A review is presented of the ocean circulation along Australia’s southern shelves and slope. Uniquely, the long, zonal shelf is subject to an equatorward Sverdrup transport that gives rise to the Flinders Current – a small sister to the world’s major Western Boundary Currents. The Flinders Current is strongest near the 600 m isobath where the current speeds can reach 20 cm/s and the bottom boundary layer is upwelling favourable. It is larger in the west but likely intermittent in both space and time due to possibly opposing winds, thermohaline circulation and mesoscale eddies. The Flinders Current may be important to deep upwelling within the ubiquitous canyons of the region.

During winter, the Leeuwin Current and local winds act to drive eastward currents that average up to 20–30 cm/s. The currents associated with the intense coastal-trapped wave-field (6–12 day band) are of order 25–30 cm/s and can peak at 80–90 cm/s. Wintertime winds and cooling also lead to downwelling to depths of 200 m or more and the formation of dense coastal water within the Great Australian Bight and the South Australian Sea. Within the Great Australian Bight, the thermohaline circulation associated with this dense water is unknown, but may enhance the eastward shelf-edge, South Australian Current. The dense salty water formed within Spencer Gulf is known to cascade as a gravity current to depths of 200 m off Kangaroo Island. This dense water outflow and meanders in the shelf circulation also fix the locations of a sequence of quasi-permanent mesoscale eddies between the Eyre Peninsula and Portland.

During summer, the average coastal winds reverse and surface heating leads to the formation of warm water in the western Great Australian Bight and the South Australian Sea. No significant exchange of shelf water and gulf water appears to occur due to the presence of a dense, nutrient-rich (sub-surface) pool that is upwelled off Kangaroo Island. The winds lead to weak average coastal currents (<10 cm/s) that flow to the north-west. 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 the formation of the eastward, South Australian Current. 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).
Increasing evidence suggests that El Nino events (4–7 year period) can have a major impact on the winter and summer circulation. These events propagate from the Pacific Ocean and around the shelf-slope wave-guide of West Australia and into the Great Australian Bight. During winter El Nino events, the average shelf currents may be largely shut-down. During summer, the thermocline may be raised by up to 150 m. The nature and role of tides and surface waves is also discussed along with uncertainties in the general circulation and future research.

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Keywords: Shelf currents; Shelf-edge; Upwelling; Downwelling; Oceanic eddies; Boundary currents
1. Introduction

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 (GAB), as well as the very steep and narrow shelves off Esperance, Kangaroo Island and the Bonney Coast (Fig. 1a and b). To the east of the Eyre Peninsula, the shelves are punctuated by the complex geography of the South Australian Sea (SAS), which comprises Spencer Gulf, Gulf St. Vincent, Backstairs Passage and Encounter Bay; and the Bonney Coast. This varied topography, coupled to the forcing by the Southern Ocean and local meteorology leads to a complex and fascinating shelf and slope circulation. Indeed, the region hosts the world’s few (if only) northern boundary current (the Flinders Current) – a small sister to the great Western Boundary Currents. Intense downwelling occurs during winter, while during summer water can be upwelled from depths of

![Diagram of Australia's southern shelves](image-url)

Fig. 1. (a) The geography and topography of Australia's southern shelves. Isobath depths are in meters. The Great Australian Bight (GAB) is labelled and the isobaths presented are for the 200, 1000 and 4000 m depths. (b) The geography and topography of the South Australian Sea. Port Lincoln (PL) and other features are labelled. The two isobaths presented are for the 100 and 200 m depths.
250 m or so. Dense water formed within Spencer Gulf mixes due to resonant tides and leads to an outflow that extends to depths of 200 m off Kangaroo Island.

Study of the region began somewhat inauspiciously. The first oceanographic expedition to the south of Australia was probably that of HMS Beagle in 1836, which sailed from Hobart to Albany. Sir Charles Darwin records in his diary for 6 March 1836: ‘Our passage has been a tolerable one; and what is surprising, we had not a single encounter with a gale of wind. Yet to me, from the long westerly swell, the time passed with no little misery. We staid there 8 days and I do not remember since leaving England having passed a more dull, uninteresting time’ (Barlow, 1933).

In the subsequent years, during which the colonies of South Australia and Victoria were rapidly developing and sailing ship traffic along the southern coast of Australia was extensive, attention was focused on the coastal circulation, and by about 1850 the existence of a coastal jet (shelf-edge) along the central section of the Southern Shelf (Fig. 2) was established which was named the South Australian Current (Black, 1857).

Over the next one hundred years, no deep-sea oceanographic studies appear to have been undertaken, until a cruise of HMAS Diamantina in 1960 along two zonal sections centred on 39°C176S. This study, as part of the Indian Ocean Expedition (Rochford, 1961; Wyrtki, 1962, 1971) revealed that a complex dynamical structure existed right across the South Australian Basin (Fig. 1a). At about this period, advances were made in under-
standing the coastal circulation. Rochford (1957) deduced that the water mass found in Bass Strait in March and November 1954 (which he called the North Bass Strait water mass) was continuous with western Victorian and South Australian waters, and a series of weighted drift bottle releases between 1958 and 1962 (CSIRO, 1968), showed that the inshore coastal current (CC) off Victoria and South Australia reversed seasonally due to the shifting of winds from westerly in winter to south-easterly in summer.

The deep-sea meridional boundaries of the South Australian Basin (approximately along 115°E and 145°E) were sampled by Discovery II in 1932 (Deacon, 1937), and station 899 (47°S, 150°E) on the winter cruise south from Tasmania provided the first evidence of the Tasman Outflow, that is of importance for the region.

Oceanographic studies in the intermediate region were not commenced until 1967, when the formation of the Horace Lamb Centre for Oceanographical Research in Adelaide, South Australia (Fig. 1a) gave the opportunity for the establishment of a repeat sampling, deep-sea oceanographic programme centred on 135°E and extending as far south as 45°S. This programme resulted in the naming of the major circulation feature of the South Australian Basin as the Flinders Current (Bye, 1972) in recognition of the fundamental voyage of exploration by Matthew Flinders along the southern coast of Australia in 1802 (Flinders, 1814). The Sverdrup dynamics of the Flinders Current and its mesoscale structure were presented in two earlier reports (Bye, 1968, 1971).

At this time also the tidal regime of the Southern Shelf began to be extensively studied (Easton, 1970), although some of its unique properties were known much earlier (Chapman, 1892), as being an essential prerequisite for safe harbour operations. The influence of the tidal circulation on the inshore physical oceanography is now well recognized.

This article presents subsequent progress that has been made in the areas of shelf-slope and coastal circulation in the South Australian Basin between Cape Leeuwin in the west, and Portland in the east (Fig. 1a). A number of features characterise the region. First, the shelf here is predominantly zonal in orientation, follows the (eastward) path of atmospheric storms and hence the Coriolis parameter is nearly constant: energy loss from the shelf through Rossby wave generation is minimal. Second, the nearly zonal shelf represents a natural barrier to the equatorward Sverdrup transport from the Southern Ocean. Third, upwelling seems to vanish to the east of Portland where the influences of Bass Strait become significant.

The purpose of this review is to provide a summary of the oceanography and important physics of the shelf and slope region and in a form that is accessible to the general marine science community. To this end, a brief summary is given at the beginning of each section. In addition, where appropriate, mention is also made of oceanic transport paths for marine biota and sediments as well as possible circulation features that may be important from an ecological viewpoint. The region is vast and our focus is on the shelf-slope circulation and not on that within the gulfs. Not a lot of data are available for the region so by necessity, we have synthesised results from both observational and numerical studies. Many uncertainties exist in our knowledge of the region and these are summarised in Section 9 along with possible ideas for future research.

2. The Flinders Current and mesoscale eddies: the mean and seasonal picture

2.1. Summary

Observations and output from ocean circulation models indicate the existence of a shelf-slope Flinders Current (FC) that may flow from Tasmania to Cape Leeuwin (Fig. 2). This current has maximum amplitude at water 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. In the GAB, the current is driven by the equatorward Sverdrup transport in the Southern Ocean and based on wind stress observations, should be largest in early summer. The bottom boundary layer of the FC extends some 50 km from the shelf through an onshore Ekman transport that leads to upwelling. The FC may therefore be important to preconditioning for wind-forced upwelling during summer.

Observations are limited, although the magnitude of the FC, is likely affected by cross-shelf density gradients and winds and may vanish or even reverse. In addition, the FC is affected by mesoscale eddy variability that is largest in the west off Albany and off the South Australia Sea. The FC may provide a deep mechanism of transport (or westward conveyor belt) for the region. More importantly, the cross-shelf pressure gradients
associated with the FC and warm-core eddies may lead to upwelling within canyons and drive nutrients and sediments towards the shelf-break, 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.

2.2. The Flinders Current: dynamics and observations

The FC is a westward flowing boundary current along the south coast of Australia. The large-scale dynamics indicate that it is driven by the positive annual mean wind stress curl to the south of Australia (Bye, 1983). North-westward transport for the region was also noted by Godfrey (1989) in a global analysis of Sverdrup transport. Indeed, the curl of the wind stress, when averaged over either the summer or winter periods (Figs. 3 and 4), leads to an equatorward Sverdrup transport in the Southern Ocean as illustrated in Fig. 2. Along Australia’s southern shelves, this transport is necessarily deflected to the west leading to the FC (Middleton and Cirano, 2002). Indeed, these authors have analysed results from the OCCAM global ocean model (Webb et al., 1998) and found the FC to be located near the slope (600 m), and with largest amplitude in the west (20 cm/s) that is seasonal in strength (see Section 2.3). In addition, the bottom boundary layer of the FC is necessarily upwelling favourable, leading to an upward tilt of isotherms 50 km or so from the slope.

Winter observations for June 1987 and for the western section off Cliffy Head (~118°E), show (Fig. 5), that the maximum westward speed of the FC is about 20 cm/s at depths of 400–600 m (Cresswell and Peterson, 1993). At and below these depths, 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 wind forcing and cooling. Very warm (>19 °C) water is found within 50 km of the coast and at depths of 100 m or less. This water can have speeds of 50–100 cm/s and represents an extension of the Leeuwin Current (LC) (see also Church et al., 1989). Below the LC, the FC may be regarded as an extension of the Leeuwin Undercurrent.

Including the transect shown in Fig. 5, there are but a hand-full of observations of the FC and these are reviewed by Middleton and Cirano (2002). In summary, the observations are largely indirect, but do provide evidence for the FC as outlined above. In the far-east, and off the west coast of Tasmania, the recent hydrographic analysis of Barker (2004) indicates the formation of two distinct water masses: Tasmanian Subantarctic Mode Water (TSAMW) is characterized by a thick well mixed layer, known as a thermostad (Seitz, 1967; McCartney, 1977). It descends to a depth of about 500 m as it propagates north-west into the South Austra-
lian Basin with a salinity of 34.67 psu and a potential temperature of 9.2 °C. In the formation region, a thick mixed layer of uniform density is observed, which initiates the sub-surface intrusion of TSAMW, apparently by thermobaric instability. The Tasmanian Intermediate Water (TIW) forms at a depth of about 1000 m, and spreads north-westward into the South Australian Basin with a salinity of 34.38 psu and a potential temperature of 5.0 °C (Barker, 2004).

The north-westward spread is consistent with the existence of an eastern extension of the FC and the contention of Cirano and Middleton (2004) that the FC is driven in part by a bifurcation of the Tasman Outflow. Current meter observations off the west Tasmanian shelf show a deep (mean of 4 cm/s) FC at a depth of 995 m. Recent evidence for the FC comes from 6 months of current observations (Wood and Terray, 2005) from the “Amrit-1” slope site just south of Portland (water depth 1395 m). During autumn (April–June), the mean currents are to the west between depths 910 and 505 m with amplitude 3–7 cm/s. The maximum speeds recorded at these depths were 29–39 cm/s and also to the west. Above the FC (depths 305–7 m), the mean currents (6–26 cm/s) were to the east. During winter (July–September), a mean westward current of 1.5 cm/s was found only at a depth of 952 m. Otherwise, the mean currents were all to the east (5–15 cm/s). Notably, maximum speeds of 23–69 cm/s (at depths of 952–501 m) were again found to be to the west. Wood and Terray (2005) suggest that some of the variability found may be due to the presence of mesoscale eddies. The reduction in magnitude of the FC during winter is also consistent with the winter reduction in Sverdrup transport (see Section 2.3).

For the mid-GAB the November 1995 hydrographic data obtained by Schodlok and Tomczak (1997a) at 120°E also show the deep thermocline (500–1000 m) to be upwelled towards the coast and over a distance of 100 km (Fig. 6) – a signature of the FC. This, and other data were also used in an inverse box model (Schodlok and Tomczak, 1997b) to infer the zonal transports through a 120°E section. They found the total transport to be dominated by that in the top 1200 m, with a net westward transport of 35 Sv between 39°S and the coast \([1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}]\). This value is about twice the 16 Sv for the global OCCAM model (Middleton and Cirano, 2002), but the directions are the same. Using a level of no motion close to 2000 m, Schodlok and Tomczak (1997a) also found the currents within 100 km of the coast and at 122°E to be directed to the west and largest at depths of order 500 m; a result that is not inconsistent with the westward maximum at 600 m shown in Fig. 5.

### 2.3. Seasonal variability: forcing and model results

The magnitude of the FC is affected by seasonally varying winds, Sverdrup transport and associated shelf-slope currents. The importance of these factors is discussed next using results from numerical models.
We have determined the monthly averaged Sverdrup transport along a zonal section at 39°S, 122–140°E, using daily winds from a global climatology (NCEP/NCAR; Kalnay et al., 1996). Fig. 7 shows the Sverdrup transport and by implication the FC, 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 (Fig. 4), Cirano and Middleton (2004) obtained numerical results for the circulation of the region that are illustrated by the schematic in Fig. 2a. These suggest the existence of a strong (≈20 cm/s) eastward flowing coastal current (CC) over the shelf (see Section 3.2.1). Over the slope, the FC is found to extend from Tasmania to Cape Leeuwin with maximum amplitudes of 10–15 cm/s at water depths of 600 m or so. In the east, the FC is forced by a bifurcation of the Tasman Outflow that is in turn forced by the East Australian Current. To the west of Kangaroo Island, the Sverdrup transport becomes increasingly important in driving the FC.

Recently, Arthur (2007) has examined monthly averaged output from three global ocean models for the region of the South Australian Basin. The model output was from OCCAM (Webb et al., 1998), POP (Mul-
Considerable differences between the model results were found for the region. In addition, the net transports through the $39^\circ$/$C176^\circ$ S zonal section (122–140$^\circ$E) from the POP and BRAN models were not correlated with the monthly averaged Sverdrup transports shown in Fig. 7. However, the monthly equatorward transport (1992–2003) from OCCAM was found to be well correlated with the Sverdrup transport during both winter and summer, but some 20–50% larger in magnitude. In addition, Arthur (2007) also found the OCCAM model output to be very well correlated with monthly averaged coastal sea level and temperature data from Esperance, Thevenard and Portland. These results lend some credibility to the OCCAM output that shows an intermittent FC near depths of 600 m with speeds of 8 cm/s in the east (137$^\circ$E) and 14 cm/s in the west (122$^\circ$E). Further discussion of the impact of the shelf and thermohaline circulation on the FC is made in Section 3.2.2.

2.3.2. Summer circulation

As noted, the Sverdrup transport is larger in early summer and should drive a stronger FC than found during winter. Middleton and Platov (2003) have developed a regional model that is driven by the summer mean
winds and (larger) summer Sverdrup transports. The coastal winds reverse during summer, the LC is largely absent and the shelf-slope circulation (Fig. 8) is very different to that found during winter: the CC flows to the west and an anti-cyclonic (anticlockwise) gyre is found in the GAB. The seaward arm of this gyre is simply the South Australian Current and which opposes the underlying FC. Despite the larger Sverdrup transports, the FC is surprisingly weaker than in winter and is only found to the west of Kangaroo Island where the maximum speed is of order 5–10 cm/s at depths of around 300–400 m (e.g., Fig. 9). An additional feature of the shelf summer break circulation is the convergence of the planetary Sverdrup transport (due to the planetary vorticity) from the south and the topographic Sverdrup transport (due to the topographic vorticity) from the north (Herzfeld and Tomczak, 1999; Middleton and Platov, 2003). Further discussion of the effects of the summer shelf circulation will be made in Section 5.2.1.

2.4. Eddy variability

Off the South Australian coast, eddies and planetary waves may also be important in modulating the strength and location of the FC. These waves and eddies are each quasi-stationary in that they are each found in similar locations and over extended periods of time. The planetary waves were originally observed (Bye, 1971) to extend polewards from the coast to 45°S between 130°E and 145°E: the observations here were made between 1967 and 1971 and 67 hydrographic stations were occupied in one summer, three autumn, three winter and one spring cruise. On plotting the mean water properties (grouped in boxes, 2° latitude and 3° longitude in size), a series of three crests and two troughs in dynamic topography were found (wavelength 500 km) and inferred to arise from planetary waves (Bye, 1971). The dynamic structure was coherent over the depth range of about 400–2000 m with a maximum intensity at around 700 m, where vertical displacements of the density surface sometimes attained 250 m. In the box centred on (36°S, 135°E), a time series of seven occupations indicated strong growth phases of the planetary waves in the winter of 1968 and the summer of 1970.
Recent evidence for the existence of smaller scale (~70 km) quasi-stationary eddies was given in the altimeter data analyses of Ridgway and Condie (2004): their sea surface height (SSH) anomalies are shown here in Fig. 10. For the July (winter) period, the anomalies indicate the presence of an alternating sequence of...

Fig. 8. (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. The 200 m (0.2 km) isobath is indicated in (a).

Recent evidence for the existence of smaller scale (~70 km) quasi-stationary eddies was given in the altimeter data analyses of Ridgway and Condie (2004): their sea surface height (SSH) anomalies are shown here in Fig. 10. For the July (winter) 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 Encounter Bay).

Bye (1983) suggested that the existence of the quasi-stationary eddy-wave train may be due to the convergences and divergences in the CC occurring at approximately the same locations throughout the year due to the direction of the coastline relative to the prevailing wind direction. Cirano and Middleton (2004) suggested that the wintertime eddies could result from such a mechanism since the offshore (onshore) meanders of the CC result in vortex squashing (stretching) because of the downwelled isopycnals. During winter, anticyclonic

![Fig. 9. Numerical simulation of shelf-break downwelling in the western Great Australian Bight (Middleton and Platov, 2003).](image)
(cyclonic) eddies are preferentially triggered by offshore (onshore) displacements of the CC due to promon-
tories (embayments).

Further evidence for the formation of a quasi-stationary, anticyclonic eddy off Kangaroo Island was out-
lined by Godfrey et al. (1986). Their hydrographic measurements indicate that salty water flows out from
Spencer Gulf during winter and then around to the south of Kangaroo Island at depths of 200 m (Fig. 11).
Such an outflow will act to enhance the quasi-stationary (winter) anticyclonic eddy off Kangaroo Island (Cir-
ano and Middleton, 2004) that is observed in both the altimeter data noted above and also drifter data (God-
frey et al., 1986; Hahn, 1986).

The sea surface height data (Fig. 10), also suggests the winter eddy variability to be smaller in the mid-GAB
region, but quite intense in the far west due to instabilities of the Leeuwin Current. Drifter trajectories, hydro-
graphic surveys and ADCP data all indicate the formation of a large anticyclonic eddy off Albany. The eddy
here appears to be quasi-stationary and related to an offshore meander of the LC as it rounds Cape Leeuwin
(Ridgway and Condie, 2004; Godfrey et al., 1986; Cresswell and Peterson, 1993). During summer, the near
slope eddy variability is weaker than in winter (Fig. 10) possibly since the CC is also reduced in magnitude (see Section 5). More recently, Ken Ridgway (personal communication, 2005) has determined the mean sea level anomalies for all months. An animation of these anomalies shows that the wintertime eddies apparent in

Fig. 10. Sea Surface Height (SSH) anomalies inferred from altimeter and coastal sea level data by Ridgway and Condie (2004). The vertical side bar gives height in meters.
Fig. 10. Detach from the shelf-slope in spring when the winds and CC reverse to the west. The currents associated with the warm (cold) core eddies over the shelf-slope can act to enhance (retard) the FC and increase upwelling and downwelling through the bottom boundary layer and within canyons.

Fig. 11. The salinity (psu) at a depth of 200 m as determined by Godfrey et al. (1986) during June–July 1982. Salinities greater than 35.6 psu are shaded.

Fig. 12. Contours of SST obtained for 2 March 1995 and for the Kangaroo Island – Bonney Coast Region. The SST is overlaid on the topography of the region that illustrates the sub-marine canyons. The contour interval is 0.4 C. The pink squares along the Bonney Coast and coast of Kangaroo Island indicate the locations where asphaltite sediments have been found. These sediments are known to lie at depths greater than 2000 m off the Bonney Coast (courtesy Peter Boult).

**Fig. 10** detach from the shelf-slope in spring when the winds and CC reverse to the west. The currents associated with the warm (cold) core eddies over the shelf-slope can act to enhance (retard) the FC and increase upwelling and downwelling through the bottom boundary layer and within canyons.
2.5. Transport and ecological implications

Finally, mention is made of oceanic transport paths for marine biota, nutrients and sediments as well as possible circulation features that may be important from an ecological viewpoint.

Although the FC 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 800 km over a 3-month period. On the shelf-slope (depths 400–600 m), the FC provides the only westward means of transport for marine biota during winter. Wind-forced downwelling during winter may provide a means of connecting shelf water to the FC.

Anti-cyclonic slope eddies and the FC will result in westward alongshelf currents that may flow over the many narrow canyons of the region (Fig. 12). For such flows, the geostrophic balance may be disrupted and the pressure force can act to accelerate water, sediments and nutrients up toward the shelf-break. In other regions, canyon upwelling is well documented (e.g., Klink, 1996). For the region here, evidence for deep upwelling is the presence of neutrally buoyant asphaltites that are associated with sediments at depths of 2000 m, but which are found along the Bonney Coast and the coast of Kangaroo Island (Fig. 12; Peter Boult, personal communication, 2005). The mechanism may be very important to deep upwelling in the South Australian Sea during summer, since wind-forced upwelling can then draw such upwelled water to the coast and surface.

3. The mean winter shelf circulation and downwelling

3.1. Summary

A combination of winds, thermohaline forcing and the LC drive an eastward coastal current (CC) and the shelf-edge South Australian Current (SAC) from Cape Leeuwin to Kangaroo Island during winter with mean speeds of order 30 cm/s: a 3-monthly seasonal scale of advection is of order 2000 km. The winds drive an onshore surface Ekman transport and a return sub-surface flow to deeper waters and lead to downwelling to depths of order 200 m or more. The net cooling over winter also gives rise to dense water formation. Within Spencer Gulf, lighter water is drawn in on the western side, and heavier water is expelled on the eastern side. This gravity current flows across the shelf west of Kangaroo Island and then to the shelf-break at a depth of about 250 m. In the Gulf St. Vincent, the dense water is well mixed in the vertical and exits into Encounter Bay on the northern coast of Backstairs Passage. Dense water is also formed in the coastal waters of the GAB although the implications for the circulation remain to be determined. 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.

3.2. Discussion

3.2.1. An overview of shelf currents: observations and numerical model results

During winter, the wind stress at the coast is directed to the east with an average amplitude between 0.05 and 0.1 Pa (Table 1 and Fig. 13). These winds drive an Ekman flux onshore that acts to raise sea level near the coast and also drive a CC from west to east (e.g., Olsen and Shepherd, 2006). In the west, the LC enters the region with speeds of up to 90 cm/s as illustrated by the velocity transect (Fig. 5).

An overview of the net effect of winds, the LC and water mass formation is presented by the results for SSH anomalies in Fig. 10. The positive SSH anomaly at the coast ranges from 14 to 10 cm between Cape Leeuwin and
Kangaroo Island. Ridgway and Condie (2004) point out that the largest cross-shelf SSH gradient is located near the shelf-edge indicating the existence of an intensified shelf-edge current – the South Australian Current (SAC). Black (1857) originally named the SAC using ship-drift reports. Godfrey et al. (1986) indicate (ship-drift) speeds to the east of more than 50 cm/s over the shelf-break at 128°E during June 1982. For the South Australian Sea and Bonney Coast, Cirano and Middleton (2004) have summarised most available current meter data (i.e. Provis and Lennon, 1981; Hahn, 1986; Schahinger, 1987). Results typical of the region are presented in Table 2. The observed mean winter currents to the east (poleward), are largest near the shelf-edge and of order 20–30 cm/s. Further evidence of the SAC is given in the sea surface temperature (SST) images (Fig. 14; plate 12) of Herzfeld (1997). In the west, these SST distributions are also consistent with the eastward advection of warm LC water.

Table 1
Meteorology for the region

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Summer: December–February</th>
<th>Winter: June–August</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean wind stress (wind)</td>
<td>−0.05 (7)</td>
<td>0.07 (8)</td>
</tr>
<tr>
<td>SD wind Stress (wind)</td>
<td>0.1 (9.3)</td>
<td>0.12 (10)</td>
</tr>
<tr>
<td>Season maxima stress (wind)</td>
<td>0.2 (12)</td>
<td>1.1 (23)</td>
</tr>
<tr>
<td>Heat flux (W m⁻²)</td>
<td>50 (100)</td>
<td>−100 (−20)</td>
</tr>
</tbody>
</table>

Typical values of the alongshore components of the mean and standard deviation (SD) February and August wind stress in Pascals. 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 et al. (1989). The heat fluxes are from the NCAR/NCEP climatology for the GAB while those in brackets are for the Head of the Bight (Herzfeld, 1997).

Fig. 13. The dark upper curve denotes the Neptune Island upwelling component of wind stress along 135°T. Gaps in 1996–2000 were filled using data from an adjacent weather station. Negative values are upwelling favourable and units are 10⁻² Pa. The dark dotted curve corresponds to the upwelling component of wind stress based on the daily NCEP averaged winds for a cell off Kangaroo Island. The light lower curve is the scaled −nino34 index so that values below −10 indicate El Nino events.

Kangaroo Island. Ridgway and Condie (2004) point out that the largest cross-shelf SSH gradient is located near the shelf-edge indicating the existence of an intensified shelf-edge current – the South Australian Current (SAC).

Black (1857) originally named the SAC using ship-drift reports. Godfrey et al. (1986) indicate (ship-drift) speeds to the east of more than 50 cm/s over the shelf-break at 128°E during June 1982. For the South Australian Sea and Bonney Coast, Cirano and Middleton (2004) have summarised most available current meter data (i.e. Provis and Lennon, 1981; Hahn, 1986; Schahinger, 1987). Results typical of the region are presented in Table 2. The observed mean winter currents to the east (poleward), are largest near the shelf-edge and of order 20–30 cm/s. Further evidence of the SAC is given in the sea surface temperature (SST) images (Fig. 14; plate 12) of Herzfeld (1997). In the west, these SST distributions are also consistent with the eastward advection of warm LC water.
The current meter data in Table 2 also provide support for the numerical results of Cirano and Middleton (2004) and their mean winter shelf circulation of the South Australian Sea (Fig. 15). The CC 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 in Section 2.4.

### Table 2

Current meter observations of Hahn (1986) and Schahinger (1987): 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 Fig. 15.

| Event       | Site and year | 1st record | Days | Lat. | Long. | Water depth (m) | Inst. depth (m) | $|U|$ (cm/s) | $\theta$ (cm/s) max |
|-------------|---------------|------------|------|------|-------|-----------------|-----------------|-------------|-------------------|
| Summer      | G4 U 82       | 11/11/81   | 78   | 35.70| 135.78| 138             | 22              | 2.4         | 161               |
|             | El Nino G4 U 83 | 02/12/82  | 95   | 35.70| 135.78| 146             | 15              | 2.9         | 183               |
|             | G4 L 81       | 12/12/80   | 50   | 35.77| 135.75| 137             | 115             | 2.0         | 306               |
|             | El Nino G4 L 82 | 11/11/81  | 78   | 35.77| 135.75| 137             | 133             | 3.5         | 152               |
|             | El Nino G4 L 83 | 02/12/82  | 95   | 35.77| 135.75| 146             | 125             | 2.9         | 120               |
|             | B 84          | 02/11/84   | 56   | 37.43| 139.72| 50              | 26              | 5.3         | 60                |
|             | El Nino B 83  | 07/02/83   | 60   | 37.43| 139.72| 52              | 24              | 3.5         | 337               |
|             | A 84          | 21/01/84   | 56   | 37.53| 139.52| 146             | 115             | 4.9         | 118               |
|             | El Nino A 83  | 07/02/83   | 60   | 37.53| 139.52| 143             | 110             | 2.5         | 83                |
| Winter      | G4 U 81       | 06/04/81   | 78   | 35.77| 135.75| 137             | 42              | 20.2        | 120               |
|             | El Nino G4 U 82 | 26/08/82  | 97   | 35.77| 135.75| 144             | 31              | 1.4         | 198               |
|             | G4 L 81       | 06/04/81   | 78   | 35.77| 135.75| 137             | 115             | 19.2        | 144               |
|             | El Nino G4 L 82 | 26/08/82  | 97   | 35.77| 135.75| 144             | 124             | 4.6         | 147               |
|             | A 83          | 07/07/83   | 57   | 37.53| 139.52| 143             | 112             | 28.5        | 139               |
|             | El Nino A 82  | 08/08/82   | 59   | 37.53| 139.52| 143             | 111             | 7.4         | 150               |

The first column indicates if the data is from an El Nino year. Observations from El Nino and non-El Nino years are paired for repeat observation sites (the first being for a non-El Nino year). The second column indicates the mooring site (as shown in Fig. 15), position in the water column by upper (U-18m) or lower (L-110m) 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 $\theta$ in degrees clockwise from north. The maximum speed registered for the deployment is given if available: all units are cm/s.

The current meter data in Table 2 also provide support for the numerical results of Cirano and Middleton (2004) and their mean winter shelf circulation of the South Australian Sea (Fig. 15). The CC 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 in Section 2.4.

#### 3.2.2. The hydrography and thermohaline forcing

The winter period is also one of surface cooling although estimates of the net heat fluxes are variable and range between 20 and 100 W m$^{-2}$ near the coast (Table 1). In conjunction with winds, the loss of heat leads to downwelling (e.g., Fig. 5) and the development of very deep surface mixed layers that may exceed 200 m (e.g., Fig. 6; Rochford, 1986; Bye et al., 1968). The loss of heat also leads to the formation of cold (dense) water in the shallow regions of the South Australian Sea and GAB as illustrated by the winter climatology of (surface) temperature, salinity and density (Fig. 16). This climatology was obtained from the CSIRO Atlas of Regional Seas (CARS; Ridgway et al., 2002). Relatively cold, salty water (14–15 °C, >36 psu) is found in the shallow waters of Encounter Bay.

Within Spencer Gulf, the CARS data (Fig. 16) and that of Bullock (1975) and Nunes Vaz et al. (1990), indicate warm (>17 °C), salty (37 psu) water that arises from evaporation during the previous summer. As shown in Fig. 16 (lower panel), the gulf water is denser (>27 kg m$^{-3}$) than the adjacent shelf water (26.8 kg m$^{-3}$) and leads to a gravity current or plume that flows out of the eastern mouth and then south and east (Fig. 11) along Kangaroo Island (Godfrey et al., 1986). The plume is well illustrated in the results of Lennon et al. (1987) that are shown in Fig. 17: water is drawn in at the surface at the western mouth of Spencer Gulf and the gulf-shelf exchange is modulated by gravity currents occurring from April to December each year. The gravity currents likely occur in pulses that geostrophically adjust during the absence of vertical mixing that accompanies the dodge tide (Bowers and Lennon, 1987; Lennon et al., 1987; Nunes Vaz et al., 1990) – also see Section 8.
Fig. 14. SST data from Herzfeld (1997) for April (Plate 9), May (Plate 10), June (Plate 11), July (Plate 12) of 1991. The temperature (colour) scale changes in each plate. The white contour denotes the 200 m isobath.
The dense water outflow from Gulf St. Vincent is much smaller (Fig. 17) and exits as a vertically well-mixed stream along the northern coast of Backstairs Passage (Ng et al., 1993). A gravity outflow also occurs in the eastern GAB and on to the continental slope south of Eyre Peninsula (Hammat, 1995). The salt flux may be an order of magnitude greater than that from the South Australian Sea (SAS), but has not yet been extensively studied (Tippins, 1996).

Evidence supporting the possibility of a gravity outflow from the GAB comes from the CARS data presented in Fig. 16 (lower panel). During winter, the water is well mixed to depths of up to 150 m and that within the GAB is densest near the coast (maximum $27.2 \text{ kg m}^{-3}$) and lighter offshore ($26.4 \text{ kg m}^{-3}$) where the water depth is larger. Thus, in the absence of geostrophic effects, the dense coastal water would be expected to cascade as a gravity current towards the shelf-break leading to downwelling. At seasonal time-scales, geostrophy will be important, although there are no observations of the thermohaline circulation on the shelf. However, we would expect the denser water near the coast to sit lower in the water column leading to a westward current that would oppose the eastward CC that is driven by wintertime winds. Over the shelf, the meridional density gradient should support a geostrophic (thermohaline) current that is directed to the east and which should enhance those driven by the winds, including the shelf-edge SAC.

Finally, we comment on the effect of the shelf-edge SAC on the shelf slope FC. While the latter lies over the slope, the sea level gradient of the shelf-edge SAC may well extend over the FC. In this case, the cross-shelf sea level gradient of the SAC opposes the pressure gradient that must exist to support the FC. Consequently, the (geostrophic) FC would be weaker. Similarly, the enhancement of the SAC by the thermohaline field may also act to reduce the magnitude of the FC, although the details are unknown.

### 3.3. Transport and ecological implications

The wintertime CC is on average 15–30 cm/s, implying an alongshelf transport scale of 15–30 km/day or 1300–2700 km over a 3-month seasonal period. The mean onshore surface Ekman transport and deep return
offshore transport provide pathways of advection across the GAB and SAS regions. Nutrients, sediments and toxins formed in the very near-shore zone will be flushed onto the shelf. Gravity current flushing and lateral exchange flushing of dense water of the gulf with the lighter waters off the Eyre Peninsula and Kangaroo Island may also be important to cross-shelf exchange.

Fig. 16. The CARS surface climatology for winter. Upper panel: temperature (interval 1 °C); mid-panel: salinity (interval 0.2 psu); lower panel: density (interval 0.2 kg m⁻³). The dotted line in each panel is the 250 m isobath. The white numbers indicate the maximum value found within Spencer Gulf.
4. Winter weather-band circulation and coastal-trapped waves

4.1. Summary

The weather-band circulation (3–12 days) represents a large component of the circulation during winter (and summer) with root mean square (r.m.s.) speeds of order 25–30 cm/s and seasonal maxima of 50–90 cm/s. This time-varying circulation is often associated with coastal-trapped waves (CTWs). These quasi-periodic waves act to displace water back and forth along the shelf over distances of 30 km or so. This ocean weather is important to the flushing and scouring of benthic communities and recirculation features around headlands and islands, but generally not to the larger scale transport of marine biota across or along

Fig. 17. The maximum salinity at any depth for 16–23 June 1986. Contour interval 0.2 psu (Lennon et al., 1987).
the shelf. In conjunction with tides, the CTWs can lead to rapid changes in coastal sea level, “storm surges” and the generation of short-term resonances within embayments that are important to sediment re-suspension and aquaculture near Port Lincoln. In Section 6, we discuss the role of the weather-band circulation (and CTWs) for summertime upwelling.

4.2. Discussion

Superimposed on the prevailing westerlies during winter, passing fronts and low pressure systems lead to an r.m.s. alongshelf wind stress of 0.12 Pa and an expected extreme of 1.1 Pa (see Table 1). The frequency of passage of these systems is 3–12 days. The mixing and cooling by these larger amplitude events can lead to very deep (>200 m) wintertime surface mixed layers (e.g., Rochford, 1986).

In addition, storms within the South Australian Basin (and on the west Australian shelf) generate a very strong weather-band circulation. From Table 2, the observations (Hahn, 1986; Schahinger, 1987) indicate weather-band winter currents within the South Australian Sea that are typically 20–30 cm/s with seasonal maxima of 50–100 cm/s. The associated sea level changes are typically 25 cm or less but can reach 50 cm or more.

Elsewhere, aspects of the weather-band circulation have been well characterised by (linear) CTW modes and theories (e.g., Chapman, 1987). The only substantive CTW analysis of data for the region here was made by Church and Freeland (1987). The coastal sea level data they examined (Fig. 18) between Esperance and Portland have energy peaks in the 6–12 day band and indicate phase speeds of 3 and 10 m/s that are consistent with a first mode CTW for the narrow and wide southern shelves. For the first CTW mode, the alongshelf 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. Given an alongshelf current magnitude of 20 cm/s (typical of winter), the CTW 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 than for the alongshore direction.

The very large seasonal maxima of shelf currents found for the region may be due in part to resonant wind forcing of CTWs within the GAB where the shelf is wide and the CTW phase speed is around 10 m/s. Uniquely, both the wind systems and CTWs propagate from west to east and the phase speed of the wind systems can be comparable to that of the CTWs, (~10 m/s) indicating resonant forcing. Noye et al. (1999a) presented results from a storm surge model of the GAB but did not examine the possibility of resonance – a topic for future research.

The first (and higher) CTW modes incident from the GAB may be scattered and dissipated by the large changes in shelf and coastal geometry of the Eyre Peninsula, gulfs and Kangaroo Island. Indeed, results from

![Fig. 18. Adjusted low-passed coastal sea level at the sites indicated (Church and Freeland, 1987). The slope of the nearly vertical lines shown are consistent with CTW phase speeds of about 3 and 10 m/s for the narrow and wide shelves, respectively.](image-url)
weather-band models (McInnes and Hubbert, 2003; Middleton and Platov, 2005) suggest that only 25–50% of sea level variability to the east of Portland results from CTWs that are generated west of the Bonney Coast. Limited evidence for such scattering comes from the sea level data of Church and Freeland (1987) shown in Fig. 18. The signals at Esperance for each period are clearly most correlated with those at Thevenard and Port Lincoln and least correlated with that at Portland. This is supported by the spectral analysis of Church and Freeland (1987). They find the squared coherence (percent of variance) between the first mode Empirical Orthogonal Function to be largest (0.81) with sea level data from Esperance, Thevenard and Port Lincoln and smallest with data from Portland (0.49).

Finally, we note that in conjunction with tides, CTWs can also be important for rapid increases in sea level (storm surges) and in the generation of short-term resonances and in the re-suspension of sediments and aquaculture (Strutton et al., 1996). A particularly devastating event occurred in April 1996, in which tuna mortalities occurred in cages located off Port Lincoln on the Eyre Peninsula. This may have been due to the advection of algal material into the region of the cages where it was maintained in suspension by strong 3 h current oscillations generated by the surge (Bye, 1998; Noye et al., 1999b).

5. The mean summer shelf circulation and upwelling

5.1. Summary

During summer, the average winds blow in an anticyclonic fashion around the GAB (Fig. 3). Unlike winter, the mean ocean circulation associated with these winds is weak (~10 cm/s or less). The wind stress curl of these mean winds and likely the thermohaline circulation, combine to produce an anticyclonic gyre within the GAB. The gyre results in part from the southward topographic Sverdrup transport that also leads to downwelling along the shelf-break of the western GAB, raised sea level and the SAC. The latter forms the seaward arm of the anticyclonic gyre. In situ data also shows that, on average, upwelling occurs off Kangaroo Island and off the Bonney Coast (Fig. 19). To the west of Kangaroo Is, the upwelled water is maintained as a sub-surface pool of nutrient-rich dense water that acts to oppose dense water outflow from the Gulfs and provide the source of upwelled water for the Eyre Peninsula.

5.2. Discussion: large-scale circulation

5.2.1. An overview of shelf currents within the GAB: Observations and numerical models

The inflow of the LC into the GAB is much reduced or even absent during summer (e.g., Church et al., 1989). On average, the coastal winds (Fig. 3) will act to lower coastal sea level, drive westward currents (e.g., Olsen and Shepherd, 2006) and upwell water towards the coast (Lewis, 1981). Within the GAB, the anticyclonic winds lead to a positive wind stress curl and a poleward (seaward) topographic Sverdrup transport (Herzfeld and Tomczak, 1999; Middleton and Platov, 2003). As noted, the numerical model of Middleton and Platov (2003), forced using such mean winds, indicates that this topographic transport results in an anticyclonic gyre within the GAB (Fig. 8): a similar result was found earlier by Herzfeld and Tomczak (1999). There are two notable features of the circulation.

The first is that the poleward (seaward) Sverdrup transport converges with the equatorward deep ocean Sverdrup transport leading to downwelling along the shelf-break in the western GAB as illustrated in Fig. 9. Middleton and Platov (2003) cited profiles of CARS data to support the existence of such summertime downwelling. The second feature of note is that the convergence of the Sverdrup transports acts to raise sea level leading to an eastward shelf-break current – the SAC that flows as far as the Eyre Peninsula (Fig. 8). Evidence for this current during summer is also given by the SST anomalies of Ridgway and Condie (2004).

The thermohaline circulation associated with the mean summer hydrography also acts to enhance the anticyclonic gyre and associated SAC. During summer, the net heat flux acts to warm the coastal waters (Fig. 20) by about 4 °C over the winter values and in a surface mixed layer that is about 50 m deep (Fig. 24). Evaporation exceeds precipitation during summer, and the salinity increases from the winter values by about 0.2 psu in this surface layer. [We note that the estimates of surface heating (50 W m⁻²) and evaporation (1–2 mm/day) indicated by the NCEP/NCAR climatology (Table 1) are uncertain: Herzfeld (1997) has shown that the heat...
flux should be larger (up to 100 W m$^{-2}$) so as to account for the warm water mass that is formed in the shallow waters of the north-west GAB (Fig. 14, plate 9).]

In the coastal waters, the density increase due to evaporation is less than the density decrease due to heating and lighter water is found within the GAB than during winter. Nonetheless, while the CARS data indicates that the warmest water ($20^\circ C$) is found in the GAB (Fig. 20), the water here is quite saline (36.4 psu) and density is again largest ($\sim 26$ kg m$^{-3}$) near the coast (Fig. 20, lower panel). The denser water nearer the coast and farther offshore should sit lower in the water column and enhance the westward CC and eastward (shelf-break) SAC. An estimate of the importance of the thermohaline circulation was given by Middleton and Platov (2003). They found that eastward currents of 3 cm/s will result if the shelf water is 0.2 kg m$^{-3}$ lighter than that farther offshore.

As in winter (see Section 3.2.2), the eastward shelf-edge SAC may act to reduce the amplitude of the underlying westward FC since the cross-shelf sea level gradient that supports the SAC opposes the pressure gradient that must exist to support the (geostrophic) FC. Again, the details of any reduction are unknown.

5.2.2. Circulation in the South Australian Sea

The likely summer mean circulation is illustrated by the numerical model results of Middleton and Platov (2003) shown here in Fig. 21. The shelf currents are generally to the north-west and largest (up to 10 cm/s) where the shelf is narrow – the Eyre Peninsula, Kangaroo Island and Robe.

The model 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

![Satellite derived SST during an upwelling event of 2 March 1995. The black curve denotes the 200 m isobath and the temperature legend is at the top (courtesy of the CSIRO).](image-url)
to the west. The latter broadly follows the 100 m isobath (not shown) and little exchange is indicated between
the gulfs and adjacent shelf.

The observational studies of Nunes Vaz et al. (1990) and Petrusevics (1993) also find little gulf-shelf
exchange during summer and the mechanism for this is thought related to the density minimum found near
the mouth of the gulfs. This local minimum is not evident in the surface CARS data (Fig. 20, lower panel),
where the temperature and salinity fronts near the mouth of the gulfs compensate to yield a surface density

Fig. 20. The CARS surface climatology for summer. Upper panel: temperature (interval 1 °C); mid-panel: salinity (interval 0.2 psu); lower
panel: density (interval 0.2 kg m⁻³). The dotted line is the 250 m isobath. The white numbers indicate the largest values found in Spencer
Gulf.
The density minimum near the gulf mouths. In this situation, a gravity driven convergence of bottom density currents can occur, leading to localised upwelling near the mouth of the gulfs, as evidenced by the formation of sea surface temperature fronts (e.g., Fig. 19). This upwelling is thought to effectively isolate gulf and shelf waters during summer (Petrusevics, 1993).

Support for the above and the model of the mean shelf circulation (Fig. 21) comes from two sources. The first source is the summer-averaged current meter results (sites E, F, G and S) indicated by the solid vectors in Fig. 21: a weak north-westward and onshore flow is indicated. Model currents nearer the surface (Middleton and Platov, 2003) are also in agreement with current meter data. These indicate a similar circulation pattern that is larger in magnitude, with currents of up to 20 cm/s. The CARS data also provides support for the circulation described above. In Fig. 22, the December–February climatology of bottom temperature is presented. It shows the sites for deep upwelling (depths ~200 m) to be located off the south of Kangaroo Island and the Bonney Coast. [The original data used in the CARS climatology was supplemented by SARDI data and XBT transects, and have been re-interpolated onto the bottom topography to separate out the effects of El Nino events. The results in Fig. 22 were obtained using summer data for non-El Nino and El Nino years, respectively.]

A surface signature of upwelling also occurs off the Eyre Peninsula as shown in the SST data in Fig. 19. The model circulation indicates that this water results from deep upwelling to the south of Kangaroo Island and subsequent north-westward drift. This scenario is consistent with the bottom temperature data presented in Fig. 22a. Indeed, Kaempf et al. (2004) noted that the scale of north-westward drift is too small to explain the simultaneous appearance of cold upwelled water off both Kangaroo Island and the Eyre Peninsula: water upwelled from 150 m or more off Kangaroo Island cannot reach the surface off the Eyre Peninsula during a
More recently, McClatchie et al. (2006) concluded that the colder water found to the west of Kangaroo Island (e.g., Fig. 22a) 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 (Fig. 19), the upwelled surface water off the Eyre Pen-

Fig. 22. (a) The (revised) CARS climatology for bottom temperature and for the December to February period. Only water of temperature 12–15 °C has been contoured (intervals indicated) for clarity and the 100 and 200 m isobaths are indicated by the dark lines. El Nino summer years of data have been excluded. (b) As in (a) but for El Nino years only (courtesy G. Platov).

single upwelling event. More recently, McClatchie et al. (2006) concluded that the colder water found to the west of Kangaroo Island (e.g., Fig. 22a) 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 (Fig. 19), the upwelled surface water off the Eyre Pen-
insula 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 paths shown in Fig. 21 and little exchange occurs with the very warm waters of the Gulf.

There is another scenario suggested by Herzfeld and Tomczak (1999). In their numerical study, they found that under conditions of very large wind stress (0.35 Pa) and curl within the GAB, bottom boundary layer advection by intense shelf currents (~50 cm/s) can 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 from the shelf-break of the GAB itself. Griffin et al. (1997) also note that upwelling is sometimes found along the western Eyre Peninsula even though the winds are not otherwise upwelling favourable. However, the climatology of bottom temperature shown in Fig. 22a does not support the general occurrence of deep shelf-break upwelling directly off the Eyre Peninsula.

6. Summer upwelling, weather-band circulation, coastal-trapped waves and recirculation features

6.1. Summary

The coastal upwelling described by the climatological data above of course does not result from the mean or average flow, but rather from two to four upwelling wind-driven upwelling events occurring between December and March. The associated coastal wind stress of 0.1 Pa or more, in conjunction with wind-forced CTWs, lead to upwelling of water from depths of 150 m off Kangaroo Island, and 250 m off the Bonney Coast. These two regions appear to be the sites of deep shelf-break upwelling, and the alongshore velocities of order 25–40 cm/s can transport water up to 200–400 km over a 10 day period. Water is transported as far as the Eyre Peninsula. The reason for the very deep upwelling off the Bonney Coast is unknown, although CTW scattering and dissipation by the Gulfs and Kangaroo Island may be important for the set-up and degree of upwelling. The upwelling also results in surface plumes of cold water (Figs. 12 and 19) and secondary recirculation features are expected near fronts, islands, bays and headlands.

6.2. Discussion

Upwelling can arise from the presence of high-pressure systems that sit in the South Australian Basin for 3–10 days with upwelling favourable wind stresses of order 0.1–0.2 Pa (Griffin et al., 1997). These stress values are 2–4 times larger than the summer average used to obtain the “mean” circulation model results shown in Fig. 21. The winds act to lower sea level, generate CTWs and can lead to upwelling.

In the west, and to the immediate south-east of Cape Leeuwin, such events can drive near-shore currents of up to 50 cm/s and upwelling – the current here forms part of the Capes Current (Gersbach et al., 1999) that rounds Cape Leeuwin and lies inshore of the (weaker) summertime LC.

In the east, and for the South Australian Sea and Bonney Coast, the r.m.s. and maximum currents are 20–50 cm/s (Table 2), indicating that the CTW (and inertial) variability can be large. Indeed, this is borne out by time series of a typical upwelling event off the Bonney Coast (Fig. 23). The data (Schahinger, 1987) describes a March 1983 upwelling event and was obtained from (see Fig. 21) site B (24 m depth, water depth 50 m) and site A (18 m and 110 m in 140 m of water). Note that 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 of order 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 by 2.5 °C to values of around 11–12 °C. This water has an equilibrium depth of about 200 m (Schahinger, 1989) indicating upwelling of at least 180 m. At the offshore site A, thermistor string data (not presented) show 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 is 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 for the 19–22 of March period, 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) are highly correlated ($r = 0.85$, 12 h 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 Fig. 24.

Further insight into the circulation and upwelling is given by the numerical solutions for the weather-band circulation obtained by Middleton and Platov (2005) 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 in a plot of bottom temperature (Fig. 25). Plumes of water (<13 °C) are upwelled to the south of Kangaroo Island and Robe. By 6 February, the upwelling favourable winds had ceased. In agreement with the CARS data, plumes of cold water moved to the north and the west of Kangaroo Island as well as to the north-west of Robe (Bonney Coast). The overlying currents are of order 25 cm/s. Over 10 days, such currents can advect water by at most 200 km, but not quite 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 the Bonney Coast, the upwelling is larger, with 13 °C water upwelled by 250 m and from depths of 275 m: the scale here is somewhat larger than that inferred from observations above (140–190 m). The deep upwelling off the Bonney Coast may well supplement the upwelling that occurs in the canyons of the region.

6.3. Coastal trapped wave scattering and Bonney Coast upwelling

The reason for the very deep, localised upwelling off the Bonney Coast is unknown although it may be related to CTW scattering and dissipation expected to occur due to the topographic irregularities of the Gulf’s and Kangaroo Island. Such scattering and dissipation can be most important in regulating the set-up and degree of wind-forced upwelling (e.g., Suginoohara and Kitamura, 1984). For steady winds, Middleton and Leth (2004) have shown that the strongest upwelling occurs where the initial CTW field has been completely dissipated. In this case, divergence of the alongshore CTW velocity field cannot “feed” the offshore surface Ekman transport. The upwelling then resembles “classical” two-dimensional wind-forced upwelling. Results from a numerical model show that the strongest upwelling of the region is found off the Bonney Coast and is largely two-dimensional (Middleton and Platov, 2003). By implication, CTWs may be significantly scattered farther to the west. As noted in Section 4, results from coastal sea level data and weather-band models (McInnes and Hubbert, 2003; Middleton and Platov, 2005) also suggest that scattering by the gulf’s and promontories is important.

6.4. Upwelling, recirculation and ecological implications

In many other areas of the world oceans, small-scale upwelling and re-circulation features are important to marine ecologies. Such features include fronts, island wakes, sea-mounts, headlands, canyons and cold water filaments (e.g., Summerhayes et al., 1995). While there are almost no observations for the region here, we can speculate on the possible importance of some of these.

A feature of the upwelled plume to the west of the Bonney Coast (Figs. 11 and 19), is that downwelling (upwelling) is expected on the seaward (shoreward) arms of the surface cold water filaments (Haidvogel et al., 1991). Such local upwelling/downwelling systems have been implicated elsewhere in the maintenance of local ecological systems.

Fronts exist both along the shelf-edge, the mouth of Spencer Gulf as well as along the edges of the cold upwelled plumes as indicated in Fig. 19. In addition, fronts within the GAB occur between the boundaries of the warm water pool formed in the north-western GAB (Fig. 14; plate 9) and the colder upwelled water
that is advected to the west by the (weak) mean coastal summer drift. A general feature of fronts is that they can support recirculation cells whereby water is upwelled near the coast, but downwelled farther offshore (e.g., Mooers et al., 1976). The GAB is also characterised by a very strong summer sea-breeze (\(\sim 10 \text{ m/s}\)). Such a breeze will act to amplify the magnitude of the alongshore (upwelling) wind stress and may lead to a similar recirculation feature: upwelling near the coast and downwelling farther offshore, where the sea-breeze vanishes.

The local curvature of the coastline (such as off Kangaroo Island and the Eyre Peninsula), may also lead to upwelling (e.g., Arthur, 1965) as well as headland eddies that can entrain water into shallower regions. As noted in Section 2.4, the ubiquitous canyons of the region (Fig. 12), may also be important to deep (600 m) slope upwelling and in the maintenance of local ecological systems.

Fig. 25. Bottom temperature and velocity from the numerical model of the weather-band circulation and upwelling (Middleton and Platov, 2005). Upper panel: Results for 27 January 1999 (JD 392 1998). Lower panel: Results for 6 February 1999 (JD 402 1998). A reference vector of 5 cm/s is indicated and the curved arrows of circulation were obtained by local interpolation. Only water with temperatures between 12°C and 18°C is colour contoured.
Island wakes can also lead to localised upwelling and these may be significant around Neptune Island during summer when nutrients are more likely to be present and not generally ventilated to the ocean surface. Other topographic features that may be important include sea-mounts and any abrupt changes in shelf topography. Flow over these features can be blocked or lead to upwelling and/or recirculation features.

7. El Nino events

7.1. Summary

ENSO events occur at intervals of 4–7 years, originate in the Pacific and affect the circulation, upwelling and downwelling of the western and southern shelves of Australia. For the Australian region, the depressed sea level and raised thermocline in the west Pacific is transmitted around Papua and New Guinea and down the West Australian shelf as a slope-trapped wave (Clarke and Van Gorder, 1994). Observations show that the wintertime LC and mean shelf currents are reduced during the onset of strong El Nino events leading to a reduction in stocks of Australian Salmon off South Australia: these fish rely on transport by the winter eastward “conveyor belt” during their larval stage. Limited observations obtained during summer show that the thermocline may be raised by 170 m during these events, although the ecological implications are unknown.

7.2. Discussion

Definitive evidence exists for the importance of El Nino events in the western shelf circulation of the Americas (Pizarro et al., 2001). In the Australian context, the studies by Bye and Gordon (1982) and Pariwono et al. (1986) were the first to show that anomalously low (high) sea level events along the western and southern shelves are related to El Nino (La Nina) 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 LC increases by 25% or 1 Sv between El Nino and La Nina events.

Pairs of El Nino and non-El Nino year shelf current data for the South Australian Sea are presented in Table 2. These (limited) data indicate that the mean wintertime currents may be largely shut-down (from 20 to 5 cm/s) during El Nino winters (Middleton et al., 2007). Surprisingly, during El Nino summers, there does not seem to be a corresponding increase in the mean currents. Middleton et al. (2007) suggest that the explanation for this asymmetry involves the thermohaline circulation of the reduced winter inflow of warm LC water and enhanced cold water upwelling during summer. These authors also find that the El Nino related changes in sea level and currents are not primarily induced by changes in the local winds. Indeed, there does not appear to be any strong correlation between the El Nino nino3.4 index, and the upwelling component of summer wind stress (Fig. 13) or the Sverdrup transport (Fig. 7).

Li and Clarke (2004) used altimeter and coastal sea level data to also show that the eastward shelf-slope currents would be reduced (enhanced) during El Nino (La Nina) events. For the South Australian region, the change was estimated to be small, of order 4 cm/s and much smaller than that indicated by the shelf current meter data in Table 2.

Middleton et al. (2007) examined all available hydrographic data from the South Australian coast for El Nino effects. As illustrated by their temperature profile data from the El Nino summers 1998 and 2003 (Fig. 26), the 11.5 °C isotherm is raised by 170 m from its equilibrium depth of 250 m off Kangaroo Island. This 80 m deep water is also two standard deviations cooler than the mean indicating it to be drawn from different (El Nino) population. The results are qualitatively consistent with that found for the west Pacific Ocean, where colder water lies at shallower (deeper) depths during El Nino (La Nina) events. Middleton et al. (2007) cite data from the Bonney Coast that show similar results. The results in Fig. 26 also indicate that anomalously cold water was also found on the shelf during the non-El Nino summer of 1999. A possible reason for this is that 1999 follows the very strong 1998 El Nino event and the 1999 upwelling favourable winds were amongst the largest for the 1962–2004 period (e.g. Fig. 13).

A more stunning representation of the enhanced upwelling is shown in Fig. 22 where the average bottom temperature for summer is presented for non-El Nino and El Nino summers. During El Nino years, the bot-
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. Typically, this water is found at depths of 200–250 m (Fig. 26).

Theories for how ENSO events are transmitted to and affect coastal ocean circulation have been developed almost exclusively by Clarke and co-workers (e.g. Clarke and van Gorder, 1994; Pizarro et al., 2001) although we do not yet have a theory that tells us what the El Nino signals look like and what their impact is on the circulation and upwelling off South Australia. The data would indicate that El Nino effects are large.

8. Surface waves, tides and inertial waves

8.1. Summary

Surface wave swell of the region generally propagates from the south-west with significant wave heights of 2–3 m and characteristic wavelengths of 90–130 m. Orbital speeds at a depth of 50 m are typically 0.1 m/s, but can reach values of 0.2–0.4 m/s when the significant wave heights exceed 6 m (10 days each year). The surface Stokes drift of 0.15 m/s (400 km/month) provides a significant onshore path of transport. Within the gulfs, the wave swell is refracted by the topography. Tidal currents on the shelf are generally small (<10 cm/s). Within Spencer Gulf, the semi-diurnal tide is amplified with currents exceeding 50 cm/s and the mixing is important to the winter flushing of Gulf water onto the shelf. Strong tidal currents are found in the shallow waters of Backstairs Passage. In addition, the two semi-diurnal tides (S_2 and M_2), have similar amplitudes leading to a “dodge” tide within the gulfs whereby maximum tidal currents (mixing and flushing) occur at approximately same time each day. The nature and role of internal tides on the shelf-slope is unknown. Inertial wave currents are found to be relatively large (20 cm/s) off the Bonney Coast and may be important to surface mixed layer deepening.
8.2. Surface waves

The South Australian Sea has a mixed wind wave/swell environment in which at any location the sea-state rapidly ‘deteriorates’ during the passage of fronts and low pressure systems, and then gradually ‘moderates’ as anticyclonic conditions return. An important feature is that the spectra of the swell and wind waves are often uni-modal (Provis and Steedman, 1985): the storm belt lies sufficiently close to the coastline so that a bimodal spectrum does not have the opportunity to develop (Young and Gorman, 1995). This characteristic is clearly shown in the predictions of the Australian Bureau of Meteorology Southern Ocean wave model (Bureau of Meteorology, 2006).

Table 3 shows the wave climatology (obtained from a similar wave model) in the deep ocean adjacent to the Southern Shelf for February and July (Caires et al., 2005), in which the wave speed \( c \), wavelength \( \lambda \) and the three particle velocities – the surface orbital velocity \( U_o \), the bottom (50 m) orbital velocity \( U_b \) and the Stokes surface drift velocity \( U_d \) – have been calculated from deep water gravity wave theory. The wave drift velocity is predominately in an onshore direction. The mean speed, of about 0.15 m s\(^{-1}\), indicates that over a period of a month, surface biota can be advected shorewards by a distance of about 400 km – a scale which exceeds the shelf width. The possible importance of this wave drift ‘conveyor belt’ is not yet known. Caires et al. (2005) also 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 orbital velocities on the open continental shelf will therefore exceed 0.2 and 0.4 m s\(^{-1}\) over these periods, leading to a significant sediment re-suspension. These results are augmented by the observations that were obtained south of Portland (water depth 1395 m) by Wood and Terray (2005) and for the April–September period of 2004. They found the waves to have a significant wave height of 3.7 m, period 13 s and to be directed from the south-west. Wave heights exceeded 8 m for 1.3% of the time, and 5 m for 17% of the time.

The propagation of the Southern Ocean swell into the shallow water of the South Australian Sea has also been investigated using the SWAN (Simulating Waves Nearshore) wave model (Hemer and Bye, 1999). It was found that the geography is the main control on the swell events. For the typical south-west swells, the normalised wave height and directions illustrated in Fig. 27 shows there to be refraction around the north of Kangaroo Island (Investigator Strait; Fig. 17). A westerly swell penetrates directly into Investigator Strait and is refracted into Spencer Gulf along the western coast of Yorke Peninsula. Investigator Strait is well protected from south-easterly swells (more typical of summer conditions), which are refracted into Spencer Gulf on the eastern coast of Eyre Peninsula. The model predicts that westerly and south easterly deep ocean swells of height 6 m, give rise to swells in the surf zone (water depth 10 m) off Adelaide with heights 0.7 and 0.4 m, respectively, and bottom orbital velocities of 1.0 and 0.6 m s\(^{-1}\). Thus, their effect on sediment re-suspension is at least as important as in the deeper water of the open shelf.

8.3. Tides

The diurnal tide propagates as a Kelvin wave from west to east without any appreciable shelf resonance (Irish and Snodgrass, 1972). On the shelves, the semi-diurnal tidal current is generally small (<10 cm/s) (Hahn, 1986; Schahinger, 1989). We are unaware of any studies of internal tides along the steep shelves of the region. The shelf data of Hahn (1986) indicate that the tides are not strongly depth-dependent. The semi-diurnal tides dominate within the gulfs (Table 4), since these are almost resonant: Gulf St. Vincent exhibits a quarter-wave resonance and Spencer Gulf a rare three quarter-wave resonance (Easton, 1970, 1978; Bowers and Lennon, 1989).

Table 3

<table>
<thead>
<tr>
<th>Month</th>
<th>( H_S ) (m) [( \sigma ) (m)]</th>
<th>( T ) (s) [( \sigma ) (s)]</th>
<th>( c ) (m/s)</th>
<th>( \lambda ) (m)</th>
<th>( U_o ) (m/s)</th>
<th>( U_b ) (m/s)</th>
<th>( U_d ) (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>February</td>
<td>2.25 [0.45]</td>
<td>7.5 [1.8]</td>
<td>11.7</td>
<td>88</td>
<td>1.9</td>
<td>0.05</td>
<td>0.16</td>
</tr>
<tr>
<td>July</td>
<td>2.75 [0.90]</td>
<td>9 [1.8]</td>
<td>14</td>
<td>126</td>
<td>2.0</td>
<td>0.16</td>
<td>0.14</td>
</tr>
</tbody>
</table>

The surface and bottom water velocities are denoted by \( U_o \) and \( U_b \) the (Stokes) drift velocity by \( U_d \). The standard deviations (\( \sigma \)) of \( H_S \) and \( T \) are also presented: units meters.
These resonances lead to tidal velocities of more than 50 cm/s (e.g., Bills and Noye, 1986; Nixon and Noye, 1999) and intense vertical mixing within the gulfs. An important feature of the semi-diurnal tide is that the $S_2$ and $M_2$ constituents have almost equal amplitudes, leading to a marked spring-neap cycle in which at neaps, the tidal signal is almost absent. This is known as the dodge tide (Chapman, 1892). The spring-neap cycle arises from the addition of the $S_2$ and $M_2$ constituents of similar frequencies $\omega_S$ and $\omega_M$, which modulates the amplitude of the semi-diurnal wave on a frequency $\omega = \omega_S - \omega_M$ and period 14.8 days.) Near Thevenard on the Great Australian Bight there is also a remarkable ter-diurnal tide (approximately 8 h) that appears to be due to a Poincare wave resonance in the deep ocean amplified by a quarter-wave shelf resonance (Hutchinson, 1988).

Table 4
Tidal constants for Adelaide and Port Augusta: tidal elevation amplitude ($a$), tidal current amplitude ($U_0$) [northerly component] and phase lag ($\varphi$) with respect to local time

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Sea level</th>
<th>Velocity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$a$ (cm)</td>
<td>$\varphi$ ($^\circ$)</td>
</tr>
<tr>
<td><strong>Adelaide</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_2$</td>
<td>50</td>
<td>105</td>
</tr>
<tr>
<td>$S_2$</td>
<td>49</td>
<td>176</td>
</tr>
<tr>
<td>$O_1$</td>
<td>16</td>
<td>24</td>
</tr>
<tr>
<td>$K_1$</td>
<td>25</td>
<td>50</td>
</tr>
<tr>
<td><strong>Port Augusta</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_2$</td>
<td>62</td>
<td>206</td>
</tr>
<tr>
<td>$S_2$</td>
<td>64</td>
<td>257</td>
</tr>
<tr>
<td>$O_1$</td>
<td>25</td>
<td>39</td>
</tr>
<tr>
<td>$K_1$</td>
<td>45</td>
<td>73</td>
</tr>
</tbody>
</table>

Adelaide: elevation from Outer Harbour, current from approximately 5 km west of Adelaide coastline, water depth 19 m (Bowers and Lennon, 1990). Port Augusta (head of Spencer Gulf): elevation from Port Augusta power station, current from under the abandoned road bridge (Schluter et al., 1995). The semi-diurnal phase difference of about 90° between the elevation and current for Adelaide indicates a standing oscillation in which the tidal energy is totally reflected, and the phase relation between elevation and current at Port Augusta indicates a northward propagation of tidal energy that is dissipated in the samphire and mangrove environment at the head of Spencer Gulf.
The tidal resonance in Gulf St. Vincent (in which the semi-diurnal constituents have very nearly the same amplitude) has received particular theoretical attention in the elegant analysis of Bowers and Lennon (1990). The near equality of the two (dominant) semi-diurnal tidal constituents in the resonant environment of the gulfs has two important consequences.

First, high water (or any other phase of the tide) occurs at approximately the same time twice a day (around spring tides). For example, at Adelaide (where the local phase of $S_2$ is approximately 180°), high water occurs at about 6 a.m. and 6 p.m. This situation implies that tidal stirring and flushing of the benthos has a well-defined rhythm, since these currents are maximal at about 12 a.m. and 12 p.m. every day: the biological implications of this are unknown. Similarly, at the head of Spencer Gulf, where the largest tides of the region occur (Schluter et al., 1995), the local phase of $S_2$ is approximately 270°, and high water usually occurs at 9 a.m. and 9 p.m. as a sudden onset (almost bore-like) in the very shallow waters of the mangrove and samphire environment.

Second, the absence of tidal stirring during neap tides (every 14.8 days), allows the water column to re-stratify and is implicated in the flushing of the gulfs occurs through two mechanisms. The first is geostrophic adjustment, whereby the fresher (saltier) vertically well mixed water on the western (eastern) side of the gulf relaxes and rotates in a cyclonic fashion. This draws fresh water in off the Eyre Peninsula and expels saltier water out, off the Yorke Peninsula (e.g., Nunes Vaz et al., 1990; Fig. 17). The second involves the formation and gravitational acceleration of salt wedges. de Silva Samarasinghe (1998) gives an admirable summary of the interplay of the two mechanisms in upper Gulf St. Vincent, where geostrophic adjustment accounts for about 75% of the flushing and 25% is due to the formation of salt wedges. This latter contribution may potentially be important for rapid removal of pollutants during the 3–4 day period around neaps. The criteria for salt wedge formation in Gulf St. Vincent and Spencer Gulf have also been investigated in theoretical studies (Bye, 1986; Nunes and Lennon, 1987).

8.4. Inertial waves

The analyses of data off Robe (e.g., Fig. 15; sites A and B) by Schahinger (1987) show that inertial wave currents can be relatively large (20 cm/s) and persist over 2–5 inertial periods. The currents change sign below the surface mixed layer and are set-up by the frequent passage of cold fronts and associated abrupt changes in winds. Wood and Terray (2005) find a similar result from their current data obtained south of Portland (water depth 1395 m). Farther to the west, the analysis of Hahn (1986) indicates inertial currents to be smaller (~5 cm/s) and also confined to the surface mixed layer: they are absent during winter when the water column is mixed to depths of 150–200 m. Elsewhere, inertial waves are known to be important for the deepening of the surface mixed layer.

9. Summary, uncertainties and future research

The Southern Shelf and slope region of Australia hosts a complex and inter-related circulation system that is strongly influenced by local winds, heating and evaporation as well as by remote forcing from the West Australian shelf and Southern Ocean.

Our understanding and ability to predict the tidal circulation within the gulfs is reasonably well established, although our knowledge of internal tides and solitons over the shelf-slope is non-existent. Idealised numerical studies such as those advanced by Holloway (1999) might be a useful and cost-effective starting point.

On the shelves, we have a first order understanding and description of the winter and summer circulation, although observational studies are few. Uncertainties remain, notably in the component of circulation associated with the thermohaline forcing that arises from the atmospheric fluxes of heat and freshwater. Seasonal climatologies of the latter are poor within the GAB and there is a clear need for both improved atmospheric data as well as process-orientated studies that can detail the importance of the thermohaline circulation.

Nonetheless, during winter, the eastward shelf circulation of the Leeuwin and South Australian Current is reinforced by the winds. This is important for the seasonal transport of marine biota along and across the shelf. The intense ocean weather (or CTWs) is likely to be important to scouring of the benthos and sediments. The possibility of resonant wind forcing of CTWs needs investigation and may be important to occasional
storm surge events. The dense water outflows from Spencer Gulf (and GAB) and semi-permanent eddies may be important for cross-shelf exchange. The onshore Stokes drift of the 2–3 m swell may also provide an important path for onshore transport. Further data and studies are needed to detail the nature of these circulation features.

During summer, a westward wind-driven shelf current is found near the coast, while near the shelf-edge, the South Australian Current is to the east. Both currents appear to be enhanced by the thermohaline circulation of the density field although further research is indicated. The South Australian Current appears to result from the convergence of Sverdrup transports along the shelf-break. This convergence can result in shelf-break downwelling in the western GAB that opposes the wind-forced upwelling. Upwelling does occur farther to the east and off the Bonney Coast and Kangaroo Island and is important to the ecology of the region. Our understanding of upwelling here is again derived from a few studies and many questions remain as to the details and dynamics of this important system. For example, why is upwelling apparently stronger off the Bonney Coast and why does it appear to begin at Portland? Where does the upwelled water come from and what is the role of local winds, CTWs, the FC, topography and canyons? How intermittent is the pool of nutrient-rich cold water off Kangaroo Island and how important is it to inhibiting the gulf-shelf exchange of water? Idealised numerical studies could assist in answering these questions prior to the design of observational programs.

An additional area of great uncertainty is the nature and role of the shelf-slope circulation including the mesoscale eddies associated with the Flinders Current. The existence of the FC was inferred from dynamical considerations, numerical studies and only a handful of observational studies. Yet, the current may be important to deep upwelling in canyons along the entire Southern Shelf-slope as well as providing a deep-water transport path from east to west and into the Leeuwin Undercurrent.

Over inter-annual time scales, El Nino events in the western Pacific Ocean appear to reduce the eastward wintertime circulation on the shelf and raise the thermocline by up to 170 m during summer. These conclusions are however based on inferences from relatively short and disparate time series of data. Moreover, we do not have a theory for just how El Nino signals propagate from the western Pacific Ocean into the GAB. Clearly there is much to do in understanding the ocean circulation as it is affected by local and remote forcing and its relation to the ecological systems of the region. At the time of writing, the Australian Government has provided $50M for an Integrated Marine Observing System around Australia and about $5M for the southern shelves. The public domain data streams that will result will go a long way to furthering our knowledge of the region.

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