Chapter 1

Introduction

Despite increasing appreciation of the impact of the oceans on the wealth of marine resources and climate, the understanding of the ocean circulation around Australia remains fairly inadequate. In this study, we seek to extend the present knowledge of the upper circulation along the west Australian coast, the eastern boundary of the South Indian Ocean, using a combination of recent observations and high resolution numerical model outputs. This region is dominated by the poleward flow of the Leeuwin Current [Cresswell and Golding, 1980], the only eastern boundary current in the world to advect heat from warm tropical regions to midlatitudes [**Figure 1.1**], a behaviour which is more characteristic of western boundary systems (e.g., Gulf Stream in the northwest Atlantic, East Australian Current in the southwest Pacific and Agulhas Current in the southwest Indian). Because of the Leeuwin Current, the ocean region off Western Australia experiences higher sea surface temperatures compared to other eastern boundaries [Dakin, 1919; Pearce, 1991; Feng *et al.*, 2003] and heat fluxes out of the ocean [Hsiung, 1985; Josey *et al.*, 1999]. The Leeuwin Current also supports an unusual distribution of tropical marine flora and fauna in temperate latitudes [Saville-Kent, 1897] and atypical pattern of oceanic primary productivity [Lenanton *et al.*, 1991; Caputi *et al.*, 1996; Moore, 2005] and low tonnage, high value fisheries [Lenanton *et al.*, 1991; Caputi *et al.*, 1996; Moore, 2005].

Given these strong influences of the Leeuwin Current in the ocean region off Western Australia, the aim of this study is:

(i) to identify the source regions of the Leeuwin Current;

(ii) to quantify the mean and seasonal variability of its volume, heat and salt transports;

(iii) to determine the driving mechanism cooling the Leeuwin Current, from North West Cape (22°S) to Cape Leeuwin (34°S).

The organisation of this study is as follows. **Chapter 2** is a review of the upper ocean circulation in the southeast Indian Ocean. In **Chapter 3**, we examine the ICM6 (Indian Current Meter 6) current meter and cruise data obtained near North West Cape (22°S), along with other complementary data to explore the Leeuwin Current in its regional context. The ICM6 current observations are the longest and most recent time series for the Leeuwin Current, which additionally give insight into the deeper current regimes, most of them measured for the first time. Hydrographic observations are used to infer potential source regions and pathways. This, however, is better understood in **Chapter 4** where model Lagrangian particles clearly reveal the links between the large scale circulation and the Leeuwin Current, proving an useful guide for the interpretation of subsequent findings in **Chapters 5** and **6**. In **Chapter 5**, the Eulerian model outputs are used to determine the mean and seasonal variability of the Leeuwin Current, from 22°S to 34°S, in terms of current structure, volume transport and transport–weighted properties (i.e., heat and salt transport). In **Chapter 6**, the model outputs are used to analyse the heat budget of the Leeuwin Current to pinpoint the processes which account for the observed cooling along its path. The outputs are derived from an eddy–permitting simulation of a global z–level model, the ⅙° Parallel Ocean Program (POP11B) from the Los Alamos National Laboratory, for a 5–year period between January 1993 and December 1997. Finally, we discuss and summarise the main findings in **Chapter 7**.

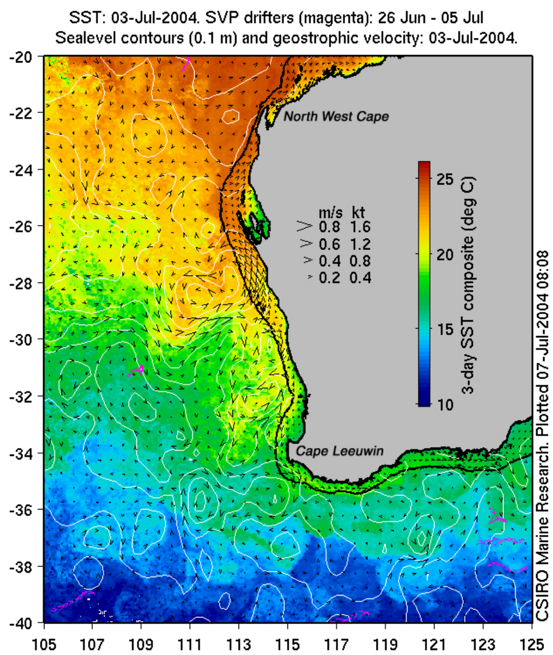

Figure 1.1. High resolution map of sea surface temperature and current off Western Australia. The Leeuwin Current is the warm boundary flow from which an anticyclonic (warm core) mesoscale eddy detaches at ~28°S. Courtesy of David Griffin and CSIRO Marine Research, Hobart, Australia [*http://www.marine.csiro.au/remotesensing/oceancurrents/*].

Chapter 2

Regional background

2.1 SHELVES AND BASINS

The southeast Indian Ocean, off Western Australia, and its surroundings are shown in **Figure 2.1**. The ocean region between the northwest coast of Australia and the Indonesian islands of Java and Sumatra is the Indo–Australian Basin. The Indonesian Seas (or Indonesian Throughflow) allow for the interocean exchange between the Pacific and Indian Oceans. The broad shelf along the northwest coast of Australia is the North West Shelf (herein we refer to it as together with the adjacent continental slope). The Great Australian Bight is the east–west oriented shelf along the South Australian Basin. The Perth Basin is the abyssal plain between the Cuvier and Naturaliste Plateau.

2.2 WINDS

The Asian–Australian monsoons, with transitions in May and November, blow mainly over the Indo–Australian Basin [**Figure 2.2**]. The hot and wet season is during the northwest monsoon (December–April) while the cooler and drier season is during the southeast monsoon (June–October) [Tomczak and Godfrey, 1994; Godfrey and Mansbridge, 2000]. About three to eight tropical cyclones pass over the North West Shelf between November and April each year [Church and Craig, 1998]. The Trade winds move anticlockwise along a high pressure atmospheric system off Western Australia. Near the Australian coast, they blow equatorward, more strongly from November to March [Godfrey and Ridgway, 1985]. The Westerlies are found in a zonally extended latitudinal band between 40°S and 60°S.

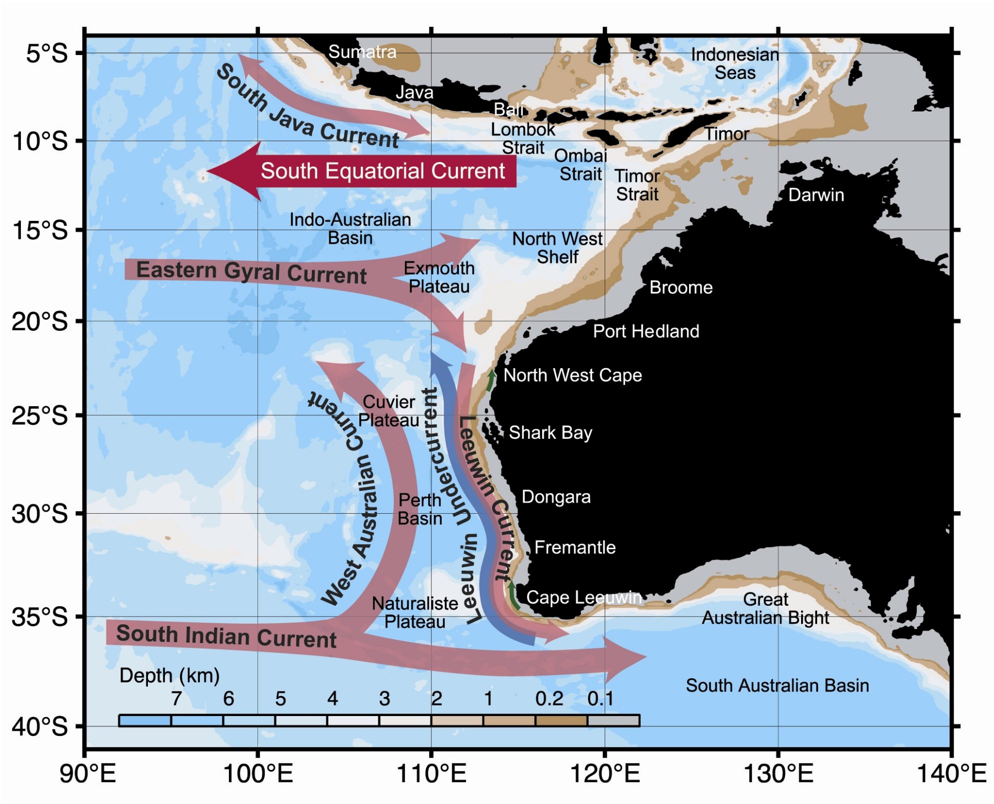

Figure 2.1. Southeast Indian Ocean. Shelves, basins, topographic features and upper ocean current schematic. The small green arrows on the west Australian shelf represent the Ningaloo Current near North West Cape (22°S) and the Capes Current near Cape Leeuwin (34°S). See text for details.

2.3 MAJOR CURRENT SYSTEMS

The swift westward flow of the South Equatorial Current (10°–15°S) [**Figure 2.1**], mainly carrying very fresh Indonesian Surface Water and Indonesian Intermediate Water [Wijffels *et al.*, 2002], is augmented by outflows from the Indonesian Seas [Godfrey, 1996] and some recirculation of the South Java Current and the Eastern Gyral Current [Quadfasel *et al.*, 1996; Sprintall *et al.*, 2002]. The South Java Current is a semi–annually reversing shallow current along the Java/Sumatra coasts, flowing strongly eastward during the monsoon transitions [Quadfasel and Cresswell, 1992; Sprintall *et al.*, 2000]. The Eastern Gyral Current is a relatively slow and shallow eastward subtropical shear in the upper 150–200 m along 16°–18°S [Meyers *et al.*, 1995]. Both South Equatorial Current and Eastern Gyral Current intensify during July–September [Meyers, 1996].

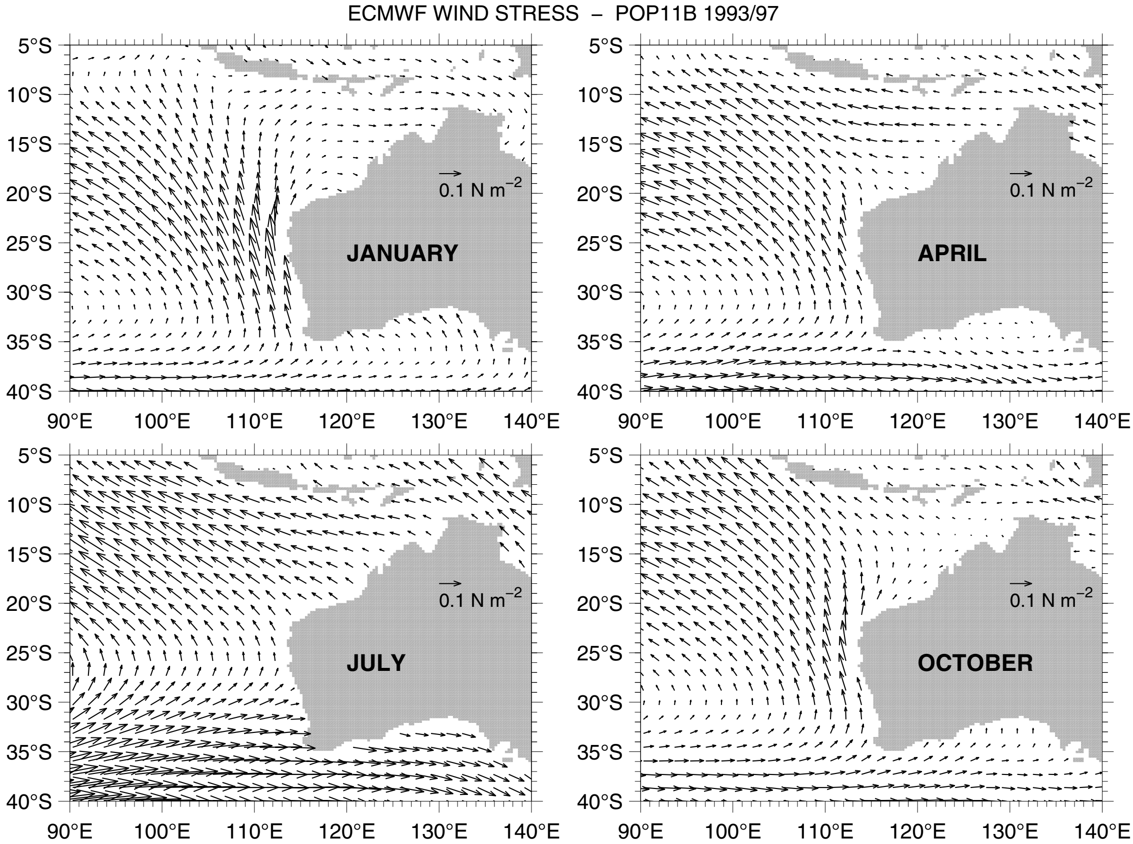

Figure 2.2. Seasonal European Centre for Medium–range Weather Forecasts (ECMWF) wind stress [every sixth vector plotted as in POP11B 1993/97 output, see **Appendix C**].

The wind–driven equatorward currents on the west Australian shelf are the Ningaloo Current (near North West Cape) [Taylor and Pearce, 1999] and the Capes Current (near Cape Leeuwin) [Pearce and Pattiaratchi, 1999] and the boundary flows are the poleward Leeuwin Current [Cresswell and Golding, 1980] and its subsurface equatorward undercurrent, the Leeuwin Undercurrent [Thompson, 1984; Smith *et al.*, 1991]. The anticlockwise circulation of the Subtropical Gyre lies in the adjacent ocean interior off Western Australia, a region of strong evaporation characterised by highly saline Subtropical Water [Warren, 1981]. The Subtropical Gyre is also a subduction region in which water from the mixed layer is pumped into the permanent thermocline through Ekman convergence driven by the anticyclonic wind stress [Karstensen and Quadfasel, 2002b]. The South Indian Ocean Current runs eastward along the southern limb of the Subtropical Gyre [Stramma, 1992; Stramma and Lutjeharms, 1997] while the West Australian Current flows along the northeastern limb [You and Tomczak, 1993]. In addition to the circulation associated with the Subtropical Gyre, broad geostrophic zonal flows, onshore at surface and offshore at subsurface, are deduced from maps of meridional pressure gradient [**Figure 2.3**] in the subtropical ocean off Western Australia [Godfrey and Ridgway, 1985].

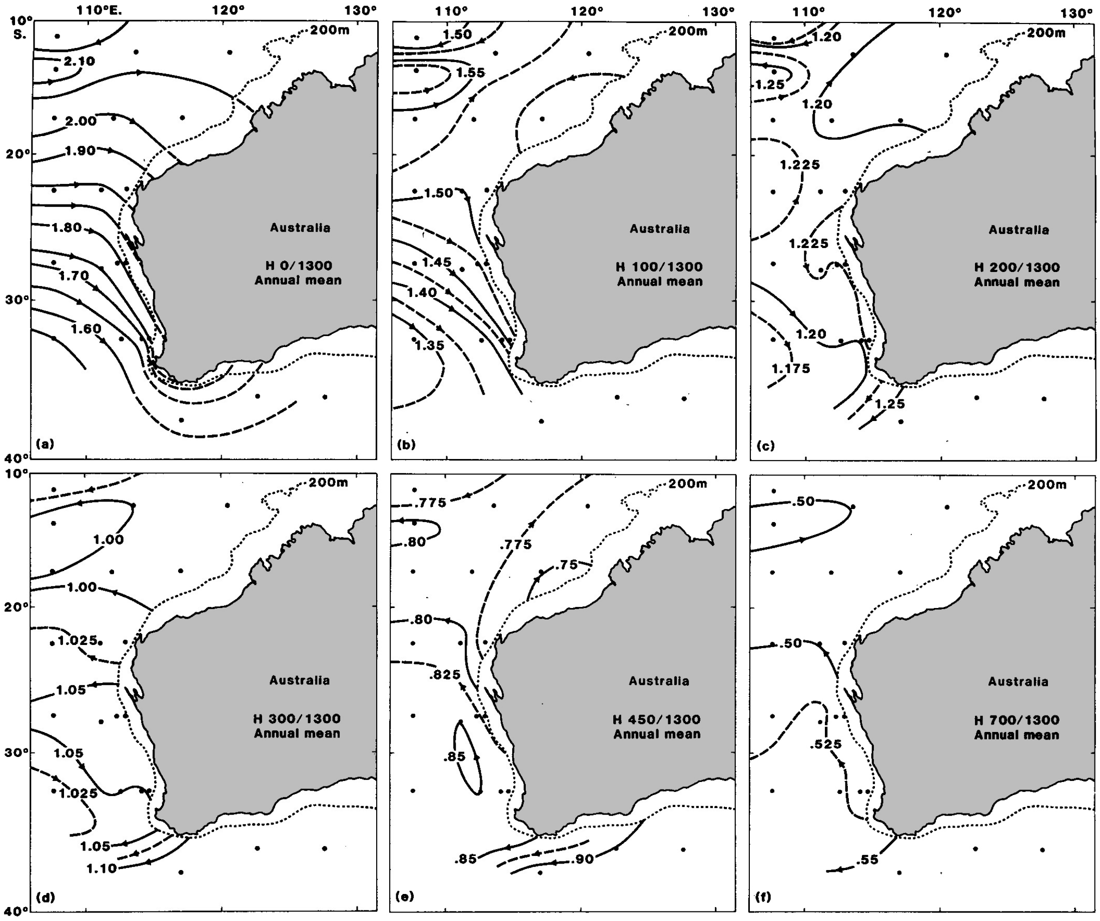

Figure 2.3. Annual average steric height relative to 1300 db: at 0 db (a), 100 db (b), 200 db (c), 300 db (d), 450 db (e) and 700 db (f) [from Godfrey and Ridgway, 1985].

2.4 SOURCE REGIONS OF THE LEEUWIN CURRENT

An outflow from Timor Strait into the North West Shelf [Sharma, 1972; Godfrey and Golding, 1981; Nof *et al.*, 2002] is thought to be the source for the relatively warm low salinity tropical water advected poleward by the Leeuwin Current along the west Australian coast. Some studies in fact refer to the current as starting from the North West Shelf [Holloway, 1995] but others only recognise it south of North West Cape (22°S) [**Figure 1.1**] where a broad raft of warm water from the tropics tapers into the west Australian shelf break/continental slope [Gentilli, 1972]. In addition to the tropical source, the Leeuwin Current is known to transport subtropical waters fed by eastward flows which veer poleward near the Australian coast. These zonal flows are a branch of the Eastern Gyral Current near North West Cape [Wijffels *et al.*, 1996] and the broad onshore geostrophic flow off Western Australia [Godfrey and Ridgway, 1985]. A number of studies have claimed that subtropical water from the onshore geostrophic flow, rather than tropical water from the North West Shelf, is the main source of the Leeuwin Current [e.g., Batteen *et al.*, 1992]. Until present, however, there is no study that has properly dealt with the problem of how and where the Leeuwin Current waters originate to confirm any of the proposed assumptions.

2.5 THE LEEUWIN CURRENT SYSTEM

Several studies propose that the Leeuwin Current apparently owes its existence to an anomalously large meridional gradient in steric height in the southeast Indian Ocean – maintained by the interocean exchange of warm tropical water from the western Pacific into the eastern Indian through the Indonesian Seas – which overcomes the opposing local wind stress and allows a poleward boundary flow along the west Australian coast [Thompson, 1984; Godfrey and Ridgway, 1985; McCreary *et al.*, 1986; Thompson, 1987; Weaver and Middleton, 1989; Godfrey and Weaver, 1991]. Subsurface, this alongshore pressure gradient is reversed [Godfrey and Ridgway, 1985] and drives the Leeuwin Undercurrent, which advects South Indian Central Water and Antarctic Intermediate Water equatorward in the upper slope (~300–700 m) [Thompson, 1984; Sprintall *et al.*, 2002; Fieux *et al.*, 2005].

Hydrographic and current observations altogether suggest that the Leeuwin Current has a strong seasonal cycle, in which fresher and warmer tropical waters are observed along the west Australian coast [**Figure 2.4**] when its poleward flow is maximum during May–June [Cresswell and Golding, 1980; Smith *et al.*, 1991]. Although Smith *et al.* [1991] have directly measured the Leeuwin Current, they only measured it for about one year and have not provided direct transport estimates (their transport estimates were based on geostrophic calculations from synoptic cruises). Very recently, Feng *et al.* [2003] have developed a high resolution regional climatology to determine the mean, seasonal and interannual geostrophic transport of the Leeuwin Current at 32°S. Seasonally, the current has a maximum poleward transport of –5 Sv during June–July. The annual mean is –3.4 Sv but it increases to –4.2 Sv in La Niña years and decreases to –3.0 Sv in El Niño years. As the Leeuwin Current seems to deepen and accelerate along its poleward path [Church *et al.*, 1989], those transport values may only represent a local estimate. The lack of observations at other locations along the west Australian coast prevents estimates of the spatial variability of the volume transport. The poleward heat and salt transport have not been well studied.

By examining the depth–integrated alongshore momentum balance at the west Australian continental shelf edge between 22.5°S and 32.5°S, Godfrey and Ridgway [1985] have determined that the seasonal cycle of the Leeuwin Current is driven by a combination of pressure gradient and wind stress [**Figure 2.5**], which reinforce one another and results in a strong poleward boundary flow in May–June. The annual variation of the alongshore pressure gradient is part of an anticlockwise wavelike progression around the northwest, west and south coasts of Australia driven by a coastally trapped Kelvin wave. This annual Kelvin wave propagates from the Indonesian Seas after an equatorial Rossby wave impinges on the western boundary of the Pacific Ocean [Potemra, 2001]. The same physics operates for interannual Kelvin/Rossby waves carrying the El Niño Southern Oscillation (ENSO) signal from the Pacific into the Indian Ocean [Pariwono *et al.*, 1986; Pearce and Phillips, 1988; Clarke, 1991; Clarke and Liu, 1994; Meyers, 1996; Potemra and Lukas, 1999; Feng *et al.*, 2003; Wijffels and Meyers, 2004]. Higher sea level anomalies, warmer sea surface temperatures and deeper thermoclines are expected in the eastern Indian Ocean during La Niña years and vice–versa during El Niños [Pariwono *et al.*, 1986; Pearce and Phillips, 1988; Clarke, 1991; Clarke and Liu, 1994; Meyers, 1996; Potemra and Lukas, 1999; Feng *et al.*, 2003; Wijffels and Meyers, 2004]. At higher frequencies, a semi–annual signal, with peaks in May and November, has been detected between 20°S and 35°S [Morrow and Birol, 1998]. This signal is related to westward propagating Rossby waves (mesoscale variability) emanating from the west Australian boundary, with timescales ranging from 100 to 200 days [Birol and Morrow, 2003]. Although it is still unclear which mechanism triggers these semi–annual waves, it is known that they are not forced by local Ekman pumping in the ocean interior nor by local variations in wind stress near the coast [Birol and Morrow, 2001].

Anomalously high mesoscale variability (eddy field) off Western Australia is an intrinsic part of the southeast Indian Ocean circulation. A range of features is evident in sea surface satellite imagery, varying from offshoots, filaments, squirts, meanders to coherent anticyclonic and cyclonic vortices [Legeckis and Cresswell, 1981; Griffiths and Pearce, 1985; Pearce and Griffiths, 1991; Cresswell and Peterson, 1993; Pearce and Phillips, 1994; Cresswell and Griffin, 2004]. Modelling and observational studies have suggested that barotropic and baroclinic instabilities of the sheared flow of the Leeuwin Current are responsible for the generation of this energetic mesoscale activity [Batteen *et al.*, 1992; Batteen and Butler, 1998; Feng *et al.*, 2005b] whose eddy kinetic energy is the highest among all eastern boundary systems [Feng *et al.*, 2005b]. The most impressive of the eddy features is the long–lived anticyclonic warm core vortices which detach from the boundary flow of the Leeuwin Current. Using a combination of altimetry, thermal and colour satellite imagery and *in situ* observations, recent work is focusing a great deal of effort on these warm core vortices to understand their role in the redistribution of heat and other properties between the boundary and the ocean interior [Fang and Morrow, 2003; Morrow *et al.*, 2003; Morrow *et al.*, 2004; Feng *et al.*, 2005a; Feng *et al.*, 2005b; Moore, 2005].

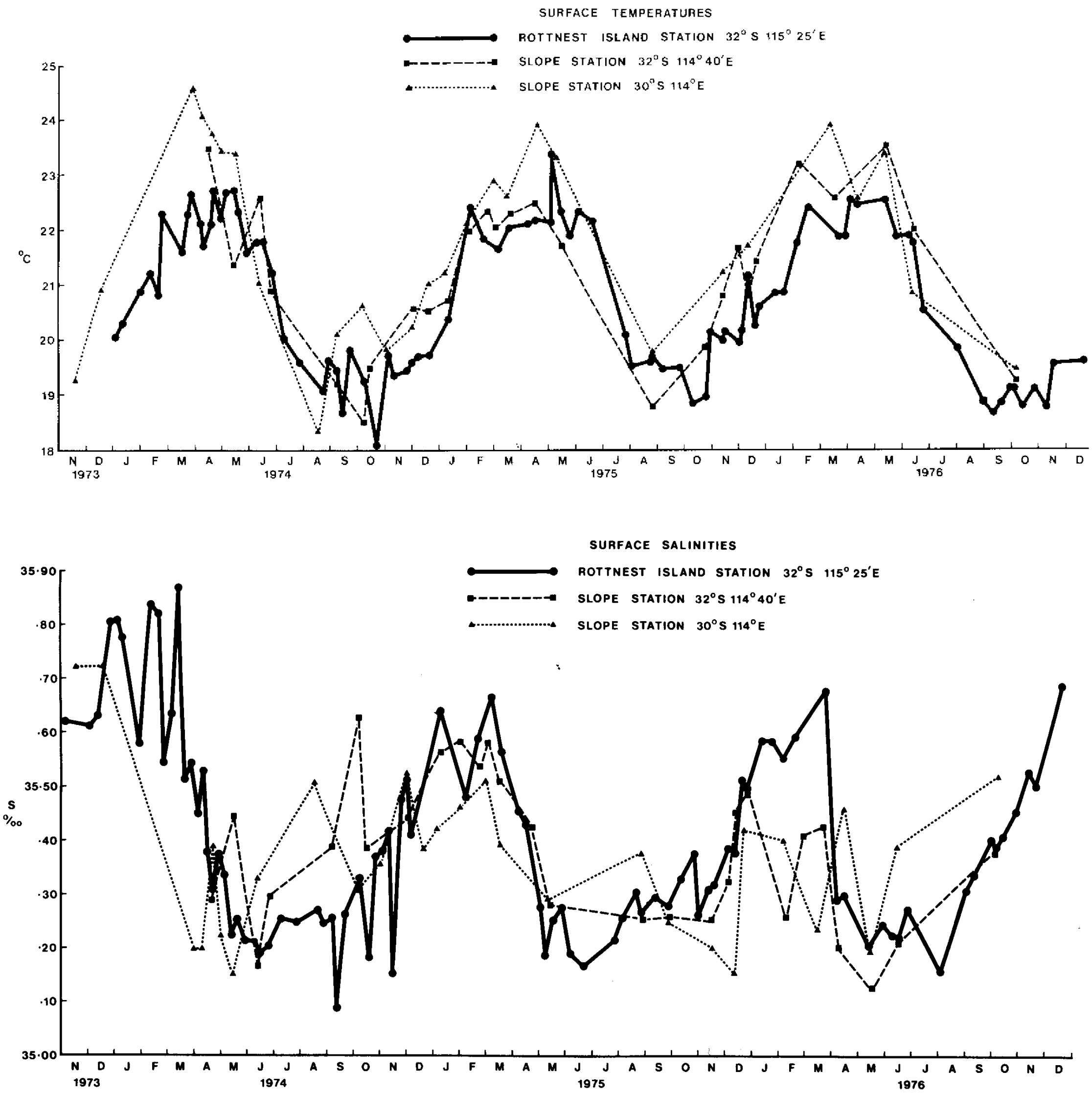

Figure 2.4. Three–year time series from Rottnest Island. Mid shelf station (full line) and continental slope stations at 32°S, 114°40' (dashed) and 20°S, 114°E (dotted) for surface salinity (top) and surface temperature (bottom) [from Cresswell and Golding, 1980].

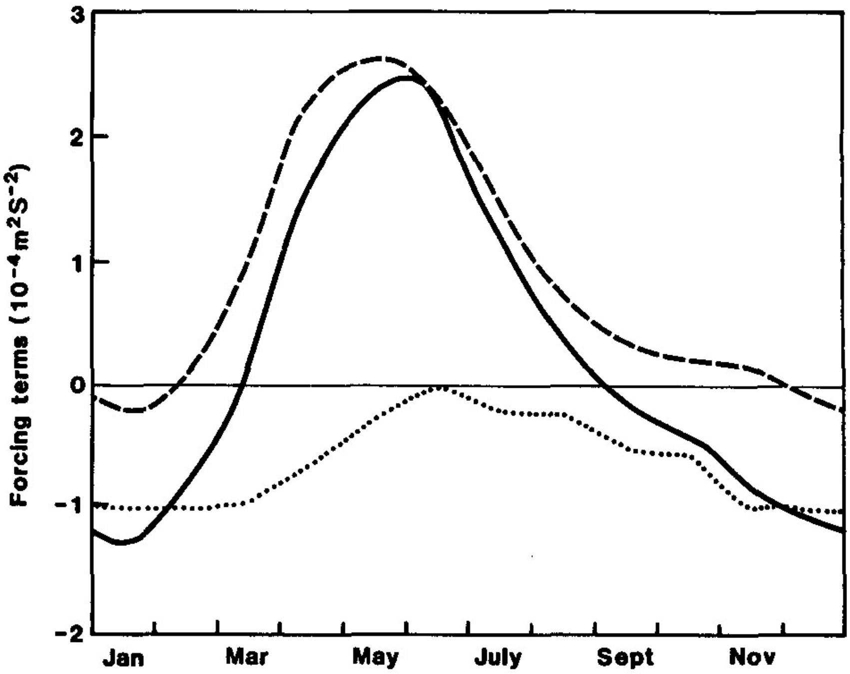

Figure 2.5. Alongshore momentum balance averaged between 22.5°S and 32.5°S. Negative of the pressure gradient term along the continental shelf edge (dashed line). Longshore component of the wind stress averaged (dotted line) along the same track (positive is poleward). Sum of the two terms (bold line) [from Godfrey and Ridgway, 1985].

2.6 COOLING OF THE LEEUWIN CURRENT

As the warm poleward flow of the Leeuwin Current along the west Australian coast is quite different from the cooler equatorward boundary flows found in all of the other subtropical eastern boundaries, the ocean region off Western Australia experiences a large heat flux into the atmosphere, more characteristic of western boundary systems [**Figure 2.6**]. Even the swift poleward flow of the Agulhas Current, in the western boundary of the South Indian Ocean, does not show an equivalent ocean heat loss at same latitudes of the Leeuwin Current. In sea surface temperature imagery the warm core jet of the Leeuwin Current loses about 5°C, from North West Cape (22°S) to Cape Leeuwin (34°S), a surface cooling of 0.5°C per 100 km [Ridgway and Condie, 2004].

In past work the cooling of the Leeuwin Current has been generally proposed to originate from air–sea fluxes. This surface flux would lead to strong turbulent mixing (convection) and deep mixed layers in the Leeuwin Current [Thompson, 1984], which, in turn, would assist the alongshore pressure gradient to overcome the equatorward wind stress and consequently to maintain the current's poleward flow [Weaver and Middleton, 1990; Godfrey and Weaver, 1991]. In more recent times, observational studies are starting to explore another cooling mechanism of the Leeuwin Current: the lateral heat transfer from the boundary jet to the ocean interior by mesoscale eddies [Morrow *et al.*, 2003]. Warm core eddies detach from the Leeuwin Current and transport heat westward to adjacent Subtropical Gyre [Fang and Morrow, 2003], where this heat is then presumably mostly fluxed to the atmosphere, resulting in that broad heat loss pattern that spreads away from the eastern boundary in **Figure 2.6**. Despite these latest studies, the relative contribution of local air–sea and eddy fluxes to the cooling of the Leeuwin Current is not yet clear.

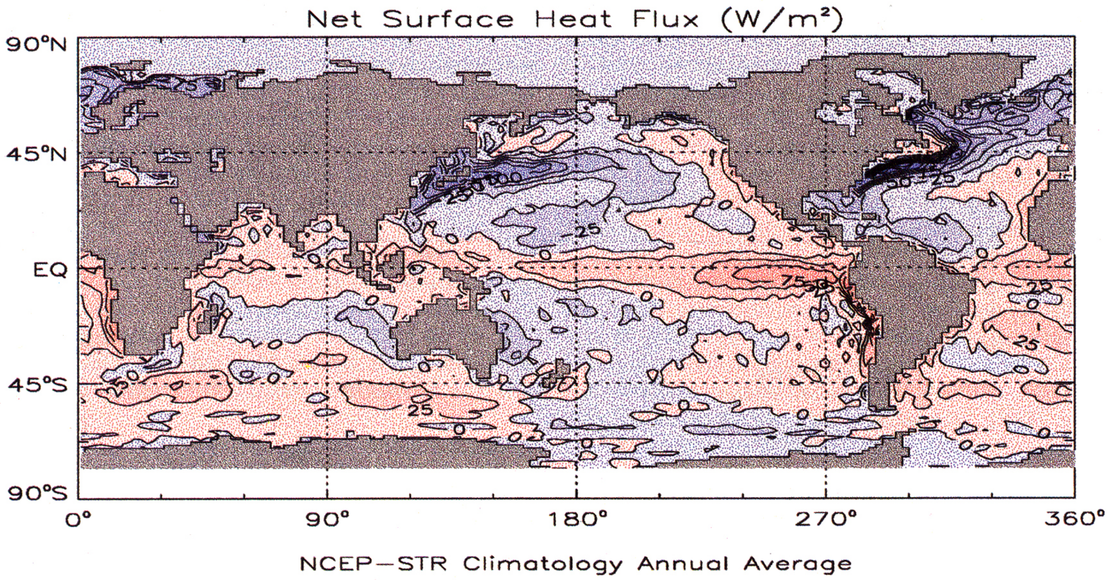

Figure 2.6. Annual mean heat flux. Contours are 25 W m^{-2}. Ocean heat loss is in blue [from Doney *et al.*, 1998].