Marine Climate Change in Australia
Impacts and Adaptation Responses 2009 REPORT CARD

El Niño – Southern Oscillation

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Summary: El Niño–Southern Oscillation (ENSO) is the dominant global mode of year-to-year (interannual) climate variability. It is a major contributor to Australia's climate, and affects Australia's Exclusive Economic Zone (EEZ) marine waters to differing degrees around the coast. ENSO has a strong and very significant effect on the intensity of the southward flowing Leeuwin Current, and Australia's west coast waters, being transmitted by ENSO-generated planetary waves that propagate from the western Pacific Ocean through the Indonesian Throughflow which become trapped along Australia's west coast. The ENSO signal in the Leeuwin Current is further transmitted along the south coast of Australia. ENSO is observed as a weaker signal in the southward flowing East Australian Current along Australia's east coast.

There have been several published studies of the effects of ENSO on marine biota and seabirds. Along Australia's west coast, for example, La Niña events have been found to assist the transport of western rock lobster (*Panulirus cygnus*) larvae, while El Niño events are better for scallops. Further, ENSO is also known to disrupt seabird spawning and the seasonal migration of whale sharks (*Rhincodon typus*) in this region. The strength of the Leeuwin Current also influences recruitment of pilchard, whitebait, Australian salmon and herring along Australia's south coast. To the east, there is evidence for a greater abundance of black marlin (*Makaira indica*) off northeast Australia during El Niño years, greater likelihood of unusually warm waters leading to coral bleaching during the late summer-autumn of the second year of El Niño events in the Great Barrier Reef, and loss of giant kelp ((*Macrocystis pyrifera*)

off the east and south coasts of Tasmania associated with major El Niño events. Along Australia's north coast, enhanced catches of banana prawns (*Panaeus merguiensis*) in the Gulf of Carpentaria during high rainfall/river flow La Niña years have also been reported.

Based on the suite of IPCC AR4 model simulations forced with projected increases in greenhouse gases, the multi-model mean represents an overall weak shift in the background state towards future climate conditions which have been described as 'El Niño-like'. While there is 80% consensus across the AR4 models for an 'El Niño-like' future climate (which could be interpreted as a shift in the mean), there is no consistent indication of future changes in ENSO amplitude or frequency. The pragmatic approach is to assume that ENSO events will continue as a source of significant interannual climate anomalies affecting the marine environment. Future ENSO events will be superimposed on 1) warmer sea surface temperatures than present – making El Niño impacts associated with unusually warm waters (e.g., coral bleaching) more severe, 2) more intense (though maybe fewer) tropical cyclones causing increased physical destruction of, for example, coral reef structures during La Niña events, c) more extreme rainfall (though changes in average rainfall are unclear), with more intense drought periods (exacerbated by warmer air temperatures) during El Niño events and more intense high rainfall events with increased freshwater/sediment flow to coastal environments during La Niña events, and d) higher sea levels which, as well as reducing land areas of island and cays (important nesting grounds for marine reptiles and seabirds), will increase impacts of tropical and extra-tropical cyclones. We expect a reduction in the overall intensity of the Leeuwin Current due to the projected change in background state towards a shallower thermocline in the Warm Pool region to the north of Australia – unless this is offset by changes in the alongshore winds and global hydrological cycle.

Moving anti-clockwise around Australia's coast from the northeast, we have high confidence that ENSO affects Australia's northeast and north coast waters, medium/high confidence that ENSO affects Australia's west coast waters, medium confidence that it affects Australia's south coast waters, and low/medium confidence that it affects Australia's southeast and east coast waters. We have low/medium confidence that the AR4-model mean projected El Niño-like conditions (change in the background state towards reduced thermocline depth in the Warm Pool) will translate to an overall reduction in the intensity of the Leeuwin Current in the future climate. In contrast, there is no consensus across AR4 models regarding changes in ENSO-event frequency or amplitude, and hence we are unable to provide any assessment of future changes in ENSO variability on Australia's marine environment under climate change.

Seasonal forecasts of ENSO have potential utility in managing impacts on biological and human systems when they occur. However, most adaptation options can only delay the eventual warming-induced impacts, particularly where they relate to temperature thresholds. Mitigation of future climate change will be critical to reducing the range of impacts in each sector. Key knowledge gaps include changes in ENSO dynamics under climate change, the nature and timing of El Niño event triggers, elucidation of the various flavours of ENSO, and ENSO impacts on marine biota.

Introduction

El Niño–Southern Oscillation (ENSO) is the dominant mode of year-to-year (interannual) climate variability observed globally (e.g., Ropelewski and Halpert 1987, 1989; Philander 1990). Substantial advances in our understanding of ENSO since the late 1960s demonstrate that ENSO is a natural mode of climate variability that exists because of the strong coupling between the tropical ocean and atmosphere (Bjerknes 1969; Zebiak and Cane 1987). Despite this close coupling, ENSO also contributes to large-scale teleconnections through the mid- to high latitudes (e.g., Glantz et al. 1991).

Our fundamental understanding of the mechanisms that underpin ENSO can be attributed to several leading paradigms. These are: (1) the delayed action oscillator theory (Suarez and Schopf 1988; Battisti and Hirst 1989); (2) the advective-reflective oscillator theory (Picaut et al. 1997); (3) the western Pacific oscillator theory (Weisberg and Wang 1997); (4) the recharge-discharge oscillator theory (Jin 1997); and (5) the unified oscillator theory (Wang 2001). Rather than detailing the differences between each of these theories, it is sufficient to point out the strong connection between theories in terms of their collective requirement for coupling the tropical upper ocean with the atmosphere as the important mechanism setting the timing of ENSO climate variability.

Aside from Australia's climate being strongly influenced by ENSO (while acknowledging the important signals that exist regionally from other large-scale climate modes, in particular the Indian Ocean Dipole and Southern Annular Mode), it also varies on decadal and longer time scales (Power et al. 1999a,b; Timbal et al. 2006; CSIRO-BoM 2007). But ENSO itself varies on (inter-)decadal time scales, and its impact on Australia appears to be modulated (e.g., Power et al. 1999a; Holbrook 2009). So what are the mechanisms behind the increased prevalence of El Niño events following the 1976/77 climate shift? Is this simply multi-decadal ENSO variability – e.g. a manifestation of the Interdecadal Pacific Oscillation? Is the extended 1990-95 El Niño 'event' a consequence of climate change (Trenberth and Hoar 1996, 1997)? Has ENSO really changed in recent decades (Wang 1995; Power and Smith 2007)? Assuming human-induced climate change has played a role in the overall bias in the Southern Oscillation index towards more negative values over the past 30 years, by shifting the Southern Oscillation index by 3 units, El Niño dominance disappears – this interpretation is at least consistent with modelling results that show global warming weakens the Walker Circulation and warms the tropical central-eastern Pacific Ocean, but has little impact on ENSO-driven variability about the new mean state (Meehl et al. 2007; Power and Smith 2007). While this is a plausible explanation, the effect of climate change on ENSO variability remains very much an open question.

This report aims to: (1) document the observed physical and biological evidence of ENSO in the marine environment around Australia, focusing on Australia's Exclusive Economic Zone (EEZ), (2) assess the climate change projections of ENSO for Australia's marine environment, (3) provide a confidence assessment of these observed and projected changes, (4) document knowledge gaps, and (5) suggest adaptation responses based on projected climate changes.

Observed Impacts

Australia's west and south coasts

Physical evidence

The major ocean current along Australia's west coast is the southward flowing Leeuwin Current (Cresswell and Golding, 1980). It is driven by the large longshore pressure gradient along the Western Australian continental shelf created by the throughflow from the western tropical Pacific Ocean to the Indian Ocean (e.g., Godfrey and Ridgway 1985; McCreary et al. 1986). This meridional pressure gradient further generates an eastward, onshore geostrophic transport that turns southward to become part of the Leeuwin Current as the water reaches the continental shelf (Ridgway and Condie 2004).

ENSO links with Australia's west coast were first noted by Pariwono et al. (1986) from analysis of variations in Australian sea level. However, it was only recently that ENSO has been shown to be an important contributor to the strength of the southward flowing Leeuwin Current (Feng et al. 2003) and shelf slope currents (Clarke and Li 2004). Using a range of observational data, Feng et al. (2003) have shown that the Leeuwin Current, which has an annual mean southward flow of ~3.4 Sv[1], weakens to 3.0 Sv during El Niño years, and strengthens to ~4.2 Sv during La Niña years. Further, the response of the Leeuwin current during ENSO years is well represented by the eddy resolving ocean general circulation model (BLUELink) used in the reanalysis effort of Schiller et al. (2007). The southward heat transport of the Leeuwin Current is one of the most important drivers of sea surface temperature variability off the west coast (Feng et al. 2008) and an example of the strong relationship that exists between west coast SSTs and ENSO (Figure 1).

Australia's south coast is dominated by extensive zonal shelves which host a seasonally varying circulation affected by zonal winds and the Leeuwin Current (Middleton et al. 2007). Recent work by Li and Clarke (2004) has shown that the sea surface height (SSH) along this southern coastline is affected by ENSO, due to the propagation of coastal waves, where El Niño (La Niña) events lead to lower (higher) than normal SSH along this extensive coast. Further, Li and Clarke (2004) showed that theoretically these changes in SSH indicate the existence of anomalous easterly (westerly) subsurface flow during La Niña (El Niño) events. This was supported by a combination of observational and modeling work (Middleton et al. 2007). Middleton et al. (2007) also showed that El Niño events lead to enhanced upwelling along this south coast, particularly along the western Eyre Peninsula.

ENSO has profound impacts on the physical marine environments off Australia's west and south coasts (Pearce and Phillips 1988; Feng et al. 2003, 2008; Wijffels and Meyers 2004; Middleton and Bye 2007), through the propagation of coastal waves (Clarke and Li, 2004). There appears to be no significant relationship between ENSO and the local winds. Table 1 summarises the observational evidence of ENSO's influence on the physical environments off Australia's west and south coasts.

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[1] Sv = Sverdrup. A unit of measure of the transport of ocean currents. 1 Sverdrup = 10^6 cubic meters per second.

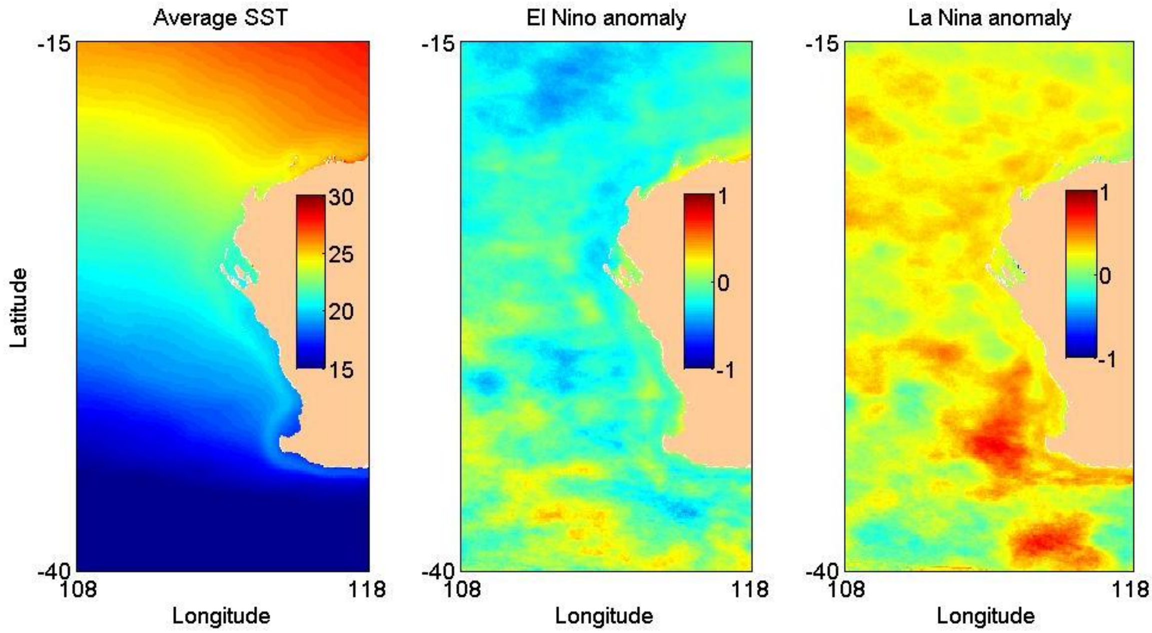

Figure 1: Sea surface temperatures (SSTs) averaged over the months of September-October-November (SON) for the 15-year period 1994-2008 along, and offshore from, Australia's west coast (left panel). Composite ENSO SST anomalies for the same west coast region are identified here as: El Niño year (1994, 1997, 2002, 2004, 2006) SON SST minus the average SON SST (middle panel); and La Niña year (1995, 1998, 1999, 2000, 2007) SON SST minus the average SON SST (right panel). SON represents the mature phase of the El Niño/La Niña year.

Table 1: Summary of El Niño/La Niña signals in the marine physical environment off Australia's west and south coasts.

El Niño	**La Niña**
Weaker Indonesian Throughflow	Stronger Indonesian Throughflow
Shallower thermocline off the west and south coasts	Deeper thermocline off the west coast
Weaker Leeuwin Current off the west coast	Stronger Leeuwin Current off the west coast
Low sea level anomaly off the west and south coasts	High sea level anomaly off the west and south coasts
Cooler sea surface temperature off the lower west coast	Warmer sea surface temperature off the lower west coast
Low rainfall, less storm activity in the SW WA region	High rainfall, more storm activity in the SW WA region
Shutdown of winter eastward coastal current/Leeuwin Current off the south coast	--

Biological impacts

ENSO's influence on marine biota off Australia's west coast is most likely due to variations in the intensity of the southward flowing Leeuwin Current off the west coast and the eastward coastal current off the south coast. The following list identifies published evidence of impacts on marine biota and seabirds associated with ENSO along Australia's west and south coasts:

- The settlements of the western rock lobster (*Panulirus cygnus*) larvae, or puerulus, are influenced by the Leeuwin Current – during La Niña years the stronger Leeuwin Current, with higher sea surface temperature, may improve the larval survival rates, while the stronger storm activities which may help larval onshore movements result in high annual puerulus settlement, especially in the southern zone of the fishery (Pearce and Phillips 1988; Caputi et al. 1995; Caputi 2008);
- During La Niña years, the stronger Leeuwin Current is linked with a deeper thermocline (nutricline) depth off the shelf edge so that the wind-driven upwelling is less effective in bringing deep nutrients onto the shelf, likely resulting in reduced summer production north of Houtman Abrolhos Islands (Furnas 2007);
- Scallop harvests in Shark Bay are higher during an El Niño year, likely due to less flushing during the spawning season (Caputi et al. 1996);
- The advection of eggs and larvae by the Leeuwin Current are found to have a negative effect on pilchard recruitment off the southwest coast (Fletcher et al. 1994), while it may have a positive effect on whitebait recruitment (Caputi et al. 1996);
- Significant correlations are found between recruitments of Australian salmon and herring off South Australia and the eastward coastal current/Leeuwin Current advection (Lenanton et al. 1991);
- Anomalous low-frequency flows associated with ENSO can transport larvae large distances – resulting in enhanced recruitment of Australian salmon to nursery grounds in the east of Australia's south coast during La Niña and decreased recruitment in this region during El Niño (Li and Clarke 2004);
- The annual sea bird spawning at the Houtman Abrolhos Islands (Dunlop 2001, 2005) and the seasonal migration of whale sharks off Ningaloo Reef (Surman and Nicholson 2009) can be disrupted by ENSO events, though the mechanism is still unknown;
- The strength of the Leeuwin Current is also found to affect alongshore connectivity (Feng et al. .2009), which allows tropical fish species to travel a long distance to the south nursery ground during La Niña years (Pearce and Hutchins 2009).

Australia's east and north coasts

Physical evidence

Australia's east coast forms a large proportion of the western South Pacific boundary which hosts the East Australian Current (EAC) (e.g., Ganachaud et al. 2007). The EAC is a southward flowing current with maximum velocities of ~1 m/s in its core which is normally located near the surface (Schiller et al. 2008). This current hugs

Australia's east coast between ~18°S and ~32 - 34°S where, on average, it separates from the continental margin. Interestingly, the variability of the EAC is as large as the mean flow (e.g., the variability at 30°S has 30 Sv-rms compared to a mean transport of 22 Sv) (Mata et al. 2000). The EAC has significant mesoscale structure and varies on sub-monthly through to decadal and longer time scales (e.g., Ridgway and Dunn 2003; Ridgway et al. 2008).

There is considerable evidence that ENSO, indirectly or directly, affects the Coral and Tasman Seas (e.g., Harris et al. 1988; Sprintall et al. 1995; Basher and Thompson 1996; Holbrook and Bindoff 1997; Sutton and Roemmich 2001; Holbrook et al. 2005a, b; Holbrook and Maharaj 2008). On the large-scale, mapped historical temperature records indicate that ENSO can be identified over most of the upper southwest Pacific Ocean, with the strongest signal in the tropics but with significant signals also evident in the subtropical gyre and south Tasman Sea (Holbrook and Bindoff 1997). Subtropical mode water formation is also enhanced in the Tasman Sea during El Niño (Sprintall et al. 1995; Holbrook and Maharaj 2008).

There have, however, been only a limited number of observational studies that report ENSO variability as being evident in the EAC – including the Great Barrier Reef region (e.g., Burrage et al. 1994), off Sydney (Hsieh and Hamon 1991), and connecting the South Equatorial Current, EAC and Tasman Front (Holbrook et al. 2005a,b). In the latter study, it was found that ENSO time scale variability is dominated by two propagating modes in the upper southwest Pacific Ocean. The second mode is consistent with variations in the subtropical gyre circulation strength, including the EAC and its separation, and continuous with the Tasman Front (Holbrook et al. 2005a, b), and appears likely to be due to the influence of Rossby waves[2]. Recent modelling studies provide further evidence to suggest that long Rossby waves are important to EAC transport variations on interannual to decadal scales (Holbrook 2009), whereby the Rossby wave contribution to EAC transport changes and coastal sea level changes appears to be connected to changes in both Tasman Sea wind stresses and South Pacific wind stresses east of New Zealand, with decadal variations in ENSO playing an important role (Sasaki et al. 2008; Holbrook et al. 2009). An example of the relationship between east coast SSTs and ENSO is provided in Figure 2. While ENSO variability is evident along Australia's east coast, it is notably weaker overall than along Australia's west coast (cf. Fig. 1).

The two phases of ENSO, El Niño and La Niña, produce distinct and different climate anomalies over eastern and northern Australia and surrounding coastal and ocean waters. ENSO events tend to evolve over 12-18 months as do the associated surface climate anomalies (e.g., Lough, 2001). Although every ENSO event evolves slightly differently, both phases are associated with reasonably well-documented levels of disturbance to the physical marine environment (Table 2), which are likely to impact the marine biota. In general, El Niño events are likely to produce biotic responses to unusually warm sea surface temperatures (SSTs) in the late summer and autumn of the second year of the event, whereas La Niña events are likely to produce biotic responses to increased freshwater flows and physical disturbances associated with a more vigorous monsoon and more tropical cyclone activity in the summer season (see El Niño and La Niña animations of SST on www.oceanclimatechange.org.au; after Figures 12 and 14 respectively in Lough, 2001). There is also presently limited observational evidence as to how the major ocean current of eastern Australia, the

[2] Planetary waves, long low-frequency waves

EAC, varies with ENSO. The extent to which we can assess typical responses of marine biota to ENSO events is further limited by the lack of long-term ecological time series and long-term studies of population dynamics including different life-history stages (Hobday et al. 2006; Poloczanska et al. 2007). Responses may be direct physiological responses to unusual climatic conditions or indirect responses as a result of changes in habitat and food availability.

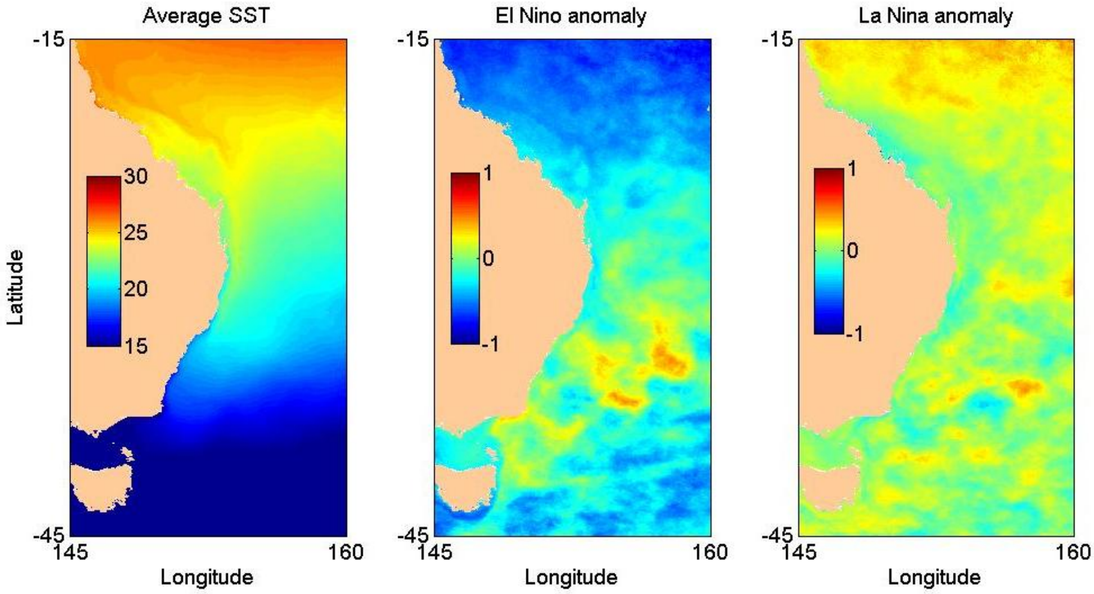

Figure 2: Sea surface temperatures (SSTs) averaged over the months of September-October-November (SON) for the 15-year period 1994-2008 along, and offshore from, Australia's east coast (left panel). Composite ENSO SST anomalies for the same east coast region are identified here as: El Niño year (1994, 1997, 2002, 2004, 2006) SON SST minus the average SON SST (middle panel); and La Niña year (1995, 1998, 1999, 2000, 2007) SON SST minus the average SON SST (right panel). SON represents the mature phase of the El Niño/La Niña year.

Table 2: Typical ENSO climate anomalies likely to affect marine biota of northern and eastern tropical Australia (Allan et al. 1996; Lough, 1994, 2007; McPhaden 2004; Steinberg 2007)

El Niño	La Niña
Weaker summer monsoon	Stronger summer monsoon
Less tropical cyclone activity in Australian region	More tropical cyclone activity in Australian region – more physical damage from strong winds, high seas, storm surges
Less rainfall/freshwater inputs to coastal environments	More rainfall/freshwater inputs to coastal environments – lowered salinity and increased coastal turbidity
Less cloud/more radiation during summer	More cloud/reduced radiation during summer
Warmer SSTs late summer/autumn of 2nd year	Less marked SST signals
Lower sea level in western Pacific	Higher sea level in western Pacific

Biological impacts

The marine environment of northern and eastern Australia encompasses a range of bioregions for which, in general, we only have a broad picture of marine species distribution and little information about interannual variability (Heap et al. 2005; Lyne and Hayes, 2005; Commonwealth of Australia, 2006). The vast area encompasses significant benthic and pelagic ecosystems including coral reefs, seagrass beds, mangroves, estuaries, coastal wetlands and kelp forests.

Even for the best studied of these ecosystems, the Great Barrier Reef (GBR), our ability to determine the biotic responses of its many component organisms to climate variability and change is limited (Johnson and Marshall 2007). Marine microbial assemblages (Webster and Hill 2007), plankton (McKinnon et al., 2007), macroalgae (Diaz-Pulido et al. 2007), seagrass beds (Waycott et al. 2007), inter-tidal mangrove, salt marshes and wetlands (Lovelock and Ellison 2007), benthic invertebrates (sponges, echinoderms, molluscs, crustaceans; Hutchings et al. 2007), sharks and rays (Chin and Kyne 2007), marine mammals (Lawler et al. 2007), marine reptiles (crocodiles, marine turtles, sea snakes; Hamann et al. 2007), fish (Munday et al. 2007, 2009) and corals (Hoegh-Guldberg et al., 2007; Lough 2008) are known to be variously sensitive to water characteristics (temperature, chemistry, nutrient supply), ocean circulation patterns and extreme events such as tropical cyclones and freshwater flood plumes.

These studies are only just beginning to consider how a changing marine climate will affect different organisms. Although one can speculate from these comprehensive reviews of climate sensitivity as to how ENSO extremes may affect particular groups of marine organisms (e.g., increased nutrient supply enhances GBR plankton production and biomass, and communities extend further out to sea during high rainfall/river flow events (McKinnon et al. 2007) which are conditions more likely during La Niña years), there are relatively few studies of how specific marine organisms respond to the two phases of ENSO.

These few published observational studies that have linked ENSO events to marine biotic and seabird responses along Australia's east and north coasts include:

- Increased recruitment in populations of the seashell *Strombus luhuanus* two years after an El Niño event (Catterall et al. 2001);
- Significant decreases in seabird populations of the southern GBR associated with El Niño events as a result of reduced availability of food for hatchlings (Congdon et al. 2007; Devney et al. 2009);
- Greater abundance of black marlin off northeast Australia during El Niño years (Williams 1984);
- More breeding green turtles in the northern and southern GBR two years after an El Niño event (Limpus and Nicholls 1988);
- Enhanced catches of banana prawns in the Gulf of Carpentaria during high rainfall/river flow La Niña years (Vance et al. 1985);
- Loss of giant kelp *(Macrocystis pyrifera*) off the east and south coasts of Tasmania associated with major El Niño events (Edyvane 2003);
- Synchronised increases in populations of damselfish on the GBR after El Niño events (Cheal et al. 2007);
- Greater likelihood of unusually warm waters conducive to coral bleaching during the late summer-autumn of the second year of El Niño events (e.g., 1997/98) compared to La Niña years (Berkelmans and Oliver 1999; Berkelmans et al. 2004; Eakin et al. 2009).

These limited observational studies are insufficient to make any generalisations about impacts of the two ENSO phases on the ecosystems of the marine bioregions of northern and eastern Australia. This requires commitment to long-term ecological studies (across several ENSO events) and identification and analyses of existing historical ecological datasets.

Potential impacts by the 2030s and 2100s

Based on various assessments of the current multi-model archive through the IPCC AR4 process, in which modern day El Niño events are better simulated than in the IPCC Third Assessment Report, there is reportedly no consistent indication at this time of discernible future changes in ENSO amplitude or frequency (Meehl et al. 2007). Based on a suite of AR4 model simulations, changes in ENSO variability differ from model to model (Meehl et al. 2007). Nevertheless, it is further pointed out by IPCC WGI that the multi-model mean – based on 80% (13 out of 16) of the AR4 climate model projections forced with increasing greenhouse gases - projects a weak shift towards conditions which may be described as ‘El Niño-like’ (Meehl et al. 2007; see their Fig. 10.16). We qualify this statement here by pointing out that the terminology ‘El Niño-like’ refers to a change in the overall ‘background state’ of the tropical Pacific Ocean – specifically to describe the pattern of weakening of the atmospheric Walker Circulation and warming of the central-eastern tropical Pacific Ocean. It does not represent changes in the overall variability associated with ENSO. The essential message here is that most AR4 models show an overall change in the west to east gradient *background state* of the tropical Pacific Ocean thermocline and sea level – where the west-east thermocline slope becomes less pronounced, resulting in a background state comprising of a shallower thermocline and lower sea level in the western Pacific and a deeper thermocline and higher sea level in the central-eastern Pacific. This is also associated with warmer sea surface temperatures in the central-eastern tropical Pacific Ocean – a sea surface temperature anomaly pattern that is El Niño-like. While the terminology 'El Niño-like' has received criticism in some recent literature (e.g., Vecchi and Soden 2007; DiNezio et al. 2009), we have chosen to retain this language for consistency with the most recent climate change consensus AR4 report, where the projected 'El Niño-like' pattern of change represents a change in the background state and does not reflect changes in ENSO dynamics or its variability.

Li and Clarke (2004) suggest that the change in background winds might be expected to lead to lower sea-level around Australia's west and south coasts (much like what is suggested in their Figure 1). This would mean a weaker Leeuwin Current and westward anomalies in flow along Australia's south coast. This is not reported by the IPCC. Conversely, recent unpublished research suggests that the intensification of the hydrological cycle in the warm pool region of the tropical Pacific may also induce a freshening trend in the Indonesian Throughflow region that would enhance the meridional pressure gradient (Ming Feng, personal communication, 2009). These complex competing processes make the overall climate change effects on Leeuwin Current intensity challenging to evaluate.

Australia's west and south coasts

While there are discrepancies between climate models on how the characteristics of ENSO will change in the future climate change scenarios, there is moderate consensus that the mean state in the tropical Pacific will become El Niño-like in the future climate, which would induce a shallow thermocline anomaly in the equatorial western Pacific and the eastern Indian Ocean. However, the future change of the Leeuwin Current may also depend on a few other factors, e.g., the thermohaline structure in the southeast Indian Ocean. While the CSIRO Mark-3.5 model projects a weakening Leeuwin Current in the future climate, a carefully designed downscaling model based on the BLUElink model will provide a more definite answer on the future trend Leeuwin Current (Chamberlain et al. 2009). Assuming that ENSO events will continue as a source of significant interannual climate anomalies affecting the marine environment off Australia's west and south coasts, future ENSO events will be superimposed on ~1^{o}C warmer SSTs by 2030 and >2°C by 2100.

Australia's east and north coasts

Projecting the potential impacts of ENSO on the marine biota of Australia's eastern and northern coasts is currently limited by two factors: 1) the few observational studies of marine biotic impacts (see scientific review section), and 2) the absence of a clear consensus amongst the present generation of global climate models as to how the frequency and intensity of the two ENSO phases will vary with continued global warming (Meehl et al. 2007).

The pragmatic approach is to assume that ENSO events will continue as a source of significant interannual climate anomalies affecting the marine environment of northern and eastern Australia. Future ENSO events will, however, be superimposed on 1) warmer SSTs than present – making, for example, El Niño impacts associated with unusually warm waters (e.g., coral bleaching) more intense, 2) more intense (though maybe fewer) tropical cyclones causing increased physical destruction of, for example, coral reef structures during La Niña events, c) more extreme rainfall (though changes in average rainfall are unclear), with more intense drought periods (exacerbated by warmer air temperatures) during El Niño events and more intense high rainfall events with increased freshwater/sediment flow to coastal environments during La Niña events, and d) higher sea levels which, as well as reducing land areas of island and cays (important nesting grounds for marine reptiles and seabirds), will increase the impacts of tropical cyclones. With the projected continued intensification and southward extension of the EAC, Australia's southeast SSTs are expected to increase ~2^{o}C by 2030 and 3^{o}-4^{o}C by 2100. The ENSO warm phase (teleconnected or otherwise to the waters of this region) might be expected to further exacerbate changes to marine biota in southeast Australia. Conversely, the long-term warming may further reduce subtropical mode water formation (Roemmich et al. 2005) over the coming decades, despite the naturally-varying interannual increases during El Niño years (Holbrook and Maharaj 2008).

Key Points

- El Niño – Southern Oscillation (ENSO):
  - is the dominant global mode of climate variability;
  - is a major contributor to Australia's year-to-year climate variability; and
  - affects Australia's EEZ marine waters to differing degrees around the coast;
- ENSO:
  - strongly affects the Leeuwin Current and Australia's west coast waters;
  - clearly affects Australia's south coast waters; and
  - is observed as a weaker signal in the East Australian Current along Australia's east coast;
- Examples of ENSO effects on marine biota include:
  - Australia's west coast - La Niña events have been found to assist propagation of western rock lobster larvae, while El Niño events are better for scallops; ENSO is also known to disrupt seabird spawning and seasonal migration of whale sharks;
  - Australia's south coast – the strength of the Leeuwin Current has been found to influence recruitment of pilchard, whitebait, Australian salmon and herring;
  - Australia's east coast – greater abundance of black marlin off northeast Australia during El Niño years; greater likelihood of unusually warm waters conducive to coral bleaching during the late summer-autumn of the second year of El Niño events; loss of giant kelp ((*Macrocystis pyrifera*) off the east and south coasts of Tasmania associated with major El Niño events;
  - Australia's north coast - enhanced catches of banana prawns in the Gulf of Carpentaria during high rainfall/river flow La Niña years;
- Based on the suite of IPCC AR4 climate model simulations:
  - The multi-model mean projects an overall weak shift towards conditions which may be described as 'El Niño-like' (representing a shift in the

background state towards an overall pattern of weakened Walker Circulation and warmer central-eastern tropical Pacific sea surface temperatures) under climate change.

- There is no consensus regarding future changes in ENSO-event amplitude or frequency – i.e., no consensus in any changes in ENSO dynamics.

Confidence Assessments

Observed impacts and potential impacts by the 2030s and 2100s

Australia's west and northwest coast waters

While we have MEDIUM-HIGH confidence that the Leeuwin Current is affected by ENSO (based on the reasonably high quantity of published oceanographic literature that the Leeuwin Current significantly decreases in intensity during El Niño and increases in intensity during La Niña, together with the high agreement between theory (Li and Clarke, 2004), observations (Feng et al. 2003) and models (Schiller et al. 2008), we have MEDIUM confidence in the robustness of the AR4 multi-model mean projection of a weak shift towards El Niño-like conditions in the future, given the 80% agreement across models (Meehl et al. 2007). There is also MEDIUM evidence, based primarily on AR4 model projections, that ENSO will become more El Niño-like in the future climate. An El Niño-like state would be expected to induce a shallow thermocline anomaly in the equatorial western Pacific and the eastern Indian Ocean. The downscaled modelling may help us to understand what this means to biota, but the expectation is that productivity would be enhanced by the shallow thermocline anomaly.

Table 3: Confidence assessment of observed and expected (2030 and 2100) ENSO changes in the Leeuwin Current and Australia's west and northwest EEZ waters

	Observed changes	**Expected changes**
Amount of evidence	Moderate/Much	Low/Moderate
Degree of consensus	High	Moderate
Confidence level	Medium/High	Medium

Australia's south coast waters

While we have MEDIUM confidence that the waters along Australia's south coast are affected by ENSO (based on the good agreement between theory (Li and Clarke 2004), observations and models (Middleton et al. 2007), but limited in physical evidence to a few peer-reviewed papers), we can only assign a LOW-MEDIUM level of confidence that the projected El Niño-like conditions in the future climate will affect Australia's south coast.

Table 4: Confidence assessment of observed and expected (2030 and 2100) ENSO changes in ENSO for Australia's south EEZ waters

	Observed changes	**Expected changes**
Amount of evidence	Low/Moderate	Low/Moderate
Degree of consensus	Moderate	Moderate
Confidence level	Medium	Low/Medium

Australia's north and northeast coast waters

We have HIGH confidence that ENSO affects the Coral Sea north and northeast EEZ waters with much published evidence and HIGH consensus of its effects on ocean temperatures, precipitation variations (and hence affects on surface salinity), and tropical cyclone numbers.

Table 5: Confidence assessment of observed and expected (2030 and 2100) ENSO changes in Australia's north and northeast EEZ waters

	Observed changes	**Expected changes**
Amount of evidence	Much	Moderate
Degree of consensus	High	Low
Confidence level		Low

Australia's east and southeast coast waters

We have MEDIUM confidence that ENSO affects broader Tasman Sea region temperature anomalies and subtropical mode water changes (most likely modulated by the influence of long oceanic Rossby waves). We have relatively LOW (medium at best) confidence that ENSO significantly (and/or directly) affects Australia's east and southeast EEZ waters, and more specifically the strength of the East Australian Current along the entire coast, although weak ENSO variations have been reported in a limited number of papers. Overall agreement between published studies of the importance of ENSO along Australia's east coast reduces as we move from tropics through to mid-latitudes along Australia's eastern EEZ waters. There is typically LOW agreement across theory, observations and models for the importance of ENSO in the EAC.

Table 6: Confidence assessment of observed and expected (2030 and 2100) ENSO changes in the East Australian Current and Australia's east and southeast EEZ waters

	Observed changes	**Expected changes**
Amount of evidence	Moderate	Low
Degree of consensus	Low/Moderate	Low
Confidence level	Low/Medium	Low

Adaptation Responses

Many marine organisms are likely to be sensitive to changes in ocean characteristics stimulated by a changing climate (Poloczanska et al. 2007) – temperature, acidity, circulation, stratification, ocean-floor, intensity and frequency of extreme events. Although the evidence and the level of confidence for the influence of ENSO events on particular ocean regions and circulatory systems are variable, there are indications that some marine ecosystems and particular marine biota are already responding to the changes in ocean characteristics provoked by such events. For example, La Niña events have been found to assist the transport of western rock lobster larvae, while El Niño events are better for scallops. These events are also known to disrupt seabird spawning and seasonal migration of whale sharks (this report card). On the south coast, the strength of the Leeuwin Current has been found to influence recruitment of pilchard, whitebait, Australian salmon and herring (this report card). On the east coast, a shift of species to higher latitudes in response to warming sea temperatures has been observed (Hickling et al. 2006).

While there will be a level of autonomous adaptation (Smit et al. 1999) among marine biota, many species will struggle to adapt. In particular, those marine and coastal ecosystems, already stressed by human activities, may not have the resilience necessary to absorb the shock of such changes leading to a decline in their productivity. Moreover, while reducing and/or removing anthropogenic stresses will likely enable autonomous adaptation of a range of marine biota, other climate-induced changes in ocean characteristics (e.g., changes in prevailing current dynamics) and non-climate factors (e.g., availability of suitable habitat) may inhibit it in some regions. Building and/or maintaining the resilience of the marine ecosystem will involve:

- refraining from activities that impede autonomous adaptation of species;
- establishing initiatives that assist species to adapt; and
- assisting those sectors dependent on the marine ecosystem through purposeful adaptation responses.

One of the major impacts of ENSO events (which tend to straddle two years across the austral summer season) on Australia's marine environment is the warming of sea surface temperatures off northeast Australia during the late summer/autumn of El Niño events. This warming occurs on top of the slowly rising temperatures due to climate change, creating new peaks in the warming.

Adaptation for biodiversity managers

Enhanced warming is a particular concern for coral bleaching in regions such as the Great Barrier Reef. Measures to adapt to coral bleaching are limited, but some actions can help reduce the impact of individual warming events, if they can be predicted. Spillman and Alves (2009) are applying seasonal forecasts from a numerical model to warn of warming events at lead times of up to five months. This allows reef managers better preparation to monitor the effect of warm events, and a chance to reduce other stressors such as agricultural runoff or human activity on the reef during warm events. Fine scale adaptation measures, such as shading of reef, while being considered by some tourist operators at scales of < 100 m, is not considered feasible at larger scales.

Adaptation for tourism

ENSO events are well correlated with rainfall in north-eastern Australia, particularly along the northeast coast. Extended rainfall and more tropical cyclone activity (characteristic of La Niña events) can have significant impacts on tourism along the coast and Reef area. Tourism in the area will also be affected by bleaching of the Reef which tends to be associated with El Niño events. Adaptation to a reduction in tourism would entail measures to diversify and localise coastal economies so that they are not so dependent on the influx of tourists. If ENSO impacts are heterogeneous in a region, then relocation of tourism activities to reef regions with less impact predicted may be possible (e.g., Game et al. 2008).

Adaptation for resource use (e.g. fisheries managers)

If recruitment patterns can be related to ENSO events, then an understanding of the future ENSO patterns may allow managers to determine if long term increases or decreases in recruitment and hence fish abundance are likely. Changing management to account for these impacts will represent an adaptation response.

Summary

Development of a comprehensive knowledge base of the range of adaptation response options and limitations on adaptation for particular marine species, ecosystems and marine resource dependent sectors is yet to be initiated. Regardless of what trends exist in ENSO *per se* under climate change, we can be confident that the general warming of global oceans will continue. Most adaptation options can only delay the eventual warming-induced impacts, particularly where they relate to temperature thresholds. Seasonal predictions of ENSO have potential utility in managing impacts on biological and human systems when they occur. Mitigation of climate change will be important in reducing the scope of needed impacts in each sector.

Knowledge Gaps

Knowledge gaps are discussed in reference to (a) understanding the influence of climate change on ENSO, and (b) the subsequent impacts of “climate influenced” ENSO on the marine environment.

Climate change and ENSO

There is no clear consensus regarding changes in ENSO dynamics – in particular, regarding changes in the frequency and amplitude of ENSO events in the future climate. In addition recent work on the “flavours of ENSO” (e.g., cold tongue versus Modoki: Ashok et al. 2009, see Figure 3) has shown that different El Niño’s may have different impacts on the marine and terrestrial environment. Prospects for predicting these two flavours of ENSO have recently been assessed using the Australian Bureau of Meteorology coupled ocean-atmosphere seasonal forecast model (Hendon et al. 2009). The future trend in the intensity and frequency of these "flavours" is unknown.

ENSO is one of several large scale climate drivers that influence the Australian marine environment. Interaction between ENSO and other large scale climate drivers, such as the Indian Ocean Dipole (IOD) (Feng and Meyers 2003; Ummenhofer et al. 2009), and the Southern Annular Mode (SAM) needs to be resolved. Changes in these drivers as a result of climate change is also unclear, although Cai et al. (2005) project an upward trend in the Southern Annular Mode (SAM) in response to increasing atmospheric CO_2 concentrations, that would reinforce the southward penetration of the EAC.

Examination of these changes in climate models that can represent ENSO, and the flavours of El Niño events, is needed. Improvement and confidence in the climate models will help to fill the knowledge gap.

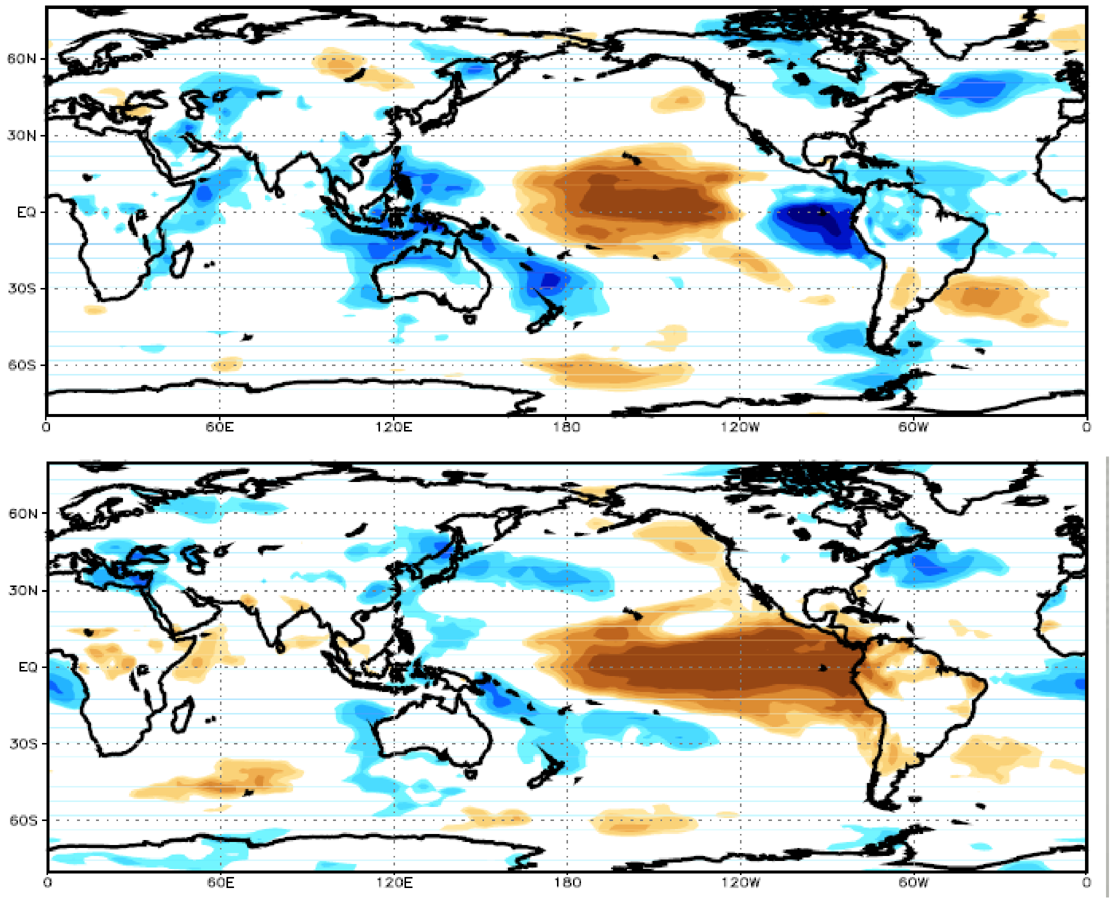

Figure 3: Upper: Sea surface temperature anomalies during a Modoki El Niño. Lower: Sea surface temperature anomalies during a cold tongue El Niño (Ashok 2009, Greenhouse 2009 presentation).

ENSO and the marine environment

In an 'El Niño-like' state under climate change, we might expect a weakening of the Leeuwin Current to become more prevalent. However, a stronger hydrological cycle may enhance the pressure gradient down the coast, possibly intensifying the Leeuwin Current. EAC changes are even less clear. Aside from these uncertainties in the physical processes, there are even larger knowledge gaps in the flow-on effects of ENSO to marine biota under climate change.

Further Information

For further general educational information on ENSO, the reader is referred to the Australian Bureau of Meteorology web-site:

<http://www.bom.gov.au/lam/climate/levelthree/analclim/elnino.htm>

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