

The Leeuwin Current

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Summary: The Leeuwin Current (LC) is a warm, poleward flowing ocean boundary current off the west and south coasts of Australia, driven by large-scale meridional (north-south) pressure gradient. On the interannual time scale, the strength of the LC is influenced by ENSO-related thermocline anomalies, and transmitted from the equatorial western Pacific into the southeast Indian Ocean through the Indonesian Archipelago. The LC and its interannual variability have profound impacts on marine ecosystems off the west and south coasts of Australia. For example, high recruitment of the western rock lobster (*Panulirus cygnus*) fishery of Western Australia is influenced by a stronger LC and the associated warmer water temperatures.

Over the period from mid-1970s to mid-1990s, a trend of shallowing thermocline (subsurface cooling) in the equatorial western Pacific, which is coupled with a weakening trend of the trade winds in the Pacific, has transmitted into the southeast Indian Ocean and the LC region and caused a multi-decadal weakening trend of the LC. Comparing climate models and forced ocean circulation models suggests that the weakening LC is likely due to a combined effect of both global warming and natural variability in the climate system.

There have been persistent warming trends observed in the LC and on the shelf in waters off the west coast during the past five decades. Over the same time period, more frequent Indian Ocean Dipole events and an upward trend of the Southern Annual Mode may have reduced the strength of the westerly winds and storm activity off the southwest coast, which may have adjusted the air-sea heat flux in the LC region and overcome the reduction of the LC heat transport to cause the warming trend. Both the changes in the LC and the air-sea freshwater flux may have also caused the observed increase in surface salinity off the coast. The surface warming and subsurface cooling, in combination with the reduction of storm activity, may have increased the vertical stratification in the water column and reduced vertical mixing in the LC region.

Climate model simulations suggest that reductions of trade winds in the tropical Pacific, increase in the frequency of Indian Ocean Dipole events, and the upward trend of Southern Annual Mode in recent decades are mostly due to the effect of the increased

greenhouse gases in the atmosphere. Climate model projections suggest these climate trends will likely continue in the future, so that the LC could continue to weaken slowly.

Introduction

The Leeuwin Current (LC) is a warm, poleward flowing ocean boundary current off the west coast of Australia (Cresswell and Golding 1980), driven by the large-scale meridional pressure gradient in the southeast Indian Ocean which is set up by the Indonesian Throughflow and thermohaline forcing (Godfrey and Ridgway 1985; McCreary et al. 1986). The LC is intrinsically unstable and mesoscale eddies are ubiquitous features of the LC. The LC has the highest eddy energy among all eastern boundary current systems in the world (Feng et al. 2005), and the heat budget in the LC is dominantly balanced by the LC heat transport and the heat released through the air-sea interface (Feng et al. 2008).

The LC is weaker during summer when there are strong opposing winds, and stronger during winter when the opposing winds cease (Smith et al. 1991; Feng et al. 2003). In late autumn/early winter, the LC accelerates and rounds Cape Leeuwin off the southwest coast of Western Australia to enter waters south of Australia, and continues as an eastward shelf current (the South Australian Current) along the southern coast of Australia (Middleton and Bye 2007; Ridgway and Condie 2004). During the summer season, sporadic wind-driven northward inshore currents and coastal upwelling events occur in limited shelf regions off the west coast, while wind-driven upwelling is more persistent off the southern coast of Australia.

On interannual time scale, El Niño-Southern Oscillation (ENSO) in the tropical Pacific has induced strong responses in the Leeuwin Current off the west and south coasts of Australia, due to the existence of equatorial and coastal waveguides. During the La Niña (El Niño) events, deep (shallow) anomalies in thermocline depth are transmitted along the west and south Australian coasts, inducing high (low) sea level anomalies, strengthened (weakened) LC volume transport, eddy energetics, and poleward transport of warm waters (Figure 1; Pearce and Phillips 1988; Feng et al. 2003; 2005; 2007; 2008; Clarke and Li 2004; Wijffels and Meyer 2004; Middleton and Bye 2007). Multi-decadal variations in the tropical Pacific (e.g. Pacific Decadal Oscillation, PDO) have also been found to influence the low-frequency variability of the Fremantle coastal sea level, an index of the strength of the LC (Feng et al. 2004).

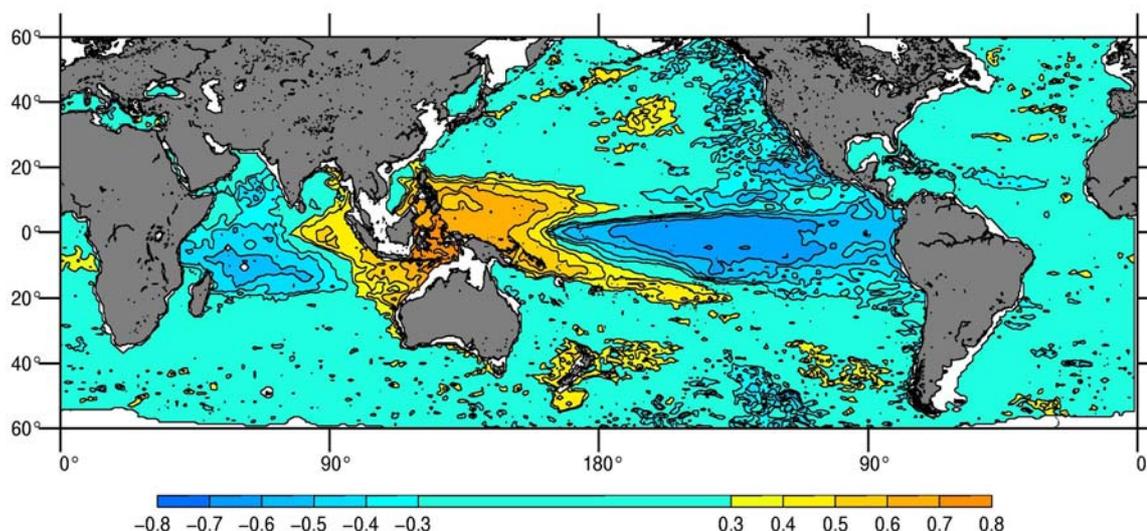


Figure 1: Correlations between the Southern Oscillation Index and altimeter derived global sea level anomalies. The correlation pattern denotes a La Niña status of sea level distribution in the world oceans.

Indian Ocean Dipole events (IOD; the Indian Ocean El Niño) is characterised by anomalous cold sea surface temperature anomalies in the equatorial southeast Indian Ocean and westward wind anomalies along the equatorial Indian Ocean (Saji et al. 1999). While the IOD does not have a direct impact on the variability of the LC, there have been observed evidences that the IOD has a teleconnection off the southwest coast of Australia, with reduced winter westerly winds and storm activity (H. Hendon, personal communication). Thus, the IOD may affect air-sea fluxes and vertical mixing in the LC, as well as cross-shelf exchanges off the west coast.

The Southern Annual Mode (SAM), a measure of the atmospheric pressure difference between the mid-latitudes and Antarctic, is the most important atmospheric influence in the temperate and polar Southern Hemisphere (Gong and Wang 1999; Kidson 1999). SAM affects the latitudinal location of the storm tracks off the southwest coast on interannual time scale, so that it also has an indirect impact in the LC region, e.g. cross-shelf exchanges during the winter season.

Many of the biological processes are strongly influenced by climate variability off the west coast. For example, the recruitment of the western rock lobster (*Panulirus cygnus*) fishery of Western Australia is influenced by a number of environmental factors, water temperatures off the lower west of Western Australia, the strength of the LC, and the strength of the westerly winds – high recruitments tend to correspond to higher water temperature, stronger LC, and stronger westerly winds in winter (Caputi et al. 2001). The LC is also one of the key drivers of the late autumn – early winter phytoplankton bloom along the oligotrophic coast (Feng et al. 2009).

Observed Impacts

Large-scale context

A warming world ocean implies a weakened Walker Circulation in the tropical atmosphere, which has induced the weakening trend of the trade winds in the tropical

Pacific over the past century (Vecchi et al. 2006). Over the period from mid-1970s to mid-1990s, the weakening trend of the trade winds in the Pacific is observed to be coupled with a trend of shallowing thermocline (subsurface cooling) in the equatorial western Pacific, which has transmitted into the southeast Indian Ocean and caused a subsurface cooling in the region (Wainwright et al. 2008).

In the Indian Ocean, there have been suggestions that there has been an increasing trend in the frequency of occurrence of the IOD events (Cai et al. 2009), which is superimposed on a general warming trend of sea surface temperature in the tropical Indian Ocean (Alory et al. 2007).

Over recent years, SAM has tended towards its positive phase, where pressures over Antarctica are relatively low compared to those in the mid-latitudes (Gong and Wang 1999). This trend entails a strengthening in westerlies that encircle Antarctica, but also drives easterly anomalies off western and southern Australia.

Region impacts

The subsurface cooling in the southeast Indian Ocean have reduced the pressure gradient that drives the LC and implies a multi-decadal weakening trend of the LC from mid-1970s to mid-1990s. Numerical models forced by winds and heat fluxes from reanalysis of weather forecast products over the past 40-50 years suggest that there has been a 10-30% reduction of the volume transport of the LC, and thus the southward heat transport of the LC, since mid-1970s (Feng and Weller, 2010). Climate models under the greenhouse gas forcing also produce a weakening trend of the LC, however, the weakening trend of the LC in the climate models is quite small compared with results from the forced ocean circulation models, suggesting that the LC trend since mid-1970s is likely driven by both the global warming effect and natural variability in the climate system (e.g. PDO; Feng et al. 2004).

Coastal sea levels at Fremantle off the west coast of Australia have risen at 1.54 mm per year over the 20th century (Feng et al. 2004), which is slightly lower than the global average trend (IPCC 2007). As the Fremantle sea level reflects the upper ocean heat content and can be used as an index for the strength of the LC, the slower rise in sea level off Western Australia corroborate the subsurface cooling observed in upper ocean temperature data off the northwest and a weakened LC during the recent decades.

The ocean off the southwest of Western Australia is observed to be one of three hot spots in the Indian Ocean where the rising trends of sea surface temperature since the 1950s are faster than the Indian Ocean basin average (Figure 2; Pearce and Feng 2007). Temperature records (surface – 50 m average) at the CSIRO Rottnest station have revealed an increase of $\sim 0.6^{\circ}\text{C}$ since the 1950s. There are less rising trends in surface temperatures off the northwest (e. g. Lough 2008) and off the south coasts of Australia. Over the past 30 years, surface temperature increases have mostly occurred in autumn-winter off the west coast, at about $0.02\text{-}0.035^{\circ}\text{C}$ per year, compared to little or no increase ($<0.01^{\circ}\text{C}$ per year) in the spring-summer period (Caputi et al. 2009a). This has caused a delay in seasonal cycles of surface temperatures off the west coast by 10-20 days.

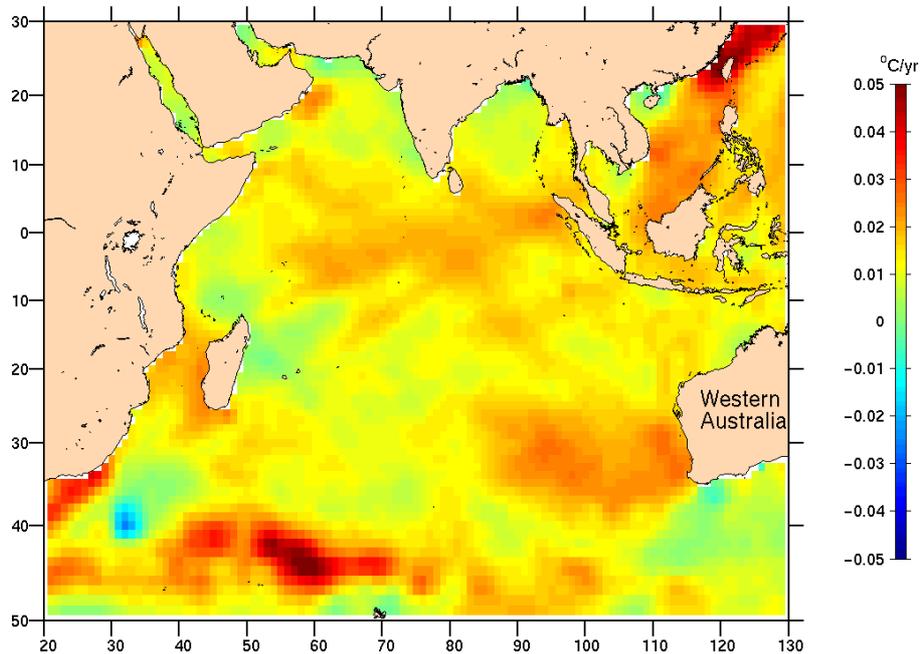


Figure 2: Rate of warming ($^{\circ}\text{C year}^{-1}$) of sea surface temperature in the Indian Ocean between 1951 and 2004 estimated from the HadISST1 data (from Pearce and Feng 2007).

The trends in IOD and SAM have induced a reduction of westerly winds and storm activity off the coast during winter, resulting in reduction in rainfalls in southwest Western Australia (e.g. Bates et al. 2008). Thus, the enhanced warming trend off the west coast is most likely due to an increase in solar radiation (a reduction in cloud cover), as well as triggered by the greenhouse gas-induced increase in downward longwave radiation, amplified by the water vapour feedback and atmospheric adjustment (Du and Xie 2008). These processes have overcome the increase in air-sea heat loss in the LC region (Yu and Weller 2007) and the reduction of the LC heat transport.

There has also been an increasing trend of sea surface salinity of 0.03 psu per decade off the coast (Pearce and Feng 2007), as shown in the time evolving surface temperature-salinity relationship at the Rottnest Island station (Figure 3). Significant interannual variations of salinity off the west coast (~ 0.5 psu) have been hypothesized to be related to freshwater budget in the Indonesian Throughflow region (Phillips et al. 2005) through the LC transport (Pearce and Feng 2007). Reduction in the LC transport, as well as the increase in evaporation and reduction in regional rainfall, may have contributed to the salinity trend. Similar temperature and salinity changes have been found at a shelf station (Maria Island) on the east coast of Tasmania, which is bathed in East Australia Current waters.

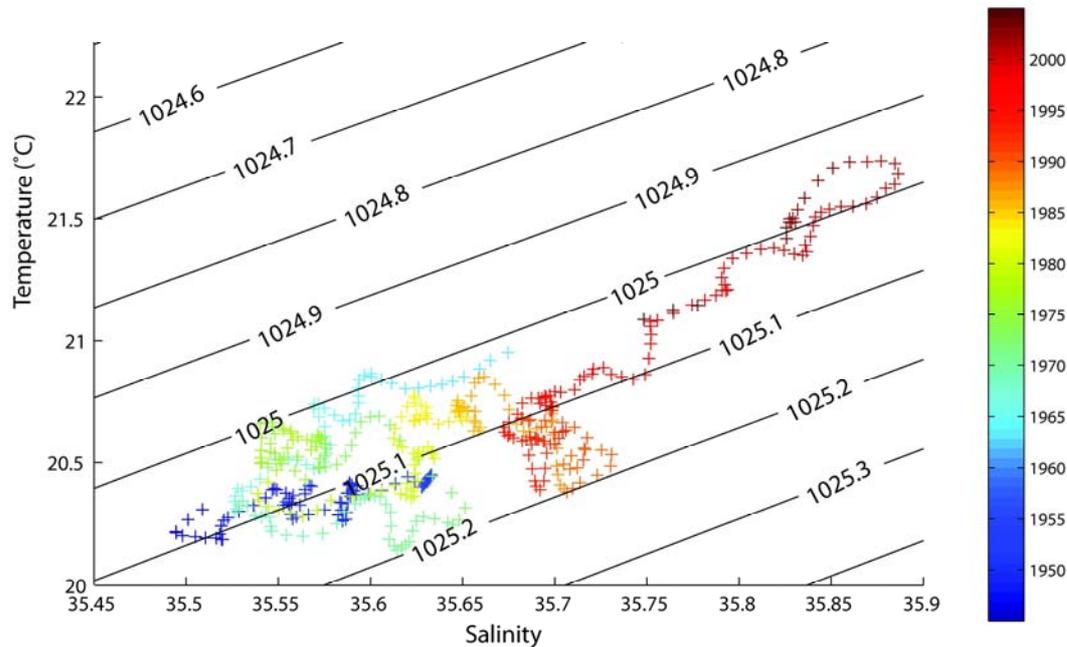


Figure 3: The time evolving temperature and salinity relationship at Rottneest Island coast station.

The observed changes in the physical environments off the west coast of Australia have been found to impact on marine ecosystems off the coast. For example, the increase in water temperature may have resulted in a decrease in size at maturity and migrating western rock lobsters off the coast (Caputi et al. 2009b). The reductions of westerly winds and storm activity due to trends of the IOD and SAM may have disrupted the western rock lobster recruitments in recent years (N. Caputi, personal communication). The surface warming and subsurface cooling trends would cause a stronger stratification off the west coast of Australia, resulting in reduced vertical turbulent flux of deep nutrients into the surface euphotic zone, an important process to drive the late autumn – early winter phytoplankton bloom in the LC system (Feng et al. 2007; 2009).

Potential impacts by the 2030s and 2100s

Most of the climate model projections forced with increasing greenhouse gases projects a weak shift towards El Niño-like conditions in the tropical Pacific, that is, there is a tendency for the Walker circulation to continue slowing down (IPCC 2007). This will continue to weaken trade winds in the tropical Pacific and elevate thermocline in the western equatorial Pacific and southeast Indian Ocean in the future climate. Global warming will also likely induce more frequent IOD events in the Indian Ocean (Cai et al. 2009). A consistent poleward and upward shift and intensification of the storm tracks is found in an ensemble of 21st century climate simulations (Yin 2005), implying a shift towards the high index state of SAM. Associated with the shift towards the high index state of the annular modes is a projected broadening and intensification of the subtropical high situated over the southeast Indian Ocean, possibly more so during the autumn-winter period and associated further precipitation decreases. Climate projections show a further reduction of westerlies off the southwest coast.

In the CSIRO MK3.5 model projection, a continued subsurface cooling (shallowing thermocline) trend is suggested in the 2030s, as compared to that of the 1990s. This subsurface cooling is simulated to disappear by 2100s as temperatures at all depths have warmed up, while the thermocline depth continues to shallow, resulting in a more stratified ocean off the west coast of Australia.

The LC, along with its transport of mass and heat, has proved difficult to capture in climate model simulations primarily due to the coarse resolution of the models. In the climate model simulations, there does not appear to be a significant change in the LC system by 2030s; however by 2100s several climate models suggest a further reduction in the volume transport and hence heat transport associated with the LC.

The observed non-uniform warming in the Indian Ocean is found to continue in the climate model simulations of the 21st century due to a combination of increased radiative forcing, namely solar and downward longwave radiation. In the CSIRO MK3.5 model, sea surface temperatures off the west Australia coast are projected to be 0.7-1.1 °C warmer by 2030s and 2.0-2.6°C by 2100s, compared to present, in close agreement with projected multi-model global averages of surface warming (IPCC 2007). The rising temperature trend in the simulation is strong along the mid-west coast (20-30°S), decreasing to the north and south off the coasts.

The projected surface salinity off the west coast appears to continue to increase in the future climate, though multi-decadal freshening events off the northwest shelf of Australia is also simulated in the MK3.5 model. The trend of increasing salinity is suggestive of a decrease in the Indonesian Throughflow waters and LC which transport fresher waters poleward along the coast of Western Australia.

Confidence Assessments

Physical variables	Observed changes	Projected changes	
		2030s	2100s
Volume transport	A weakening trend of the LC volume transport since mid-1970s due to more frequent El Niño events in recent decades (MEDIUM)	No significant change (LOW)	Slightly weakening (LOW)
Coastal sea level	<u>Fremantle sea level</u> : A rising trend of 1.54 mm per year over the 20th century, which is slightly less than the global trend (MEDIUM)	Sea level rises at a similar trend as global average (MEDIUM)	Sea level rises at a similar or slightly lower trend as global average (MEDIUM)
Sea surface temperature	Warming recorded off Rottneest Island of about 0.6°C since 1950s; Rising sea surface temperatures are faster off the lower west coast and during winter (HIGH)	<u>SST</u> : a continued warming by 0.7 - 1.1°C; most pronounced along mid-west coast (20 - 30°S) (HIGH)	<u>SST</u> : Rise by 2.0 – 2.6°C (HIGH), which may be slightly higher than global average (MEDIUM)

Physical variables	Observed changes	Projected changes	
		2030s	2100s
Thermocline	Thermocline depth has shallowed by up to 20 metres off northwest Australia since 1950s (MEDIUM)	Continue shallowing trend of thermocline depth (LOW)	The trend tends to persist (LOW)
Sea surface salinity	Sea surface salinity has risen by 0.1 – 0.2 psu off the west coast as recorded off Rottnest Island (LOW)	Decrease by 0.2 – 0.35 psu in NWWA possibly linked to freshening in the Pacific, and a further slight increase by ~0.025 psu in SWWA due to increased evaporation (LOW)	Increase by 0.15 – 0.85 psu; most pronounced adjacent to WA coastline and decreasing westward (LOW)
Air-sea heat fluxes	Rising trends in incoming longwave, solar radiation, and latent heat fluxes off WA from 1980s (LOW)	A slight decrease in ocean heat gain from air-sea fluxes due to increased latent heat (stronger offshore drier winds) (LOW)	Increased ocean heat gain due to a combination of increased solar, downward longwave radiation (LOW)
Winds	Weakening of the westerlies off the southwest coast of Australia during winter since mid-1970s (MEDIUM)	Broadening and intensification of subtropical high appears to result in easterly anomalies centred at 30°S (MEDIUM)	Dominance of the subtropical high to continue to extend southeastward (MEDIUM)
Precipitation	Decrease in intense events noted for recent years (MEDIUM)	Slight decrease by ~0.2mm/day in water flux (E – P) except for NWWA implies more (less) evaporation (precipitation) (MEDIUM)	Larger decreases by 0.3 – 1.2 mm/day (larger in north) suggests continued trend of more (less) evaporation (precipitation) (MEDIUM)

Adaptation Responses

The physical environment and marine ecosystem off the west and south Australia coasts are rather sensitive to climate variability, people should be aware that any long term trends in the Leeuwin Current system induced by climate change will be superimposed on interannual and decadal variations, which can sometimes overwhelm the trend signals. Although the levels of confidence on regional projections in the Leeuwin Current system is between LOW and MEDIUM, existing evidences of responses of marine ecosystems to observed changes in the physical environment (e.g. Poloczanska et al. 2007; Caputi et al. 2009b) suggest the need for adaptations in marine climate change, with the focus on conservation responses to increase resilience of our marine biodiversity as well as adapting our businesses and practices.

Knowledge Gaps

- Regional downscaling to increase resolution of the Leeuwin Current, shelf circulation and mesoscale dynamics in climate projections

- Establish time series of the Leeuwin Current volume and heat transports using observation programs such as Integrated Marine Observing System
- Establish/extend time series of the Indonesian Throughflow volume and heat transports using observation programs such as Integrated Marine Observing System
- Extend programs to measure sea surface salinity to infer the hydrological cycle of the climate system which could potentially be important for regional ocean circulation (e.g. Wijffels and Durack 2009)
- Improved understanding of the nature of decadal and multi-decadal variations of the climate systems in the tropical Pacific, Indian Ocean, and Southern Ocean

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