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Climate change: knowledge integration and future projection

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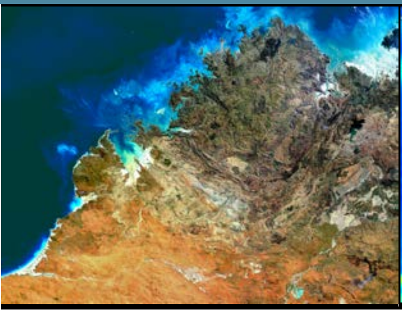
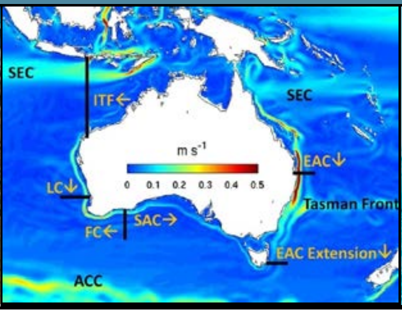
WAMSI Kimberley Marine Research Program

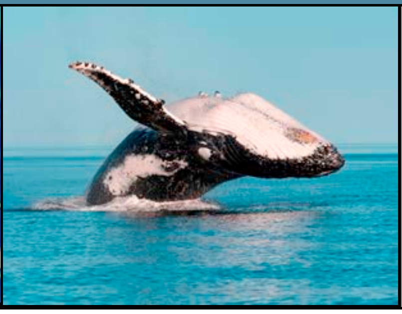
Final Report

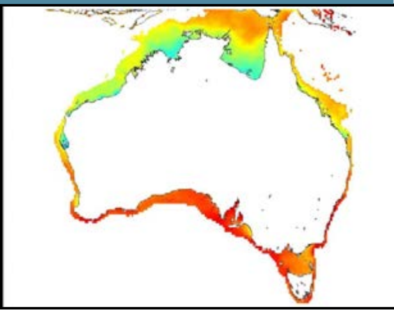
Project 2.2.7

September 2017









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WAMSI Kimberley Marine Research Program

Initiated with the support of the State Government, the Kimberley Marine Research Program is co-invested by the WAMSI partners to provide regional understanding and baseline knowledge about the Kimberley marine environment. The program has been created in response to the extraordinary, unspoilt wilderness value of the Kimberley and increasing pressure for development in this region. The purpose is to provide science based information to support decision making in relation to the Kimberley marine park network, other conservation activities and future development proposals.

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Front cover images (L-R)

Image 1: Satellite image of the Kimberley coastline (Image: Landgate)

Image 2: Mean surface current velocity from OFAM3 model simulation (source: CSIRO)

Image 3: Humpback whale breaching (Image: Pam Osborn)

Image 4: Linear trends of sea surface temperature of shelf regions around Australia from 1981 to 2014 (source: CSIRO)

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Contents

Executive Summary

In Kimberley Marine Research Program (KMRP) Project 2.2.7, historical data and numerical models have been used to identify the climate sensitivity of the Kimberley coast (Western Australia) to interannual and decadal climate variability in the Pacific and Indian Ocean over the past several decades. The project focused on the variability of ocean temperature, precipitation and salinity, sea level, and shelf current associated with El Niño–Southern Oscillation (ENSO), Indian Ocean Dipole, and Pacific Decadal Oscillation. These analyses have provide the background understanding of the climate change impacts on ocean temperatures, sea levels and precipitation off the Kimberley coast, to improve the predictability of climate-driven environmental variability, especially extreme events such as marine heatwaves. We have also utilised ocean downscaling models to project future climate change impacts on the marine environment such as the ocean temperature and internal wave characteristics. Key scientific findings from this project include:

- Precipitation variability of the Kimberley coast is highly sensitive to ENSO variability in the Pacific. High precipitation tends to occur during La Niña and low precipitation tends to occur during El Niño, due to ENSO modulation of the strength of the Australian monsoon and atmospheric convection activities. El Niño induces weaker Australian monsoon and less cloud coverage in the region;
- Coastal sea level variability of the Kimberley coast is also influenced by ENSO, through the ocean waveguides. High sea levels during La Niña and low sea levels during El Niño are influenced by ENSO-related trade wind and sea level anomalies in the western Pacific, transmitted through the Indonesian Seas. High sea level anomalies off the Kimberley coast during La Niña often accompany stronger Indonesian throughflow transport. Shelf circulation is also influenced by the Pacific ENSO – the Holloway Current is stronger under the La Niña condition;
- Due to the decadal strengthening trend of trade winds in the Pacific toward a La Niña-like condition over the past two decades, there have been fast rising trends of the coastal sea levels off the Kimberley coast since the 1990's. During the same time period, precipitation rates in the region have also increased, influenced by the dominant La Niña condition. The 2015-16 strong El Niño may indicate the start of a shift of the decadal trends to lower sea levels and reduced precipitation;
- Unlike the west coast of Australia, sea surface temperatures off the Kimberley coast are less influenced by ENSO-induced variability of ocean boundary current, and more influenced by air-sea exchanges. During El Niño, the increased solar radiation (due to less cloud coverage) and weakened Australian monsoon would warm the ocean surface. The co-occurring Indian Ocean Dipole would damp the warming tendency. Thus, the warming off the Kimberley coast can be rather strong under the El Niño without co-occurring Indian Ocean Dipole, such as the 2015-16 summer. Sea surface temperatures off the Kimberley coast have moderate rising trend over the past 30 years, mostly in the austral winter;
- From historical data and numerical model analysis, it is identified that the marine heatwaves are more likely to occur in the tropical reefs of Western Australia during El Niño events, such as the Kimberley coast, Scott Reef and Rowley Shoals. The marine heatwaves would be particularly strong during El Niño without co-occurring Indian Ocean Dipole. Intraseasonal variations such as the Madden-Julian Oscillation also affect the strength and timing of the marine heatwaves;
- As in observations and model simulations, the Indonesian throughflow waters and the coastal waters off the Kimberley have reduced in salinity by more than 0.2 psu during the extended La Niña conditions in 2010-11. The reduced salinity of the Kimberley coastal waters was mostly due to the anomalously high precipitation rates in the region. There appeared to be a decadal trend in the reduction of salinity in the region, influenced by decadal trend of the large-scale Pacific climate;
- From the 1960s to 1990s, there was a climate trend toward more frequent El Niño events in the Pacific, however, this trend has reversed over the past two decades and there have been more frequent La Niña events in recent years, which have affected the occurrences of extreme climatic events off the Kimberley coast and may have masked some of the long term climate change signals;
- Future climate projections suggest that ocean temperatures will warm by more than 1 degree Celsius (°C) in the next 50 years off the Kimberley coast. The sea surface temperature rising trends of 0.035 to

0.04°C per year are much higher than the historical trends in observations. The warming will likely increase the water column stratification on the continental shelf; and

- The future climate projection using a high-resolution shelf model suggests that internal wave energy on the continental shelf will likely increase, due to surface warming and increased stratification on the shelf; thus increased cross-shelf exchange may occur in the future climate which could bring more deep nutrients onto the shelf.

Implications for management

From the scientific findings of this project, the following key considerations and recommendations for management and end-users are provided:

- Ocean temperature and salinity fluctuations affect the growth and health of marine species. The fisheries and pearl aquaculture industry along the Kimberley coast needs to understand the climate driven temperature and salinity variations in the region; warming during El Niño events and reduced ocean salinity resulting from heavy precipitation during La Niña events. It is recommended that these industries use available tools such as ENSO prediction hosted on the Bureau of Meteorology website and CSIRO Bluelink model results hosted on the Integrated Marine Observing System (IMOS) website to monitor the current climate information and oceanographic conditions off the coast and prepare adaptation responses;
- Coral bleaching is one of the key threats to coral reef communities and most of the coral bleaching occurs during the extreme warming events, the marine heatwaves. Off the Kimberley coast, marine heatwaves are more likely to occur after the peak of an El Niño event and an El Niño event without a companion Indian Ocean Dipole is more likely to drive higher temperature extremes. Variability of the Australian summer monsoon and other weather variability like the Madden-Julian Oscillations are also likely to trigger the occurrences of the marine heatwaves; and
- Ocean temperatures off the Kimberley coast are likely to warm by more than 1 °C in the next 50 years, influenced by human-induced climate change, which would exceed the temperature tolerance of many marine species, such as seagrasses and macroalgae. Sea level will continue to rise due to the ocean temperature warming and the melting of ice sheets. Under the future climate change, extreme ENSO events are likely to occur more often such that the marine heatwaves may become more extreme. These changes will affect marine ecosystems off the Kimberley coast. Although the tropical Pacific climate will become El Niño-like condition in the future climate, the projections for the precipitation changes off the Kimberley coast are not robust. This knowledge has been incorporated into the ecosystem model projections in the Management Strategy Evaluation KMRP Project 2.2.8.

Management implications are also discussed in Appendix 1.

Key residual knowledge gaps

This project has significantly increased our understanding of climate variability and change impacts on the Kimberley coast, and has also highlighted a number of knowledge gaps.

The prediction skills of ENSO have greatly improved over the years, however, the Indian Ocean predictability is still rather limited. Thus, although ocean temperatures off the Kimberley coast are often warmer during an El Niño event, the magnitude of the warming is still hard to predict, and the timing of the marine heatwave events is sometimes related to the short-term climate variability, which still lacks prediction skills.

Through the Centre for Southern Hemisphere Oceanography Research (CSHOR), we have set up a new project to make additional offshore measurements of upper ocean temperature structure and air-sea fluxes to help improve model predictions of the short-term climate variability – the Madden Julian Oscillation (MJO).

Additional regional model experiment for the Kimberley coast using the CSIRO regional model targeting a few MJO events in austral summer would further enrich our knowledge and capability on the predictability of shelf current and temperature responses to the MJO forcing. Off the Pilbara coast, it has been proven that the MJO forcing is important for coral larval dispersal during the mass spawning events.

Climate change not only will induce warmer ocean temperatures, it will also affect the water column stratification in the coast regions. The stratification change may affect the vertical mixing of nutrient and limit the sediment resuspension in the coastal region. However the mechanisms of how physical environment changes affect the biology and marine ecosystem are still largely unknown.

It is suggested that there should be more work on how the stratification on the Kimberley shelf affect the marine ecosystem, such as the onshore transport of deep nutrient and vertical mixing. Further measurements are necessary to clarify these. It is important to deliver further study on how the shelf stratification change during different climate event and under climate change events to improve our understanding of the impact of the climate change on the biology and marine ecosystem.

1 Introduction

Ocean climate is largely defined by its temperature, salinity, ocean circulation, and the exchange of heat, water and gases (including carbon dioxide [CO_2]) with the atmosphere. Ocean climate experiences significant interannual and decadal variations, mostly due to the dominant modes of climate variability in the coupled atmosphere-ocean system, such as El Niño-Southern Oscillation (ENSO). Understanding the impacts of the interannual and decadal climate variability and long-term climate change on regional ocean climate, its temperature, salinity, and ocean circulation, is crucial for sustained marine environment management. The Kimberley coast situated in tropical northern Australia is strongly influenced by the Australian monsoon and ENSO variability, and to some extent by the Indian Ocean Dipole and Madden-Julian Oscillation (MJO).

1.1 Climate drivers

The Australian monsoon season generally lasts from December to March. It is associated with the influence of moist westerly to north-westerly winds into the monsoon trough, producing convective cloud and heavy rainfall over northern Australia (Figure 1.1). The northern Australian wet season encompasses the monsoon months but can extend several months on either side. Seasonal wind patterns off the Kimberley coast are dominated by the monsoonal variation. West-southwesterly winds dominate during the austral summer (December to February), followed by weak to moderate wind period (March to April); the strong east-southeasterly trade winds resume in May, lasting until September, before entering the monsoon transition period of weak winds.

The intraseasonal variability of the Australian monsoon are mostly associated with the MJO activities. MJO is the major fluctuation in tropical weather on weekly to monthly timescales. It is characterised as an eastward moving pulse of cloud and rainfall near the equator, typically recurring every 30 to 60 days, from western Indian Ocean to the Pacific. MJO has been found to impact on surface winds, ocean temperature, coastal sea levels, and shelf circulation off the Kimberley coast (Marshall and Hendon 2014).

On interannual timescale, precipitations into Maritime Continent and northern Australia are suppressed during a warm phase of ENSO, the El Niño. This is likely due to the fact that El Niño induces an eastward shift of the convection zone in the Pacific and a late onset and weaker Australian monsoon. On the other hand, during the cold phase of ENSO, the La Niña, the local convection and the Australian monsoon is enhanced, so that there are more precipitations in the Maritime Continent and northern Australia region. It is still uncertain how the climate change would impact on the rainfall patterns of the Kimberley coast.

It is not clear yet to what extent the Kimberley coastal waters are influenced by the direct air-sea exchange, river run-offs and continental shelf processes. Generally, there is a net heat input into the oceans through air-sea interface in summer and there is a net cooling through air-sea interface in winter. During the summer monsoon, there is net freshwater input into the region from precipitation whereas in winter the evaporation rate surpasses precipitation. The summer monsoon winds push a high sea level pressure head towards the Gulf of Carpentaria; and when the summer monsoon relaxes, the pressure head is released and drives south-westward shelf flow, the Holloway Current, in autumn and winter (D'Adamo et al. 2009).

ENSO drives interannual variations of the Indonesian throughflow and Leeuwin Current, due to variations of trade winds along the equatorial Pacific (Meyer 1996; Feng et al. 2003). Both the Indonesian throughflow and the Leeuwin Current are stronger during La Niña phase of ENSO, and weaker during El Niño. Continental shelf of the Kimberley coast is the pathway of the Pacific ENSO signals that influence the strength of the Leeuwin Current further downstream (Feng et al. 2003). Upper ocean heat content off the north-west Australia coast is very sensitive to ENSO variability, being high during La Niña events and low during El Niño events (Hendon and Wang 2009). On the continental shelf, there are north-eastward flow anomalies during El Niño events and there are south-westward flow anomalies during La Niña events, as simulated in numerical models (Schiller 2011).

Over the past three decades, there have been enhanced precipitations in the maritime continent and northern Australia, associated with the intensification of the Pacific trade winds and the convergence of moisture into the region (Kosaka and Xie, 2013). The trends of sea surface temperature and trade winds in the Pacific over the past three decades are consistent with the phase shift of inter-decadal Pacific oscillation (IPO). There have been strengthening trends of the Indonesian throughflow and Leeuwin Current transports during this time period (Feng et al. 2011; Liu et al. 2015). These decadal trends are likely due to the natural climate variability in the Indo-Pacific, instead of being part of the global warming trend.

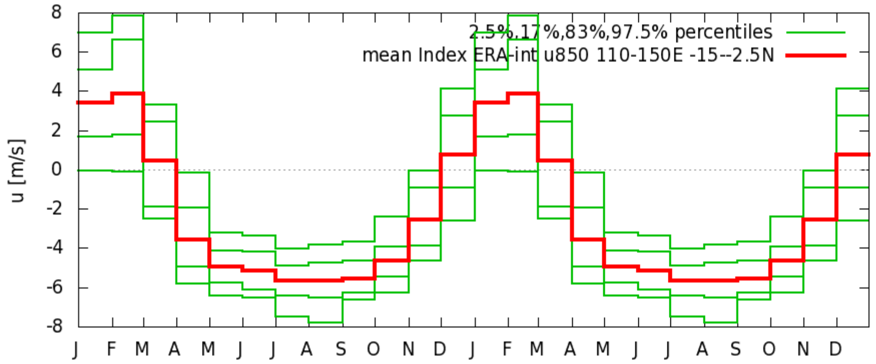

Figure 1.1. Mean Australian monsoon index, derived from the average zonal wind speed at 850 mbar in the 110-150°E, 15-2.5°S. The wind data is from European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis.

1.2 Objectives

Given the climate sensitivity of the Kimberley coast, it is likely that the projected future climate change will have significant impacts on the physical environment off the Kimberley coast. It is crucial to better quantify these climate sensitivities and develop modelling tools to downscale the future climate change impacts for the marine managers to be better prepared for managing the marine resources in a warming climate. The project was designed around three objectives:

1. A detailed analysis and review of influences of the past climate variability and change on ocean temperature, salinity, sea levels, and shelf current off the Kimberley coast;
2. Projected future changes in the physical environment off the Kimberley coast using downscaled numerical model; and
3. An improved understanding of climate change impacts on key biophysical indicators such as coastal water retentions and dispersals off the Kimberley coast.

Whereas the expertise in the project is on physical oceanography and ocean modelling, the focus of the research has been on the delivery of the first two objectives over the life of the project. Members of the project team have actively engaged in discussions with biological oceanographers and researchers from other WAMSI KMRP projects on the biophysical impacts in the Kimberley region. Objective 3 has largely been delivered through collaborations with other projects.

Based on the objectives, we investigated how regional processes are influenced by climate variability and change, such as:

- coastal sea levels;
- sea surface temperature;
- coastal current;
- wind;

- internal tides;
- upper ocean salinity; and
- marine heatwaves.

2 Materials and Methods

2.1 Historical data

Coastal sea level data for Broome, Wyndham, and Darwin were obtained from the University of Hawaii Sea Level Center, the Global Sea Level Observing System (GLOSS), and WA Department of Transport (Figure 2.1). Data for the Broome station started from 1966 (Department of Transport), but its quality and time coverage were rather poor before 1992. This dataset was combined with two other data sources before 1992 to form a monthly time series for Broome. The Wyndham data are from 1984 to 2012, obtained from the GLOSS website. Sea level data at Darwin (and Fremantle) from the 1984 to 2013 are obtained from the University of Hawaii.

Daily values of the optimally interpolated sea surface temperature (SST) at 25 km resolution were downloaded from the NOAA public FTP site (ftp://ftp.cdc.noaa.gov/Datasets/noaa.oisst.v2.highres). The data spans from September 1981 through May 2014. The data were binned into monthly values.

Monthly climatology, or long term monthly averages, were calculated from the sea level and SST data and then subtracted from the monthly field to derive the monthly anomaly fields.

The monthly Southern Oscillation Index (SOI), which is an index for ENSO, was downloaded from the Bureau of Meteorology website.

The Western Pacific SST gradient (WPG) is defined as the SST difference between Central Western Equatorial Pacific and the Western Pacific Warm Pool.

The Australia monsoon index was derived from the zonal wind field from the European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis, following the definition of Kajikawa et al. (2010). The index is defined as the average zonal wind speed at 850 mbar in the region of 110-150°E, 15-2.5°S during the December to February period.

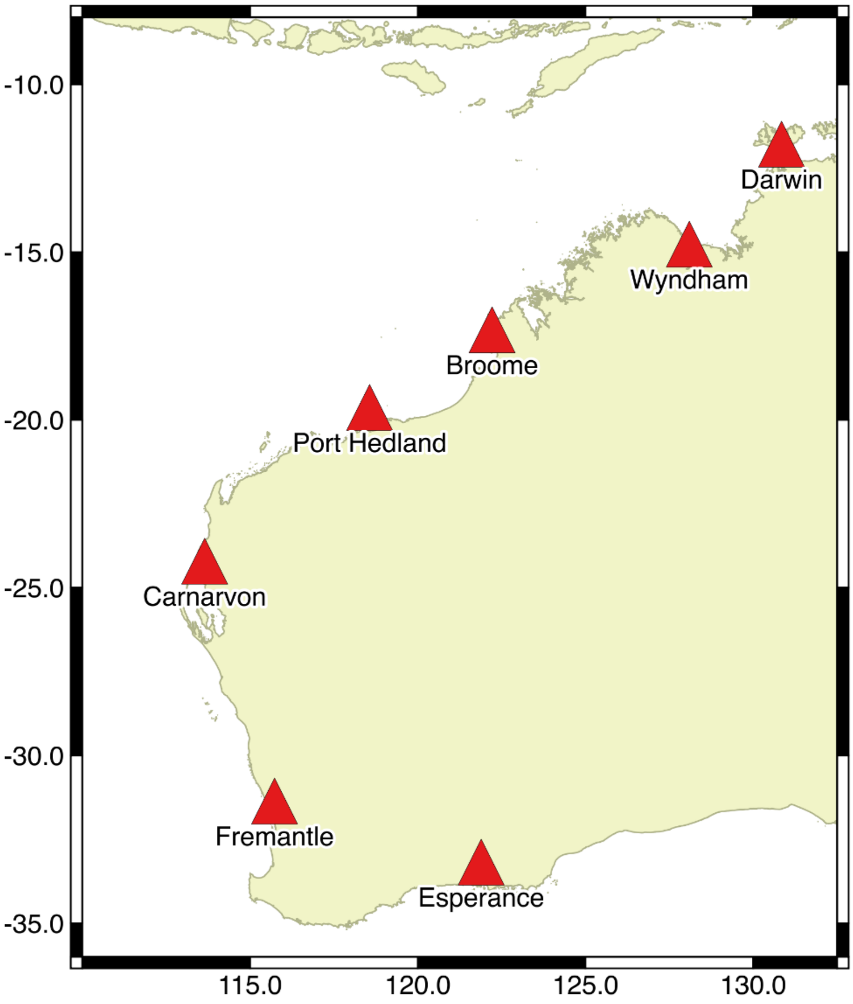

Figure 2.1. Coastal sea level station locations around Western Australia (from the University of Hawaii Sea Level Centre). The symbols from north to south denote Darwin, Wyndham, Broome, Dampier, Carnarvon, and Fremantle.

2.2 Numerical models

2.2.1 OFAM

The Ocean Forecasting Australia Model version 3 (OFAM3) is a near-global configuration of version 4p1d of the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (Griffies et al. 2004). The OFAM3 model grid has (1/10)° horizontal grid spacing between 75°S and 75°N. The vertical model coordinate is z^* with 51 vertical levels and 5 m resolution down to 40 m depth and 10 m vertical resolution to 200 m depth. Three experiments are performed by using OFAM3: (1) a historical run during 1979–2014 (Zhang et al. 2016), driven by the Japanese 55-year Reanalysis (JRA-55) (Kobayashi et al. 2015); (2) a future climate downscaling run under the Representative Concentration Pathway 8.5 (RCP8.5 run) during 2006–2101, driven by merged atmospheric forcing which includes long-term climate change signals from the ensemble of 17 CMIP5 climate models and high-frequency component (cutoff period 7 years) from JRA-55 reanalysis over 1981–2012 repeated three times; and (3) a control run over 1979–2101 using repeated 1979 JRA-55 forcing (Feng et al. 2017).

OFAM3 is forced with 3-hourly surface heat, freshwater and momentum fluxes. The turbulent air-sea fluxes—i.e. evaporation, sensible and latent heat flux—are calculated with bulk formulae and updated every time step (Zhang et al. 2016). Surface salinity is restored to monthly sea-surface salinity from CSIRO Atlas of Regional Seas (CARS), released in 2009 (Ridgway et al. 2002), with a restoring time scale of 180 days, in the historical and control runs. In the RCP8.5 run, long-term climate change anomalies of surface salinity from an ensemble of 17 CMIP5 climate models are added to the CARS climatology to derive the restoring terms. A climatological nonadaptive (i.e. independent of model state) deep ocean restoring of temperature and salinity below 2000 m to CARS climatology is applied to OFAM3 in order to minimize model drift while allowing penetration of the anthropogenic heat (Zhang et al. 2016), with a restoring time scale of 1 year. As we have applied the same climatological deep ocean restoring in both the control run and the RCP8.5 run, we are able to detect and remove any spurious trends in the RCP8.5 run, which are generally small.

The upper ocean circulation around Australian is well captured in the model. This study has revealed that the major ocean boundary current systems around Australia, the East Australian Current (EAC), the Indonesian Throughflow (ITF), the Leeuwin Current, the South Australian Current and the Flinders Current, have strengthened during 1979–2014, consistent with existing observations (Zhang et al. 2015; Feng et al. 2016a; Figure 2.2).

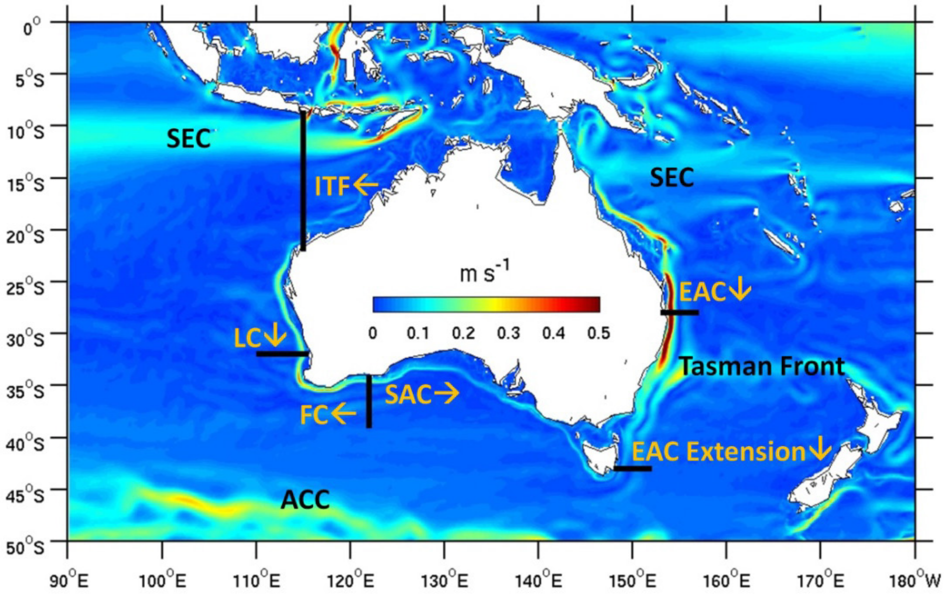

Figure 2.2. Mean surface current velocity (0–50 m average of square root of mean kinetic energy) from OFAM3 model simulation. The black lines denote the sections used to calculate the boundary current transports and the arrows denote the direction of the flows. EAC: East Australia Current; FC: Flinders Current; ITF: Indonesian Throughflow; LC: Leeuwin Current; SAC: South Australian Current; SEC: South Equatorial Currents in the Indian Ocean and Pacific. (from Feng et al. 2016).

2.2.2 ROMS

The regional ocean modeling system (ROMS) was set up for the Kimberly region. Horizontal grids are rotated spherical grids with uniform 0.02° resolution. The x-axis of the grid is roughly 40° from the circles of latitude, so that it roughly aligns with the coast line (Fig. 2.3). Vertical grids consist of 30 grid points on the s-coordinate. Atmospheric fluxes are calculated using the COARE bulk parameterization (Fairall et al. 2003). Horizontal mixing is harmonic. Vertical mixing scheme is essentially the k-ω model with the stability functions by Canuto et al. (2001) but reformulated based on the generic length scale model by Umlauf and Burchard (2003). Model bathymetry was taken from STRM30plus (Becker et al. 2009), and wetting-drying scheme was not implemented (minimum depth is set to 7 m).

The ROMS shelf model is nested within the OFAM model outputs, to simulate the coastal circulation off the Kimberley during 2009-2012. Initial conditions and horizontal open boundary conditions for the ROMS model were taken from daily-mean output of OFAM3 (Zhang et al. 2016). Horizontal boundaries were also forced with tides from TPXO7.2 (Egbert and Ray 2003). Atmospheric forcing was given by 3 hourly winds, air temperature, humidity, and radiative fluxes from the Japanese 55-year reanalysis (JRA) (Kobayashi et al. 2015), same as the OFAM simulation. Since river discharge results were not delivered in time from another subproject of WAMSI KMRP for the model period, we used climatology river discharges from the Fitzroy River and Mitchell River from

Dai et al. (2009) as model boundary conditions at the river mouths. A horizontal dispersion coefficient of 5 m^2/s was used in the ROMS model based on the grid resolution and (Okubo 1971). Sponge zones to ensure the smooth transition from the OFAM model and the ROMS model were used along the open boundaries.

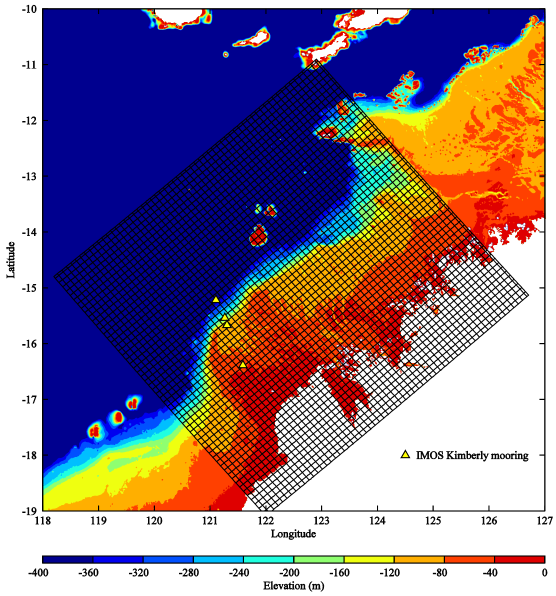

Figure 2.3. Model grid and bathymetry. Model grid boundaries are shown every 5 grid points.

Comparisons of modelled and observed tidal constituents are shown in Figs. 2.4 and 2.5. Observed values are calculated from currents and pressure measured by ADCPs of IMOS Kimberly moorings for individual deployment periods. Higher resolution in ROMS modelling improves the amplitudes of tidal currents in shallow (<100m) water from the TPXO7.2, which was used to force the model (Fig. 2.6). Although the phases do not always agree with observations for constituents with smaller amplitudes (K1 and O1), comparisons of time series show that the time series are reproduced well by the model.

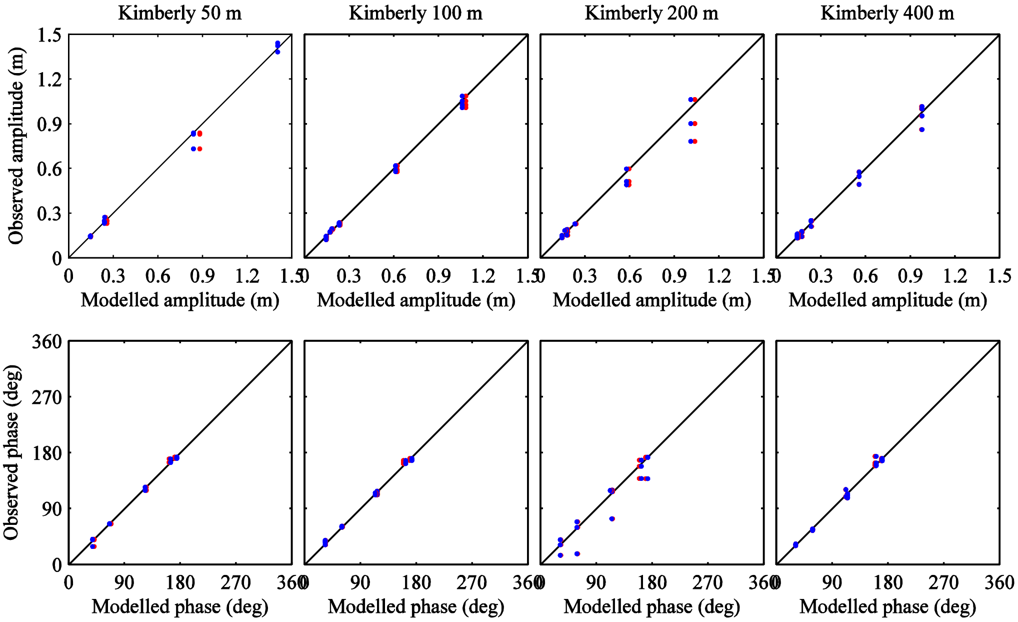

Figure 2.4. Comparison of harmonic constants for surface elevation at IMOS KIM050, 100, 200, and 400 sites. Blue and red corresponds to ROMS output and TPXO7.2 (input data for ROMS), respectively.

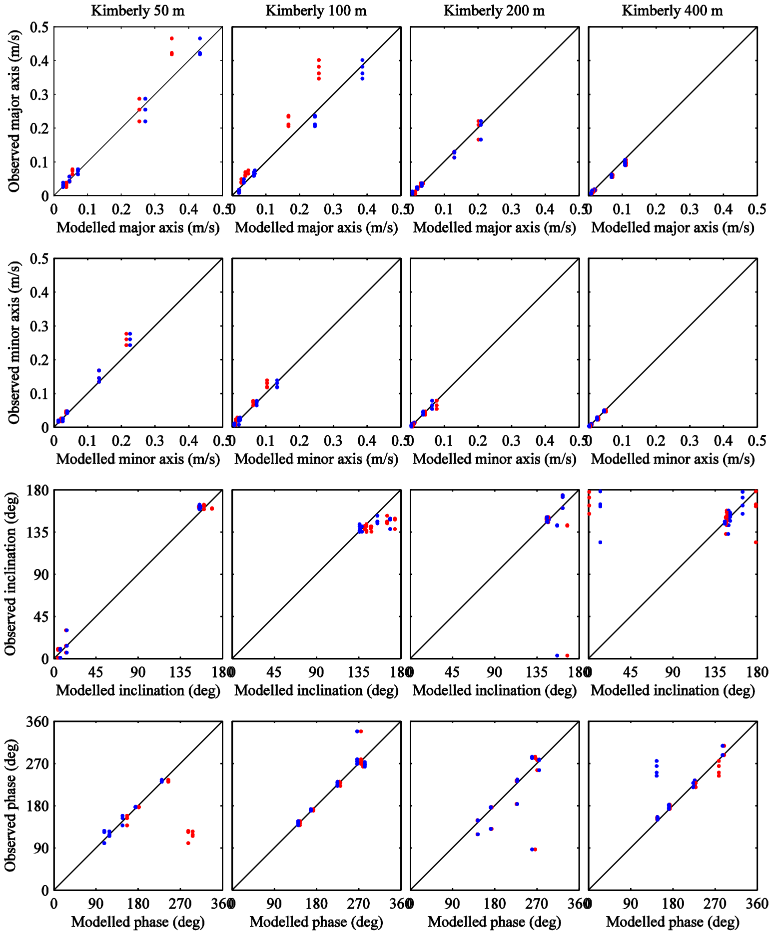

Figure 2.5. Comparison of harmonic constants for barotropic currents at IMOS KIM050, 100, 200, and 400 sites. Blue and red corresponds to ROMS output and TPXO7.2 (input data for ROMS), respectively.

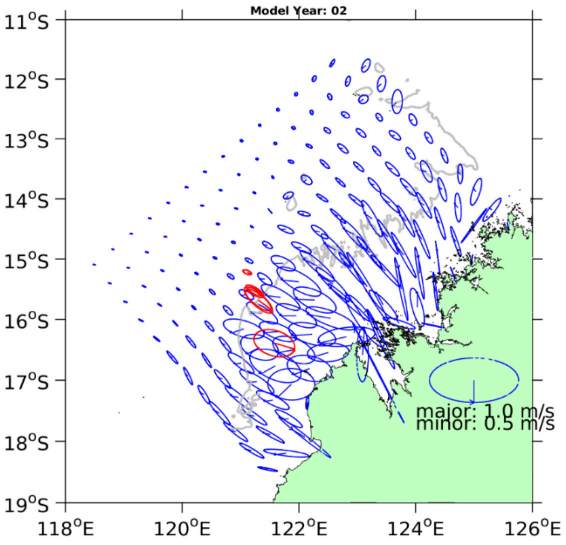

Figure 2.6. Semidiurnal baratropic tidal ellipses from the ROMS model (blue) and from IMOS observations (red) Tidal phases are denoted with radial bars.

2.3 Climate downscaling

For our regional downscaling, we used the existing ROMS model simulation for the period 2009-2012 as the current climate, which has captured some extreme ENSO climatic events, such as the 2009-10 El Niño and the 2010-11 La Niña. For the future climate, we used the equivalent period during 2066-2069 to nest our ROMS model within the OFAM simulation under the RCP8.5 scenario. The OFAM model provides the initial and open boundary condition for ROMS, and the ROMS model was forced with the same reconstructed atmospheric fields, as described in section 2.1.

3 Results

3.1 Natural climate variability

3.1.1 Climate forcing

Consecutive positive SOI above a certain threshold usually indicates a La Niña event, and consecutive negative SOI below a certain threshold usually indicates an El Niño event. An El Niño or La Niña event often peaks during the austral summer. Over the past few decades, prominent El Niño events occurred in 1982-83 and 1997-98, when the SOI was below -20 for extended periods (Figure 3.1). During the last decade, there have been more frequent La Niña events, such as the extended 1998-2000 and 2010-12 events in the tropical Pacific. Some of the recent events are associated with extensive marine heatwaves off the west and the north-west coast, causing ecological impacts in the region, such as the 2011 and 2012 marine heatwave events off the Pilbara coast, and the 1998 and 2016 coral bleaching events off the Kimberley coast.

The strength of the Australia summer monsoon is defined using the zonal wind speed at 850 mbar, averaged in the region of 110-150°E, 15-2.5°S over December-February (Figure 3.2). A strong monsoon is when the index is one standard deviation above its mean value, and a week monsoon is when the index is one standard deviation below its mean value. Typically the Australian monsoon is strong during La Niña and weak during El Niño. The Australian summer monsoon was relatively strong during the 2010-11 La Niña/west coast marine heat wave event, and some of the strongest Australia summer monsoon occurred in the early 1990s.

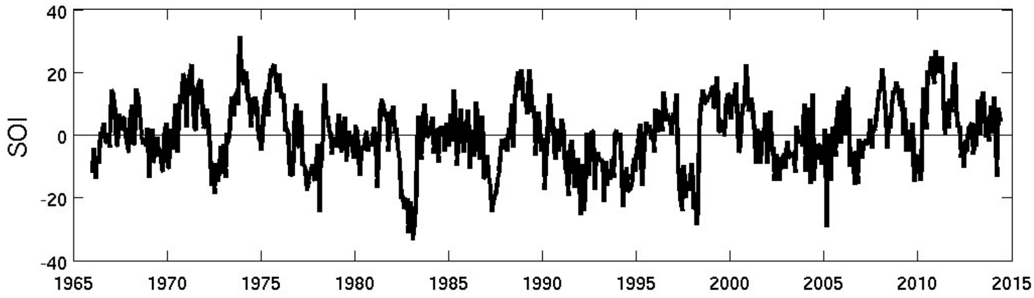

Figure3.1. monthly Southern Oscillation Index.

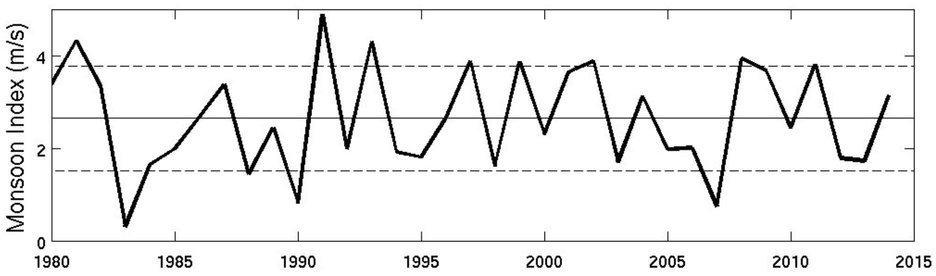

Figure 3.2. Australian summer monsoon index. The index is defined as the average zonal wind speed at 850 mbar in the region of 110-150°E, 15-2.5°S during December-February, derived from the ECMWF interim reanalysis. The mean value and the standard deviation of the index are also shown.

3.1.2 *Coastal sea levels*

Coastal sea levels along the Kimberley coast have distinct annual cycles, higher in late summer-early autumn, and the lower in winter-early spring (Figure 3.3). On the annual cycle, Wyndham has higher peak-to-peak amplitude (346 mm) compared to Broome (225 mm), and tends to lead the annual phase by about a month. The peak sea level at Wyndham is in March, and that at Broome is in April. Both sea levels lag the Darwin station, which peaks in February to March. The lowest sea level at Wyndham is in July, and that at Broome is in August. The phase relationship among different stations may indicate the south-westward direction of the annual signal propagations and their large scale driver of the monsoon wind variability (Ridgway and Godfrey 2015).

On the interannual time scale, there is good correspondence between high sea levels and positive SOI values – La Niña condition, in all the 3 stations at Broome, Wyndham and Darwin, such as the high sea levels around the 2000 La Niña period (Figure 3.4). After removing the annual cycle, there are significant correlations between the sea level anomalies and the ENSO index, the Southern Oscillation Index (SOI), at Broome and Wyndham (Figure 3.5). The correlations are lower than that at Darwin, but higher than at Fremantle. Wyndham has the highest linear regression coefficient with SOI, while Fremantle has the lowest, indicating the ENSO-driven coastal Kelvin waves also propagate through the Kimberley coast from the Indonesian seas.

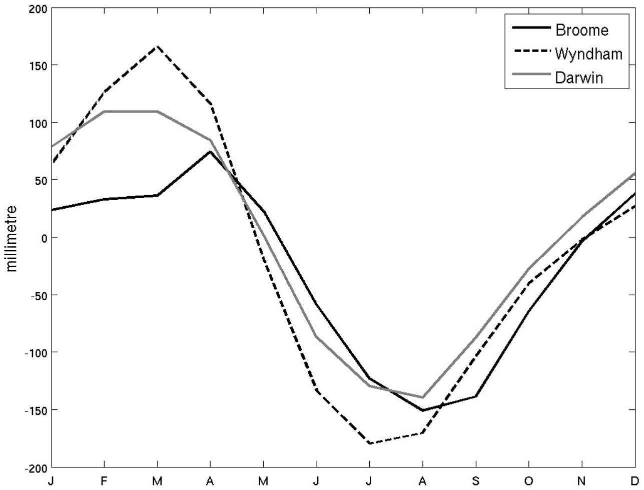

Figure 3.3. Annual cycles of coastal sea levels from Broome and Wyndham off the Kimberley coast, and their comparison with the Darwin sea level.

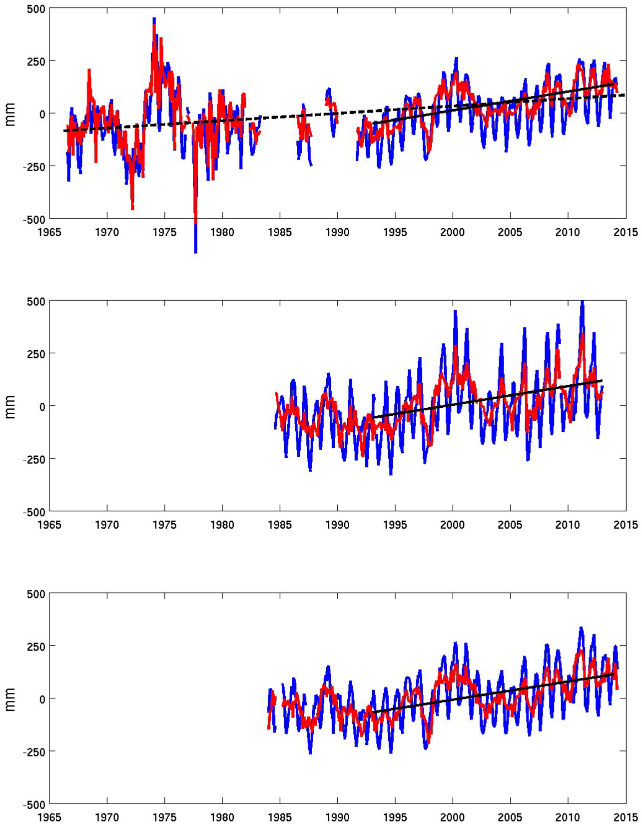

Figure 3.4. Time series of coastal sea levels in northern Australia at Broome (top), Wyndham (middle) and Darwin (bottom). The blue curves display the monthly sea level values, and the red curves display the monthly values after the seasonal cycle is removed (sea level anomalies). The straight lines are linear regressions of the sea level anomalies.

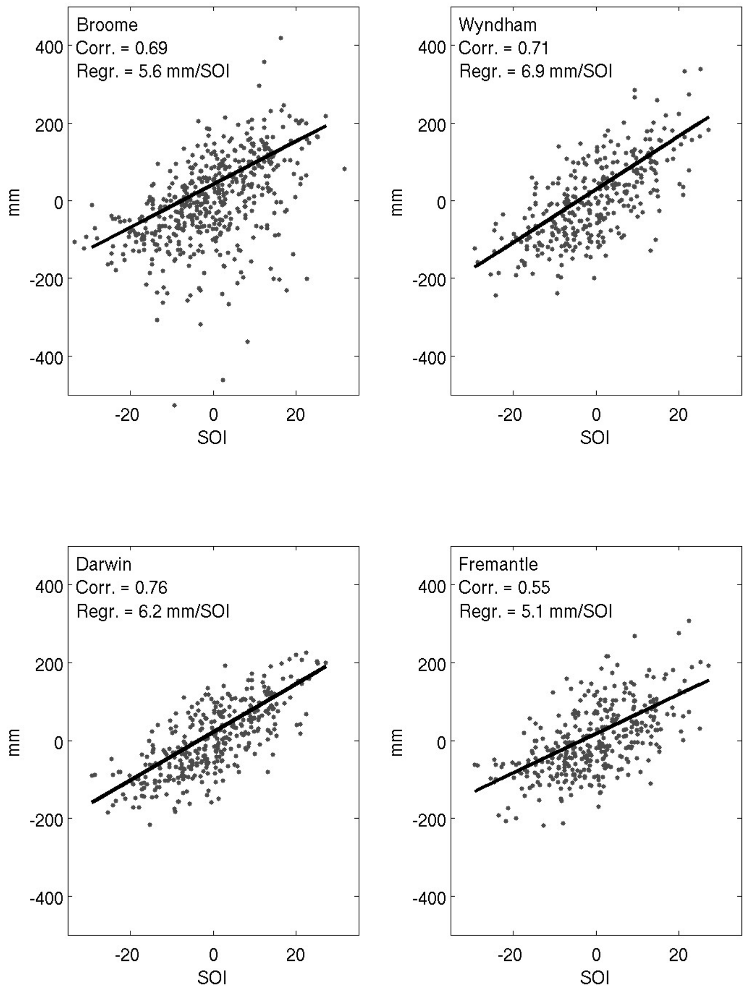

Figure 3.5. Scatter plot of monthly sea level anomalies and the Southern Oscillation Index, for tide of each stations at Broome, Wyndham, Darwin and Fremantle. The linear correlation and regression slope are also denoted.

3.1.3 Ocean temperatures

Off the Kimberley coast, sea surface temperatures are higher during summer and cooler during winter, with the seasonal ranges between 4 to 5°C in the monthly climatology (Figure 3.6). Seasonal variations of sea surface temperatures off the Kimberley coast have less range than those off the Pilbara coast and Beagle Gulf. The warm season lasts from November through April and the cool months range from July through August, particularly in the coastal region south of Broome (Figure 3.7). Unlike the coastal regions off Ningaloo, where the highest temperature variability is in summer, the highest temperature variability off the Kimberley coast will occur May to June and then in September to October, indicating that transitions between wet and dry seasons encompass variable weather conditions (Figure 3.8). Sea surface temperatures off the Kimberley coast tend to have neutral or negative skewness, indicating they are less prone to have extreme warm temperatures; whereas on the other hand, in the coastal regions off Ningaloo, sea surface temperatures are positively skewed in summer (Figure 3.9), indicating more extreme warm events.

Unlike ocean temperatures off the west coast, sea surface temperatures off the Kimberley coast are not positively correlated with the ENSO index, SOI, despite the good correlations between coastal sea level at Broome and the SOI (Figure 3.5). Such that a dramatic warming event occurred off the Kimberley coast at the peak of the 2015-16 El Niño (Figure 3.10a). In the developing year of an El Niño, SST anomalies in the Indian Ocean are indicative of positive IOD events, which often develop during austral winter/spring in conjunction with El Niño (2015 is defined as a neutral IOD year if we use the IOD eastern pole is used to define the IOD events), and cold SST anomalies appear off northern Australia (Figure 3.10b,c). As El Niño matures in austral summer, SST anomalies off northern Australia switch to positive, and then strengthen and expand to a large tropical region during the autumn (Figure 3.10d,e). Cold SST anomalies persist southward of 20°S along the WA coast (Figure 3.10). During La Niña, positive SST anomalies first establish off the northwest coast of Australia during winter and spring, and then shift southward down the coast during austral summer, with notably high SST anomalies southward of 20°S at the mature phase of La Niña (Figure 10f–i). Lower than normal SSTs occupy the northern coast in summer. Thus, coral reefs off the Kimberley coast including the Scott Reef are more prone to marine heatwave and coral bleaching impacts during an El Niño event (Zhang et al. 2017). The warming off the Kimberley coast during El Niño is mostly due to increase of surface heat flux in the tropical southeast Indian Ocean, which is mainly due to shortwave radiation and latent heat anomalies driven by large scale atmospheric responses to El Niño, such as weakened Australian monsoon (Zhang et al. 2017).

A Lalang-garram/Camden Sound Marine Park sea surface temperature index, defined as average temperature within the marine park triangle, provides a better understanding of the temperature variability in the region (Figure 3.11). The dominant temporal variation of the temperature index is the annual cycle, accompanied by a weak semi-annual cycle. There is also 30-90 day intra-seasonal variability and 2-4 year interannual variability. On the interannual time scale, the monthly temperature anomalies at Camden Sound (after removing the average annual cycle) highly correlated with accompanying anomalies along the Kimberley coast and across the shelf (Figure 3.12). Zoom in to the Camden Sound, the highest correlation is located at the north-western region of the marine park (Figure 3.13). The correlation pattern for the high-frequency variability of sea surface temperature at Camden Sound is very similar to the interannual signals, only with a smaller footprint of high correlation across the region (Figure 3.14).

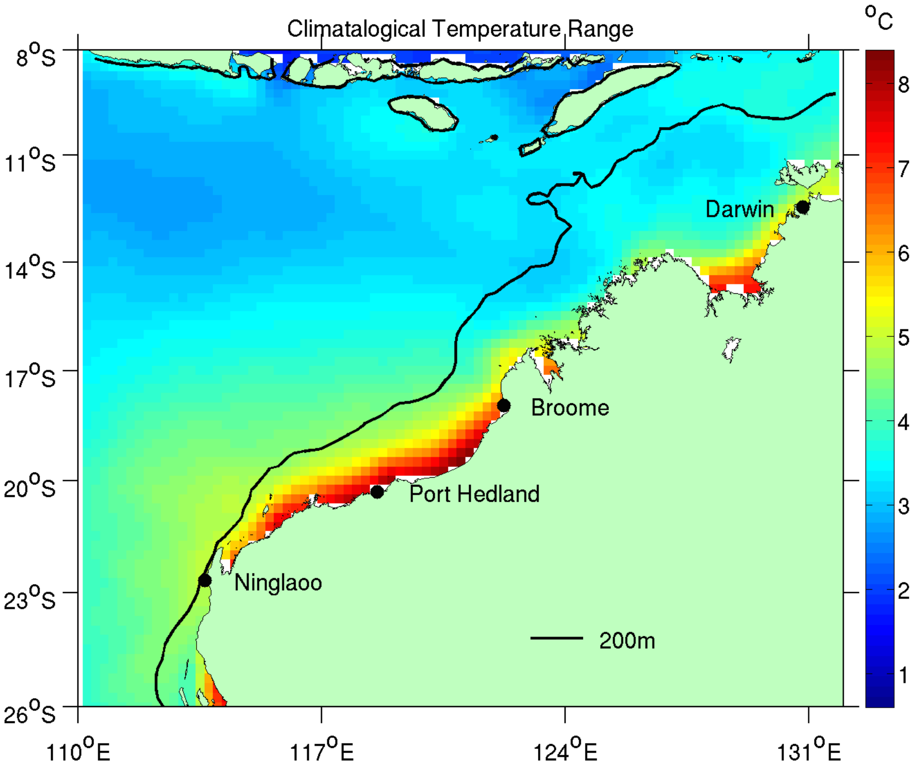

Figure 3.6. Sea surface temperature range from the monthly climatology for northwestern Australia derived from OISST averaged during 1981-2014.

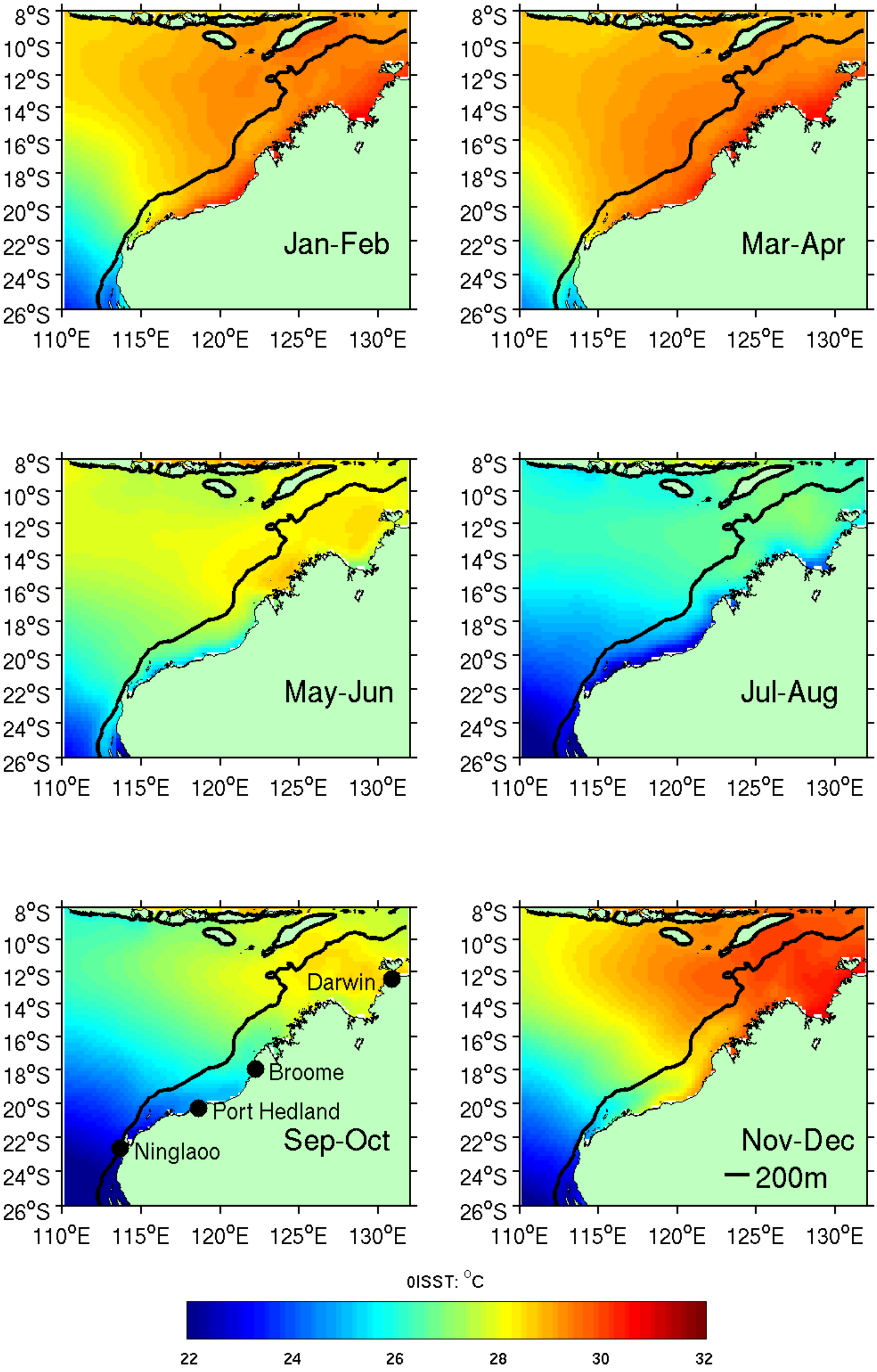

Figure 3.7. Bimonthly sea surface temperature for northwestern Australia derived from OISST averaged during 1981-2014.

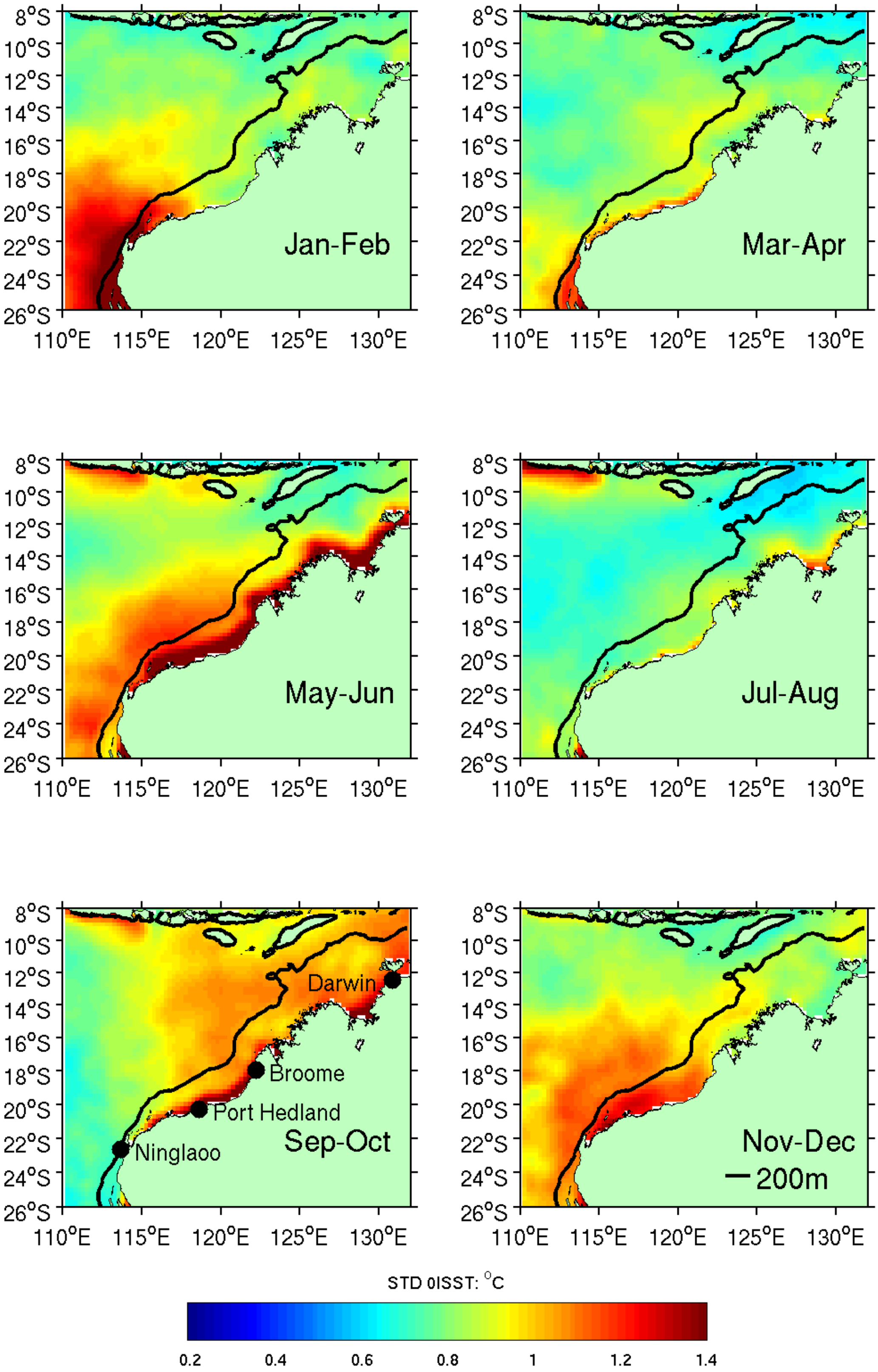

Figure 3.8. Bimonthly standard deviations of daily sea surface temperature off north-west Australia during 1981-2014, as derived from OISST.

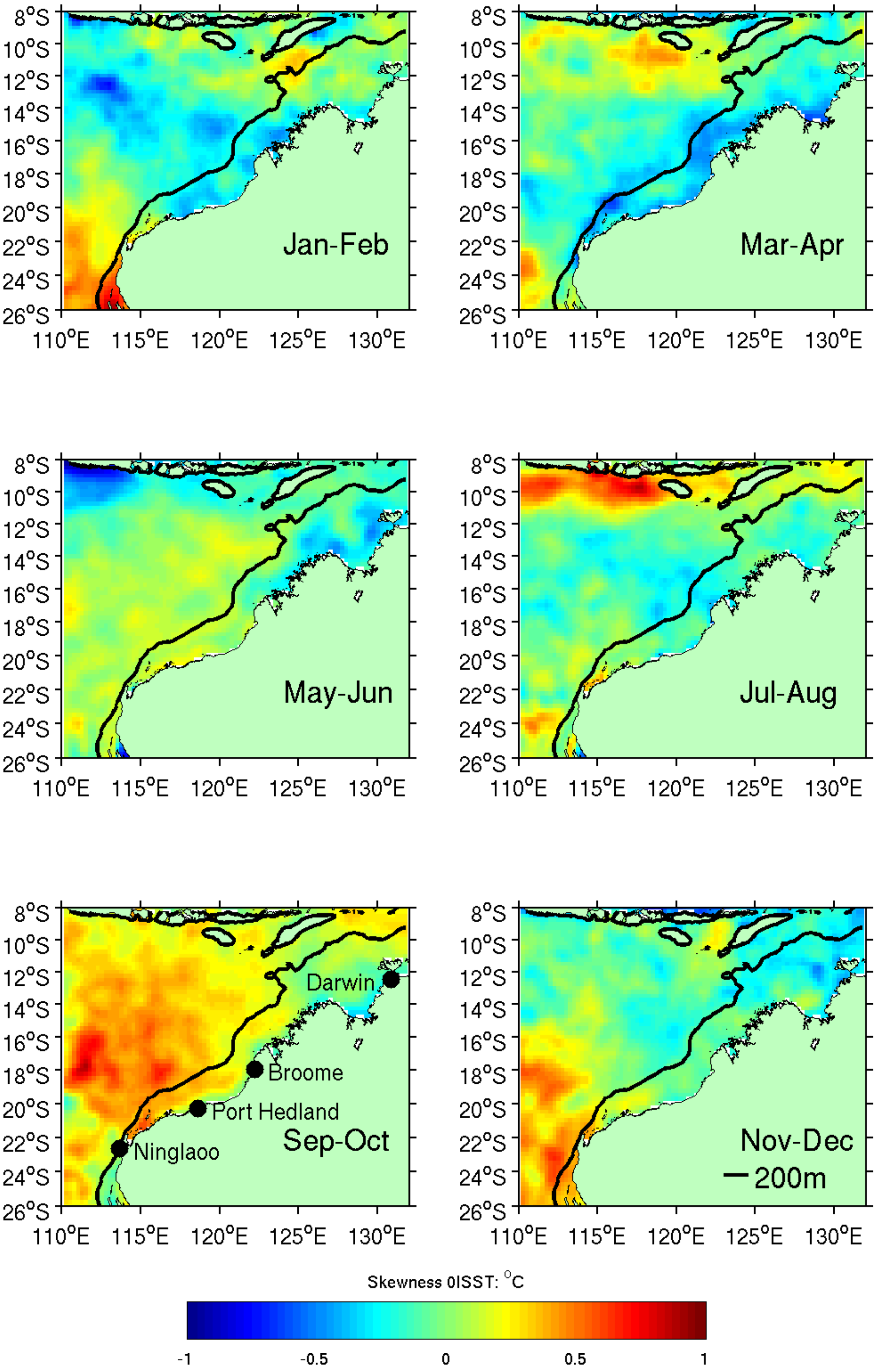

Figure 3.9. Bimonthly skewness of daily sea surface temperature off north-west Australia during 1981-2014, as derived from OISST.

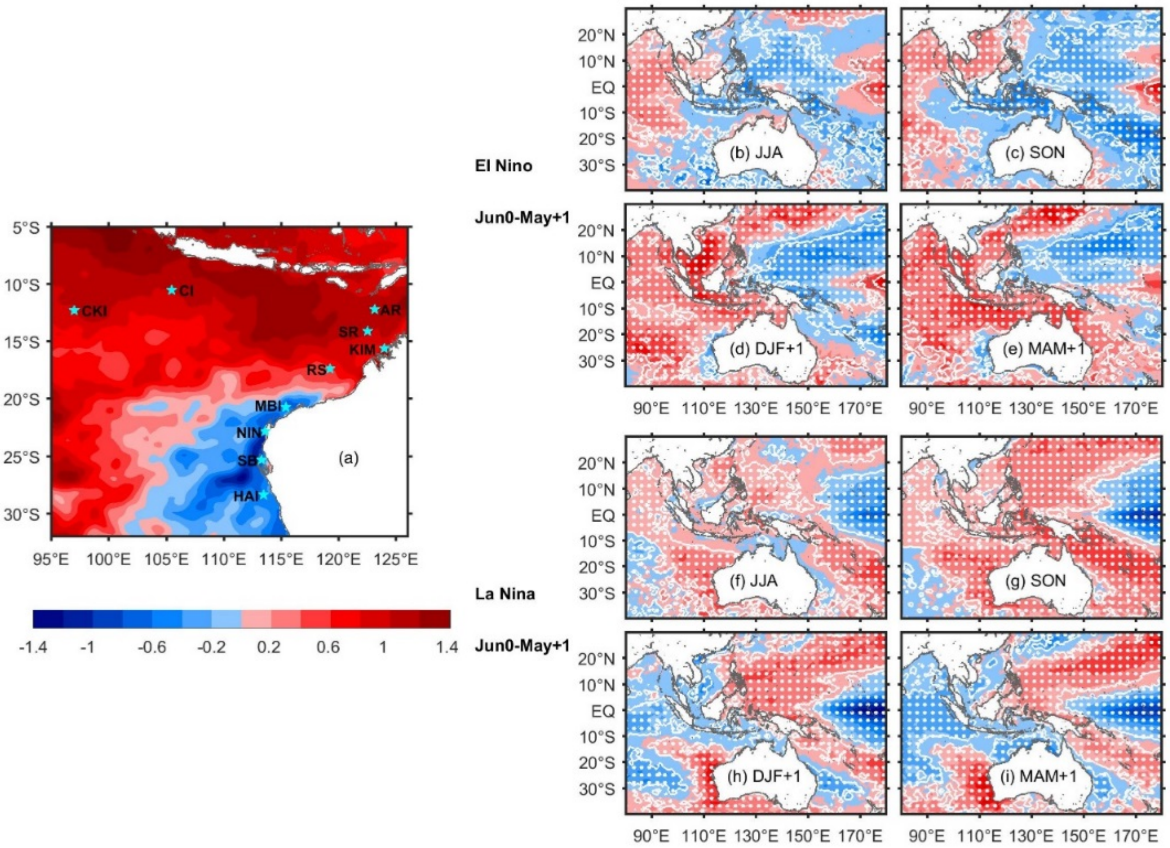

Figure 3.10. (a): averaged SST anomalies in the SEIO during December 2015 - April 2016. Stars denote locations of representative SEIO reefs. (b)-(e): composited SST anomalies for the El Niño events during January 1982- April 2015 and (f)-(i): for the La Niña events in the same time period. The white contours and dots indicate anomalies exceeding the 95% significance level based on a two-tailed Student's t test. JJA=June to August, SON=September to November, DJF=December to February of year 1, MAM=March to May of year 1. From Zhang et al. (2017).

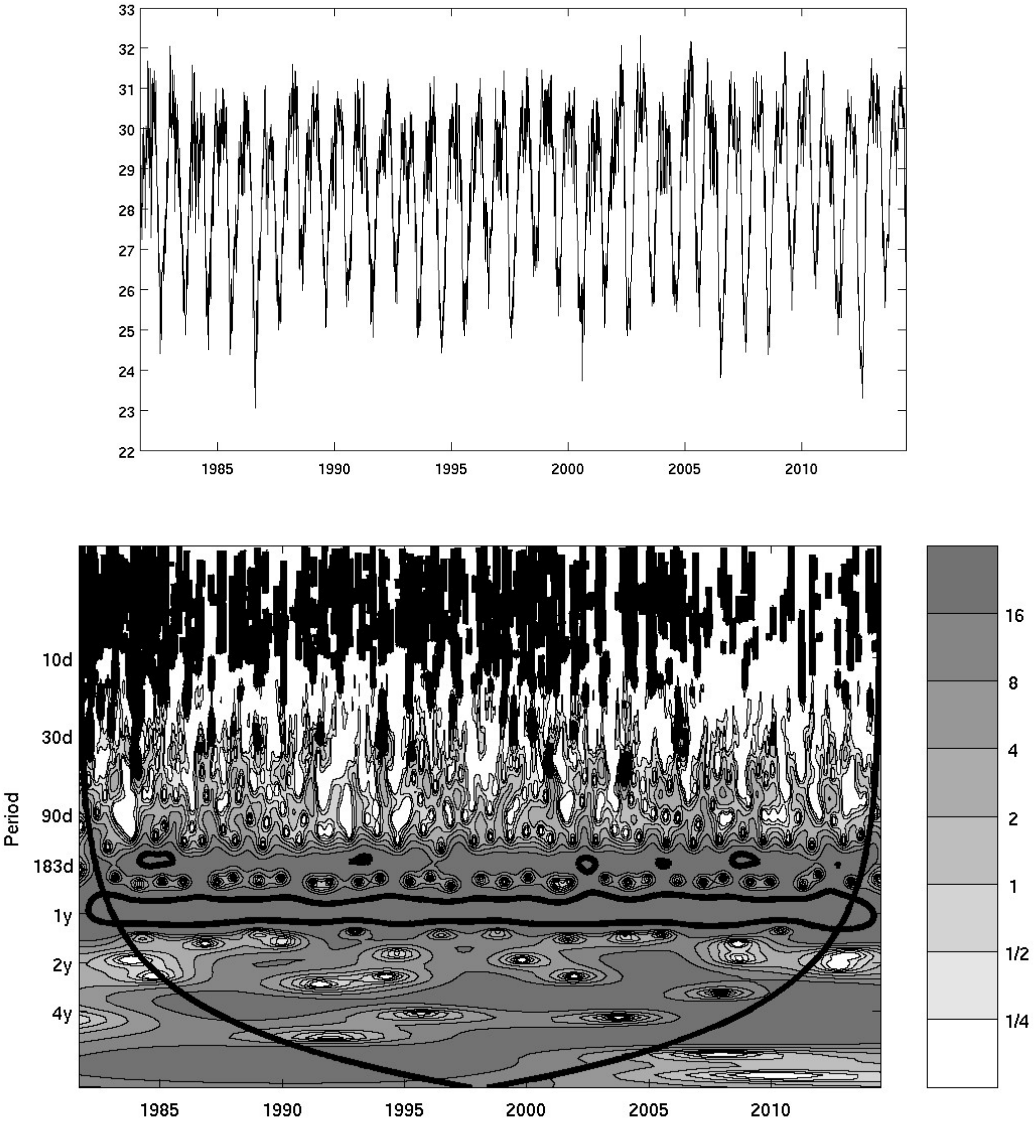

Figure 3.11. The Camden Sound Marine Park temperature index. Upper panel: daily sea surface temperature averaged within the marine park triangle; lower panel: A wavelet analysis of the temperature index, highlighting the dominant period of the temporal variability.

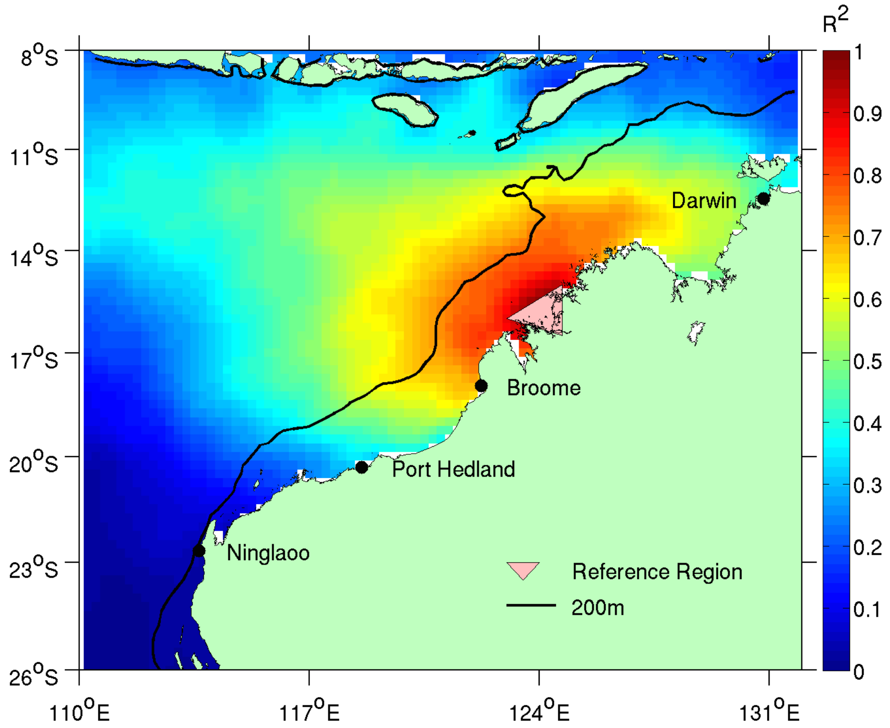

Figure 3.12. Linear correlations between the monthly sea surface temperature anomalies and the Lalang-garram/Camden Sound Marine Park temperature index, average within the pink triangle.

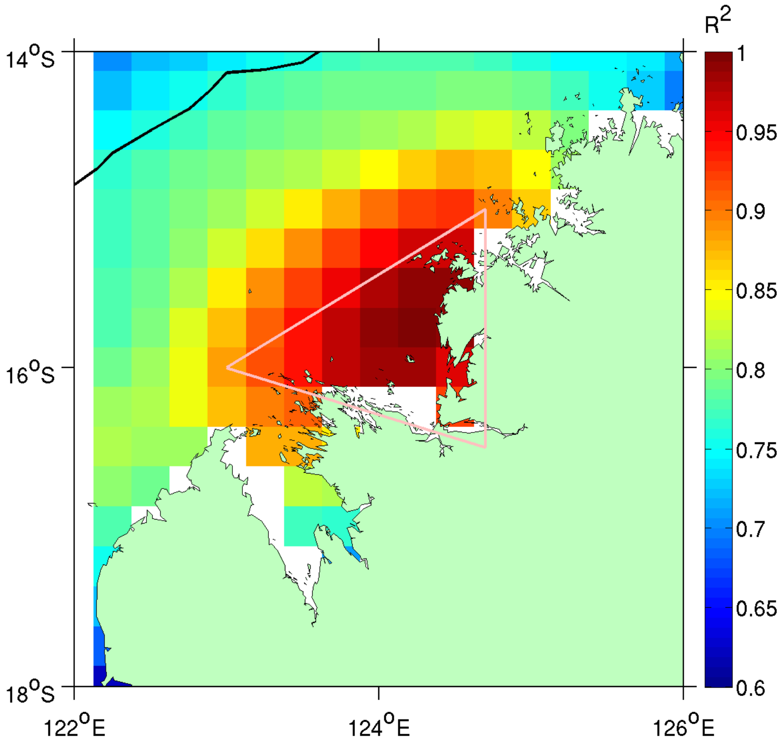

Figure 3.13. A zoomed-in view of the correlations in Figure 3. 12. Note that different colour scales are used. The area within the triangle is used to define the Lalang-garram/Camden Sound Marine Park sea surface temperature index.

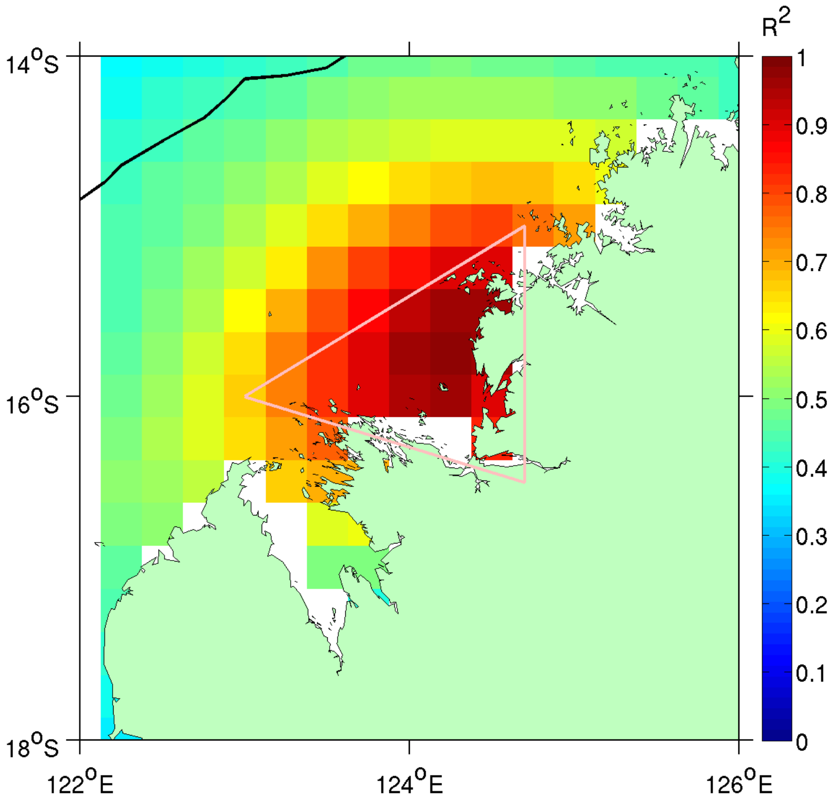

Figure 3.14. Correlations between high-frequency sea surface temperature variations (60-day high-pass filtered) and the Lalang-garram/Camden Sound Marine Park temperature index.

3.1.4 Precipitation

Monthly precipitation records in the Kimberley region from 1979-2014 show a distinct annual cycle, with most of the rainfall occurring from December to March (Figure 3.15). On interannual time scale, heavy precipitations occurred during La Niña conditions. The record summer rainfall over the past 30 years occurred during the 2010-2011 La Niña/Ningaloo Niño event (Figure 3.15). There is a significant correlation between the summer rainfall in the Kimberley region and the Southern Oscillation Index, however, the relationship between the summer rainfall and the strength of the summer monsoon is not significant (Figure 3.16).

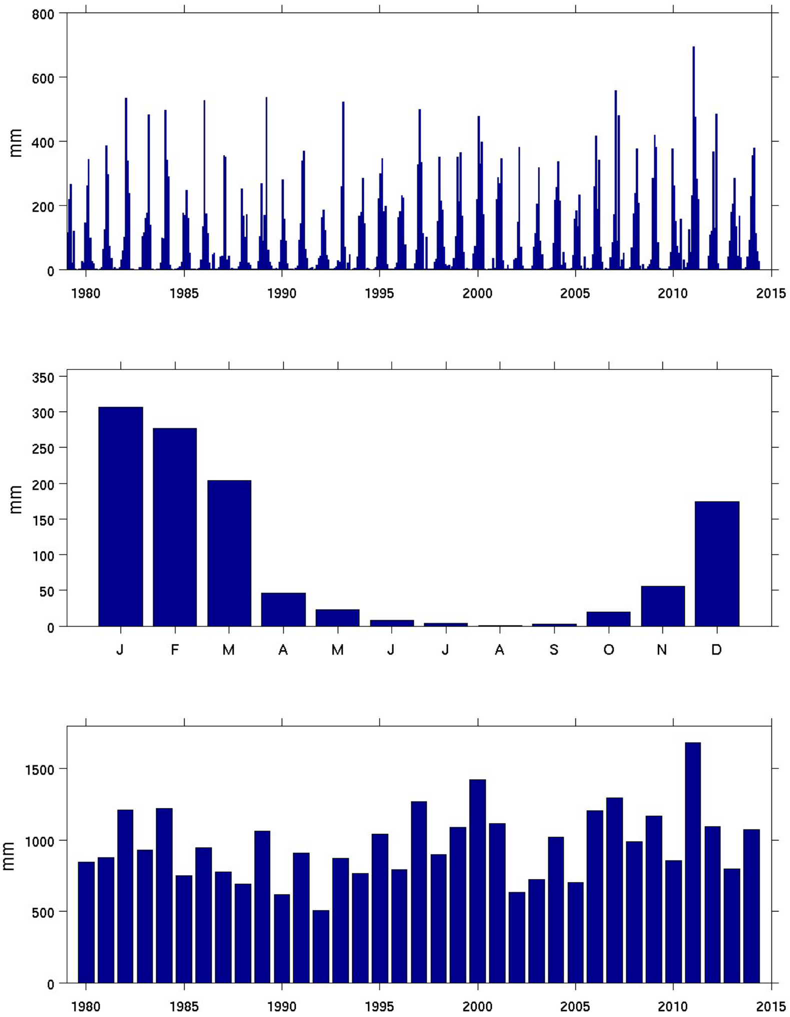

Figure 3.15. Monthly rainfall in the Kimberley region from AWAP product. Top panel: monthly rainfall averaged in the land region within 122-126°E, 18-14°S; middle panel: average monthly rainfall in the region; lower panel: December-March average rainfall in the region.

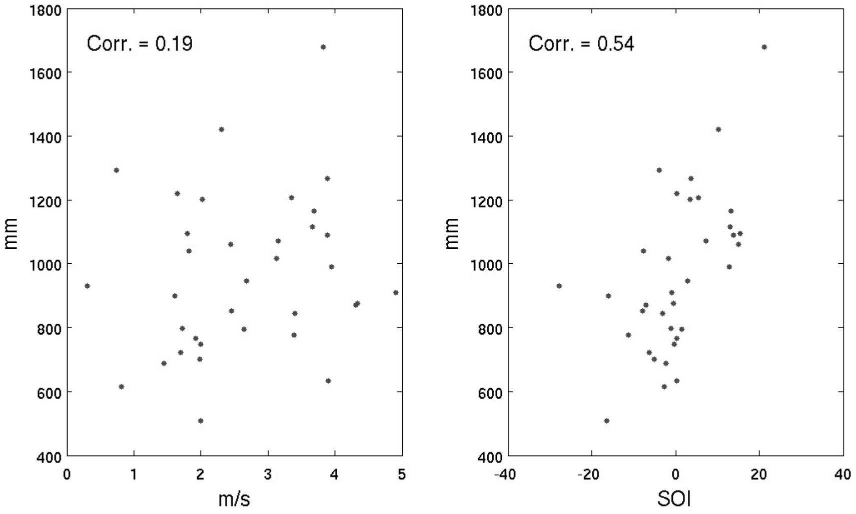

Figure 3.16. Relationship between summer rainfall (average over December-March) in the Kimberley region from AWAP product and the December-February average Australian monsoon index (left panel); and the November-January average Southern Oscillation Index (right panel).

3.1.5 Coastal salinity

Heavy precipitations in the Indonesian seas and off the north coast of Australia during the 2010-11 La Niña and Ningaloo Niño (Figure 3.17) caused significant freshening of the surface waters of the Maritime Continent and the coastal waters off the north coast of Australia, including the Kimberley coast (Figure 3.18). The freshening anomalies are carried southward by the Leeuwin Current. The freshening anomalies persisted long after the climate event and were part of the decadal climate trend. Interannual variability of ocean salinity has been found in the region, the region is fresher during La Niña, and saltier during El Niño. Composite and budget analyses reveal that interannual variations in precipitations drive the surface salinity anomalies off the Java-Lesser Sunda coast; between 12°S and the northwest Australian coast, the surface salinity variations are influenced by both advection anomalies and local precipitation anomalies (Zhang et al. 2016).

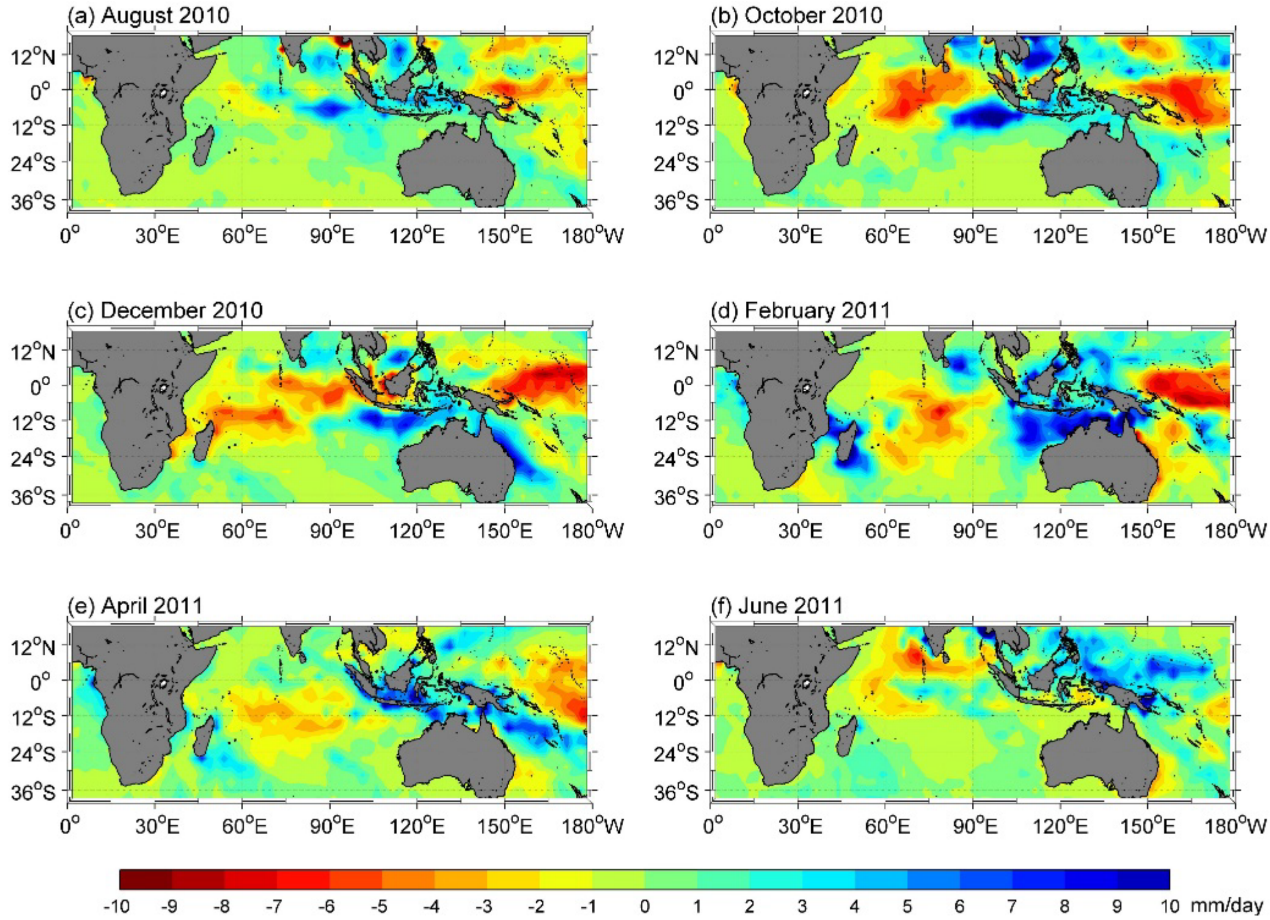

Figure 3.17. Monthly precipitation anomaly maps in the Indian Ocean-Western Pacific region from CMAP (relative to 2005-2012 monthly climatology) in (a) August 2010, (b) October 2010, (c) December 2010, (d) February 2011, (e) April 2011, and (f) June 2011 (from Feng et al., 2015).

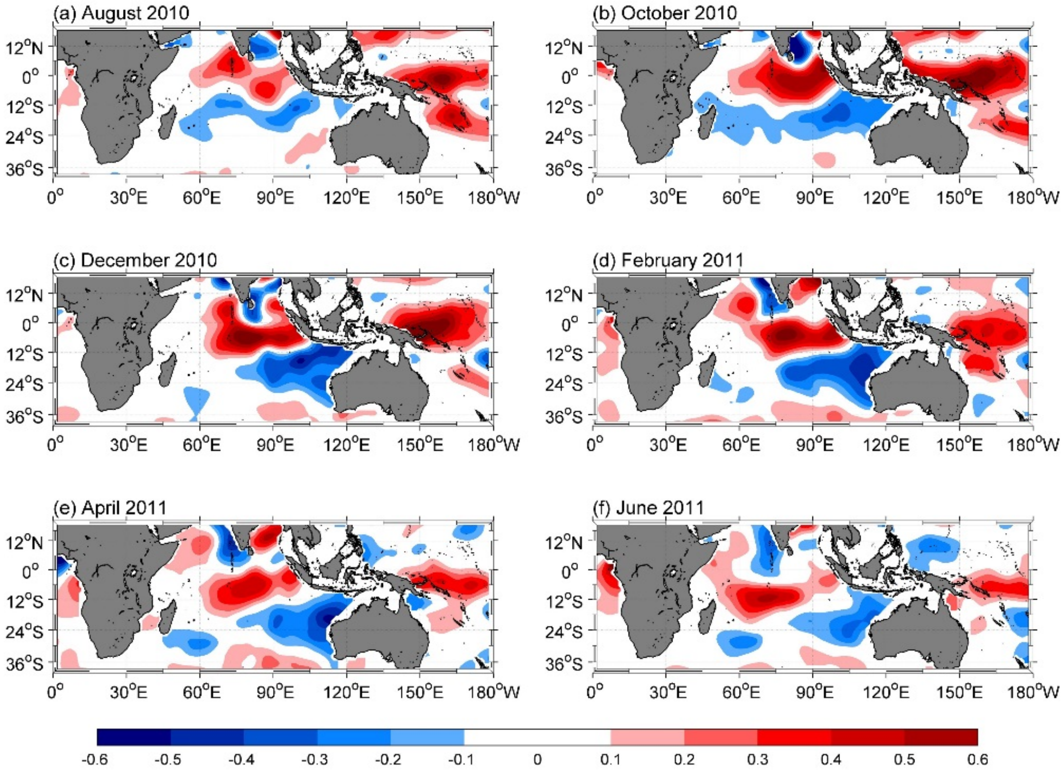

Figure 3.18. Sea surface salinity anomalies (psu) derived from BRAN 3p5 model output in the eastern Indian Ocean and western Pacific region (relative to 2005-2011 monthly climatology) in (a) August 2010, (b) October 2010, (c) December 2010, (d) February 2011, (e) April 2011, and (f) June 2011 (from Feng et al. 2015).

3.1.6 *Marine heatwaves*

Among 10 representative tropical/subtropical reef sites; Cocos Keeling Island (CKI); Christmas Island (CI); Ashmore Reef (AR); Scott Reef and Browse Island (SR); Kimberley (KIM); Rowley Shoals (RS); Montebello and Barrow Island (MBI); Ningaloo Reef (NIN); Shark Bay (SB); and Houtman Abrolhos Island (HAI) (Fig. 3.19), the northern sites (CKI, CI, AR, SR, KIM, and RS) tended to have positive SST anomalies in the summer months during El Niño; whereas at the southern sites (MBI, NIN, SB and HAI) tended to have positive SST anomalies in the summer months during La Niña . There were significant warm SST anomalies at CKI and RS prior to summer during La Niña. The positive SST anomalies caused by El Niño events are usually less than 0.5°C; while La Niña causes stronger warming of near or more than 1°C at the southern sites. Seasonal warming is often associated with marine heatwave events.

For example, SST anomaly averaged in austral summer months (December to April) at Scott Reef were positively correlated with the November to January average Niño4 index, with positive anomalies corresponding to El Niño events and negative anomalies corresponding with La Niña events. There were exceptions, such as 1994 and 2006, when strong positive IOD occurred, which were associated with negative SST anomalies in the tropical eastern Indian Ocean. The SST anomaly series at Scott Reef shows a positive linear tendency, with a maximum reaching more than 1°C in the summer of 2015/2016, when large amounts of coral bleaching are reported here. On the other hand, the summer SST anomalies at Ningaloo Reef are negatively correlated with the Niño4 index, and all the La Niña years are followed by positive SST anomalies with a maximum reaching 2°C in 2010. The 2010-11 Ningaloo Niño warming event was followed by another two warmer than normal summers (Caputi et al. 2014; Feng et al. 2015), and caused severe damage to the marine species and severe coral bleaching events on the Northwest Shelf of Australia in 2013 (Depczynski et al. 2013; Caputi et al. 2014). Besides, the SST anomaly series at the Ningaloo Reef has significant decadal variabilities and more warming events after the 1997/1998 El Niño, in conjunction with a phase shift of the Interdecadal Pacific Oscillation (IPO) towards a cold phase (Feng et al. 2010; Merrifield 2011; Han et al. 2013; Feng et al. 2015).

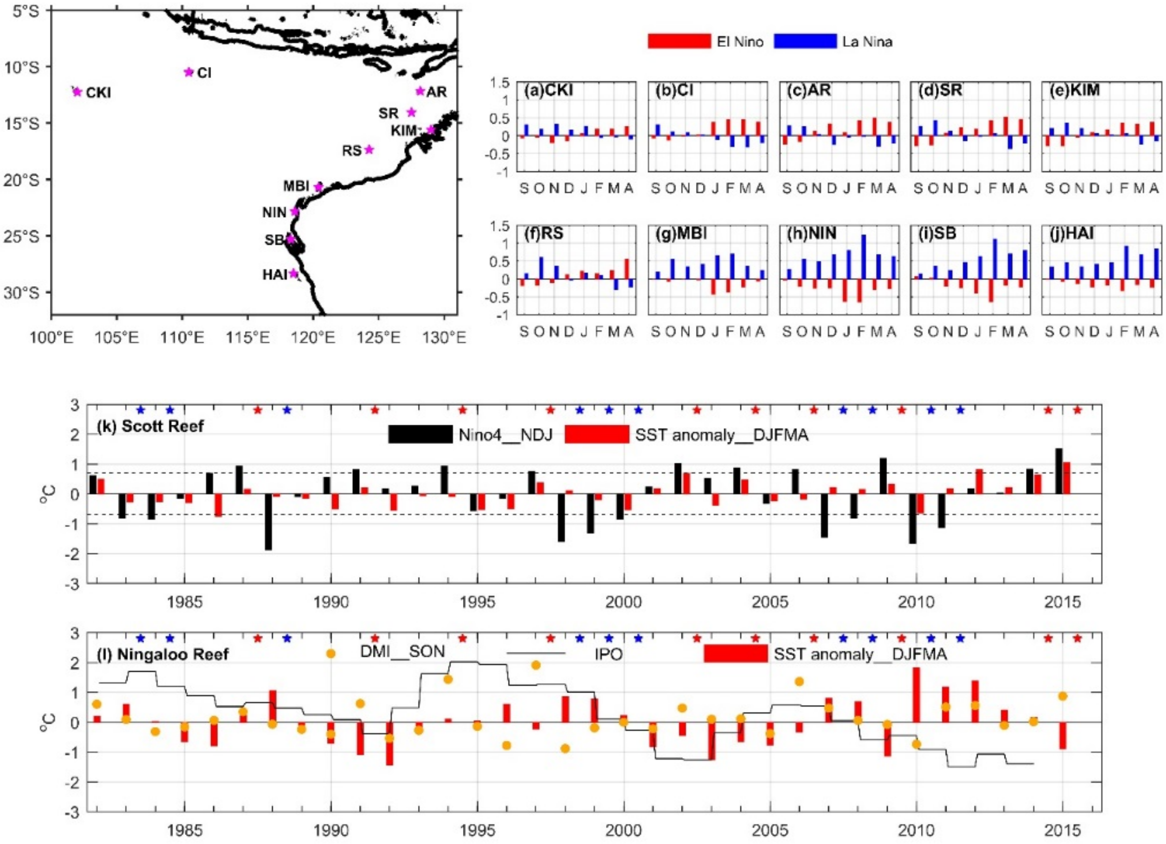

Fig. 3.19. The stars in the upper-left map stand for the locations studied. (a)- (j) are SST anomaly series composited during El Niño and La Niña events at the ten reef sites. (k) Time series of Niño 4 NDJ index and SST anomaly averaged during December to April at Scott reef; (l) Time series of DMI NDJ index, IPO index, SST anomaly averaged during December to April at Ningaloo reef. The dashed lines in (k) are one standard deviation of Niño4 index during 1982-2005. The red (blue) stars correspond to the developing years of El Niño (La Niña). (Abbreviations: CKI- Cocos Keeling Island; CI- Christmas Island; AR- Ashmore Reef; SR- Scott Reef and Browse Island; KIM- Kimberley; RS- Rowley Shoals; MBI- Montebello and Barrow Island; NIN- Ningaloo Reef; SB- Shark Bay; HAI- Houtman Abrolhos Island.)

3.2 Climate change detections

In this section, we briefly review the detected long term changes of coastal sea levels, temperature, and precipitation off the Kimberley coast, as well as the climate drivers, to set the scene for the future climate downscale modelling.

3.2.1 Climate drivers

From the 1960s to 1990s, there was a climate trend toward more frequent El Niño events in the Pacific, however, this trend has reversed over the past two decades and there have been more frequent La Niña events in recent years. Some of the la Niña events have caused very strong Leeuwin Current and extreme ocean temperature anomalies of the west and the north-west coast of Australia.

3.2.2 Coastal sea levels

There is a sea level rising trend of 3.5 mm per year at Broome during 1966 to 2013 (Figure 3.4). During the more recent period, 1993-2013, the satellite altimeter era, the linear sea level rising trends are 9.0, 8.8, and 8.6 mm per year at Broome, Wyndham and Darwin respectively, as compared with the sea level trend at Fremantle of 8.0 mm per year during the same period (Figure 3.4). These trends to a large extent reflect a recent rebound of the trade winds in the Pacific and the Indonesian Throughflow (Feng et al., 2011).

3.2.3 Precipitation

Summer rainfall at Kimberley region has increased over the past 2 decades, mostly due to the increase of La Niña events in the Pacific, which has caused an overall increase of rainfall in the maritime continent.

3.2.4 Ocean temperatures

There are generally rising trends of sea surface temperature on the continental shelves around Australia, but the temperature rising trends are not uniform. Off Western Australia, temperature rising trends are relatively high off the mid-west and the southwest coast. Off the Kimberley coast, there is only weak rising trends of temperature in the southern half of the cost.

The temperature trends of the Kimberley coast have a strong seasonal variation, with slight cooling trends from January to early winter, and strong warming trends in late spring to early summer, during the period between 1981 to 2013 (Figure 3.20).

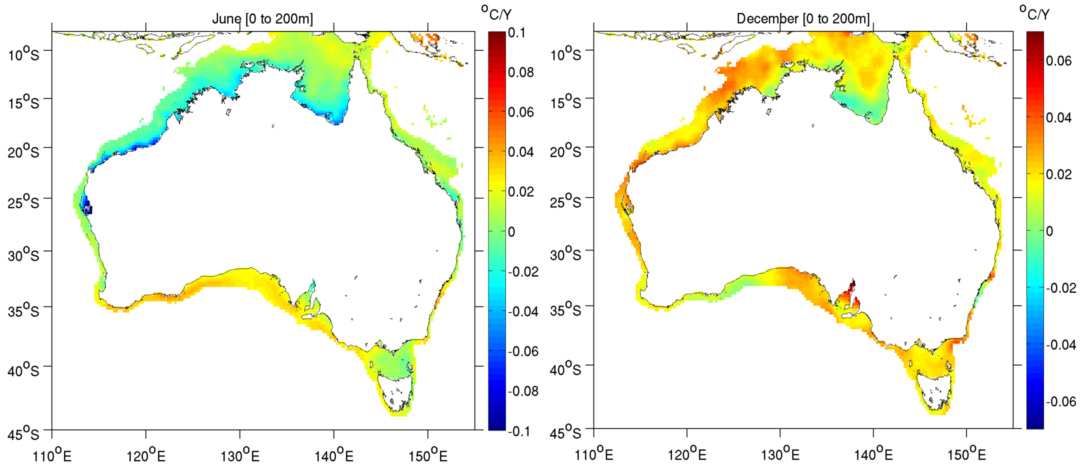

Figure 3.20. Linear trends of sea surface temperature on the continental shelves around Australia in June and December.

3.3 Coastal modelling and future projections

3.3.1 OFAM model projections

As the ROMS model is nested within the OFAM model output, the OFAM model simulation is briefly introduced in this section. Seasonal variations of ocean surface current show that the Indonesian throughflow South of Timor is weaker during austral summer, and stronger in austral winter (Figure 3.21). The model captures the strong south-westward flow of the Holloway Current during the autumn period. The Holloway Current tends to become weaker from spring, and the coastal currents switch to north-eastward direction in summer.

In the future projection downscaling model under RCP8.5, sea surface temperatures in the area tend to increase by 1-3 °C, with the highest temperature rise in the northern Kimberley region (Figure 3.22). The sea surface temperature rising trends of 0.035-0.04 °C per year are much higher than the historical trends in observations (Figure 3.23), with slightly higher rising trend in the northern Kimberley coast. Similarly, the sea level rising trends are also higher than the historical trends in observations over the past 50 years, at about 5-10 mm per year.

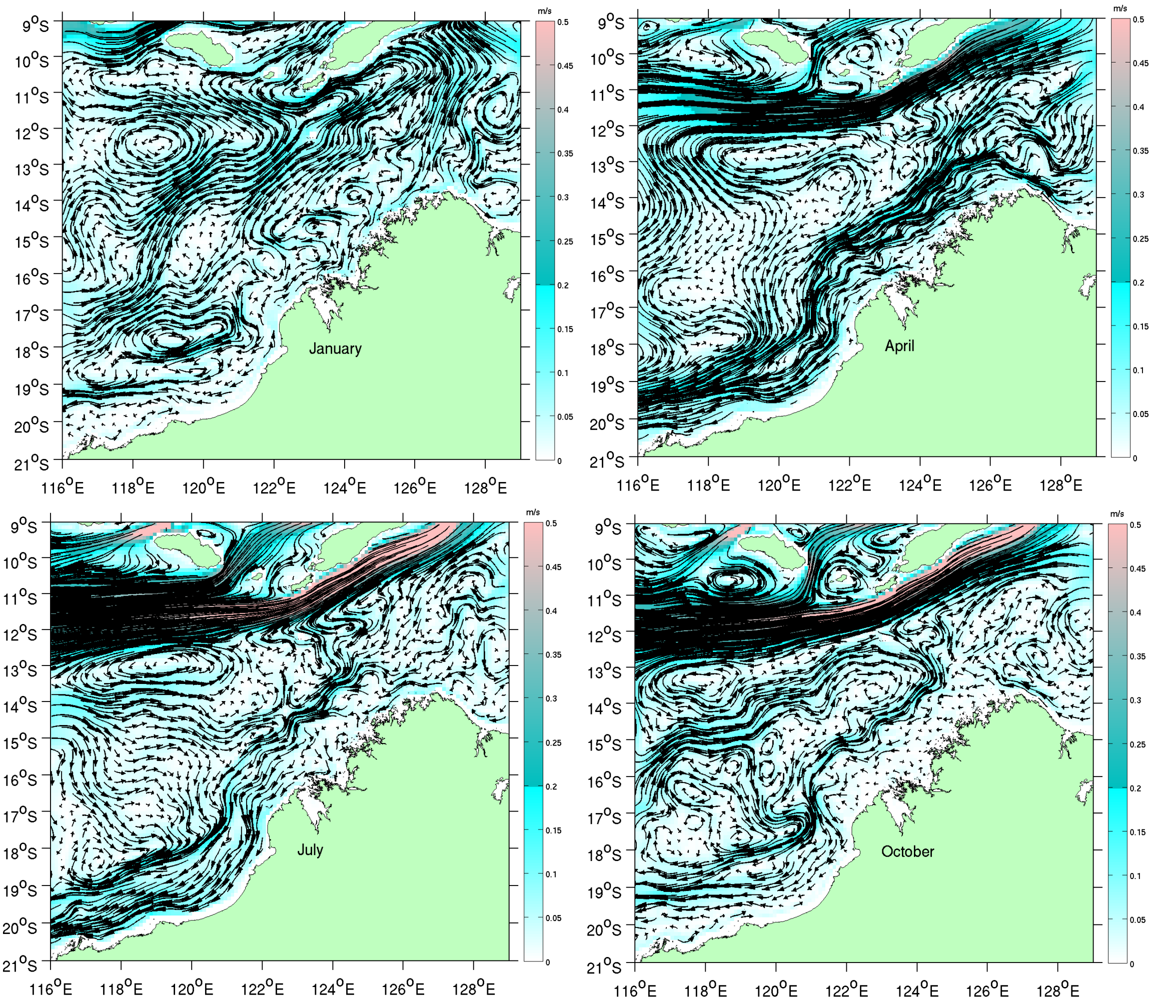

Figure 3.21. Seasonal variations of ocean surface current off northwest Australia, simulated by the OFAM model during 2009-2012.

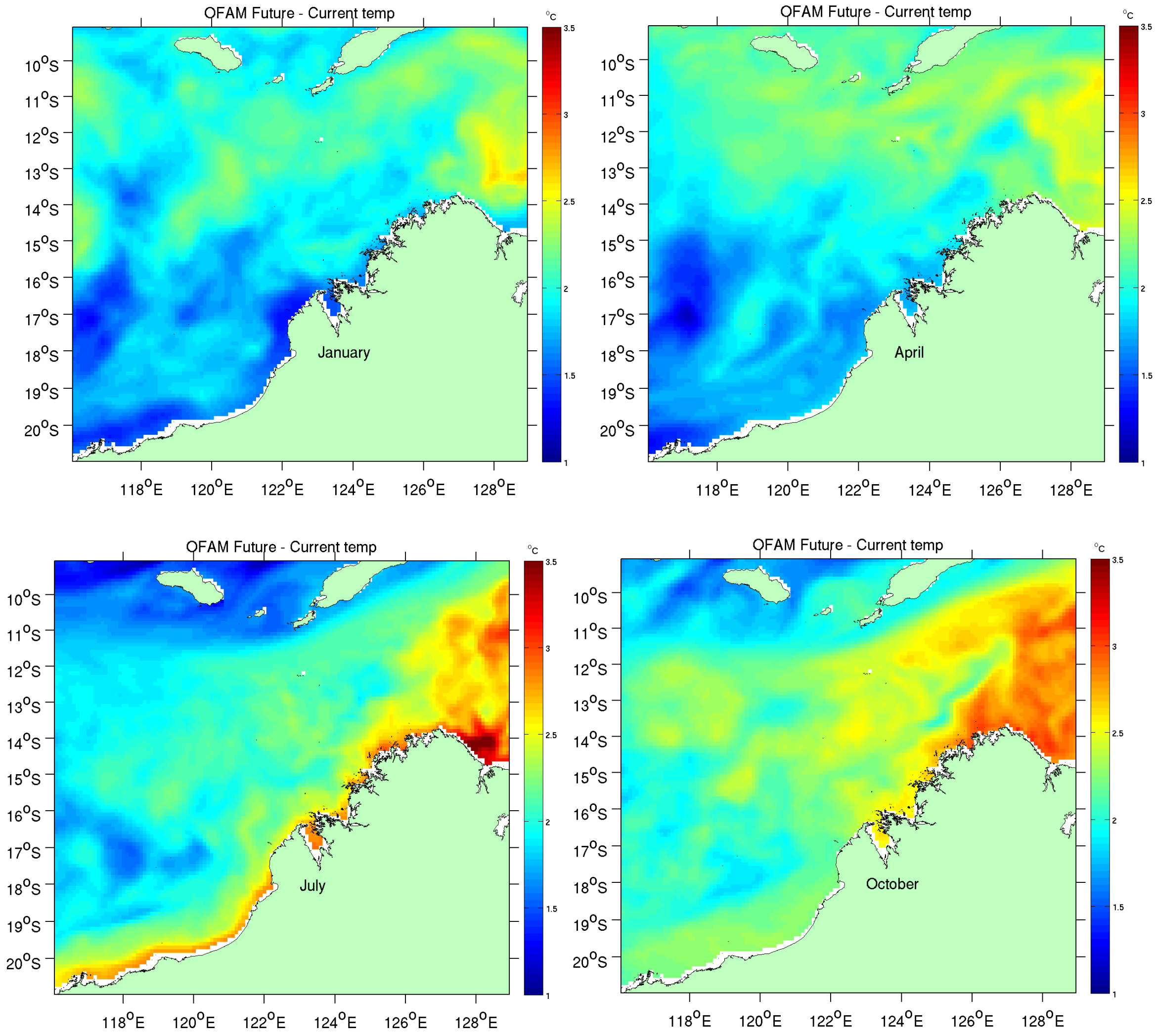

Figure 3.22. Seasonal variations of ocean surface temperature increases off northwest Australia in the future climate under Representative Concentration Pathway – RCP8.5, simulated by the OFAM model. The differences calculated between 2060's in the future climate and during 2009-2012.

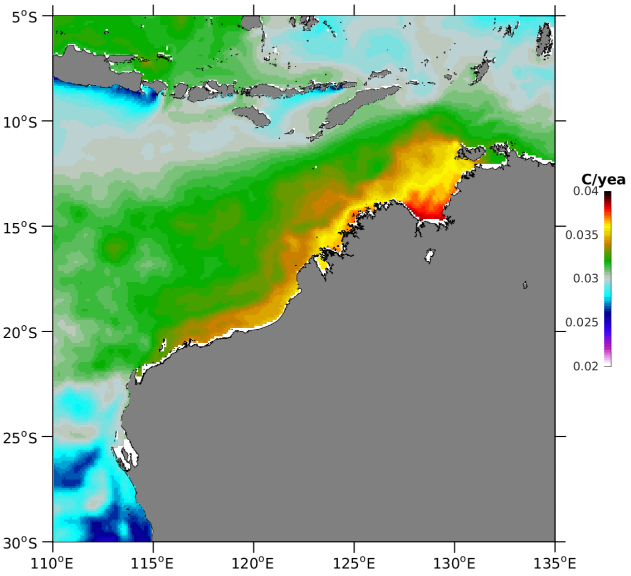

Figure 3.23. Linear trend of sea surface temperature during 2006-2101 in the OFAM model simulation.

3.3.2 Coastal modelling

Seasonal variations of the coastal circulation off the Kimberley coast simulated by the ROMS model agree with the OFAM simulation (Figure 3.24). The model also well captures the seasonal variation of the sea surface temperature off the coast (Figure 3.25), and simulates some fine details of the salinity variability not captured by the satellite observations, such as the low salinity signatures in King Sound (Figure 3.26).

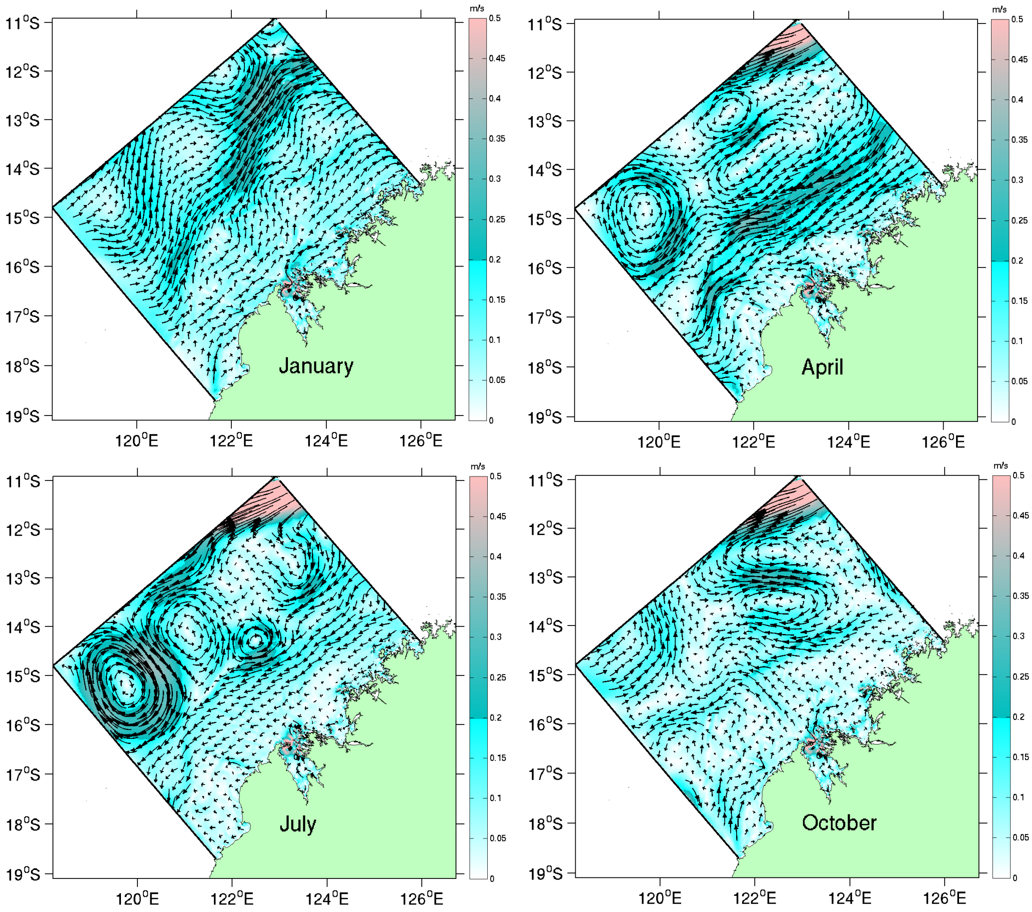

Figure 3.24. Seasonal variations of surface current off the Kimberley coast simulated with the ROMS model.

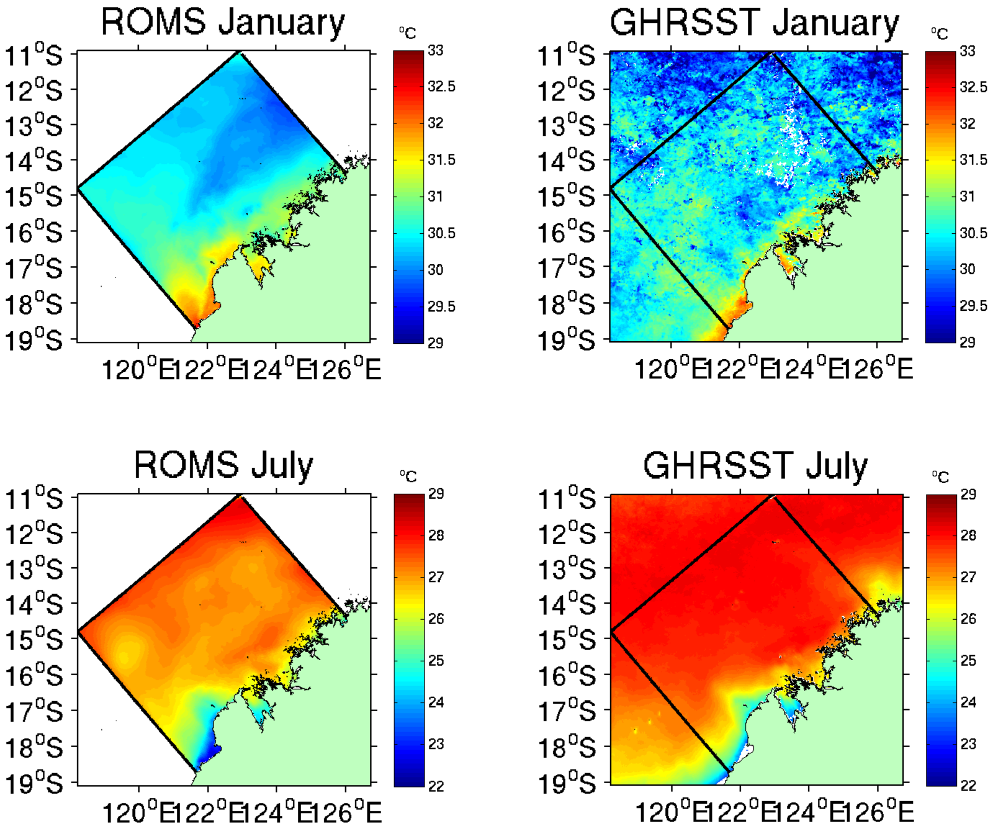

Figure 3.25. Sea surface temperature simulated in ROMS and comparison with satellite observations.

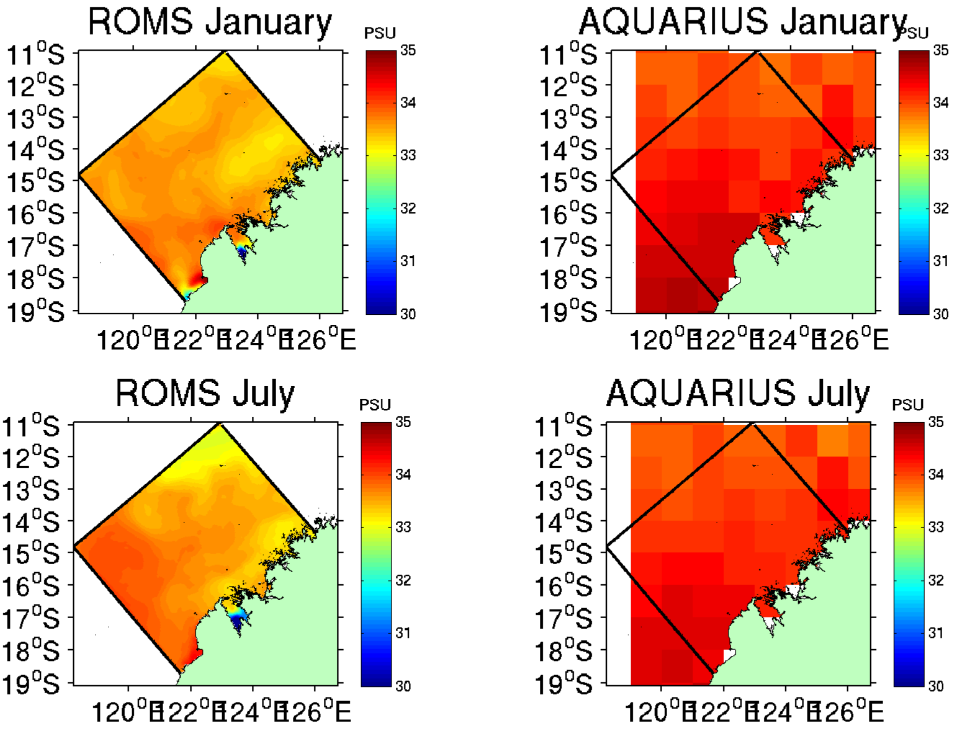

Figure 3.26. Sea surface salinity simulated in ROMS and comparison with satellite observations.

3.3.3 Future climate downscaling

An assessment shows that there are consistencies between the projected sea surface temperature changes between 2060s and the present from the OFAM model and those derived from the ROMS downscaling model (Figure 3.27). Generally, the sea surface temperature warming along the coast in the next 50 years is about 1-3°C, with fast warming trend during austral winter season. Warm sea surface temperatures induce stronger water column stratification on and off the continental shelf.

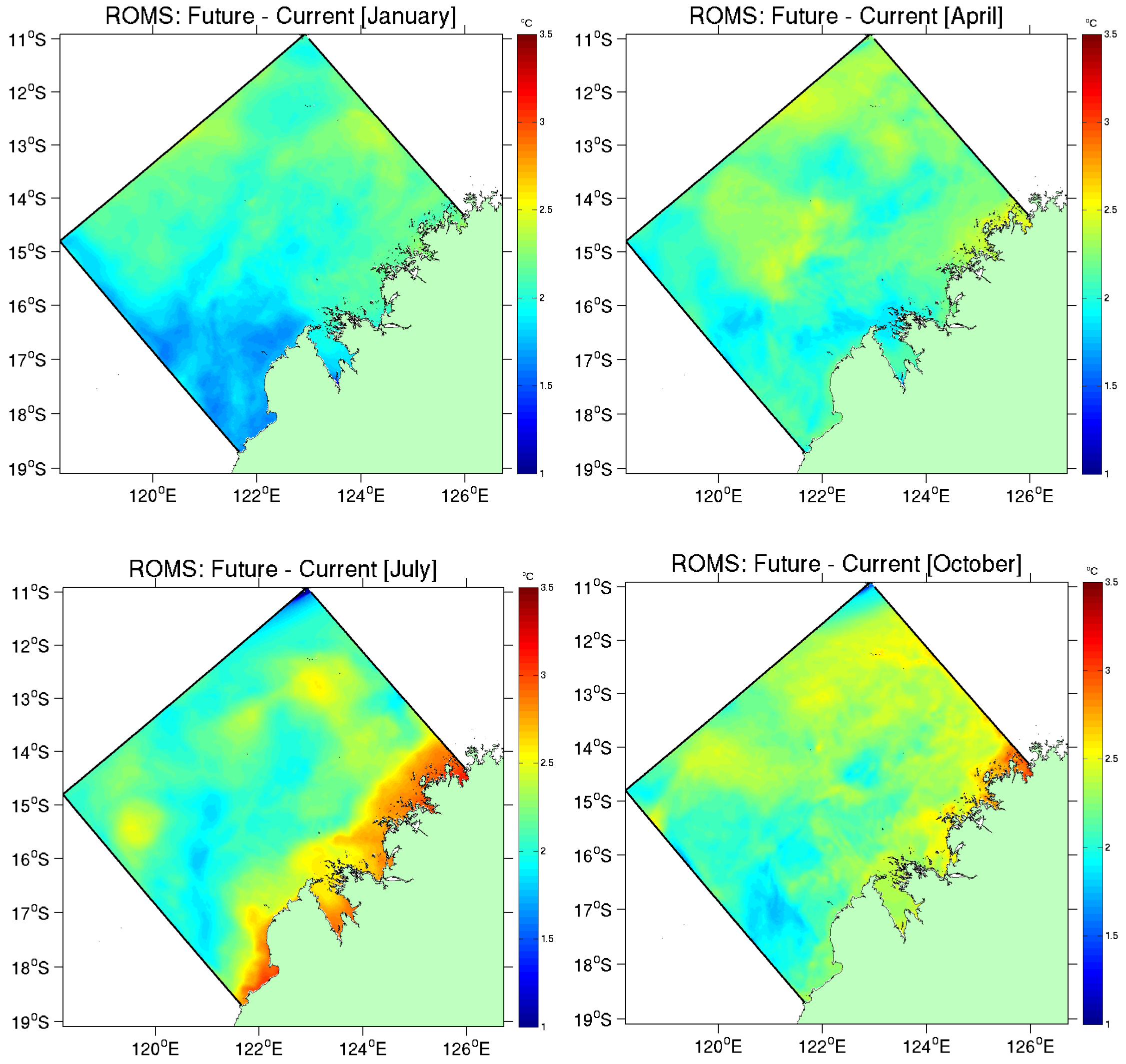

Figure 3.27. Sea surface temperature differences between 2066-2069 average and 2009-2012 average using ROMS downscale model.

3.3.4 Precipitation

While the precipitation is not part of the downscaling project, we briefly reviewed some relevant studies. Increasing summer rainfall and decreasing temperature trends over northwest Australia in the last few decades suggest that the aerosols originated from the northern hemisphere may act as a driver (Rotstayn et al. 2007; Shi et al. 2008b; Smith et al. 2008; Rotstayn et al. 2009; Cai et al. 2011), though there is still debate. In the future climate change, these trends may not continue, as the aerosol effects may be alleviated. There is no consensus in the climate model projections on the future precipitation trends in the region.

3.3.5 Biological implications - Coastal connectivity

We used biophysical dispersal modelling based on Regional Ocean Modelling System (ROMS) with 2 km resolution to construct a site-pairwise matrix of oceanographic connectivity. The model was nested within the Ocean Forecasting for Australia Model 3 (OFAM3) simulation (Zhang et al. 2015) and forced by 3-hourly meteorological measures derived from Kobayashi et al (2015). The model simulation occurred over the 2009 to 2012 time period. Hourly sea surface current velocities (0-5 m) were extracted from the model output and used for particle tracking modelling. The particle tracking model results have been used to understand the connectivity among seagrass populations off Kimberley, as part of WAMSI KMRP 1.1.3 project (Hernawan et al, 2017), A total of 100 particles were seeded in seagrass sampling sites during austral spring-summer (September-January), at 3-day intervals. This particle release period was chosen to represent the fruiting season of the seagrass based on field observations. A 4th-order Runga-Kutta sub-time-stepping scheme was used to update the particle locations every hour (Feng *et al.* 2010). Using the random walk effect of 1 m^2s^{-1}, particles were tracked for 7 days based on the potential dispersal duration of the seagrass fruits (Lacap et al. 2002). The grid size for tracking the particles from each sampling site was set to 500m x 500m. Connectivity among sampling sites was estimated as the average number of particles released from one site to another site, this ranged from 0 to 7.49 per release period, based on 48 simulation replicates in each year of the 4-year time period. The oceanographic connectivity matrix was visualized using the package qraph (Epskamp et al. 2012) (Figure 3.28). The oceanographic connectivity based on the regional model has also supported genetic observations in WAMSI KMRP Project 1.1.3 and the particle tracking model has also been applied to other marine species (DiBattista et al. in press).

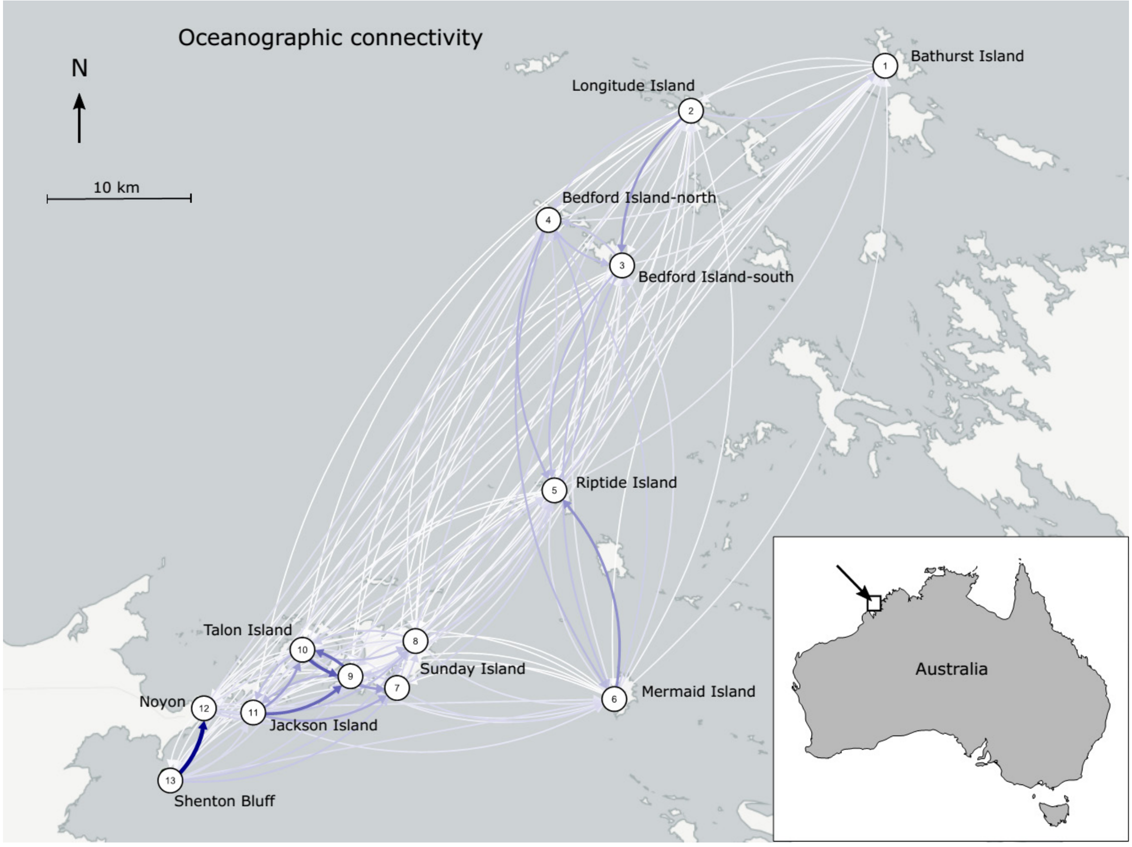

Figure 3.28. Oceanographic connectivity as the average number of particles released from one site to another site, ranged from 0 to 7.49 particles/release period. Sampling sites (populations) were represented by numbers within circles. Number of particles were represented by curved lines. The thicker the lines, the higher level of connectivity between populations. The base map was obtained from OpenStreetMap contributors (https://www.openstreetmap.org/copyright). From Hernawan et al. (2017).

3.3.6 Biological implications - Internal wave energetics

Internal tide energetics have been analysed from the ROMS model outputs. The model produces strong internal tidal energy near the shelf break (Figure 3.29), similar to previous studies (Rayson et al. 2011). In the future climate, the internal tidal energy on the shelf would increase by more than 50% in various locations, which would have drastic effects on the onshore fluxes of deep ocean nutrients and instigate primary production in the water column.

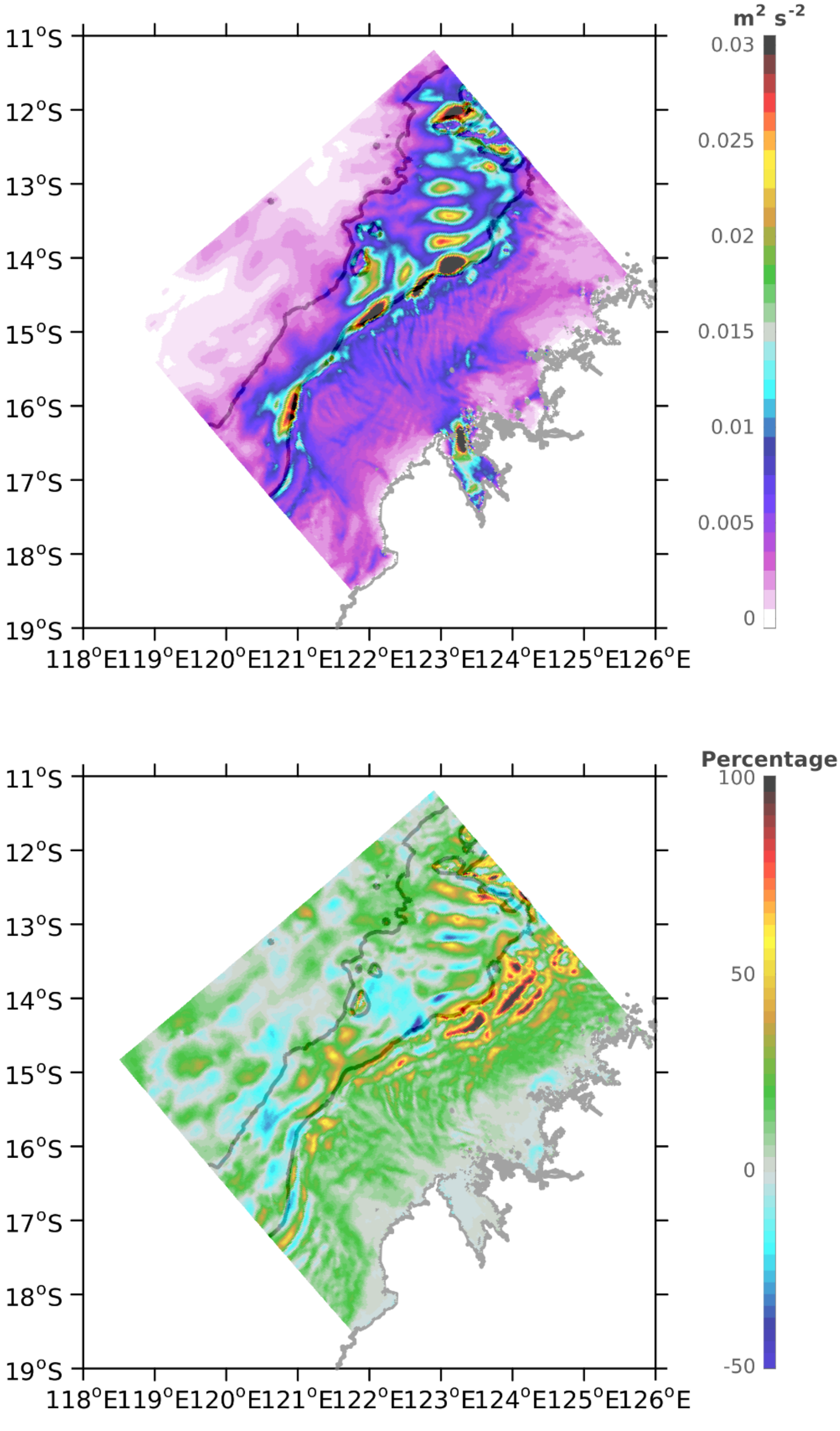

Figure 3.29. Internal tide energy during January-March season averaged over the 4 year ROMS model simulations during 2009-2012 (top panel), and the percentage increase in internal tide energy in the future climate projection compared with 2009-2012 average (lower panel).

4 Summary

In the KMRP Project 2.2.7, we have used historical observations and numerical model simulations to understand the variability of ocean temperature, salinity, sea level, and shelf current off the Kimberley coast in response to climate variability in the Indo-Pacific. One key finding is that summer ocean temperatures off the coast tend to be warmer during El Niño event and strong El Niño events are often associated with extreme marine heatwave events off the coast, causing coral bleaching in the offshore atolls such as Scott Reef. Given that the extreme El Niño events will become more extreme in a warming climate, the region may become more and more susceptible to bleaching events in the future.

Ocean temperatures off the Kimberley coast have been observed to rise steadily in the past few decades, and coastal sea levels also show rising trend. Model projections show that sea surface temperature in the region will rise by more than one degree over the next 50 years, and coastal sea levels will rise at the average rate of global projections, that is, by half a metre to one metre at the end of the century based on the high emission scenario. Warming temperature and rising sea level are the two most important physical environment changes that need to take into account for future marine ecosystem management.

Rising ocean temperature is also associated with an increase in water column stratification. Model simulations show that the onshore propagation of internal tidal energy would increase in a warming ocean, especially when coastal waters become more stratified. Strategy needs to be developed on how to monitor the variation and long term changes of ocean temperature on the shelf. It is also crucial to set up process research as well as modelling studies on how the increase in stratification and internal tide energy would have an impact on the vertical mixing and onshore fluxes of nutrient that support the health of the shelf ecosystem.

Objective 1: A detailed analysis and review of influences of the past climate variability and change on ocean temperature, salinity, sea levels, and shelf current off the Kimberley coast

The KMRP Project 2.2.7 has made substantial progress in understanding the influences of past climate variability and changes on the Kimberley coast, in terms of variability and changes in ocean temperature, salinity, sea levels, and shelf currents. The project has greatly improved our understanding of the sensitivity of ocean temperatures off the Kimberley coast to the dominant modes of climate variability in the Indo-Pacific, ENSO, Indian Ocean Dipole, and the Madden-Julian Oscillation. Marine heatwaves and associated coral bleaching potentials are more likely to occur during the El Niño period, and positive Indian Ocean Dipole may compensate the El Niño influence on sea surface temperatures in the region. There have been observed decadal modulations of the occurrences of marine heatwaves off the Western Australian coast (Feng et al. 2015; Zinke et al. 2015), which are also in response to decadal climate variations in the Pacific Ocean.

There has been clear observational evidence from tide gauges around the Kimberly region that the coastal sea levels have been rising. These trends are consistent with global trends attributed to factors like anthropogenic induced melting of the Greenland ice sheet (Watson et al. 2015). The increased sea level has implications for coastal communities including mangroves (Lovelock et al. 2015) which are known nurseries for various commercially important fish species in the region: “Many coastal species that have commercial importance use mangal habitats as breeding and nursery areas,” (in chapter 5 of The Biogeography of the Australian North West Shelf [Wilson 2013]). Coastal infrastructure designed around assumptions of slower to no sea level rise may be in jeopardy of failure if these trends are not taken into account (Haigh et al. 2013).

Ocean temperatures have exhibited consistent rising trends over the past few decades in response to human-induced global warming. Ocean salinity also has a notable decadal trend (Du et al. 2015). It is recommended that coastal monitoring networks continue to operate in the region to not only observe the long-term changes of the physical environment, but also the biological responses to the regional warming and rising sea levels.

Objective 2: Projected future changes in the physical environment off the Kimberley coast using downscaled numerical model

WAMSI project scientists have been involved in a major climate downscaling project led by CSIRO, which uses an eddy-rich 10-km resolution near global model to downscale decadal climate variations and future climate change impacts on ocean circulation around Australia (Feng et al. 2016). The model has been used to understand the centennial changes of the Indonesian throughflow, driven by the slowdown of global overturning circulation (Feng et al. 2017), and the future changes of ocean temperature and shelf circulation off the Kimberley coast. The model suggests there will be more than 1 °C warming trend over the next 50 years off the Kimberley coast and the associated sea level rise in the region is comparable with the global sea level rising trend. The project has used a high-resolution shelf model to downscale the climate change impacts on the physical environment off the Kimberley coast. The model product is available for WAMSI scientists to further assess the regional impacts of climate change.

Objective 3: An improved understanding of climate change impacts on key biophysical indicators such as coastal water retentions and dispersals off the Kimberley coast

The downscaling model suggests that internal wave energy on the continental shelf will likely increase in the future climate, due to surface warming and increased stratification of the shelf. As stratification and internal waves are important processes for the deep nutrients to be brought and mixed onto the shelf, the implications for biogeochemical processes on the shelf in the future climate need to be further assessed.

The impacts of regional hydrodynamics on larval retention and dispersals have been assessed with the collaborations from other WAMSI projects. The impacts of climate change on these processed will continue to be assessed after the lifetime of the current WAMSI projects.

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6 Communication

6.1 Students supported

Ningning Zhang, Ocean University of China, PhD program.

Doctor Dissertation BS010413, Ocean University of China: “The effects of interannual signals from tropical Pacific on the upper layer temperature and salinity in the southeast Indian Ocean”, N. Zhang, 31 May 2017; Supervisors, Jian Lan and Ming Feng

6.2 Journal publications

Feng, M., H. H. Hendon, S.-P. Xie, A. G. Marshall, A. Schiller, Y. Kosaka, N. Caputi, and A. Pearce (2015) Decadal increase in Ningaloo Niño since the late 1990s, Geophys. Res. Lett., **42**, 104-112, doi:10.1002/2014GL062509.

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6.3 Proceedings/Technical Reports

None noted.

6.4 Submitted manuscripts

As Above.

6.5 Presentations

Feng M, Benthuysen, J, Zhang N, **Slawinski D**, Freshening of the Indonesian Throughflow and the Leeuwin Current during the 2010-11 La Niña/Ningaloo Niño, Australian Marine Sciences Association Conference, Geelong, Australia, 5-9 July 2015.

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Feng M (2017) Climate drivers of marine heatwaves off the Kimberley coast, AMSA Annual Conference, Darwin, 2-6 July 2017.

6.6 Other communications achievements

Giant corals reveal WA's heatwave history, WAMSI bulletin, October 2015.

Indian Ocean creates its own flow-on effect, WAMSI bulletin, November 2015.

Brown J, Cahill M, **Feng M**, Zhang X, The good news El Niño story for Western Australia's oceans. The Conversation (https://theconversation.com/the-good-news-el-Niño-story-for-western-australias-oceans-41744), 15 May 2015.

Madeleine Cahill, Is La Niña coming? OceanCurrent News, oceancurrent.imos.org.au, 4 July 2016.

Climate swings enhance marine heatwave risk off the Kimberley coast, WAMSI bulletin, May 2017

6.7 Knock on opportunities created as a result of this project

Ming Feng, now leads a new $2M 5-year project from the Centre of Southern Hemisphere Oceanography and Climate (CSHOR), to better understand the interaction between the ocean temperature and air-sea coupling off northwest Australia on intra-seasonal timescale.

6.8 Key methods for uptake (i.e. advisory committee, working group, website compendium of best practice.)

KISSP Presentation mid 2016.

Lunch and Learn presentation at Department of Biodiversity, Conservation and Attractions, 29 August 2017.

Meeting with Node Leader and KMRP Advisory Group to discuss management needs and application

6.9 Other

WAMSI Project 2.2.7 summary [Appendix 2]

7 Appendices

Appendix 1. WAMSI Project 2.2.7 climate change management questions

KMRP Project 2.2.7 directly addresses the following questions outlined in the Kimberley Marine Research Program Science Plan and in the Project Agreement.

Key Question Informed Response
What are the main climate change threats to the marine biodiversity of this region (e.g. air and sea temperature rise, precipitation trends, sea level?) Air and ocean temperature rise is one the main threats to the marine biodiversity off the Kimberley coast. As climate variability will become more intense under the climate change, such as extreme El Nino and La Nina, there will also more likelihood of more frequent and stronger marine heatwaves in the region. Sea level will steadily rise in the region at a rate of a few centimetres per decade, with high uncertainties. The future changes of precipitation is uncertain due to competing climate impacts between increase in greenhouse gas in the atmosphere and the potential reduction of Asian aerosol influence.
How will existing marine habitats and communities and large marine fauna populations change? The mean temperature rise will drive poleward shift of marine biota with certain temperature tolerance range. Extreme warming events such as the marine heatwaves will cause coral bleaching and other associated ecosystem damages. Stronger surface temperature warming will cause increase in water column stratification on the shelf, which may limit the vertical nutrient cycling; however, this may facilitate onshore propagation of internal waves though their contribution to the overall nutrient budget is still unclear.
What are good potential indicators of climate change that should be followed to understand the potential impacts to bio-physical asset condition? It has been identified that temperature measurement at one location in Camden Sound would be able to represent the variability across the marine park on different time scales, from intraseasonal to interannual. At key locations on the continental shelf, such as 50 and 100m depth, it would be useful to establish long term water column temperature loggers to monitor temperature and stratification variations and changes; and establish baseline biophysical monitoring program such as benthic mapping and nutrient cycling etc. A framework of similar monitoring has been established by the IMOS program through its National Reference Stations.
What are the stakeholders (incl. management agencies) requirements for adapting to climate change? Management measures to deal with rising temperature and extreme events are crucial to maintain the biodiversity in the region. It is important for the management to keep track of climate predictions issued by the Bureau of Meteorology on the ENSO and Indian Ocean Dipole development, as well as be aware of the future projection of the physical and biogeochemical environment in the region.
Which species and communities are threatened? All species and communities. It is important to understand how the marine species deal with extreme climate conditions such as marine heatwaves and how they recover from the impacts of the marine heatwave, in order to better understand their resilience to long-term climate change.
How will they respond e.g. shifts in distribution patterns, adaptation or local extinction? Not within the scope of this study.
How will key physical processes (e.g. calcification, connectivity, herbivory, predation) be influenced by climate change?

While this is still speculative, the El Nino-like condition in the Pacific may cause weaker Australian monsoon and weaker intraseasonal variations of weather patterns, which may affect larval dispersal pattern for many marine species. Water column stratification change is also an important process that affects the nutrient sources in the region and vertical cycling of nutrients.

Where should DBCA measure temperature (possibly other factors) and to what level?

Temperature should be measured at least monthly intervals at a selected site in the Camden Sound, along with nutrient and plankton samples. It is also useful to maintain mooring observations of water column temperature stratifications at 50 and 100 m depth contour further offshore.

NEW QUESTIONS POSED BY MANAGERS

What can we as managers do? [need to understand not necessarily change]

As a minimum, managers need to understand the risks of climate change for the region, and actively engage with the climate research community to better appreciate climate predictions and projections, especially on the extreme climatic events and their predictions.

Do we need to consider change within the perspective of long term historical change? What kind of influence can we really have?

Understanding the historical changes and impacts will help us to better pinpoint how the future projected climate changes will affect our marine ecosystems. Such as, with the steady warming trend, extreme events like marine heatwaves will more likely to have a stronger impacts on the marine environment. Reducing the greenhouse emission will limit the future warming, however, we may have to identify measures to mitigate the already committed warming due to past and ongoing greenhouse gas emission.

How does the speed at which climate change is occurring affect us? Will things be able to adapt? What do we do with this information?

Climate change has driven a slow pace warming trend off the Kimberley coast, however, the associated episodically occurring extreme events tend to have more dramatic effects, such as the 1998 and 2016 marine heatwave events, causing significant impacts on regional marine systems. In the climate change future projection, the warming trend off the Kimberley coast will likely speed up, with mean temperature rising by 1-2 °C in 50 years depending on different greenhouse emission scenarios. This warming trend will be exaggerated by extreme marine heatwaves, with higher magnitude and longer duration, and the cumulative impacts of marine heatwaves may double in the 50-year time frame. It is important to assess the full impacts of these extreme events so as to understand the adaptation capacity of marine biota.

How do climate change adaptation strategies feed into planning and where does this kind of research relate to that?

Identifying hotspots of climate change impacts will help the managers implement strategies to reduce other stressors on the marine ecosystem. This project provides physical background of the past and future change impacts. Understanding the magnitude of the changes will help better design an adaptation strategy.

How does this project feed into/interact with the others, particularly in making recommendations for species and their management? (need to consider for synthesis reports and potential guidelines/statements)

There has been ongoing dialogues between this project and KMRP Project 2.2.8 (marine ecosystem modelling) on the future climate change scenarios off the Kimberley to help them prepare species level climate change projections. The project has also been helping the connectivity project in understanding the regional connectivity of seagrass and populations, however, climate change impacts study has not been carried out in these areas.

The key messages from the project have been listed in the draft final report.

From a CC perspective, at what level should we be monitoring at? What are we looking for?

As mentioned above, long term monitoring of ocean temperature is crucial, along with regular biogeochemical surveys. The long term trend may vary seasonally, so that it is important to have consistent monitoring program throughout the year. It is also important to capture the extreme events which may occur on a shorter time scale.

It is important to understand how the marine species deal with extreme climate conditions such as marine heatwaves and how they recover from the impacts of the marine heatwave, in order to better understand their resilience to long term climate change.

What (and where in their life history) is sea temp rise impacting on species?

This has not been dealt within the project. It is clear that more dialogues between biologists and oceanographers are necessary to full address these questions.