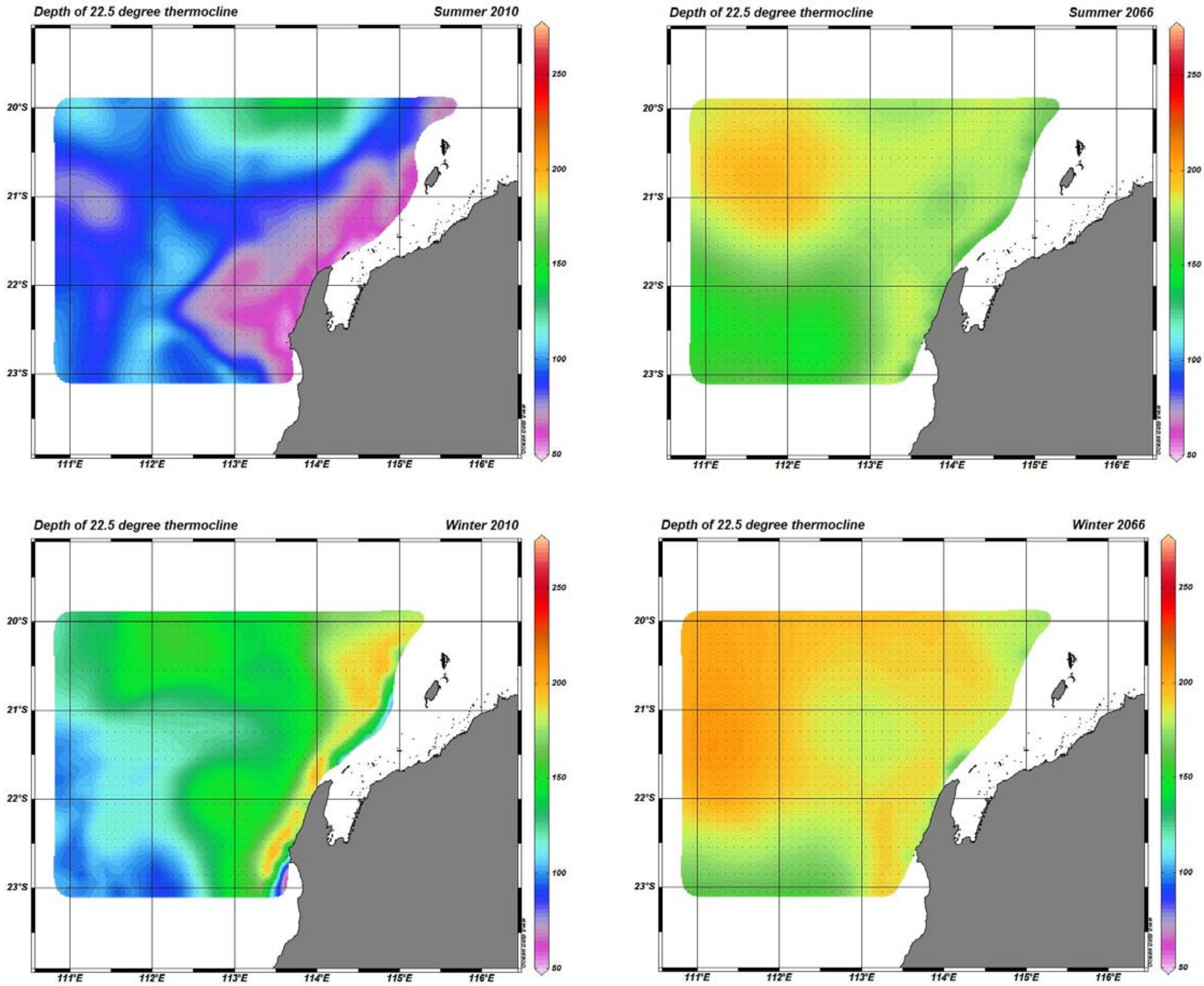

Figure 14. Depth of the 22.5 degree isotherm under contemporary (left) and future (right) conditions for summer (top) and winter (bottom), based on OFAM simulations of present and future conditions.

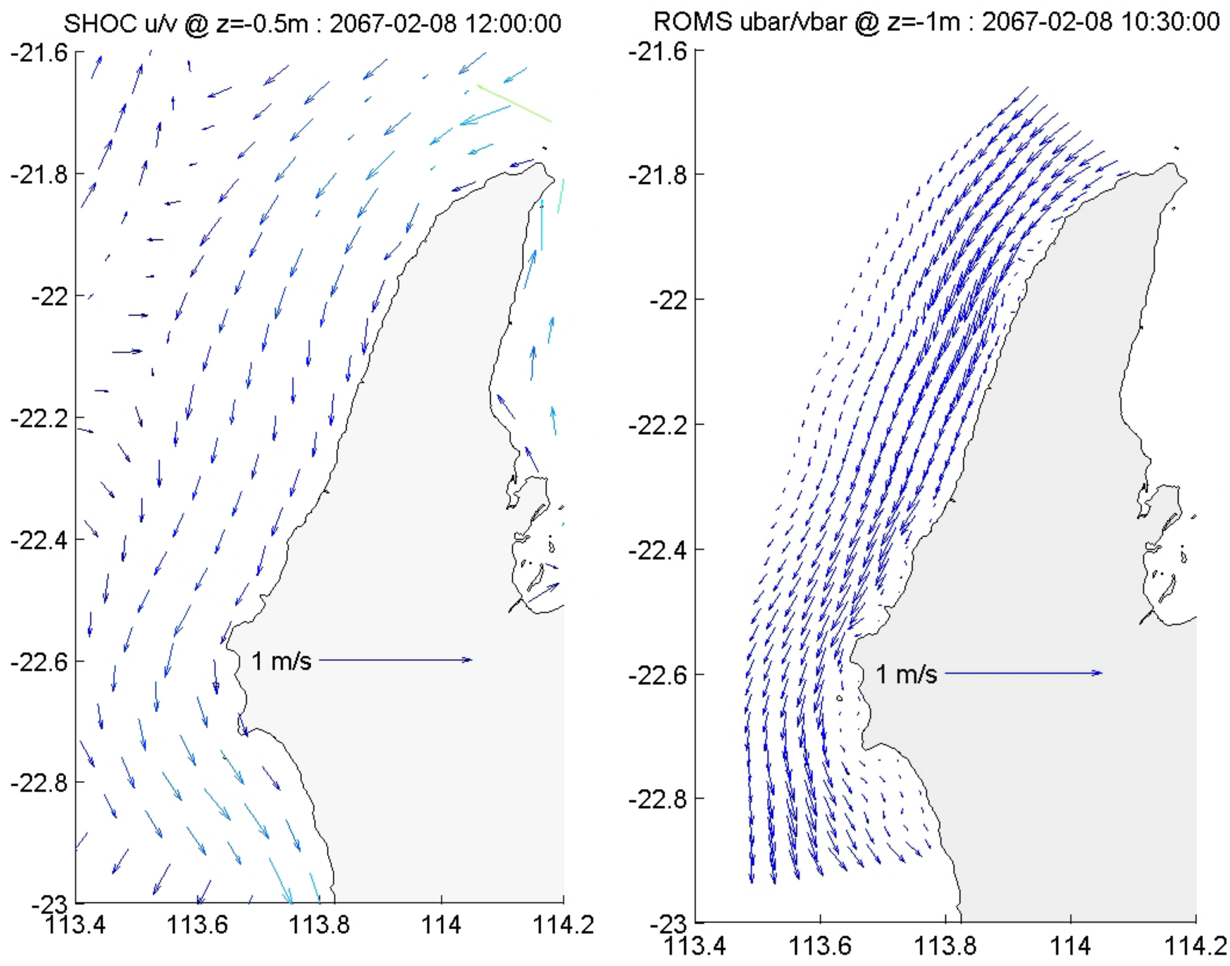

Figure 15. Snapshot of surface velocity fields from regional and coastal models under future climate scenarios

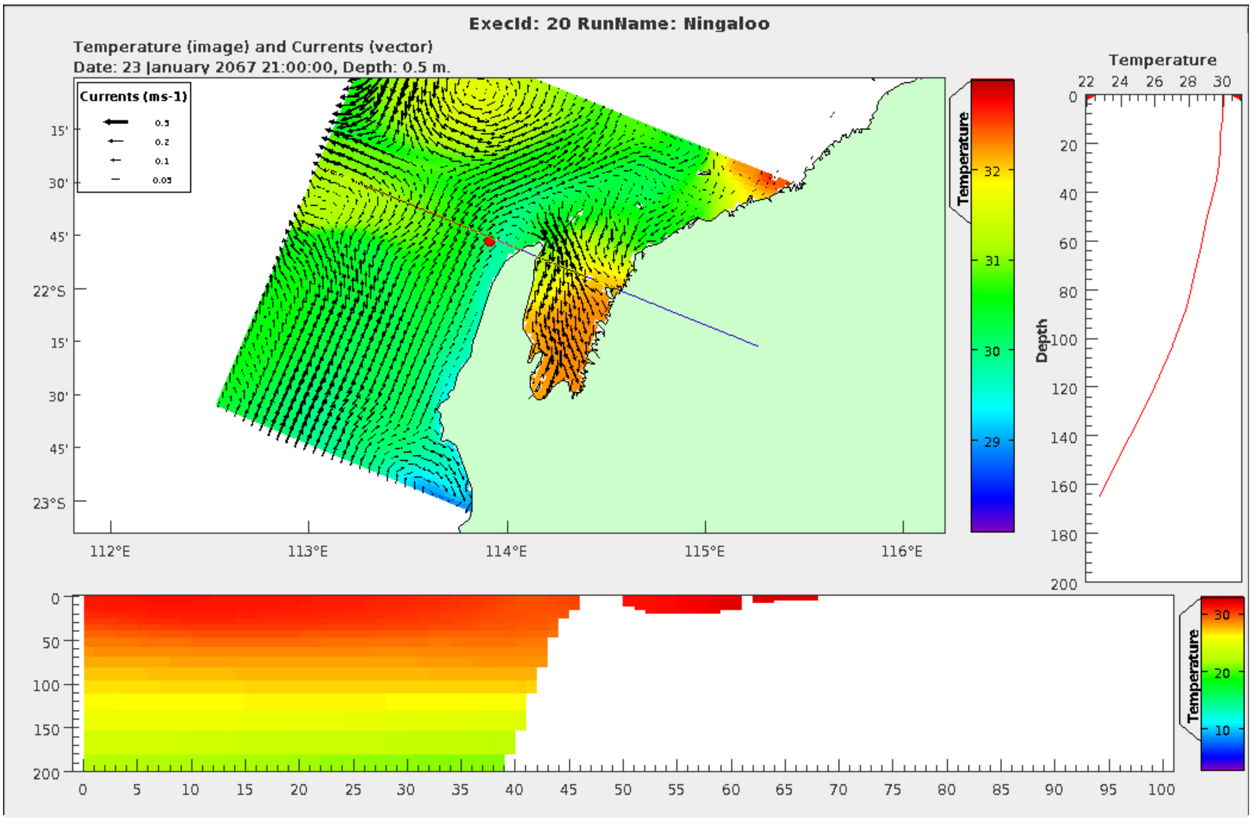

Figure 16. Snapshot of simulated surface current and temperature fields in January 2067(top), from downscaled regional model . Predicted temperature profile (top left) at location shown by red dot in plan view. Section through model grid (bottom) showing across shelf temperature structure.

5. Discussion

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

This study has shown, through the analysis of observations and the application of numerical models, that the upwelling dynamics at Ningaloo Reef are controlled by a combination of local (wind) and remote (mesoscale eddy) forcing. Increased southerly winds during the summer months drive the northwards flowing Ningaloo Current and associated upwelling which is hypothesised to 'insulate' Ningaloo from temperature induced coral bleaching; indeed Ningaloo Reef had not experienced widespread bleaching until March 2011. However, a climatology of alongshore currents show that upwelling favourable northwards coastal currents peak in both summer (January) and again in winter (July - August) with greater variability during winter, when southerly wind stress diminished to near zero. This increase in winter upwelling suggests that during winter, remotely forced regional circulation features such as eddies are a significant contribution to the nearshore coastal flows. These dynamics were reproduced by regional hydrodynamic models downscaled from the OFAM global circulation model. Model simulations showed rapid and significant vertical excursion of the thermocline in response to the alongshore current variability.

Analysis of future ocean simulations, as produced by the downscaling of CSIRO Mk3.5 model A1B future climate scenario using OFAM (WAMSI project 2.2.) indicate significant differences in the timing and duration of upwelling favourable currents along Ningaloo Reef, with the suggestion of reduced upwelling compared to a contemporary climatology, during summer for a number of years of the future forecast period (2060-2069). Results from the downscaling to regional and coastal model confirm the variability in timing and duration of upwelling favourable alongshore currents, as well as suggesting increased heat content in surface waters, deeper isothermal surfaces, and increased stratification, suggesting that in the future there will be less buffering of thermal stress on local coral communities by upwelling of cooler water.

Problems encountered (if any) – Describe any major problems/issues encountered during the study and how they were addressed.

- Re-allocation during 2007-2008 of AIMS staff involved in Project 2.3 resulted in significant delays to the progress of a number of this project's Milestones. This issue and the implications for the progress of project 2.3 were discussed at the WAMSI Node 2 Science Review in November 2008. As a result of this review, the Project Leader was requested to prepare, with advice from the Node Leader, a revised project proposal demonstrating how the three intended outputs (2.3.1, 2.3.2 and 2.3.3) would be achieved within the originally intended time frame, and including clear technical milestones and target dates for these steps to be achieved. This plan was submitted to WAMSI in November 2008 and accepted in January 2009.
- The field exercise to collect a broader spatial observational data set originally planned for April 2010 was delayed until September 2010, due to the scheduling of the AIMS Research Vessels. This new timing of the field campaign has caused a similar delay in the task to verify nested models against this new field data.

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Overall Project Accomplishments

Students supported – N/A

PhD theses, – N/A.

Publications

Taebi S, Lowe RJ, Pattiaratchi C, Ivey G, Symonds G and Brinkman RM (2011) Nearshore circulation in a tropical fringing reef system. Journal of Geophysical Research 116:C02016.

Lowe RJ, Ivey G, Brinkman RM and Jones NL (Submitted) Seasonal circulation and temperature variability near the North West Cape of Australia. Journal of Geophysical Research

Presentations

June 2008: **Richard Brinkman** participated in the WAMSI Node 2 technical workshop at BOM Melbourne.

September 2008: **Richard Brinkman** presented overview of Project 2.3 at WAMSI Node symposium "Climate Processes, Predictability and Impacts in a Warming Indian Ocean"

R Brinkman "Downscaling regional circulation at Ningaloo Reef" presented at WAMSI Node 2 Symposium: Climate Processes, Predictability and Impacts in a Warming Indian Ocean, CSIRO Floreat, 25 March 2010

R Lowe (UWA) and **R Brinkman** "Climatology of circulation and temperature variability off Ningaloo" presented at WAMSI Node 2 Symposium: Climate Processes, Predictability and Impacts in a Warming Indian Ocean, CSIRO Floreat, 25 March 2010

Overall Project Benefits

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

Discovery and Application of New Products and Processes (if applicable) - Describe any actual or anticipated products or processes discovered or developed in the project.
Analysis of the temporal variability of the surface current along the Ningaloo coast suggests extremely transient episodes of northward flow driven by both local (wind) and remote (mesoscale eddies) forcing. Northward flow events peak in summer and winter in response to seasonality in the wind forcing and the influence of mesoscale eddies, respectively. The northwards flow, often referred to as the 'Ningaloo Current' is therefore not a persistent current like southward flowing the Leeuwin further offshore, but is a highly dynamic and can transition from strongly downwelling favourable flows towards the south to upwelling favourable flows to the north within a period of 7 days. The changes in alongshore currents drive strong responses in the depth of the thermocline along the reef front, with fluctuations of up to 50m in the depth of the 25°C isotherm accompanying the transition from southerly to northerly alongshore flow. Rapid response of thermocline to remote and local forcing, coupled with enhanced mixing due to internal waves provides mechanism for increase nutrient delivery to the reef system. This work has increased our understanding of the local ocean dynamics along Ningaloo Reef, and provided an indication of how these dynamics may change in the future.
Tools, Technologies and Information for Improved Ecosystem Management - Describe how project results are being (or will be) translated into sustainable use and management of coastal and ocean ecosystems. Tools might include benthic habitat maps or environmental sensitivity indicators. Technologies might include remote and bio-sensing, genetic markers, and culture systems. Information might include technical assistance, training and educational materials.
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 give scenario(s).
Forecasting for Natural Resource Management Decisions - Describe how results already are being used - or are expected to be used after project completion - by natural resource management to make decisions based on project forecasts. Forecasts may be due to field and laboratory studies and models. Examples include hypoxia forecast models, algal bloom alerts, forecasts of fishery harvest, and prediction of impacts from ecosystem stressors such as pollutants or invasive species. *Impacts - Impacts are higher order, usually long-term results of a project's activities that have significant scientific, economic or social benefits. Impacts may involve behavioural, policy or economic changes. Describe impacts (anticipated or realized. These impacts may involve behavioural, policy or economic changes. Seminal contributions to science are considered impacts especially if the research findings lead to major progress in a particular field, implementation of new technologies or have a substantive bearing on an economic or societal issue.*
Outputs and uptake are still within in the research realm. Potential usage includes application to understanding the future responses of dissolved and particulate nutrient delivery adjacent to Ningaloo Reef, thereby triggering local increases in primary production and increasing nutrient fluxes to coral communities

8. Project Metadata and Data Generated

These must be available at an open access repository/data centre/iVEC.
Metadata describing field observations entered in AIMS metadata system

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

WAMSI 2.2 – regional scale climate downscaling WAMSI 3.5 – numerical modelling of Ningaloo Reef, and nearshore circulation. IMOS – sustained observations of the circulation adjacent to the Ningaloo Reef – now the site of a National Reference Station Mooring. ANNiMS – Springboard project with UWA (Nicole Jones), UTas (Peter Strutton) 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.

10. Other Comments and General Discussion

11. Annexures

ABSTRACT

Seasonal circulation and temperature variability near the North West Cape of Australia

Ryan J. Lowe, Gregory N. Ivey, Richard M. Brinkman and Nicole L. Jones

The circulation and temperature variability on the inner shelf near the North West Cape of Australia off Ningaloo Reef was investigated using field data obtained from two moorings deployed from 2004 to 2009. The results revealed the shelf circulation was, on average, only weakly influenced by the offshore poleward (southward) Leeuwin Current flow, i.e., monthly-averaged alongshore current velocities were ~0.1 m s -1 or less. The presence of a consistent summer-time wind-driven equatorward (northward) counter flow on the inner-shelf (referred to in the literature as the Ningaloo Current) was not observed. Instead, the shelf waters were strongly influenced year-round by episodic subtidal current fluctuations (time scale 1-2 weeks) that were driven by local wind forcing. Analysis of the current profiles showed that periods of strong equatorward winds were able to overcome the dominant poleward pressure gradient in the region, leading to upwelling on the inner-shelf. Contrary to prior belief, these events were not limited to summer periods. The forcing provided by these periodic wind events and the associated alongshore flows can explain much of the observed temperature variability (with timescales <1 month) that influences Ningaloo Reef.