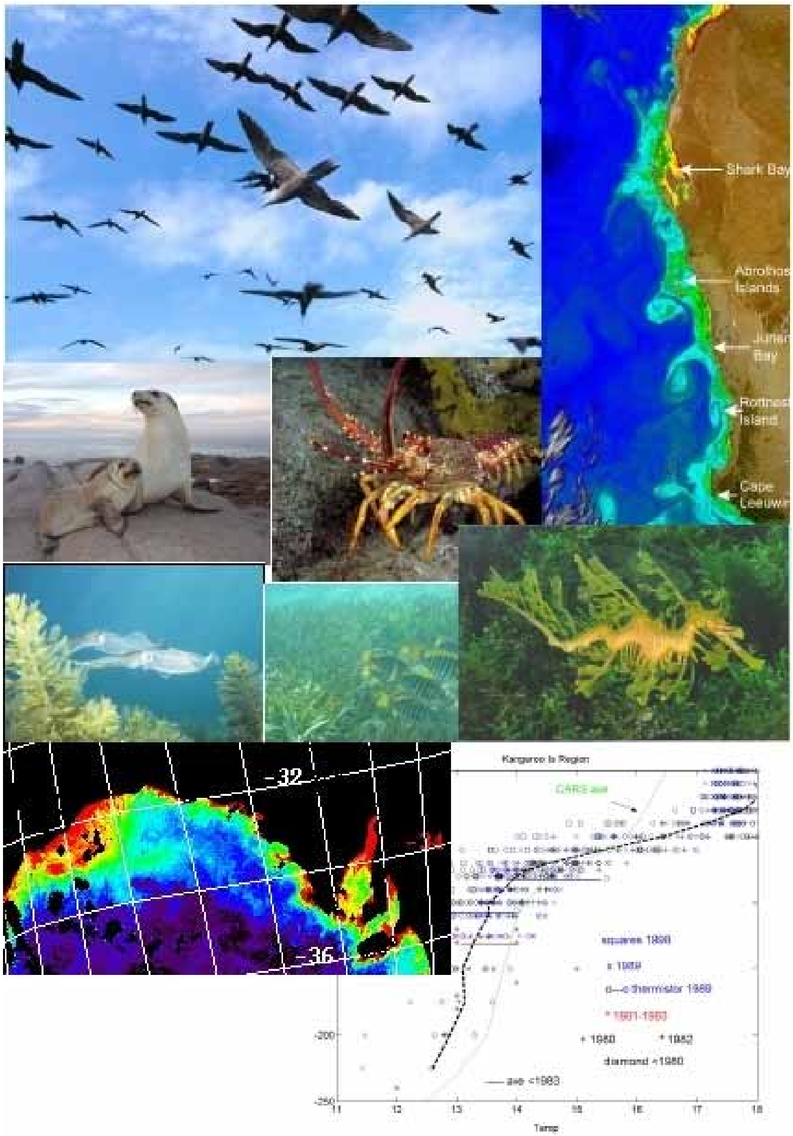
The South-west Marine Region:
Ecosystems and Key Species Groups

Department of the Environment and Water Resources



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Contents

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1 Executive summary

1.1 Purpose, focus, and structure of the report

The purpose of this report was to undertake a comprehensive review of the current knowledge of the key ecological characteristics of the South-west Marine Region (the Region). This region covers Australian waters from the eastern-most tip of Kangaroo Island (South Australia) to the outer coast of Shark Bay (Western Australia) (Figure 1.1.1). The focus of this report is waters beyond three nautical miles from the coastal baseline; information on inshore waters is included only where there are important processes that influence processes on the shelf and slope. The objective is to produce an integrated report on the ecosystem of the Region, which is aimed at scientists who are not necessarily specialists in the area. The information embodied in the report will provide background to inform policy decisions where there is a need for scientific information about the region; information that was previously widely scattered and less accessible.

The Department of the Environment and Water Resources defined a list of functional groups of organisms that have either commercial (target and significant by-catch species), recreational, conservation, or cultural importance. The list includes introduced species. These functional groups are:

- Flora including Seagrasses, Mangroves, kelp, etc.
- Corals
- Seabirds
- Echinoderms
- Sharks and rays
- Squids and cuttlefish
- Crabs and lobsters
- Prawns
- Molluscs of commercial, recreational, cultural or ecological significance
- Cetaceans
- Seals and sea lions (or Pinnipeds)
- Seahorses, sea-dragons and pipefish
- Mackerels and tunas
- Small pelagic fish
- Inshore demersal (those species predominantly caught in waters less than 50 metres in depth)
- Deepwater fish (those species predominantly caught in waters greater than 50 metres in depth) (treating slope and shelf communities separately)
- Introduced marine species.

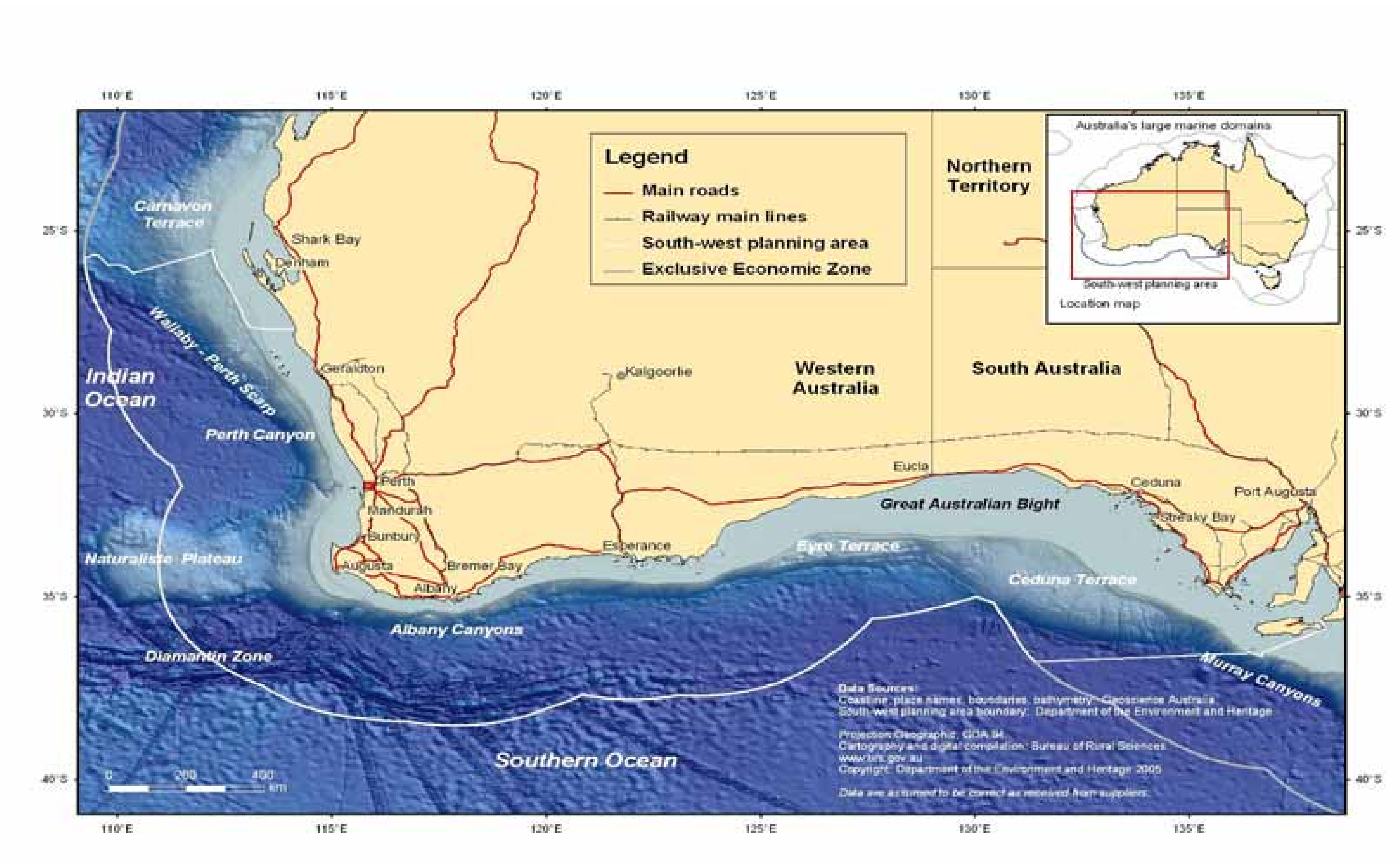

Figure 1.1.1 Boundaries of the South-west Marine Region. The focus of this report is on the shelf and slope, including the inshore only where there are important processes that influence processes on the shelf and slope**.**

The Department of the Environment and Water Resources also provided a list of species that were considered to be of significance to commercial, recreational fisheries, of conservational value, or to have cultural importance in the Region. Knowledge of each of these species is addressed within the descriptions of the respective functional groups. Although the focus of this report is on the shelf and slope, there is a certain inconsistency between the shelf/slope focus and some of the species that are predominantly inshore (such as seagrasses, mangroves, kelp, and inshore fishes).

Sections 2 and 3 (Part 1) of this report provide an overview of the physical and ecological characteristics of the Region. Readers should note that the Region's physical environment is better understood than that of the Region's ecology. As result, it is considered that while this report provides an appropriate overview of the Region's physical environment, coverage of the regions ecology remains partially incomplete — reflecting the current state of knowledge. A separate reference list is provided for the ecological and physical overviews of the region (sections 2 and 3).

Section 4 (see Part 2 of the report) comprises the bulk of the report. The species included in this section are made up of functional groups that have either commercial (target and significant by-catch species), recreational, conservation, or cultural importance – including introduced species. Each of the chapters in Section 4 describes the functional species groups, and was written as a stand-alone contribution that is intended to be a reference point. As such, each chapter has a reference list that is specific to the functional species group. These reference lists are intended to provide a means for interested readers to access more specialised studies and to a large extent do not overlap with each other or with the reference list for sections 2 and 3.

1.2 Overview

The Region encompasses a range of biogeographical provinces (defined by the Integrated Marine and Coastal Regionalisation for Australia version 4.0 (IMCRA v4.0) and the National Marine Bioregionalisation). Major oceanographic current systems within the region include the Leeuwin Current and Flinders Current as well as the seasonal current systems such as the Capes Current (along the south-west coast), and those within the Great Australian Bight. The region also consists of different local scale marine "systems" where the geomorphology and physical processes exercise a certain amount of control on the ecological processes. These processes include the seasonal upwelling systems (off the West Australian and South Australian) coasts, submarine canyon systems, island and headland wake regions, and offshore eddy systems.

The physical environment has a great effect on the functioning and structure of the Region. Effects range from the near isolation of commercially important species within the South Australian gulfs, to the enrichments driven by seasonal upwelling, transport of whole communities by eddies, and the role of sedimentary facies in structuring benthic communities on large scales. Interannual changes in the physical regime, such as El Niño also impact the biological communities by intensifying currents and altering the upwelling regime. However, it is important to bear in mind that we still do not fully understand the drivers of ecosystem structure in the Region.

Executive summary

Ecosystems can be structured by bottom-up forces, top-down forces, or may operate as wasp-waist systems. Bottom-up structure implies the importance of physics, through nutrients to primary production; top-down systems are structured by the pressures imposed by higher predators on the food web; and in wasp-waist systems, the influence of physics is mediated by the role of intermediate trophic levels, and the non-linear dynamics that relate them to both higher and lower trophic levels in the system. Until we understand which paradigm best fits the Region, we cannot say that we understand how the system works, and what the drivers of change are.

One of the most important drivers of ecosystem change is climatic influences. Climate variability operates on a range of time-scales, and can be conceived as the noise that occurs around a trend. Trends in climate operate on much longer time-scales and are referred to as climate change. Climate variability includes the effects of El Niño or La Niña cycles. Little is known about the effects of climate variability in the Region, and much of what is known was studied in the context of fisheries recruitment and the effects of environmental variability on recruitment. Recent modelling studies, summarised in Section 2 of this report, indicate that intensification of current systems during El Niño, and subsequent relaxation in the summer after an El Niño event, can increase the intensity of upwelling along the South Australian coast. This may lead to enhanced productivity, a result contrary to what is observed with El Niño in the northern hemisphere. However, the time-series are short and so these effects are difficult to verify statistically.

There is almost no work addressing how pelagic communities, benthic communities or fisheries would respond to interannual climate variability and long-term climate change. We are only beginning to understand how large-scale ocean-atmosphere interactions such as El Niño affect the physical oceanography of the region. There is also limited information on the effects of environmental variability on fisheries recruitment of species like rock lobster, King George whiting, garfish, Australian salmon, herring, pilchard, or prawns. Most of the studies cited in this report are relate to the western part of the Region. There is a need for integrated studies of the effects of environmental variability of productivity as well as recruitment of commercially important species in the South Australian region. There is reason to believe that there will be significant relationships between recruitment and environmental variables for scale fish, rock lobster and prawns.

Seasonal coverage is limited for virtually all of the studies and all of the taxa of the Region. The exception is the seasonal information derived from satellite remote sensing of phytoplankton. The seasonal cycle of phytoplankton pigments at large scale, low-resolution (5 km, monthly composites) is provided by satellite imagery from the MODIS-Aqua sensor. While this information is extremely valuable, it misses some important features. These data are limited to the upper layer (~ upper 10 m), and so miss the deep chlorophyll maxima known to occur over the shelf in the eastern Great Australian Bight. They also suffer from uncertainties in calibration, particularly in near-shore Case 2 waters (i.e. waters where the backscattered irradiance is derived from other substances in addition to phytoplankton).

The widely accepted concept that the southern Australian coast supports a uniquely rich regional biodiversity still needs further quantitative study. Non-quantitative evidence suggests higher regional biodiversity in some well-known groups (e.g.

benthic algae), as well as a high degree of endemism, but the area is under-explored for many groups (e.g. sponges). The spatial coverage of sampling in the region is patchy, and large areas have not received much attention. The current state of knowledge of ecological structure and function of the Region is quite unbalanced in the sense that some taxa, such as fish, sponges or benthic macroalgae, are much better catalogued than others.

The largest part of this report (Part 2) deals with the species group descriptions. These descriptions are necessarily uneven because there is far more information about some groups than others. Each chapter is designed to provide a stand-alone review and reference point on the current state of knowledge and literature for the respective groups. The functional groups described are (in alphabetical arrangement for easy reference) Ascidians, Bryozoans, Cetaceans, Corals, Demersal fish (inshore, shelf and slope), Elasmobranchs, Infauna, Mackerels, Tunas and billfishes, Macroalgae, Mangroves, Marine pests, Molluscs, Phytoplankton, Pinnipeds (seals and sea lions), Prawns, Rock lobster, Seabirds, Seagrasses, Sponges, Small pelagic fish, Syngnathids and Zooplankton.

Part 1 - Ecosystems

2 Physical oceanography

Principal contributors

Chari Pattiaratchi
John Middleton

2.1 Shark Bay to Esperance

Introduction

During the past two decades the physical oceanographic processes off Western Australia have been the subject of many studies. One motivating factor for these studies was the observation that, as a rule, eastern ocean basins are highly productive ecosystems supporting high primary productivity and large pelagic finfish stocks. However, the exception to this rule is the Western Australian coast where although the wind regime is similar to other eastern ocean margins, the waters are oligotrophic. Thus, the initial studies were concentrated on addressing why the circulation off Western Australia was different to other eastern margins. This led to the discovery of the Leeuwin Current and the subsequent determination of its dynamics. Indeed, it has been shown that the Leeuwin Current system is made up of three currents: the Leeuwin Current, the Leeuwin Undercurrent and shelf current systems consisting of the Ningaloo, Capes and Cresswell currents (Woo et al. 2005).

The main contribution to the understanding of the physical oceanography of this region has come from Andrews (1976, 1977, 1983); Cresswell and Golding (1980); Hamilton (1986); Smith et al. (1991); Pearce and Walker (1991); Cresswell and Peterson (1993); Gersbach et al. (1999); Pearce and Pattiaratchi (1999); Feng et al. (2003); Morrow et al. (2003); Ridgway and Condie (2005); Woo et al. (2005); and Rennie et al. (2005).

The main oceanographic features of the region between Shark Bay and Esperance are comprised primarily of the following surface and subsurface current systems (figures 2.1.1 and 2.1.2):

- The West Australian Current
- The Leeuwin Current
- The Leeuwin Undercurrent
- The Flinders Current
- Continental shelf current systems: the Ningaloo, Capes and Cresswell currents

Physical oceanography: Shark Bay to Esperance

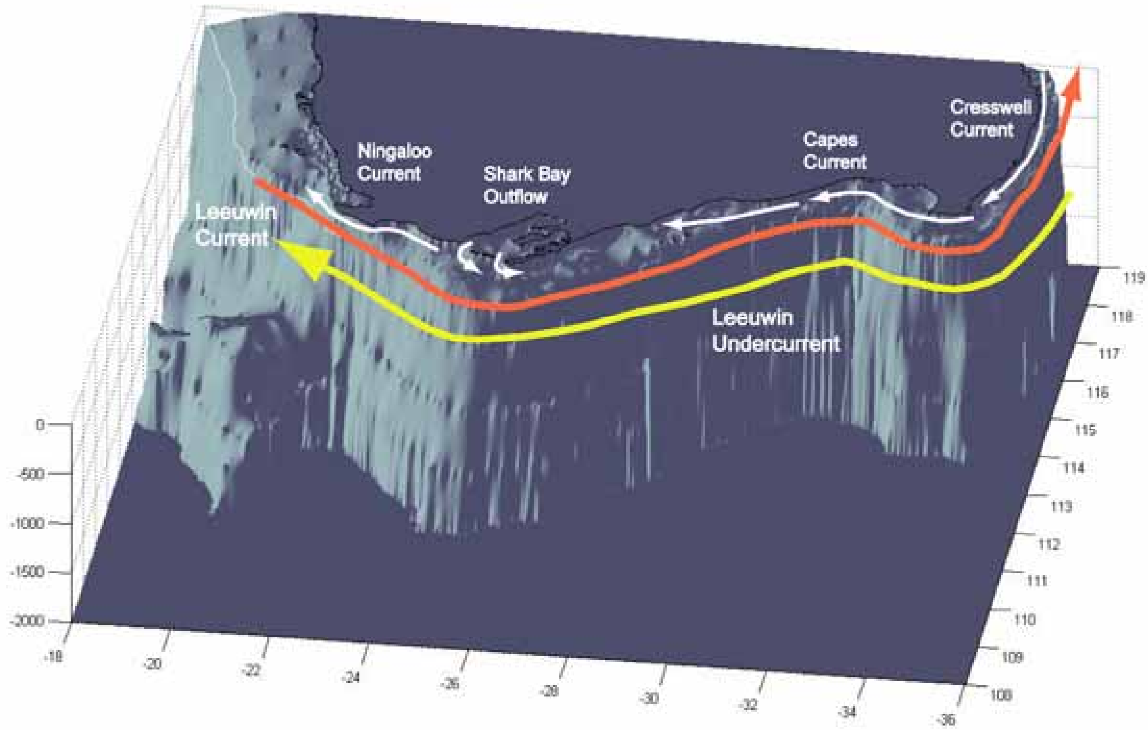

Figure 2.1.1 Schematic of surface and subsurface currents along the Western Australian coastline

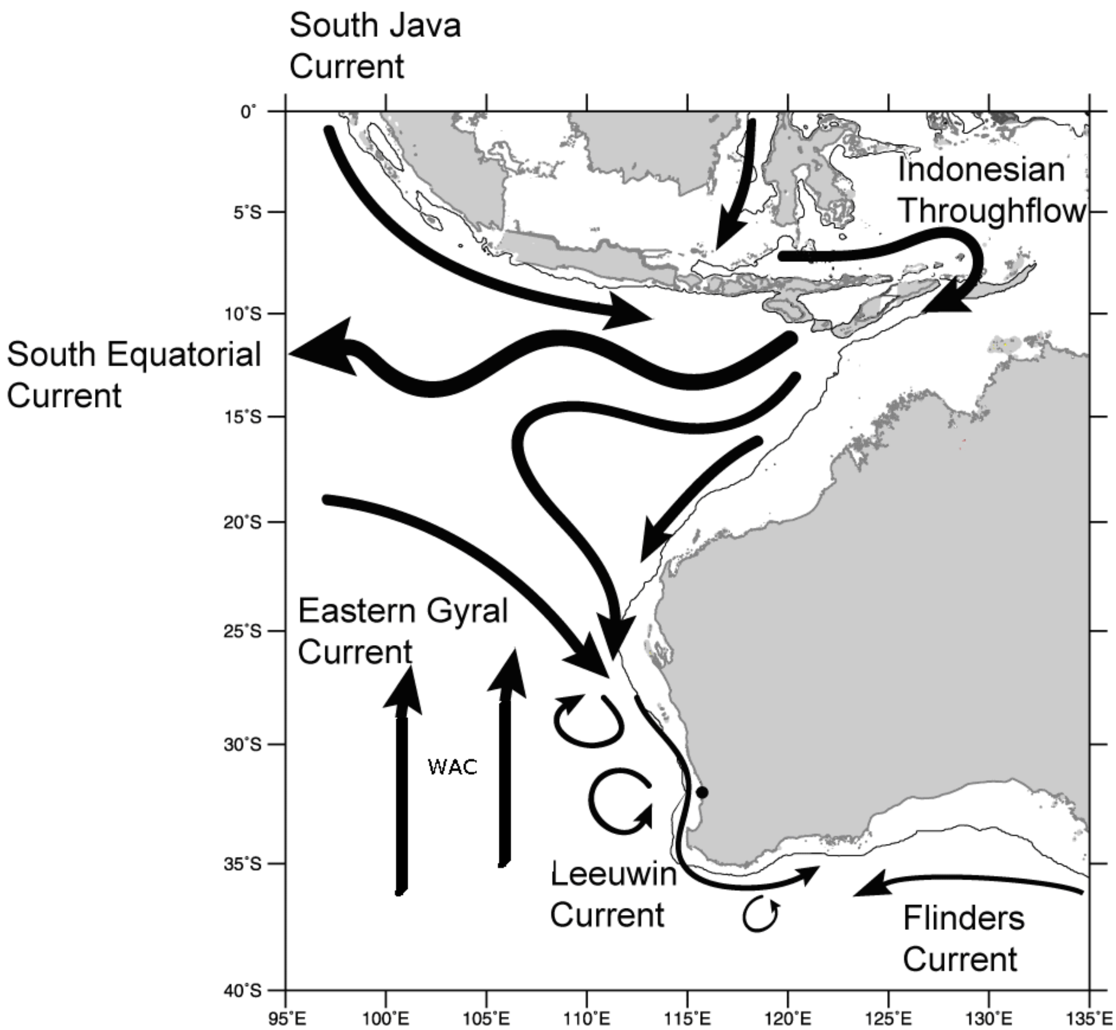

Figure 2.1.2 Schematic of surface currents along the Western Australian coastline (WAC = Western Australian Current).

The West Australian Current

Eastern boundary currents occur along most eastern ocean boundaries as slow and broad equatorward currents (in contrast to the intensified poleward western boundary currents) and make up one part of the anticyclonic subtropical gyre in each hemisphere’s oceans. These gyres result from the Sverdrup balance: a balance between wind stress, pressure gradients and coriolis acceleration. The eastern boundary current regions are characterised by cooler (through upwelling) water and high primary productivity thus supporting major pelagic finfish industries. Western Australia does not have the level of biological productivity induced by the Humboldt Current (South America) or the Benguela Current (Africa) because the Leeuwin Current opposes the equatorward West Australian Current and suppresses the upwelling of cooler nutrient-rich water along the continental shelf (see below). The continuity of mass required for maintaining the anticyclonic subtropical gyre in the southern Indian Ocean is achieved through the West Australian Current, which is necessarily located further offshore. Schott and McCreary (2001) postulated that the northward current extends westward from Western Australia up to latitude of 60° E (Figure 2.1.3).

Earlier, Andrews (1977, 1983) described the West Australian Current as a much narrower 100–200 km-wide cyclonic stream identified during the summer months as a trough, shown by mixed layer depths, surface isotherms and dynamic height anomaly. The current here was identified to be centred over the Naturaliste Plateau (Figure 2.1.2) and extends 800 km north-east to the coast where it turns south along the south-west coast of Western Australia. The transport of this current is 10 Sverdrups (10^7 m^3 s^{-1}) towards the north-east and is confined near the surface. The discrepancy of size and location of the West Australian Current, with that later suggested by Schott and McCreary (2001) is likely due to the effects of mesoscale eddies and also the general lack of data for the region.

Recent work by Cresswell and Peterson (1993) focused on the source of the Leeuwin Current in the summer months, which they linked to the West Australian Current. This study was motivated by the observation that the Leeuwin Current flowing eastward along the south coast of Western Australia during the summer months had a higher salinity signature in summer than in winter, implying that its source was more of subtropical origin. It is unclear whether the inflow of subtropical water is due to geostrophic inflow or the inflow of the West Australian Current, though the work of Andrews (1977, 1983) appeared to be consistent with the investigations of Wyrtki (1962), Hamon (1972) and, to a limited extent, Cresswell and Peterson (1993). Observations of the West Australian Current have not been repeated during the winter months and therefore the contribution of the West Australian Current during this period is unclear.

Andrews (1983) emphasised this problem by stating that the eastward inflow had rarely been studied in winter and the Leeuwin Current had not generally been investigated in summer, implying that the Leeuwin Current and the West Australian Current might be seasonally mutually exclusive or might coexist. It is therefore often implied or stated (Cresswell & Peterson 1993, for example) that the West Australian Current supplements the Leeuwin Current in the summer months.

While the details of the current system are not well understood, the results of Andrews (1983) do show that the West Australian Current does have some features in common with other eastern boundary current systems. It is relatively shallow, with 66% of the total transport above the depth of 1300 m contained in the region above 400 m depths. Similarly, Andrews (1983) surmised that the West Australian Current transports marginally less volume than a typical eastern boundary current system, with a representative flow of 10 Sv (1 Sv = 10^6 m^3 s^{-1}) that may be compared to values of 18 Sv and 15 Sv for the other southern ocean eastern boundary currents: Humboldt (Peru) and Benguela (Africa) currents respectively.

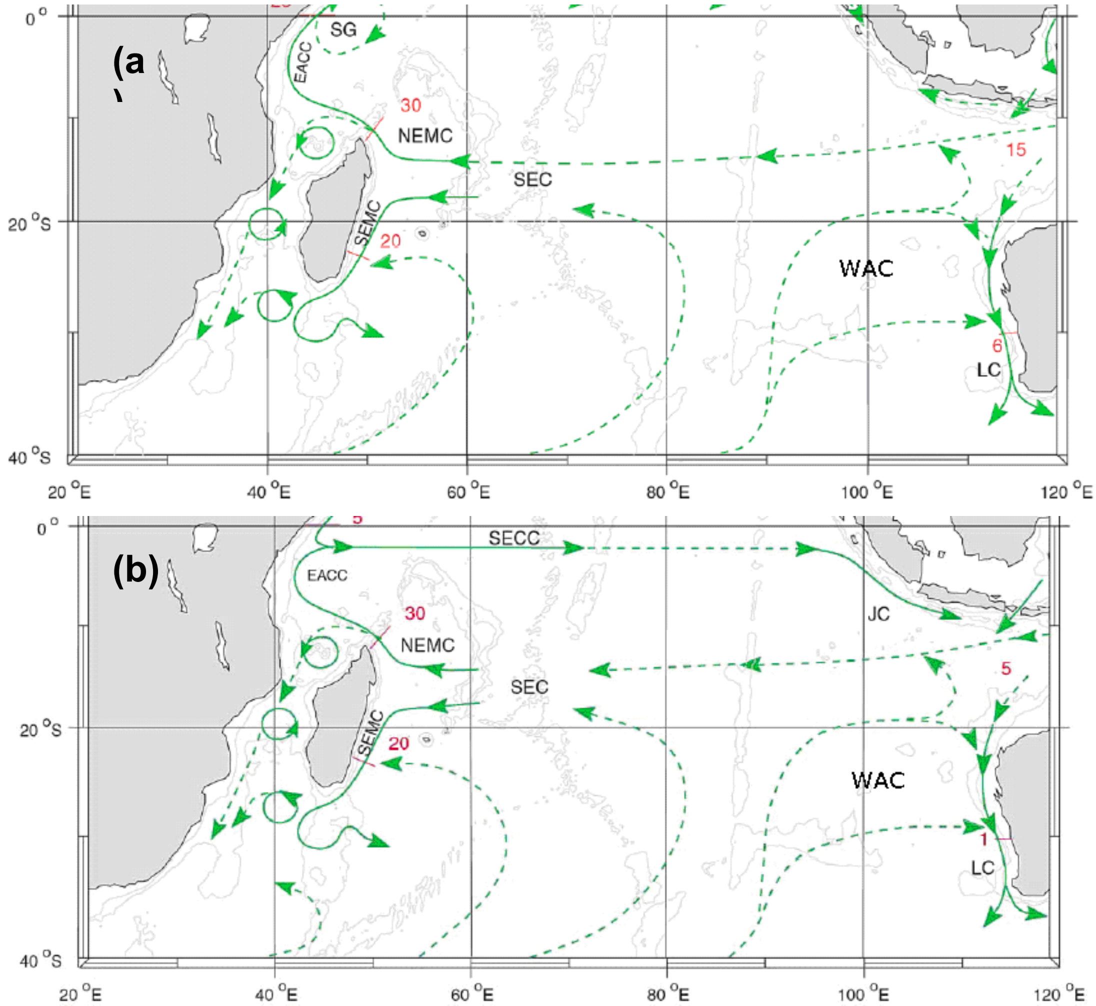

Figure 2.1.3 A schematic representation of the surface circulation in the southern Indian Ocean Monsoon, including the volume transport (1 Sv = 10^6 $m^3 s^{-1}$). Currents indicated are the (possible location) of the West Australian Current (WAC), the South Equatorial Current (SEC), the South Equatorial Countercurrent (SECC), the Northeast and Southeast Madagascar currents (NEMC and SEMC), the East African Coast Current (EACC), the South Java Current (JC) and the Leeuwin Current (LC)
(a) South-west monsoon – austral winter; and, (b) north-east monsoon – austral summer (from Schott & McCready 2001)

The Leeuwin Current

It has been known for several decades that the circulation off the Western Australian coast is different from any other western continental margin (Schott 1935; Smith et al. 1991; Pearce 1991). In each of the main ocean basins, the surface circulation forms a gyre with poleward flow along the westward boundary of the basin and equatorward flow along the eastern margin. In addition, the eastern margins (off South America and South Africa, for example) are areas of high productivity due to upwelling. The exception to this rule is off the Western Australian coast, where the Leeuwin Current transports water poleward (Figures 2.1.1 and 2.1.2).

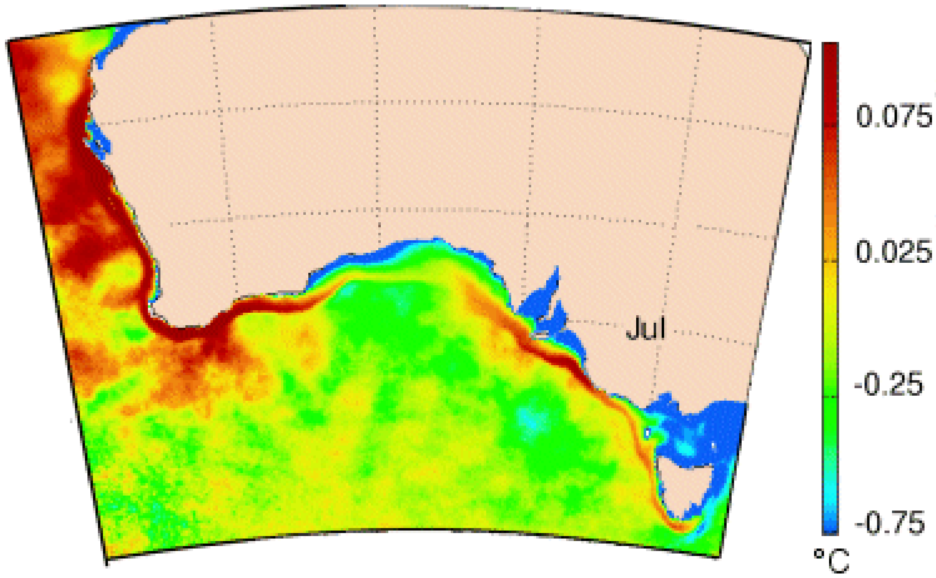

Figure 2.1.4 A composite satellite image of sea surface temperature anomalies in July. The Leeuwin Current can be identified as a narrow band of warmer water adjacent to the coast (from Ridgway & Condie 2004) extending from Western Australia to the mid-Bight and Eyre Peninsula region.

The Leeuwin Current is a shallow (<300 m), narrow band (<100 km wide) of warm, lower salinity, nutrient depleted water of tropical origin that flows poleward from Exmouth to Cape Leeuwin and into the Great Australian Bight (Church et al. 1989; Smith et al. 1991; Ridgway & Condie 2004). Together with the South Australian Current and eastward shelf currents off South Australia and Tasmania, the Leeuwin Current forms the longest boundary current in the World (Ridgway & Condie 2004; Cirano & Middleton 2004). Here, we follow the same definition as Cresswell and Petersen (1993) to define the Leeuwin Current as “a warm water current of tropical origin that, during the summer months, is augmented by the addition of (salty) water from the West Australian Current” (see Section 3.2).

Warmer, lower salinity water flows through the Indonesian archipelago from the Pacific to the Indian Ocean and results in lower density water being present between Australia and Indonesia compared to the cooler and more saline ocean waters off south-western Australia. This density difference results in a change in sea level of about 0.5 m along the Western Australian coast and is the driving force of the Leeuwin Current. Due to the effect of the earth’s rotation, water is entrained from the Indian Ocean into the Leeuwin Current as it flows southward; thus, the Leeuwin Current becomes stronger as it flows southward.

Studies undertaken over the past decade have shown that, along the west coast, the Leeuwin Current is driven by an alongshore pressure gradient which overwhelms the opposing equatorward wind stress (Thompson 1984; 1987; Godfrey & Ridgway 1985; Weaver & Middleton 1989; Batteen & Rutherford 1990; Godfrey & Weaver 1991; Pattiaratchi & Buchan 1991). These investigators have demonstrated that the pressure gradient (in the upper 250–300 m of the ocean) overcomes the upwelling favourable winds inducing an onshore surface flow resulting in downwelling at the coast. Onshore geostrophic flow from the central Indian Ocean occurs towards Western Australia between the latitudes of approximately 15° S and 35° S. Geostrophic inflow in the north (15–28° S, augmented by tropical water from the North-west Shelf, forms the warm, low salinity core of the Leeuwin Current (Smith et al. 1991; Woo et al. 2005).

It has been postulated that south of about 30° S the Leeuwin Current intensifies (increase in the transport and the velocity) due to the geostrophic inflow of subtropical water from the south-west, especially during the summer months (Hamilton 1986; Cresswell & Peterson 1993). The current continues beyond Cape Leeuwin eastward into the Great Australian Bight (Ridgway & Condie 2004). Here, the dynamics are thought to be similar to that along the west coast in that the current is still driven by the alongshore pressure gradient, the magnitude of which is slightly lower than that along the west coast (Godfrey & Vaudrey 1985). However, the results of Ridgway and Condie (2004) and Cirano and Middleton (2004) indicate that alongshore winds play a more dominant role – compared to the alongshore pressure gradient – in driving eastward currents along the south coast during winter.

Leeuwin Current eddies

The Leeuwin Current is generally associated with mesoscale eddies and meanders (Pearce & Griffiths 1991; Fang & Morrow 2003; Morrow et al. 2003; Feng et al. 2005; Fieux et al. 2005). Eddies form at the shelfbreak and eventually separate from the current and drift westward. These eddies are apparent in sea surface temperature satellite imagery (Griffin et al. 2001) and in altimeter data (Fang & Morrow 2003). Interaction of the Leeuwin Current with changes in the bathymetry and offshore water of different densities results in the generation and subsequent offshore transport of eddies – in particular, off Shark Bay, the Abrolhos Islands, Jurien Bay, Rottnest Island and Cape Leeuwin (Figure 2.1.5).

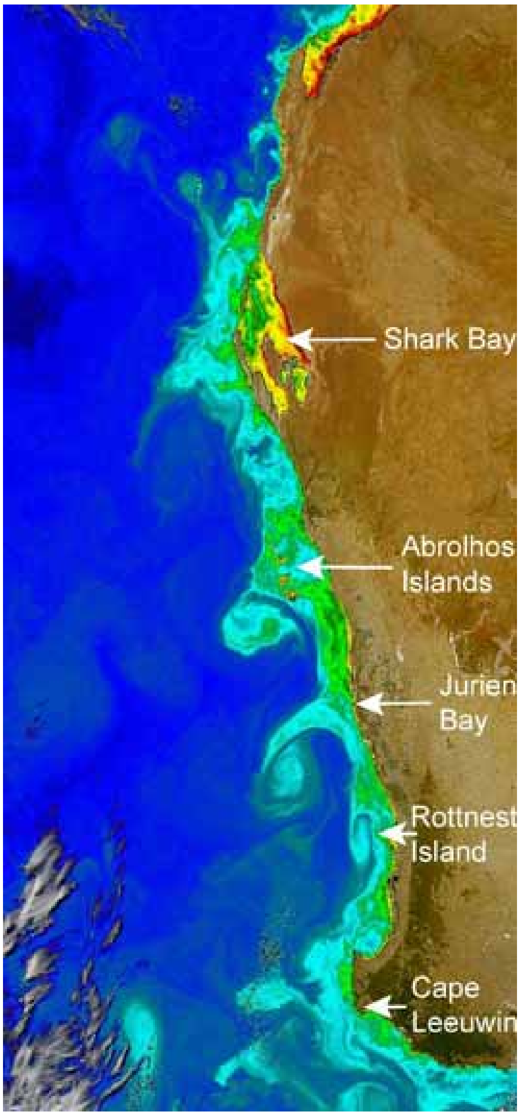

Figure 2.1.5 Ocean colour image showing the eddy structure of the Leeuwin Current. Water with higher chlorophyll levels is located on the shelf and is entrained into the Leeuwin Current.

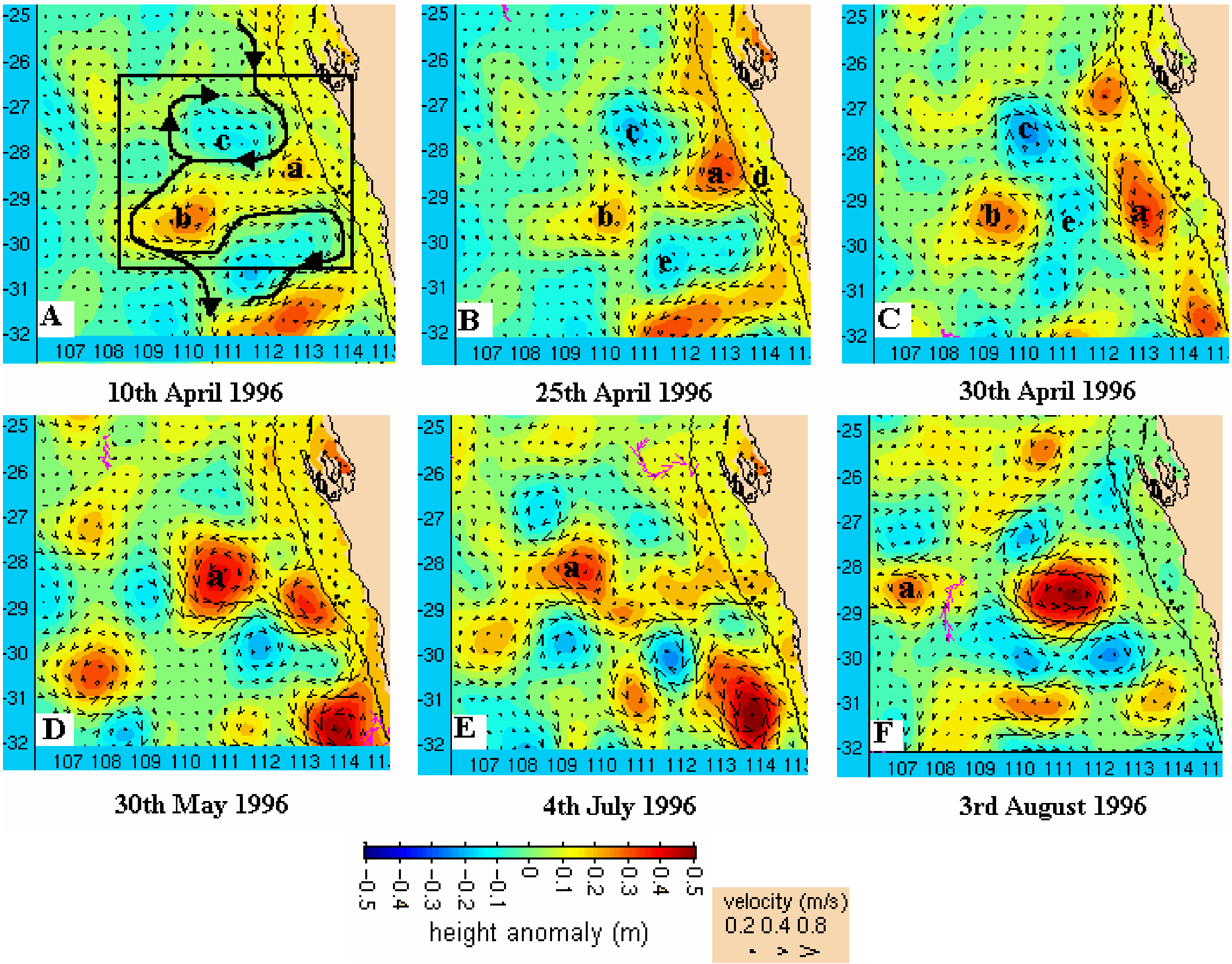

Figure 2.1.6 Time series of satellite altimeter imagery of the surface height anomaly revealing the dynamic nature of the Leeuwin Current off the Abrolhos Islands (from Meuleners et al. 2005)

Pearce and Griffiths (1991), Fang and Morrow (2003) and Morrow et al. (2003) have shown the complex nature of the Leeuwin Current system. A sequence of TOPEX/POSEIDON satellite images of the surface height anomaly (Figure 2.1.6) highlights a number of key mean flow and eddying features of the Leeuwin Current. Figure 2.1.6A shows the meandering nature of the mean current (Pearce & Griffiths 1991) and demonstrates that the path of the mean current is closely linked with the generation of anticyclonic eddies near the shelfbreak. More specifically, the time sequence shows the entrainment of the warm water offshore by a cyclonic eddy “c” forming a dipole eddy pair with anticyclonic eddy “b” (Figure 2.1.6A). The importance of the cyclonic eddy “e” in a detachment process of the anticyclonic eddy “b” is shown on figures 2.1.6B and 6C. As eddy “b” migrates westwards, it remains attached to the shelfbreak until eddy “e”, located initially to the south (Figure 2.1.6B), migrates northward between it and the generation site (Figure 2.1.6C) entraining the offshore flow and isolating the eddy. The detachment time scale is of the order of 30 inertial periods (at this latitude the inertial period = 24.7 hours). Observations and modelling studies (Meuleners et al. 2005) have indicated that anticyclonic eddies are initiated and developed in close proximity to the shelfbreak and often in association with a cyclonic eddy before either dissipating or detaching and moving offshore.

The flow that initiates these eddy features can persist for considerable time. The sequence of images show the formation of the anticyclonic eddy “a” which subsequently detaches and migrates within the boxed area (Figure 2.1.6A) for approximately 115 inertial periods (~118 days) before moving beyond the image boundary. The mean speed of migration over this time is of the order of 8 km/day. Similarly, the cyclonic eddy annotated ”c” develops and remains almost stationary during its development stage but as it begins to dissipate, it moves within the eddy field at speeds comparable with its anticyclonic eddy neighbours and has a life cycle of the order of 90 inertial periods (~93 days). Fang and Morrow (2003) and Morrow et al. (2003) give a similar description of the eddying dynamics and the associated temporal and migrational scales.

Fang and Morrow (2003) identified a number of locations along the west coast of Australia for preferential eddy shedding: each was associated with some topographic features including headlands and changes in shelf width. Results from other studies in the south-west and southern coasts of Western Australia also reveal the role of topography in eddy generation (Cresswell & Petersen 1983; Rennie et al. 2005). The main regions of eddy generation may be summarised as follows:

1 West of Rankin Bank (20–21.5° S, 114.5–115.5° E). Here, the slope of the continental slope changes abruptly due to the presence of the Ranking Bank. One third of all long-lived, warm-core eddies were shed from this region (Fang & Morrow 2003).
2 South-west of Shark Bay (26–27° S, 113–114° E) over one third from 28–31° S. At Shark Bay (~25° S, Figure 2.1.5) the coastal topography undergoes a 90-degree change in orientation: to the north, flow along isobaths is directed to the south-west; to the south, the flow turns abruptly to the south-east (Fang & Morrow 2003; Woo et al. 2005). Field data indicate that in this region the strength of the Leeuwin Current changes. In the wider shelf off Shark Bay the current speed is weaker as it is distributed along the wider shelf. To the south, the current accelerates as the continental shelf narrows and continental slope becomes steeper (Woo et al. 2005).
3 Western edge of the Abrolhos Island chain (28–29° S, 113–114° E). The instabilities generated in the Leeuwin Current as it flows past Shark Bay and accelerates (see (2) above), together with interaction with the Leeuwin Undercurrent results in the generation of eddies in this region (Meuleners et al. 2005).
4 South-west of Jurien Bay (29–30° S, 114–115° E). The eddies generated offshore of the Abrolhos Islands have a length scale of approximately 200 km (Figure 2.1.5) and the interaction between the eddies generated to the north and the coastline at Jurien Bay results in the offshore movement of water resulting in the generation of eddies (Figure 2.1.5).
5 Perth Canyon (32° S, 115° E). The Perth canyon is the major topographic feature along the continental slope and has the effect of trapping eddies within the canyon. The influence of the Leeuwin Undercurrent in the formation of eddies has been documented by Rennie et al. (2005).
6 South-west of Cape Naturaliste and Cape Leeuwin. At Cape Leeuwin (34–35° S, Figure 2.1.5), the coastal topography undergoes a 90-degree change in orientation: to the north, flow along isobaths is directed to the south whilst to the south, the flow turns abruptly to the east.

7 South of Albany. Here, the coastal topography also undergoes a change in orientation: to the west, flow along isobaths is directed to the south-east whilst to the east, the flow is directed to the east-north-east.
8 South of Esperance. Similar to Albany, the changes in bathymetry, location of the numerous islands (Recherche Archipelago) result in the generation eddies.

Numerical Modelling studies of the Leeuwin Current system

Numerical modelling studies of the Leeuwin Current system have been predominantly large-scale investigations of the general ocean dynamics. Thompson (1987) investigated why the flow was poleward and why no upwelling was observed given the favourable alongshore wind stress. Weaver and Middleton (1989) using the Bryan-Cox Ocean General Circulation Model investigated the mechanisms for the generation of the Leeuwin Current. Batteen and Rutherford (1990, 1992) investigated the generation and stability of the Leeuwin Current using wind and thermal forcing respectively; they found mixed barotropic/baroclinic instability was the primary driving mechanism. Batteen and Butler (1998) also examined eddy development using thermal forcing and confirmed the earlier findings of Batteen and Rutherford (1990, 1992). Batteen and Huang (1998) investigated the effect of salinity on the density driven flow and found that both the temperature and salinity are required to accurately characterise the large-scale circulation of the Leeuwin Current system.

More recently, Griffin et al. (2001) simulated the ocean dynamics of the Leeuwin Current using the Regional Ocean Model System together with an idealised bathymetry to ensure computational stability, and a data-assimilation technique to force the model. The results simulated the observed features of the circulation, although there were discrepancies with the in situ observations of the surface current. However, Griffin et al. (2001) indicated that the model's poorest estimates of the surface velocity occurred where the model's topography differed most from the reality. All of the previous studies, including the current study, used a multi layered primitive equation model resolving the eddy field, explicitly. However, in the study of Griffin et al. (2001), a finer resolution model, incorporating detailed bathymetry and coastline features, is used to examine oceanic processes in a specific region.

Seasonal changes

Many investigators (see for example, Sturges 1974; Reed & Schumacher 1981; Pearce & Phillips 1988) have shown that changes in mean sea level monitored at tide gauges may be used to derive oceanographic information such as variations in flow and/or changes in thermohaline properties.

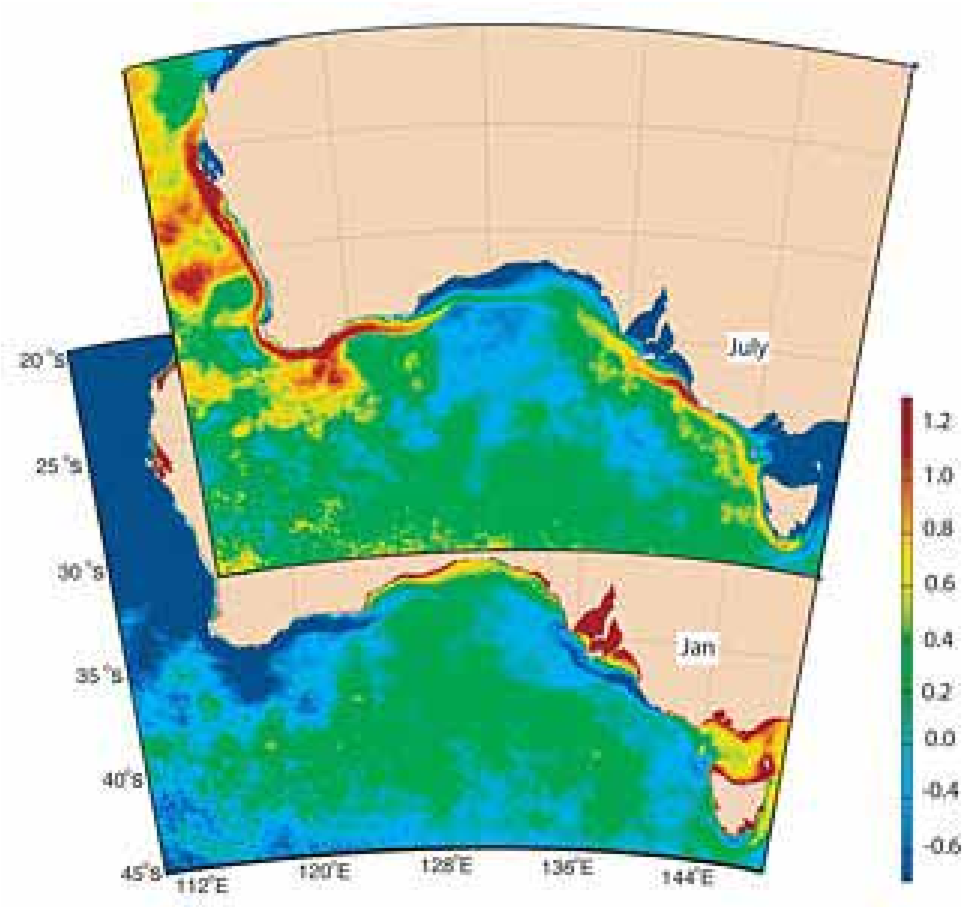

Figure 2.1.7 Composite satellite images of sea surface temperature anomalies in July and January showing the seasonal variability of the Leeuwin Current for the Western Australian region (Ridgway & Condie 2004). The anomalies represent departures from the annual mean.

For the Leeuwin Current, Pearce and Phillips (1988) have assumed that changes in the strength of the current are reflected in mean sea level changes that have annual mean amplitude of 20 cm (Pattiaratchi & Buchan 1991). Feng et al. (2003) demonstrated that the changes in Fremantle sea level anomalies (departures from the annual mean) result from changes in the strength of the Leeuwin Current. The sea level is higher between April and August than it is between October and January. During October to March the Leeuwin Current flows against the maximum southerly winds, whereas between April and August, the southerly winds are weaker (Godfrey & Ridgway 1985). Thus the Leeuwin Current is stronger during winter and weaker during the summer months due mainly to changes in the wind stress which is reflected in remotely sensed data (Figure 2.1.7).

Geographical distribution of the seasonal variations in mean sea level along the west coast of Australia indicates a progressive feature (Pariwono et al. 1986). On the North-west Shelf, the maximum occurs during March whilst in the south-west corner, the maximum occurs in May or June; this seasonal movement of the sea level maximum reflects the southward passage of the Leeuwin Current pulse (Church et al. 1989).

In summary, although the Leeuwin Current flows all year round, it exhibits a strong seasonality with the stronger flows occurring during the winter months (May–July) which is reflected in the coastal mean sea level. Godfrey and Ridgway (1985) have also shown that there is a very good correlation between the coastal mean sea level at Geraldton and the steric sea level. Hence, the mean sea level at Fremantle (or at any other south-west coast station) may be used as an indicator of the strength of the current.

Inter-annual variability

El Niño – Southern Oscillation events are the result of complex interactions between the ocean and the atmosphere in the tropical Pacific Ocean and have been associated with climatic and environmental anomalies around the world (Philander 1990). During El Niño – Southern Oscillation events, warm equatorial water from the western Pacific Ocean is transported eastward and flows southwards along the Peruvian coast to replace the cold, nutrient-enriched waters.

Pearce and Phillips (1988) have demonstrated a strong correlation between the Southern Oscillation Index (the normalised difference in surface atmospheric pressure between Darwin and Tahiti; a measure of the potential of El Niño – Southern Oscillation events), west coast sea levels (a measure of the strength of the Leeuwin Current; see above) and the Puerulus Settlement Index (a measure of recruitment to the rock lobster fishery). During normal years, the coastal annual mean sea levels are relatively high indicating that the Leeuwin Current is strong and the settlement of pueruli in coastal reefs is relatively high. During El Niño – Southern Oscillation years, coastal sea levels fall and the inferred transport in the Leeuwin Current is weaker (Feng et al. 2003).

As the Leeuwin Current is driven by the alongshore geopotential gradient, any changes to this gradient will result in changes to the strength of the current. Although the alongshore geopotential gradient is almost constant throughout the year, it varies during El Niño – Southern Oscillation events (Feng et al. 2003).

A weaker Leeuwin Current during an El Niño – Southern Oscillation event may be explained as follows: in a “normal” situation, the south-east trade winds in the Pacific Ocean set up high steric heights at the northern end of the Australasian continent; the gradient between these high steric heights and the thermally set low steric height off south-western Australia drives the Leeuwin Current. During El Niño – Southern Oscillation years, the trade winds relax and the steric height at the northern end of the Australasian continent is lower. This results in a decreased alongshore pressure gradient along the West Australian coastline resulting in a weaker Leeuwin Current.

The Leeuwin Undercurrent

The Leeuwin Undercurrent has received the least attention in the literature. Studies by Thompson (1984, 1987) indicated that there was an equatorward undercurrent flowing beneath the Leeuwin Current. Current meter data from the LUCIE experiment (Smith et al. 1991) confirmed the observations of Thompson (1987) and indicated that the equatorward undercurrent was narrow and situated between 250 m and 450 m in depth over the continental slope. The undercurrent transports 5 Svedrups of higher salinity (> 35.8 ppt) oxygen-rich nutrient-depleted water northward at a rate of 0.32–0.40 m s-1 (Thompson 1984). Measurements indicate that the current is stronger during November–January (Thompson 1984; Smith et al. 1991; Woo 2005).

The Leeuwin Undercurrent is driven by an equatorward geopotential gradient located at the depth of the undercurrent (Thompson 1984). This geopotential gradient or force arises from the equatorward slope of sea level (higher sea level to the north) and density (lighter, warmer water to the north). The sea level and density slopes oppose each other, but at depths of 250–450 m, the slope and resultant pressure force is to the north and drives the Leeuwin Undercurrent. Evidence of this pressure force, and by implication the Leeuwin Undercurrent, is apparent in the geopotential anomaly data at depths of 500 db/3000 db (Wyrtki 1971) and 450 db/1300 db (Godfrey & Ridgway 1985). Sub-surface slopes of 0.4×10^{-7} and 0.2×10^{-7} were reported by Thompson (1984) and Smith et al. (1991), respectively; Woo et al. (2005) estimated a slope to be much larger at 1×10^{-7}. These variations in slope are indicative of variations in the strength of the Leeuwin Undercurrent.

The Leeuwin Undercurrent is closely associated with the Subantarctic Mode Water (see Section 3.5). A feature of this water mass, resulting from convection to the region south of Australia, is high dissolved oxygen concentration and thus a cross-section of the Leeuwin Undercurrent core can be identified from the dissolved oxygen distribution; the core of the current consists of dissolved oxygen maximum (252 μM/L) centred at a depth of approximately 400 m (Figure 2.1.8).

The Leeuwin Undercurrent may be considered as an extension of the Flinders Current northwards along the west coast. The Flinders Current has a subsurface maximum located at 400 m depth adjacent to the continental slope similar to that of the Leeuwin Undercurrent. Along the south coast, the Flinders Current interacts with the Leeuwin Current at the shelfbreak, where the Flinders Current flows beneath the eastward-flowing Leeuwin Current similar to the Leeuwin Undercurrent observed on the west coast. This behaviour together with numerical model results (Figure 2.1.9) and temperature or salinity characteristics indicate that the Flinders Current is one source of the Leeuwin Undercurrent (Church et al. 1989; Woo et al. 2005).

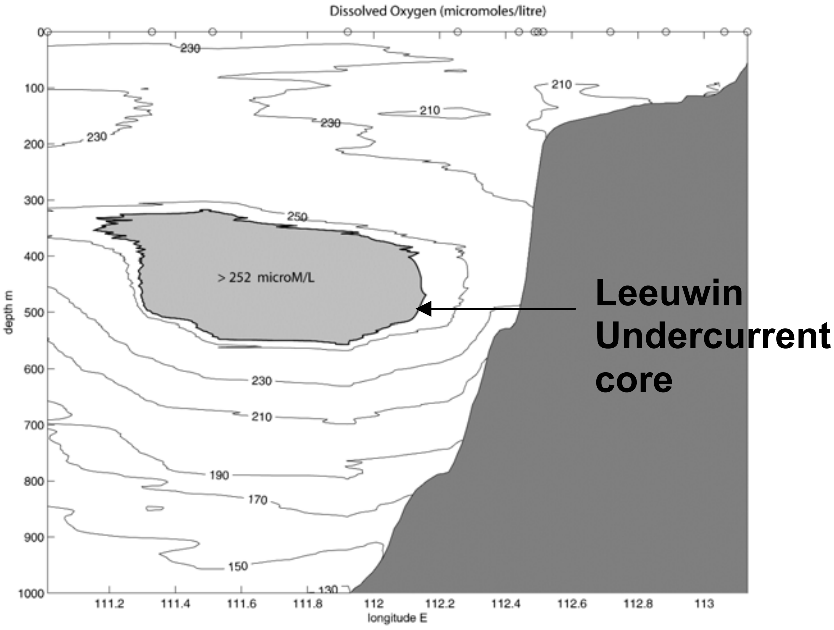

Figure 2.1.8 Cross-section of dissolved oxygen concentration along 29° S shows the presence of a >252 microM/L core at 400 m depth – which is interpreted as the core of the Leeuwin Undercurrent

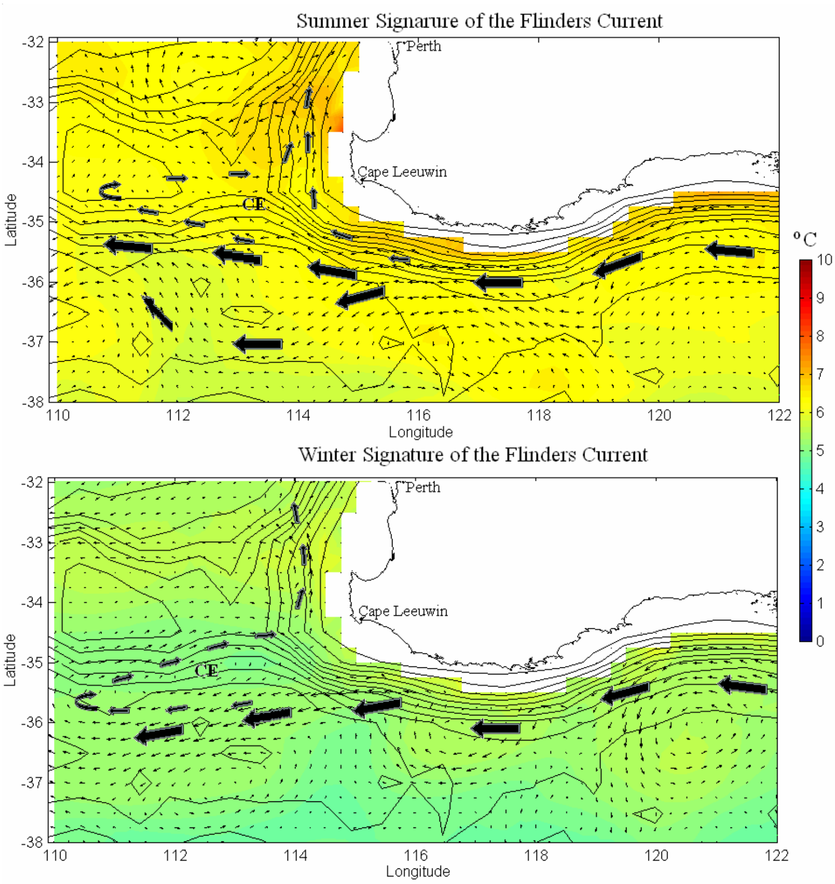

Figure 2.1.9 Velocity and potential temperature at 400 m depth during summer and winter obtained from the OCCAM global model showing the path of the Flinders Current along the south coast flowing from east to west. The continuation of the current northward along the west coast is the Leeuwin Undercurrent.

Coastal currents off Western Australia

The structure of the continental shelf circulation during the summer months along the west coast of Australia has been addressed in several recent studies using field data and satellite imagery (Cresswell et al. 1989; Cresswell & Peterson 1993; Pearce & Pattiaratchi 1997; Pearce & Pattiaratchi 1999; Gersbach et al. 1999; Woo et al. 2004). These studies have shown the existence of a cooler northward current on the continental shelf (the Capes and Ningaloo currents) with the southward-flowing Leeuwin Current, in general, located further offshore.

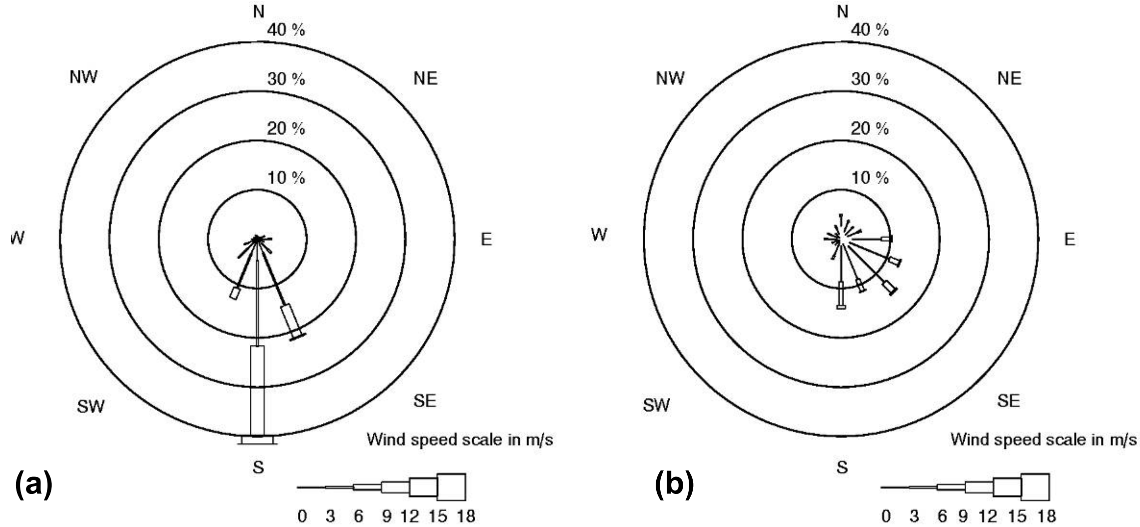

Figure 2.1.10 Seasonal wind roses from Rottnest Island showing the predominantly southerly winds during the summer (a) and variable wind directions during winter (b).

The Capes Current

Pearce and Pattiaratchi (1999) defined the Capes Current as a cool inner shelf current, originating from the region between capes Leeuwin (34° S) and Naturaliste, which moves equatorward along the south-western Australian coast in summer (figures 2.1.11 and 2.1.12). It has been postulated the Capes Current may extend as far north as the Abrolhos Islands (32° S); this has been confirmed through field data by Woo et al. (2005). The current is more saline (35.37–35.53 ppt) and cooler (21.0–21.4 °C) than the Leeuwin Current.

The Capes Current appears to be well established around November when winds in the region become predominantly southerly (Figure 2.1.10) due to the strong sea breezes (Pattiaratchi et al. 1997) and continues until about March when the sea breezes weaken. Gersbach (1999) has shown that the source water of the Capes Current arises from upwelling between capes Leeuwin and Naturaliste and is augmented by water from the south, to the east of Cape Leeuwin.

The dynamics of the Capes Current, off Cape Mentelle, has been described by Gersbach et al. (1999). Here, the southerly wind stress overcomes the alongshore pressure gradient. This results in the surface layers moving offshore, colder water upwelling onto the continental shelf, and the Leeuwin Current migrating offshore (Figure 2.1.13). Numerical model results have shown that a wind speed of 8 ms^{-1} is sufficient to overcome the alongshore pressure gradient on the inner continental shelf (Gersbach 1999).

The Capes Current is sourced from shallow upwelling of water from the bottom of the Leeuwin Current (~100 m) (Gersbach et al. 1999; Pearce & Pattiaratchi 1999; Hanson et al. 2005). This water mostly comes from the region between capes Naturaliste and Leeuwin.

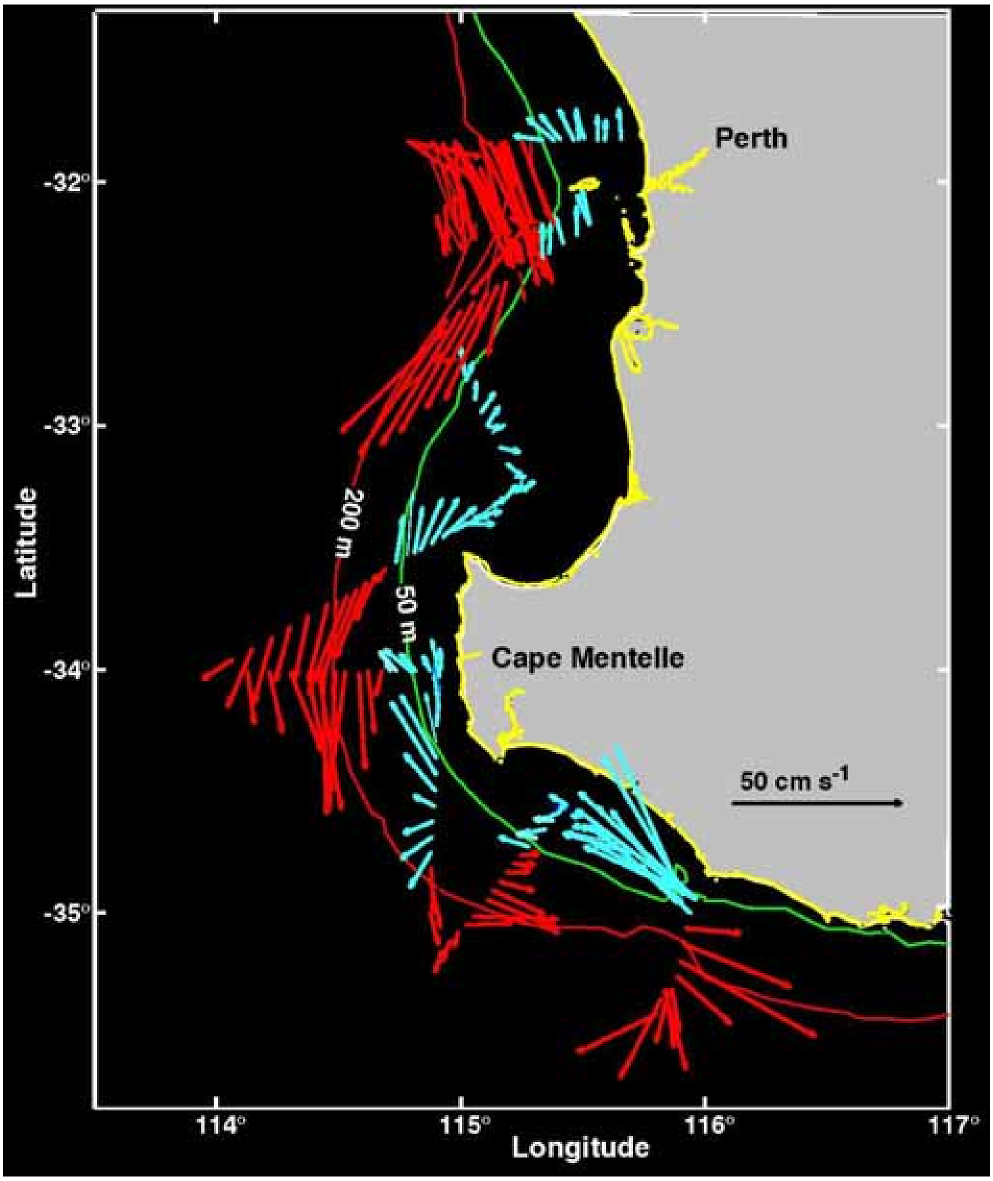

Figure 2.1.11 Depth averaged current vectors from 15–18 December 1994 showing the northward flowing Capes Current inshore of the 50 m depth contour (green) and the southward flowing Leeuwin Current (from Gersbach et al. 1999).

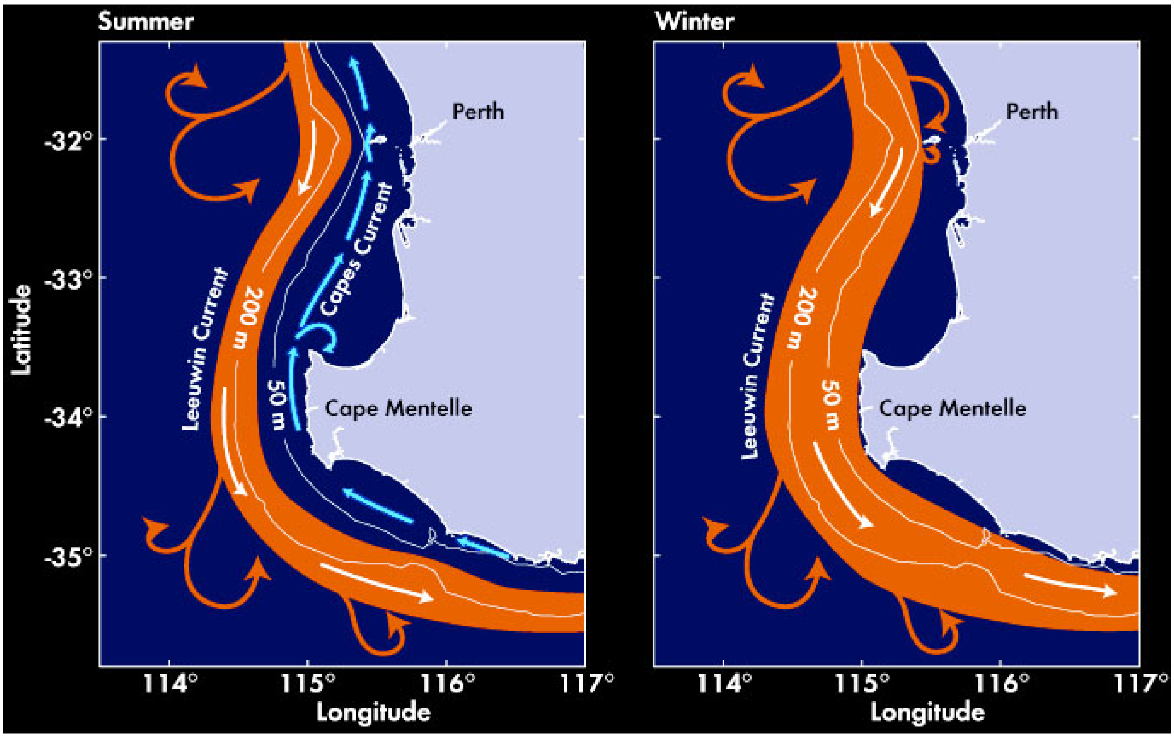

Figure 2.1.12 Schematic of the surface summer and winter current regime off south-western Australia (from Hanson et al. 2005)

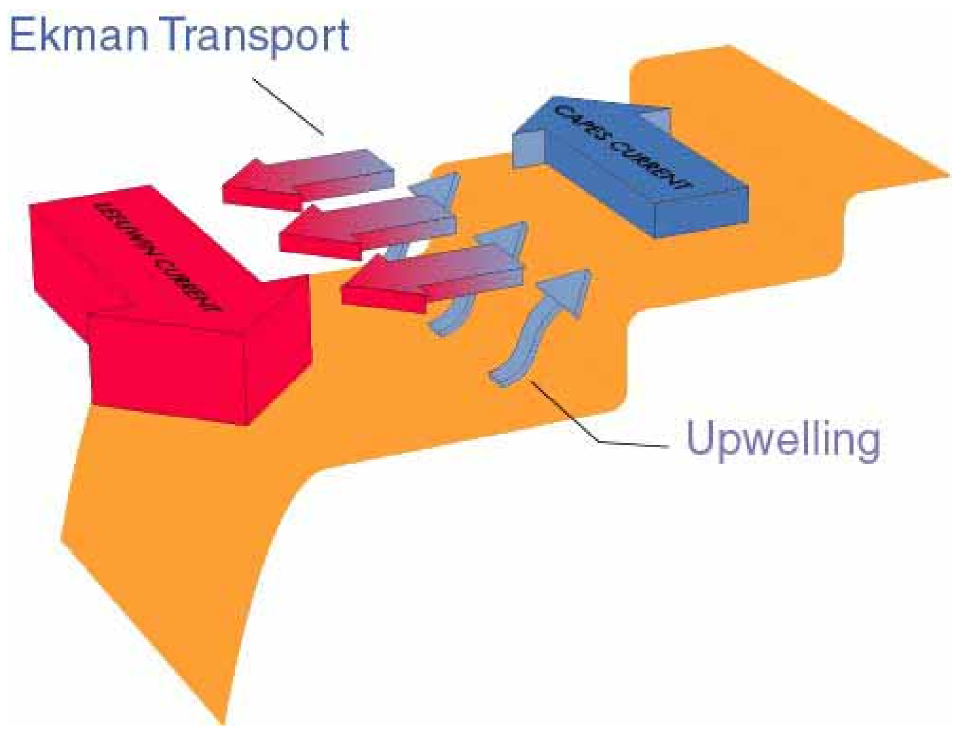

Figure 2.1.13 Cross-sectional schematic of the steady-state summer current regime off south-western Australia (from Gersbach et al. 1999)

Ningaloo Current

The Ningaloo Current, which is defined as a coastal current, is identical to the Capes Current and flows counter to the Leeuwin Current. It was observed in the north-west region of Western Australia between 21° S and 24.5° S. CTD and ADCP data indicated the coastal flow consisted of colder (<23 °C) saline (34.92 ppt) water when compared with offshore waters (Woo et al. 2005). Woo et al.'s (2005) field measurement data also showed the surface water mass, with a depth of 50 m, moved northward with the prevailing wind.

Cresswell Current

The dynamics of coastal circulation in the southern region are largely unknown. Upwelling of cold deep water in this region was observed in recent studies from the Recherche Archipelago and adjacent waters (van Hazel, 2001) and is illustrated by the schematic (Figure 2.1.14). It has been postulated that the wind-driven coastal current (the Cresswell Current) which moves westward with the south-easterly wind south of Western Australia in summertime, is similar to the Capes Current and the Ningaloo Current and causes this upwelling.

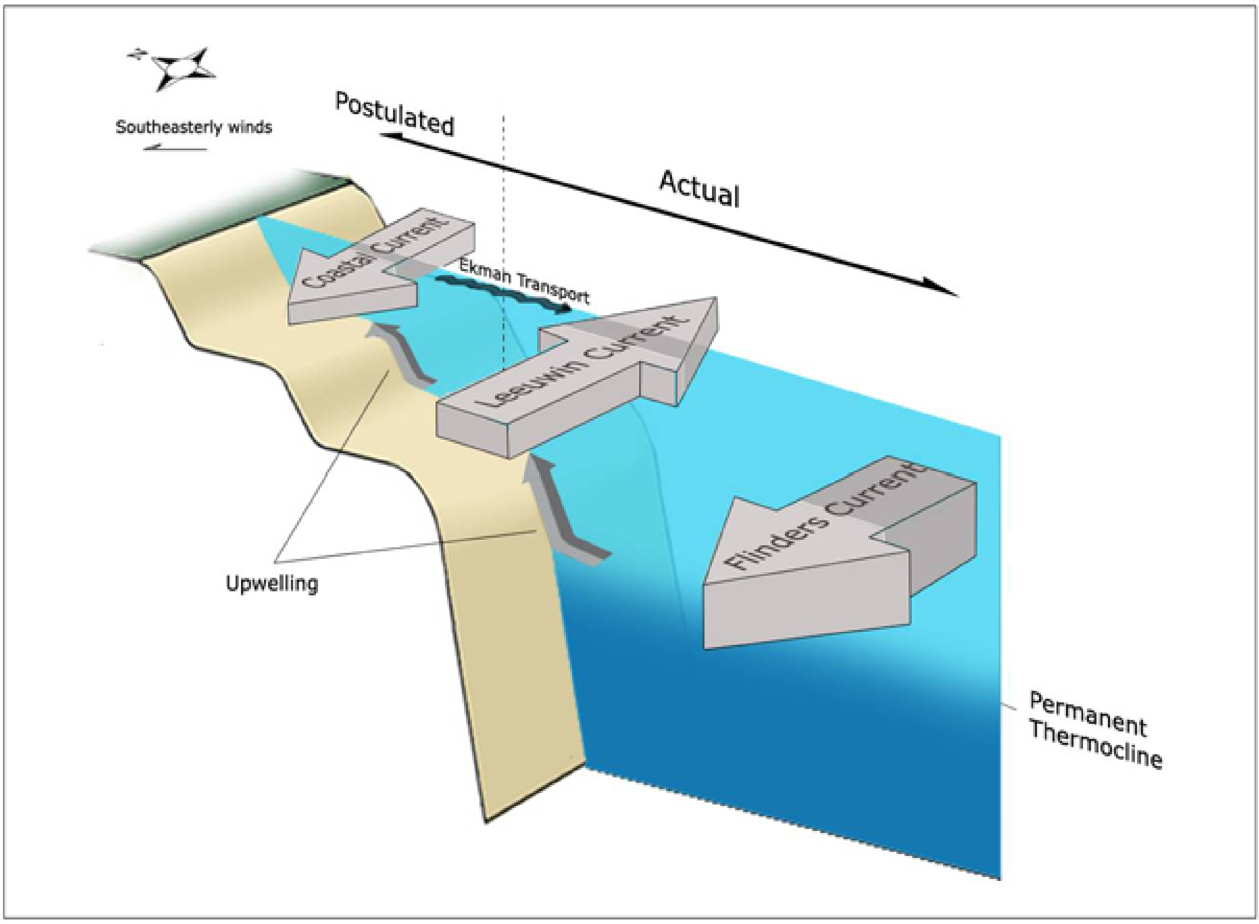

Figure 2.1.14 Cross-sectional schematic of summer current regime south of Western Australia, showing the Cresswell (or Coastal), Leeuwin, and Flinders currents

Water mass characteristics

Analysis of temperature data from bathythermographs and CTDs, reveals the general structure of the water column. Usually a well mixed layer exists at the surface and is produced by turbulent mixing; for example, by surface wind stress, and also by the presence of the Leeuwin Current. The well mixed layer is deeper within the Leeuwin Current than onshore or offshore. The variation in the well mixed layer can be greater than 100 m. The mixed-layer depth varies with season and with El Niño – Southern Oscillation events (Feng et al. 2003). Below the well mixed layer, the thermocline usually descends to around 400 m, although sub-layers may exist in this depth range. The seasonal changes include a cooler sea surface temperature corresponding to the austral winter, and a warmer sea surface temperature in the austral summer, with the deepest mixed-layer depths occurring during winter (Hamilton 1986; Feng et al. 2003).

Woo et al. (2005) identified five different water mass types in the upper Indian Ocean along the Western Australian coast (see Table 1) and they correspond with accepted classical water masses of the Indian Ocean (Wyrtki 1971; Warren 1981). These were observed in the vertical distribution of salinity and dissolved oxygen as interleaving layers of salinity and dissolved oxygen. In terms of increasing depth, these water masses were:

(i) lower salinity tropical surface water
(ii) higher salinity South Indian Central Water
(iii) higher oxygen Subantarctic Mode Water
(iv) lower salinity Antarctic Intermediate Water
(v) lower oxygen North West Indian Intermediate water

The location of each of the above five water masses and their position relative to each other can be identified for the whole length of the coastline from North West Cape (21° S) to Cape Leeuwin (35° S) using both salinity and oxygen (Figure 2.1.15). In the following sections, the characteristics of each of the water masses are discussed in detail.

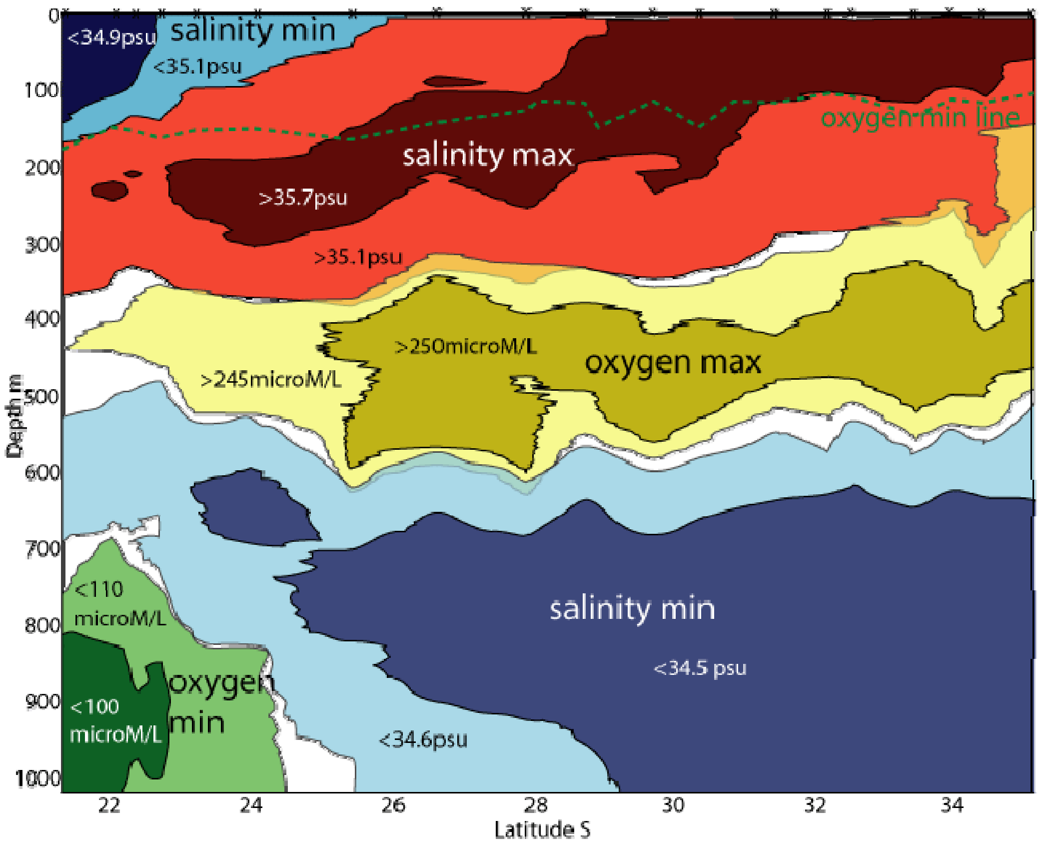

Figure 2.1.15 Major water masses observed at the 1000 m isobath along the Western Australian shelf. Asterisks on the surface indicate CTD station positions.

Table 2.1.1 Characteristics of the water masses found in the upper 1000 m of the water column along the Western Australian coastline

Water mass	Temperature range (°C)	Salinity range (ppt)	Dissolved oxygen range (µM/L)
Tropical surface water	**22–24.5**	**34.7–35.1**	**200–220**
South Indian Central Water	**12–22**	**35.1–35.9**	**220–245**
Subantarctic Mode Water	**8.5–12**	**34.6–35.1**	**245–255**
Antarctic Intermediate Water	**4.5–8.5**	**34.4–34.6**	**115–245**
North West Indian Intermediate water	**5.5–6.5**	**~ 34.6**	**100–110**

Tropical surface water – salinity minimum

In the top 300 m, a layer of lower salinity (<35.1 ppt) warmer (>22 °C) tropical water was found in the surface water in the northern region and corresponded with the temperature or salinity characteristics of the Leeuwin Current water. This water mass is derived from the Australasian Mediterranean Water (AAMW), a tropical water mass with origins in the Pacific Ocean Central Water and formed during transit through the Indonesian archipelago (Tomczak & Godfrey 1994). Tomczak and Godfrey's (1994) field data revealed that this surface water mass was associated with lower nutrient (near zero) and higher dissolved oxygen concentrations.

At the North West Cape (21° S), the northern extent of the study region, this water mass extends to 180 m (Figure 2.1.15) with the surface salinity less than 34.9 ppt. The depth of the water mass decreases southwards with the passage of the Leeuwin Current and at approximately 26° S its salinity signature (<35.1 ppt) disappears. This is due to the dynamics of the Leeuwin Current. The Leeuwin Current is driven by an alongshore geopotential gradient; entrainment of cooler more saline South Indian Central Water (see below) from offshore due to geostrophic inflow is a feature of the Leeuwin Current (Woo et al. 2005a).

South Indian Central Water – salinity maximum

South Indian Central Water is identified here as a salinity maximum layer (35.1–35.9 ppt). Along the 1000 m bathymetric contour, ADCP data revealed the core of the South Indian Central Water to be moving northward along the 26.8 (σT) density surface, with a maximum speed of 0.3 m s^{-1}. However, near the shelfbreak this same water mass is part of the Leeuwin Current flowing southwards (Woo et al. 2005a). Here, ADCP data indicated that the Leeuwin Current extends up to 300 m water depth which is the total depth of this water mass (Figure 2.1.15). South Indian Central Water had a temperature range of 12 °C to 22 °C and was associated with weak minima of dissolved nitrate, silica, and phosphate. It was found at the surface south of 29.0° S and the depth of the salinity maximum increased northward: from the surface at 29.0° S to 245 m at 21.5° S.

In the northern latitudes of the study region, the water mass subducted underneath the tropical surface water derived from Australasian Mediterranean Water. The observation of surface salinity maximum is in agreement with Wyrtki (1971) who found higher salinity water across the breath of the Indian Ocean surface at latitude range 25–35° S. At these latitudes, an excess of evaporation over precipitation forms the higher salinity water at the sea surface (Baumgartner & Reichel 1975). This water is then subducted below the surface water (Karstensen & Tomczak 1997), extending northward until 12–16° S (Church et al., 1989) where it meets the lower salinity Australasian Mediterranean Water flowing westward from the Indonesian archipelago in the South Equatorial Current (Sharma 1972; Tomczak & Godfrey 1994).

In addition to being termed 'South Indian Central Water' (Webster et al. 1979; Rochford 1969a) and 'Indian Central Water' (Karstensen & Tomczak 1997), this high salinity band has also been referred to as 'southern subtropical surface water'

(Muromtsev 1959), 'tropical surface waters' (Ivanenkov & Gubin 1960) and 'subtropical surface water' (Wyrtki 1973).

Subantarctic Mode Water – oxygen maximum

Beneath the South Indian Central Water, a water mass with high dissolved oxygen concentrations of 245–255 µM/L can be identified as Subantarctic Mode Water, the core of which occurred at 400–510 m. The data revealed that Subantarctic Mode Water consisted of water with a temperature range of 8.5–12 °C and salinity range of 34.6–35.1 ppt. Its density ranged between 28.9 ppt and 29.5 ppt.

Subantarctic Mode Water is formed by deep winter convection at 40–50° S in the zone between the Subtropical Convergence and the Subantarctic Front to the south of Australia (Wyrtki 1973; Colborn 1975; McCartney 1977; Toole & Warren 1993; Karstensen & Tomczak 1997). It is postulated that the Subantarctic Mode Water formed to the south of Australia is transported westward by the Flinders Current (Middleton & Cirano 2002) and is the source water for the Leeuwin Undercurrent, transporting water northward along the Western Australian coast (see below).

As Subantarctic Mode Water is formed by deep convection rather than subduction, newly formed Subantarctic Mode Water penetrates to a greater depth than the newly subducted South Indian Central Water (thus, it is comparatively better ventilated) and then moves northward from its formation region. Due to its high oxygen content, the Subantarctic Mode Water plays an important role in ventilating the lower thermocline of the southern hemisphere subtropical gyres (McCartney 1982).

Subantarctic Mode Water also corresponds to the Indian Ocean Central Water defined by Sverdrup et al. (1942). Subantarctic Mode Water and Indian Ocean Central Water often have similar temperatures and salinities; consequently Subantarctic Mode Water has been thought to contribute to the depth range of Indian Ocean Central Water (Karstensen & Tomczak 1997). According to Karstensen and Tomczak (1997), the source characteristics of Subantarctic Mode Water differ from region to region depending on prevailing atmospheric conditions during its formation.

Antarctic Intermediate Water – salinity minimum

Below the Subantarctic Mode Water,a salinity minimum (34.4–34.6 ppt) was observed, indicating the presence of Antarctic Intermediate Water along the coast. The water was cold (4.5–8 °C) and the position of its core became shallower northward (core depth of 875 m at 27.5° S and 520 m at 21.5° S). Its σT values spanned 30.3–31.0. It has been reported that the Antarctic Intermediate Water extends northward from the Antarctic Polar Front to latitudes 10–15° S, and is thought to flow more slowly than the oxygen maximum layer above it (Warren 1981).

Northwest Indian Intermediate water – oxygen minimum

An oxygen minimum signature of less than 110 µM/L in the northern region (21.3–24.5° S) indicated the presence of Northwest Indian Intermediate water immediately beneath the Antarctic Intermediate Water. Occupying depths of 800–1175 m, with density values of 31.8–32.4, its orientation implied southward deepening. As such, it is possible that North West Indian Intermediate water extends further south into the deeper ocean. The temperature of the North West Indian Intermediate water was recorded at less than 5 °C and its salinity ranged 34.55–34.6 ppt. North West Indian Intermediate water was associated with maxima of dissolved nitrate, silica and phosphate.

A similar water mass of Red Sea origin (Rochford 1964) was observed by Rochford (1961), Newell (1974), Webster et al. (1979), Warren (1981), and Toole and Warren (1993) in other regions of the Indian Ocean. The low oxygen values are the result of in-situ consumption of dissolved oxygen in water that has not been in contact with the atmosphere for a long time, presumably due to much slower overall horizontal flow at such depths (Warren 1981).

Leeuwin Current impacts

The anomalous condition that is a result of the Leeuwin Current strongly affects the meteorological and climatological responses of the environment in this region. It is clear that the driest terrestrial climates are found on the western sides of the southern continents of the earth. Western Australia’s annual coastal rainfall at 32° S is 869.4 mm (data from Bureau of Meteorology website – Mount Lawley annual average rainfall), whereas corresponding locations in Chile and Namibia have annual coastal rainfall of less than 300 mm and 200 mm respectively (Gentilli 1991). This sharply decreases near the latitude 24° S, with Western Australia receiving 233.3 mm (Geraldton airport), Chile nearly nil and Namibia approximately 25 mm (Gentilli 1952). This rainfall differential is unusual considering that Western Australia is an analogue of these other locations (Smith 1989).

Gentilli (1991) indicates that the increased amount of rainfall received in Western Australia (compared to other supposedly analogous climates), is chiefly due to the absence of a cold-water current, and is not due to the presence of the warmer Leeuwin Current. However, this indicates that because of the presence of the Leeuwin Current and the subsequent movement of colder water further from the coast, greater rainfall occurs. On these grounds it is reasonable to attribute higher rainfall to the Leeuwin Current flow.

It can be extrapolated that the heat loss from the warm water of the Leeuwin Current to the atmosphere in the north-western shelf waters may be responsible for driving the poleward gradient and in turn driving the Leeuwin Current flow (Church et al. 1989). This too may be the one of the sources of higher rainfall over Western Australia’s south-west when compared to western coastal boundaries of other continents in the southern hemisphere (Telcik 2000).

The effects of the Leeuwin Current on the shelf biology have been studied in depth. It has been documented exhaustively that the presence of the Leeuwin Current is the reason that tropical corals (and associated organisms) can exist as far south as Rottnest Island (32° S). Numerous studies have indicated that many marine species may depend on the Leeuwin Current and similarly on the Capes Current and similar inner-shelf currents for larval dispersal. In particular, studies by Caputi et al. (1996), Hutchins (1991) and Phillips et al. (1991) have analysed the effect of the Leeuwin Current on the dispersal of tropical fish species and the Western Rock Lobster.

The study by Caputi et al. (1996) indicates that due to the presence of the Leeuwin Current (and resulting warmer surface waters), the system is dominated by invertebrate species, rather than finfish – an anomalous condition compared to other eastern boundary flows. Caputi et al. (1991) attributes this to the low productivity of the system as a result of the low nutrient concentration of the contributing Northwest Shelf waters. A study undertaken by Lenanton et al. (1991) supported the study by Caputi et al. (1991) and agreed that the lack of nutrients reduced finfish numbers. For this reason it was indicated that higher numbers of finfish were found in the highly productive estuarine and protected coastal marine systems. The dependence on terrestrial inputs and the limited period of these (winter/spring) in the south-west, indicated a highly competitive environment for finfish development (Lenanton et al. 1991).

Hutchins (1991) indicates that the presence of several species of reef dependent tropical fish and the presence of coral reefs as far south as 32° S (Rottnest Island – and extending to 29° S) are both attributable to the presence of the Leeuwin flow. The coral *Pocillopora damicornis* is the chosen habitat for several tropical fish species, preferring the protected inner lagoon regions, whereas the more exposed regions on the outside reef are typical of temperate reef systems, with corresponding species dominating (Hutchins, 1991).

Phillips et al. (1991) studied the recruitment of rock lobster larvae and its relationship to the strength of the Leeuwin Current. A link between the settlement and the inter-annual variability of the Leeuwin flow is understood to control the dynamics of the fishery (Phillips et al., 1991). It was recorded during the years of 1986 and 1987 (years of uncharacteristically weak Leeuwin Current flow; El Niño – Southern Oscillation years) that no settlement of the larvae occurred (Phillips et al. 1991). This indicates the vital role that the poleward Leeuwin Current plays in recruitment and settlement of the puerulus stage of the rock lobster's life cycle.

2.2 Esperance to Robe

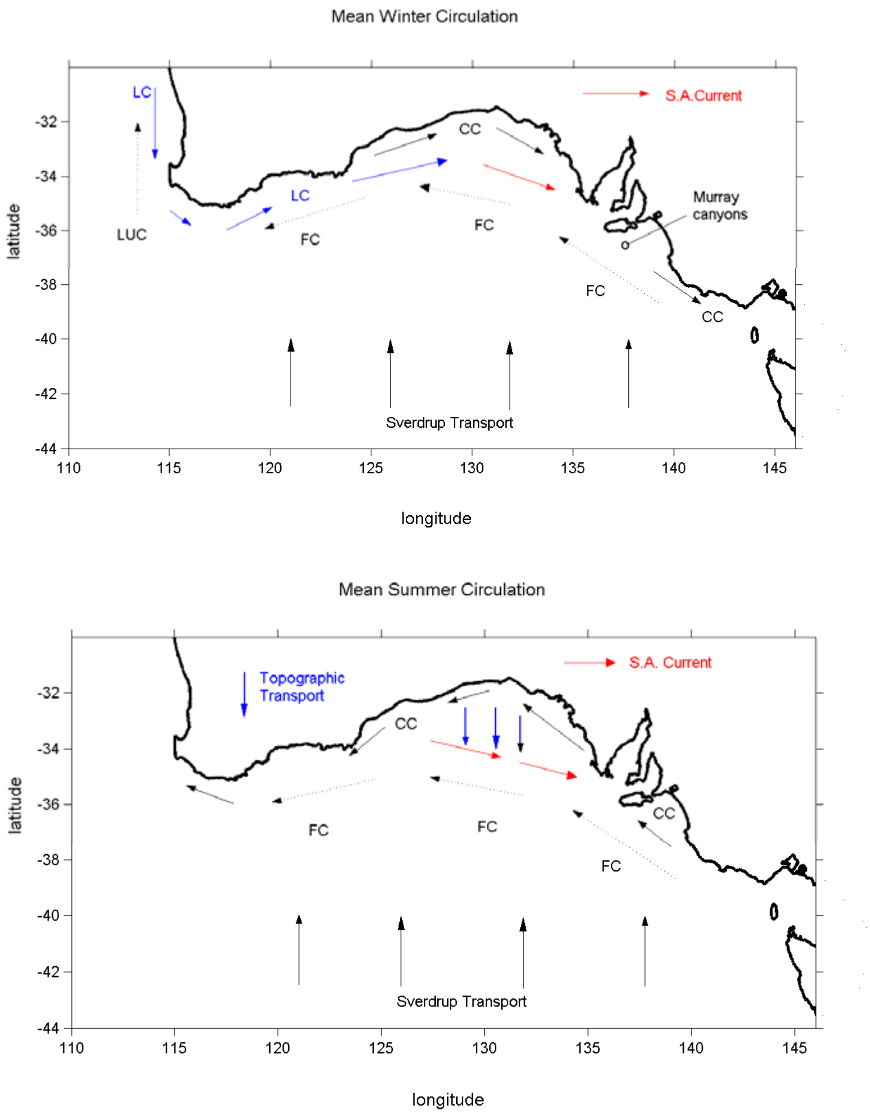

Figure 2.2.1 **Upper panel**: A schematic of some key circulation features for winter, including the Leeuwin Current, the Leeuwin Undercurrent, the Flinders Current and the shelf-edge South Australian Current. Water is downwelled throughout and there is a dense salty outflow from the gulfs. **Lower panel**: Summertime circulation and upwelling occurs off Kangaroo Island and the Bonney Coast. Shelf edge downwelling may occur in the western Great Australian Bight.

Summary

The region between Cape Leeuwin and Portland hosts the world's longest zonal mid-latitude shelf (~2500 km). The topography includes both the very wide shelf of the Great Australian Bight, as well as the very steep and narrow shelves off Esperance, Kangaroo Island and the Bonney Coast (Figure 1.1.1). The shelves are punctuated by the gulfs and promontories of the Eyre Peninsula, Kangaroo Island and the

Bonney Coast. This varied topography, coupled with the forcing by the circulation of the Southern Ocean and local winds, leads to a complex shelf and slope circulation that is highly seasonal and dependent on the local and remote wind forcing and (density driven) thermohaline circulation.

Uniquely, the long, zonal shelf is subject to an equatorward Sverdrup transport from the Southern Ocean (Figure 2.2.1) that is largest in early summer. This transport gives rise to the Flinders Current that is a small sister to the world's major western boundary currents including the Gulf Stream and the East Australian Current. (These western boundary currents arise from the equatorward Sverdrup transport over the entire North Atlantic and South Pacific basins and are typified by strong currents (~50–100 cm/s)). The Flinders Current is thought to be driven mainly by the transport south of Australia. It is trapped to the 600 m isobath where the current speeds can reach 20 cm/s and the bottom boundary layer is upwelling favourable. The Flinders Current is smaller in the east and is likely to be intermittent in both space and time possibly due to opposing winds, thermohaline circulation and the presence of mesoscale eddies along the slope. The Flinders Current may be important to deep upwelling within the ubiquitous canyons of the region.

During winter, the warm inflow of the Leeuwin Current is largely trapped by the shelfbreak and the associated thermohaline circulation may account for around 35% of the total shelf transport off the Eyre Peninsula. The westerly winds drive some 47% of the total transport and the eastward currents average up to 20–30 cm/s. The currents associated with the intense coastal-trapped wave field (6–12 day band) are in order of 25–30 cm/s and can peak at 80–90 cm/s. These winds and wintertime cooling also lead to downwelling to depths of 200 m or so. The net evaporation leads to the outflow of dense salty water from the gulfs and to depths of 300 m on the slope and south-east of Kangaroo Island. The dense water outflow and meanders in the shelf circulation also appear to fix the locations for the growth of mesoscale eddies between the Eyre Peninsula and Portland. Such eddies (~50 km radius) detach from the shelf at the end of winter and may be important to cross-shelf exchange.

During summer, the coastal winds reverse on average and the surface heating leads to the formation of warm water in the western Great Australian Bight and gulfs. No significant exchange of shelf water with the gulfs appears to occur. The winds lead to weak average coastal currents (<10 cm/s) that flow to the north-west (Figure 2.2.1b). In the Great Australian Bight, the wind stress curl can lead to an anticyclonic circulation gyre that can result in shelf-break downwelling in the western Great Australian Bight and an eastward South Australian Current (Figure 2.2.1b). These relatively weak circulation features can be modulated or overwhelmed by variations in the wind and thermohaline circulation.

In the east, upwelling favourable winds and coastal-trapped waves can lead to deep upwelling events off Kangaroo Island and the Bonney Coast that occur over 3–10 days and some 2–4 times a season. The alongshore currents here can be large (~40 cm/s) and the vertical scales of upwelling are of order 150 m (off Kangaroo Island) and 250 m (off the Bonney Coast).

An increasing amount of evidence suggests that El Niño events (4–7 year period) can have a major impact on the winter and summer circulation. These events propagate from the Pacific and around the shelf-slope wave-guide of Western Australia and into the Great Australian Bight. During winter El Niño events, the average shelf currents may be largely shut down. During summer, the thermocline appears to be raised by up to 150 m and impacts on the upwelling off Kangaroo Island and the Bonney Coast.

Surface waves are also important to sediment stirring. The mean (significant) wave height during summer and winter is around 2.3–2.8 m, with dominant periods and wavelengths of 7–9 s and 88–126 m. On average, the wave direction is from the south-west and south. The bottom velocities of these waves can exceed 20 cm/s for 30–60 days of each year, and 40 cm/s for 0–10 days each year. Time averaged currents of these waves can transport surface material and biota by more than 300 km over a one-month period. While tidal velocities are large (~50 cm/s) within the gulfs, they are small (~2–5 cm/s) on the shelves and within the Great Australian Bight.

Shelf slope currents and the Flinders Current: the "mean" seasonal picture

Summary

Limited observations and output from ocean circulation models indicate the existence of a shelf slope Flinders Current that may flow from Tasmania to Cape Leeuwin (Figure 2.2.1). This current has maximum amplitude at depths of 600 m or so and increases in magnitude from 5 cm/s in the east to 20 cm/s in the west, where it forms part of the Leeuwin Undercurrent during winter. The Flinders Current is driven by the equatorward Sverdrup transport in the Southern Ocean and based on wind stress observations, it should be largest in early summer. The bottom boundary layer of the Flinders Current extends some 50 km from the shelf and is necessarily upwelling favourable. The Flinders Current may therefore be important to preconditioning for wind-forced upwelling during summer.

The magnitude of the Flinders Current is, however, affected by cross-shelf density gradients and winds and may vanish or even reverse direction. In addition, the Flinders Current is affected by mesoscale eddy variability that is largest in the west off Albany and off the gulfs region of South Australia. The Flinders Current may well provide a deep westward conveyor belt for the region. More importantly, the cross-shelf pressure gradients associated with the Flinders Current and warm core eddies might be important to upwelling within canyons and might drive nutrients and sediments towards the shelfbreak, where wind-forced upwelling can be important.

The eddy field is strongest during winter, and there is strong evidence for the existence of a sequence of alternating high (warm) and low (cold) eddies along the slope between the Eyre Peninsula and the Bonney Coast: such eddies may detach at the end of winter, when the shelf currents reverse, leading to a significant exchange of water between the shelf slope and deep ocean.

An overview

The existence of the Flinders Current along Australia's southern shelves was first noted in the analysis of hydrographic data of Bye (1972). The dynamics of the current were subsequently explored by Bye (1986) and Godfrey (1989); the latter noted that a north and westward transport for the region should exist in his global analysis of Sverdrup transport. Indeed, the Flinders Current results from the curl of the wind stress that when averaged over the summer and winter periods (figures 2.2.2 and 2.2.3), leads to an equatorward Sverdrup transport in the Southern Ocean as illustrated in Figure 2.2.1.

Along Australia's southern shelves, this transport is deflected to the west leading to the Flinders Current. Middleton and Cirano (2002) have analysed results from the OCCAM global ocean model (Webb et al. 1998) and found the Flinders Current to be trapped along the slope (600 m), largest in the west (20 cm/s) and seasonal in strength (see below). In addition, the bottom boundary layer is necessarily upwelling favourable leading to an upward tilt of isotherms 50 km or so from the slope.

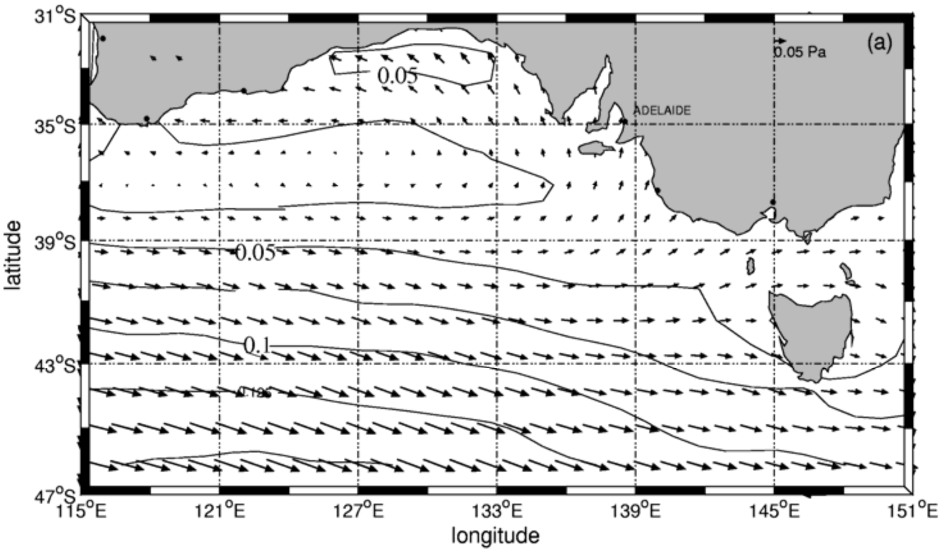

Figure 2.2.2 The mean wind stress field for summer. A legend vector of 0.05 Pa is indicated.

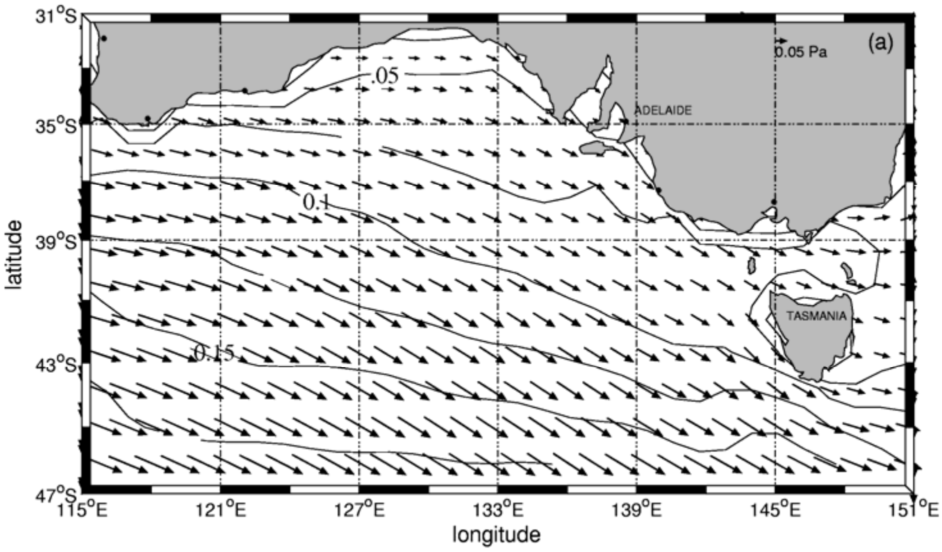

Figure 2.2.3 The mean wind stress field for winter. A legend vector of 0.05 Pa is indicated.

For winter and for a western section off Cliffy Head (~118° E), observations (Figure 2.2.4) show the maximum westward speed to be about 20 cm s^{-1} at a depth of 400–600 m. At and below this depth, the isotherms are upwelled and the associated thermal wind shear acts to reduce the magnitude of the boundary current to near zero at a depth of 1000 m. Above 400 m, the isotherms are downwelled as a result of the wind forcing and cooling. Very warm (>19 °C) water is also found within 50 km of the coast and at depths of 100 m or less. This Leeuwin Current water has speeds of 50–100 cm s^{-1} (see also Church et al. 1989). The Flinders Current also acts to feed the Leeuwin Undercurrent that is observed on the Western Australian slope.

Including the transect shown in Figure 2.2.4, there are but a handful of observations of the Flinders Current and these are summarised by Middleton and Cirano (2002). In summary, the observations are largely indirect but do provide evidence for the Flinders Current as outlined above. An example comes from the hydrographic analysis and data of Schodlok and Tomczak (1997a, b). The latter is presented in Figure 2.2.5 and shows the deep thermocline (500–1000 m) to be upwelled towards the coast and over a distance of 100 km (Figure 2.2.5) – a signature of the Flinders Current.

Seasonal and eddy variability

The magnitude of the Flinders Current is affected by seasonally varying winds (Sverdrup transports), mesoscale eddies and the density field and associated shelf slope currents. The importance of these factors is discussed below.

Winter circulation
In order to determine seasonal variability, the monthly averaged Sverdrup transport along the 39° S zonal section (122–140° E) has been determined using daily winds from a global climatology (NCEP/NCAR). The averaged results in Figure 2.2.6 show the Sverdrup transport, and by implication the Flinders Current, to be generally seasonal, with smallest values (~4 Sv) during winter and largest values (~7 Sv) during early summer.

Using the (smaller) winter Sverdrup transports and mean winter winds (Figure 2.2.3), Cirano and Middleton (2004) obtained numerical results for the circulation of the region that are illustrated by the schematic in Figure 2.2.1. These suggest the existence of a strong (~20 cm/s) eastward flowing coastal current over the shelf (discussed below). Over the slope, an equatorward Flinders Current is found to extend from Tasmania to Cape Leeuwin with maximum amplitudes of 10–15 cm/s and at depths of 600 m or so. In the east, the Flinders Current is forced by a bifurcation of the Tasman Outflow that is in turn forced by the East Australian Current. Off Kangaroo Island and to the west, the Sverdrup transport becomes increasingly important in driving the Flinders Current.

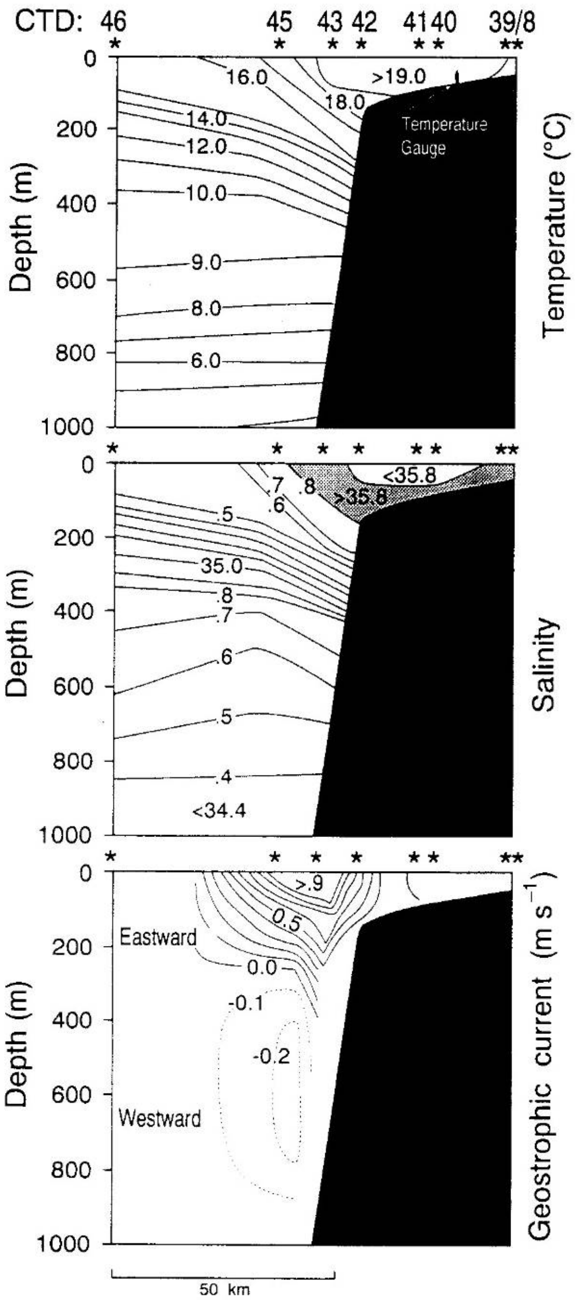

Figure 2.2.4 Cross-shelf ADCP and CTD sections obtained during June by Cresswell and Peterson (1993). Station numbers 38–43 are indicated at the top of the plot.

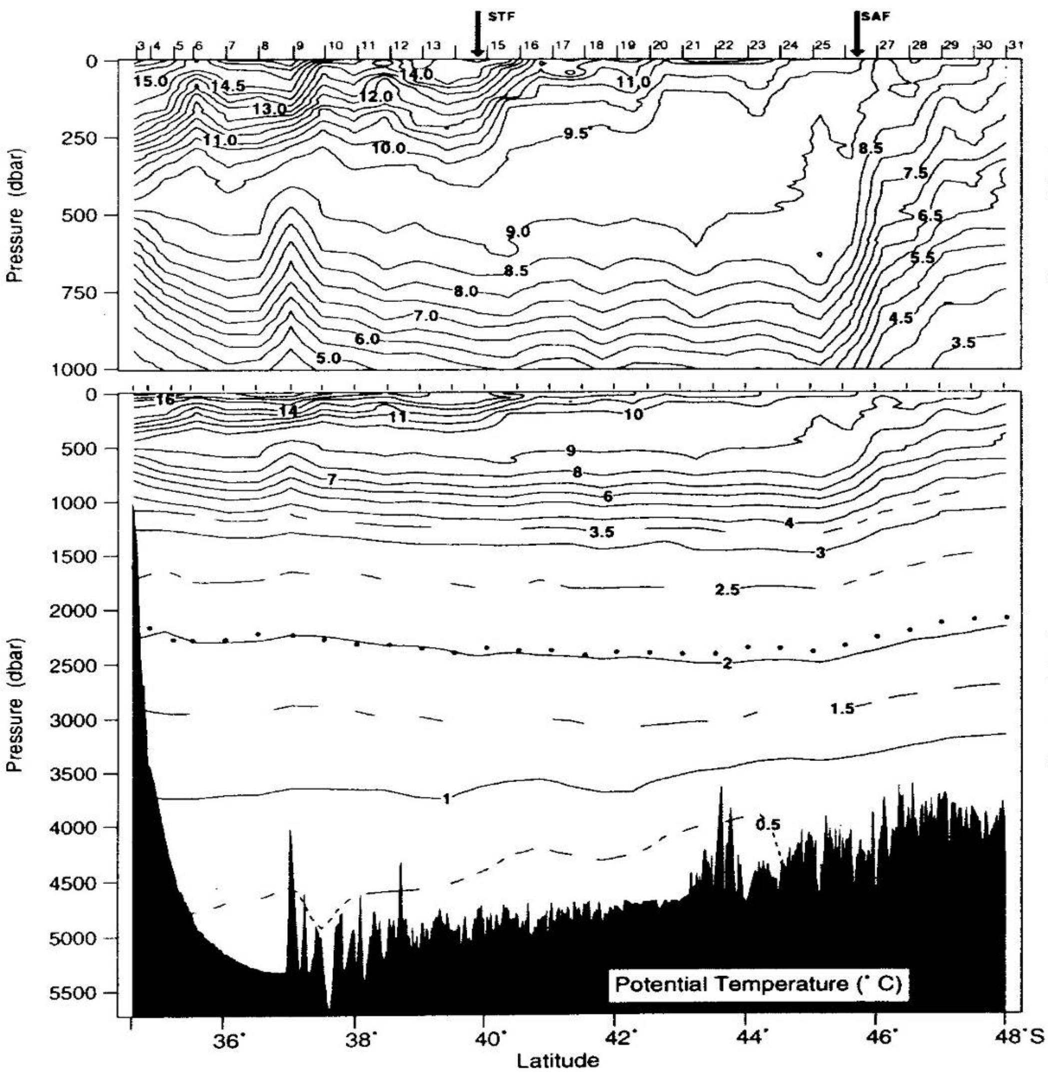

Figure 2.2.5 Isotherms (°C) for a temperature section obtained by Shodlock and Thomczak (1997b) for the November period at 120° E . A detail of the top 100 m is given in the upper panel and illustrates the deep upwelled bottom boundary layer of the Flinders Current. The vertical axis gives depth in terms of pressure where 1 dbar equals 1 m. Station numbers 3–31 are indicated at the top of the plot along with the locations of the Sub-tropical Front (STF) and the Sub-Antarctic Front (SAF).

Winter Eddy variability

Off the Kangaroo Island – Eyre Peninsula region, a sequence of quasi-permanent (wintertime) eddies also seem to be important in modulating the strength of the Flinders Current. Evidence for these eddies is given in the altimeter data analyses of Ridgway and Condie (2004) and their sea surface height anomalies shown in Figure 2.2.7. For the July period, the anomalies indicate the presence of an alternating sequence of high-pressure (warm-core) meanders off the topographic promontories associated with the Eyre Peninsula, Kangaroo Island and the Bonney Coast. Low pressure (cold core) eddies are found between these sites, farther offshore and at locations where the shelf widens (Spencer Gulf and the Coorong).

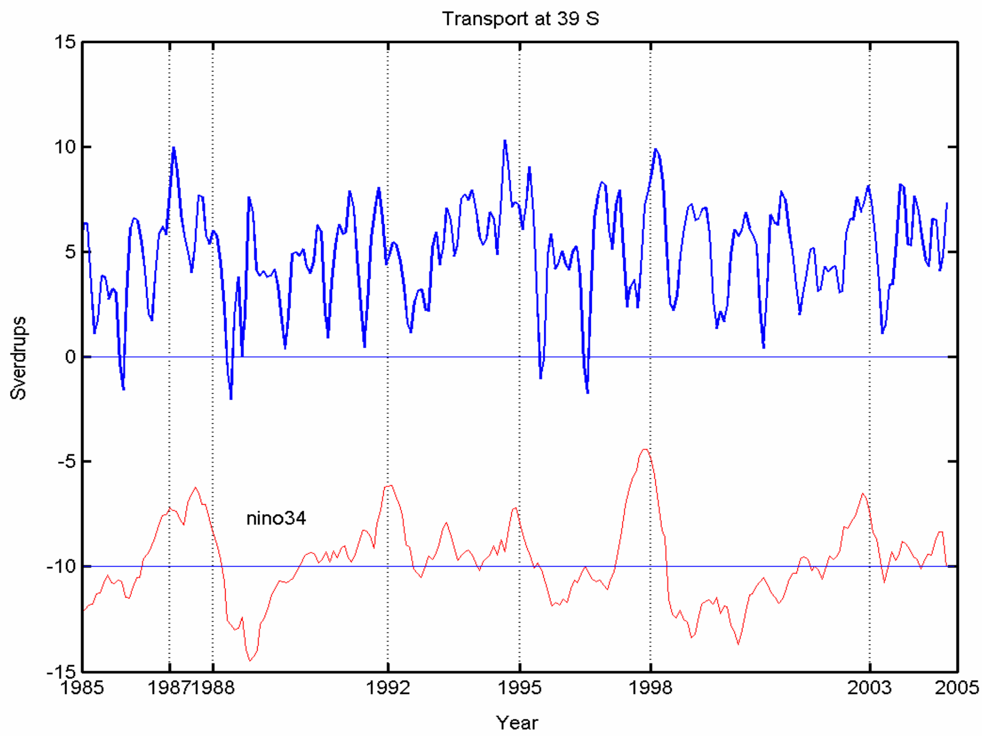

Figure 2.2.6 The monthly averaged Sverdrup transport calculated at 39° S (122–140° E) based upon the NCEP wind stress curl (units Sverdrups). The (non-dimensional) nino34 index is indicated in red: values above -10 indicate El Niño conditions; the vertical dashed lines denote significant El Nino summers.

Similar high and low pressure eddies are found at just these locations in the numerical study of Cirano and Middleton (2004) (see Figure 2.2.12 below); an explanation is given for the growth of the eddies. Further evidence for the formation of a quasi-permanent, low-pressure (anticyclonic) eddy off Kangaroo Island was outlined by Godfrey et al. (1986). Their CTD measurements indicate that salty water flows out from Spencer Gulf during winter and then around to the south of Kangaroo Island at depths of 300 m (Figure 2.2.8). Such an outflow will act to enhance the quasi-permanent (winter) anticyclonic eddy off Kangaroo Island (Cirano & Middleton 2004) that is observed in both altimeter data noted above and also in drifter data (Godfrey et al. 1986; Hahn 1986).

The sea surface height data (Figure 2.2.7) also suggests the eddy variability to be smaller in the mid–Great Australian Bight region, but quite intense in the far west due to instabilities of the Leeuwin Current. Drifter trajectories, CTD surveys and ADCP data all indicate the formation of a large anticyclonic eddy off Albany. The eddy here appears to be quasi-permanent and related to an offshore meander of the Leeuwin Current as it rounds Cape Leeuwin (Ridgway & Condie 2004; Godfrey et al. 1986; Cresswell & Peterson 1993). The radial currents associated with the warm (cold) core eddies over the shelf slope can act to enhance (retard) the Flinders Current and increase upwelling and downwelling through the bottom boundary layer and within canyons (see below).

More recently, Ridgway (pers. comm., 2005) has determined the monthly sea level anomalies for the entire year. An animation of these anomalies shows that the pattern of winter high/low eddies apparent in Figure 2.2.7 becomes detached when the winds and coastal current reverse to be westward. The eddies then detach from the slope region and propagate to the west.

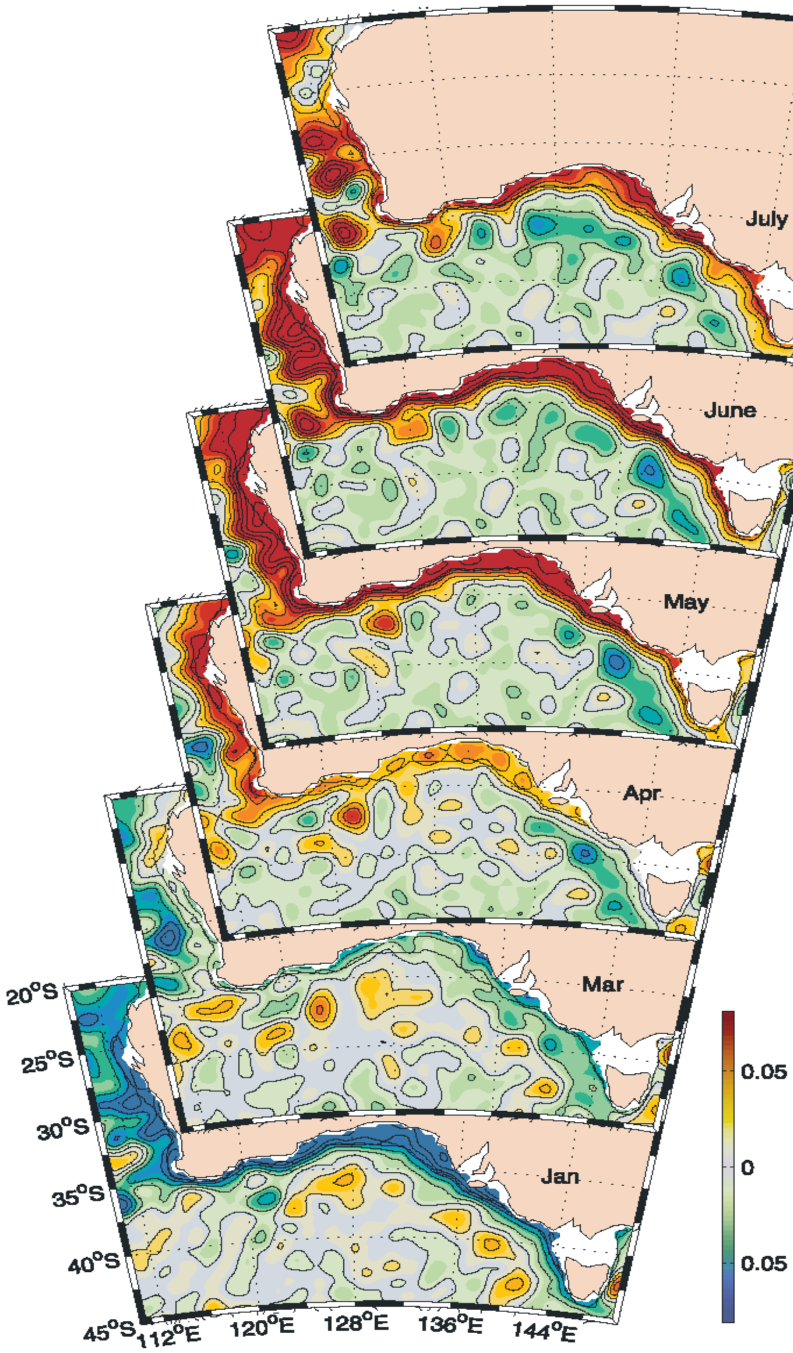

Figure 2.2.7 Sea surface height anomalies inferred from altimeter and coastal sea level data by Ridgway and Condie (2004). The vertical side bar gives height in metres.

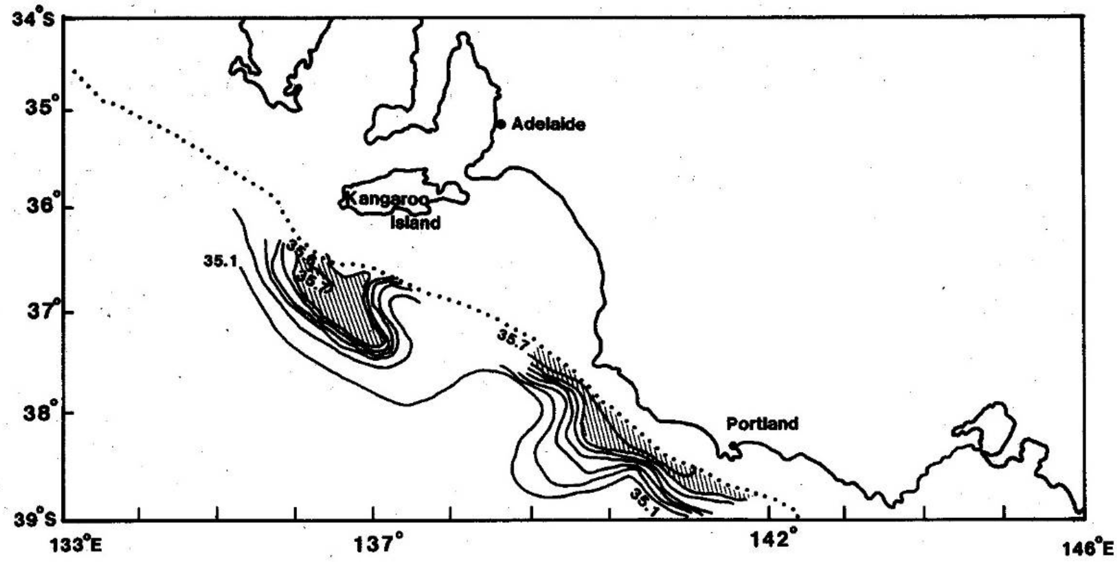

Figure 2.2.8 The salinity (ppt) at a depth of 200 m as determined by Godfrey et al. (1986) during June–July 1982

Summer circulation

As noted, the Sverdup transport is larger in early summer and should drive a stronger Flinders Current than found during winter. Middleton and Platov (2003) have developed a model that is driven by the summer mean winds and (larger) summer Sverdrup transports. The coastal winds reverse during summer, the Leeuwin Current is absent and the shelf-slope circulation is very different to that found during winter. As shown in the schematic (Figure 2.2.1) and numerical results (Figure 2.2.10), the coastal current flows to the west and an anticyclonic (anticlockwise) gyre is found in the Great Australian Bight. The seaward arm of this gyre opposes the underlying Flinders Current. Given the larger Sverdrup transports, the Flinders Current is surprisingly weaker in summer than in winter and is only found in the western half of the Great Australian Bight where the maximum amplitude is in the order of 5–10 cm/s at depths of around 400 m (Figure 2.2.10). We now review the causes of these circulation features.

Wind effects

During summer, the reversal of the winds (to be westward) leads to profound changes in the shelf and slope circulation. An anticyclonic gyre is evident in the Great Australian Bight and shoreward of the 200 m isobath (Figure 2.2.9). This gyre is driven by the positive wind-stress curl in the Great Australian Bight and leads to a poleward (seaward) topographic Sverdrup transport. Herzfeld and Thomczak (1999) found a similar result in their numerical study.

Middleton and Platov (2003) showed that in the western half of the Great Australian Bight, this transport converges with the (deep sea) Sverdrup transport leading to downwelling along the shelfbreak and the raising of sea level. Such downwelling is illustrated by the numerical solutions for a mid–Great Australian Bight section shown in Figure 2.2.10. Middleton and Platov (2003) cited profiles of CARS data as evidence of such summertime downwelling.

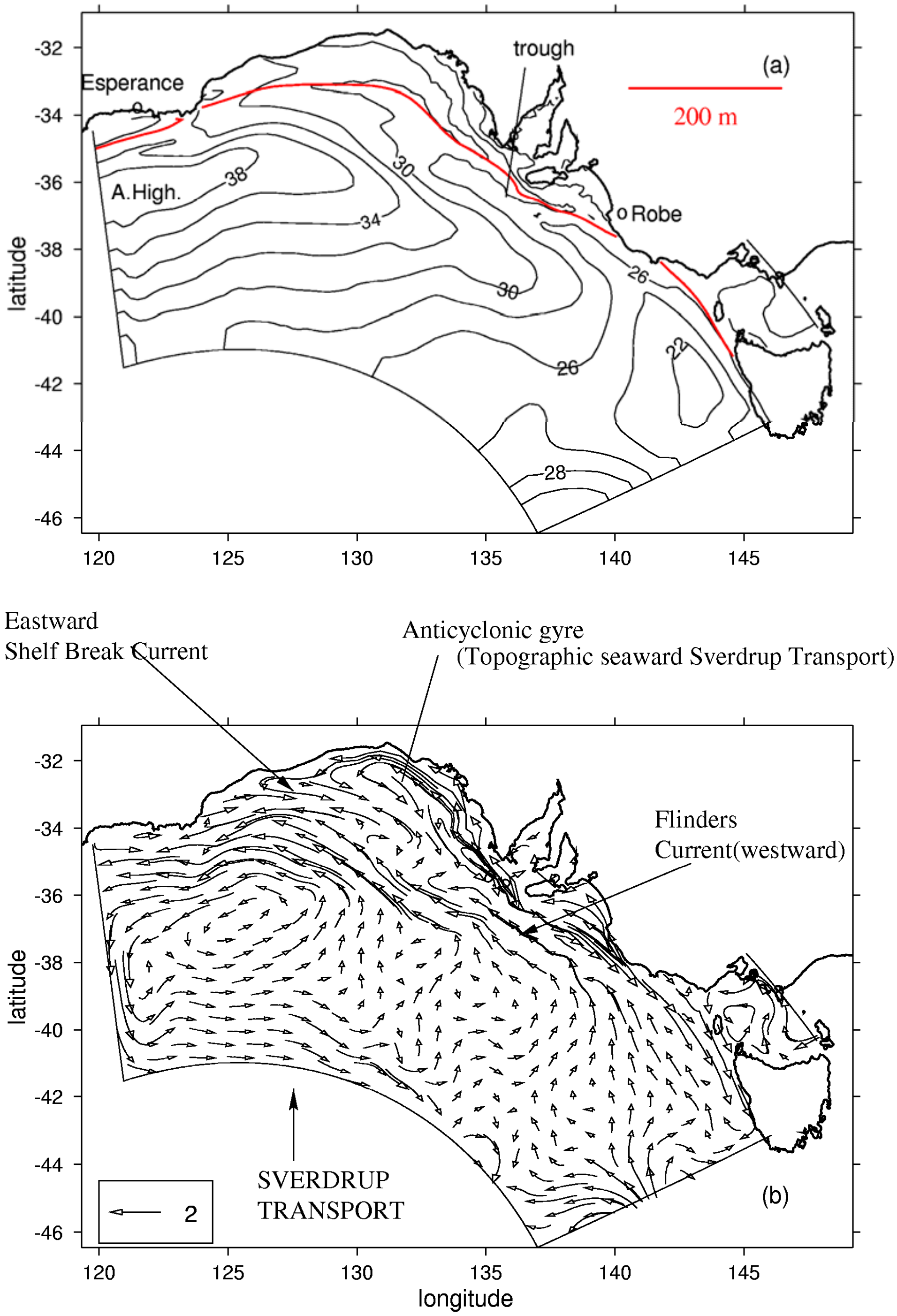

Figure 2.2.9 a) The sea level (units cm) and b) depth-averaged velocity from the numerical model of Middleton and Platov (2003) as driven by summertime mean winds. A vector length of 2 cm/s is indicated in (b) along with some major current systems.

In an analysis of sediment samples, James et al. (2001) also concluded that downwelling must occur along the shelfbreak and in the western half of the Great Australian Bight.

Middleton and Platov (2003) point out that the convergence of the two Sverdrup transport fields also acts to raise sea level leading to an eastward shelfbreak current that opposes the Flinders Current, and which flows as far as the Eyre Peninsula (Figure 2.2.9). This summer (and winter) current has been called the South Australian Current (Black 1853; James et al. 2001; Hahn 1986). Evidence for it is given in the SST images of Herzfeld (1997): see plate 12 in Figure 2.2.11. Indeed, some of the warm water formed in the north-west of the Great Australian Bight during summer is subsequently transported along the shelf edge indicating the existence of both an eastward shelf current and an anticyclonic gyre within the Great Australian Bight. The SST anomalies of Ridgway and Condie (2004) support this scenario.

In contrast to the numerical results cited above, Ridgway and Condie (2004) suggest that the (summer) sea level gradients indicated in Figure 2.2.7 are the surface manifestation of a Flinders Current that flows across the entire Great Australian Bight. However, without further data, the extent of the Flinders Current cannot be determined.

Summer Eddy variability

The summer sea level anomalies presented by Ridgway and Condie (2004) (Figure 2.2.7), also show that the eddy variability is much weaker during summer than winter. A possible reason for this is that the shelf coastal current, now directed to the west is much weaker than during winter so that offshore meanders and the resultant eddies are also weaker.

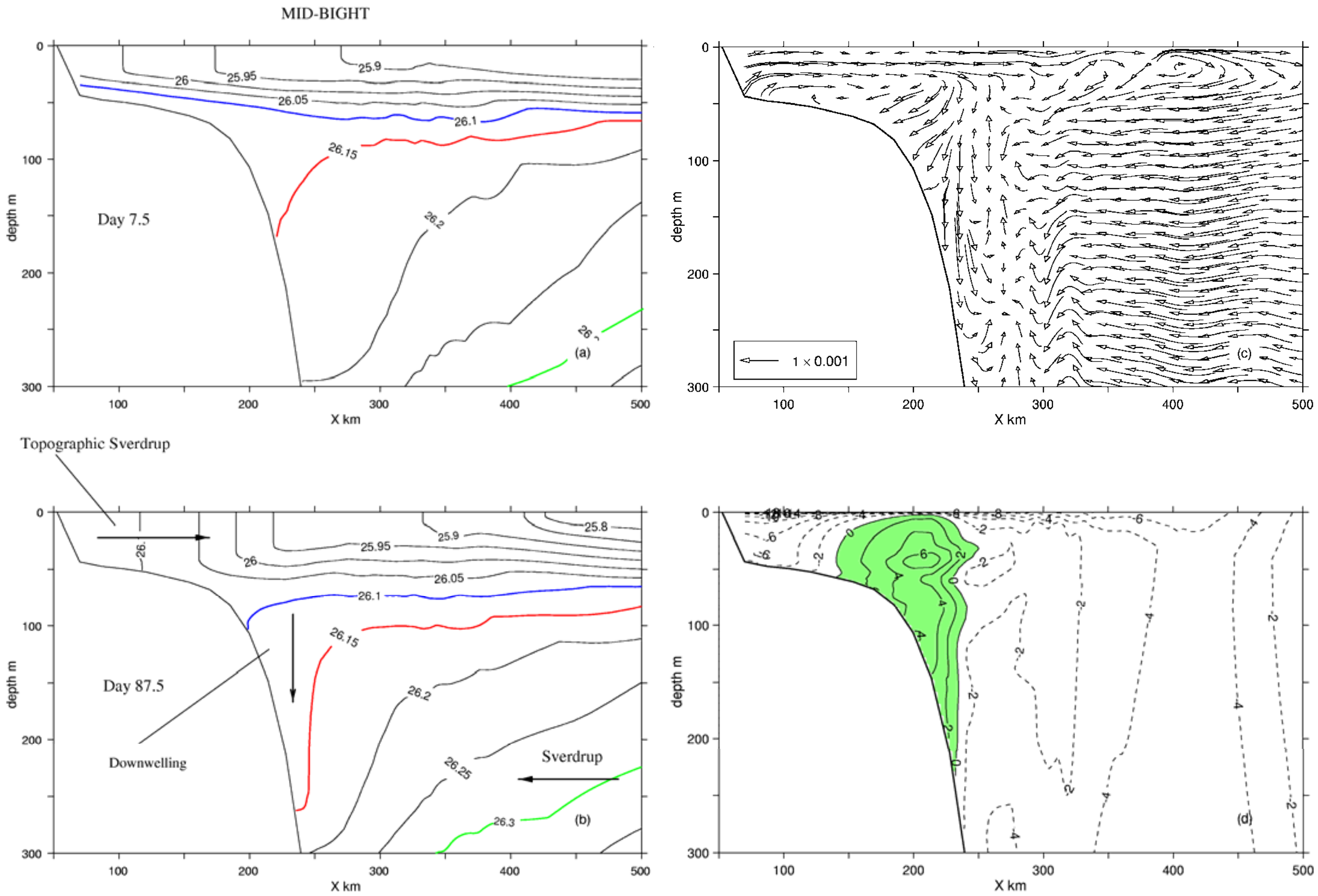

Figure 2.2.10 Numerical simulation of shelf-break downwelling in the western Great Australian Bight (Middleton & Platov 2003); **Top left panel**: The initial density field (interval 0.05 kg/m^3) adopted by Middleton and Platov (2003). Note: following convention, a constant value of 100 kg/m^3 has been subtracted from the density; **Bottom left panel**: The density field at day 87.5 illustrating the shelf-break downwelling of isopycnals; **Top right panel**: The cross-shelf velocity field illustrating the convergence of Sverdrup transports and downwelling over the shelf-break (200 m). The length of the legend vector arrow indicates 1 cm/s in the horizontal and 1 mm/s in the vertical; **Bottom right panel**: The alongshore velocity field (shaded) is positive to the east (units cm/s)

Transport implications of the Flinders Current and eddies

Canyons and upwelling

Through geostrophy, the cross-shelf pressure force associated with the westward Flinders Current is directed shoreward. When these currents flow over the ubiquitous narrow canyons of the region, the geostrophic balance may be disrupted and the pressure force can act to accelerate water, sediments, and nutrients up toward the shelfbreak. In other regions, canyon upwelling is well documented (e.g. Klink 1996). For the Bonney Coast region, the only evidence for this is the presence of neutrally buoyant asphaltites that are associated with sediments at depths of 2000 m or more, but which are found along the Bonney Coast (Peter Boult, PIRSA, pers. comm. 2005). The mechanism may be very important to deep upwelling for the South Australian region during summer, since wind-forced upwelling can then draw the upwelled water much closer to the coast. In the west, and during winter, the shelfbreak currents are downwelling favourable and the mechanism may only be important for cross-shelf exchange at depths of 200 m or more.

Alongshore advection – a deep westward conveyor belt

While the Flinders Current may be intermittent, the shelf slope speeds of 10 cm/s (~9 km/day) imply that fluid and matter can be advected to the west by 810 km over a three-month period. While the Flinders Current is a very deep current, it does provide the only westward means of transport during winter. Wind-forced downwelling during winter provides a means of connecting shelf water to the Flinders Current .

The eddies

The semi-permanent eddies found during winter off South Australia may be implicated in both local shelf slope ecological communities. In addition, the detachment and propagation of these eddies away from the shelf at the end of winter may have implications for cross-shelf exchange of water, nutrients and marine biota.

The “mean” winter shelf circulation and downwelling

Summary

A combination of winds, thermohaline forcing and the Leeuwin Current drive an eastward coastal current from Cape Leeuwin to Kangaroo Island during winter with mean speeds of order 30 cm/s or so. A three-monthly seasonal scale of advection is of order 2000 km. The winds drive an onshore surface Ekman transport and a return subsurface flow to deeper waters lead to downwelling to depths of order 200 m or so. The net cooling and evaporation over winter also leads to dense water formation. Within the gulfs, tidal mixing can lead to the fortnightly flushing of dense water with the lighter shelf waters. Light water is drawn from the Eyre Peninsula and expelled along the west then southern coast of Kangaroo Island and to depths of 300 m. Dense water is also formed along the shallow waters of the Coorong and north-western Great Australian Bight. Over the narrow shelves off Esperance, the Eyre

Peninsula and Kangaroo Island, the alongshore currents can exceed 50 cm/s and may be implicated in both alongshore and offshore sediment transport within the bottom boundary layer.

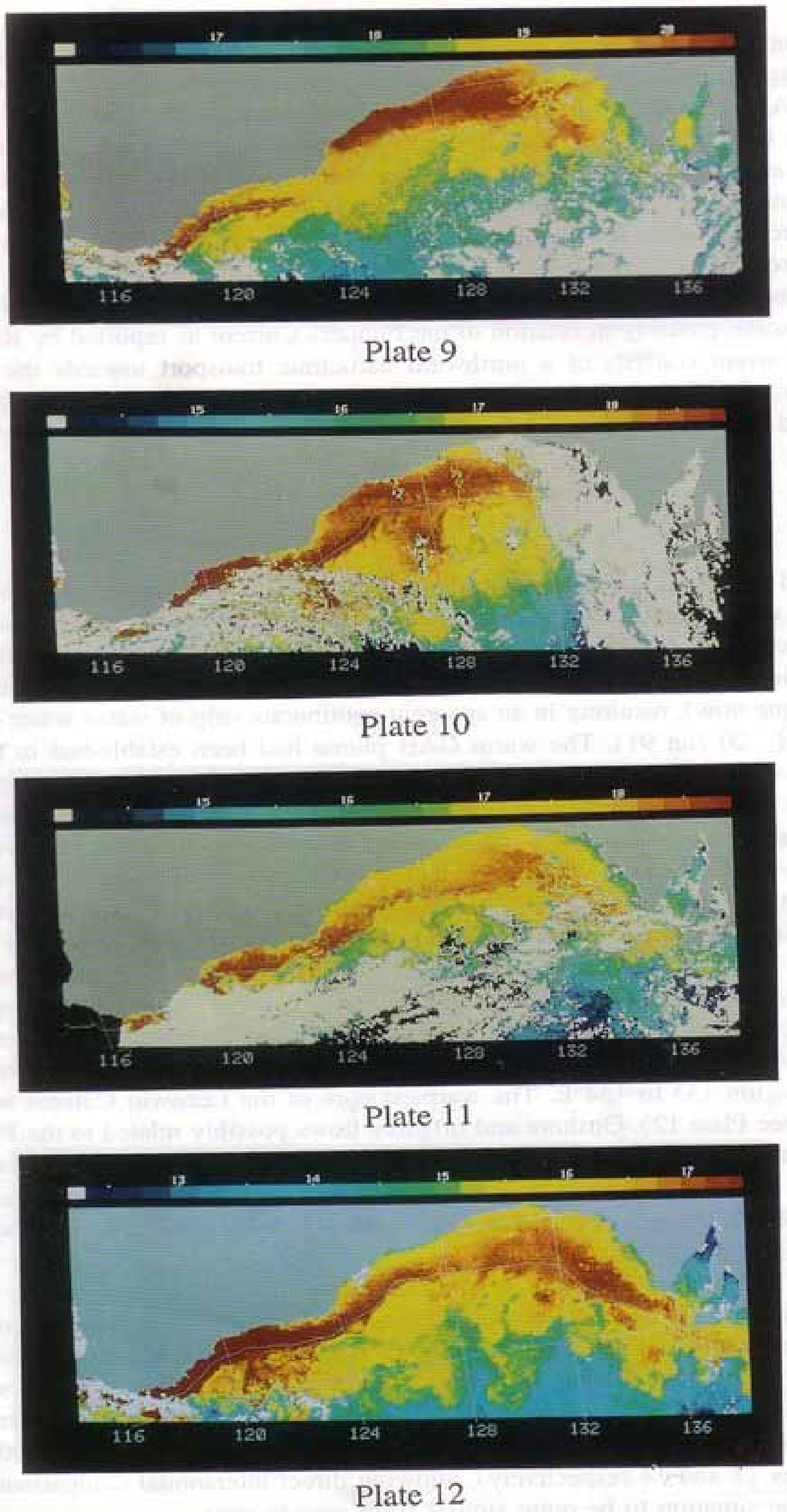

Figure 2.2.11 SST data from Herzfeld (1997) for April (plate 9), May (plate 10), June (plate 11) and July (plate 12) of 1991. The temperature (colour) scale changes in each plate. The data shows the generation of the western Great Australian Bight warm pool during late summer/autumn (plate 9) and the subsequent wintertime intrusion of the Leeuwin Current into the Great Australian Bight and along the shelf-break (plates 11 and 12). The white line in plate 12 indicates the 200 m isobath.

Discussion

Forcing mechanisms

During winter, the wind stress at the coast is directed to the east with an average amplitude of between 0.05 Pa (7 m/s) to 0.1 Pa (9 m/s). These winds drive an Ekman flux onshore that acts to raise sea level near the coast and drive a coastal current from west to east. In the west, the Leeuwin Current enters the region with speeds of up to 90 cm/s as illustrated in the ADCP transect (Figure 2.2.4) off Cliffy Head (Cresswell & Peterson 1993).

The winter period is also one of surface cooling with net heat fluxes of about 60–100 W/m^2 near the coast (Herzfeld 1997; Table 2.2.1 below). The loss of heat leads to the formation of cold (dense) water in the shallow regions of the gulfs, the Coorong and the north-west section of the Great Australian Bight as illustrated by the SST anomalies presented by Ridgway and Condie (2004). Evaporation also exceeds precipitation with a net loss of freshwater of about 1–2 mm/day (NECP/NCAR). This loss of freshwater enhances dense water formation in the regions noted above.

Quantity	Summer	Winter
Mean wind stress (wind)	-0.05 (7)	0.07 (8)
S. dev. wind stress (wind)	0.1 (9.3)	0.12 (10)
Season maxima stress (wind)	0.2 (12)	1.1 (23)
Heat flux (W/m^2)	50 (100)	-100 (-20)

Table 2.2.1 Meteorology for the Region
Typical values of the alongshore components of the mean and standard deviation (S. dev.) February and August wind stress (units Pa). The same statistic is presented in brackets but in m/s: 10 m/s = 36 km/h. A positive mean is directed to the south-east along the shelf. The maximum wind stress most likely to be experienced in any year is also given and was inferred from Trenberth at el. (1989) and Whittington (1964). The heat fluxes are from the NCAR/NCEP climatology for the Great Australian Bight region while those in brackets are for the Head of the Bight (Herzfeld 1997).

An overview of shelf currents – observations and numerical model results

An overview of the net effect of winds, the Leeuwin Current and water mass formation is presented in the results for sea surface height anomalies and SST in figures 2.2.7 and 2.2.11. The positive sea surface height anomaly at the coast ranges from 14 cm to 10 cm between Cape Leeuwin and Kangaroo Island. Ridgway and Condie (2004) point out that the largest cross-shelf sea surface height gradient is located near the shelf edge, indicating the existence of an intensified shelf edge South Australian Current.

As noted, published observations of the South Australian Current are almost non-existent. Black (1853) named the current based on ship-drift reports. Godfrey et al. (1986) indicate (ship-drift) speeds to the east of more than 50 cm/s over the shelfbreak and at 128° E during June 1982. For the gulfs region and Bonney Coast, Cirano and Middleton (2004) have summarised most available current meter data (Provis & Lennon 1981; Hahn 1986; Schahinger 1987). Results typical of the region are presented in Table 2.2.2. While the shelf is much narrower, observed mean winter currents are to the east (poleward), largest near the shelf edge and of order 20–30 cm/s.

The current meter data in Table 2.2.2 also provide support for the numerical results of Cirano and Middleton (2004) and their “mean” winter shelf circulation (Figure 2.2.12). The shelf coastal current can reach values of 50 cm/s off the topographic constrictions of the Eyre Peninsula, Kangaroo Island and Robe. The offshore flow induced here also acts to trigger the sites of the mesoscale eddies discussed above (Cirano & Middleton 2004).

Thermohaline forcing

Relatively cold, salty water (14–15 °C, >36.2 ppt) is produced in the Coorong and north-west section of the Great Australian Bight. The warm anomaly associated with the Leeuwin Current that enters the Great Australian Bight is also evident as a plume along the shelf edge to the mid–Great Australian Bight as shown in the SST data (Figure 2.2.11). The thermohaline circulation and momentum input of the Leeuwin Current may be expected to enhance the coastal current and South Australian Current near the shelfbreak. To resolve the relative importance of these mechanisms (and wind), Cirano and Middleton (2004) determined the net transport due to each for a cross-shelf section off the Eyre Peninsula. The results indicate that of the total transport over the shelf (1.9 Sv shoreward of the 200 m isobath), 47%, 35% and 18% is respectively driven by the alongshore winds, thermohaline effects and the Leeuwin Current. The results confirm that the momentum input by the Leeuwin Current is largely expended at the Eyre Peninsula and that thermohaline effects are important.

Within the gulfs, evaporation leads to water that is denser (>27 kg m^{-3}) than the shelf (26.8 kg m^{-3}) and a plume that flows out of the eastern mouth and then south and east (Figure 2.2.8) along Kangaroo Island (Godfrey et al. 1986). Water is drawn in at the surface at the western mouth of Spencer Gulf and the gulf–shelf exchange is modulated on a fortnightly basis by mixing due to the large tidal signal within the gulfs (Nunes Vaz et al. 1990; Bowers & Lennon 1986; Lennon et al. 1987). The circulation represents a significant mechanism for cross-shelf exchange.

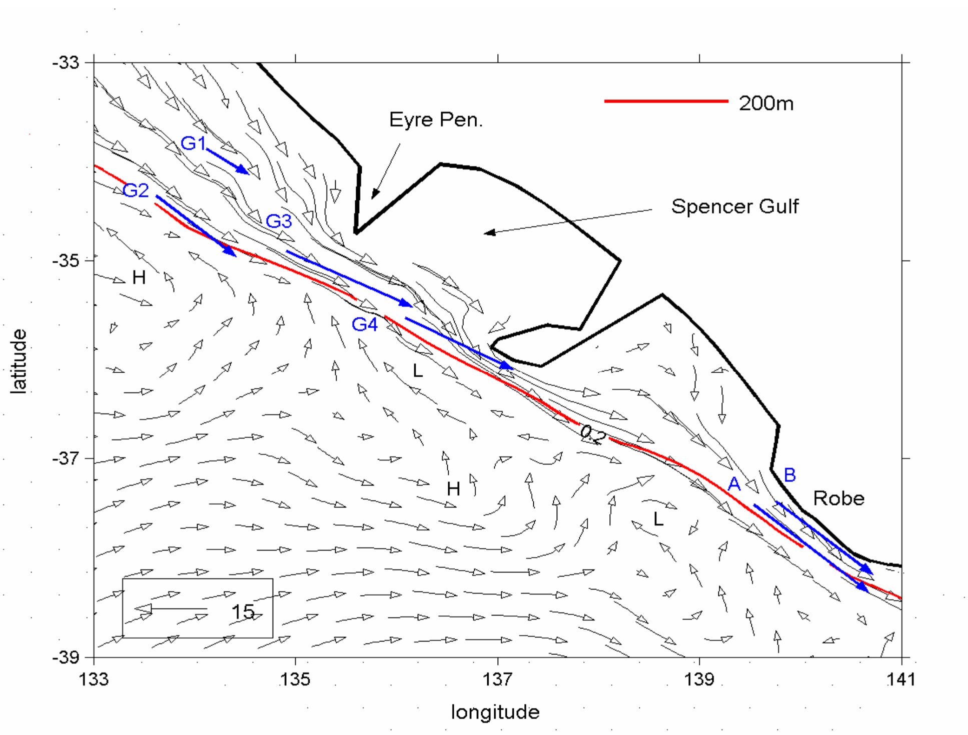

Figure 2.2.12 A numerical simulation of the quasi-steady winter circulation (Cirano & Middleton 2004) and some of the observed mean currents (the dark blue vectors) at sites G1–G4, A and B.

Table 2.2.2 Current meter observations: The tables present mean current speeds and directions obtained from available and published data for summer and winter periods for sites G4, A and B shown in Figure 2.2.12. The first column indicates whether the data is from an El Niño year. Observations from El Niño and non-El Niño years are paired for repeat observation sites (the first being for a non-El Niño year). The second column indicates the mooring site (as shown in Figure 2.2.13), position in the water column by upper (U) or lower (L) and year. The columns labelled “1st record” and “Days” indicate the start time and number of days used to compute the statistics. The magnitude of the vector mean |**U**| is given along with its direction θ in degrees anticlockwise from east. The maximum speed registered for the deployment is given if available: all units are cm/s.

SUMMER

Event	Site and year	1st Rec. dd/mm/yy	Days	Lat.	Long.	Water Depth (m)	Inst. Depth (m)	|U| cm/s	θ	s. dev. cm/s	max
	G4 U 82	**11/11/81**	**78**	**35.70**	**135.78**	**138**	**22**	**2.4**	**289**	**24**	**50**
El Niño	**G4 U 83**	**02/12/82**	**95**	**“**	**“**	**146**	**15**	**2.9**	**267**	**28**	**60**
	G4 L 81	**12/12/80**	**50**	**35.77**	**135.75**	**137**	**115**	**2.0**	**144**	**21**	**45**
	G4 L 82	**11/11/81**	**78**	**"**	**"**	**137**	**133**	**3.5**	**298**	**17**	**45**
El Niño	**G4 L 83**	**02/12/82**	**95**	**“**	**“**	**146**	**125**	**2.9**	**330**	**20**	**45**
	B 84	**021/1/84**	**56**	**37.43**	**139.72**	**50**	**26**	**5.3**	**30**	**24**	**50**
El Niño	**B 83**	**07/02/83**	**60**	**“**	**“**	**52**	**24**	**3.5**	**113**	**23**	**-**
	A 84	**21/01/84**	**56**	**37.53**	**139.52**	**146**	**115**	**4.9**	**332**	**16**	**80**
El Niño	**A 83**	**07/02/83**	**60**	**“**	**“**	**143**	**110**	**2.5**	**7**	**20**	**-**

WINTER

Event	Site and year	1st Rec. dd/mm/yy	Days	Lat.	Long.	Water Depth (m)	Inst. Depth (m)	|U| cm/s	θ	s. dev. cm/s	max
	G4 U 81	**06/04/81**	**78**	**35.77**	**135.75**	**137**	**42**	**20.2**	**-30**	**34**	**100**
El Niño	**G4 U 82**	**26/08/82**	**97**	**“**	**“**	**144**	**31**	**1.4**	**-108**	**25**	**55**
	G4 L 81	**06/04/81**	**78**	**35.77**	**135.75**	**137**	**115**	**19.2**	**-54**	**30**	**90**
El Niño	**G4 L 82**	**26/08/82**	**97**	**“**	**“**	**144**	**124**	**4.6**	**-57**	**21**	**45**
	A 83	**07/07/83**	**57**	**37.53**	**139.52**	**143**	**112**	**28.5**	**-49**	**25**	**80**
El Niño	**A 82**	08/08/82	**59**	**“**	**“**	**“**	**111**	**7.4**	**-60**	**22**	**-**

Transport implications

The wintertime coastal current is on average 15–30 cm/s implying an advective scale of 15–30 km/day or 1300–2700 km over a three-month seasonal period. The mean onshore surface Ekman transport and return offshore transport provide well defined pathways of advection across the entire Great Australian Bight and gulfs region. Nutrients, sediments and toxins formed in the very near-shore zone will be flushed onto the shelf. The regular fortnightly episodic flushing and outflow of dense water of the gulfs with the lighter waters off the Eyre Peninsula and Kangaroo Island may also be important.

The weather-band circulation and coastal-trapped waves

Summary

The weather-band circulation (3–12 days) represents the largest component of the circulation during both summer and winter with rms (root mean square) currents in the order of 25–30 cm/s and seasonal maxima of 50–90 cm/s. The time-varying circulation is often described by coastal-trapped waves. While intense, these quasi-periodic waves act to displace water back and forth along the shelf over short distances of 30 km or so. This ocean weather will be important to the flushing and scouring of benthic communities, but generally not to the transport of marine biota across or along the shelf. However, coastal-trapped waves are elsewhere known to be important for the setup and shutdown of upwelling and may be implicated in the very strong upwelling off the Bonney Coast. Such scattering may also lead to the formation of smaller scale recirculation features near large changes in shelf topography.

Discussion

Superimposed on the prevailing westerlies during winter, passing fronts and low pressure systems lead to an rms along-shelf wind stress of 0.12 Pa and an expected annual extreme of 1.1 Pa (see Table 2.2.1). The frequency of passage of these systems is 3–12 days. The mixing and cooling of these larger amplitude events leads to a very deep (~150 m) wintertime Surface Mixed Layer (SML) (see Figure 2.2.18 below).

In addition, the intense storms within the Great Australian Bight (and on the west Australian shelf) generate a very strong weather-band circulation. From Table 2.2.2, the observations (Hahn 1986; Schahinger 1987) indicate weather-band winter currents near the gulfs region that are typically 20–30 cm/s with seasonal maxima of 50–100 cm/s. The associated sea level changes can reach 50 cm and together with tides can lead to coastal flooding and flushing of coastal bays and estuaries. However, with these exceptions, little has been published detailing the weather-band winter circulation.

More observations are available for the summer weather-band circulation. From Table 2.2.2, the rms weather-band currents are in the order of 23 cm/s with seasonal maxima of 50 cm/s. These are somewhat smaller than the winter currents since the rms wind stress from Table 2.2.1 is also correspondingly smaller (0.1 Pa). Unlike winter, the summer rms current variability generally exceeds the mean so that the summer circulation is largely dominated by weather-band variability. Thus, we will first review aspects of the limited data and analyses of the summer and winter weather-band variability before discussing the summertime circulation more fully below.

Elsewhere, the weather-band circulation has been well characterised by (linear) coastal-trapped wave modes and theories (e.g. Chapman 1987), and is useful in understanding the nature of wind-forced upwelling (Suginohara 1987). The only substantive coastal-trapped wave analysis of data for the shelf region here, however, was made by Church and Freeland (1987). The coastal sea level data they examined (Figure 2.2.13 below) between Esperance and Portland have an energy peak in the 6–12 day band and indicate a phase speed of about 3 m/s which is consistent with a first mode coastal-trapped wave.

For the first coastal-trapped wave mode, the along-shelf velocity is everywhere directed to the east (west) when the coastal sea level anomaly is positive (negative) and the slope velocity is generally very small. However, given an along-shelf current magnitude of 20 cm/s (typical of winter), the coastal-trapped wave can, over a period of 10 days, advect matter 30 km backwards and forwards along the shelf. The cross-shelf velocities and advective scales are an order of magnitude smaller.

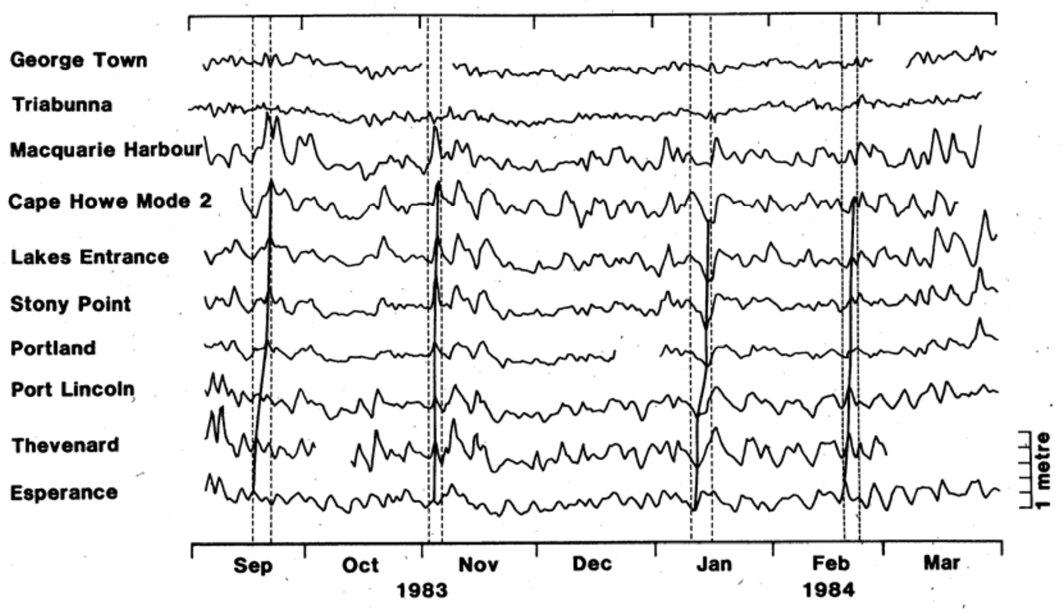

Figure 2.2.13 Adjusted low-passed coastal sea level at the sites indicated (Church & Freeland 1987). The vertical lines allow the phase speed of events between the various coastal sites to be determined. For the shelf between Esperance and Portland, a phase speed of 3 m/s is implied which is consistent with the theoretical first mode speed.

The summer shelf circulation and upwelling

Summary

During summer, the average winds blow in an anticyclonic fashion around the Great Australian Bight (Figure 2.2.2). Unlike winter, the mean circulation associated with these winds is weak (~10 cm/s or less). However, such anticyclonic wind systems are found to reside in the Great Australian Bight for 3–10 days, 2–4 times each summer. The associated coastal wind stresses of 0.05 Pa lead to upwelling of water by 150 m off Kangaroo Island, and 250 m off the Bonney Coast. These two regions appear to be the sites of deep shelfbreak upwelling, and the alongshore velocities of order 25–40 cm/s can transport water up to 215–430 km over a 10-day period. Water is transported as far as the Eyre Peninsula, where local winds during subsequent upwelling events bring it to the surface – a pool of nutrient rich upwelled water is likely to be maintained off Kangaroo Island. The upwelling also results in surface plumes of dense water (Figure 2.2.14) and secondary recirculation features are expected near fronts, islands, bays and headlands. In the western Great Australian Bight, shelf-break downwelling is expected.

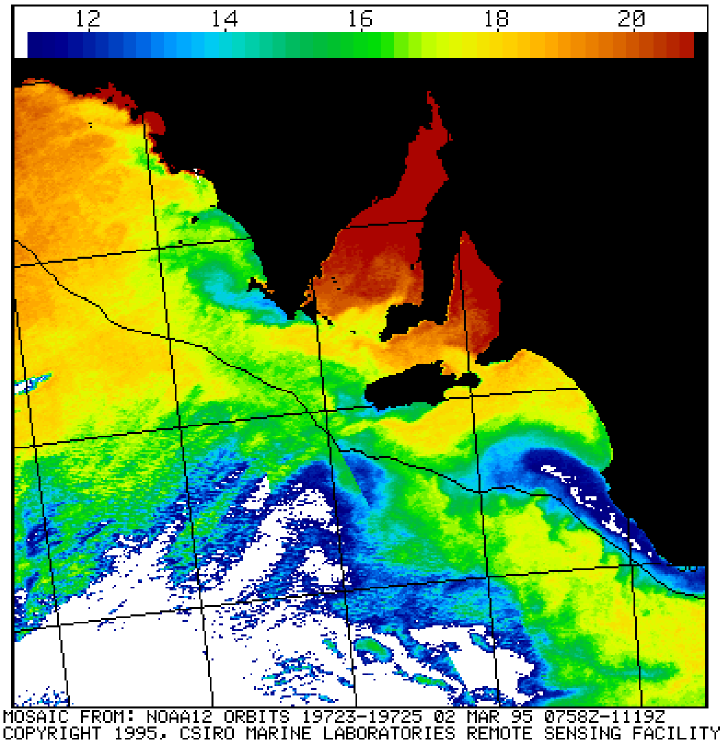

Figure 2.2.14 Satellite derived SST during an upwelling event of March 1995. The black line denotes the 200 m isobath.

Discussion – the large scale

Mean shelf currents in the Great Australian Bight

The inflow of the Leeuwin Current is largely absent during summer (e.g. Church et al. 1989) and on average, the coastal winds will act to lower coastal sea level, drive westward currents and upwell water towards the coast. As noted above, the numerical results of Herzfeld and Thomczak (1999) and Middleton and Platov (2003) suggest that an anticyclonic gyre in the shelf circulation should exist in the Great Australian Bight and shoreward of the 200 m isobath (Figure 2.2.9). This gyre is driven by the positive wind-stress curl in the Great Australian Bight that leads to a poleward (seaward) topographic Sverdrup transport. This transport converges with the (deep sea) Sverdrup transport leading to downwelling (Figure 2.2.10) along the shelfbreak and the raising of sea level and a summer South Australian Current which flows as far as the Eyre Peninsula (Figure 2.2.10). Evidence for these features was cited above. The anticyclonic gyre and South Australian Current are both dependent on there being a curl in the wind stress; that is, the north-westward winds decrease in magnitude away from the coast (e.g. Figure 2.2.2). When the average winds are more nearly constant, the topographic Sverdrup transport, shelf-break downwelling, anticyclonic gyre and the South Australian Current may be absent.

The importance of thermohaline forcing for the summer period was estimated by Middleton and Platov (2003). The warmer lighter waters over the shelf sit higher relative to those in the Southern Ocean leading to eastward alongshore currents of up to 10 cm/s. These currents oppose the westward coastal currents driven by winds and demonstrate the importance and sensitivity of the circulation to the thermohaline forcing and fluxes of heat (and freshwater).

The gulfs region

The likely summer mean circulation at a depth of 35 m is illustrated by numerical models results shown in Figure 2.2.15. The shelf currents are generally to the north-west and largest (up to 10 cm/s) near where the shelf is narrow – the Eyre Peninsula, Kangaroo Island and Robe.

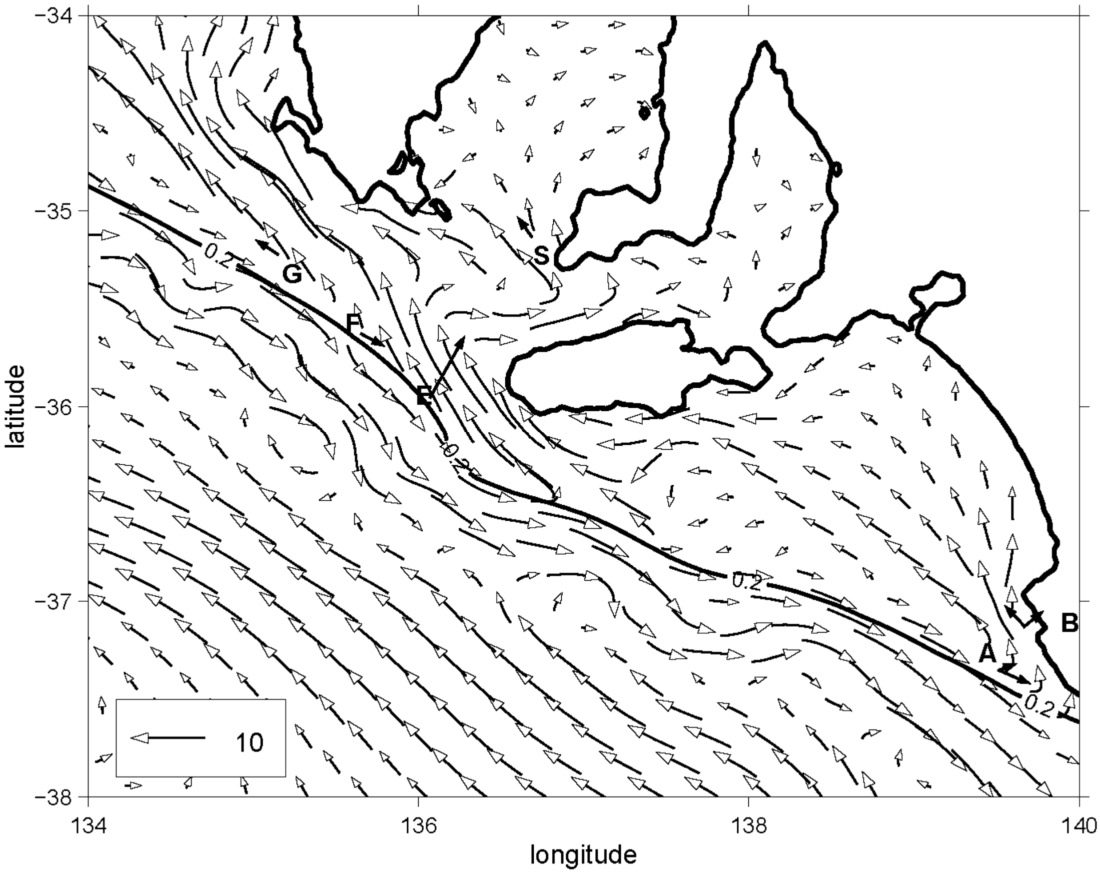

Figure 2.2.15 A detail of the surface flow (depth 35 m), as obtained in the numerical model of Middleton and Platov (2003). A reference vector of 10 cm/s is indicated. The dark arrows represent summer averages from current meters at depths of 10 m or so and at the sites S, G, F, E and A indicated. Note: site F corresponds to G4 in Table 2.2.2. The solid dark line is the 0.2 km or 200 m isobath.

The flow also bifurcates near the western end of Kangaroo Island. Part of the flow is to the north-west towards the Eyre Peninsula while another part moves around to the north of Kangaroo Island and then moves to the west. The latter broadly follows the 100 m isobath (not shown).

Support for the model shelf circulation comes from two sources. The first is the summer-averaged current meter results (E, F, G) indicated by the solid vectors in Figure 2.2.13: a weak north-westward flow, and onshore flow is indicated. Current meter and model results nearer the surface (see Middleton & Platov 2003) are also in agreement. These indicate a similar circulation pattern that is larger in magnitude, with currents up to 20 cm/s.

The model circulation above is also supported by data obtained from the *CSIRO Atlas of Regional Seas* (CARS, Ridgway et al. 2001). In Figure 2.2.16a the December–February climatology of bottom temperature is presented and the sites for deep upwelling (200 m) are to the south of Kangaroo Island and the Bonney Coast. (The original data used in the CARS climatology (including XBT transects), has been re-interpolated onto the bottom topography to separate out the effects of El Niño events. The results in Figure 2.2.16a and b were obtained using summer data for non-El Niño and El Niño years only.)

Surface upwelling off the Eyre Peninsula also occurs as shown in Figure 2.2.14. However, the model circulation would indicate that this water results from the deep upwelling to the south of Kangaroo Island and subsequent north-westward drift. This scenario is consistent with the bottom temperature data presented in Figure 2.2.16a.

Indeed, McClatchie et al. (2005) concluded that the colder water found to the west of Kangaroo Island in Figure 2.2.16a represents a nutrient-rich pool that acts to feed subsequent upwelling events off the Eyre Peninsula; that is, while cold surface plumes of water can appear simultaneously off the Eyre Peninsula, Kangaroo Island and the Bonney Coast (Figure 2.2.14), the upwelled water off the Eyre Peninsula results from water drawn from the Kangaroo Island pool that was established during a prior upwelling event. This water is transported to the Eyre Peninsula along the path shown in Figure 2.2.15 and little exchange occurs with the very warm waters of the gulf – a result that is also consistent with the studies of Nunes-Vaz et al. (1990).

There is another scenario suggested by Herzfeld and Thomczak (1999). In their numerical study, they found that under conditions of very large wind stress (0.35 Pa) and curl within the Great Australian Bight, bottom boundary layer advection by intense shelf currents (~50 cm/s) could lead to upwelling along the western Eyre Peninsula. The source of the upwelled water here might be a combination of that from Kangaroo Island as well as the Great Australian Bight itself. Griffin et al. (1997) also note that upwelling is indeed found along the western Eyre Peninsula even though the winds are not otherwise upwelling favourable. The climatology of bottom temperatures shown in Figure 2.2.16a does not support the general occurrence of deep shelfbreak upwelling directly off the Eyre Peninsula.

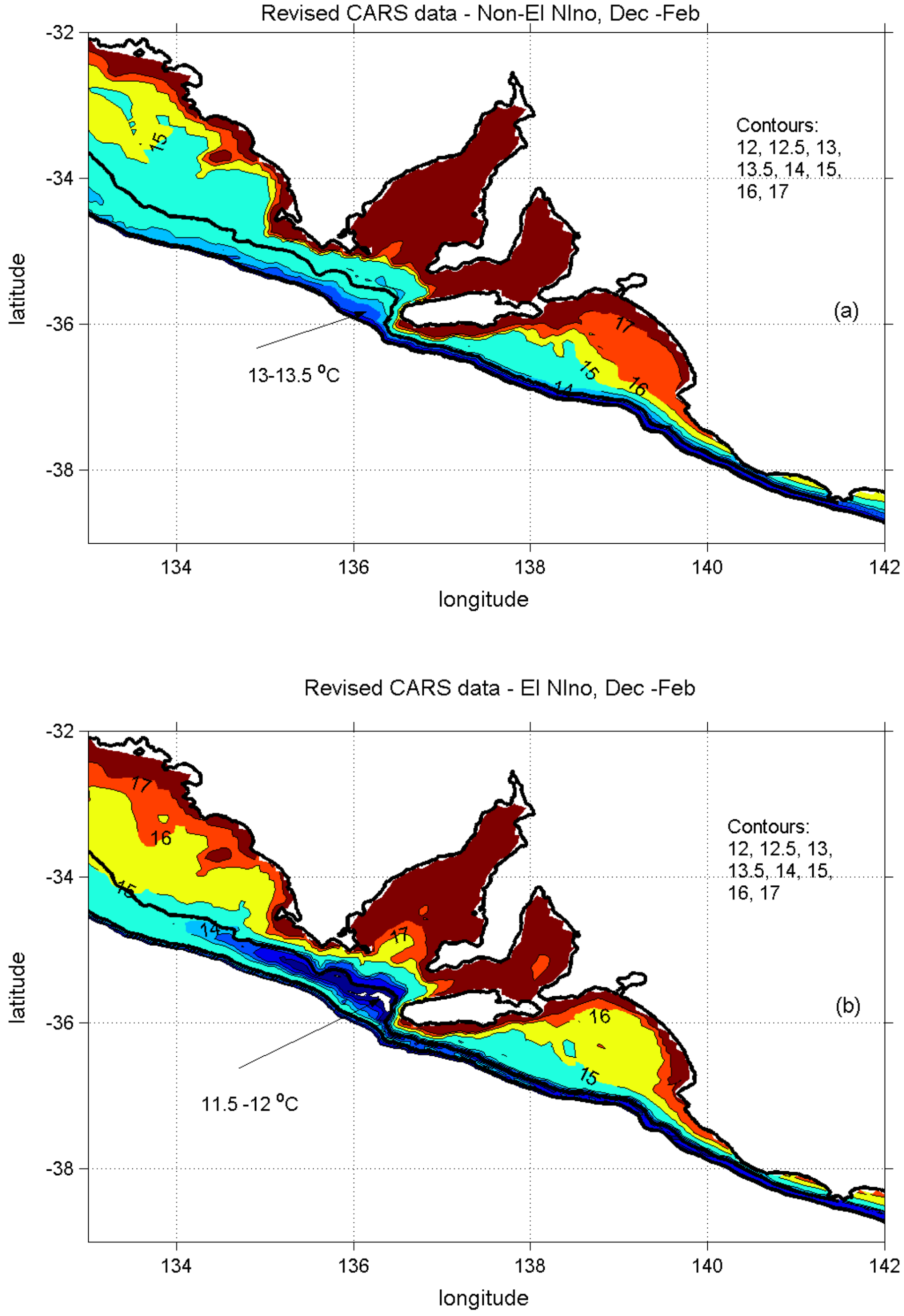

Figure 2.2.16 Top (a): The (revised) CARS climatology for bottom temperature and the December to February period. Only water of temperature 12 °C to 15 °C has been contoured (intervals indicated). For clarity and the 100 m and 200 m isobaths are indicated by the dark lines. El Niño summer years of data have been excluded. Bottom (b): As in (a) but for El Niño years only. (Source: Middleton et al. 2005)

Weather-band circulation and large-scale upwelling

The gulfs and Robe region is one of the few locations along the Australian coastline where a surface signature of upwelling is regularly found (e.g. Figure 2.2.14). The upwelling discussed above does not result from the mean or average flow but rather from 2–4 upwelling events that occur between December and March (Griffin et al. 1997). These events are characterised by the presence of high-pressure systems that sit in the Great Australian Bight for 3–10 days with upwelling favourable wind stresses of order 0.1–0.2 Pa. These stress values are 2–4 times larger than the summer average used to obtain the numerical model results shown in Figure 2.2.15.

The rms and maximum currents for the region are 20–50 cm/s (Table 2.2.2) indicating that the coastal-trapped wave variability can be large. Indeed, this is borne out by the time series of a typical upwelling event off the Bonney Coast (Figure 2.2.17 below). The data (Schahinger 1987) comes from a March 1983 upwelling event and from the two current meter moorings sites (A and B) shown in Figure 2.2.15.The mooring data shown was taken from site B (24 m depth, water depth 50 m) and A (18 m and 110 m in 140 m of water). The wind stress direction is "from" degrees clockwise of true north. Thus from 13–24 March, the wind is about 7 m/s and blows from the south-east – upwelling favourable. The adjusted sea level (labelled Eq. Sea) drops by around 20 cm during this period. As Schahinger (1987) points out, the sea level is highly correlated with the (negative) currents that are in the order of 40 cm/s and directed to the north-west (negative).

The temperatures measured at the inshore site B (depth 24 m) show a general drop in temperature of 2.5 °C to values of around 12 °C. This water has an equilibrium depth of about 200 m (Schahinger 1989) indicating upwelling of 180 m or so. At the offshore site, the thermistor string shows a drop of more than 3 °C to values less than 11 °C at a depth of 110 m. The equilibrium depth of this water is about 250–300 m indicating upwelling of 140–190 m. Recall that the winds here are not strong (~7 m/s) so that upwelling from greater depths might be expected at other times.

It would seem likely that transport within the bottom boundary layer is important given the currents are so large. Indeed, the patch of 11 °C water evident in the thermistor data and for the 19–22 March corresponds to the maximum in the alongshore currents at A110 (around 50 cm/s).

Schahinger (1989) also points out that the alongshore currents off Robe (A110) were found to be highly correlated (r=0.85, 12-hour lag) with those obtained off Neptune Island (site F=G4) and for the same summer 1983 period by Hahn (1986). Indeed, the March 1983 upwelling event was also recorded in the thermistor data of Hahn (1986) that is shown in Figure 2.2.18.

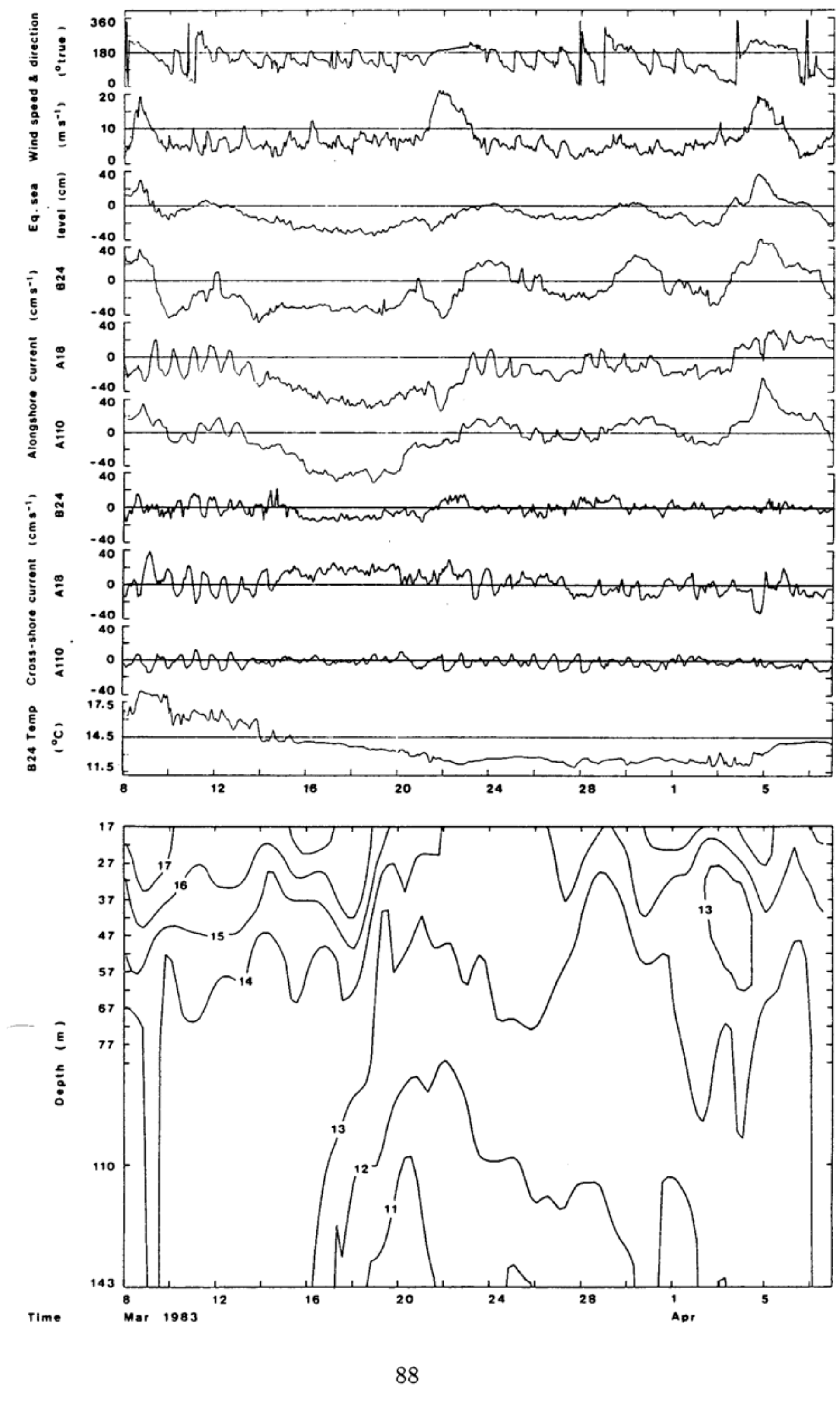

Figure 2.2.17 **Top panel**: Time series of wind speed and direction (clockwise from north), sea level and currents at sites B and A that were resolved along the axes indicated (Schahinger 1987). **Bottom panel**: A time series of temperature (17–143 m) obtained at offshore site A.

Further insight into the circulation and upwelling is given by the numerical solutions for the weather-band circulation obtained by Middleton and Platov (2004). The solutions were obtained in order to simulate the circulation and upwelling for the summer of 1999. Upwelling favourable winds occurred between 17 January (magnitude 0.07 Pa) and 29 January. The model upwelling associated with this event on 27 January is presented below in a plot of bottom temperature (Figure 2.2.19). Plumes of water (<13 °C) are upwelled to the south of Kangaroo Island and Robe. By 6 February, the upwelling favourable winds have ceased. In agreement with the CARS data, plumes of cold water have moved to the north and the west of Kangaroo Island as well as to the north-west of Robe. The overlying currents are in the order of 25 cm/s. Over 10 days, such currents can advect water by at most 215 km and not as far as the western Eyre Peninsula. The water here must then be brought to the surface by future upwelling events.

While the validity of these results is uncertain, the scales of deep shelf-break upwelling predicted by the model are also of interest. Off Kangaroo Island, 13 °C water is upwelled by 150 m and from depths of 250 m. Off Robe the upwelling is larger, with 13 °C water upwelled by 250 m and from depths of 275 m. The deep upwelling off the Bonney Coast may well supplement the upwelling that should occur in the canyons of the region.

The reason for the very deep upwelling off the Bonney Coast is unknown but may be related to the coastal-trapped wave scattering expected to occur due to the topographic irregularities of the gulfs and Kangaroo Island. Clearly, the observations for the region are few and the results of the numerical studies to date must remain somewhat speculative.

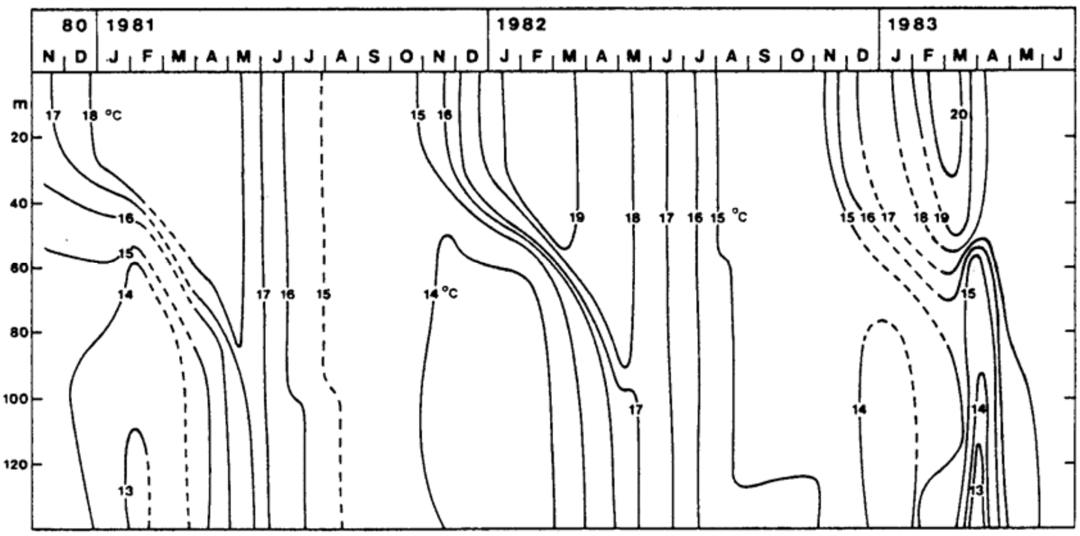

Figure 2.2.18 Thermistor data from the shelf edge site F (seaward of Neptune Island; Figure 2.2.18) obtained by Hahn (1986). Note the 13 °C water upwelled during March 1983.

El Niño events

Summary

El Niño – Southern Oscillation events occur within a 4–7 year period, originate in the Pacific and affect the circulation, upwelling and downwelling of the west and south shelves of Australia. For the Australian region, the depressed sea level and raised thermocline in the west Pacific is transmitted around Papua New Guinea and down the west Australian shelf as a type of shelf slope-trapped wave (Clarke & Van Gorder 1996). Observations show that the wintertime Leeuwin Current and shelf currents are substantially reduced during El Niño events. During summer, limited observations show that the summer thermocline is also raised by 150 m or so during these events.

Discussion

Definitive evidence exists for the importance of El Niño events in the western shelf circulation of the Americas (Pizzaro et al. 2001). In the Australian context, the study of Pariwono et al. (1986) was the first to show that anomalously low (high) sea level events along the western and southern shelves are related to El Niño (La Niña) events in the west Pacific. Using observations of temperature and sea level, Feng et al. (2003) and Wijffels and Meyers (2004) have shown that the strength of the Leeuwin Current increases by 25% or 1 Sv between El Niño and La Niña events.

For the South Australian region, the current meter data presented in Table 2.2.2 shows that the mean wintertime currents are largely shut down (from 20 cm/s to 5 cm/s) during El Niño winters. Surprisingly, during El Niño summers, there does not seem to be a corresponding increase in the mean currents. Middleton at el. (2005) suggest that the explanation here involves the thermohaline circulation of the reduced winter inflow of warm Leeuwin Current water and enhanced cold water upwelling during summer.

Li and Clarke (2004) used altimeter and coastal sea level data to show that the eastward shelf slope currents would be enhanced (reduced) during La Niña (El Niño) events. For the South Australian region, the change was estimated to be small – in the order of 4 cm/s – and much smaller than that indicated by the shelf current meter data in Table 2.2.2.

Middleton et al. (2006) have examined all available CTD data from the South Australian region for El Niño effects. They find that during the El Niño summers of 1998 and 2003, the 11.5 °C isotherm is possibly raised by 150 m from its equilibrium depth of 250 m off Kangaroo Island; that is, as expected, colder water lies at shallower (deeper) depths during El Niño (La Niña) events. The 1999 summer was anomalous since it follows a very strong El Niño event and the upwelling favourable winds were amongst the largest for the 1962–2004 period. Middleton et al. (2006) cite data from the Bonney Coast that show similar results.

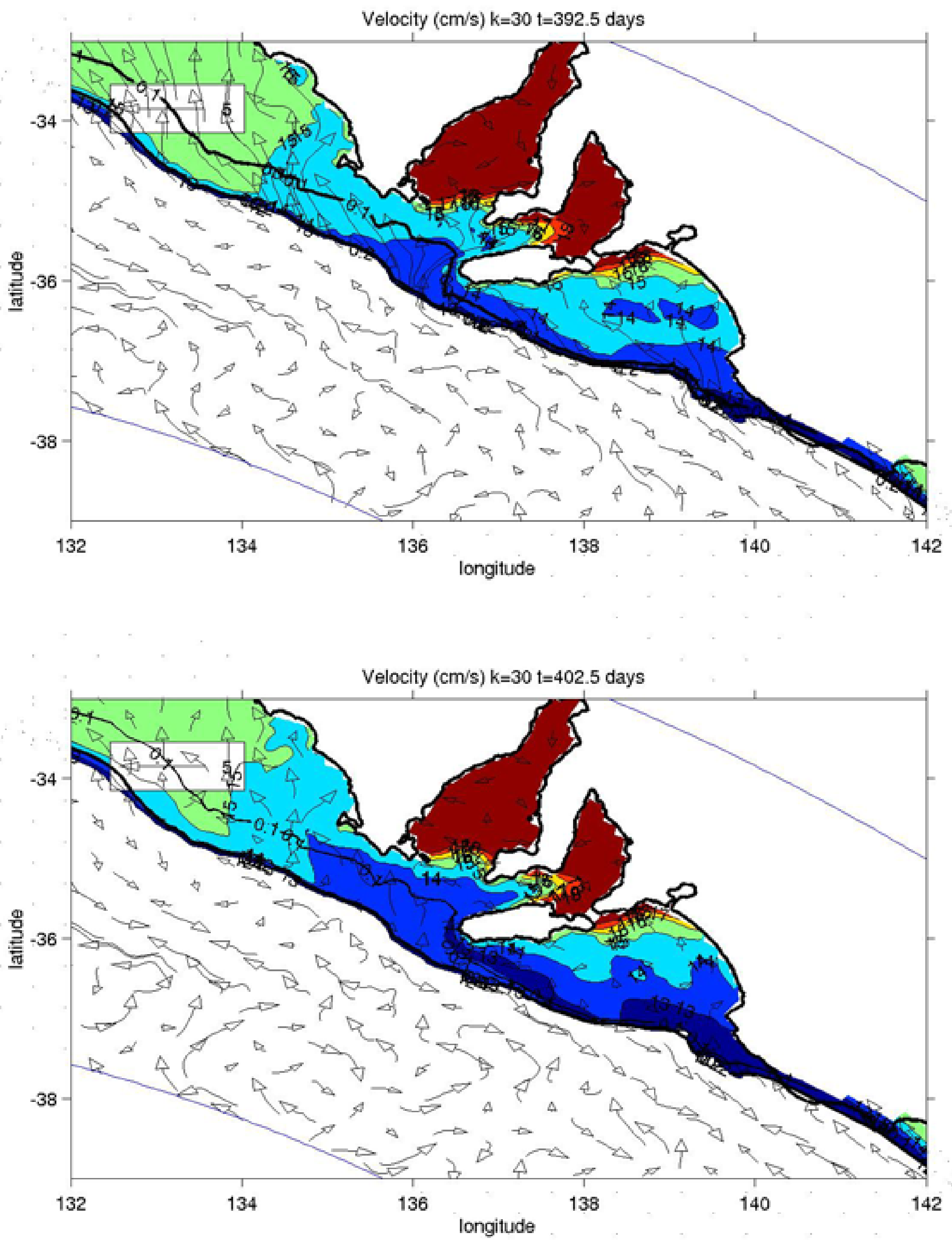

Figure 2.2.19 Bottom temperature and velocity from the numerical model of the weather-band circulation and upwelling (Middleton & Platov 2004). **Top panel**: results for 27 January 1999 (JD 392 1998). **Bottom panel**: results for 6 February 1999 (JD 402 1998). A vector legend of 5 cm/s is indicated. Only water with temperatures between 12 and 18 degrees are colour contoured.

A stunning representation of the enhanced upwelling is shown in Figure 2.2.16 where the bottom temperature for summer is presented for El Niño and non-El Niño summers. During El Niño years, the bottom temperature is typically a degree cooler than normal years. Off Kangaroo Island, a plume of 11.5–12.5 °C water is found close to the 100 m isobath. This water is more typically found at depths of 250–150 m.

Theories for how ENSO events are transmitted to and affect coastal ocean circulation have yet to be developed for this region. For other regions, they are quite idealised (e.g. Pizarro et al. 2001).

Surface waves and tides

Little has been published about surface waves for the region, although they are known to be important to sediment stirring and transport (James et al. 2001). Published data sources include Hemer and Bye (1999), Young and Holland (1996) and the more recent web-based atlas by Caires et al. (2005).

In Table 2.2.3 we present a summary of wave climatology (data from Caires et al. 2005) for February and July. The significant wave height (H_S) is the (monthly) averaged height of the highest one-third of the waves. It is about equal to the average height of the waves as estimated by an experienced observer. The phase speed (c) is the speed of the wave pattern (not the water speed) and the directions of the waves from the south-west and south (Gulev et al. 2005), although these directions are poorly known. The wave period (T) and wavelength (λ) are listed.

Table 2.2.3 Wave climatology for the mid–Great Australian Bight as inferred from Caires et al. (2005) including the significant wave height (H_S), period (T), phase speed (c) and wavelength (λ). The surface and bottom water velocities are denoted by U_o and U_b and the (Stokes) drift velocity by U_d. The standard deviations (σ) of H_S and T are presented.

Month	H_S (m) σ_S	T (s) σ	c (m/s)	λ (m)	U_o(m/s)	U_b(m/s)
Feb	**2.25** **0.45**	**7.5** **1.8**	**11.7**	**88**	**1.9**	**0.05**
July	**2.75** **0.90**	**9.0** **1.8**	**14.0**	**126**	**2.0**	**0.16**

For both summer and winter, the wave climatology is similar, although waves are somewhat larger during winter and of order 2–3.7 m in height with periods of 7–12 s. The wave speed c and wavelength are based on the mean wave period (T) presented.

Using “deep water” wave theory, we have calculated the surface water speed (U_o) as well as the speed (U_b) at a “bottom” depth of 50 m. The surface speeds are large (~2 m/s), while those at the bottom are in the order of 16 cm/s during winter. These are the average velocities and will be exceeded often during a given year. Caires et al. (2005) indicate that the wave height will exceed 3 m for 30–60 days of the year and 6 m for 0–10 days of the year. The bottom velocity will therefore exceed 20 cm/s and 40 cm/s over these periods leading to significant sediment re-suspension. The 100-year wave height is 12.5 m implying a bottom velocity of over 1 m/s. The wave heights and suspension bottom velocities will also be larger in shallower water.

A second feature of the wave field is the time-averaged (Stokes) drift velocity (U_d). This velocity is in the direction of wave propagation (north-east to north) and ultimately towards the shore. The speeds here are in the order of 15 cm/s. Over a one-month period, this drift can advect surface matter and biota by 380 km – a scale that exceeds the shelf width. The role of this wave-drift velocity is unknown, but provides a generally onshore conveyor belt near the surface.

Finally we comment on the tides of the region. While large (~50 cm/s) in the gulfs due to a resonance effect (Easton 1978), they are generally small (2–5 cm/s) on the adjacent shelves and within the Great Australian Bight and likely unimportant to the ecology of the region. Tidal studies of the region include Schahinger (1990), Hahn (1986), Noye et al. (1998) and Platov and Middleton (2000).

3 Ecological integration

3.1 Biodiversity

Principal contributors

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Introduction

The south-western corner of Australia is a region of high species diversity and endemism for many marine organisms; for example, marine macroalgae (Womersley 1990; Phillips 2001), invertebrate taxa such as corals, ascidians, molluscs and echinoderms (Shepherd & Thomas 1982, 1989; Roberts et al. 2002), and nearshore (Hutchins 1994) and continental slope demersal fish (Williams et al. 2001). High species richness in the region is attributed to the lack of mass extinction events associated with unfavourable environmental conditions – such as glaciation – over the recent geological past, and the moderating influence of the Leeuwin Current since the Eocene (McGowran et al. 1997). High endemism is the product of long isolation of the marine flora and fauna as Australia has been separated from other land masses for the past 80 million years (Veevers 1991; Phillips 2001).

Regional geomorphology

Shape and composition of the seafloor

The nature of the seafloor has an important influence on the composition and distribution of marine benthos. Knowledge of the shape and form of the seabed is therefore central to our understanding of patterns in biodiversity. Sediments cover much of the world's seafloor, and provide habitat and refuge for an extraordinary diversity of burrowing organisms. Where the bottom currents are strong, sediments can be eroded and the underlying bedrock exposed to provide secure attachment points for a variety of sessile forms. A range of other factors including water depth, proximity to land, and the types of organisms inhabiting the pelagic realm, also influence substrate type and thereby affect benthic community structure.

The South-west Marine Region covers approximately 1.3 million km^2 of seafloor, 35% of which lies offshore in abyssal depths (>5000 m). The majority of the Region's bedforms (40%) lie between 200 m and 5000 m depth and comprise the continental slope and rise, while the remainder (25%) fringes the coast and constitutes a shallow continental shelf (<200 m). Most of this seafloor is composed of soft unconsolidated sediments, but due to large variations in bathymetry there are marked differences in sedimentary composition and benthic assemblage structure across the Region.

Continental shelf

The crescent-shaped shelf of the Great Australian Bight is a dominant bathymetric feature of the southern margin of the Australian continent (Figure 3.1.1). This immense, relatively flat, submarine plain extends some 1300 km from Cape Pasley (Western Australia) to the Cape Catastrophe (South Australia), and covers an area of almost 200 000 km^2. The shelf is about 260 km wide near the Head of the Bight, but becomes progressively narrower with increasing distance to the east and west, and is approximately 80 km wide at either end. The Great Australian Bight shelf may be divided into a shoreward inner shelf (<50 m depth), a vast middle shelf (50–120 m depth), and an outer shelf that extends to the shelfbreak (150–160 m depth). Along the outer margin, the shelf is 10–30 km wide, but towards the west the shelf narrows to a few kilometres (James et al., 2001).

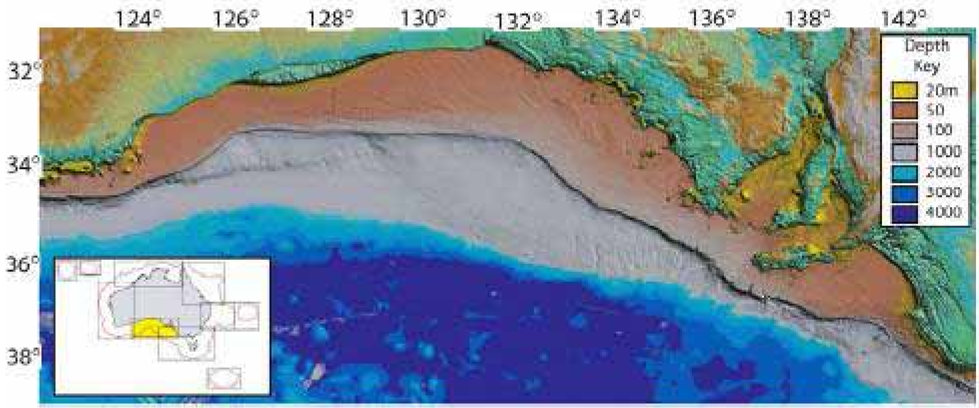


Figure 3.1.1 False-colour bathymetric image of the Great Australian Bight (from Harris et al. 2005; courtesy of Geoscience Australia).

The inland portion of the Great Australian Bight is characterised by very low annual rainfall. There are no major rivers in the region and thus the supply of terrigenous sediments to the marine realm is low. As a consequence, the shelf bedforms of the Great Australian Bight are largely biogenic and form part of the world's largest expanses of temperate carbonate sediments (Connolly & Von Der Borch 1967; Wass, et al. 1969). The Holocene sediments of the shelf are principally composed of fragments of bryozoa, mollusc, foraminifera and coralline algae, with minor amounts of sponge, crustacean and echinoderm (Connolly & Von Der Borch 1967; Wass et al. 1969; Gostin et al. 1988). The inner shelf supports abundant carboniferous macrophytes, and is an area of active sediment production and accumulation. The huge middle shelf is an area of sediment erosion and winnowing, while the outer shelf is a region of sedimentary deposition and variable sediment production (James et al. 2001). As a result, the sediments are generally course-grained and gravelly inshore but become progressively finer and muddier with increasing depth and distance offshore (Connolly & Von Der Borch 1967).

Patterns of Holocene sedimentation on the shelf of the Great Australian Bight are closely linked to the area's modern oceanography. The north-west area of the shelf supports the highest average water temperatures in the Bight and is one of the most prolific sites for rhodolith growth (James et al. 2001). These warm nutrient-depleted waters drift eastwards across the shelf and suppress sediment production on the central and eastern mid-shelf. This arrested production is countered further to the east, off the western Eyre Peninsula, by summer upwelling, which promotes prolific bryozoan growth and sediment production. Upwelling is also thought to play an important role in promoting localised growth of bryozoan communities across the outer shelf, except in the central region. Here, year-round downwelling contributes to off-shelf fine sediment transport and carbonate mud deposition (James et al. 2001).

There is a marked contrast between the flat and gently sloping shelf of the main Great Australian Bight region and the more rugged and uneven topography of the Recherche Shelf off southern Western Australia (Conolly & Von Der Borch 1967). The Recherche Shelf extends from Israelite Bay at the western edge of the Great Australian Bight to Cape Leeuwin, and covers an area of nearly 65 000 km^2 (Carrigy & Fairbridge 1954; Harris et al. 2005). The shelf here is characterised by a 15–50 km-wide plain that slopes gently to a depth of 100 m. Further offshore, the seafloor drops quickly before reaching the shelfbreak at between 100 m and 140 m depth. In the east, the shelf is up to 65 km wide and punctuated by islands of the Recherche Archipelago. These islands are scattered across the entire width of the shelf and extend for more than 160 km along the coast. The shelf varies between 30 km and 65 km in width to the west of the archipelago, but most islands in the western shelf occur within 8 km of the mainland (Conolly & Von Der Borch 1967).

The shelf between Cape Leeuwin and Geraldton is referred to as Rottnest Shelf (Carrigy & Fairbridge 1954). This shelf ranges in width from 45–100 km and covers an area of approximately 52 000 km^2 (Harris et al. 2005) (Figure 3.1.2). The Rottnest Shelf can be divided into a steep shoreface (<30 m depth), a wide, flat inner shelf plain (30–50 m depth), a linear ridge complex that shallows to about 40 m depth, and an outer shelf that slopes seaward to the shelf edge at about 200 m. Rottnest Island in the south and the Abrolhos Reefs in the north are key features of the ridge complex (James et al. 1999).

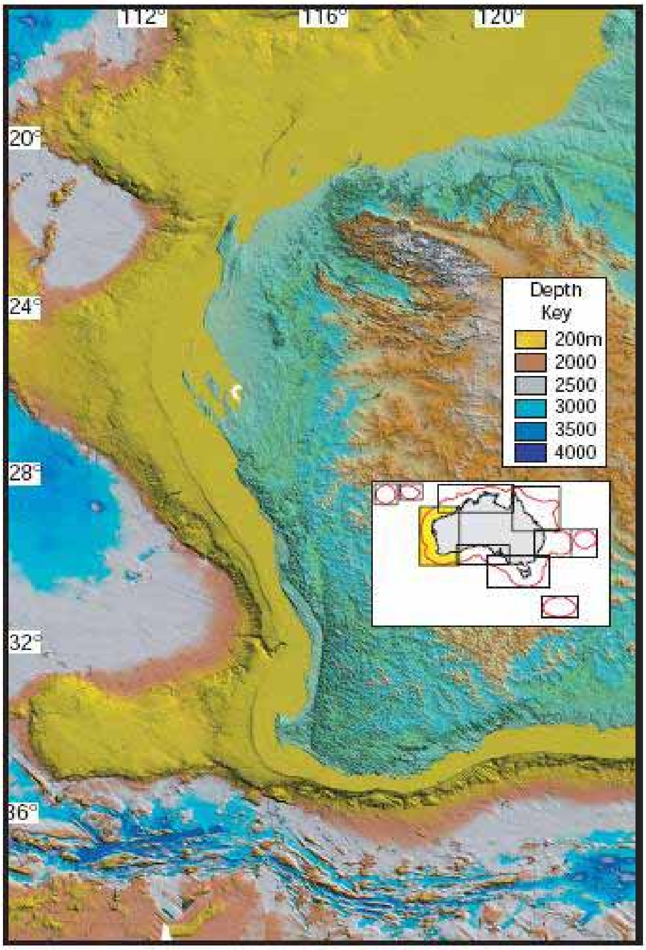


Figure 3.1.2 False-colour bathymetric image of the western Australian margin (from Harris et al. 2005; courtesy of Geoscience Australia).

The shoreface and the adjacent inner plain of the Rottnest Shelf support a variety of benthic habitats including rocky substrates with prolific growths of algae and sponges, rippled sand with clumps of non-calcareous red algae, and open rippled sand (which may be locally modified by burrows and surface traces). Sponges, ascidians, non-calcified red algae and *Ecklonia* are all common here to depths of 65 m, while seagrass such as *Thalassodendron* occurs to depths of 40 m. Encrusting coralline algae form rhodolites around limestone nuclei, and branching forms are present to 60 m depth. The main sedimentary elements identified in this part the shelf are quartzose skeletal sands, and more widespread skeletal gravels and coarse sands containing rhodolites, bryozoans and gastropods (James et al. 1999).

Further offshore, the Rottnest ridge complex is 3–8 km wide and supports a prolific hard substrate biota consisting of bryozoans, ascidians, sponges and algae. The gravel sediments of this region are mainly composed of rhodolites and skeletal sand. In the Houtman Abrolhos region the ridge complex is capped by emergent reef platforms (Pelsaert, Easter and Wallabi reefs). These reefs support rich and diverse coral communities on their leeward sides, and some 184 coral species from 42 genera have been recorded here (Collins et al. 1993a; Collins et al. 1996; Collins et al. 1997; Collins et al. 1998; James et al. 1999).

The outer Rottnest Shelf is a zone of rippled sand and rocky outcrop. The structure of the sediments range from mud to gravel, and are mainly composed of skeletal bryozoan fragments. Sandy substrates are widespread and are intensely burrowed. These sediments support a diverse but generally sparse epifauna composed largely of bryozoans and sponges. Rocky substrates, where present, support prolific bryozoans, sponges and encrusting bivalves (James et al. 1999).

The transition between the Rottnest Shelf and Carnarvon Ramp to the north (formerly known as the Dirk Hartog Shelf) is gradational. The ridge complex and outer shelf become deeper and more subdued northward until both have disappeared and the seafloor is a gently sloping ramp to a subdued shelf edge. These changes in bathymetry are accompanied by changing sedimentary facies, and include the loss of sediment associated with the ridge complex (sands and rhodolite gravel) and loss of the outer shelf bryozoan sands (James et al. 1999).

The inner Carnarvon Ramp is characterised by eolianite cliffs and dunes, with inlets and passes into Shark Bay and Ningaloo Reef. A narrow mid-ramp (50–100 m depth) passes almost without break to the outer ramp, which downlaps onto the Carnarvon Terrace at about 600 m. Key habitat features of the inner ramp include the extensive seagrass banks and tidal flats of Shark Bay, and the fringing coral reefs and lagoons of Ningaloo (Collins 2002; Collins et al. 2003b; Cassata & Collins 2004).

The mid Carnarvon Ramp is an open sand plain with few living benthic organisms. The sparse biota is delicate infaunal bivalves and vagrant bryozoans. Living rhodolites, bryozoans and sponges are present locally on hard substrates, and the calcareous algae *Halimeda* occurs in depths less than 40 m but is absent in sediments. Relict carbonate grains are common in the sediments, which are intraclast skeletal sands, with bryozoans, molluscs and foraminifers present as the most common skeletal constituents. Cemented hard grounds are locally present seaward of Shark Bay and Ningaloo Reef (James et al. 1999).

Like the mid ramp, the outer Carnarvon Ramp has little living material on the seafloor. Bivalves are most abundant, with corals, gastropods and echinoids also present. The outer shelf sediments vary with depth and consist of mainly planktic intraclast sands between 100 m and 150 m. Planktic sand and silt occur between 120 m and 200 m, while a muddy mixture of planktic foraminifers, carbonate silt, and well washed planktic sand extend between 170 m and 500 m (James et al. 1999).

Continental slope

The continental slope drops gradually beyond the shelf of the Great Australian Bight and consists of two marginal terraces: the Ceduna Terrace in the east and the Eyre Terrace in the west (Conolly et al. 1970; Willcox et al. 1988). Both terraces are separated from the continental shelf by an incipient slope between the shelfbreak and the uppermost smooth surface of the terrace (Conolly et al. 1970). The sigmoid-shaped Ceduna Terrace is the larger of the two features and extends for more than 500 km along the southern shelf margin, covering an area of almost 70 000 km^2. This terrace slopes gently to the southwest with an average gradient of 1 in 100, before merging into the continental rise (Conolly et al. 1970; Tilbury & Fraser 1981).

The most striking features of the terrace bathymetry are the numerous submarine valleys that dissect the otherwise gently sloping seafloor. These are mostly broad (<20 km wide) and shallow (<100 m depth) and form a dendritic tributary system feeding submarine canyons on the lower slope (Tilbury & Fraser 1981).

The wedge-shaped Eyre Terrace extends for 240 km along the south-western margin of the shelf, and is 65 km wide in its central portion. Its seaward margin occurs between 1000 m and 1600 m and merges seaward into a fan-valley system consisting of several canyons and fan deposits. The Eyre Canyon forms a broad valley more then 80 km long through the central region of the terrace. Another larger canyon to the east, the Eucla Canyon, delineates the Eyre and Ceduna terraces and extends for over 100 km between the shelf-break and the lower continental slope (Conolly & Von der Borch 1967; Conolly et al. 1970).

The sediments of the southern continental slope off the Great Australian Bight are characterised by muddy foraminiferal, spicule and pteropod oozes. The slope sediments may also contain large quantities of skeletal organic remains derived from the shelf, including bryozoan echinoid and mollusc fragments (Conolly et al. 1970; Harris et al. 2000; James et al. 2001).

Numerous canyons incise the narrow continental slope to the west of the Great Australian Bight. These include the Pasley and Esperance canyons offshore from the Recherche Archipelago, and the Albany Canyon Group (>30 canyons), which cleave the continental slope at regular intervals between Hood Point and Point D'Entrecasteaux (Von der Borch 1968). Recent sonar surveys in the Albany Canyon Group have shown that some individual cannons here may up to 2000 m deep and 90 km long, and extend uninterrupted between the shelf-break and the abyssal plain (Exon et al. 2005).

The slope is variable in width and gradient along the south-western margin of the continent between Cape Leeuwin and Shark Bay. In the south, the Rottnest Shelf slopes gently offshore for some 100 km to the west of Cape Leeuwin before rising to form the Naturaliste Plateau. This submarine table is over 400 km long and 250 km wide, and covers almost 90 000 km^2 of seafloor between 2000 m and 5000 m depth (Borissova 2002; Harris et al. 2005). To the north, the slope narrows and becomes steeply inclined and broken by terraces. The Perth Canyon crosses the slope here, and meanders for more than 160 km between the shelf-break west off Rottnest Island and the abyssal plain to the north of the Naturaliste Plateau (Playford et al. 1976). The slope at the northern-most extent of the South-west Marine Region (known as the Carnarvon Terrace) is relatively gentle and represents a 100 km seaward extension of the gradually sloping outer Carnarvon Ramp. Carbonate silts consisting of bryozoan fragments and sponge spicules blanket the seafloor here, together with planktic forams, pteropods and echinoid fragments (James et al. 1999).

Continental rise and abyssal plain

One of the most notable features of the seafloor in the South-west Marine Region is the development of an extensive and wide continental rise that flanks the foot of the slope and extends towards the abyssal plain (Conolly & Von der Bosch 1967). The rise is delineated by changes in gradient with the slope and the abyss, and forms a largely unbroken apron skirting the complete length of the southern continental slope. In the south-east, the rise extends from about 3000 m depth before merging into the Great Australian Bight Abyssal Plain (5000–5500 m depth) (Conolly & Von der Bosch 1967). The seafloor here is soft and muddy and the surficial sediments are characterised by foraminiferal and coccolith oozes (Conolly & Von der Bosch 1967; Harris et al. 2000).

The abyssal plain to the west of the Great Australian Bight displays considerable topographic relief as a result of continental drift. In the Daimantina Zone, off the south-western continental margin, the abyssal seafloor is heavily folded into a series of east–west tending ridges. Some of these ridges are over 1000 m in height and in excess of 200 km in length (Harris et al. 2000). The bottom topography of the Perth Abyssal Plain is poorly developed by comparison. This plain extends inbound between the Naturaliste Plateau in the south and the Carnarvon Ramp in the north, and forms a relatively flat and featureless bedform below 5500 m depth.

General patterns of biodiversity within the South-west Marine Region

The south-west region's marine flora and fauna are highly diverse. The species section (Section 4 – Part 2) outlines the current knowledge base for each major group (see Table 3.1.1). The following section describes the general knowledge of diversity and abundance of benthic and pelagic groups from inshore and offshore continental shelf and continental slope environments.

Shark Bay to Esperance (nearshore)

Studies of biodiversity of marine flora and fauna have been patchy, focused on key locations on the west and south coasts of Western Australia during the past few decades. Large taxonomic surveys have occurred as part of the International Marine Biological Workshops, convened by Dr Fred Wells (WAM and Fisheries Western Australia). These workshops have been held in the Houtmans Abrolhos and at Rottnest Island on the west coast of Western Australia and in Albany and Esperance on the south coast of Western Australia. Museum researchers have also surveyed areas of coastline as part of their ongoing taxonomic studies. The distribution of nearshore demersal fish has been detailed by Barry Hutchins, and the distribution of molluscs by Dr Fred Wells. The Department of Conservation and Land Management has coordinated baseline surveys in prospective marine parks including Jurien, Marmion, Cape Naturaliste to Cape Leeuwin, and Bremer Bay to Hopetoun. Fisheries Western Australia has also run active programs on the biology and ecology of commercial fish species across much of the Western Australia coastline. The most notable commercial species studied have been western rock lobster and abalone; gillnet and longline fisheries have also been studied. Fisheries Western Australia, in collaboration with the Fisheries Research Group at Murdoch University, has systematically studied the biology, feeding and ecology of nearshore demersal finfish species including the endemic dhufish. The Western Australian Government – CSIRO SRFME program has focused on the Jurien region of the coast, with biodiversity surveys from Geographe Bay, Bunbury, Perth, Jurien and Green Head. University researchers have also moved our knowledge of the biodiversity of marine organisms forward. The most notable recent studies have been the taxonomy of

Western Australian macroalgae by Dr John Huisman (Murdoch University), and the broad spatial studies of fish, sessile invertebrates and macroalgae between capes Leeuwin and Naturaliste, and the Recherche Archipelago by Drs Kendrick, Harvey, and McDonald (University of Western Australia) and others.

This patchy but geographically extensive data has resulted in some broad geographic synthesis papers that help us to define the biodiversity setting. Roberts et al. (2002) in a global study of coral reef biodiversity hotspots found that the west coast of Western Australia from Ningaloo Reef to Rottnest Island had moderate to high species richness, but was one of the global hotspots for endemism. Wernberg et al. (2003) combined quantitative surveys of macroalgal diversity on limestone reefs from Marmion, north of Perth, Hamelin Bay and Hopetoun and concluded that there was a cline in overlapping species distributions from the west coast to the south coast and inferred that this cline indicated mixing of species from north to south. A barrier to eastward species dispersal has been found at the Great Australian Bight. Hutchins (2005) found the nearshore demersal fish fauna of the Recherche Archipelago totalled 263 species, with 53 species only found in Western Australia.

Esperance to Kangaroo Island (nearshore)

Due to the remote and generally inaccessible nature of the coastline, the marine ecosystems of the eastern South-west Marine Region have received considerably less research attention than other areas of temperate Australia. Despite this, a growing body of research suggests that the waters spanning the Great Australian Bight support a rich diversity of organisms, which in some instances is unparalleled both in Australia and overseas (Edyvane 1999a; Ward et al. 2006). Moreover, it is becoming more apparent that the waters of this region are an area of global significance as breeding grounds for a number of rare and endangered marine mammals including the endemic Australian sea lion *Neophoca cinerea* (Gales 1990) and the southern right whale *Eubalaena australis* (Bannister 2001).

The waters of the Great Australian Bight are located at the centre of the Flindersian Biogeographic Province first described by Knox (1963). This region extends across the entire southern coast of the continent and is characterised by a marine benthic flora and fauna with warm to cool-temperate affinities. Within this Flindersian Province over 1000 species of macroalgae, 22 species of seagrass, 600 species of fish, 110 species of echinoderm and 189 species of ascidian have been recorded (Wilson & Allen 1987; Womersley 1990; Shepherd 1991: cited in Edyvane 1999a). Much of this fauna has not been recorded outside the region, and approximately 85% of fish species, 95% of molluscs and 90% of echinoderms are thought to be endemic (Poore 1995). By comparison, it has been estimated that only 13% of fish, 10% of molluscs and 13% of echinoderms are endemic in tropical regions of Australia (Poore 1995). The relatively high levels of biodiversity and apparent endemism for southern Australian waters have been attributed to a range of physical factors. These factors include the continent's long period of geological isolation (> 65 million years), the unusually large width of the continental shelf, and the characteristically low nutrient status of Australia's southern coastal waters (Poore 1995).

While temperate marine organisms characterise much of the biota of the Great Australian Bight, a warm Indo-Pacific element is also apparent in both the demersal and pelagic fauna (Maxwell & Cresswell 1981). Seasonal influxes of warm, low salinity water from the Leeuwin Current are thought to be responsible for the dispersal of many pelagic and demersal marine fauna from the warm waters of the northwest of Australia to the southern seaboard including the Bight (Maxwell & Cresswell 1981). The Leeuwin Current is also thought to be responsible for the relatively high representation of tropical phytoplankton in the area (Markina 1976: cited in Edyvane 1999a).

Studies of the regional marine flora and fauna have largely concentrated on shallow nearshore environments, and in particular have considered the taxonomy and general distribution of invertebrates (Shepherd & Thomas 1982, 1989; Shepherd & Davies 1997), algae (Womersley 1984, 1987, 1994, 1996, 1998, 2003) and seagrasses (Shepherd & Womersley 1971, 1976, 1981). More recent studies have integrated results from remote sensing and benthic surveys to map broadscale patterns in species, habitats and ecosystems throughout South Australia's nearshore waters (Edyvane & Baker 1995, 1996a–d).

A major outcome from the research by Edyvane and Baker (1996) has been the recognition and division of South Australian state waters into a series of spatially explicit marine bioregions. Three of these bioregions (Eucla, Murat and Eyre) are recognised as capturing broadscale patterns in biodiversity in the eastern waters of the Great Australian Bight (Edyvane 1999b). In the west, the subtidal coastal habitats of the Eucla bioregion refect the area's exposure to strong south-westerly swells. Much of the seafloor here is composed of bare sand with patches of reef supporting low-diversity algal communities (mainly the kelp *Ecklonia radiata* and the fucoid *Scytothalia dorycarpa*) (Edyvane 1999b). The Murat bioregion, to the east, is more variable in nature and offers a greater variety of habitats. Shield-islands of the Nuyts Archipelago protect the mainland coast from south-westerly swells here, and aid the development of several large sheltered embayments. Many of these sandy bays support significant mixed beds of seagrass (*Posidonia sinuosa, Amphibolis Antarctica, Heterozostra tasmanica*) and scattered stands of mangrove (*Avicennia marina*) (Edyvane 1999b). Reefs in this area have strong floral affinities with those in the Eucla bioregion but are typically more diverse, particularly in the lee of offshore islands (Edyvane 1999b). By contrast, the Eyre bioregion, further to the east, is a site of localised upwelling (Wenju et al. 1990). Periodic influxes of cold, nutrient-rich water enhance primary production in this area (Ward et al. 2006), and probably explain the occurrence here of cool-temperate algal species not found on reefs to the west (Edyvane 1999b).

Seabirds

Approximately 1.5 million pairs of seabirds belonging to 16 species breed in South Australia. Of these, more than 75% occur in the eastern Great Australian Bight. Short-tailed shearwaters (*Puffinus tenuirostris*) and white-faced storm petrels (*Pelagodroma marina*) are numerically dominant and collectively account for some 1.3 million pairs (Copley 1996). Other important species represented in the region include the little penguin (*Eudyptula minor*), which is endemic to southern Australia and New Zealand, and the osprey (*Pandion haliaetus*) which nests on cliffs across the Great Australian Bight. Non-breeding migratory seabirds are also known to frequent the coastal and shelf regions of the Great Australian Bight and include albatrosses, petrels and prions (Copley 1996).

Marine mammals

The Great Australian Bight provides critical habitat for two species of marine mammal that are recognised internationally as priorities for conservation: the southern right whale (*Eubalaena australis*), which is listed as endangered under the *Commonwealth Environment Protection and Biodiversity Act 1999*, and the Australian sea lion (*Neophoca cinerea*), which is listed as threatened under the same Act. The Great Australian Bight region is also recognised as an important seasonal habitat for many other species of marine mammals including blue whales, sperm whales, and humpback whales (Kemper & Ling 1991).

Continental shelf and slope

Benthos

Almost all of the seafloor beyond the state water limits (3 nm) out to the edge of the Australian Exclusive Economic Zone (200 nm) is composed of soft sediments but despite the prevalence of this habitat, very little is known about the diversity and distribution of the associated biota. Few systematic surveys of benthic infauna and epifauna have been undertaken in shelf and slope waters anywhere in Australia (Poore 1995). Moreover, there is currently no comprehensive information base for the abundance and distribution of benthic biota in the Australian EEZ (Heap et al. 2005).

In 2002, researchers from SARDI made significant advances in our understanding of the benthic biodiversity of the eastern Great Australian Bight by undertaking the first quantitative epibenthic survey of the region (Ward et al. 2006). This study involved sampling of epifauna throughout the eastern shelf, and was primarily aimed at assessing the effectiveness of the Great Australian Bight Benthic Protection Zone in representing regional biodiversity[1]. A total of 798 species were collected during the survey, including 360 species of sponge, 138 ascidians and 93 bryozoans (many of which are new to science). In comparisons with other similar studies conducted overseas, it appears that the eastern shelf of the Great Australian Bight supports one of the world's most diverse soft-sediment ecosystems.

[1] *The Benthic Protection Zone (BPZ) of the Great Australian Bight (GAB) Marine Park was proclaimed in 1998 to preserve a representative sample of benthic flora and fauna and sediments (Department of Environment and Heritage, 2005). The BPZ consists of a 20 nm-wide strip orientated north to south and extending from 3 nm from the coast to the edge of Australia's Exclusive Economic Zone (EEZ), 20 nm offshore. Within this zone, the benthic assemblages are protected from demersal trawling and other potentially destructive human activities. Before the BPZ was proclaimed, vessels of the GAB Trawl Fishery conducted demersal trawls in depths of 120–160 m (Caton 2001).*

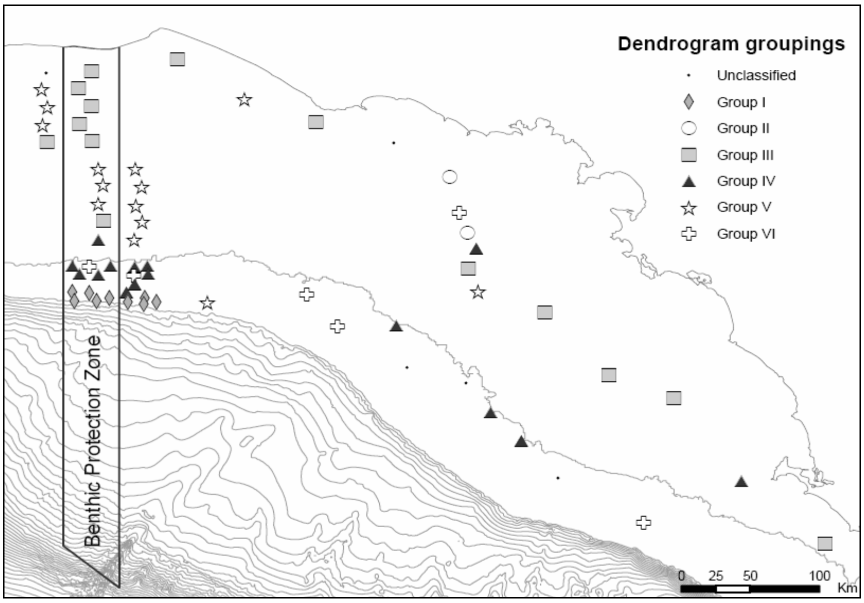


Figure 3.1.3 Map of the eastern Great Australian Bight showing the locations of 65 epifaunal sampling sites and their classification into six groups following cluster analysis of species biomass data (from Ward et al. 2006).

The same epibenthic survey has also provided novel insight into patterns of faunal distributions on the shelf and their relationships to environmental factors (Figure 3.1.3). The study has shown that species richness and biomass generally declines with increasing depth and distance offshore. Large total biomasses and high numbers of species characterise the inner shelf waters off the western Eyre Peninsula (an area of seasonal upwelling and enhanced primary productivity) and inshore waters at the Head of the Bight (a region of year-round elevated water temperatures). By comparison, relatively fewer species and individuals are represented in the outer shelf. This broad-scale environmental gradient is interrupted by regional variations in oceanography that modify the sedimentary characteristics and the associated bottom fauna. As a result, marked differences are evident in the types of species inhabiting different sedimentary facies on the shelf (Ward et al., 2006).

Sessile, suspension-feeding biota dominate the eastern shelf of the Great Australian Bight, but also appear to be conspicuous components of the shelf fauna elsewhere in the South-west Marine Region. Some of the earliest evidence for this comes from the 1962 voyages of *HMAS Gascoyne*, in which grab samples and photographs of the seafloor were collected across southern Australia at depths of about 75 m, 150 m and 300 m (Anonymous 1967). These collections have indicated a shelf fauna dominated by sponges, with bryozoans flourishing between 90 m and 210 m depth (Conolly & Von der Borch 1967; Wass et al. 1970). More recent sampling along the southern and south-western shelfs have highlighted the dominance of filter-feeding organisms, and particularly their importance in generating the carboniferous sediments that blanket the seafloor of the shelf and slope (James et al. 1999, 2001).

No published studies are available on the composition or distribution of benthic biota beyond the shelf-break in the South-west Marine Region. The biodiversity of the slope fauna can therefore only be inferred from studies elsewhere. The most regionally relevant comparison is a study of the crustacean isopod fauna from between 200 m and 3150 m depth off the south-eastern continental slope (Poore et al. 1994). In this study, a total of 359 species belonging to 36 families were identified, of which only 10% had been previously described. The results of this survey support the observation that species diversity at this temperate latitude is higher than at similar latitudes in the northern hemisphere. As the slope waters of the South-west Marine Region span similar latitudes to those sampled by Poore and his co-workers, a rich fauna may be suggested for this region. Benthic surveys recently initiated on the south-western continental margin (RV Southern Surveyor Cruise, No. S10/2005) are likely to prove revealing in this regard.

Fish

Shelf

The marine fish fauna of southern Australia is broadly characterised by a diverse range of species, with high rates of endemism at the specific and generic level (Wilson & Allen 1987). Poore (1995) estimated that some 85% of southern Australia's 600 fishes are endemic to the region; this is in strong contrast to the fauna of northern Australia where only 13% of fish are endemic. Current best estimates suggest that approximately 400 fish species belonging to 86 families are represented on the continental shelf of the South-west Marine Region (Gomon et al. 1994), but levels of endemism for the shelf fish fauna are not well defined. The lack of robust measures of endemism for the shelf is partly due to sporadic influxes of mid-water and pelagic fishes that are typically widespread and often migratory in nature. Little is known about the migratory pathways and distribution patterns of pelagic fishes overall; however, the oceanic pelagic fauna tends to be cosmopolitan and does not exhibit the same zoogeographic patterns of the inshore zone (Wilson & Allen 1987).

Slope

The knowledge base for deep-water fishes from the Australian continental slope has expanded rapidly in recent years following the commercial exploitation of the slope resources (Williams et al. 1996). Much of the commercial fishing on the slope of the South-west marine region has been concentrated in the Great Australian Bight where blue grenadier (*Macruronus novaezelandiae*), gemfish (*Rexea solandri*) and orange roughy (*Hoplostethus atlanticus*) have been targeted (Lynch & Garvey 2003). The first survey of the Bight slope fish resources was conducted in 1988 (Newton and Klaer 1991), and this multi-vessel study remains the most informative guide to the composition and distribution of the regional fauna.

The demersal slope fish fauna of the Great Australian Bight comprises at least 166 species from 125 genera and 71 families (Newton & Klaer 1991). Like other slope faunas in the North Atlantic and New Zealand, grenadiers (Macrouridae) and dogfishes (Squalidae) are the most speciose families, with 26 and 13 species represented respectively. Other families with five or more species represented include the ghost sharks (Chimaeridae), slickheads (Alepocephalidae), morid cods (Moridae) and sawbellies (Trachichthyidae). Whilst apparently large numbers of species and families are represented in the Bight, it is difficult to assess whether the slope fauna is unusually diverse. This is because comparisons between studies are almost always confounded by differences in the types of trawl gear used, and the frequency and geographic coverage of the sampling.

The first regional collection of fishes from the continental slope off the west coast of Australia was taken between 1989 and 1991 during exploratory trawling (Williams et al. 1996). In this study, demersal fish were sampled from 95 locations along the Western Australian slope between Cape Leeuwin (35° S) and North West Cape (20° S) at depths of between 200 m and 1500 m. These collections included 388 species from 108 families, and represent a substantial component of the known Australian fish fauna. In total, the fauna comprise about 9% of the 4100-plus known species (Yearsley et al. 1997) and over 35% of the 300 families currently recognised (Paxton et al., 1989). Due to the relatively low sampling density and large trawl mesh employed in this survey, it is considered likely that many fish species were unsampled. Further sampling with a variety of sampling gears is therefore expected to enlarge the number of species recorded (Williams et al. 1996).

The apparent high diversity of the Western Australian slope fauna is largely attributed to the overlap of tropical and temperate faunas (Williams et al. 2001). This high faunal richness is particularly evident in shallower depths (Hutchins 1994), and appears to be promoted by a complex interaction of oceanic currents at near-surface and intermediate depths. Water circulation patterns are also thought to play a role in the vertical stratification of fish communities on the Western Australian slope. Strong depth-related differences in community structure are evident, and are most pronounced between the shelf-break and upper-slope communities at about 250–350 m, and between upper-slope and mid-slope communities at about 700–800 m (Williams et al. 2001).

Distinct faunal changes with latitude are also apparent on the western slope of the continent, but are less evident in deeper water (Williams et al. 1996). A sharp biotone is recognised in the vicinity of latitudes 32° S and 33° S, and this area appears to be the north-western boundary of a widely distributed benthopelagic slope fish community (Williams et al. 2001). Fish occurring on the mid-slope below this latitude are thought to form part of a larger faunal assemblage that extends across southern Australia to New Zealand (Koslow et al. 1994).

Gaps in knowledge of biodiversity

Inshore

It is difficult to assess biodiversity in the region given the paucity of sampling effort for select organisms across the region. For example, the Terebellidae (Polychaeta) are not well described in depths greater than 30 m, and the distribution of nemerteans along the coast of Western Australia has been largely ”neglected” in terms of sampling (Gibson 1991). Records of the distribution of marine Enchytraeidae and Tubificidae would also benefit from more collections, particularly along the continental shelf (Coates 1991; Erseus 1991). In addition, a range of other groups have been recognised as requiring attention. These include the echinoderms (Marsh 1991), decapod crustaceans (Morgan & Jones 1991), sessile invertebrates

(McDonald 2005), and macroalgae; particularly between the capes region, Albany, offshore from the Fitzgerald biosphere area, and Esperance).

Offshore

The shelf and slope biota of the South-west Marine Region has received relatively little research attention. Of the research that has been conducted, most has concentrated on the fish biota; this is due to the economic importance of some demersal and pelagic fish species. As a result, some good general information on the composition and distribution of the shelf and slope fish fauna is available, but most other taxonomic categories represented on the shelf and slope have received only limited consideration. This is particularly the case for the greater diversity of fauna that typically inhabit the seafloor. Although some benthic surveys have been conducted in the shelf waters of the eastern Great Australian Bight, the benthic biota for most of the shelf and slope in the South-west Marine Region remain largely unexplored.

Ecological integration: Biodiversity

Table 3.1.1 Summary table of distribution of marine species groups and species numbers in the South-west Marine Region (SWMR). Note inferred presence = (Yes)

Species group	Inshore	Shelf	Slope	Number of species, [Location – note southern or South Australia] (Number of endemic species)	Authority for species numbers, (chapter authors in brackets)
PLANTS					
PHYTOPLANKTON	**Yes**	**Yes**	**Yes**	**148 [in Western Australia]**	**Thompson and Waite 2003 (LTwomey et al)**
MACROALGAE **Phaeophyta** **Rhodophyta** **Chlorophyta**	 **Yes** **Yes** **Yes**	 **Rhodoliths**		 **231–240, (57–60%) [in southern Australia]** **800, (75–77%) [in southern Australia]** **124-140, (30–40%) [in southern Australia]**	**Womersley, 1990; Edgar. 2000; Phillips, 2001 (N Goldberg)**
SEAGRASSES	**Yes**			**17 [in SWMR]**	**Various, (S Bryars/G Kendrick)**
MANGROVES	**Yes**			**1 [2 var in SWMR]**	**Duke, 1991, (S Bryars)**
PLANKTON					
ZOOPLANKTON	**Yes**	**Yes**	**(Yes)**	**15 [Likely species in SWMR]**	**Dakin and Colefax, 1940; Ritz et al., 2003, (S.McClatchie/D.Gaughan)**
INVERTEBRATES					
SPONGES	**Yes**	**Yes**	**Yes**	**139 [Great Australian Bight]** **77 [Houtman Abrolhus, Western Australia]** **243 [Marmion, Western Australia]** **300 [Recherché Archipelago, Western Australia]**	**Fromont, 1999; Sorokin et al., 2005 (S Sorokin/J Fromont)**
CNIDARIA (not corals) **Hydroids** **Anenomes** **Octocorals**	**Yes**	**Yes**			**(no chapter)**
CNIDARIA: CORALS (stony)	**Yes**		**Yes**	**6 [Western Australia]** **39 [South Australia]**	**Veron, 2000 (J Stoddart)**
MOLLUSCS **Gastropoda** **Bivalvia** **Cephalopoda** **Other gastropods** **Specimen shells (cowries)**	 **Yes** **Yes** **Yes** **Yes**	 **Yes** **Yes** **Yes** **Yes**		 **4 [SWMR]** **8 [SWMR]** **10 [SWMR]** **550 [Western Australia]**	**Beezley et al., 1988 (M Steer/S Mayfield)**
BRYOZOANS	**Yes**	**Yes**	**Yes**	**500 [southern Australia]**	**Bock, 1982 (D Currie)**
ECHINODERMS **Crinoids** **Asteroids** **Ophiuroids** **Echinoids** **Holothuroids**	**Yes**	**Yes**	**Yes**	**347 [southern Australia]** **50 [Great Australian Bight]** **83 [from Albany, Western Australia]** **7 [southern Australia]** **7 [Albany, Western Australia]** **51 [southern Australia]** **25 [Albany, Western Australia]** **73 [southern Australia,** **27 [Albany, WA]** **49 [southern Australia]** **12 [Albany, Western Australia]** **40 [southern Australia]** **12 [Albany, Western Australia]**	**O'Hara and Poore, 2000 (No chapter)** **Ward et al., 2006** **Marsh, 1990** **Shepherd et al., 1982** **Marsh, 1991** **Zeidler and Shepherd, 1982** **Marsh, 1991** **Baker, 1982a** **Marsh, 1991** **Baker, 1982b** **Marsh, 1991** **Rowe, 1982** **Marsh, 1991**
DECAPODS (in general)	**Yes**	**Yes**	**Yes**	**392 [southern Australia]**	**O'Hara and Poore, 2000, (No chapter)**
DECAPODS: PRAWNS (commercial)	**Yes**	**Yes**		**3 [SWMR]**	**(C Dixon et al.)**

Species group	Inshore	Shelf	Slope	Number of species, [Location – note southern or South Australia] (Number of endemic species)	Authority for species numbers, (chapter authors in brackets)
DECAPODS: ROCK LOBSTER **Southern** **Western**	**Yes**			 **1 [SWMR]** **1 [SWMR]**	 **(A Linnane)** **(N Caputi)**
ASCIDIANS	**Yes**	**Yes**		**300 [southern Australia]** **138 [Great Australian Bight]**	**Edgar, 2000; Kott, 1990, 1992, 2001; Ward et al., 2006 (J McDonald/S Sorokin)**
INFAUNA	**Yes**	**Yes**	**Yes**	**Multi-species**	**(D Currie/S Sorokin)**
FISH					
ELASMOBRANCHS **Sharks** **Rays** **Chimaeras**	 **Yes** **(Yes)** **(Yes)**	 **Yes** **(Yes)** **Yes**	 **Dogfish** **Yes**	152 total [in SWMR] **95 (8)** **51 (14)** **6**	**Shark Advisory Group 2002 (D Trinder)**
DEMERSAL FISH inner	**Yes**			**695 [in SWMR]**	**Compiled from several texts including Gomon et al., 1994 plus Museum data and unpublished records, (J Baker)**
DEMERSAL FISH shelf		**Yes**		**>400 [in SWMR]**	**(L McLeay)**
DEMERSAL FISH slope			**Yes**	**463 [in southern zone of SWMR]** **398 [in south western transit zone]** **480 [in central western zone of SWMR]**	**Last et al., 2005 (D Trinder)**
MACKERELS, TUNA & BILLFISHES **Scrombidae** **Xiphiidae** **Istiophoridae**	 **Mackerels**	 **Mackerels** **Sailfish**	 **Tunas** **Swordfish** **Billfishes**	 **21 [west coast, south of Shark Bay]** **14 [Cape Leeuwin to Kangaroo Island]** **1 [SWMR]** **5 [west coast]**	**Several including Froese and Pauley, 2005 and fishbase (H Kemps/J Totterdell)**
MESOPELAGIC FISH **Myctophids** **Sternoptichidae**			**150-1000m**	 **2 [southern Australia]** **1 [southern Australia]**	**Paxton et al., 1989; May and Blaber, 1989; Blaber and Bulman, 1987 among others (S McClatchie)**
SMALL PELAGIC FISHES	**Yes**	**Yes**		**11**	**Gomon et al., 1994; Kloser et al., 1998 (P Rogers et al.)**
SYNGNATHID FISH	**Yes**			**~40**	**Several includes museum records (J Baker)**
MAMMALS/BIRDS					
SEABIRDS	**(Yes)**			**81 [22 breeding]**	**Surman and Wooler, 2000, (C Surman/L Nicholson)**
PINNIPEDS	**(Yes)**			**3 [in SWMR]**	**Campbell, 2005; Shaughnessy et al., 2005 (S Goldsworthy et al.)**
CETACEANS **Baleen whales** **Toothed whales**	**Yes**	**Yes**	**Yes**	38 total [in SWMR] **10** **28**	**Bannister et al., 1996 (P.Gill et al.)**

3.2 Food webs

Principal contributors

Sam McClatchie

Gary A Kendrick

Overview

The food webs in the South-west Marine Region shelf and slope are not well studied. The lack of information means that inferences need to be made about the food webs in the region based on studies in other areas such as Tasmania and Victoria. Such extrapolation is dangerous, however, as there are distinct differences between dominant feeding guilds of demersal fish between the west coast of Australia and the south and south-east coasts (Williams et al. 2001). There seems to be more similarity between outer shelf and slope fish assemblages on the North-west Shelf and those in the temperate western continental shelf and slope. The current level of knowledge about feeding relationships, which is largely based on gut contents and stable isotope studies, while very useful, is insufficient to quantitatively characterise the pelagic and benthic food webs. At best we can make some general statements about guilds that are likely to be important in the South-west Marine Region.

Diets of benthic invertebrates on the shelf are poorly known in the shelf and slope environment of the South-west Marine Region. In overseas studies, diets of benthic invertebrates tend to be inferred from taxonomic studies that permit species to be assigned to general feeding guilds such as deposit feeders or suspension feeders. As discussed in Section 3.1, the taxonomy of benthic invertebrate communities, especially the infauna, is poorly known in this region, and so little can be specified about the diets of the benthic invertebrates. Biological data for two large invertebrates, the champagne crab *Hypothalassia acerba* and crystal crab *Chaceon bicolor*, have shown that they occupy different depths on the outer continental shelf and slope (Smith et al. 2004). On the west and south coasts, the abundance of champagne crabs was greatest at depths of 200 m and 145 m respectively, with water temperatures of 16.1–17.1 °C. On the west coast, the crystal crab lives in depths of 450–1220 m, where temperatures are only 4–6.5 °C (Smith et al. 2004). Whether this depth differentiation is resource partitioning or driven by the physiological requirements of the crabs is unknown.

Most of the available information on food webs in the South-west Marine Region pertains to the demersal fish, which are discussed below. The situation for plankton and nekton is similar to that for the benthic invertebrates. There is virtually no species-specific information on feeding. A recent large-scale study of the pelagic biophysical dynamics across the continental shelf and slope off Two Rocks, north of Perth, Western Australia found distinct phytoplankton and zooplankton assemblages from on-shelf and offshore areas (Keesing & Heine 2005). The surface waters of the south-western Australian shelf, waters of the Leeuwin Current and surface waters offshore were very low in nitrogen (less than 0.5 µmol) year round and primary productivity was nitrogen limited. (Lourey et al. 2006). Preliminary mesozooplankton feeding studies found a strong negative relationship between large diatoms and mesograzers. A full pelagic trophic model has yet to be produced.

The small pelagic fishes are plankton feeders, and exploit different sizes of plankton. Among the small pelagic fish, sardine and anchovy are omnivorous planktivores, consuming phytoplankton and zooplankton as well as fish eggs and larvae (including their own). The diet of anchovy tends to contain larger particles than that of sardine (van der Lingen 2002). These forage fishes fall prey to a wide size range of epipelagic predators, ranging from the tunas to Australian salmon, pike and barracouta. Mid-size pelagics like the mackerels generally feed on epipelagic nekton. Information on mackerels may be gleaned from Tasmanian studies. Jack mackerel (*Trachurus declivis*) are known to feed on coastal krill (*Nyctiphanes australis*), and their recruitment may be related to fluctuations in krill abundance (Young et al. 1993).

We can use information on Australian salmon (*Arripis truttaceus*) from Victorian waters (Hoedt & Dimmlich 1994) to infer predation further west. The salmon in Victorian waters consumed mainly anchovy of a range of sizes. Juvenile sardine were the second most common prey, and sandy sprat were occasionally common in the stomachs of the salmon. A preliminary sample from the eastern Great Australian Bight indicates that Australian salmon eat bullseyes, small specimens of their own species, sardines, and sandfish (Page et al. 2005). Shortfin pike or snook (*Sphyraena novaehollandiae*) and barracouta (*Thyrsites atun*) were reported to have a diet similar to the Australian salmon (Hoedt & Dimmlich 1994). Longfin pike, swallowtail and snapper prey heavily on krill (Page et al. 2005). Preliminary data from the eastern Great Australian Bight indicate that barracouta consume redbait, pilchards and arrow squid (Page et al. 2005).

The large, migratory predators like tunas are pelagic piscivores. Bluefin tuna (*Thunnus maccoyii*) are known to consume sardines (*Sardinops sagax*), blue mackerel (*Scomber australasicus*) and anchovy (*Engraulis australis*) as well as saury (*Scomberesox saurus*), arrow squid, jack mackerel (*Trachurus* spp.) and several other fish (Ward et al. 2006).

Benthopelagic fish are likely to exploit the vertically migrating mesopelagic fish (myctophids and lightfish) when they descend near the bottom over the shelf, particularly at the shelf edge. The same mesopelagic fishes provide food for tunas and mackerels when their vertical migrations take them into midwater and near the surface at night. The vertically migrating mesopelagic fish, as well as shrimps, squids, and offshore krill species (e.g. *Euphausia* spp.) form an important and almost unstudied link between the pelagic and the epibenthic food webs. Diets of mesopelagic fishes in this region are totally unknown, but from other studies it seems probable that lightfish (*Maurolicus australis*) and the myctophids (*Lampanyctodes hectoris*) eat euphausiids and copepods, compared to Lanternfishes *Diaphus danae* that eats a greater proportion of fish such as the smaller myctophids (*L. hectoris*) (Young & Blaber 1986).

For the demersal shelf fishes (50–200 m depths) there is a surprising lack of information on diet, even in terms of qualitative stomach contents. Diet information is confined to flathead (Burnell & Newton 1989), King George whiting and snapper (Robertson 1977; Jones 1981; Jones et al. 1990) and Westralian dhufish (Western Australian Fisheries, 1992). For other shelf fishes, it is necessary to infer the diets of the species in the South-west Marine Region from more comprehensive studies of the diets of the same species in south-eastern Australia (Bulman et al. 2001; Davenport and Bax 2002). Using this approach, gemfish (*Rexea solandri*), deepwater flathead (Neoplatycephalus conatus) [by analogy with the sand flathead (*Platycephalus bassensis*)] and tiger flathead (*Neoplatycephalus richardsoni*)), can be broadly categorised as benthic or bentho–pelagic piscivores (Bulman et al. 2001). Information on the diets of demersal slope fish is even sparser. Some of the important slope fish like Bight redfish (*Centroberyx affinis*) and orange roughy (*Hoplostethus atlanticus*) feed more on crustacea than on fish, exploiting deepwater shrimps and other midwater nekton, and can be classed as pelagic crustacean feeders and omnivores (Bulman et al. 2001; Williams et al. 2001).

The western continental slope (below 400 m) is characterised by many relatively small benthic-feeding species that are predominantly grenadiers (Macrouridae and Bathygadidae), dogfishes (Squalidae) and cucumberfishes (Chlorophthalmidae) (Williams et al. 2001). These benthic feeders appear not to be dependent on vertically migrating mesopelagic fish. The vertical distribution and relative abundance of mesopelagic micronekton off the west coast of Western Australia is unknown, and the seafloor topography has not been fully surveyed. However, the lack of elevated fish density at depth, as well as the absence of a mid-slope fishery after decades of exploratory commercial fishing, indicates that predation on mesopelagic micronekton does not result in enhanced fish production on the mid-slope off Western Australia (Williams et al. 2001) as demonstrated in south-eastern Australia. This suggests care should be taken when extrapolating tropic dynamics from the east coast to the temperate west coast.

Page et al. (2005) reviewed the diets of the higher predators. New Zealand fur seals take a surprisingly high number of cephalopds and birds. Approximately 28–34% of the fur seals' diet at Pearson and Neptune islands in the eastern Great Australian Bight consisted of cephalopods (mainly arrow squids, *Nototodarus gouldii*, and *Todarodes* spp.) and 18–34% consisted of birds (little penguin, *Eudyptula minor*, and shearwaters, *Puffinus* sp.). Fish constituted 31–54% of the New Zealand fur seal diet at Neptune and Pearson islands, and 55–70% of the fish comprised only three species (Ocean jacket, *Nelusetta ayraudi,* Swallowtail, *Centroberyx lineatus,* and redbait, *Emmelichthys nitidus*).

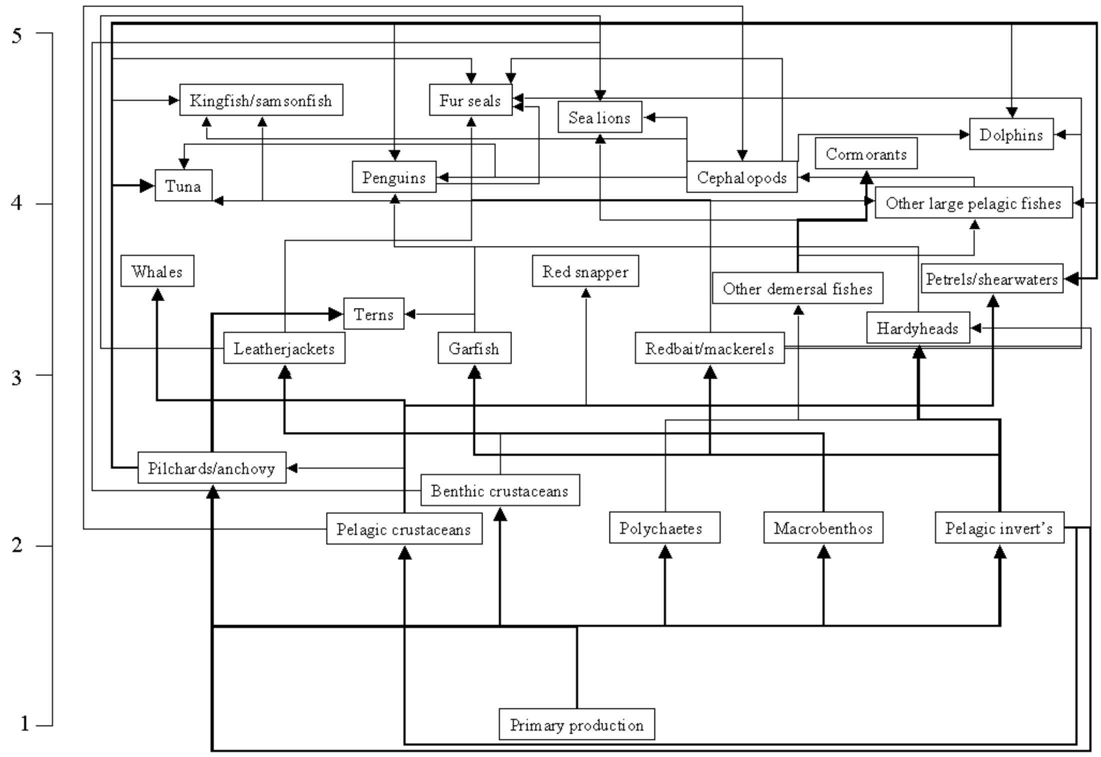


Figure 3.2.1 Simplified food web that summarises the main trophic interactions among species groups in the eastern Great Australian Bight. Species' trophic levels are indicated on the left. To improve clarity, dietary contributions ∫50% are indicated by bold lines, contributions <50% are indicated by fine lines and contributions <10% have been omitted (from Ward et al., 2005)

Little penguin (*Eudyptula minor*) diets seem to be quite variable in the eastern Great Australian Bight. Penguins on Troubridge and Reevsby islands eat mainly fish including hardyheads (*Atherinason esox, Paranesus ogilbyi*), sardine (*Sardinops sagax*), anchovy (*Engraulis australis*), sandy sprats (*Hyperlophus vittatus*), blue sprats (*Spratelloides robustus*), garfish (*Hyporhamphus melanochir*), leatherjackets (various genera), pipefish (various genera), and redbait (*Emmelichthys nitidus*) as well as squid. In contrast, the penguins on Pearson and Greenlie islands had eaten more cephalopods and zooplankton, including arrow squid (*Notododarus gouldii*), cuttlefish (*Sepioteuthis sp.*), krill (*Nyctiphanes australis*), and crab larvae, as well as anchovies (Page et al. 2005). Shearwaters in the mouth of the Spencer Gulf seem to take mainly krill and copepods, as well as some anchovies; on the other hand, crested terns from Troubridge Island feed more on fish (including sardines, anchovies, garfish and leather jackets).

Of note is a trophic study of the continental shelf of south-eastern Australia where stable isotopes of carbon and nitrogen were used to determine the trophodynamics position of 87 fish species, penguins, marine mammals and invertebrates (Davenport & Bax 2002). The stable isotopes were found to be more useful than gut content analyses. A similar study has not been performed for the southern and western shelfs of Australia, although such a study should treat the western continental shelf separately from the southern shelf. There is a broad tropical–temperate transition north–south along the western continental shelf, with highly diverse but low biomass demersal fish assemblages varying with latitude and depth (Koslow et al. 1997; Williams et al. 2001).

Ecological integration: Food webs

A preliminary food web of the eastern Great Australian Bight developed for ecosystem modelling using EcoPath (Ward et al. 2005) is shown in Figure 3.2.1. This structure can really only be regarded as preliminary since the data that it is based on are sparse. A notable omission is the mesopelagic fish that are likely to be an important component of the shelf food web, especially at the edge of the continental shelf. The mesopelagic fish are omitted because there are very little data available for this group.

Gaps in knowledge of benthic food webs

- Diets of benthic invertebrates are poorly known in the shelf and slope environment of the South-west Marine Region.
- Little is known of the pelagic links to benthic food webs. An ecosystem level approach to the study of trophic connections along a broad latitudinal gradient on the western shelf and southern shelf and slopes is highly recommended.
- Application of existing south-eastern food web models ignore the different physiognomy, sedimentology and habitats available to demersal fish in the south-west region. The spatially explicit fish-habitat approach used by Williams and Bax (2001) should also be extended to food webs.

3.3 Pelagic and benthic production

The south-west of Australia has been commercially fished for decades for a wide range of species including demersal and pelagic invertebrates and finfish. The following analysis of the relative importance of pelagic and demersal fisheries production is based on landings data reported to the FAO by Australia between 1950 and 2002. These data have been spatially reaggregated across Australia's seven recognised large marine ecosystems (<www.seaaroundus.org>) and here we are using the Australian south-west and west coast large marine ecosystems that correspond approximately to the South-west Marine Region. As the west coast large marine ecosystem includes Shark Bay, those species fished exclusively within Shark Bay have been excluded from the analysis.

In the Region, landings have been reported for 144 taxonomic groups including 71 species and 73 higher taxanomic groupings (typically to family). Of these, 18 taxa (or 12%) are found exclusively in the west coast large marine ecosystem and may represent taxa caught in the northern part of the west coast large marine ecosystem which is not part of the planning region. However, these taxa comprise 7.3% of the total landings between 1950 and 2002 with no individual taxa comprising more than 1% of the total landings over the period considered. Thus, it is likely that the incidental inclusion of rare species caught only in the northern area of the west coast large marine ecosystem will not influence the overall analysis of the relative importance of pelagic and demersal fisheries production within the Region.

In the Region, a total of 1.6 million tonnes of fish and invertebrates was landed between 1950 and 2002. These landings included demersal finfish and invertebrates, rays and sharks (considered as demersals in this analysis), and pelagic finfish and invertebrates. Total mean annual landings have increased by 168% in the period between 1950 and 2002, with significant increases across all groups (Table 3.3.1; Figure 3.3.1). In terms of rate of change, the most significant relative increase in mean landings are among the pelagic invertebrates, with greater focus on species such as the teuthid squids. There has also been an increase in landings of demersal rays, sharks and finfish; landings of demersal invertebrates and pelagic finfish have been more modest (184% and 79% respectively).

Between the 1950s and the 1993–2002 period, there have been significant shifts in the relative importance of demersal and pelagic species to the overall catch. Demersal species of invertebrates and finfish comprised 60.2% (±1.5% se) of the total mean annual landings in the 1950s. By the mid 1990s, the proportion of the landings comprised of demersal species had increased to 71.4% (±0.9% se), largely due to the increases in landings of demersal finfish. Indeed, whereas demersal finfish comprised 24.0% (±1.8% se) of the total mean annual finfish landings in the 1950s, this mean had increased to 44.1% (±1.1% se) of the mean annual landings from 1993–2002. With respect to invertebrates, demersal species have consistently comprised more than 98% of the landings.

The significant increase in landings across all major groups plus the shift to increased relative importance of demersal productivity, and in particular demersal finfish, has significant implications for long-term sustainability of fisheries productivity. The marine waters of the Region are relatively nutrient poor and there are thus significant questions as to the total primary production available to support fisheries. It is also likely that benthic primary producers turn over more slowly than water column systems and thus the relative availability of primary production within demersal food webs may be lower.

Additionally, many of the demersal species subject to increasing fishing pressure, such as the sharks and the blue grenadier (*Macruronus novaezelandiae*), have low resilience to fishing given their relatively low reproductive rates and high trophic level. So, although the majority of finfish landed in the Region remain pelagics, demersal finfish are of increased importance in commercial fisheries.

Table 3.3.1 Changes in mean annual total landings (tonnes) between the 1950s and the period 1993–2002 with the percentage increase over that period indicated.

Category	Landings 1950–1959	Landings 1993–2002	% increase
Demersal finfish	1 248	5 153	313
Demersal inverts	7 300	20 727	184
Rays and sharks	608	3 711	511
Pelagic finfish	6 273	11 252	79
Pelagic inverts	4	530	13 160
Total	15 432	41 374	168

Figure 3.3.1 Total landings in tonnes by group from 1950 to 2002

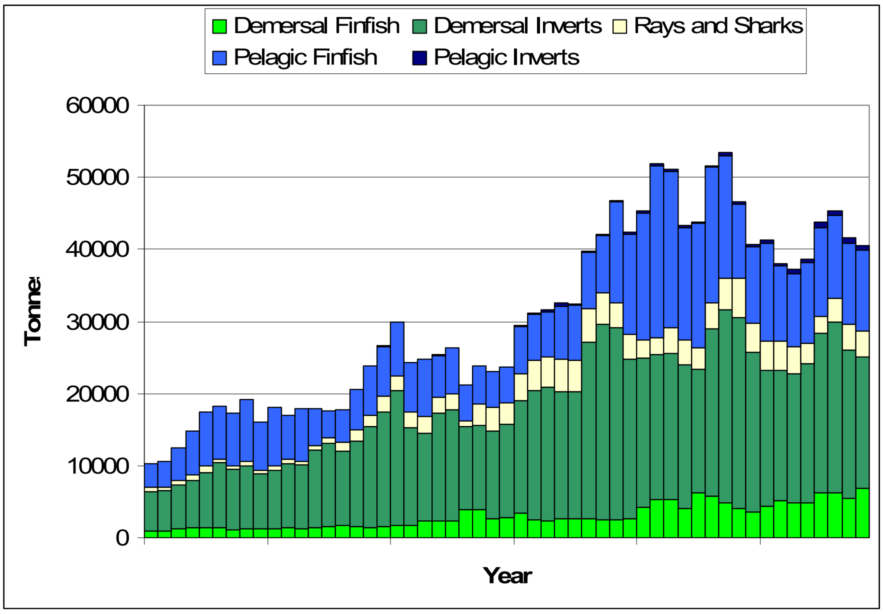
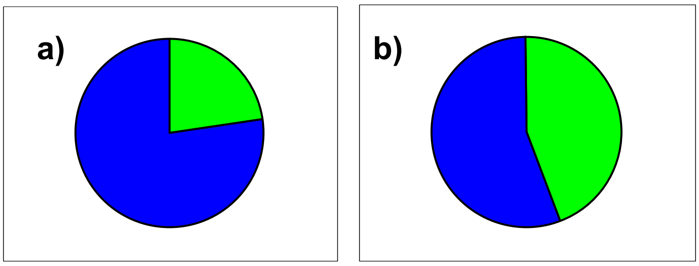


Figure 3.3.2 Relative proportion of demersal (green) and pelagic (blue) finfish between (a) 1950s and (b) 1993–2002.



3.4 Seasonal cycles

3.4.1 Kangaroo Island to Esperance

Principal contributor

Sam McClatchie

Primary production

The seasonal cycle of phytoplankton over the South-west Marine Region can only be inferred from remotely sensed ocean colour because only these data have the spatial coverage over the entire area. Hayes et al. (in press) used monthly composites from the MODIS-Aqua sensor for January, April, July and October to illustrate the annual seasonal cycle (and discussed the limitations of these data in some detail). A consistent feature of the cycle is the low levels of chlorophyll (<1.0 mg Chl a mg^{-3}) over the shelf. Although Hayes et al. refer to chlorophyll levels of 0.75–1.0 mg Chl a mg^{-3} as high, compared to chlorophyll concentrations in shelf seas at comparable latitudes, chlorophyll in the Great Australian Bight is low.

The seasonal snapshots (Hayes et al. in press) show some interesting features over the shelf and slope of the Great Australian Bight between Kangaroo Island and Esperance. In January there is evidence of a connection between higher (0.5–0.75 mg Chl a mg^{-3}) chlorophyll levels on the shelf and higher chlorophyll in offshore waters of the Subtropical Convergence (Figure 3.4.1.1). This feature may be associated with mesoscale eddies in the region evident in the SST imagery (Hayes et al., in press). By April (Figure 3.4.1.2) there is some evidence of propagation of higher chlorophyll (0.75–1.0 mg Chl a mg^{-3}) towards the east over the shelf (Hayes et al. in press). In the winter month of July, there is some evidence for higher chlorophyll in the eastern part of the Great Australian Bight compared to the west (Figure 3.4.1.3). By October, chlorophyll concentrations are low over the shelf (0.25–0.75 mg Chl a mg^{-3}) (Figure 3.4.1.4), although the spring bloom has begun in the Subtropical Convergence offshore (Hayes et al. in press). These remote sensing composites suggest that there may be a seasonal propagation of production from the western area around Esperance towards the eastern Great Australian Bight.

Hayes et al. (in press) also used weekly composites of the SeaWiFS ocean colour sensor to examine spatial and temporal patterns in phytoplankton biomass. They conclude that the Great Australian Bight has a simple seasonal cycle. Chlorophyll is low on the shelf and north of the Subtropical Convergence between November and April. From April, a band of higher chlorophyll develops and spreads across the shelf producing higher chlorophyll in the Head of the Bight. Chlorophyll spreads northward from the Subtropical Convergence at the same time. The higher chlorophyll in the Great Australian Bight persists until late spring, and then recedes back to the Subtropical Convergence (Hayes et al. in press).

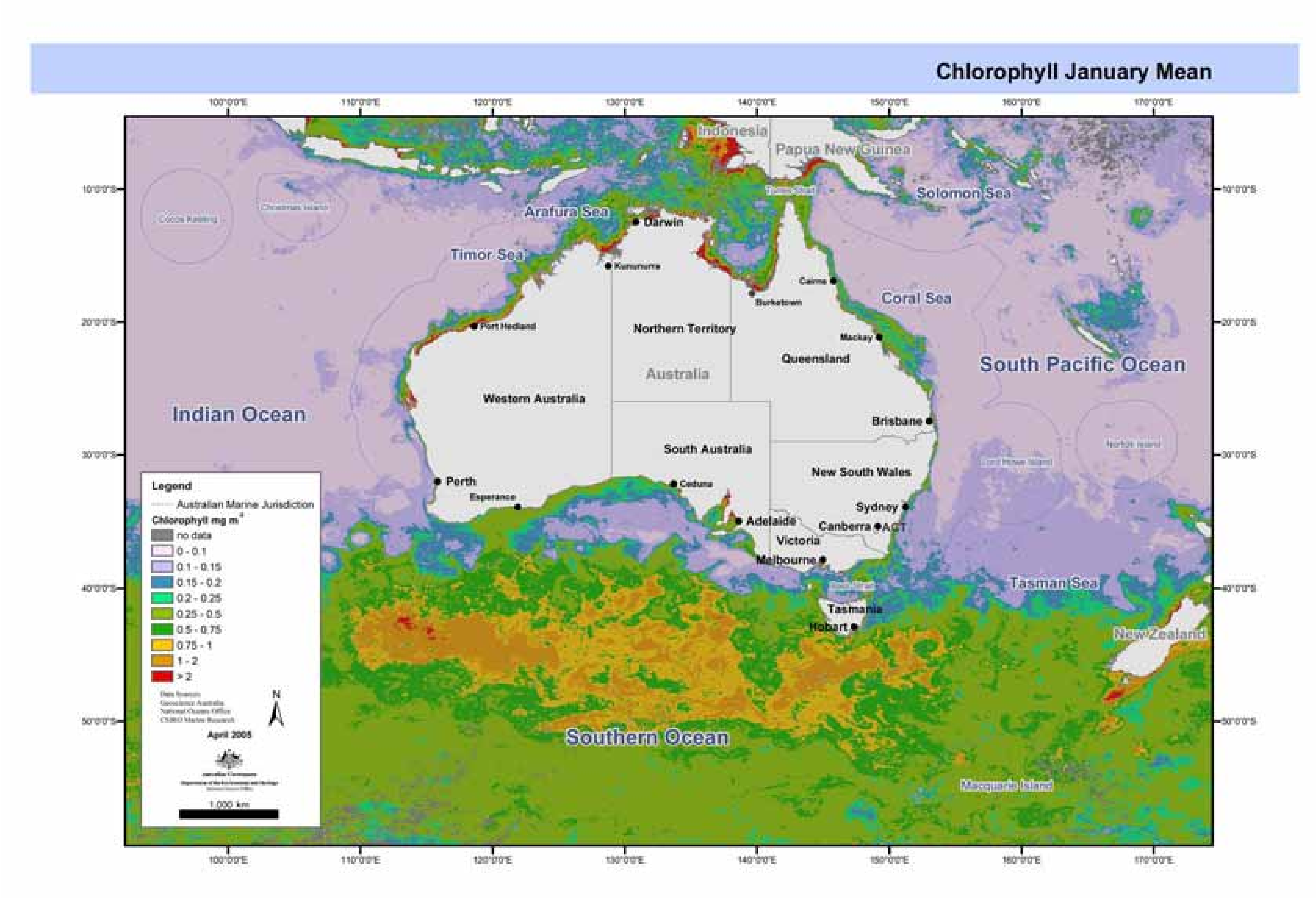


Figure 3.4.1.1 Monthly composites of MODIS ocean colour data showing the seasonal progression of phytoplankton growth – January (from Hayes et al. 2005.)

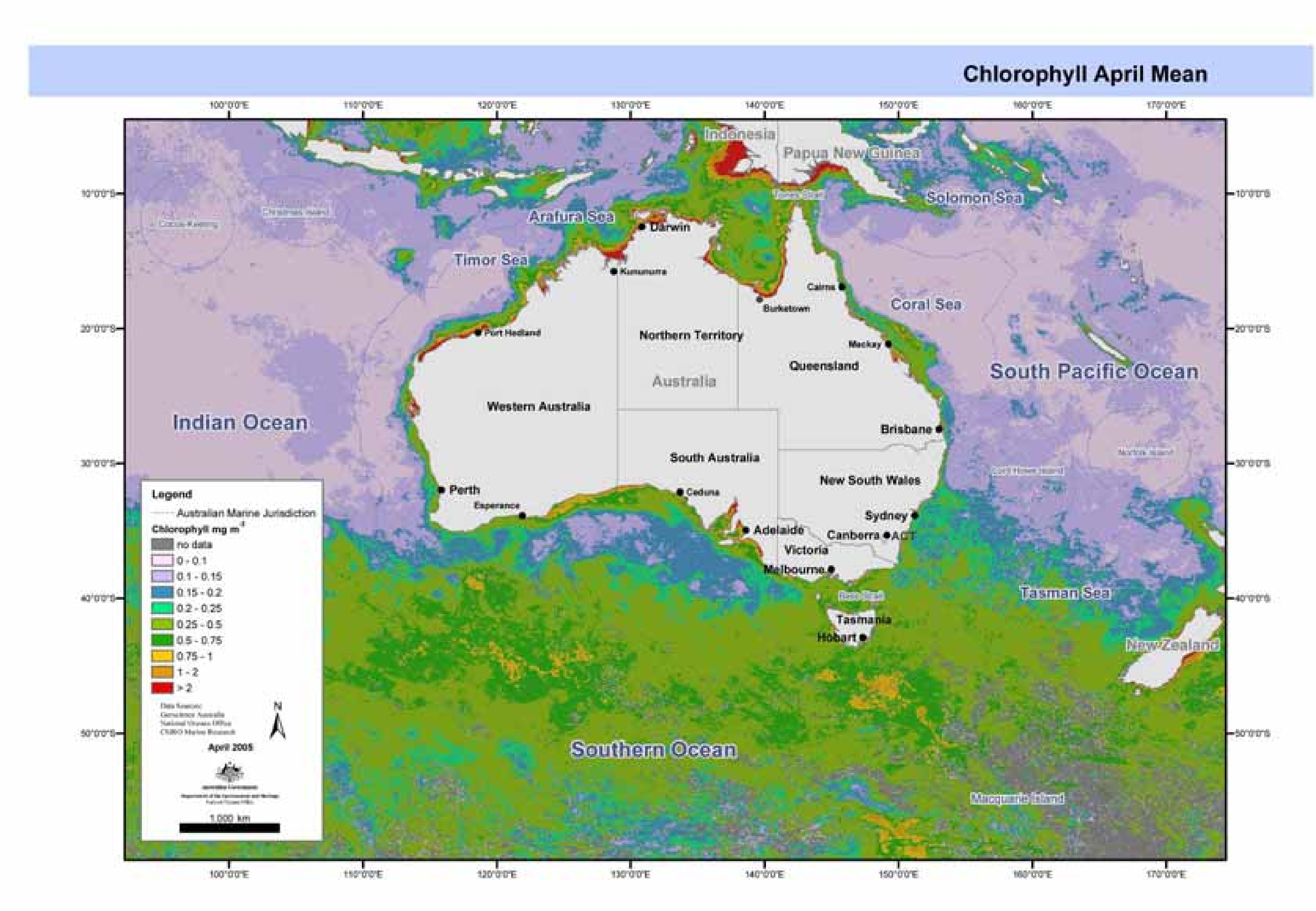


Figure 3.4.1.2: Monthly composites of MODIS ocean colour data showing the seasonal progression of phytoplankton growth – April (from Hayes et al. 2005.)

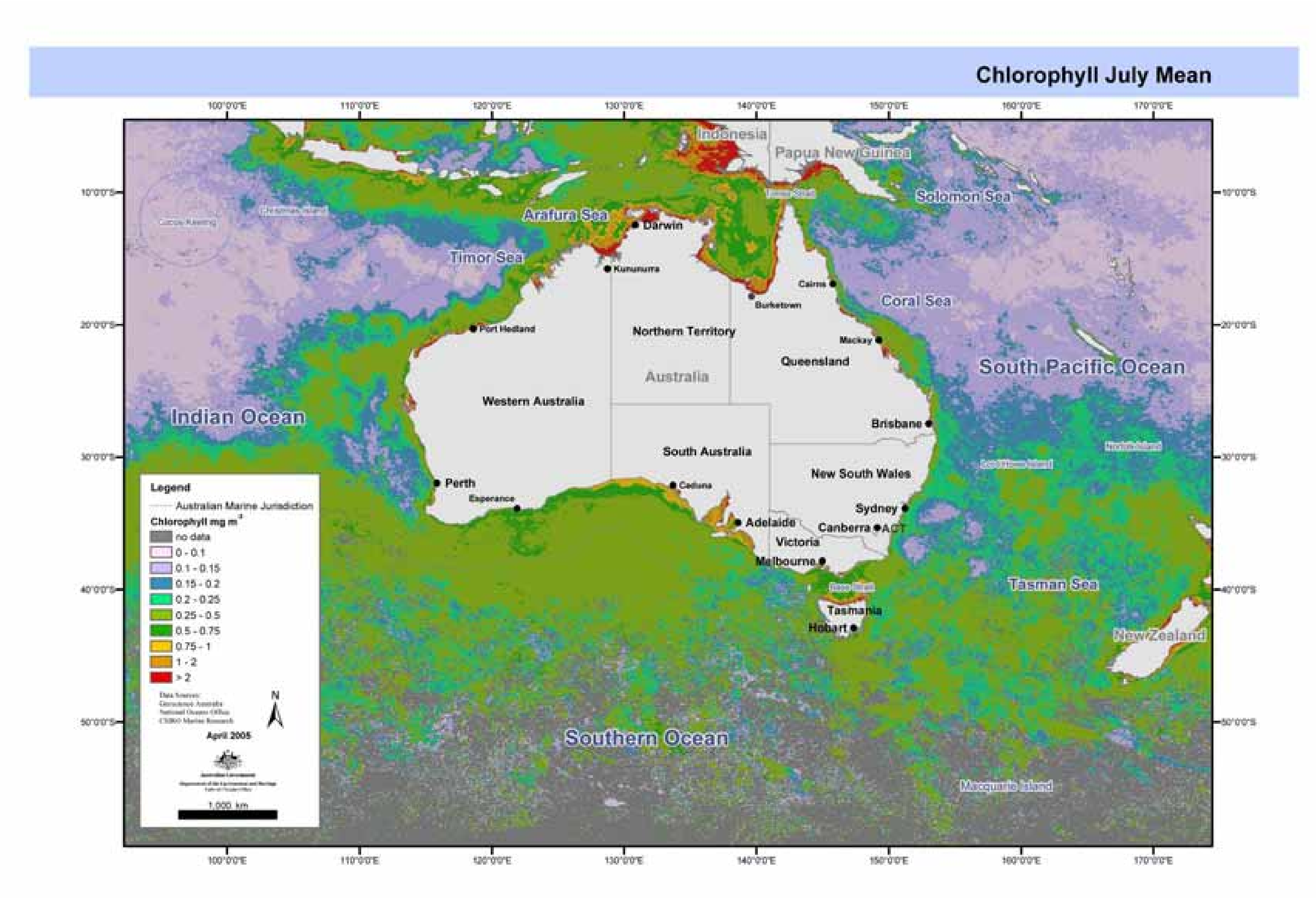


Figure 3.4.1.3 Monthly composites of MODIS ocean colour data showing the seasonal progression of phytoplankton growth – July (from Hayes et al. 2005.)

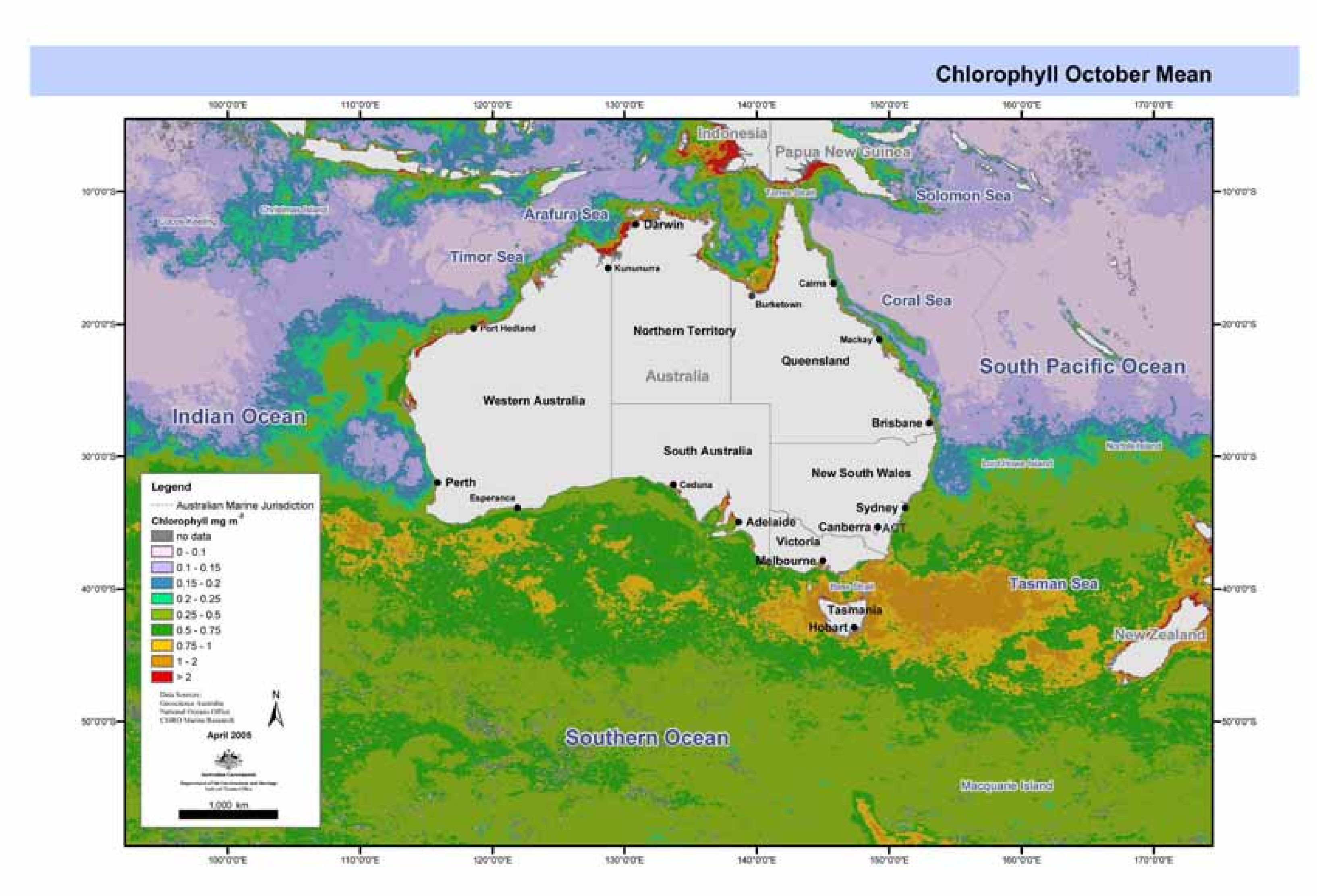


Figure 3.4.1.4 Monthly composites of MODIS ocean colour data showing the seasonal progression of phytoplankton growth – October (from Hayes et al. 2005.)

Primary productivity and seasonal cycle

Measurements of primary productivity in the South-west Marine Region are sparse. Hayes et al. (in press) compiled historical data from 27 naval cruises (1959–1964), but the only measurements in this region were made in the autumn (March–May). Most of these measurements were made either along the shelf edge or further south in the Subtropical Convergence.

Hayes et al. (in press) presented seasonal primary production based on modelled estimates from remote sensing. While there are many problems with the production model, the remote sensing data provide the only regional estimates of the seasonal cycle of primary productivity.

Although there is considerable mesoscale variability, the general pattern of primary production shows a seasonal progression southwards beginning at the end of the winter (July), developing into a major bloom on the shelf and in the Subtropical Convergence in spring (October) then becoming confined to the Subtropical Convergence in mid-summer (January) before retreating northwards again in the autumn (April) (Hayes et al. in press).

Secondary production

The paucity of sampling in the region from Kangaroo Island to Esperance is more serious for zooplankton than for phytoplankton because the distribution of zooplankton cannot be inferred from remote sensing imagery. Historical data from 27 naval cruises (1959–1964) compiled by Hayes et al. (in press) shows that zooplankton biomass estimates were only available for a scattering of stations in winter (June–August) and autumn (March–May). As for the phytoplankton, most of the samples in the historical dataset were on the shelf edge or offshore in the Subtropical Convergence. The historical dataset is insufficient to be informative about seasonality of zooplankton in the Kangaroo Island to Esperance region. An interesting feature of these data is the striking abundance of carnivorous gelatinous zooplankters recorded in autumn (March–May) off Esperance. Remotely sensed chlorophyll imagery suggests advection between the shelf and offshore waters in January off Esperance. The accumulation of predatory zooplankton in autumn may indicate that production on the shelf is being exported and consumed offshore.

3.4.2 Shark Bay to Esperance

Principal contributor

Chari Pattiaratchi

Primary production

The seasonal cycle of phytoplankton biomass (as estimated via chlorophyll a) in the waters off Western Australia can be inferred using satellite-derived data and *in situ* data collected offshore from the Perth metropolitan region (the CSIRO SRFME transect; Haine 2005). The satellite-derived chlorophyll a concentration assessment is limited to near-surface values only. In the South-west Marine Region, the deep chlorophyll maximum is generally present at the base of the euphotic zone, close to the nutricline and represents a significant proportion of the depth integrated productivity (Hansen et al. 2005). The satellite-derived chlorophyll a concentration data represent surface values as the sensors do not penetrate to the base of the euphotic zone. Hence, the analysis presented here is limited mainly to the surface values and does not include the seasonal and spatial variations of the deep chlorophyll maximum.

Two distinct seasonal scenarios characterise the oceanographic conditions along the west and south coasts of Western Australia. During the autumn and winter months, when equatorward wind stress is weakest, the Leeuwin Current flows strongly southwards and can flood much of the continental shelf (Hansen et al. 2005). During this period, the mixed layer is deeper leading to shoaling of the nutricline. During the summer months, southerly winds weaken the Leeuwin Current's flow and generate localised upwelling along the inner continental shelf, forming the source water of the Capes Current (Gersbach et al. 1999). Here, the southerly wind stress overcomes the alongshore pressure gradient which is the driving force of the Leeuwin Current. This results in the surface layers moving offshore and colder water upwelling onto the continental shelf with the result that the Leeuwin Current migrates further offshore.

Data presented by Lourey et al. (2006) have shown that the surface waters of the South-west Marine Region – including the continental shelf, Leeuwin Current and offshore waters – may be considered to be nitrogen limited, with diatom production in shelf waters also limited by the availability of silicate.

In the South-west Marine Region and within the constraints of the *in situ* and satellite data, Leeuwin Current and offshore waters may be characterised as very low surface chlorophyll a environments (<0.25 mg m^{-3}) (Lourey et al. 2006), with slightly elevated concentrations found along the continental shelf (<1.0 mg m^{-3}) (Pearce et al. 2000; Lourey et al. 2006). Higher chlorophyll a values (~2–5 mg m^{-3}) are considered to be representative of shelf waters or estuaries subjected to anthropogenic nutrient inputs (Pearce et al. 2000). Satellite imagery also indicates that the shelf waters are generally higher in chlorophyll a concentrations when compared to Leeuwin Current and offshore waters, in both summer and winter (Figure 3.4.2.1). Interaction between the Leeuwin Current and shelf waters entrains the higher chlorophyll a water into mesoscale eddies which are then advected offshore (Figure 3.4.2.2).

Annual cycles, of temperature, salinity, nitrate, phosphate, silicate and chlorophyll a concentration for the surface waters of the Leeuwin Current and the south-western Australian shelf have been presented by Lourey et al. (2006). In terms of the seasonal cycle, the chlorophyll a concentrations along the continental shelf, Leeuwin Current and offshore waters were higher in winter than in the summer (Figure 3.4.2.3). The summer to winter chlorophyll a increased from ~0.10 mg m^{-3} to 0.25 mg m^{-3} (i.e. a range of ~0.15 mg m^{-3}) in the Leeuwin Current and offshore regions. On the continental shelf, the increase may be larger, possibly up to 0.75 mg m^{-3} (from 0.25 mg m^{-3} to 1 mg m^{-3}) between summer and winter (Lourey et al. 2006). Satellite observations also indicate that the late autumn/early winter bloom is a coherent feature from the Abrolhos Islands to Cape Leeuwin coinciding with intensification of the Leeuwin Current (Figure 3.4.2.4).

The winter increase in chlorophyll a concentration throughout South-west Marine Region is associated with a corresponding increase in the nitrogen concentration which has been attributed to several sources: (1) supply from deeper water through the erosion of the thermocline; (2) regeneration along the continental shelf region through increased storminess; and, (3) through terrestrial sources such river inputs (Hansen et al. 2005; Lourey et al. 2006). However, as the winter chlorophyll a concentration is uniform throughout the whole region (see Figure 3.4.1.4), input from terrestrial sources may only have a minimal impact. It is also important to note that although there is an increase in the chlorophyll a concentrations on the shelf as a result of upwelling and the associated Capes Current, the winter increase in nutrients has a more dominant role in controlling the chlorophyll a concentrations, with the winter values higher than the summer values – although the latter is associated with upwelling.

Primary productivity and the seasonal cycle

In contrast to the chlorophyll a concentrations which were higher in winter than in summer, the primary production rates indicated higher values associated with summer upwelling (Hanson et al. 2005). Here, maximum production rates of 945 mg C m^{-2} d^{-1} were measured during the summer, whilst the maximum winter production rates were 400 mg C m^{-2} d^{-1} (Hanson et al. 2005). This reduction in productivity was attributed to a combination of nutrient availability and the light climate. During the winter, the stronger Leeuwin Current flow leads to increased nutrient levels associated with entrainment of seasonally nutrient-enriched shelf waters. In contrast, lower surface irradiance and increased light attenuation result in lower primary productivity during the winter months.

Secondary production

Seasonal variability in the secondary production is only available from the SRFME transect, offshore Perth (Haine 2005). Measurements undertaken along a cross-shore transect indicated that the secondary production was low in comparison with productive (upwelling dominated) marine environments but were comparable to estimates off Australia's North West Cape (Haine 2005). The seasonal cycle of zooplankton reflected the primary production, with the zooplankton biomass higher in late autumn and winter. The zooplankton assemblages also exhibited differences between nearshore and shelf or offshore waters as well as exhibiting differences with season (Haine 2005).

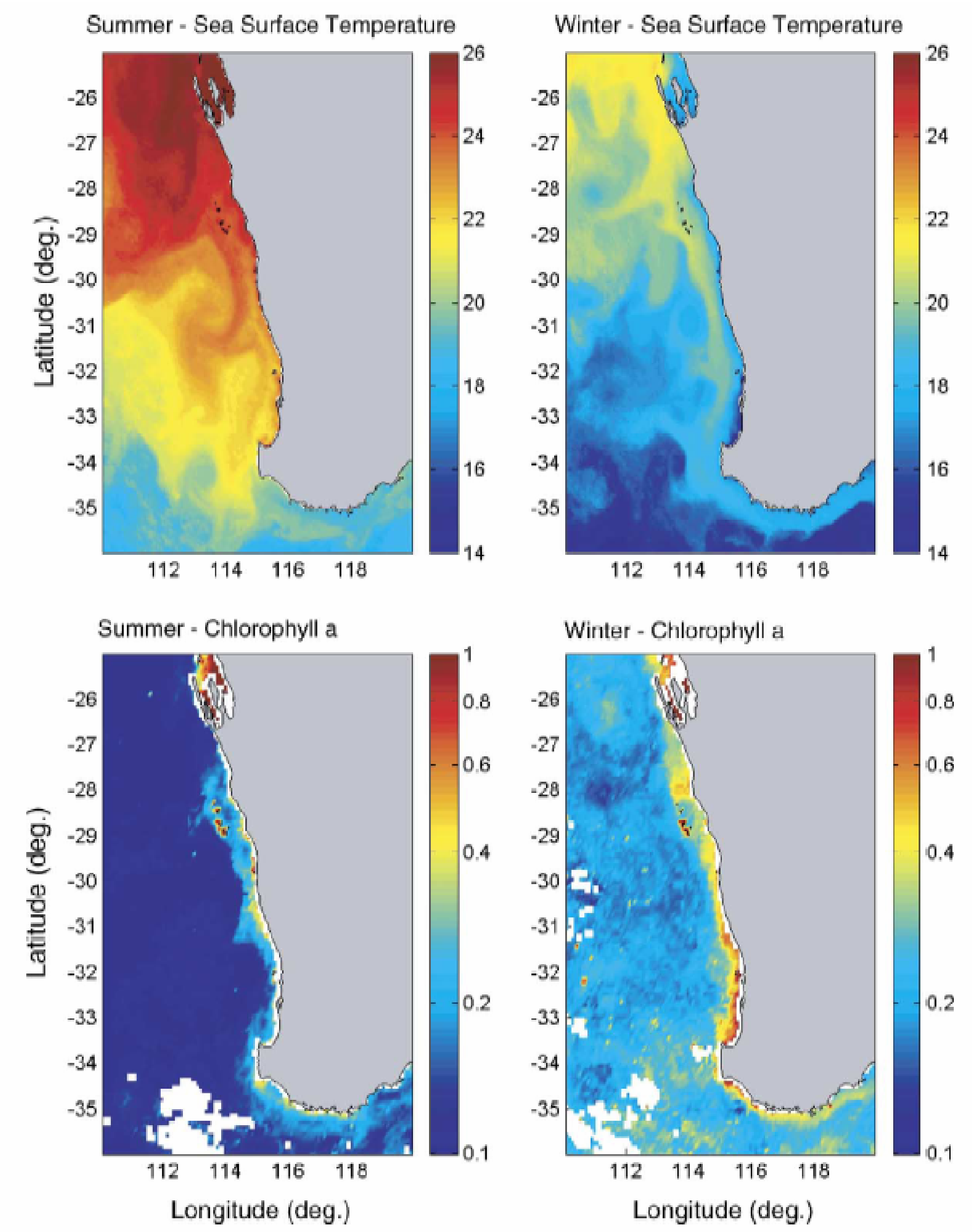


Figure 3.4.2.1: Summer (early February) and winter (mid August) synoptic plots of satellite sea surface temperature (Celsius) and SeaWIFS chlorophyll a concentration (mg m^{-3}) from Lourey et al. (2006).

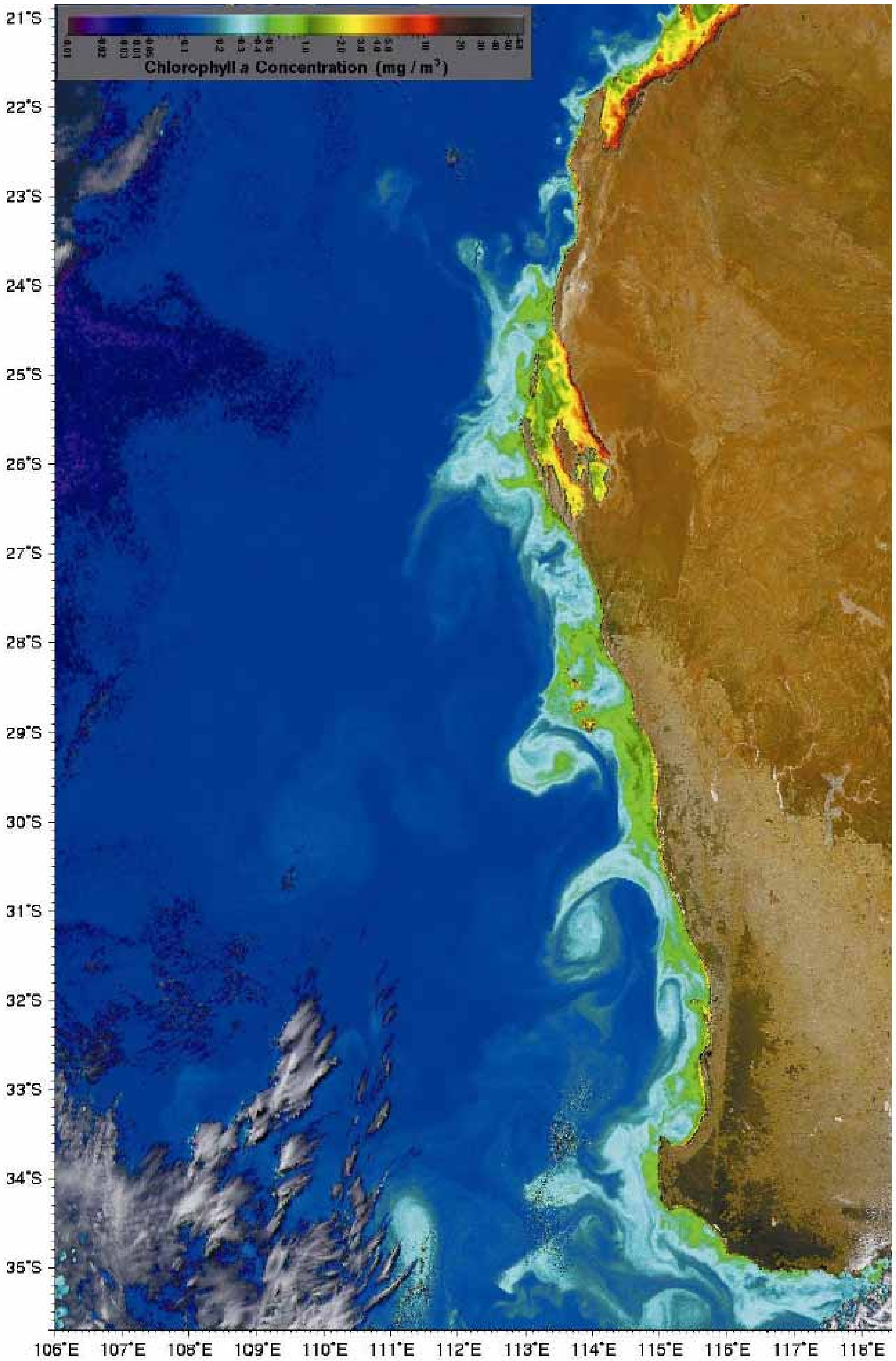


Figure 3.4.2.2 SeaWiFS image from 5 April 2002, illustrating relatively higher chlorophyll a concentrations on the continental shelf and lower concentrations in Leeuwin Current and offshore waters. The two large eddies between 29° S and 32° S show the entrainment of shelf waters into the Leeuwin Current.

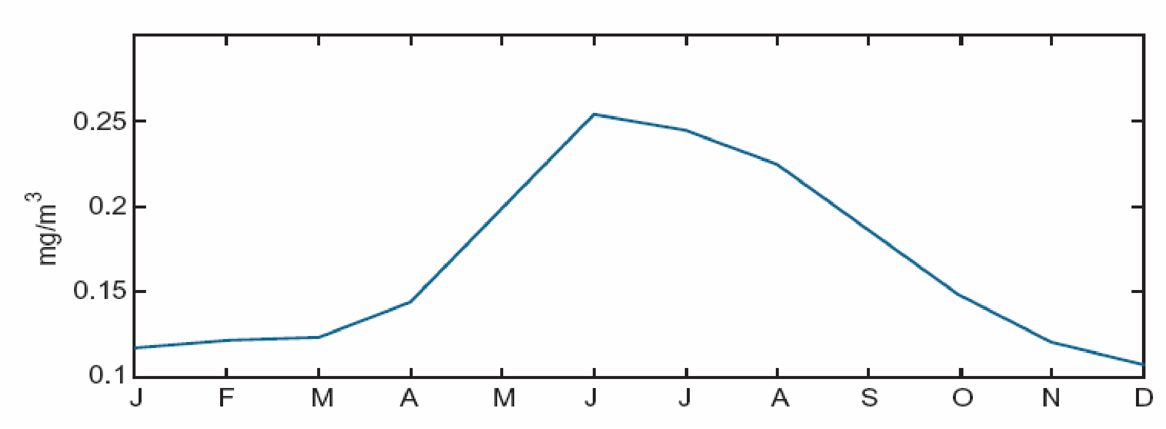


Figure 3.4.2.3 The climatological mean for surface chlorophyll a concentrations off the Western Australian coast (from Feng et al. 2005).

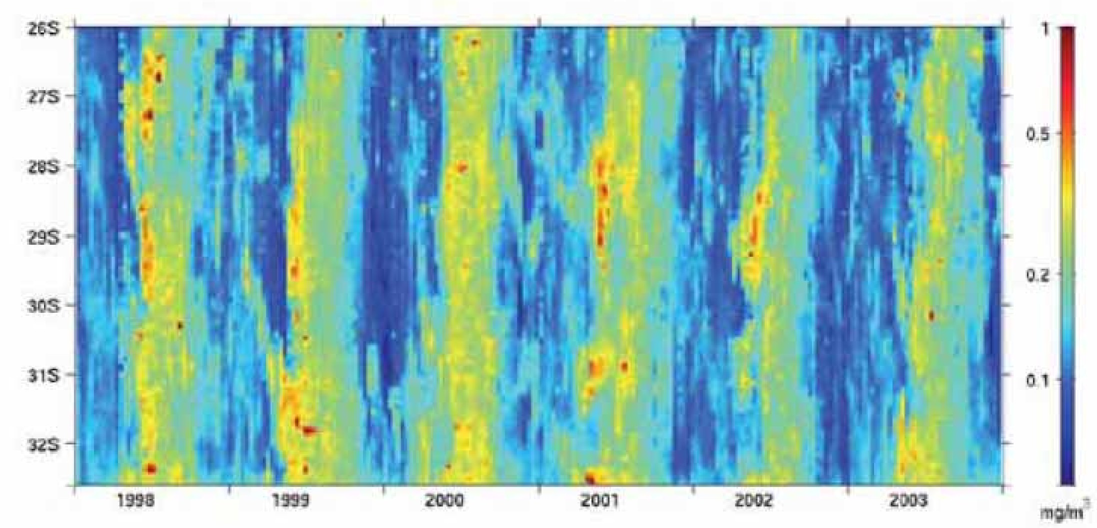


Figure 3.4.2.4 The chlorophyll a distribution estimated using SeaWiFS ocean colour data along the shelfbreak off the west coast of Western Australia from 26° S to 32° S over the period 1998–2003. A late autumn or early winter bloom extends along the coast, with relatively high chlorophyll a levels maintained through much of the winter (from Feng et al. 2005).

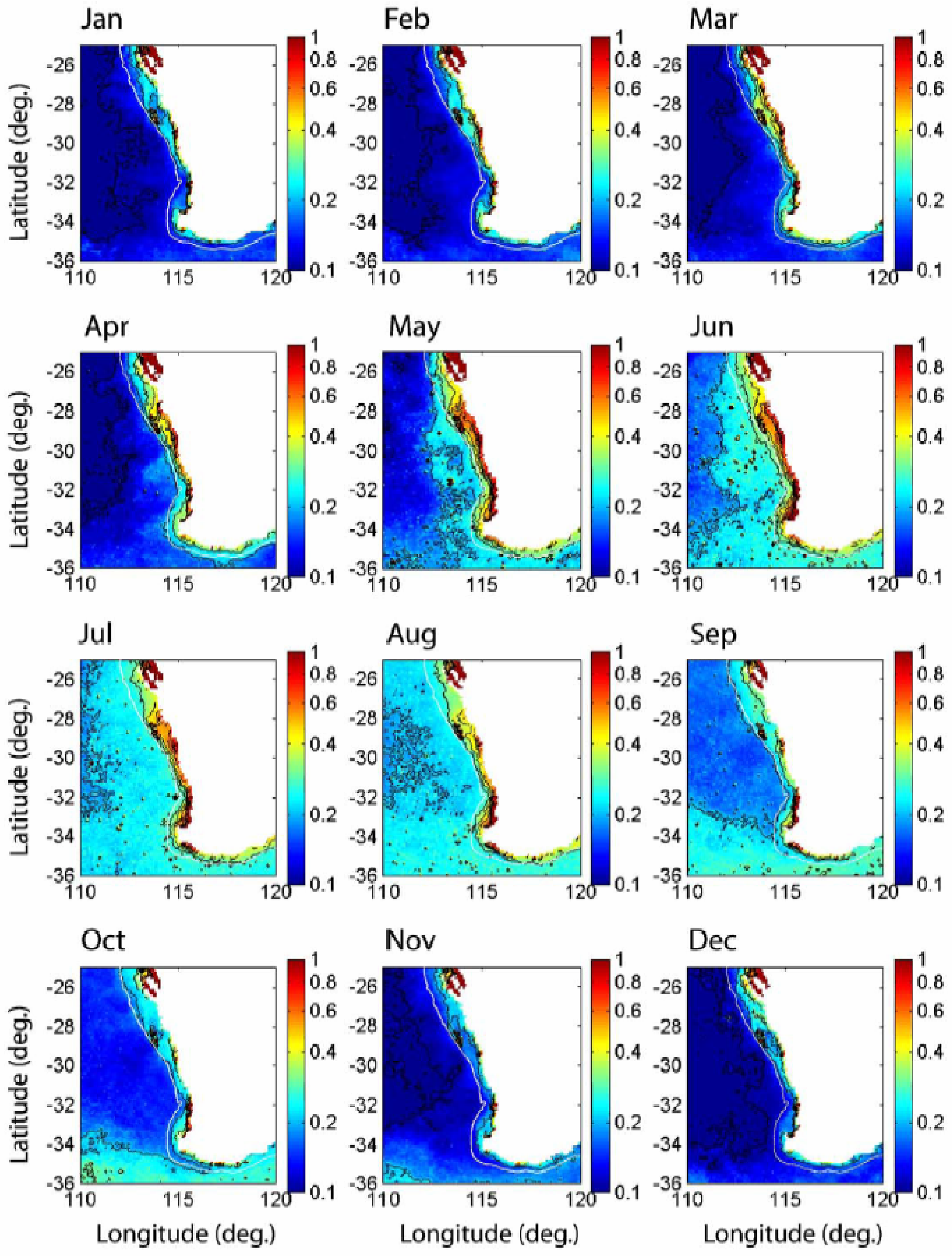


Figure 3.4.6 Monthly mean distribution of surface chlorophyll a (mg m^{-3}) derived from SeaWIFS data (September 1997 – August 2004). The white line marks the shelf break (from Lourey et al. 2006).

3.5 Links to ocean circulation processes

Principal contributors

Sam McClatchie
John Middleton
Gary A Kendrick

Connectivity

The seasonal progression of phytoplankton production derived from remote sensing indicates that there is zonal and meridional connectivity in the South-west Marine Region. The striking seasonal north–south wave of primary production may be associated with changing Sverdrup transport and seasonal stratification, but may not reflect a connection in the sense of mixing of biological communities between the Subtropical Convergence and the shelf waters. The eastward progression of seasonal phytoplankton production in the Great Australian Bight parallels the path of the Leeuwin Current but is unlikely to be driven by the low nutrient water and is more likely to reflect a breakdown of summer stratification in the warm pool water mass, with associated release of nutrients into the mixed layer. However, the Leeuwin Current water will transport biological communities (e.g. phytoplankton and zooplankton) from west to east in the Great Australian Bight (and may aid movement of Australian salmon as discussed below).

Within these broad north–south and east–west seasonal patterns, there is evidence for connectivity between the shelf and offshore waters off Esperance, where offshore advection may affect the food web and have implications for fisheries recruitment (discussed below). In the eastern Great Australian Bight there is another known connection between 200–300 m deep waters west of Kangaroo Island and the nearshore waters of the Eyre Peninsula, due to the path of Ekman-driven upwelling (McClatchie et al. 2006). In what follows, a range of different oceanographic processes are addressed in terms of how they affect ecological structure and function.

The main oceanographic features of the region between Shark Bay and Esperance are:

- The West Australian Current
- The Leeuwin Current
- The Leeuwin Undercurrent
- The Flinders Current
- Continental shelf current systems: the Ningaloo, Capes and Cresswell currents.

Ecological integration: Links to ocean circulation processes

The west coast of Western Australia was demonstrated by Roberts et al. (2002) to be one of the world's diversity hotspots with high endemism in corals, fish, gastropods and lobsters. The geological long-term stable gradient in ocean climate along the west coast was inferred as being a major driver for both high species richness and high endemism in this region. The predominant pattern of species distributions on the west coast of Australia is a gradient of mixing of tropical and temperate marine fauna and flora, with assemblages dominated by tropical species to the north and temperate species in the south. This pattern is best demonstrated in the corals. There is a decline in species richness of corals in offshore islands from 184 species in the Houtmans Abrolhos, to 23 species 400 km south at Rottnest Island, to five species in the Recherche Archipelago off Esperance. Onshore, there are fewer species over this latitudinal gradient, with 35 species recorded off Kalbarri, 10–15 species on the central west coast, and eight species in Albany (see Part 2, Section 4.4: Corals for greater detail).

Greater mixing and northward movement of waters are related to onshelf counter currents, and the reduced influence of the Leeuwin Current onshelf and nearer to the Western Australian coast. Similarly, macroalgae demonstrate a cline along the west and south coasts of Western Australia. Macroalgal assemblages near Perth, Western Australia are similar to those found near Cape Leeuwin, but the south coast flora recorded from Bremer Bay and the Recherché Archipelago indicate that the dominant canopy of *Ecklonia radiata* and warm-temperate *Sargassum* species are replaced by mixed species canopies of *Ecklonia*, *Cystophora*, *Scytothalia* and cold-temperate *Sargassum* species (Wernberg et al. 2003, Goldberg & Kendrick 2005). This shift is gradual, inferring strong connectivity between warm-temperate west coast and cold-temperate south coast floras.

Influence of the Leeuwin Current

The Leeuwin Current is a shallow (<300 m), narrow band (<100 km wide) of warm, lower salinity, nutrient depleted water of tropical origin that flows poleward from Exmouth to Cape Leeuwin and into the Great Australian Bight (Church et al. 1989; Smith et al. 1991; Ridgway & Condie 2004) and to the North-west Cape of Tasmania. It is the longest boundary current in the World (Ridgway & Condie 2004). The Leeuwin Current has greatest influence on the upper continental slope, and suppresses upwelling on the coast as it is driven in the opposite direction to the equatorial wind stress by an alongshore pressure gradient. The Leeuwin Current is low in nutrients and has a low chlorophyll a signature from satellite remote sensing. Primary and associated secondary production is much greater at the interface between the Leeuwin Current and deeper Undercurrent at approximately 150–200 m depths. Pelagic production appears decoupled from surface primary production measured as chlorophyll a.

The Leeuwin Current also has a major effect on recruitment of the biota of the south-western Australian shelf (Morgan & Wells 1991; Caputi et al. 1996). Strong Leeuwin years correlated to high puerulus settlement for western rock lobster (*Panulirus cygnus*). The Leeuwin Current has a significant negative effect on recruitment of saucer scallops in Shark Bay. The pilchard (*Sardinops sagax neopilchardus*) recruitment is negatively correlated to the strength of Leeuwin flow two years earlier. There is a positive relationship between the strength of the Leeuwin Current and recruitment of the Australian salmon (*Arripis truttaceus*) in South Australia. Intertidal platforms at the western end of Rottnest Island support a number of tropical taxa, the larvae of which are carried southwards on the Leeuwin Current. The Leeuwin Current and its influence on the coastal climate and marine life were the subject of a published symposium (Pearce & Walker 1991).

The Leeuwin Current is predominantly found over the continental slope across Region, but it does meander and has been shown to flood the continental shelf near the Jurien area on the west coast of Western Australia (CSIRO SRFME) and from Albany to Bremer Bay. These meanders influence the recruitment of western rock lobster in the Jurien Bay region and recruitment of tropical taxa in the Bremer Bay area.

The Leeuwin Current is stronger during winter and weaker during the summer months due mainly to changes in the wind stress (Figure 2.1.7; Section 2.1). Coastal counter currents like the Capes Current are stronger during summer months, and their influence on production is predominantly a summer phenomenon.

There is a strong correlation between ENSO events and weakening of the Leeuwin Current. This has demonstrable effects on puerulus settlement of the western rock lobster: higher settlement is recorded when the Leeuwin Current is strongest (Pearce & Phillips 1988). During normal years, the coastal annual mean sea levels are relatively high, indicating that the Leeuwin Current is strong and the settlement of pueruli in coastal reefs is relatively high. During ENSO years, coastal sea levels fall and transport in the Leeuwin Current is weaker (Feng et al. 2003).

Onshelf counter currents

Upwellings associated with onshelf counter currents are restricted to weak onshelf upwelling associated with the Capes Current near Cape Leeuwin, the Ningaloo Current and are also associated with the Abrolhos Islands. Waters associated with these upwelling events affect phytoplankton productivity and composition by shifts from dominant communities of micro- and nano-plankton to more productive communities of larger diatoms in areas of upwelling.

Hansen et al. (2005) studied the seasonal influence of the Capes Current on primary production in south-western Australia and found that although the Capes Current resulted in higher nutrients and higher nearshore primary production in summer between Cape Leeuwin and Cape Naturaliste, during winter the nutrient levels associated with the Leeuwin Current were also higher than expected; Hansen et al. (2005) invoked entrainment of nutrient-rich shelf waters at the base of the Leeuwin Current as an explanation. The interactions between the Leeuwin Current and onshelf counter currents is an area that requires further investigation.

Deep westward conveyor belt

The Flinders Current is a deep (~600 m) flowing current moving from east to west. It is too deep to influence epipelagic communities in summer but in winter, wind-forced downwelling may entrain epipelagic organisms into the deep Flinders Current. Whether these organisms can survive at depth long enough to undergo significant westward transport by the Flinders Current is unknown. The connection provided by the Flinders Current may be one reason why the slope demersal fish communities are relatively homogeneous in terms of species composition all along the southern Australian continental shelf margin (Last et al. 2005). A similar homogeneity of mesopelagic communities might be expected as a result of this flow pattern but there are no data to confirm this.

Upwelling system

The narrow south-east shelf to the east of the South-west Marine Region underlies a large summertime upwelling plume (called the Bonney Upwelling) that extends to the north-west as a series of discrete upwelling centres off western Kangaroo Island (Kitani 1977) and along the Eyre Peninsula (Anonymous 2001; Kampf et al. 2004) (see Figure 3.5.1). The eastern boundary of the South-west Marine Region is artificial in the sense that it transects the upwelling system that underpins the productivity of the eastern part of the South-west Marine Region. For that reason, this report includes some discussion of the broader upwelling system here.

Early work on upwelling off South Australia focused on the narrow shelf area off Robe, south-east of the two gulfs, where upwelling of sub-Antarctic water (following terminology of Newell (1974)) comes to the surface in the summer months, forming the Bonney Upwelling (Rochford 1977; Lewis 1981; Bye 1983; Provis & Lennon 1981). Rochford (1977) measured moderate nitrate enrichment in surface waters off Port MacDonnell and speculated that Ekman flux driven by south-east winds (upwelling-favourable in the southern hemisphere) contributed to upwelling in the area. Using a more extensive set of cross-shelf transects, and five years of monthly samples of temperature, salinity, nitrate and silicate at Port MacDonnell, Lewis (1981) measured nitrate concentrations six times higher in the lower layer of sub-Antarctic water compared to the upper layer of sub-tropical water in summer. He described three summer upwelling centres where sub-Antarctic water reaches the surface in the Bonney Upwelling (south-east of Port MacDonnell, south of Southend, and south of Robe). Lewis (1981) made a qualitative link between upwelling intensity and the occurrence of south-east winds, and speculated that the canyons at the shelf edge might play a role in focusing the upwelling.

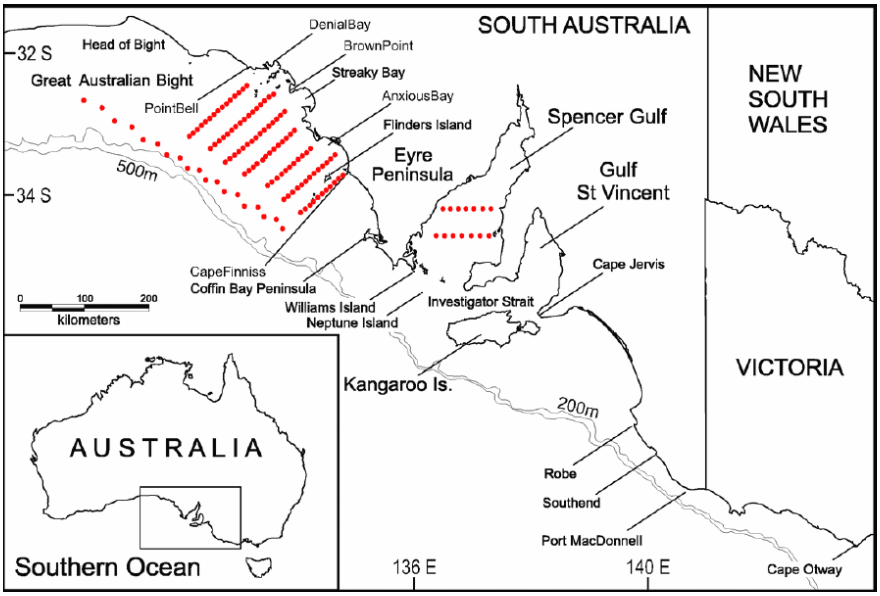


Figure 3.5.1 Map of the eastern Great Australian Bight showing locations mentioned in the text.

Schahinger (1997) used time-series measurements of wind stress, currents from three current meters, and bottom temperatures combined with CTD sections to examine the dynamics of the Bonney Upwelling. He calculated the internal Rossby radius to give the subsurface scale of thermocline uplift, discussed the strengthening effect of the daily sea breeze, and examined the timing and duration of two upwelling events. He related cross-shelf gradients in density to vertical differences in alongshore velocity using the thermal wind equation, and estimated the thickness of the surface Ekman layer and mixed layer which was used to compare the calculated mean flows with the measured flows. Schahinger (1997) speculated that the spatial scale of the upwelling was on the order of 20 km, and agreed with Lewis (1981) that the upwelling centres were localised while the spatial effect of the upwelling was broadened by advection.

Later modelling work (Wenju et al. 1990) simulated the onset of upwelling along the Bonney Coast and tested the effects of wind direction, bottom topography and interfacial stress. Wenju's three layer and two layer models were able to simulate wind-driven upwelling, and predicted uplift of interfaces beginning a day after the onset of favourable winds. The effect of bottom topography rather than coastal curvature was shown to be significant, and the most favourable areas for upwelling were in an approximately 20–30 km wide band adjacent to the coast between Portland and Cape Jaffa, near Robe (see Figure 3.5.1), as well as on the western edge of Kangaroo Island (Wenju et al. 1990). The model also predicted a westward-flowing jet of up to 70 cm s^{-1} adjacent to the coast. Another researcher (Anonymous 2001) made extensive use of remote sensing imagery of the south-east region, clearly showing the Bonney Upwelling, as well as upwelling off western Kangaroo Island and Coffin Bay Peninsula (see Figure 3.5.1) between December and March. The eastern Great Australian Bight along the western coast of the Eyre Peninsula (Figure 3.5.1) is also an upwelling region (Middleton & Platov 2003; Middleton & Cirano 2002; Baird 2003; Kampf et al. 2004) and it is assumed that the upwelling-driven enhancement of primary and secondary production supports the large pelagic fish resource.

Exactly how the enrichment occurs, its spatial and temporal scales and its variability are poorly understood, although the seasonal shelf circulation has been modelled (Middleton & Platov 2003; Middleton & Cirano 2002). Recent work showed that there are on average two to three wind-driven upwelling events during the austral summer (Kampf et al. 2004). These events are associated with south-easterly winds that prevail between December and April (Bye 1983). The coastal upwelling was shown to produce surface phytoplankton patches within a week of the upwelling event (Kampf et al. 2004), that may sink and form the observed subsurface chlorophyll a maxima (Kampf et al. 2004).

Two-dimensional modelling studies predict that upwelling in the eastern Great Australian Bight is strongly influenced by bathymetry (Baird 2003). Where the shelf is narrow and bathymetry is steep, modelling suggests that upwelling occurs within 10 km of the coast, raising cool water and nutrients to the surface where phytoplankton concentrations then develop. Zooplankton patches lag the development of phytoplankton concentrations and generally occur downstream (Baird, 2003). In contrast, where the shelf is broad and relatively shallow out to 200 km offshore, modelling predicts that upwelling of cooler water will occur more slowly and be located at the shelf break rather than inshore. Here the model suggests that nutrients are utilised by phytoplankton before reaching the surface, a subsurface phytoplankton peak develops, and the phytoplankton and zooplankton patches are spatially and temporally co-located (Baird 2003).

For the mid to western end of the Great Australian Bight, the study of Middleton and Platov (2003) indicates that downwelling and not upwelling should occur along the shelfbreak. The downwelling results from convergence of deep ocean and shelf slope Sverdrup transports that are both driven by the generally positive wind stress curl. In the region separating the Bonney Coast upwelling and the western Eyre Peninsula upwellings, Hahn (1986) conducted an extensive seasonal study at the mouth of the Spencer Gulf by repeating CTD transects in the axis, and across the mouth, of the Spencer Gulf combined with a moored current meter and thermistor array on the shelf. His work showed the development of strong stratification on the shelf in summer, outflow of high salinity water from the Spencer Gulf in the autumn, and well mixed water on the shelf and in the mouth of the Spencer Gulf in the winter. The inverse estuary characteristics of the Spencer Gulf and the high salinity autumn outflow into shelf waters were described by Lennon et al. (1987) and Nunes Vaz et al. (1990). The interface between Spencer Gulf and shelf water creates a front in summer (Hahn 1986), where larval fish have been shown to aggregate (Bruce & Short 1990), possibly as a result of convergent flows, although convergence was not demonstrated.

Both numerical model results (Middleton & Platov 2003) and the CARS climatology of bottom temperature (December–January) provide strong evidence that shelf break upwelling is confined to the Kangaroo Island region and does not occur further to the west off the Eyre Peninsula. Rather, the upwelled water is likely to remain in the Kangaroo Island "pool" until subsequent upwelling events draw the water to the shallower and surface coastal regions of the eastern Great Australian Bight. In this manner, the surface upwelling apparent off the Bonney Coast, Kangaroo Island and the eastern Great Australian Bight can appear to be simultaneous. Moreover, it appears likely that the water within the Kangaroo Island pool remains nutrient rich.

Support for this model comes from the CTD sections collected during March 2004 for the eastern Great Australian Bight. In particular, the data show that the upwelled signal (cool <17 °C, fresher <35.6 ppt, dense σT >26 kg m^{-3}) diminishes in width and intensity with increasing distance from Kangaroo Island. The pattern of fluorescence is similar to that for temperature and indicates that the Kangaroo Island pool remains nutrient rich.

The warmest water is found near the shelf break along with very low values of fluorescence and relatively higher levels of oxygen, suggesting nutrient-limited growth of phytoplankton. These data support the notion that the upwelled nutrient-rich water is supplied from the Kangaroo Island pool and not by shelf break upwelling in the eastern Great Australian Bight. The coldest water lies nearest the Kangaroo Island pool and has high values of fluorescence and low values of oxygen. The data also indicates anomalously fresh water due to groundwater discharge (aquifiers) at depths of 40 m or more. In addition, the coastal bays are sources of anomalously salty water – a likely result of evaporation. The eastern Great Australian Bight upwelling signal near the coast is also most evident as two distinct patches of cool water centred on Brown Point (separating Streaky Bay and Denial Bay), and the southern side of Cape Finnis and Flinders Island. Upwelling around headlands and bays is known to occur elsewhere due to local wind effects (e.g. Roughan et al. 2005) as well as advection by headland eddies (e.g. Leth & Middleton 2004; Oey 1996; Penven et al. 2000). Unfortunately, without further ocean current data, we cannot determine the mechanisms for the localised upwelling

Headlands

The area around Flinders Island (34° 45' S 134° 30' E) shows evidence of localised enrichment of phytoplankton in remote sensing imagery, with strong indications that a filament may be generated along a ledge and the inner edge of the island (Figure 3.5.2), forming a cyclonic eddy in Anxious Bay (McClatchie et al. 2006). This feature may be associated with the local bathymetry; in particular, the shallow ridge that extends normally to the shore and the enriched phytoplankton may indicate an upwelling centre (i.e. an intensified coastal upwelling with comparable along-shore and cross-shore spatial scales (Brink 1983)). Roughan et al. (in press) described a small-scale, isolated upwelling associated with a headland in the lee of Point Loma, California. This upwelling was not associated with wind stress (currently thought to be the primary driver of upwelling on the western Eyre Peninsula), but was driven by divergence of the prevailing flow as it passes the headland (Roughan et al. in press). A similar phenomenon may be occurring at Flinders Island. The enriched phytoplankton produced in the area by the proposed upwelling mechanism may attract concentrations of zooplankton and micronekton that in turn could be eaten by pelagic fish. Pelagic fish (sardines, mackerels) are known to aggregate on the northern side of the island, but little is known about the temporal variability in their distribution.

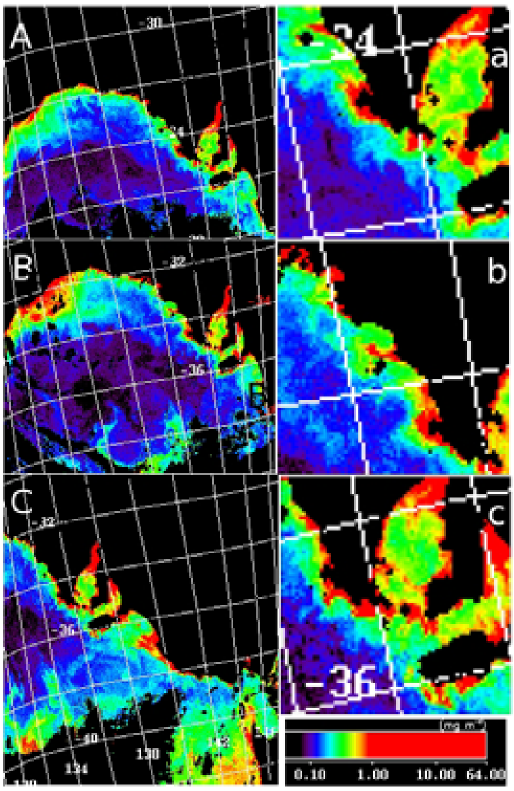


Figure 3.5.2 SeaWIFS imagery of the eastern Great Australian Bight (left panel) in March 2004 with enlargements of the western Eyre Peninsula (right panel). Chlorophyll concentrations should be regarded as relative near shore (in Case 2 waters where the scattering may be from material other than chlorophyll). A: a = 2 March 2004; B: b = 19 March 2004; C: c = 28 March 2004.

The South Australian gulfs

Deep salinity outflow from Spencer Gulf

For most of the year, there is relatively little circulation between the shelf and the warm and salty Spencer Gulf waters (see Chapter 2 of this report). A temperature front is present in the mouth of the Spencer Gulf and is known to be an area rich in ichthyoplankton (Bruce & Short 1990). Although the frontal dynamics of this area have not been studied in detail, it is likely that the strong daily sea breezes in the area will produce coupled bands of upwelling (where the sea breeze is strong) and downwelling (where the sea breeze dies out further offshore)(see physical review). The recirculation cell produced by sea breeze forcing may retain plankton in the frontal zone, and explain why Bruce and Short (1990) found concentrations of fish larvae in the area. The link between physical dynamics and the biota has not yet been verified by observations.

Although the Spencer Gulf is largely isolated from the shelf, there is a mass flux of salt from the Spencer Gulf onto the shelf in the autumn (Lennon et al. 1987; Nunes Vaz et al. 1990). This efflux of warm, salty water must transport plankton and particulate organic matter from the gulf into the continental shelf waters. In addition, such a large flux of denser water may have an effect on mixing at the mouth of the Spencer Gulf, and such mixing may affect local productivity. The effect on productivity may be to enhance nutrients and increase primary production, but it may also remove some phytoplankton production from well-lit surface waters, thereby reducing primary production.

Links between the gulfs, coastal embayments and the shelf

Prawns

There is little published information on the recruitment and movement of juvenile prawns in the Spencer Gulf, Gulf of St Vincent and west coast (Eyre Peninsula) fisheries (see Carrick & Ostendorf 1999; Carrick & Williams 2000; Svane 2003; Svane & Johnson 2003). At present juvenile prawns in these three fisheries are thought to be separate stocks, with limited exchange of adults between them (Cameron Dixon, pers. comm.). The size structure of prawns in the mouth of the Spencer Gulf suggests that any movement between the gulfs and the shelf would be by adult rather than juvenile prawns. Any exchange would be limited to the region near Kangaroo Island, but is difficult to verify because population structure data come from commercial catches that do not extend below ~60 m (Cameron Dixon, pers. comm.).

The Spencer Gulf stock does not rely upon coastal embayments for recruitment, but rather serves as a single, large hyper-saline body of water. Larvae of western king prawns (*Melicertus latisulcatus*) are concentrated in the northern part of the Spencer Gulf (north of 34° S) (Carrick & Ostendorf, 1999). The distribution of western king prawn juveniles indicates that the shallow, inshore nursery areas are north of Cowell in the west and Wardang Island in the east of Spencer Gulf (summarised in Carrick & Ostendorf 1999). These boundaries correspond with the part of the Spencer Gulf that is shallower than 17 m (except for the central channel which extends to 25 m deep). Juveniles were denser on the western side compared to the eastern side of the gulf. The prawns from these nursery areas recruit to the whole of the Spencer Gulf (see map of principal trawl grounds in Carrick & Ostendorf 1999).

The west coast prawn fishery relies upon the hypersaline lagoons, such as Venus Bay, for recruitment, with the estuary in Venus Bay being the main source for larvae (Carrick & Ostendorf 1999). Although there are no tagging data to verify movements, based on what is known of prawn ecology, it is likely that juvenile prawns move out from the west coast lagoons (that may include Baird Bay and the inlets off Ceduna) and mangrove areas onto the shelf as they increase in size and become less tolerant of salinity changes.

Marine scalefish

There is relatively little exchange of fish between the South Australian gulfs and the shelf waters, although there is a seasonal migration of yellow-tailed Kingfish (*Seriola lalandii*) from the islands at the mouth of the Spencer Gulf into the upper reaches of the gulf (McGlennon 1997; Fowler et al. 2003). These are large fish (>10 kg), in contrast to escaped 1.5–3.5 kg Kingfish from the farms now established in the gulf. Spencer Gulf has not previously been exposed to smaller Kingfish and there is currently a lack of understanding about the influence of escaped cultured Kingfish on the Spencer Gulf ecosystem (Fowler et al. 2003). Small escaped Kingfish may prey on fish, squid and crustaceans (Fowler et al. 2003), including King George whiting, garfish, western king prawns and trevally (McGlennon 1997).

The multi-species fisheries in Spencer Gulf and Gulf of St Vincent (collectively termed marine scalefish) largely exist in isolation within the gulfs. The key species in the marine scalefish fishery are snapper (*Pagrus auratus*), King George whiting (*Sillaginodes punctata*), garfish (*Hyporhamphus melanochir*), and squid (*Sepioteuthis australis*).

Snapper

It was originally thought that snapper moved between the Spencer Gulf and the shelf waters on an annual basis (McGlennon & Jones 1997). Snapper spawn in the shallow upper reaches of the Spencer Gulf, and McGlennon and Jones (1997) suggested that a proportion of recruits were resident in these waters throughout the year. They suggested that as snapper age, a greater proportion of them move out into the shelf waters and return annually to the gulf waters to spawn. McGlennon and Jones (1997) proposed that fish older than nine years tend more often to remain in the Spencer Gulf rather than pursue an annual movement onto the shelf.

Pre-recruit snapper (year 0+) are found in the upper reaches of the Spencer Gulf (north of ~33° 30' S) in association with muddy sediments and an essentially featureless bottom terrain (Fowler & Jennings 2003). An analysis of the age-related elemental composition of snapper otoliths collected thr0oughout state waters showed that composition was similar in the first three years of life, although with some indication of separation between the northern Spencer Gulf and the northern Gulf of St Vincent. This indicates that all of the snapper come from a single stock, or at most from two stocks in the two gulfs (Fowler et al. 2005). For older fish, the elemental composition diverges with age for snapper of 3–5 years old. After age 5+, the divergence in elemental composition of the otoliths ceased. This indicates that snapper dispersed and then became resident in different parts of South Australian coastal waters (Fowler et al. 2005). The otolith chemistry data show that there is no support for seasonal migration into and out of the Spencer Gulf, but despite the lack of evidence from this method, some seasonal exchange of snapper between gulf and shelf waters cannot be discounted (AJ Fowler, pers. comm.). Otolith chemistry data also show that there is most likely a single stock of fish that disperses throughout the gulf and shelf waters (as deep as 200 m) with age (Fowler et al. 2005).

King George whiting

The recruitment dynamics, relationships to ocean circulation and spatial scale of the stocks of King George whiting (*Sillaginodes punctata*) are quite different in the South-west Marine Region off South Australia compared to the South-east Marine Region off Victoria. Off Victoria the population of King George whiting is a single stock and recruitment is driven by larval advection from the west. The larvae are transported several hundred kilometres by strong currents over the continental shelf during the winter and spring from a single region to the west (Jenkins et al. 2000). In South Australian waters, the King George whiting spawn on offshore reefs from where the larvae are transported up the gulfs and finally settle out in inshore shallow bays (Fowler et al. 1999). The bays may be vegetated with seagrass or have a bare, sandy bottom (Fowler & Short 1996). The juveniles tend to move into deeper parts of the bays and eventually into open water as they grow (Jones et al. 1996).

The more complex size structure of the populations in the southern parts of the Gulf of St Vincent and Spencer Gulf compared to the northern parts of these gulfs indicates movement of fish down the gulfs with age (Fowler et al. 2000). In contrast with Victoria, the movement of larvae in South Australia is more restricted. There is minimal exchange of larvae between discrete populations, and movement is restricted to less than 100–200 km (Fowler et al. 2000). There appears to be no evidence for exchange between discrete stocks in the Spencer Gulf and the Gulf of St Vincent. What transport there is appears to be driven by relatively weak coastal currents, and the front at the mouth of the Spencer Gulf is thought to act as a barrier to movement (Fowler et al. 2000). The scale of these discrete stocks is smaller than the unit stock in Victoria.

Eddies

Mesoscale eddies and their influence on production

The Leeuwin Current is associated with mesoscale eddies and meanders (Pearce & Griffiths 1991; Fang & Morrow 2003; Morrow et al. 2003; Feng et al. 2005; Fieux et al. 2005). Eddies form at the shelfbreak and eventually separate from the current and drift westward. These eddies are apparent in sea surface temperature satellite imagery (Griffin et al. 2001) and in altimeter data (Fang & Morrow 2003) (Figure 2.1.5, Section 2.1). Eddies are associated with changes in the bathymetry and offshore water of different densities and their generation and offshore transport occur off Shark Bay, the Abrolhos Islands, Jurien Bay, Rottnest Island and Cape Leeuwin.

Eddies west of Rottnest were recently studied as part of a Southern Surveyor Cruise and the Western Australian Government – CSIRO SFRME joint venture. Results of the cruise will be published as a single issue of *Deep Sea Research* in 2006. Studies of the cruise's results have found that while there was no demonstrable nutrient upwelling between interacting cyclonic (anticlockwise rotating) eddies and anti-cyclonic (clockwise rotating) eddies these eddy systems may drive offshore pelagic production but do so in unexpected ways; further research is required.

Cresswell and Griffin (2004) describe the propagation of westward-moving anti-cyclonic eddies south of the Leeuwin Current on the south coast of Western Australia. Weak eddies drift westward from south of Victoria and first encounter the continental slope near the Recherche Archipelago where they take on warm water from the Leeuwin Current and strengthen, moving westward for up to 18 months. They also described effects on the Leeuwin Current of encounters with cyclonic and anti-cyclonic eddies, the former accelerating flow and the latter decelerating Leeuwin Current flow and diverting it out to sea. The effects of these structures on pelagic production may be profound but as yet these effects have not been studied in detail.

Significant anti-cyclonic eddies are visible in remote sensing data of sea surface height along the south coast of Australia (Anonymous 2001). These eddies initially propagate eastward, partially influenced by the Leeuwin Current, and then move away from the shelf to the west (see Chapter 2 of this report). Eddies are known to have a significant effect on shelf plankton communities including larval fish (Govoni 2005), when shelf water becomes entrained in an eddy (Richards et al. 1989; Nishimoto & Washburn 2002). The development of an entrained community depends upon whether eddies are upwelling (cold core) or downwelling (warm core). Generally warm-core eddies lead to reduced production within the eddy (Brandt, 1981) and decay of the plankton community over time, in contrast to cold-core eddies where an enriched community may flourish until nutrients are depleted (McGillicuddy & Robinson 1997). In both cases the eddy community tends to be distinct from the surrounding water, and shows considerable horizontal structure in terms of species composition, both across the eddy filaments and with depth (Muhling et al. submitted). The enclosed communities tend to be successional in nature, as previously mentioned.

In the eastern Great Australian Bight, eddies induce upwelling and so nutrient enrichment is predicted, with possible subsequent phytoplankton growth. If such eddies stay on the shelf and retain larval fish, enhanced recruitment may result (Dickey-Collas et al. 1996; Kimura et al. 2000; Nakata et al. 2000; Logerwell et al. 2001). Where eddies entrain larval fish off the shelf (Fang and Morrow 2003; Morrow et al. 2003), they may advect them away either from suitable feeding areas or from suitable settlement areas (Heath 1992), which can negatively affect recruitment. Fish eggs and larvae may also be exposed to enhanced predation within the eddy community. In the cold-core eddies, located off the shelf, that are described here, the feeding environment for larval fish in the eddy may be adequate due to the expected enriched production. Transport of plankton into other water masses by an eddy can also result in the death of larval fish due to temperature stress (Colton, 1959). That eddies can have a significant effect on fish recruitment was demonstrated by Myers and Drinkwater (1989) who showed that recruitment in 15 of 17 groundfish stocks was negatively influenced by greater numbers of Gulf Stream rings near the continental shelf of North America. In the South Australian case, the effect of advection by eddies may be mainly due to transport of larvae away from suitable settlement areas on the shelf. It is predicted that the impact of the off-shelf eddies would be more severe for demersal and semi-demersal fish than for pelagic species in this case, but there are no studies in the eastern Great Australian Bight that substantiate this speculation. The topic is the subject of active research in the western part of the South-west Marine Region (Muhling, unpublished manuscript).

Topographic influences

Canyons and seamounts

The south-western continental margin of Australia is transitional (Morgan & Wells 1991) between the cool water carbonate shelf of southern Australia and the warm water North-west Shelf. Submarine canyons are distinctive features of the continental slope with the Rottnest Canyon on the west coast, and the Bremer Canyon on the south coast being the most distinctive. The canyons influence movement of both the Leeuwin Current and the Leeuwin Undercurrent.

The Rottnest Canyon has been the focus of study as part of the Western Australian Government – CSIRO SRFME joint partnership. Rottnest Canyon influences the volume of water moving southward in the Leeuwin Current and the number and scale of eddy formations and propagations west of Rottnest Island. In strong Leeuwin flow years, more eddies are propagated than in low-flow years. The canyons on the south coast of Western Australia have been studied less, although similar effects on surface and midwater circulation and currents would be expected.

The edge of the continental shelf south of Kangaroo Island is incised by spectacular canyon complexes. The processes that affect upwelling within canyons are known to include tidal mixing and rectification as well as large-scale along-slope currents (Huthnance 1995; Hickey 1995). In the context of large-scale along-slope currents, Klink (1996) showed that the shoreward pressure gradient that is normally balanced by geostrophy is ruptured over a “narrow” canyon and can drive fluid, sediments and nutrients up-slope ("narrow" in this context means relative to the internal deformation radius, about 30–50 km for the Bonney Coast – Kangaroo Island region). For this region, there are two sources of westward current needed for upwelling. The first source is the Flinders Current (Middleton & Cirano, 2001) that flows from east to west at depths of 400–800 m with speeds 5–10 cm/s and is driven by the onshore Sverdrup transport from the Southern Ocean. The Flinders Current appears to be strongest during summer, although it appears that it can be non-existent or reversed by currents forced by winds and the thermohaline circulation. In addition, the numerical simulations of upwelling during 1999 (Middleton & Platov 2004) show that the Flinders Current, and shelf slope currents can be influenced by mesoscale eddies that are common during the summer months (see Figure 3.5.3 below). This second source of westward slope currents associated with warm-core eddies may well also lead to upwelling within the canyons of the region.

Closer to shore, wind-forced upwelling can raise water and nutrients from depths of 150 m or so to near the coasts of Kangaroo Island and Robe (Lewis 1981; Middleton & Platov 2003, 2004; Schahinger 1987; Griffin et al. 1997). The paths of nutrient and sediment upwelling between the deep slope and coast remain to be determined, although notably tar balls have been found on the Bonney Coast and may well have come from oil-bearing sediments located on the adjacent shelf slope (200–600 m depth) (see below).

In addition, it has recently been shown that upwelling is almost certainly enhanced by the El Niño signal that propagates from the equatorial Pacific and into the Bonney Coast – Kangaroo Island region (Li and Clarke 2004; Middleton et al. 2005). The data available suggest that 11.5 °C water can be raised from depths of ~250 m and onto the shelf (60 m) during these signals. More data on deep-slope upwelling are needed both during normal and ENSO years.

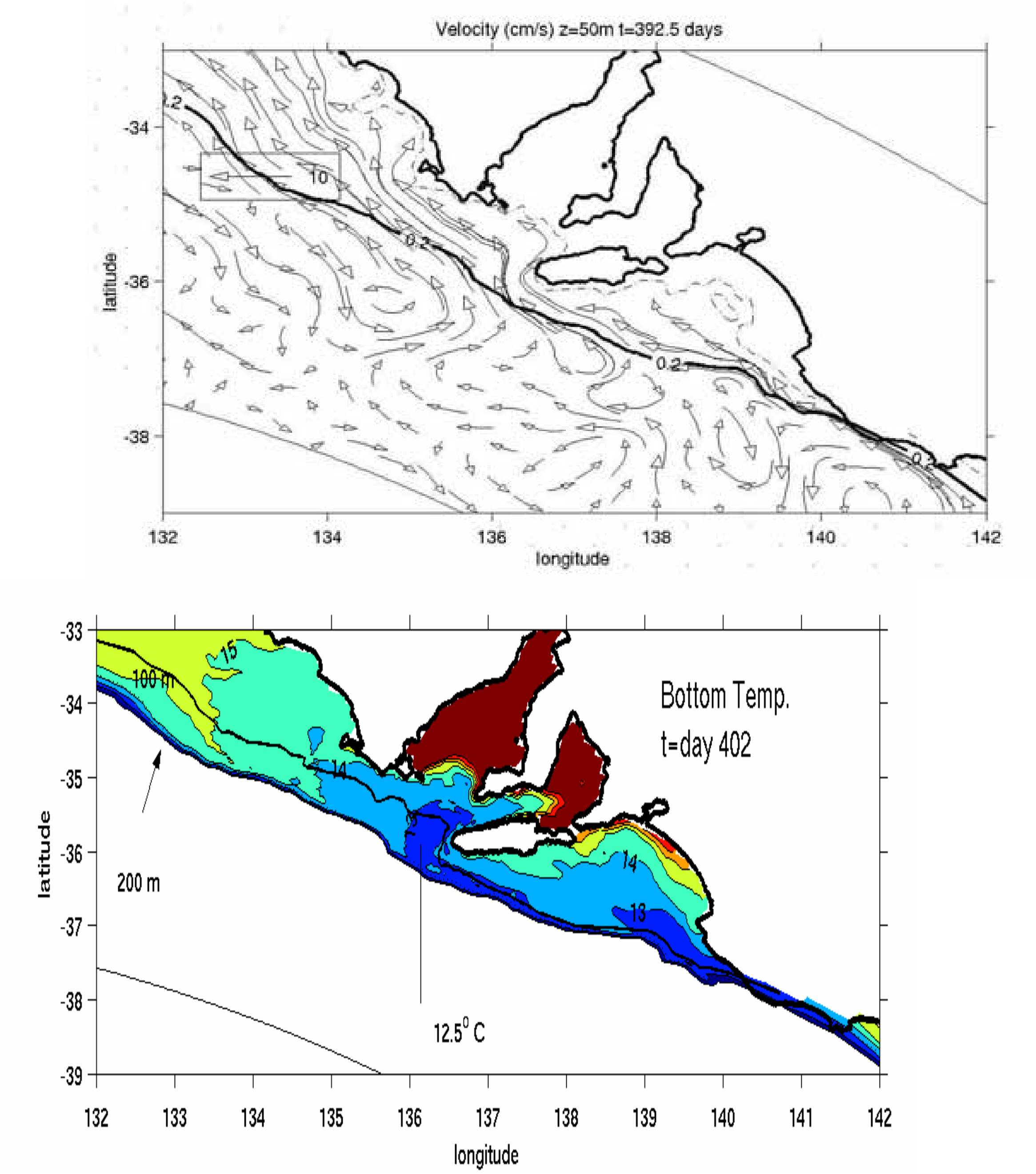


Figure 3.5.3 Results from the SA Regional Ocean Model. **Top panel**: The velocity field at a depth of 50 m at 27 January 1999 ,with active coastal upwelling. A vector of 10 cm/s is indicated. The dark line is the 200 m isobath and the presence of warm (cold) core eddies, that extend to depths of >300 m, will drive deep upwelling (downwelling) in the canyons. **Bottom panel**: The bottom temperature 10 days later (6 Feb 1999) when the winds have vanished. Only water of temperatures between 11 °C and 18 °C is contoured. Upwelling has occurred as indicated by the plumes of 13 °C water off Kangaroo Island and the Bonney Coast. This water was initially at a depth of 250 m.

Significance of the canyons to marine productivity hotspots

Abrupt topography and the biophysical mechanisms of prey aggregation are becoming more recognised as creating key hotspots of productivity in the oceans (Genin 2004); these hotspots are vitally important to sustaining fish production. Overseas studies in the Mediterranean, Georges Bank, and off the Oregon and Canadian west coasts have shown that canyons generate complex flows, the net result of which can be higher regional productivity. As such, they form important hotspots of biological production. Dense krill concentrations accumulate in the heads of the canyons off Georges Bank (Greene 1988), providing a "prey subsidy" that helps to sustain high fish production on the banks. While smaller zooplankton and phytoplankton are advected by the deep and temporally variable flows generated around canyons, swimming and vertically migrating micronekton such as krill and mesopelagic fish can maintain position by behavioural interaction with the flow field (Macquart-Moulin & Patriti 1996; Mackas et al. 1997; Allen et al. 2001). These aggregations of micronekton are preyed upon by commercial species such as *Sebastes* on the North American west coast (Pereyra et al., 1969), and provide a rich food source for cetaceans (Bosley et al. 2004). Astoria canyon off Oregon is an important fishery area with extensive groundfish dependent upon the rich prey field of the canyon (Pereyra et al. 1969). Work on the South Australian canyons, scheduled for 2007, will be the first effort to expand these findings into the South-west Marine Region and to investigate the importance of the canyons as key habitats underpinning the fisheries within the Region.

Benthic communities

Water circulation patterns can influence benthic communities in several ways. Most importantly, they modify other water column processes, such as near-bottom flow, that bring food and new recruits to the community (e.g. Snelgrove & Butman 1994). Moreover, bottom currents largely determine sediment type and food supply to the benthos, which in turn influence benthic patterns (Gray 1981). Circulation also affects larval supply to benthic habitats because larval supply is thought to be primarily passive over broad scales (Bradbury & Snelgrove 2001). Circulation is closely linked to wind as well as to topographic features such islands, banks and canyons which can create enhanced larval retention through eddies (Lobel & Robinson 1986; Tremblay et al. 1994) and also produce highly productive areas associated with upwelling that may influence larval transport and survival (e.g. Shanks 1995). All of these processes act in concert with post-settlement processes such as disturbance (Barry & Dayton 1991), predation (Thrush 1999) and competition (Peterson 1977), to influence benthic patterns of distribution and abundance.

Most soft-bottom communities at depths below the photic zone are dependent on sinking water column production as the major food source, and thus the quality and quantity of organic matter reaching the seabed is likely to be an important influence on benthic community structure and biomass (Smetacek 1984). Horizontal advection can complicate this linkage through transport of sinking particles (detritus, larvae) to a bottom area that is distant from the surface waters where they were abundant (Lampitt et al. 1995). In addition, decoupling between herbivory and primary production can result in greater export of production to the bottom as a result of lowered zooplankton grazing rates (Ambrose & Renaud 1995).

Previous macrofaunal studies have typically found a positive relationship between benthic abundance and biomass and enhanced flux of organic carbon to the seabed (Davies & Payne 1984). For example, Grebmeier et al. (1988) found a significantly greater benthic biomass in the Bering Shelf region where water column primary production was much higher, and Ambrose and Renaud (1995) found water column and benthic chlorophyll concentration were the most important predictors of infaunal density and biomass. In spite of such findings, linkages between the pelagic realm and the benthic community pattern are not well understood, especially in cold ocean systems (Snelgrove et al. 2000). This is especially true of the South-west Marine Region.

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