Chapter 7

Conclusion

7.1 SUMMARY AND DISCUSSION

The primary aim of this study has been to investigate the Leeuwin Current System off Western Australia (22°S–34°S) in the context of the large scale circulation of the southeast Indian Ocean. More specifically, the mean and seasonal Leeuwin Current and its interaction with the surrounding ocean have been described. We have also gained new insight into the regional system in which the Leeuwin Current is embedded: the Eastern Gyral Current, the Leeuwin Undercurrent, the Subtropical Gyre zonal jets and some deeper currents near 22°S.

This study relied on a combination of observations and numerical model outputs. In Chapter 3, we analyse current meter and hydrographic observations obtained from the ICM6 array, off North West Cape (22°S), as part of the Australian contribution to the World Ocean Circulation Experiment. The interpretation of those observations was supported by complimentary sea surface temperature imagery, regional hydrographic climatology, sea level anomaly altimetry, and other WOCE–related observations. In Chapters 4, 5 and 6, we analyse numerical model output from the Los Alamos Parallel Ocean Program, simulation POP11B 1993/97. In Chapter 4 the model diagnostics used were Lagrangian trajectories (online particle tracking), while in Chapters 5 and 6 the gridded Eulerian outputs were used. In this chapter, we summarise the results and discuss their implications.

At 22°S the mean Leeuwin Current (1994/96) emerges as a shallow and narrow coastally trapped poleward jet in the upper 150–200 m transporting Tropical Water of a variable θ–S content. The variable θ–S relationship is likely explained by seasonal and/or interannual changes in the water mass transformations driven by air–sea fluxes and in changing advection patterns of the Indo–Australian Basin, the Leeuwin Current's source area. Unfortunately, because of the frequent meandering of the Leeuwin Current in and out of the array domain, the ICM6 observations do not properly characterise its full flow. Thus we observe a relatively small mean volume transport of less than 0.3 Sv and lack of a clear seasonal transport modulation. The well observed part of the Leeuwin Current, immediately adjacent to the shelf break, has dominant synoptic variability and occasionally contains large spikes in its transport time series arising from the passage of tropical cyclones. Offshore, the dominant current/temperature variability is in the near semi–annual band (60–180 days) in the upper 800 m depth, largely consistent with the sea level fluctuations detected in altimetry [Morrow and Birol, 1998; Birol and Morrow, 2001, 2003]. The increase in the poleward transport of the Leeuwin Current towards the end of the time series along with the gradual deepening of the thermocline agree with the transition from an El Niño (1994) to a La Niña (1996) condition [e.g., Meyers, 1996; Wijffels and Meyers, 2004]. What has not been observed before in the above studies, as the XBT lines used to investigate the ENSO signal only extend down to 700–800 m, is the fact that the signal penetrates to greater depths of at least ~1500 m within the coastal waveguide and may have a reversed sign at ~2500 m.

New insights into the sources and pathways of tropical inflow to the Leeuwin Current are revealed by the online numerical particle tracking during the model's 5–year integration (1993/97). Particles in the Indo–Australian Basin which fed the Leeuwin Current originate from remote areas as far as the western/central Tropical Pacific and the Somali Basin in the tropical Indian Ocean. In both oceans, near equatorial surface currents (upper 100 m) advect particles towards the Indonesian archipelago which then reach the Indo–Australian Basin via the South Java Current (Indian) and the Indonesian Throughflow (Pacific). Once in the Indo–Australian Basin, these particles subsequently travel along and southward across the westward–flowing South Equatorial Current (~10°–15°S) and eastward–flowing Eastern Gyral Current (~16°–20°S), either following an "S" (via North West Shelf) or "C" (otherwise) route before joining the poleward flow of the Leeuwin Current along the west Australian coast. These results contest the widespread belief that the tropical waters feeding the Leeuwin Current flow poleward along the North West Shelf and are purely of Indonesian Throughflow/Pacific origin. A strong connection with the tropical Indian Ocean is found in these numerical trajectories.

The fact that water parcels do not necessarily follow the "S" route, and also that the "C" route appears to be preferred by the North Indian particles, may have implications for the advection of nutrients, planktonic larvae, heat, salt and other tracers. For instance, the North West Shelf is an area notorious for large internal waves and associated turbulence which may lead to intense vertical mixing of the water column [Holloway, 1994, 1996; Holloway *et al.*, 2001]. So, whether water does or does not flow along that region might be important for the vertical distribution of properties.

In addition to the tropical source from the Indo–Australian Basin, near surface eastward jets within the southeast Indian Subtropical Gyre are responsible for injection of

Subtropical Water into the Leeuwin Current. Many studies have argued that this subtropical inflow, which has always been deemed a broad onshore flow rather than a series of zonal jets as observed in the POP model and in a recent work [Wijffels *et al.*, *in prep.*], is the primary source of the Leeuwin Current. Although the online particle tracking has provided a clearer understanding of the regional circulation, it does not contain a sufficiently large number of trajectories to obtain quantitative estimates of the importance of the two source regions for the Leeuwin Current.

A comprehensive portrait of the structure, volume transport and transport–weighted properties of the mean and seasonal Leeuwin Current along the west Australian coast has been constructed based on the model's Eulerian diagnostics. In the mean, the Leeuwin Current is a year–round poleward boundary flow that progressively deepens from 150 to 300 m, but does not uniformly accelerate downstream. There are three distinct regions in which its poleward transport increases or decreases following net lateral inflows or outflows. It starts with –1.2 Sv at 22°S; gains another –1.1 Sv between 22°–27°S through a net eastward inflow; loses –0.8 Sv through a net westward outflow between 27°–33°S; and finally gains –0.7 Sv through a second net eastward inflow, increasing its transport to –2.2 Sv at 34°S. In terms of transport–weighted salinity, θ and σ_θ the Leeuwin Current respectively gains 0.6 psu, loses 6°C and gains 2 kg m^{-3} along its path from North West Cape (22°S) to Cape Leeuwin (34°S). so it becomes cooler, saltier and denser. The Leeuwin Current is quiescent during summer (–0.5 to –1.5 Sv) and strongest during wintertime (peaking in May–June, –4.0 to –4.5 Sv), at which time it is freshest and warmest. Winter is also the period when the water properties of the Leeuwin Current are more vertically homogeneous (e.g., deeper mixed layers).

Instabilities of the stronger winter Leeuwin Current jet evolve into mesoscale eddies, which detach from the boundary and migrate offshore. July–August is the period when the eddy activity is most intense. From September, the activity begins to decay and the Leeuwin Current progressively returns to its summertime condition. This seasonal cycle appears to be partially forced by the anticlockwise progression of an annual Kelvin wave, starting in April as a coastal positive sea level anomaly trapped along the Australian coastline, as suggested in Godfrey and Ridgway [1985] and more recently implied by Potemra [2001]. A departure from this seasonal variation is found near Cape Leeuwin (34°S), where the transport maximum lasts from April to November and is presumably related to the temporal variations of one of the eastward subtropical jets that feeds into the Leeuwin Current. What has been quantified in this portrait of the Leeuwin Current has been known in great part in a qualitative viewpoint, with quantitative estimates limited to specific sites [Smith *et al.*, 1991; Feng *et al.*, 2003]. This close agreement between the model and observations gives us good confidence in the simulation, despite expected underestimation of the volume transport values by the model's eddy–permitting resolution (e.g., ~50% of the mean volume transport at 32°S in comparison to Feng *et al.* [2003] but only ~10% during the maximum peak in winter).

Part of the changes in water properties observed along the downstream path of the Leeuwin Current – for instance, the ~0.6°C cooling per 100 km – must arise from air–sea fluxes, and part due to lateral exchanges with the adjacent ocean. Global maps of surface heat flux [e.g., Josey *et al.*, 1999] indicate an ocean heat loss along the eastern boundary of the southeast Indian Ocean since the Leeuwin Current carries heat poleward, similar to a western boundary current. Although poleward flows have been reported in other eastern boundaries, none of them contain as much heat as is transported by the Leeuwin Current as they flow at much higher latitudes and do not have a warm tropical source. Recent studies have started to investigate the exchange of the Leeuwin Current with the adjacent ocean by surveying the amount of heat contained in long lived anticyclonic warm core eddies which originally separated from its boundary jet. Despite the inflow of Subtropical Water by the eastward jets, westward advection of particles from the Leeuwin Current into the Subtropical Gyre by eddy motion is also observed in the numerical particle tracking. The particles either remain offshore (mainly east of 100°E) until the end of the model simulation or reentrain into the Leeuwin Current jet. While offshore or within the jet, these particles have their properties transformed into water of more subtropical characteristics.

The mechanisms cooling the model Leeuwin Current and adjacent ocean have been quantitatively determined. The heat advected from the tropics towards subtropical latitudes off Western Australia is most intense and mainly carried poleward by the mean boundary jet of the Leeuwin Current. This heat is then transferred to the offshore ocean by the divergence of eddy heat fluxes. This lateral export (upper 185 m depth) accounts for about 70% of the cooling of the mean jet. Only 30% of the heat is lost from the ocean mixed layer to the atmosphere through air–sea fluxes over the jet.

The heat gained from the eddy heat flux divergence along the outer edge of the Leeuwin Current is the primary means by which the ocean interior warms up (~70% eddy divergence against ~30% mean divergence). The eddy warmed ocean interior is then locally cooled by the air–sea fluxes which now operate over a larger surface area. Due to temporal limitations in model output we could not diagnose which process drives the divergence of the eddy heat fluxes, though a Reynolds decomposition shows it occurs at submonthly time scales. Associated with this eddy heat flux must be a bolus transport which impacts the potential vorticity structure of the jet.

The model westward eddy heat flux of 27 TW is comparable to an observational estimate of 22–44 TW [Feng *et al.*, 2005b]. Both values suggest that the heat removed from the Leeuwin Current by long lived warm core eddies, in the order of 4 to 5 TW [Morrow *et al.*, 2003], is a small percentage of the overall westward eddy heat flux. We suspect, however, that short lived warm core eddies may play an important role.

The model's Eastern Gyral Current emerges as two subsurface–intensified eastward jets, one centred at 15°S and the other at 19°S. The current is fed by a recirculation of the South Equatorial Current in its upper portion but it is not clear from where water is supplied to its lower portion. As the Eastern Gyral Current exists in a more subtropical environment, its surface water is not as fresh and warm as the Indonesian Surface Water found in the South Equatorial Current (10°–15°S). However, it is clearly the Eastern Gyral Current surface (tropical) water that is advected by the Leeuwin Current near 22°S, as verified by hydrographic observations. Presumably the context set by the Indonesian Surface Water together with the lack in knowledge about the source of the Eastern Gyral Current have led previous studies to think of it as a subtropical stream [Meyers *et al.*, 1995; Wijffels *et al.*, 1996; Bray *et al.*, 1997]. In spite of this, these studies have correctly postulated its fate, in which one branch of the Eastern Gyral Current continues towards the Indo–Australian Basin and eventually returns as part of the South Equatorial Current, while a second one veers poleward near 22°S to feed into the Leeuwin Current ("C" route). The numerical particle tracking supports this hypothesis but has also revealed that the branch of the Eastern Gyral Current moving towards the Indo–Australian Basin augments boundary currents along the North West Shelf which flow in opposite directions. The upper portion of the branch flows into a poleward surface flow which feeds the Leeuwin Current ("S" route) whereas the lower portion flows into an equatorward subsurface flow, which veers into the South Equatorial Current. This equatorward subsurface flow is also fed by waters of the Leeuwin Undercurrent that make their way into the Indo–Australian Basin. Although the North West Shelf apparently presents a surface poleward current and an equatorward undercurrent, both connected with the flows of the Leeuwin Current and Leeuwin Undercurrent respectively, we prefer to consider them distinct features as they reverse direction seasonally and thus differ from more permanent currents, as observed along the west Australian coast.

In addition to the Leeuwin Current, the water column at 22°S is characterised by a rich variety of currents, such as the Leeuwin Undercurrent, a poleward flow below the undercurrent and narrow bottom–intensified flows. The equatorward flow of the Leeuwin Undercurrent is trapped along the upper continental slope, between 150/200 and 500/750 m depth, with a maximum centred at 200–300 m. Unfortunately the direct observations barely resolved the undercurrent's structure but the hydrographic observations indicate it carries Subtropical Water (salinity maximum), Indian Central Water (θ–S linear relationship) and Antarctic Intermediate Water (salinity minimum). Below the undercurrent, a poleward flow spreads a mixed Intermediate Water at ~700–1400 m depth, which partially owes its salinity characteristics to outflows from the Red Sea and Persian Gulf. It is the same mixed Intermediate Water reported in Wijffels *et al.* [2002] and transported by a deep eastward current along 16°–18°S. So this deep zonal flow (or multiple narrow jets) seems to veer near the Australian coast, similar to what happens near surface with the Eastern Gyral Current. θ–S diagrams reveal that strong interleaving occurs between the mixed and the Antarctic Intermediate Water. The most prominent bottom–intensified flow lies at 1515 m depth, with a 470–day mean poleward velocity of –2.4 cm s^{-1}. In all likelihood it would be very difficult to estimate this flow using the thermal wind relationship because of its narrowness and proximity to the ocean floor. Another aggravation is the fact that near synoptic hydrography will tend to be aliased by strong internal tides, at least near 22°S, and consequently will not produce valid geostrophic estimates. This first ever view of the current structure below the Leeuwin Undercurrent derived from direct observations suggests that much yet has to be learned about the deep eastern boundary system off Western Australia.

The source of Subtropical Water flowing in the Leeuwin Undercurrent at 22°S is far from the coastal boundary, in the centre of the Subtropical Gyre (~30°S). We suggest that eastward jets supply this water, similar to the eastward jets that supply the Leeuwin Current at higher latitudes. The model particle tracking does corroborate this and also shows the two–way exchange between the boundary flows and the ocean interior. Most of the inflow supplied to the Leeuwin Undercurrent by the subsurface–intensified eastward jets is returned to the Subtropical Gyre at deeper depths by westward outflows of the Leeuwin Undercurrent. The result is then a net anticyclonic movement, which forms the eastern limb of the Subtropical Gyre. The Western Australian Current might be understood in this way or, alternatively, as the weaker northerly drift in which the dominant zonal flows are embedded. The subtropical westward jets are also, in part, fed by an outflow from the South Australian Basin. The augmentation of the Leeuwin Undercurrent is influenced by the gradual deepening of the eastward jets towards the coast associated with subduction driven by Ekman pumping and, presumably, also with eddy subduction, more relevant where mesoscale activity is most intense.

7.2 CONCLUSIONS

The combination of observations and model output has strengthened the interpretation and understanding of various aspects of the Leeuwin Current System. Consequently, to some extent, we have replaced the somewhat piecemeal picture of the regional circulation of the southeast Indian Ocean. The conclusions arising from this study related to the questions proposed in the introduction are as follows.

7.2.1 Source regions of the Leeuwin Current

Using model Lagrangian particles, we have confirmed the tropical (Indo–Australian Basin) and subtropical (Subtropical Gyre) inflows of the Leeuwin Current but also contest some of the inferences made in the past.

- The tropical source of the Leeuwin Current is not exclusively of Indonesian Throughflow/Pacific origin as implied in earlier work. We have established significant contribution from the tropical Indian Ocean, via the South Java Current.
- There are two main routes through the Indo–Australian Basin by which particles reach the Leeuwin Current: one via a poleward flow along the North West Shelf ("S" route) and the other via a poleward veering of the Eastern Gyral Current nearer North West Cape ("C" route). Both routes involve the southward traverse of zonal currents in the upper 100 m and water mass transformation (cooling and evaporation) along their paths. The tropical Indian source of the Leeuwin Current seems to prefer the "C" route.
- There is no direct path between the outflow from Timor Strait and the poleward flow along the North West Shelf, augmenting the Leeuwin Current. In the model, the outflow from Timor Strait first goes into the South Equatorial Current which later redirects some of its water to the poleward flow along the North West Shelf.
- In the literature the Eastern Gyral Current is thought of as a subtropical stream but we have shown that, at least, its upper portion is augmented by surface water flowing out of the South Equatorial Current. Despite this tropical origin, the water properties of the surface water of the Eastern Gyral Current are not as fresh and warm as those in the South Equatorial Current, as it is subjected to stronger cooling and evaporation in the transition area between tropics and subtropics.
- We have discovered that the subtropical source region of the Leeuwin Current is also a source region for the Leeuwin Undercurrent. Until we examined the ICM6 hydrographic observations in the context of the large scale circulation, the link between the eastward jets and the Leeuwin Undercurrent was not previously suspected. Near surface eastward jets carrying Subtropical Water are predisposed to augment the Leeuwin Current along the southern section of the west Australian coast and the Leeuwin Undercurrent along the northern section. So, in this eastern boundary system of the South Indian Ocean salt is meridionally transported in both directions.

7.2.2 Mean flow and seasonality of the Leeuwin Current

- The mean poleward volume transport of the Leeuwin Current calculated from the ICM6 observations (1994/96) is less than –0.3 Sv and lacks a clear seasonal cycle. Part of this is explained by a shallow, narrow and relatively weak poleward boundary jet at 22°S compared to further downstream, however, the other part is explained by shortcomings in the observations as the Leeuwin Current jet often meandered away from the array domain. In the well observed part of the Leeuwin Current, synoptic variability (several days to a few months) dominates. Some of the transient peaks in the transport time series of the Leeuwin Current were clearly associated with the passage of tropical cyclones.
- At 22°S the Leeuwin Current exclusively advects Tropical Water of variable θ–S properties as seen in the ICM6 hydrographic observations. This variable θ–S content appears to be caused by seasonal and interannual variability in water mass transformation due to air–sea fluxes and in advection patterns in the source area, the Indo–Australian Basin. Below the Leeuwin Current, the Leeuwin Undercurrent transports Subtropical Water, South Indian Central Water and Antarctic Intermediate Water equatorward between 150/250 to 500/750 m depth. There is a poleward flow just below the Leeuwin Undercurrent transporting a mixed Intermediate Water partially associated with outflows from the Red Sea and Persian Gulf. Narrow bottom–intensified currents are also part of the rich vertical current structure observed at 22°S.
- In terms of variability, the ENSO signal seems to penetrate down to at least 1500 m, and may have a reverse sign at 2500 m, along the coastal waveguide at 22°S. Mesoscale variability (60–180 days) dominates in the 200–800 m depth in the offshore part of the ICM6 array. However, the temperature/current meter time series are not sufficiently long to properly address both signals.
- In the 5–year model average (1993/97), the Leeuwin Current is a poleward flow found year–round along the west Australian coast, from 22°S to 34°S. The magnitude of its mean transport does not steadily increase downstream as it depends on net lateral inflows and outflows occurring at different latitudes. However, the current essentially has double the transport at 34°S (–2.2 SV) compared to at 22°S (–1.2 SV). In addition to the mean maximum at 34°S, the Leeuwin Current has a second mean maximum at 27°S (–2.3 Sv) due to a net eastward inflow of 1.1 Sv north of 27°S. Along its boundary path, the Leeuwin Current becomes cooler, saltier and denser respectively by 0.6 psu, 0.6°C and 2 kg m^{-3}. At 32°S, the model transport magnitude is about 50% of the geostrophic value calculated by Feng *et al.* [2003].

- The seasonal variability of the model Leeuwin Current follows a wintertime intensification and a summertime decay, as proposed in the literature. It carries about –4 to –4.5 Sv during May–June, mostly between 26°S and 32°S. This seasonal peak is almost equivalent to the estimate in Feng *et al.* [2003], and is responsible for the poleward advection of the warmest and freshest water observed along the west Australian coast. A departure from this seasonal variation appears near 34°S, where the maximum poleward transport lasts from April to November. Apparently the seasonal variability of the Leeuwin Current is initially triggered by the poleward propagation of a coastally trapped Kelvin wave during April, evident in the model sea surface height, and reinforced by a subsequent minimum in the local equatorward wind stress in July, as suggested in Godfrey and Ridgway [1985].

7.2.3 Cooling mechanism of the Leeuwin Current

- The mechanism responsible for ~70% of the cooling of the Leeuwin Current along the west Australian coast (0.6°C per 100 km) is the divergence of the eddy heat flux associated with submonthly processes. Just which mechanism is not revealed by the heat budget. The air–sea fluxes have a minor role in the cooling of the Leeuwin Current (~30%), whereas seasonal rectification processes are negligible.
- The heat removed from the coastal boundary, over a narrow region along the outer edge of the Leeuwin Current, by the divergent eddy heat flux is laterally transferred to the adjacent ocean interior. This accounts for 70% of the warming observed in a large area of the offshore ocean, which consequently sustains strong heat losses to the atmosphere.
- The determination of the heat balance and their controlling factors is certainly an initial step towards the understanding of the implications of eddy processes in climate variability of the southeast Indian Ocean. The "leakiness" between the eastern boundary and the ocean interior may also be an important process for the cross–shelf transport of crustacean larvae of valuable commercial interest (e.g., western rock lobster).