Understanding areas of high productivity within the South-west Marine Region

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Charitha Pattiaratchi

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School of Environmental Systems Engineering

The University of Western Australia

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SUMMARY

The Australia's South-west Marine Region between Shark Bay and Kangaroo Island can be classified as an oligotrophic environment because of the Leeuwin current's dominance. The Leeuwin current transports warm, low nutrient, low salinity water of tropical origin southwards, and its signature is found throughout the planning region. The Leeuwin current's presence also inhibits large-scale upwelling, common to other eastern ocean basins, despite the upwelling-favourable prevailing winds. In this oligotrophic environment, localised effects due to surface and subsurface current systems, strong winds, and a combination of topographic features (headlands, islands, submarine canyons, etc.) can produce regions of high productivity. Six such regions were identified in the south-west marine region between Shark Bay and Kangaroo Island: (1) the Perth Canyon; (2) the Albany Canyon group, including the Leeuwin Canyon; (3) the Kangaroo Island canyons and adjacent shelf break; (4) the Kangaroo Island "pool"; (5) predictable eddy fields; and (6) Cape Mentelle upwelling. The physical processes and ecological significance of these regions is summarised, and a list of available data sets is included.

The Perth Canyon and Kangaroo Island pool regions have been studied extensively, with data sets covering not only physical and chemical processes, but also ecological processes ranging from primary production to the locations of whale aggregations. In the regions of predictable eddy fields, physical and biological oceanographic data exist although there is no evidence of fish or whale aggregations in these regions. Limited physical and primary production data are available for the Cape Mentelle and Albany canyons groups. The Kangaroo Island canyons and the adjacent shelf break can be considered to be part of the Kangaroo Island pool.

1. INTRODUCTION

In general, regions along the eastern ends of ocean basins are highly productive ecosystems, supporting high primary productivity and large pelagic finfish stocks. This is due to the earth's rotation (the 'Coriolis' force) and shore-parallel equatorward winds upwelling cold, nutrient-rich water. Here, surface waters in the weak currents are deflected offshore and replaced by the upwelling of cold, nutrient-rich water from depth. Fluxes of "new" nitrogen (as nitrate) into the euphotic zone stimulate high primary production rates (Barber and Smith 1981; Mann and Lazier 1996). The proliferation of large (> 5-µm diameter) phytoplankton species helps develop a herbivorous food web (Cushing 1989; Legendre and Rassoulzadegan 1995), with a short trophic pathway causing the large finfish stocks common to eastern boundary currents (Cushing 1971).

Off the south-west Australian coast, however, although the prevailing wind regime is similar to other eastern ocean margins, the waters have little nutrients and low primary production (oligotrophic). However, under certain conditions, for example, under higher winds during the summer and/or interaction between surface and subsurface currents and topographic features (submarine canyons), regions of higher productivity are present along the coast. This report reviews six regions in the South-west Marine Region between Shark Bay and Kangaroo Island (Figure 1.1):

(1) Perth Canyon
(2) Albany Canyon group, including the Leeuwin Canyon
(3) Kangaroo Island canyons and adjacent shelf break
(4) Kangaroo Island "pool"
(5) predictable eddy fields
(6) Cape Mentelle upwelling.

The attributes of these regions are summarised in Table 1. It should be noted that the processes that are discussed refer to the summer periods, where spawning and aggregations normally occur. Eddy fields, however, are active through the year, but are more intense in winter when the Leeuwin current is stronger. McClatchie et al. (2006) summarised the region's physical oceanography, including the seasonal variability of the current systems.

The Leeuwin current's dominance in this region has impacted on the marine productivity, extending the range of tropical species southwards (Morgan and Wells 1991) and producing some of the highest latitude coral reefs in the world (Hatcher 1991). Interannual variations in the Leeuwin current's strength, related to the El Niño – southern oscillation cycle, have shown empirical relationships with recruitment patterns of invertebrates and finfish (Lenanton et al. 1991; Caputi et al. 1996). Pelagic planktivorous fish species, similar to those found in other eastern boundary current systems, are present in the south-west bioregion, but the commercial catch of these species is low. For example, in the Humboldt current, the commercial catch of finfish is around 13 million tonnes a year, whereas off the WA coast the catch is < 0.001 million tonnes a year. As the Leeuwin current is low in nutrients, and because of the absence of upwelling, the main input of nutrients to the region is through runoff, groundwater, and inshore biological processes during the winter (Pearce et al. 1985). Thus the main finfish resources are confined to the region inshore of the Leeuwin current. However, localised, high productivity regions can influence the secondary and tertiary production.

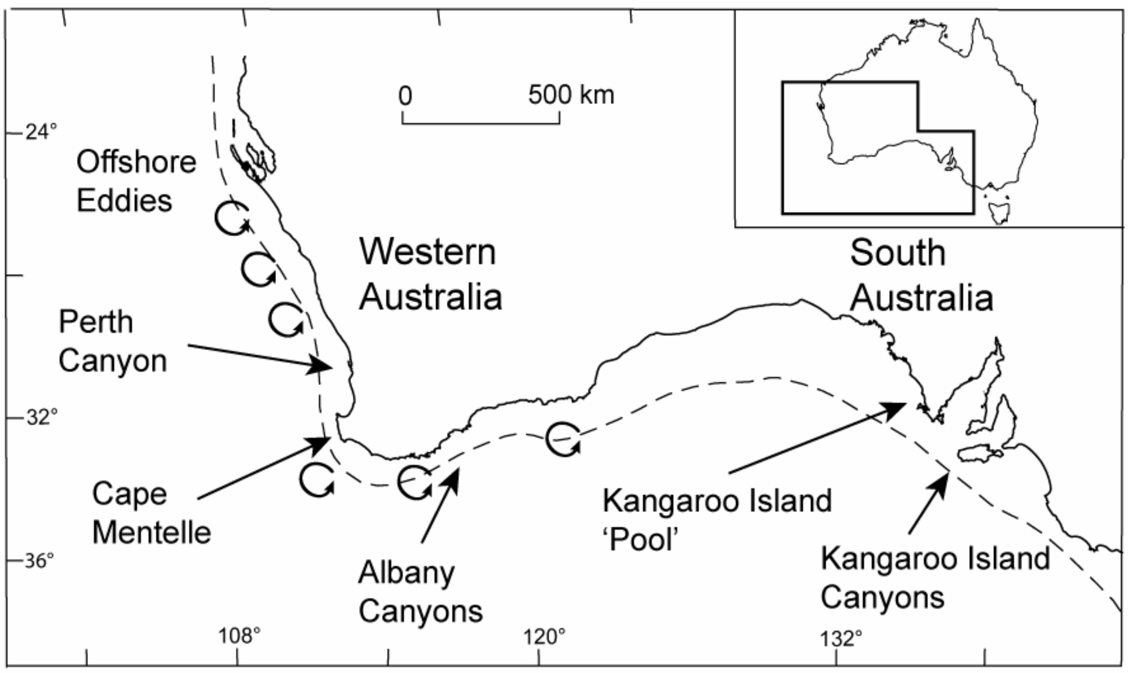

Figure 1.1. High productivity locations in the south-west marine region.

Table 1. Summary of high productivity regions in the south-west marine region and their main attributes.

Key ecological feature/ region	Attributes
Perth Canyon and adjacent shelf break	**high productivity; feeding aggregations; unique seafloor feature.** The Perth Canyon is associated with deep upwelling, which enhances local productivity and attracts aggregations of marine life. The Perth Canyon is prominent among these canyons because of its size, location on the shelf and slope, and ecological importance. The Perth Canyon marks the southern boundary for many tropical species groups on the shelf, including sponges, corals, decapods, and xanthid crabs. Deep ocean currents upwelling in the canyon create a cold-water, nutrient-rich oasis under the warm waters of the Leeuwin current, and attract feeding aggregations of deep-diving mammals, such as pygmy blue whales and beaked whales, and large, predatory fish, which feed on aggregations of small fish, krill, and squid.
Albany Canyons group and adjacent shelf break including Leeuwin Canyon	**high productivity; feeding aggregations; unique seafloor feature.** The Albany canyons, comprising 32 canyons along 700 km of continental slope, are associated with small, periodic upwelling, which enhances productivity and attracts aggregations of marine life. Anecdotal evidence suggests these canyons support fish aggregations that attract toothed and deep-diving whales.
Kangaroo Island canyons and adjacent shelf break	**high productivity; feeding and breeding aggregations; unique seafloor feature.** The Kangaroo Island canyons, a small group of narrow, steep-sided canyons, are thought to be associated with seasonal upwelling, which enhances productivity and attracts aggregations of marine life to the shelf and shelf break. This upwelling is associated with aggregations of krill, small pelagic fish, and squid, which attract marine mammals (e.g. pygmy blue whales, toothed whales, dolphins, and New Zealand fur seals); sharks; large, predatory fish; and seabirds. Evidence suggests this is an area of enhanced productivity, where orange roughy, blue grenadier, and western gemfish aggregate and are thought to spawn (empirical evidence of high density orange roughy eggs from the area exists). The area is also thought to be an important pupping area for school sharks, and the adjacent shelf break is associated with high productivity of giant crab and southern rock lobster.
Kangaroo Island pool and Eyre Peninsula upwellings	**high productivity; feeding aggregations.** The Kangaroo Island pool and Eyre Peninsula upwellings are known to be associated with seasonal aggregations of marine life. The nutrient-rich upwelling enhances the production of plankton communities and supports seasonal aggregations of krill, small pelagic fish, and squid, which attract marine mammals (e.g. toothed whales, dolphins, and New Zealand fur seals); sharks; large, predatory fish; and seabirds.
Predictable eddy fields (several locations)	**high productivity; feeding aggregations.** Eddies and eddy fields form at predictable locations off the western and south-western shelf break (i.e. south-west of Shark Bay, offshore of the Abrolhos Islands, south-west of Jurien Bay, south-west of Cape Naturaliste and Cape Leeuwin, and south of Albany and Esperance). The region's mesoscale eddies are important transporters of nutrients and plankton communities, taking them far offshore into the Indian Ocean. Cyclonic eddies may also be important for "lifting" deep water, which can be cooler and richer in nutrients, towards the surface where it can enhance the production of plankton communities, which attract aggregations of marine life.
Cape Mentelle upwelling	**productivity (pelagic).** The Cape Mentelle upwelling draws nutrient-rich water from the base of the Leeuwin current (i.e. where nutrient levels are higher), up the continental slope, and onto the continental shelf, where it is characterised by phytoplankton blooms in the surface waters. Higher densities of phytoplankton form the basis of an extended food chain, characterised by aggregations of small pelagic fish, larger predatory fish, seabirds, dolphins, and sharks.

2. THE PERTH CANYON

Submarine canyons can be defined as steep-sided valleys on the seafloor of a continental slope. They are generally extensions of river systems, although not all submarine canyons are associated with rivers. A submarine canyon's influence on the circulation, and therefore ecology, depends on the valley configuration of the continental shelf and slope irrespective of the forcing characteristics of the circulation. Important parameters are the continental shelf depth, canyon depth below the shelf, canyon width, canyon length, canyon's distance from the coast, the canyon's intrusion into bay areas, and the depth of the canyon mouth. The interaction between shelf and slope current systems causes localised flow patterns, which influence the ecology in the canyon vicinity.

Compared with their nearby surroundings, submarine canyons have higher biodiversity and biological productivity (Hickey 1995). This is often attributed to upwelling at the canyon site enriching the photic zone with nutrients. Submarine canyons have been the focus of many studies encompassing physical and biological oceanography, sediment transport, biodiversity, and marine conservation. Their higher productivity means marine megafauna often inhabit or feed in them (Schoenherr 1991; Vetter and Dayton 1998; Hooker et al. 2002; D'Amico et al. 2003), making them important marine conservation areas.

The abrupt changes in the bottom contour's direction and depth on encountering submarine canyons can influence the continental shelf and slope currents. Generally, currents flow parallel to depth contours; however, when the change in the contour direction increases, the flow is forced to cross the depth contours. The changes in the water column depth change the potential vorticity (a measure of the water column rotation), forming eddies and meanders around the canyons. Eddies are often trapped around canyons and seamounts for the same reason. In the southern hemisphere, eddies with clockwise circulation are associated with upwelling, and anticlockwise circulation is associated with downwelling. Thus the flow direction over a canyon determines whether upwelling or downwelling occurs.

Studies undertaken in submarine canyons worldwide have shown submarine canyons have enhanced productivity and biodiversity. Studies of the Scripps and La Jolla canyons (southern California) showed the canyons had deeper communities than elsewhere along the continental slope. This pattern was attributed to the submarine canyons providing a better food source and bottom habitat (Vetter and Dayton 1998).

Allen et al. (2001) found an upwelling-favourable eddy trapped in the Barkley Canyon off the coast of Vancouver Island, Canada, which trapped zooplankton. Macquart-Moulin and Patriti (1996) found that, in some canyons off the French coast in the Mediterranean Sea, zooplankton species with diurnal migrations greater than the shelf depth accumulated over the canyons. Here, when the zooplankton migrated into deeper water, the canyon's funneling effect trapped them within the canyon.

Many submarine canyons have been associated with whale aggregations. Aggregations of blue whales have been observed in the Monterey Bay Submarine Canyon in California (Schoenherr 1991; Croll et al. 2000). More than ten species of cetaceans have also been observed in the Gully, a large submarine canyon off the coast of Nova Scotia, Canada (Hooker et al. 1999).

The Perth Canyon is an extension of the Swan River system, and cuts into the continental shelf west of Perth and Rottnest Island (Figure 2.1). The Perth Canyon, which starts at the 50-m contour, is ~100 km long and ~10 km wide near the canyon head, and reaches depths more than 1000 m. It is 3 km deep at the shelf slope, and cuts 4 km deep into the continental slope. The canyon "head" refers to the canyon's shoreward section, and the "tip" refers to the head's closest point to the coast. The canyon bends at 10 km and 50 km from the tip, and branches south at 40 km and 50 km (Figures 2.1 and 2.2). The bend at 50 km is referred to as the "dogleg". At the canyon head, the depth plunges from 200 m to 1000 m, with the canyon mouth opening onto the abyssal plain at a depth of 4000 m. Hence the Perth Canyon can be described as long, deep, narrow, steep-sided, and intruding into the continental shelf.

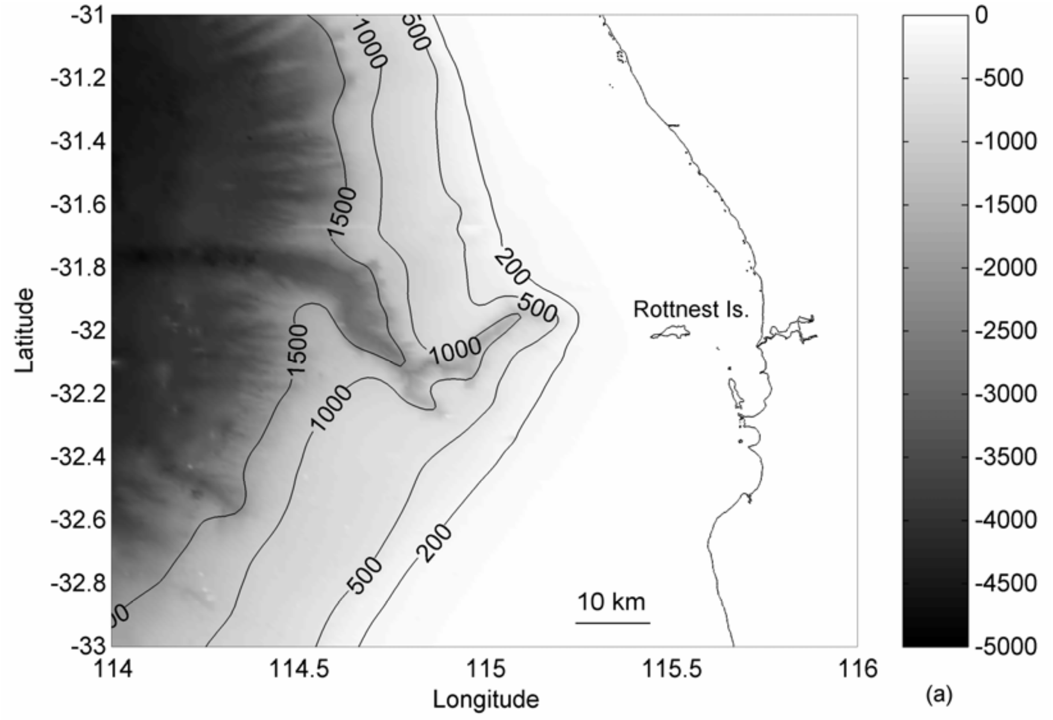

Figure 2.1. Location of the Perth Canyon (depth in metres).

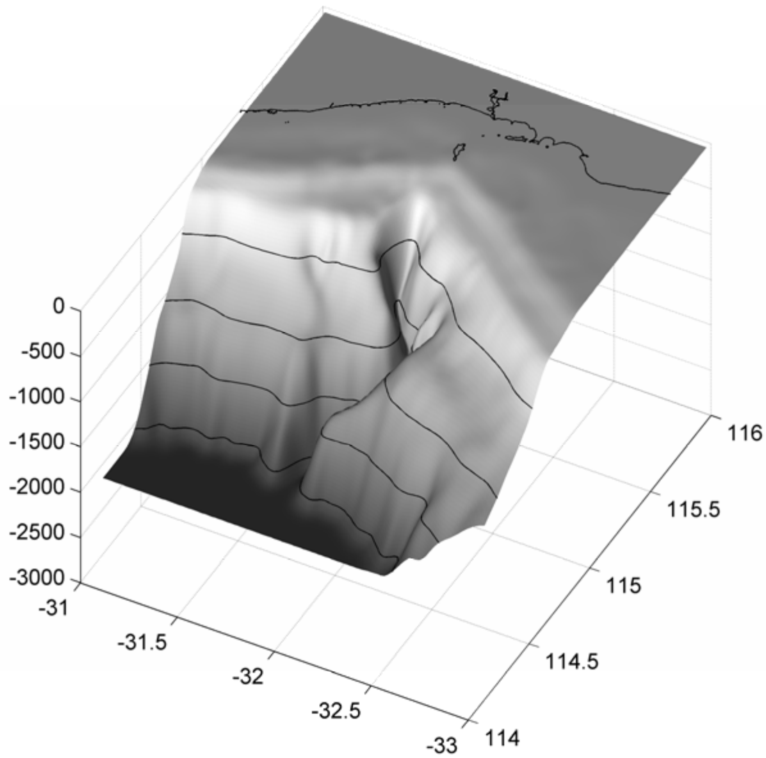

Figure 2.2. A three-dimensional view of the Perth Canyon (from Rennie et al. submitted).

2.1 Circulation (from Rennie et al. submitted, a,b.)

Numerical studies (Rennie et al. submitted(a)) and field measurements (Rennie et al. submitted(a)) have been used to describe the circulation in the Perth Canyon; these findings are summarised below.

The circulation in the canyon was temporally variable with few repeated patterns. Strong vertical stratification and current shear were present at 300–350-m depth—the interface between the southerly flowing Leeuwin current and the northward flowing Leeuwin undercurrent. Thus the canyon's influence on the Leeuwin current dynamics was limited to the canyon head. However, the curvature of the continental shelf in the canyon vicinity (Figure 2.1) and the separation of the Leeuwin current from the continental shelf formed anticlockwise eddies at the surface (Figure 2.3).

The Leeuwin undercurrent interacting with the canyon generated eddies. These eddies, which were formed over five to ten days, migrated offshore, and other eddies would form in the canyon. The eddies were clockwise, and thus favoured upwelling in their centre. Eddies sometimes recurred within the canyon, suggesting the canyon regulated the circulation, with several circular eddies present, both spatially and at different depths, in the canyon at any given time (Figure 2.3). Eddies formed in the canyon were first confined to the canyon and then migrated offshore; however, at least one eddy, even if it was weak, was present in the canyon at any given time.

Eddies caused regions of upwelling or downwelling, with deep upwelling stronger in the canyon than elsewhere on the shelf. Near-surface vertical transport was strong everywhere when wind forcing was present. The circulation in the canyon contributed to upwelling and downwelling, and produced upwelling to above 300 m, mainly at the head and along the canyon rims. Upwelling alone was insufficient to transport nutrients to the euphotic zone because the canyon rims are deep. Increased upwelling, combined with entrapment within eddies and strong, upwelling-favourable winds, caused the high primary productivity in the canyon. The Leeuwin current formed a strong barrier to the water upwelling to the surface. The model results also suggested upwelling at the canyon head occurred when a clockwise surface eddy was centred over the south rim, whereas an eddy (either clockwise or anticlockwise) centred on the north rim caused net downwelling.

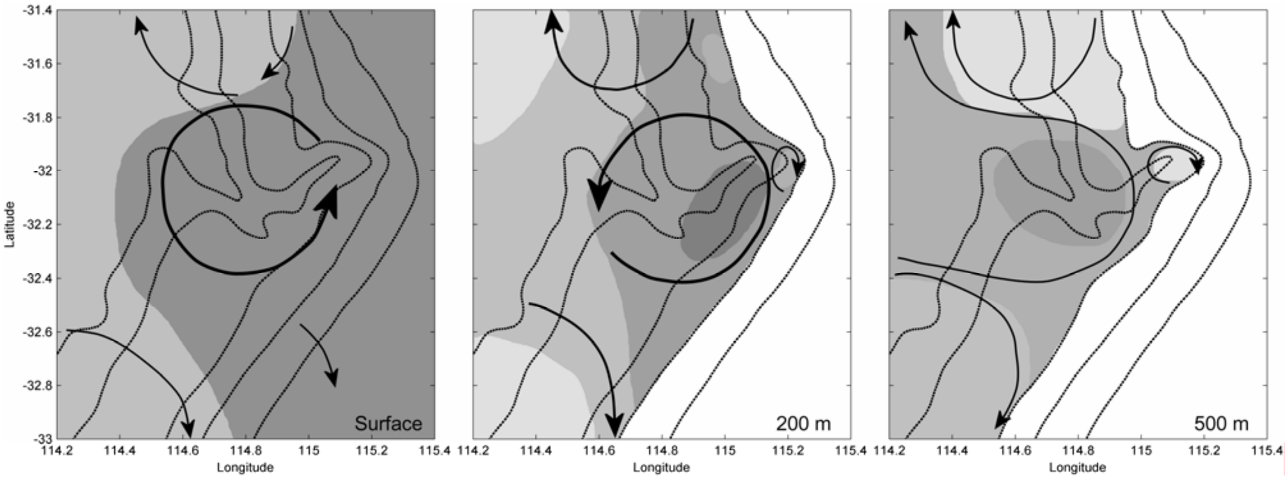

Figure 2.3. Example flow patterns in the Perth Canyon at the surface, 200 m, and 500-m depths. Shading indicates temperature, with lighter shades showing the upwelling regions (from Rennie et al. submitted(b)).

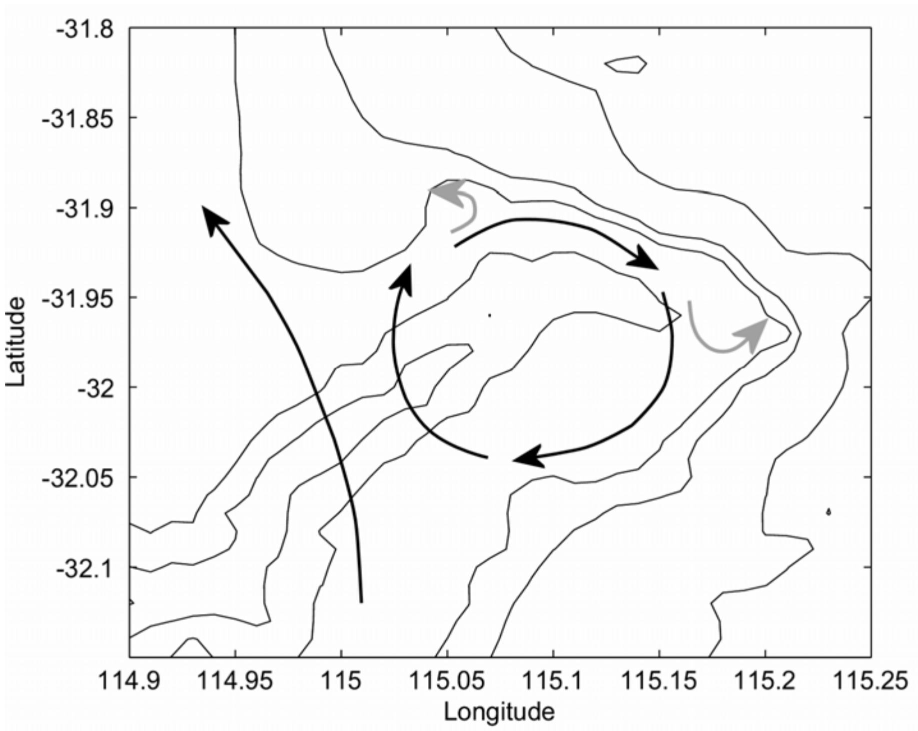

Figure 2.4. Typical flow patterns (at a depth of 500 m), present for at least half the time, in the Perth Canyon (from Rennie et al. submitted(b)).

2.2 Primary production (from Rennie et al. submitted(a)*)*

Primary production field data collected from the Perth Canyon and its surroundings are available from two oceanographic cruises. Voyage 1 (SS09/2003) took place in late spring 2003 (24 October–9 November) with Prof. C Pattiaratchi as the chief scientist. Voyage 2 (SS02/2004) took place in midsummer 2004 (29 January–4 February) with Dr R McCauley as the chief scientist. Both voyages were undertaken on the National Facility research vessel *Southern Surveyor*.

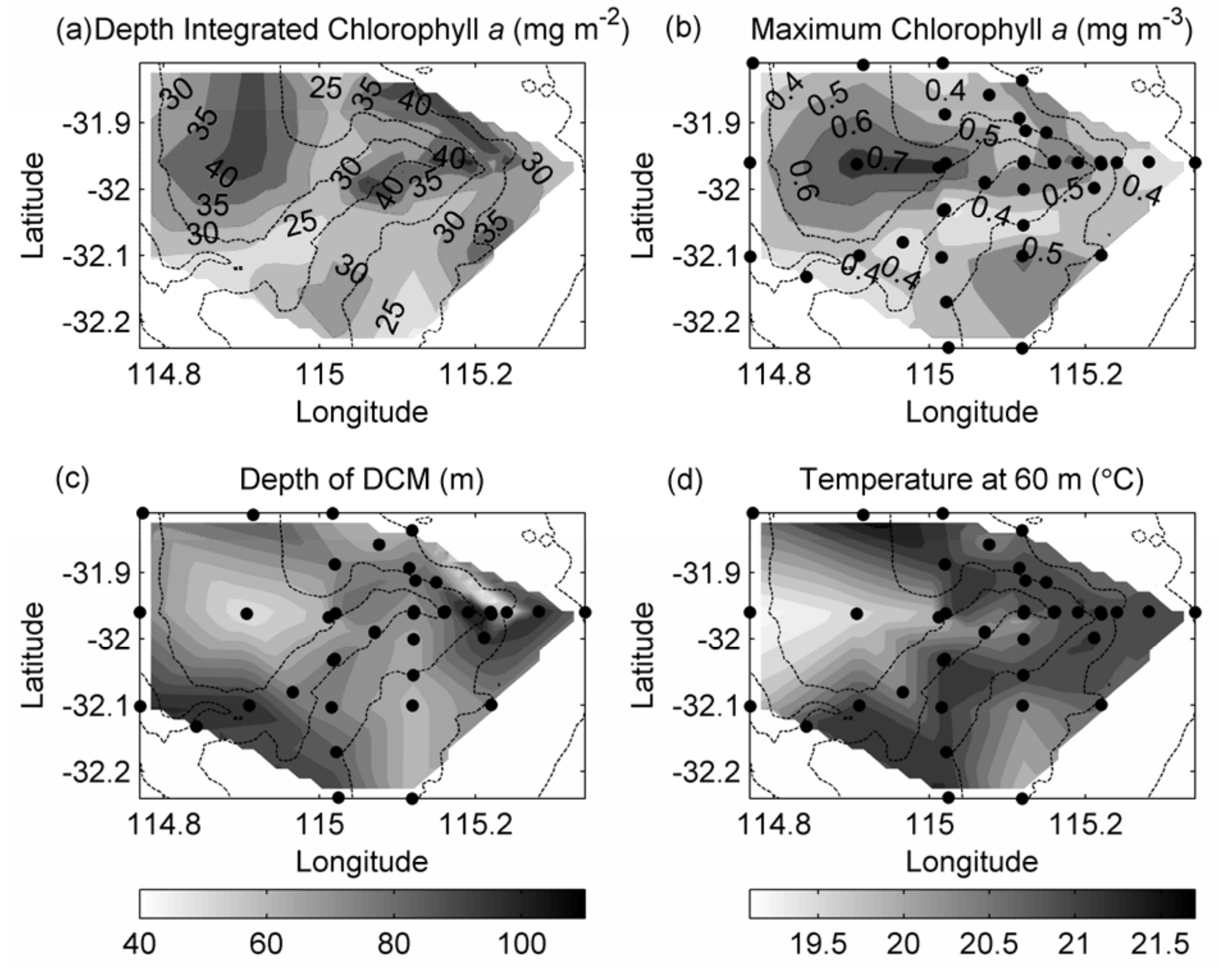

Figure 2.5. (a) Chlorophyll a integrated to the depth of the euphotic zone; (b) maximum measured chlorophyll a concentration for voyage 2; (c) depth of chlorophyll a maximum (in m); (d) temperature at 60 m—the approximate mean depth of the chlorophyll a maximum. Station locations are marked as (●) (from Rennie et al. submitted(a)).

Detailed spatial and temporal distributions of chlorophyll a patterns obtained on voyage 2 are shown in Figure 2.5. The chlorophyll a showed patchiness over the canyon on a scale of at least several nautical miles. Higher, depth-integrated concentration patches occurred near the head (mean 38 mg chl a m^{-2}), with other high values (up to 51 mg chl a m^{-2}) occurring on the rims (Figure 2.5a); these estimates were of a similar magnitude to those obtained in the canyon on voyage 1 (45–60 mg chl a m^{-2}; Twomey et al. in press). The depth of the maximum value was variable (Figure 2.5c), but the temperature implied a similar distribution to the chlorophyll maximum and its depth; that is, the chlorophyll concentrations were shallow (between 50 and 80 m) and higher in regions where the temperature was low at 50–60 m (Figure 2.5d).

It is evident from Figure 2.5 that the regions with the highest phytoplankton biomass accumulation were near the canyon head. Size-fractionated chlorophyll measurements (undertaken on voyage 2) were used to examine the proportion of phytoplankton biomass in small (< 5 µm—picoplankton and small nanoplankton) and large (> 5 µm—larger nanoplankton and microplankton) size classes. At all sampling depths, the small size fraction dominated the phytoplankton biomass, with an average of only 2.5% of the total chlorophyll found in the large size fraction. Water samples with higher proportions (from 5 to 17%) of large-sized phytoplankton were more common at the canyon head than in other regions. The total depth-integrated primary production in the region averaged 545 mg C m^{-2} d^{-1}, ranging from 360 mg C m^{-2} d^{-1} in offshore waters to 760 mg C m^{-2} d^{-1} along the 1000-m contour on the canyon's southern side (Figure 2.6). Higher values were also recorded at the canyon tip. The mean attenuation coefficients calculated using the vertical light profiles ranged between 0.050 m^{-1} (voyage 1) and 0.055 m^{-1} (voyage 2), yielding a mean depth of euphotic zone (0.1% of surface PAR) of 138 m on voyage 1 and 125 m on voyage 2.

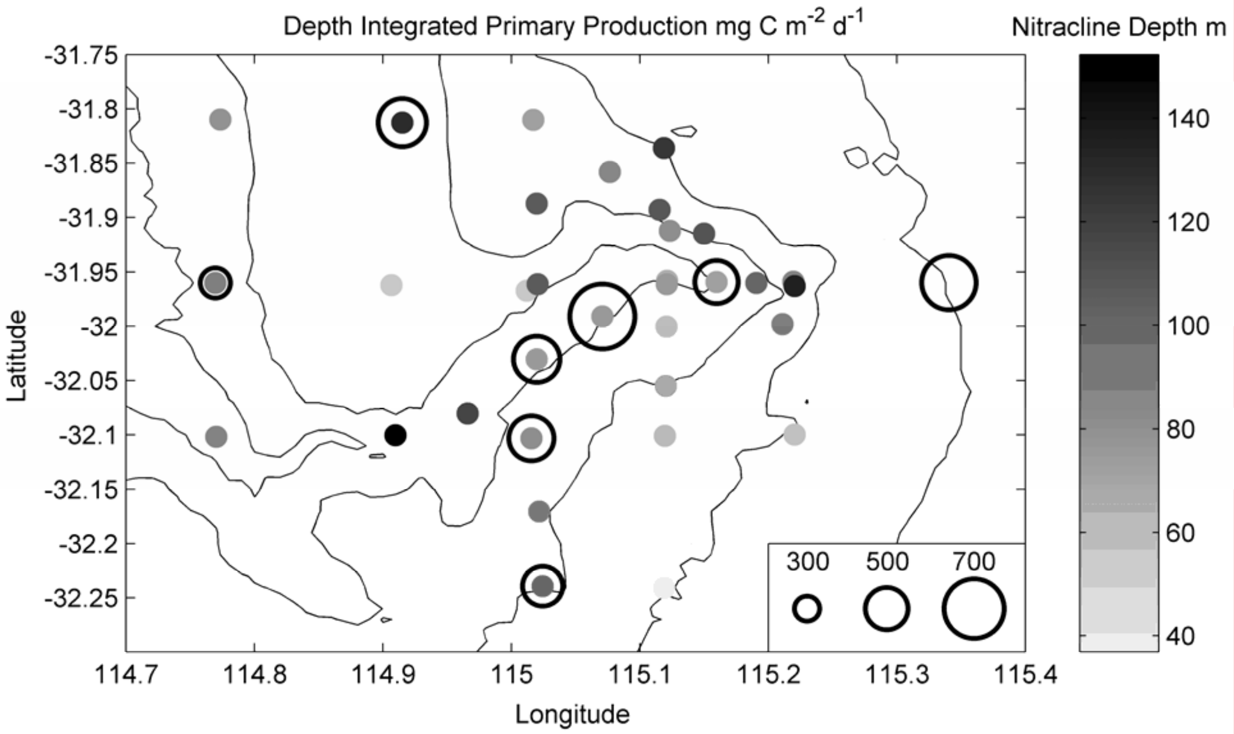

Figure 2.6. Total depth-integrated particulate primary production (mg C m^{-2} d^{-1}) measured at selected stations showing the variation in nitracline depth (m) in the Perth Canyon (from Rennie et al., submitted(a)).

2.3 Whale aggregations (from McCauley et al. 2004; Rennie et al, submitted(a))

Population surveys of pygmy blue whales (*Balaenoptera musculus brevicauda*) in the Perth Canyon and surrounding areas were undertaken between 1999 and 2004 by the Centre for Whale Research (boat), Western Australian Museum and Western Whale Research (aircraft), and Curtin University of Technology (passive acoustics). These surveys aimed to estimate the population size of the whales, form a database of identified individuals, tag individuals with satellite GPS trackers, obtain samples for DNA analysis, and examine their behavioural patterns. The results were presented in a report for Australian Defence at the end of the Western Australian Exercise Area Blue Whale Project, which was funded to study the pygmy blue whales and their habitat.

The aerial surveys and acoustic detections showed the blue whales reached the canyon as early as November, with whale numbers peaking during the following March–May. From aerial survey transect analyses, and allowing for "missed" whales, an average of 30 blue whales were in the canyon in the "peak" season. After May, the whale numbers dropped, and by late June most whales had migrated away, although some acoustics were detected in July. Evidence suggested the whales arrived from the north early in the season and departed to the north late in the season, although, as a general trend, this was inconclusive.

In the Perth Canyon, pygmy blue whales mainly prey on *Euphausia recurva*, as identified by samples streamed from the whales' mouths at the surface, krill mouthparts in faecal samples, and plankton tows through dense aggregations in the water column. Blue whales are expected to continue feeding only when the metabolic return from feeding outweighs the energetic costs associated with feeding. Given their large body size, blue whales are expected to feed in areas with only high prey densities. In the surveyed area, daily whale sightings occasionally numbered above 30; however, it is unlikely such numbers would be sustained for long in an area not known for high productivity. Annual mean whale call rates from passive acoustics carried out between 2000 and 2005 indicated an annual variability suggestive of an oscillatory seasonal visitation pattern, although a correlation with variables such as the southern oscillation index (to denote El Niño periods) was not found with such a short sampling period.

The results from the boat surveys (Figure 2.7) revealed whales were found in a water depth range of 300–600 m along the canyon rim, but were more concentrated along the northern plateau (Figure 2.8). The mean whale resighting period (from boat surveys) was 21.3 ± 8.3 days (± 95% CI), which suggested the whales stayed within or near the canyon for between two and four weeks. Satellite tags gave additional information on several whales' movements (Jenner and Gales, unpublished data). Of four whales that were tagged, one stayed in the canyon for eight days in March 2002, foraging around the rims and the canyon head. A whale tagged in Geographe Bay around 1.5° south of the canyon in December 2002 was found 43 days later in the subtropical convergence zone at 122° E. The whale tagged in late March 2004 spent 16 days traversing a region between the canyon (32° S) and the shelf break at 31° S. The whale tagged in late March 2004 traversed the shelf north to the Abrolhos Islands, but farther offshore, travelling about 425 km in seven days.

Many dolphins were also seen in the canyon, as well as other whales, including beaked, sperm, minke, Risso's, humpback, and southern right whales. Acoustic detections implied true

(Antarctic, B. musculus intermedia) blue whales overwintered around the canyon and headed south in mid-October.

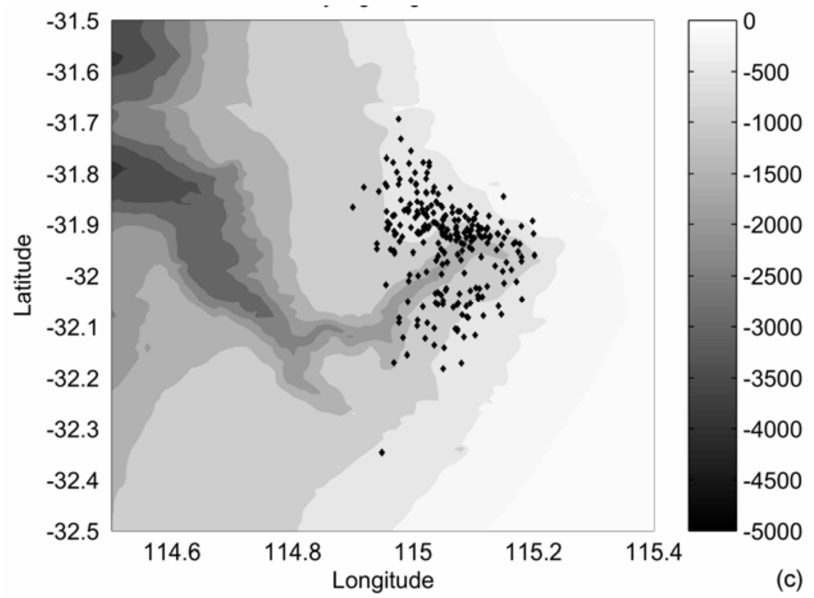

Figure 2.7. Sightings of pygmy blue whales from boat surveys (from Rennie et al., submitted(a)).

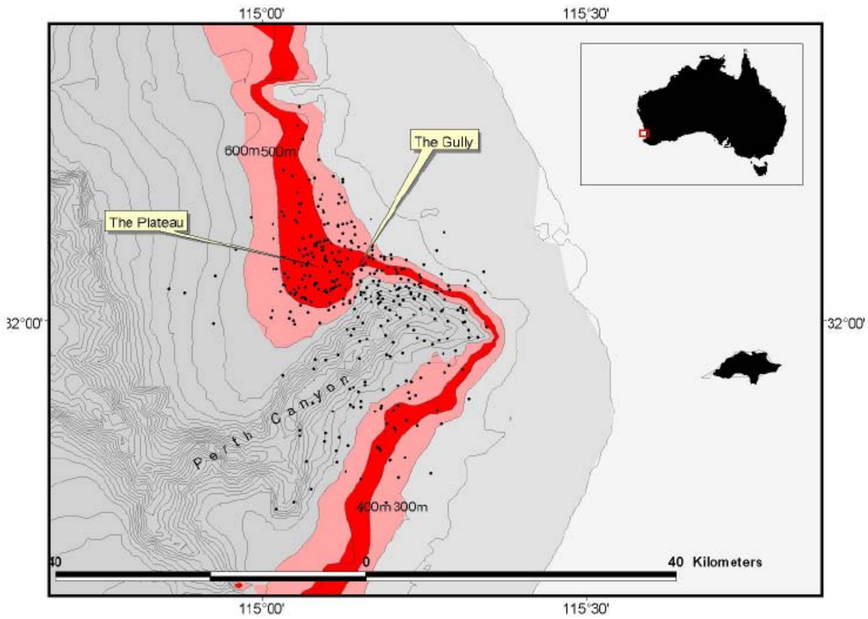

Figure 2.8. Distribution of blue whales over the Perth Canyon in relation to the Gully and Plateau regions. Red shaded area = 400–500-m depths (from McCauley et al. 2004).

3 ALBANY CANYON GROUP INCLUDING THE LEEUWIN CANYON

The Albany canyons consist of about 32 canyons over a length of 700 km of continental slope from 115 to 124° E (Exon et al, 2005). They include the Leeuwin Canyon in the west and Malcolm Canyon in the east. In contrast to the Perth Canyon, which cuts into the continental shelf, only the Leeuwin Canyon has a signature on the continental shelf. All the other canyons are confined to the continental slope. Von der Borch (1968) described in detail the shape and geology of selected canyons.

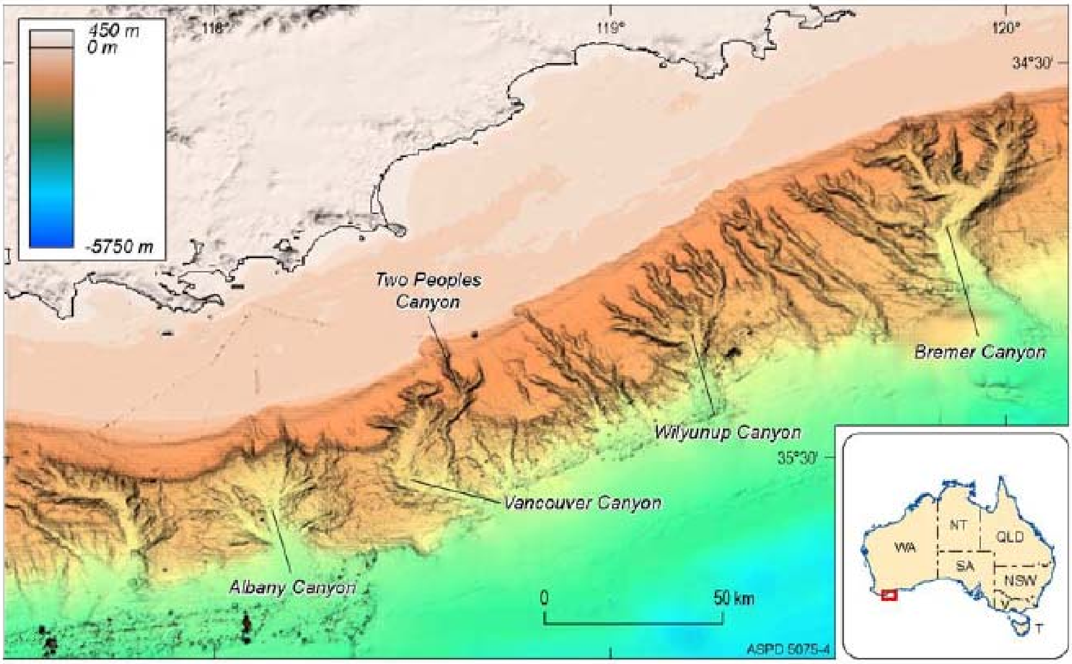

Figure 3.1. The geomorphology and bathymetry of several canyons in the Albany group. The Leeuwin Canyon is located to the west (from Richardson et al. 2005).

Three main current systems dominate the circulation along the southern coast: (1) the eastward flowing Leeuwin current at the shelf break (~200 m); (2) the westward flowing Flinders current, flowing offshore and beneath the Leeuwin current; and (3) the wind-driven, westward flowing Cresswell current on the continental shelf with dynamics similar to that of the Capes current (Section 7) during the summer. Similar to the west coast, the Leeuwin current is downwelling-favourable, and as such forms a barrier to upwelling. Satellite-derived sea surface temperature and chlorophyll a concentrations during the summer revealed a similar process to that along the west coast: the warmer Leeuwin current is located along the shelf break, with the higher chlorophyll water inshore of the current and high, localised values next to the coastline, especially close to prominent headlands (Figure 3.2). As the Albany canyons are located at the shelf break, any localised effects could be confined to the subsurface and may not have a surface signature. Twomey (pers. comm.) undertook field measurements, which identified upwelling events off Albany, but they were limited to the subsurface.

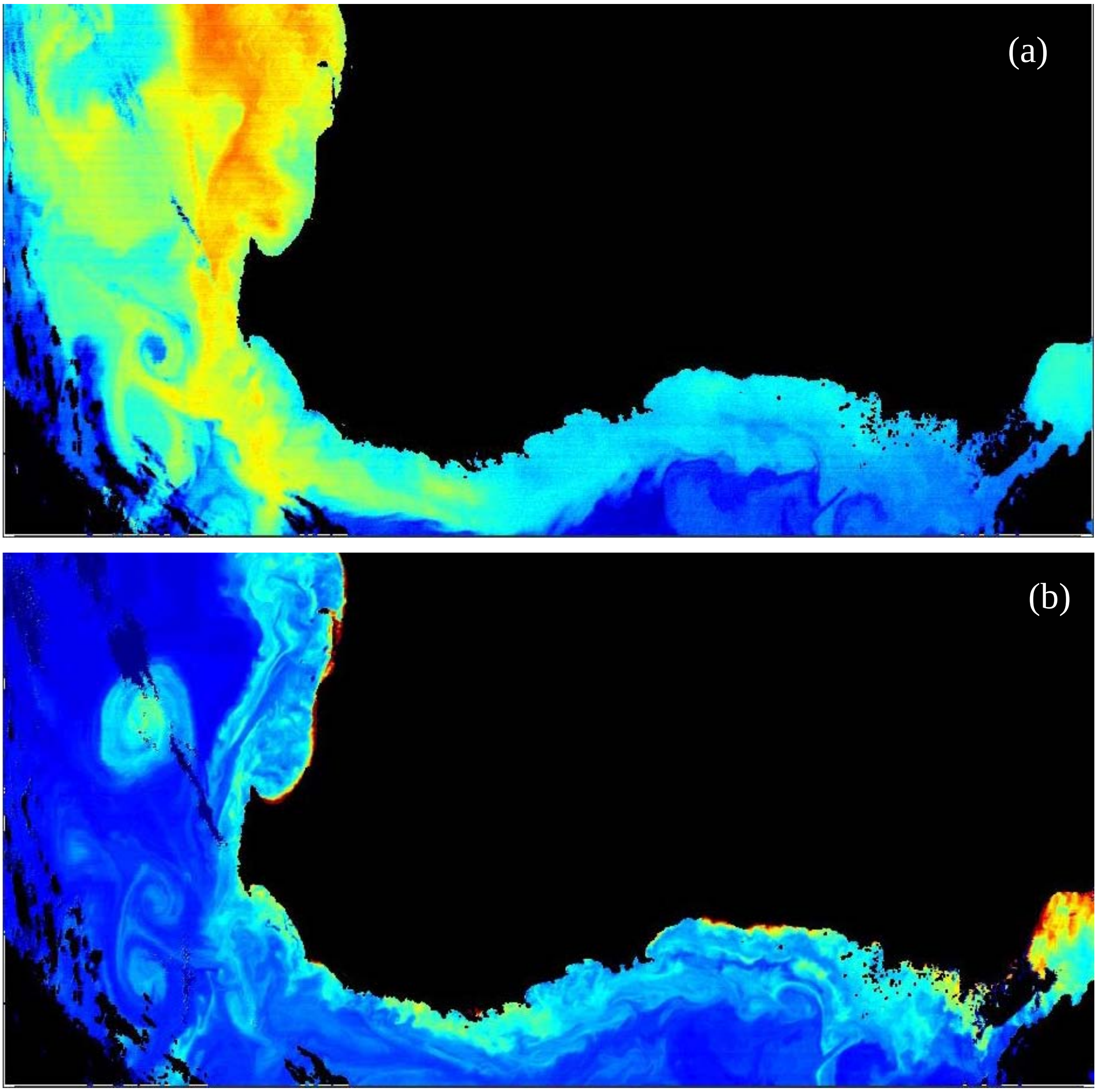

Figure 3.2. Satellite-derived sea surface temperature (a) and the corresponding surface chlorophyll a concentrations (b) along the southern coast obtained on 8 April 2006.

Sea surface temperature data obtained using underway measurements on the *Southern Surveyor* voyage (April 2006), however, showed the warm, eastward flowing Leeuwin current and, more importantly, a patch of colder water in the Bremer Canyon vicinity (Figure 3.3). This feature was also present in the surface salinity data (not shown) and could have been related to localised upwelling in the canyon vicinity (work is in progress to relate these data to nutrients and phytoplankton data obtained on the voyage).

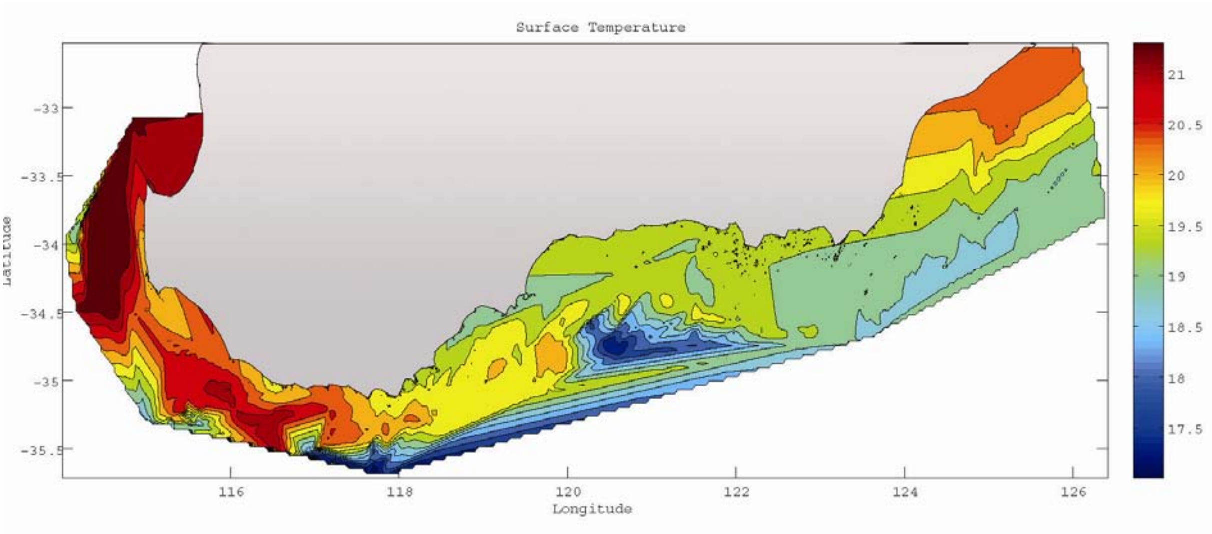

Figure 3.3. Sea surface temperature data from the *Southern Surveyor* voyage in April 2006 showing localised, lower temperature water at the Bremer Canyon head.

Few detailed fishery studies and studies of the physical and biological oceanographic processes have been undertaken in this region. The studies have also been broad (or data are currently being analysed and results unavailable, e.g. the *Southern Surveyor* voyage of April 2006). Therefore, as shown below, it was hard to determine whether the Albany canyons had ecological significance.

4 KANGAROO ISLAND CANYONS AND ADJACENT SHELF BREAK

Spring (1947) and von der Borch (1968) described a group of submarine canyons located offshore Kangaroo Island. The group is 60 km to the south of Kangaroo Island (Figure 4.1), and comprises several canyons, including Sprigg, Murray, and Du Couedic Canyon. It is assumed these canyons were formed through discharges of the Murray–Darling River. The Du Couedic Canyon (Figure 4.1) is also thought to be a conduit of the higher salinity plumes from Spencer Gulf (Lennon et al. 1987). These canyons are located at the boundary between the south-east and south-west marine planning regions. The influence of these canyons on the productivity of the continental shelf region to the west of Kangaroo Island is described in this section.

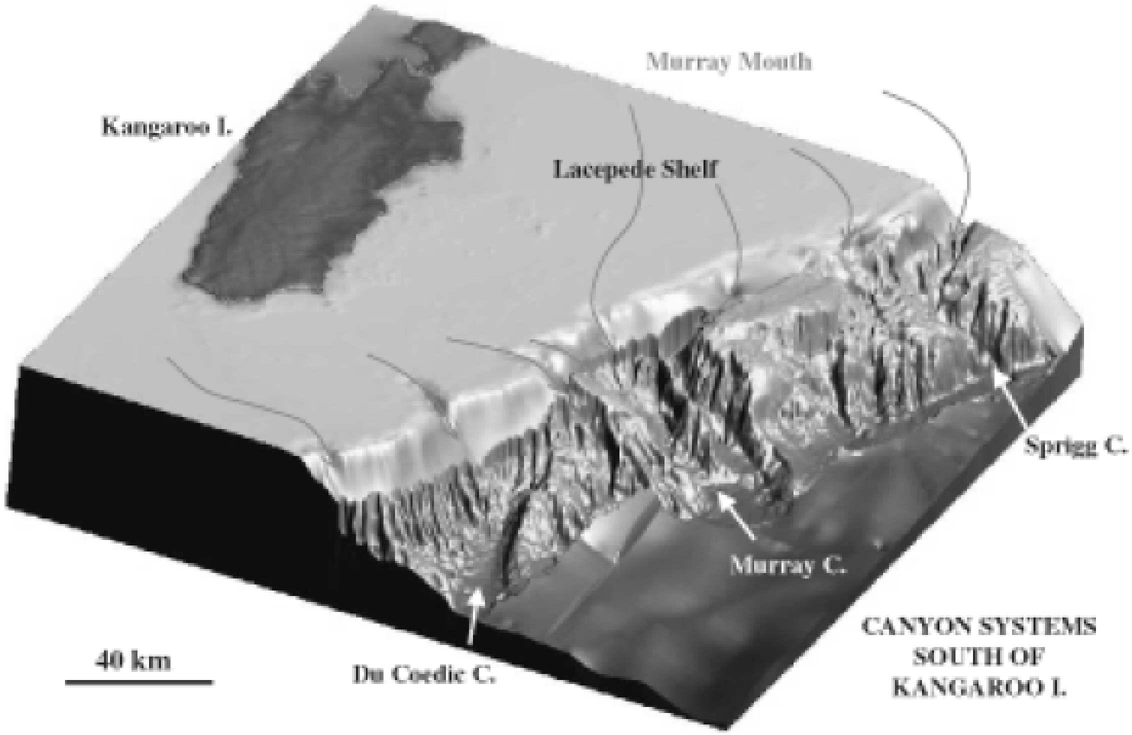

Figure 4.1. Seabed topography south of Kangaroo Island showing the deep sea canyons (from Hill et al. 2005).

The canyons are located along the continental slope, with only small depth changes along the continental shelf (Figure 4.1). The large-scale wind stress curl to the south of Australia drives the westward flowing Flinders current to dominate the circulation along the continental slope (Middleton and Bye 2007). The Flinders current, which is stronger in summer, extends from the surface to a depth of ~1000 m, with peak currents of ~0.20 m/s at about 600-m depth. Kaempf (2007) used idealised numerical experiments to demonstrate upwelling due to interaction between a deep, westward flowing current and a submarine canyon. The westward flowing current formed an anticlockwise eddy in the canyon and, in combination with the canyon's funnelling effect, caused upwelling from below 300-m depth onto the continental shelf (Figure 4.2). A similar situation may be happening in the region south of Kangaroo Island.

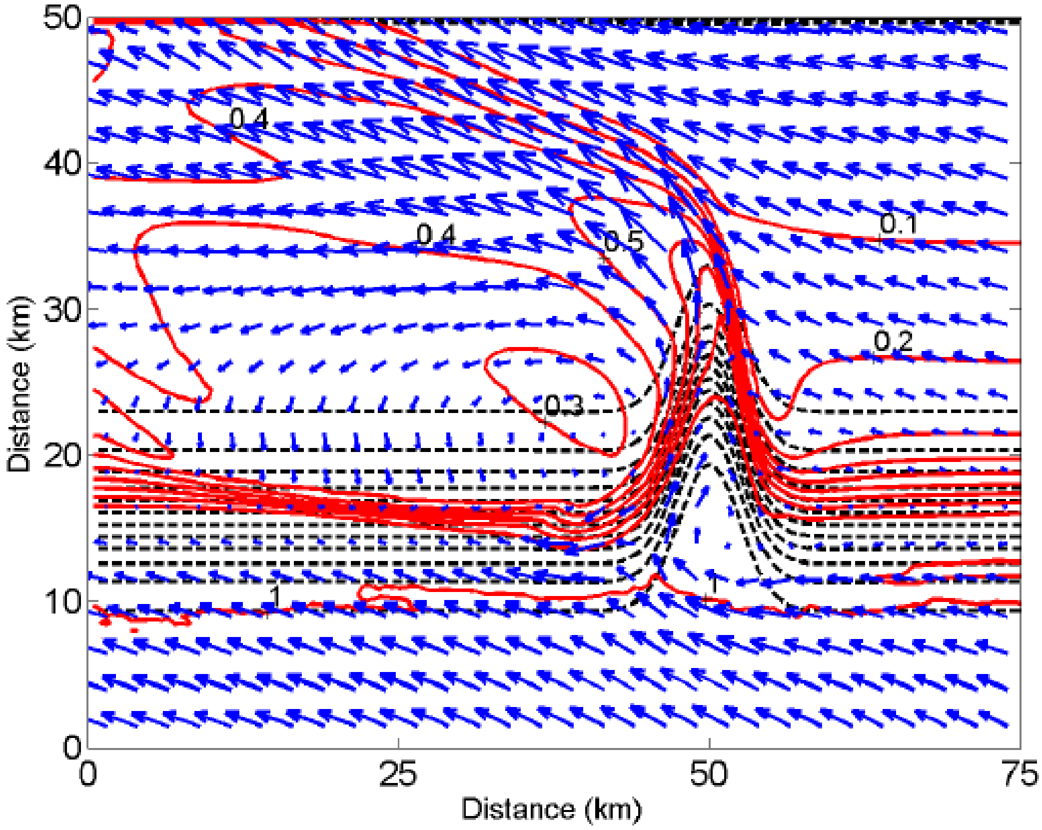

Figure 4.2. Numerical model results of the near-bed flow field five days after a simulation of an idealised submarine canyon in the southern hemisphere was started. Dashed black lines are bathymetric contours; solid red lines are concentrations (CI = 0.1) of slope water originating from a depth > 300 m. Maximum speed was 0.27 m/s (from Kaempf, 2007).

Middleton et al. (2007) used long-term field measurements collected from the region to show the coldest water was generally found to the south-west of Kangaroo Island, along the 100-m isobath (Figure 4.3); the upwelling was related to the El Niño cycle, with El Niño events since 1982 resulting in colder water on the shelf. This upwelled water was then maintained as a subsurface pool of dense, nutrient-rich water, which opposed dense water outflow from the gulfs, and was the source of upwelled water for the Eyre Peninsula (Middleton and Bye, 2007).

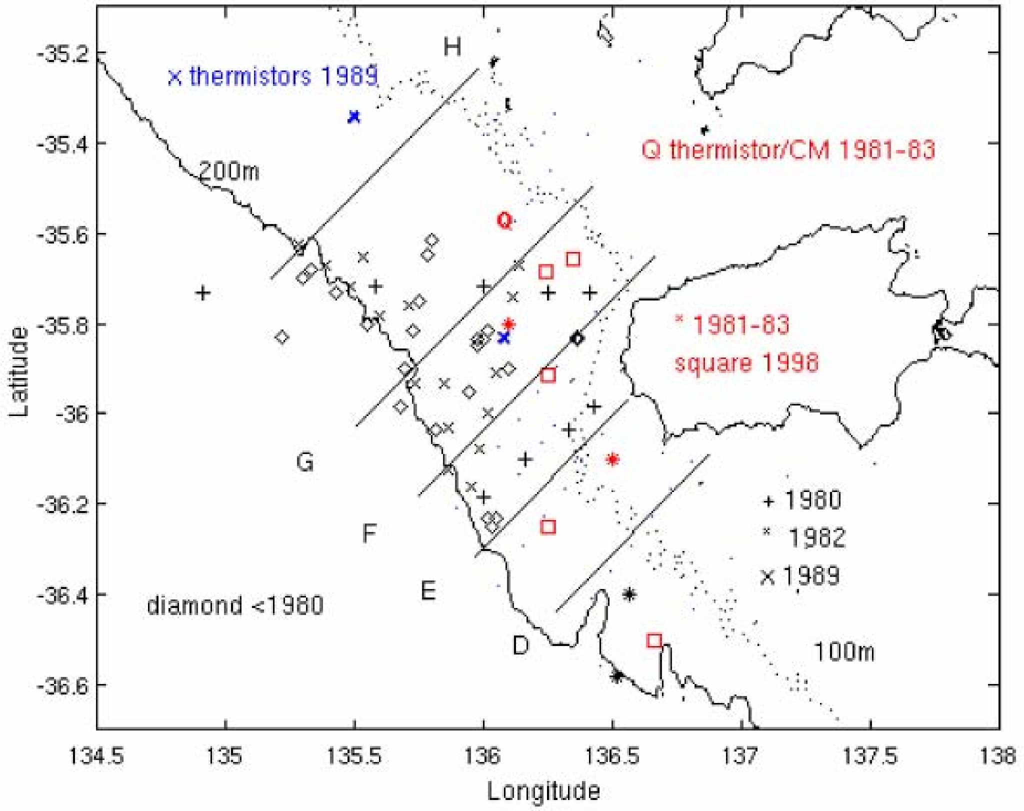

Figure 4.3. Locations of the CTD sections, thermistors, and current meter moorings for data collected off Kangaroo Island. The 100-m (dotted curve) and 200-m (solid curve) isobaths are shown (from Middleton et al. 2007).

It was hard to separate the ecological data collected as part of the Kangaroo Island pool studies, especially the chlorophyll a concentrations and the distribution of eggs and larvae; this will be discussed in Section 5.

Flaherty (1999) hypothesised that sperm and beak whale strandings along the South Australian coast were due to these species aggregating in and around the Murray Canyon system. Bannister (2004) reported that in Australian waters, sperm whales were found south-west of Kangaroo Island and generally in deep water (depths > 200 m). The Murray Canyon system has also been identified as a habitat for Australian sea lions, New Zealand fur seals, and school and gulper sharks (southern dogfish).

5. KANGAROO ISLAND "POOL"

5.1 Circulation and upwelling (from Kaempf et al. 2004; Middleton and Bye 2007)

Numerical model results were used to illustrate the mean summer circulation (Middleton and Platov 2003), which is shown in Figure 5.1. The continental shelf currents were generally to the north-west because of the prevailing winds, with the maximum current (up to 10 cm/s) located where the shelf was narrow: off the Eyre Peninsula, Kangaroo Island, and Robe. The flow branched near the western end of Kangaroo Island to form two streams: (1) to the north-west towards the Eyre Peninsula; and (2) to the north of Kangaroo Island and then to the west (Figure 5.1). The flow in (2) seemed to follow the 100-m isobath. Exchange was negligible between the gulfs (Spencer and St Vincent) and the nearby shelf.

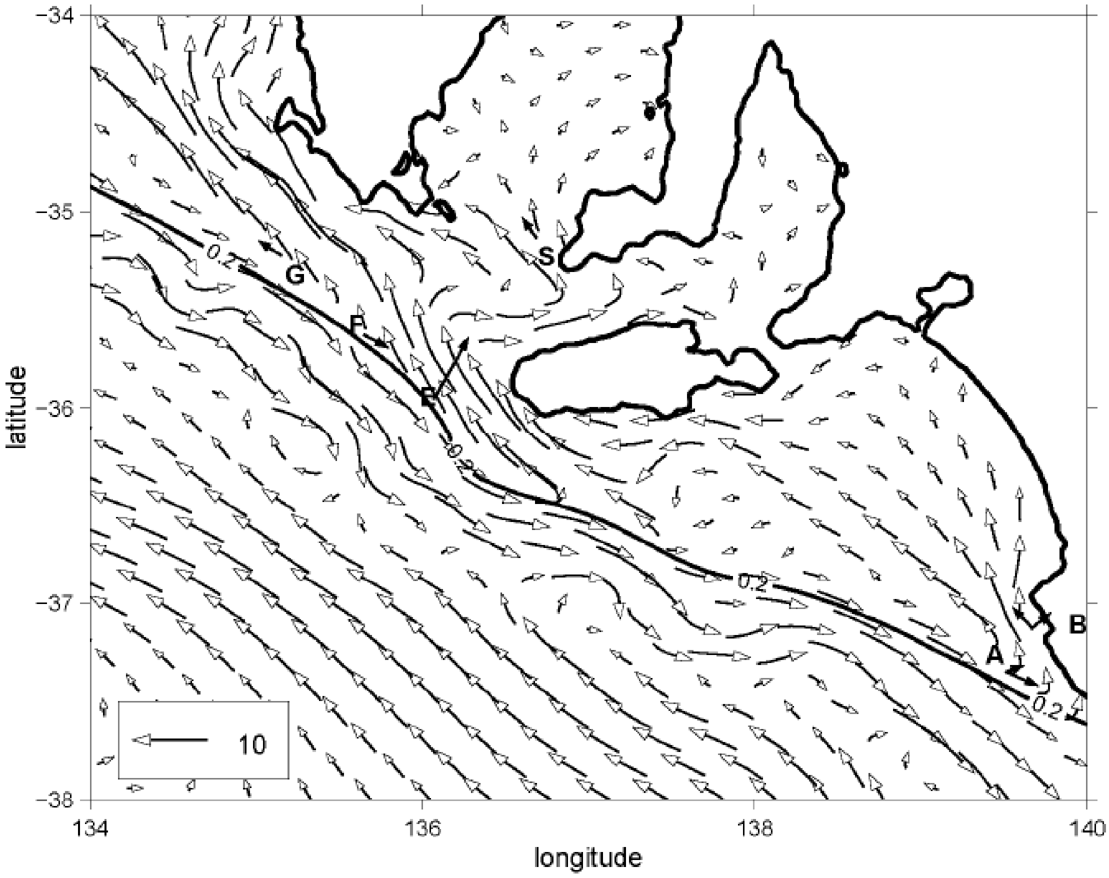

Figure 5.1. Surface (35 m) current patterns predicted using the numerical model of Middleton and Platov (2003). A reference vector of 10 cm/s is shown. The 200-m isobath is shown as a dark, solid line (from Middleton and Bye 2007).

The prevailing winds along the Great Australian Bight form an anticlockwise circulation, with south-easterly (shore-parallel) winds along the eastern end of the gulf. These winds are upwelling-favourable (e.g. Griffin et al. 1997; Middleton and Platov 2003; Kaempf et al. 2004). Ward et al. (2006) found upwelling-favourable winds comprised half the time in the wind records obtained from Neptune Island during the summer (November to April). In winter, the winds were downwelling-favourable. Kaempf et al. (2004) reported an average of two to three wind-driven upwelling events a year in the summer/autumn. Kaempf et al (2004) also found that the scale of north-westward flow was too small to explain the simultaneous appearance of cold, upwelled water off Kangaroo Island and the Eyre Peninsula. This was because the upwelled water from > 150-m depth off Kangaroo Island could not reach the surface off the Eyre Peninsula during a single upwelling event.

McClatchie et al (2006) analysed data to show the colder water found to the west of Kangaroo Island (Figure 5.2) was the source water for subsequent upwelling events off the Eyre Peninsula. Middleton and Bye (2007) concluded that cold surface water plumes may appear simultaneously off the Eyre Peninsula, Kangaroo Island, and the Bonney Coast, and that the waters off the Eyre Peninsula were from water drawn from the Kangaroo Island pool (Figure 5.2), which was created during a prior upwelling event. This water was transported to the Eyre Peninsula along the path shown in Figure 5.1.

Griffin et al. (1997) found strong, upwelling-favourable winds were not always associated with strong upwelling, suggesting wind may not be the only process controlling upwelling in the region. Ward et al. (2006) confirmed this when they found a low correlation between wind stress (using the upwelling index) and near-bed temperature at two sites in the Kangaroo Pool. They concluded that factors other than the wind contributed to the upwelling, and that other processes may also have influenced the distribution of near-bed temperatures in the region. They suggested that a complex combination of wind-driven Ekman pumping, boundary current intensification driving bottom water intrusions, and coastally trapped waves caused upwelling along the South Australian coast. Middleton et al (submitted) reported interannual variability in the upwelling and stronger upwelling events (evidenced by the presence of colder water on the shelf) during the 1998 and 2003 El Niño events.

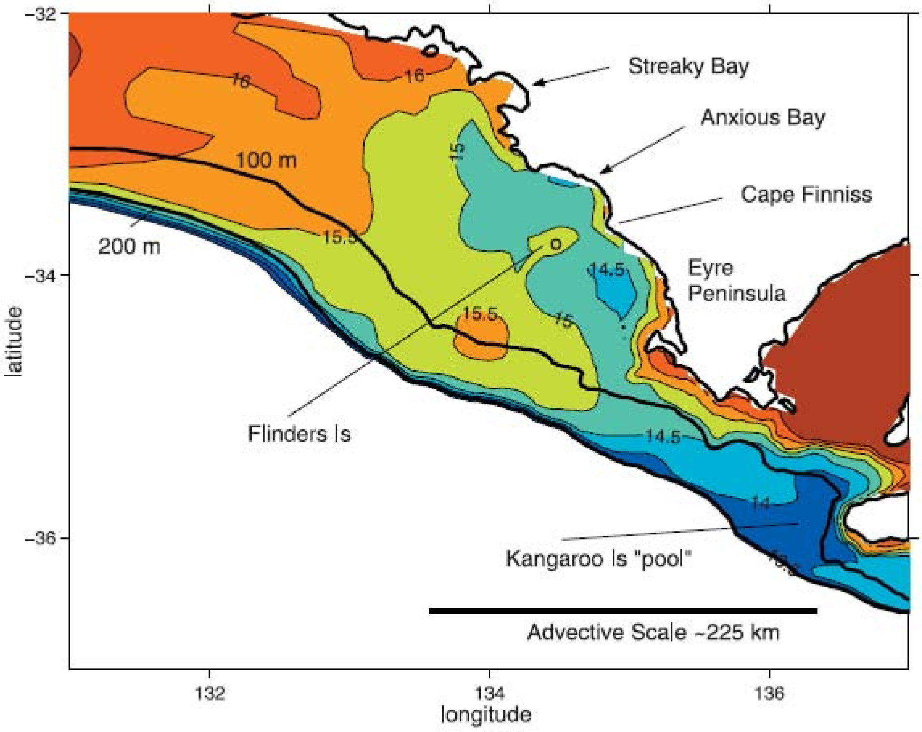

Figure 5.2. The climatology of bottom temperature in the region showing the Kangaroo Island ''pool'' of cold, nutrient-rich water and its northerly extent along the western Eyre Peninsula (from McClatchie et al. 2006).

An upwelling event, which occurred on 1 March 2004 (reported in McClatchie et al. 2006), is shown in Figure 5.3. As Kaempf et al. (2004) reported, during upwelling events, colder surface waters were present in three locations: (1) the Bonney Coast; (2) south-west of Kangaroo Island; and (3) the western part of the Eyre Peninsula. Figure 5.2 does not include the Bonney Coast, but the other two locations are shown. The colder water off south-west Kangaroo Island and the Eyre Peninsula, which is visible in Figure 5.3a, was associated with elevated surface chlorophyll concentrations (Figure 5.3b). Colder water and associated higher chlorophyll levels, most likely due to the effects of the headland and the strong currents, were also apparent off Cape Spencer at the northern end of Investigator Strait (Figure 5.3). The colder and higher chlorophyll water was also present along the western part of the Eyre Peninsula between Coffin Bay Peninsula and Anxious Bay (Figure 5.3).

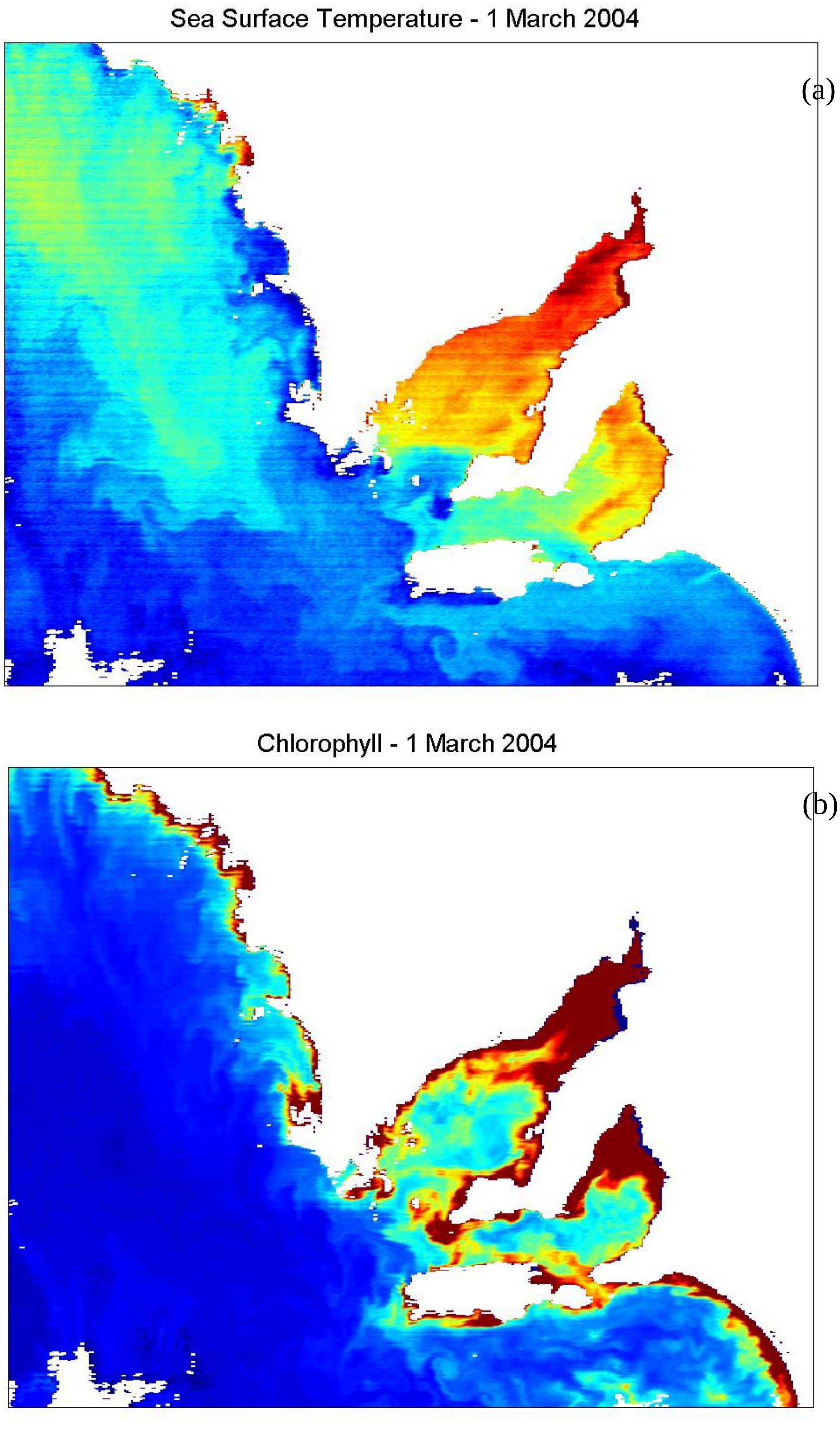

Figure 5.3. Satellite-derived sea surface temperature (a) and the corresponding surface chlorophyll a concentrations (b) along the southern coast obtained on 1 March 2004.

5.2 Primary production (from Dimmlich et al. 2004; Ward et al. 2006)

Primary production data from the region were limited to surface chlorophyll a concentrations and vertical fluorescence profiles from CTD casts. Ward et al. (2006) produced data of the chlorophyll surface distribution in the region for 1999 and 2000; Dimmlich et al. (2004) produced the data for 2000 and 2001 (Figure 5.4). The chlorophyll a concentrations in the surface waters were higher in summer and autumn compared with winter. In summer, the concentrations ranged between 0.06 and 4.5 mg m^{-3}, with the higher values recorded at stations in the cooler waters south and west of the Eyre Peninsula and at the mouth of Spencer Gulf (Figure 5.4; see also Figure 5.3b).

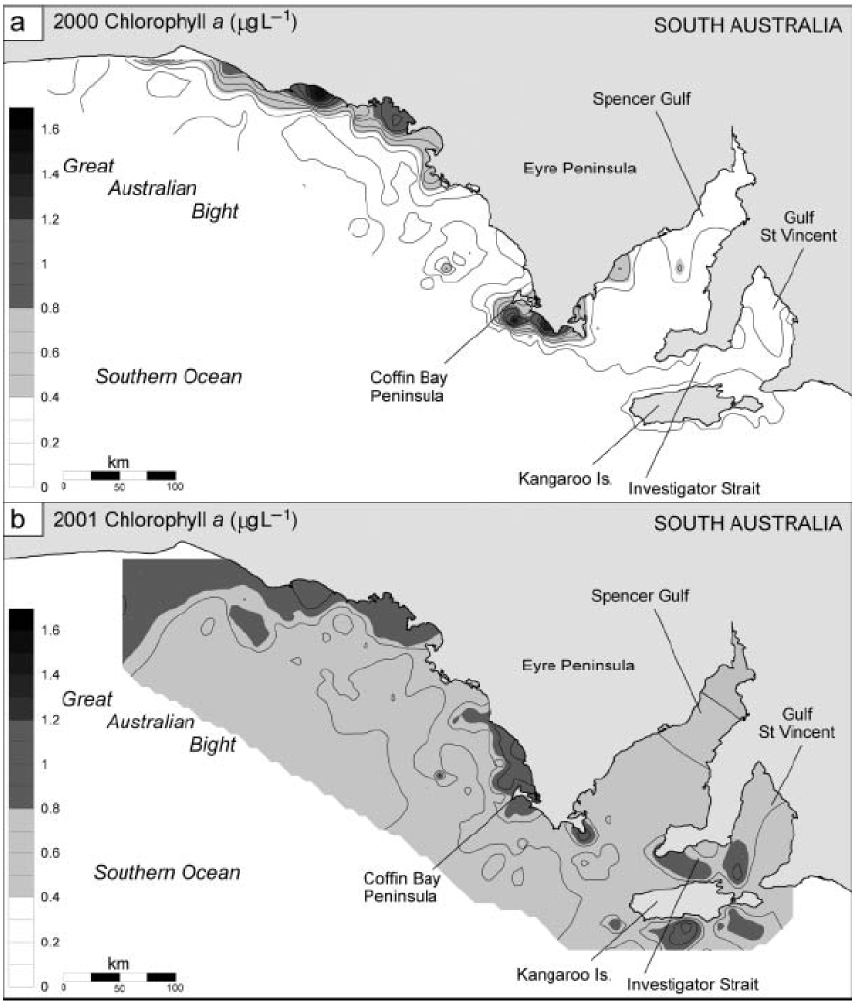

Figure 5.4. Surface chlorophyll a concentrations in the Kangaroo Pool region in summer 2000 (a) and 2001 (b) (from Dimmlich et al. 2004).

5.3 Fisheries (from Dimmlich et al. 2004; Ward et al. 2006)

The eastern Great Australian Bight supports Australia's largest finfish fishery based on sardines (*Sardinops sagax*) and anchovies (*Engraulis australis*)—species generally associated with large-scale upwelling along the eastern boundaries of ocean basins. The upwelling in the Kangaroo Pool region (Section 5.1) is the main reason for the increased catch of these species in this region.

Data collected over 1986 to 2001 (Dimmlich et al. 2004) showed the peak spawning season of sardines and anchovies in the shelf water off South Australia was from January to March, corresponding to the peak upwelling period. Ward et al. (2006) showed that localised increases in chlorophyll a concentrations (see Section 5.2) were associated with zooplankton biomass (Figure 5.5). Anchovy larvae > 10-mm total length were mainly found in the colder, higher chlorophyll shelf waters associated with upwelling; larvae > 15-mm total length were present only in the shelf waters next to upwelling regions (Dimmlich et al. 2004). Sardine and anchovy eggs and larvae are abundant and widely distributed in the shelf waters, with higher densities in areas (Figure 5.6) with high zooplankton biomass (Ward et al. 2006). Dimmlich et al. (2004) concluded that sardines mainly spawned in shelf waters, as few eggs and no larvae were present in the samples collected from the northern gulfs. Ward et al. (2006) suggested the spawning biomass of sardines in the waters off South Australia was an order of magnitude higher than elsewhere in southern Australia.

Sardines account for more than half of the prey species of the juvenile southern bluefin tuna (*Thunnus maccoyii*); the availability of sardines as a food source may be why juvenile (one-year-old) and more mature (two to five-year-olds) southern bluefin tuna aggregate in the eastern Great Australian Bight (Ward et al. 2006). The juvenile southern bluefin tuna travel southwards with the Leeuwin current from their spawning grounds in the North West Shelf region; the two to five-year-olds return to the region, via the Antarctic circumpolar current, from their winter feeding grounds to the south of Australia (Ward et al. 2006).

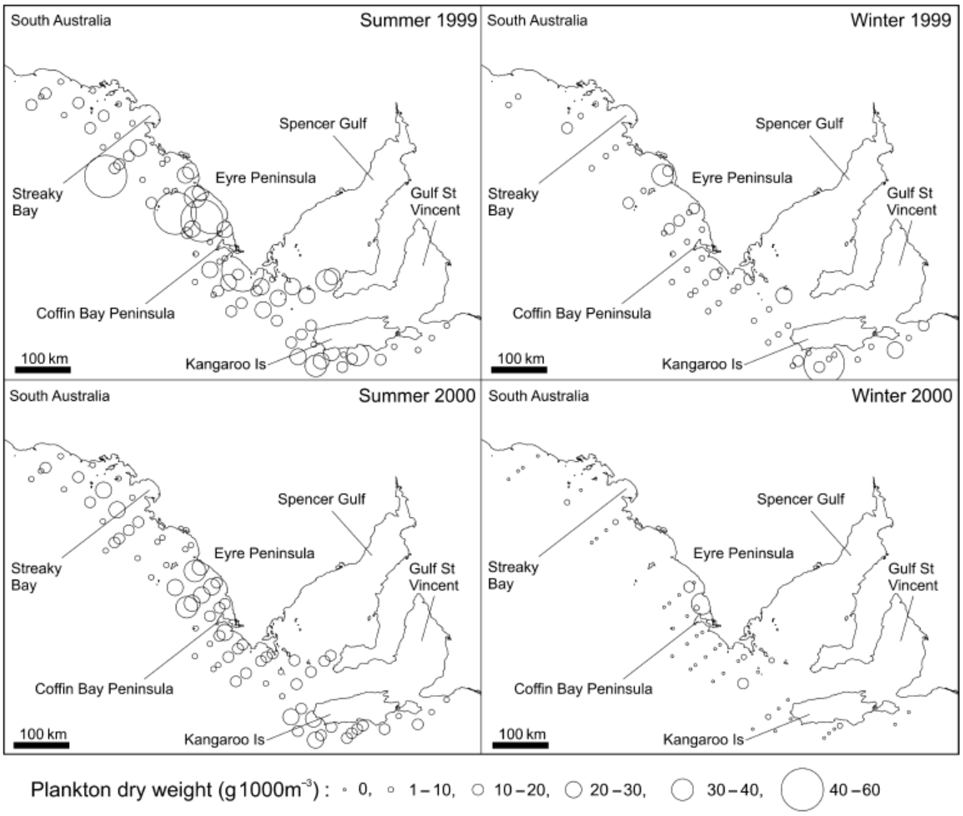

Figure 5.5. Distribution of relative zooplankton biomass in the eastern Great Australian Bight in the summer–autumn and winter of 1999 and 2000 (from Ward et al. 2006).

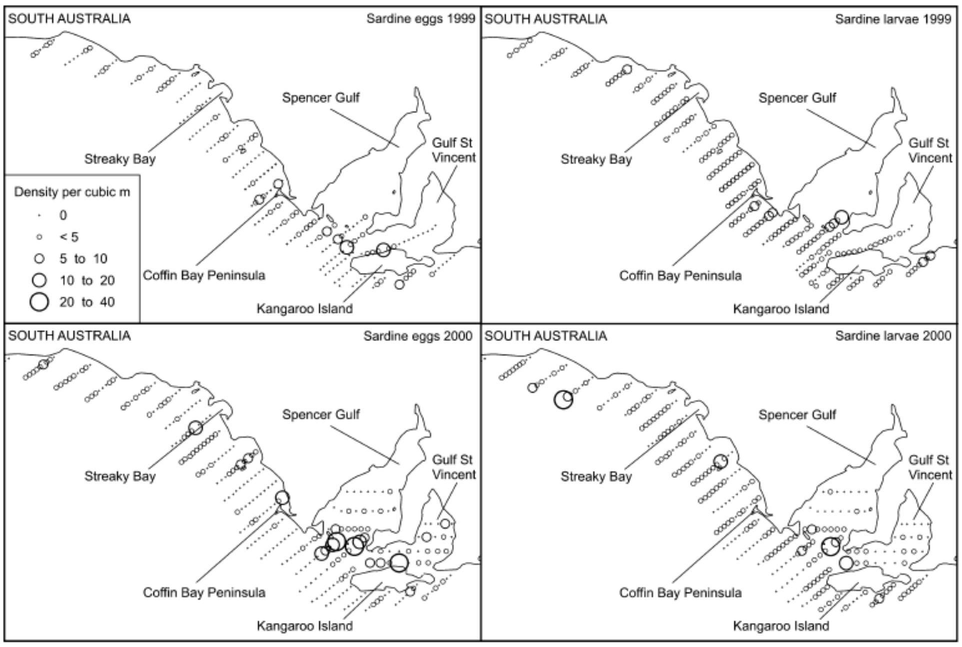

Figure 5.6. Distribution of sardine eggs and larvae in the eastern Great Australian Bight in the summer–autumn of 1999 and 2000 (from Ward et al. 2006).

5.4 Whale aggregations (from Morrice et al. 2004)

The whale ecology group at Deakin University undertook aerial surveys of blue whale (*Balaenoptera musculus*) distribution in the region to the south and west of Kangaroo Island in December 2003 for Santos Pty Ltd. Between 2 and 13 December, 152 blue whales were sighted, with a maximum of 48 adult whales observed in one day (13 December). All the observed whales were within 15 km of the 200-m depth contour (Figure 5.7), with most of the sightings concentrated inshore of the submarine canyons (Morrice et al. 2004). Several large surface krill swarms were identified in the regions where the blue whales were seen.

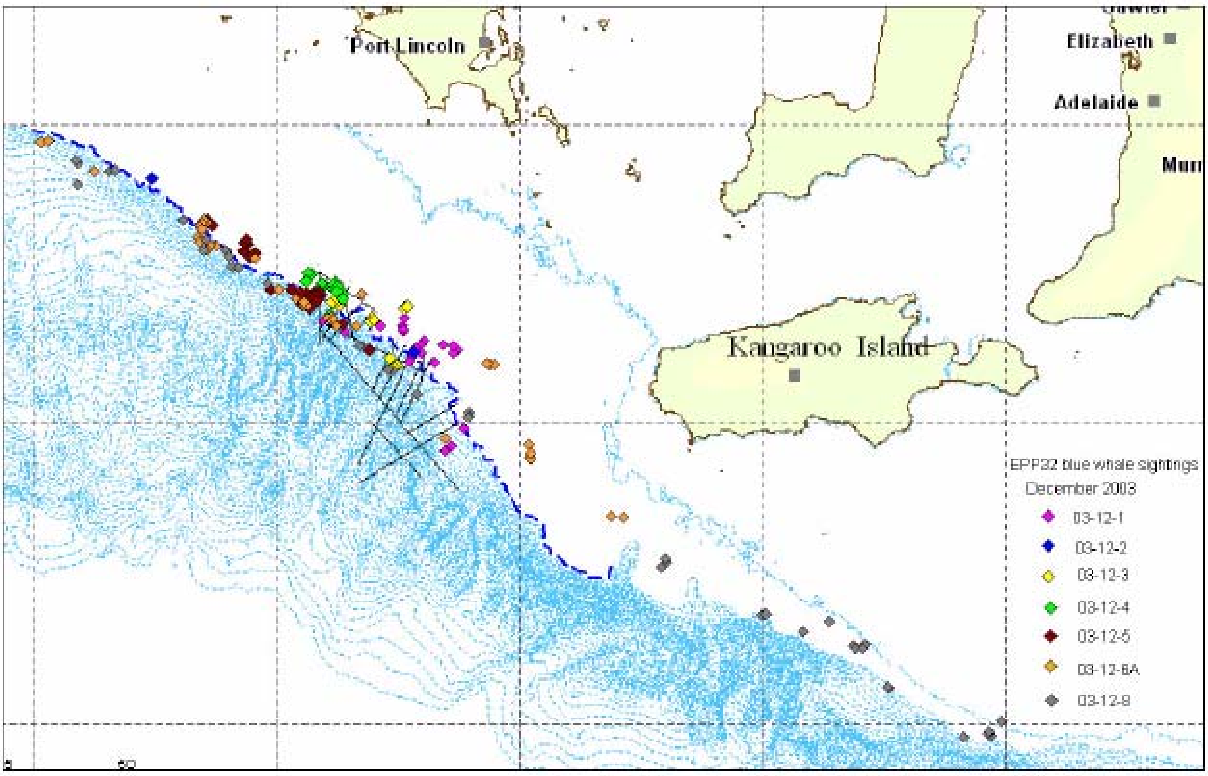

Figure 5.7. Blue whale sightings from December 2003 aerial surveys (from Morrice et al. 2004).

Although the locations of whale sightings and sea surface temperature distributions did not correspond, a strong correlation was seen with the satellite-derived chlorophyll a concentrations (Figure 5.8). The whales were in waters with chlorophyll a concentrations ranging from 0.3 to 0.4 mg m^{-3}. The blue whales were located (Morrice et al. 2004) along a tongue of higher surface chlorophyll a, which followed the 200-m contour towards the north-west (Figure 5.8).

The locations of whale sightings could be classified into five groups (Figure 5.8):

group 1	along the band of higher surface chlorophyll a water, which followed the 200-m contour
group 2	to the west of Kangaroo Island, offshore of the 200-m isobath, south-east of the band of higher chlorophyll a water
group 3	inshore of the 200-m isobath in low to intermediate chlorophyll a water
group 4	along the western edge of a high chlorophyll a plume originating from Kangaroo Island
group 5	in a region upstream of the higher chlorophyll a water.

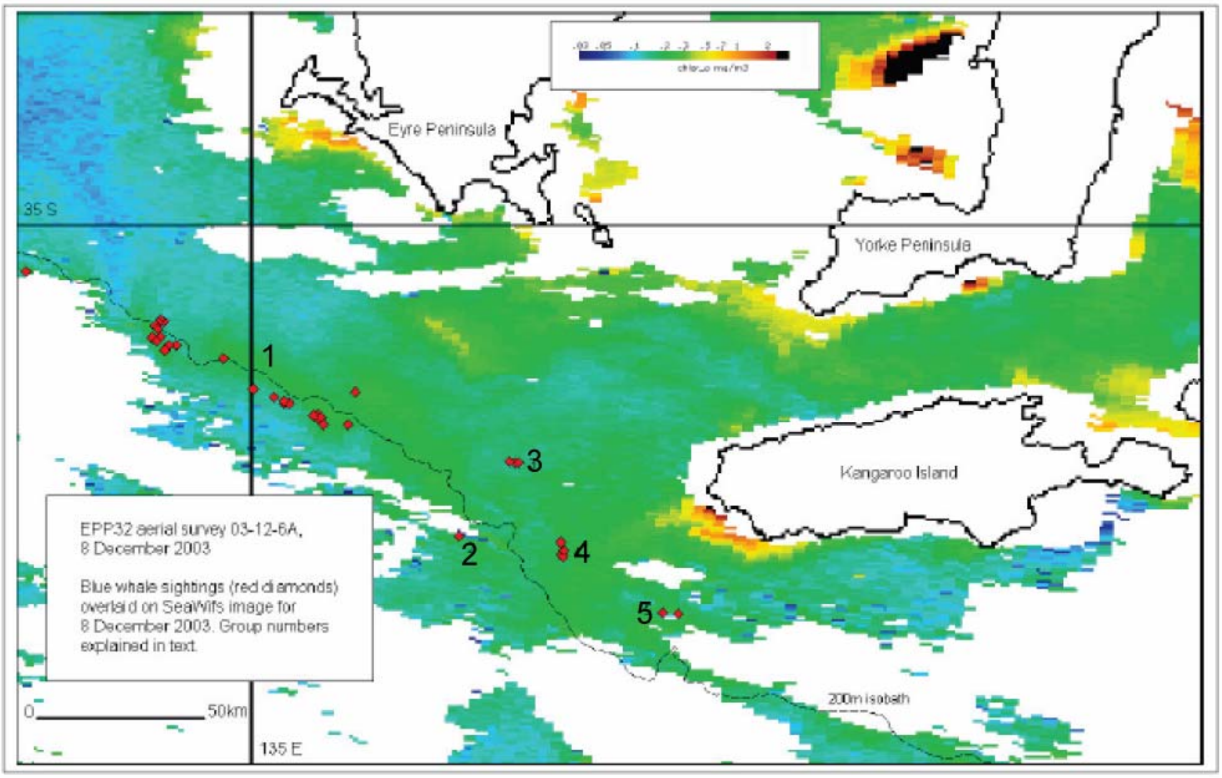

Figure 5.8. Blue whale sightings (five groups) on 8 December 2003 overlaid on a SeaWiFS image (from Morrice et al. 2004).

The aerial surveys also identified seven sperm whales (*Physeter macrocephalus*), but in deeper waters (1000 to 2000 m). Nineteen groups of dolphins (with up to 300 in a group) were also seen between the 100 and 200-m depth contours.

6 PREDICTABLE EDDY FIELDS

The Leeuwin current is generally associated with mesoscale eddies and meanders (Pearce and Griffiths 1991; Cresswell, 1996; Fang and Morrow 2003; Morrow et al. 2003; Feng et al. 2005; Fieux et al. 2005; Meuleners et al. 2007; Rennie et al. 2007; Waite et al., 2007a). Eddies form at the shelf break, separate from the current, and drift westwards. These eddies are apparent in sea surface temperature satellite imagery (Griffin et al. 2001) and altimeter data (Fang and Morrow 2003).

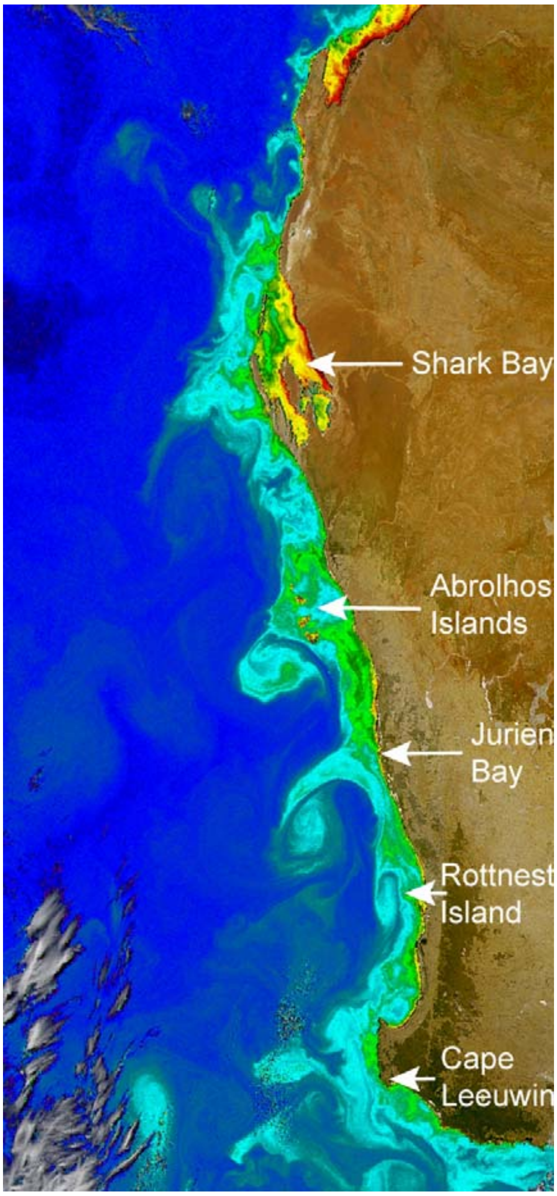

Figure 6.1. Ocean colour image showing the eddy structure of the Leeuwin current. The higher chlorophyll water is located on the shelf and is entrained into the Leeuwin current.

The Leeuwin current interacts with changes in the bathymetry and offshore water of different densities to generate and transport eddies offshore—in particular, off Shark Bay, the Abrolhos Islands, Jurien Bay, Rottnest Island, and Cape Leeuwin (Figure 6.1). The main eddy-generating regions can 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 because of the presence of Ranking Bank. One-third of all long-lived, warm-core eddies are shed from this region (Fang and Morrow 2003).
(2) south-west of Shark Bay (26–27° S, 113–114° E). At Shark Bay (~25° S; Figure 6.1), the coastal topography undergoes a 90° change in orientation: to the north, the flow along isobaths is directed to the south-west; to the south, the flow turns abruptly to the south-east (Fang and Morrow 2003; Woo et al. 2006). Field data revealed that in this region, the Leeuwin current's strength changed in the wider shelf off Shark Bay; the current's speed was slower, as it was distributed along the wider shelf. To the south, the current accelerated, as the continental shelf narrowed and the continental slope steepened (Woo et al. 2006).
(3) the western edge of the Abrolhos Island chain (28–29° S, 113–114° E). The instabilities created in the Leeuwin current and as the Leeuwin current flows past Shark Bay and accelerates (see 2 above), together with the Leeuwin current's interaction with the Leeuwin undercurrent, generate eddies in this region (Meuleners et al., 2007).
(4) south-west of Jurien Bay (29–30° S, 114–115° E). The eddies formed offshore Abrolhos Islands have a length scale ~200 km (Figure 6.1); the interaction between the eddies formed to the north and the coastline at Jurien Bay moves water offshore and generates eddies (Figure 6.1).
(5) Perth Canyon (32° S, 115° E). The Perth Canyon is the main topographic feature along the continental slope and traps eddies in the canyon. Rennie et al. (2007) examined the Leeuwin undercurrent's influence on eddy formation.
(6) south-west of Capes Naturaliste and Leeuwin (32° S, 115° E). At Cape Leeuwin (34–35° S; Figure 6.1), the coastal topography undergoes a 90° change in orientation: to the north, the flow along isobaths is directed to the south; to the south, the flow turns abruptly to the east.

(7) south of Albany (32° S, 115° E). Here, the coastal topography undergoes a change in orientation: to the west, the flow along isobaths is directed to the south-east; to the east, the flow is directed to the east-north-east (Figure 3.2).

(8) south of Esperance (32° S, 115°E). Similar to Albany, the locations of the many islands (Recherche Archipelago) and the changes in the bathymetry generate eddies (Figure 3.2).

The satellite images off the west Australian coast (such as that shown in Figure 6.1) were similar to those observed in other continental shelf areas off California (Pelaez and McGowan 1986), the South Atlantic Bight (McClain et al. 1988), South Africa (Lutjeharms and Walters 1985), and north-west Africa (Barale and Doerffer 1993). In all these regions, the higher chlorophyll concentrations were found in the continental shelf's colder waters, inshore of the main current system. This was due to the upwelling of colder, nutrient-rich water onto the continental shelf.

Although there is no large-scale upwelling off the west Australian coast, the continental shelf waters are higher in nutrients because of recycling and terrigenous inputs. Heat loss to the atmosphere and the presence of warmer tropical water offshore causes the colder water near the coast. In the case of the southern Atlantic Bight, nutrient-rich Gulf Sstream water intruding onto the shelf increases the biological productivity on the shelf (McClain 1993). The high productivity is also associated with frontal features, where high chlorophyll concentrations are present over lengths more than several hundred kilometres, but only 20 km wide (McClain 1993). In contrast, off Western Australia, no elevated chlorophyll values were found near the frontal region between the Leeuwin current and shelf waters; the chlorophyll concentration was uniform (homogeneous) along the whole shelf and extended hundreds of kilometres (Figure 6.1).

Elevated chlorophyll values at the centre of an eddy have been attributed to the upwelling of colder, nutrient-rich waters enhancing production (McClain and Atkinson 1993). Off the Western Australian coast, higher chlorophyll levels were found at the centre of cold-core eddies; however, the higher chlorophyll levels were due to the entrainment of continental shelf water into the eddies rather than upwelling at the eddies' centre.

Analysing the satellite images (Pattiaratchi et al. unpublished) revealed three processes responsible for moving high chlorophyll continental shelf water offshore:

(1) the Leeuwin current impinging on the continental shelf, partially entraining shelf water into its boundary
(2) the Leeuwin current flooding the shelf, thereby fully entraining (i.e. mixing completely with and absorbing) the shelf water
(3) unknown mechanisms, perhaps wind and topographic interactions.

The dynamics and primary productivity of the eddies off the Western Australian coast have been studied over the past few years. Some of the earlier results will be presented as a special issue of *Deep-Sea Research Part II: Topical Studies in Oceanography* (Waite et al., 2007a). Here, the physical structure, primary production, and larval fish assemblages in warm-core and cold-core eddy were examined.

Muhling et al. (2007) sampled larval fish assemblages in two mesoscale eddies, and showed the assemblages in the warm-core eddy were different from those in the cold-core eddy. The main differences were between the assemblages from the centre and body, and the centre and perimeter of the warm-core eddy. In contrast, differences were small across zones in the cold-core eddy. In the vertical, the assemblages were more structured with depth in the cold-core eddy than in the warm-core eddy (Muhling et al. 2007).

Gaughan (2007) concluded the Leeuwin current eddies imposed a net negative impact on the success of teleost eggs and larvae along the WA coast. This was because when shelf teleost larvae were entrained and trapped in the Leeuwin current eddies, they were propagated offshore, and did not contribute much to recruitment on the shelf. As the copepods population was less within an eddy when compared with shelf waters, and the larval teleosts mostly feed on copepods, the general larval feeding conditions in an eddy were inferior to those on the continental shelf. Gaughan (2007) also stated that if larvae with sustained swimming capabilities escaped from the eddy and directed themselves towards the shelf, they would lose energy when trying to return to the shelf.

7. CAPE MENTELLE UPWELLING

7.1 Circulation and upwelling (from Gersbach et al. 1999; Hanson et al. 2005)

The Leeuwin current's presence promotes an oceanic environment that supports downwelling in the continental shelf and break region along the west Australian coast. The combination of the alongshore pressure gradient (the Leeuwin current's driving force) and the Coriolis force transports water onshore, causing downwelling. The prevailing southerly winds, especially in the summer, have the opposite effect: the combination of the wind stress and the Coriolis force moves water offshore, causing upwelling along the continental shelf. Thus the resulting circulation depends on these two processes competing. In general, the alongshore pressure gradient dominates, causing downwelling. Under strong wind conditions, however, the wind effects can dominate, causing upwelling.

One such region where this process—termed here as the 'Cape Mentelle upwelling'—occurs is between Capes Leeuwin and Naturaliste in the south-west corner of Australia. The Capes current also originates from this region. 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 and extends northwards past the Abrolhos Islands. The Capes current seems to be well established around November, when winds in the region become mostly southerly because of the strong sea breezes (Pattiaratchi et al. 1997), and continues until about March when the sea breezes weaken. Gersbach et al. (1999) showed the Capes current source water was from upwelling between Capes Leeuwin and Naturaliste, which was augmented by water from the south to the east of Cape Leeuwin.

Gersbach et al. (1999) described the dynamics of the Capes current, off Cape Mentelle. The continental shelf in Australia's south-west comprises a step structure, with an inner shelf break at 50 m and an outer shelf break at 200 m (Pearce and Pattiaratchi 1999). This bathymetry influences the circulation (Figure 7.1), especially in the summer. In the summer, the alongshore wind stress overwhelms the alongshore pressure gradient on the inner shelf (depths < 50 m), moving surface layers offshore, upwelling colder water onto the continental shelf, and pushing the Leeuwin current offshore (Figure 7.1). Here, the Capes current is present on the inner shelf and bounded offshore by the Leeuwin current on the lower shelf, with upwelling occurring over the inner shelf break (Gersbach et al. 1999). Numerical model results showed a wind speed of 7.5 ms^{-1} was sufficient to overcome the alongshore pressure gradient on the inner continental shelf (Gersbach et al., 1999). The Leeuwin current strengthens in the winter, and, in the absence of wind stress, migrate closer inshore, flooding upper and lower terraces (Pearce and Pattiaratchi 1999).

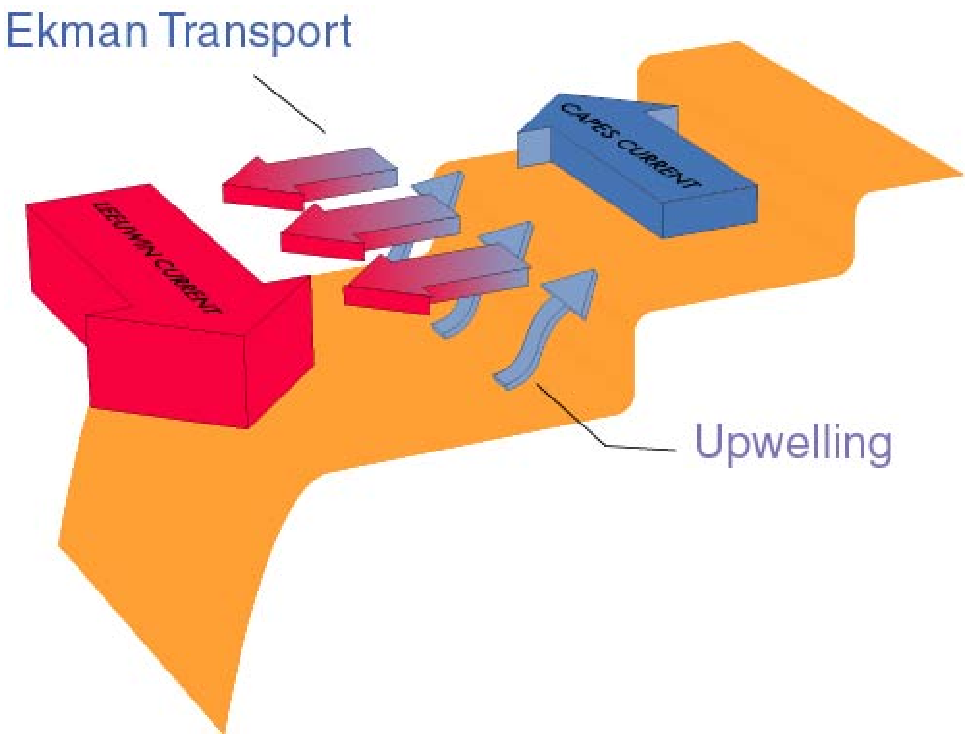

Figure 7.1. Cross-sectional schematic of the steady-state summer current regime off south-western Australia (from Gersbach et al. 1999).

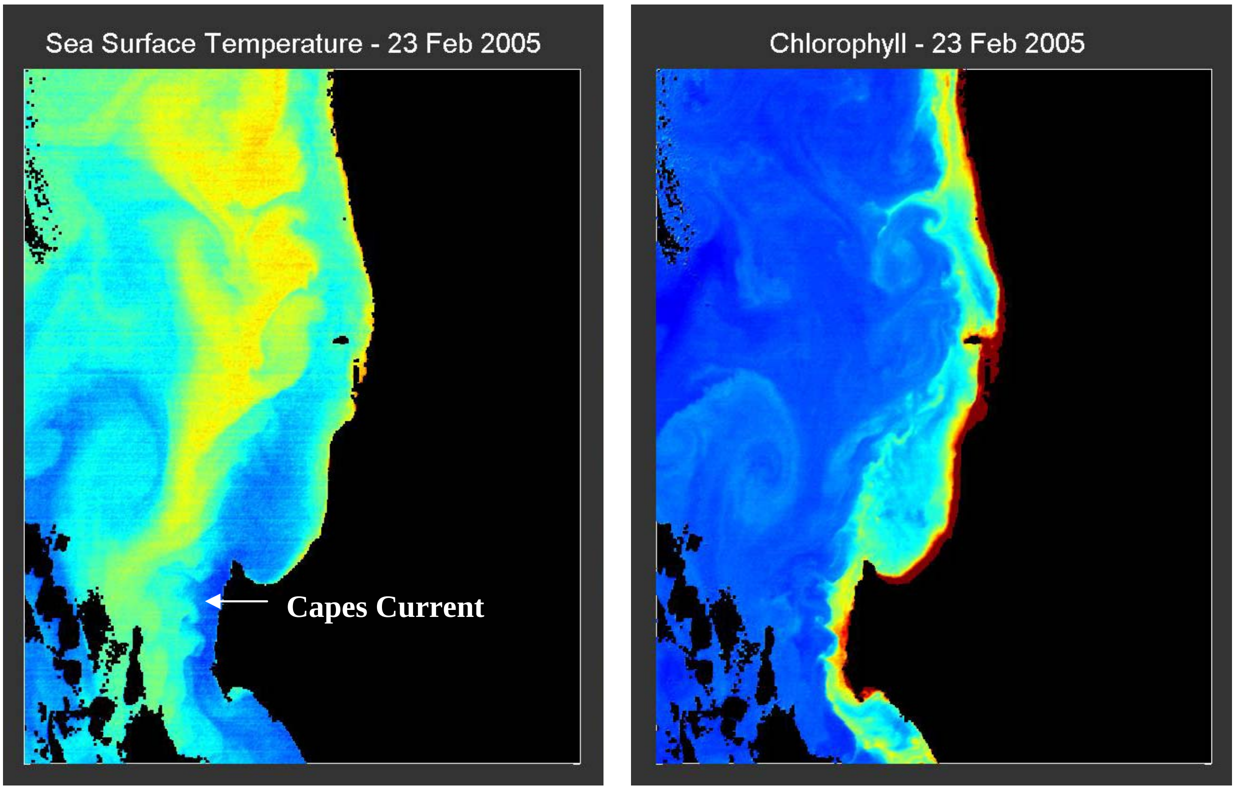

Figure 7.2. Ocean colour images off south-western Australia showing the sea surface temperature and the upwelling of cold water onto the Capes current with the associated high chlorophyll concentration.

Although the Capes current extends from Cape Leeuwin to past the Abrolhos Islands, the most intense upwelling, and therefore the highest concentration of surface chlorophyll a (Figure 7.2), occurs between Capes Naturaliste and Leeuwin, as the winds are strongest along this section of the coast compared with the north.

Gersbach et al. (1999) found water upwelled from the base of the Leeuwin current contained only slightly elevated nutrients (0.4 µM NO_3^-), compared with the bulk of the Leeuwin current (0.2 µM NO_3^-). In contrast, Hanson et al. (2005) upwelling in the Capes region transported higher nitrate concentrations (> 1.0 µM) into the upper euphotic zone (< 50 m). The nutrients were was sourced from the nutricline at the base of the mixed layer beneath the Leeuwin current. Hanson et al. (2005) found that because of the upwelling of higher nutrient water, seasonal upwelling in the Capes region supported high primary production rates. Maximum production rates were 945 mg C m^{-2} d^{-1}, with the higher depth averages produced at the 50-m contour (Figure 7.3). Hanson et al (2005) also found that in winter, the stronger Leeuwin current flow, and its interaction with the shelf water upstream of the Capes region, increased the nutrient levels (nitrate levels of ~2–3 μM) in the Capes region; however, compared with summer, the lower subsurface light conditions (lower solar angle and higher attenuation due to storm action) in winter lowered the primary production.

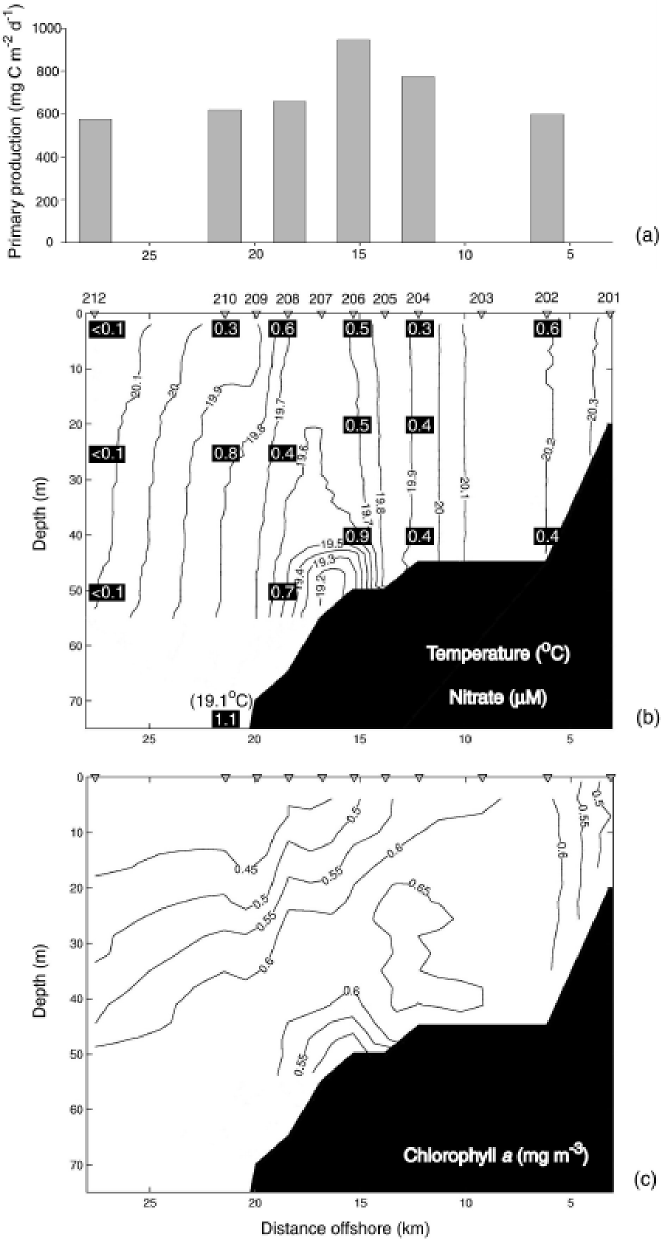

Figure 7.3. A cross-section of (a) depth-integrated primary production; (b) temperature contours overlaid with discrete nitrate concentrations from Niskin sampling depths; (c) chlorophyll a derived from calibrated in situ fluorescence (from Hanson et al. 2005).

7.2 Phytoplankton species composition (Hanson et al. 2005)

Hanson et al. (2005) found small monads and flagellates dominated the phytoplankton cell counts in upwelling (Figure 7.4) and non-upwelling conditions, with a distinct peak in cell numbers at the 50-m shelf break during winter. In the summer, the abundance of diatoms (mainly small pennates, e.g. *Pseudonitzschia* spp.) and dinoflagellates peaked near the upwelling core (station 206—Figure 7.3b). In contrast, in the winter, diatoms were evenly distributed across the shelf while dinoflagellate numbers peaked at the shelf break and the offshore station.

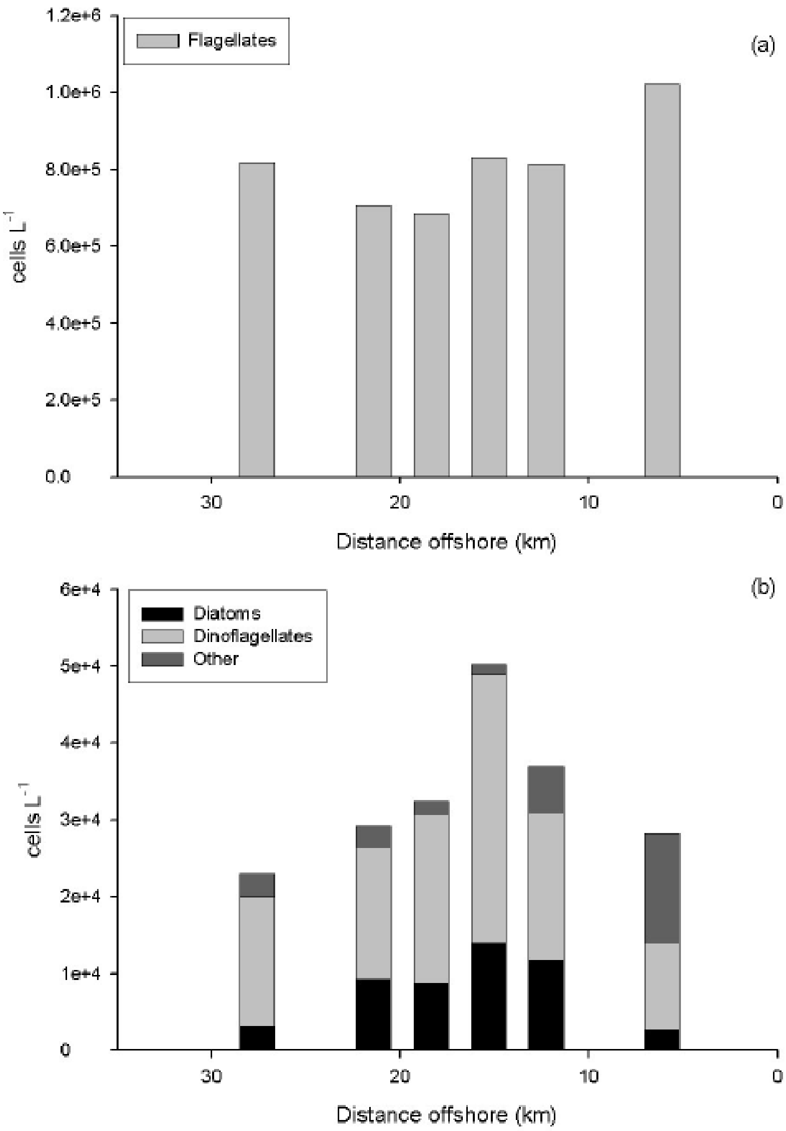

Figure 7.4. Cross-sectional abundance (cells L^{-1}) of the main phytoplankton taxonomic groups in surface (< 2 m) waters during upwelling conditions (from Hanson et al. 2005). (a) Flagellates; (b) Diatoms, Diniflagellates and others

7.3 Fisheries

Along the WA coast, the main finfish resources are confined to the continental shelf waters landward of the Leeuwin current (Lenanton et al. 1991), where primary production is also the highest (see Section 7.1). Hence the region between Cape Leeuwin and Naturaliste – the Cape Mentelle upwelling could influence the migration and spawning patterns of several important species of fish.

The Western Australian salmon (*Arripis truttaceus*) is thought to spawn mostly along the south-west coast, especially between Cape Leeuwin and Cape Naturaliste during the late summer (Walker 1982). The Leeuwin current then transports the larvae and juveniles eastwards. In later years, the mature fish migrate west to spawn (Lenanton et al. 1991). This spawning “run”, which provides the basis for a commercial and recreational fishery in Western Australia, normally occurs between late February and late April, with most of the spawning thought to take place between Black Point (between Windy Harbour and Augusta) and Cape Naturaliste. This corresponds with the peak of upwelling in terms of location and timing. Hence fish are likely to take advantage of the northward flowing Capes current to migrate and to spawn in the higher nutrient water between January and March.

The pilchard (*Sardinops sagax*) also spawns in this region in late summer/early autumn. When this species is associated with regions of intense upwelling (e.g. other eastern ocean boundaries such off South Africa and South America), it forms the basis of some of the world’s largest fisheries. The fishery for pilchards along the south and lower west coasts, while small on a global scale, is still the largest pelagic fishery in Western Australia.

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APPENDIX A

Key researchers and references associated with each ecological study region

Key ecological feature/ region	Key researchers	Key references
Perth Canyon and adjacent shelf break	Rob McCauley (Curtin) Christine Hanson (ECU) Mike Mackie (WA Fisheries) Luke Twomey (Swan River Trust) Lynnath Beckley (Murdoch)	Rennie (2006) Rennie et al. (2007) Rennie et al. (submitted, a.) Rennie et al. (submitted, b)
Albany canyons group and adjacent shelf break, including Leeuwin Canyon	Luke Twomey (Swan River Trust) Anya Waite (UWA) Dan Gaughan (WA Fisheries) Hans Kemp (MIRG)	
Kangaroo Island canyons and adjacent shelf break	Jochen Kaempf (Flinders) Tim Ward (SARDI)	
Kangaroo Island pool and Eyre Peninsula upwellings	John Middleton (SARDI) Tim Ward (SARDI)	Ward et al. (2006)
Predictable eddy fields (several locations)	Anya Waite (UWA) Lynnath Beckley (Murdoch)	Waite et al. (2007b)
Cape Mentelle upwelling	Christine Hanson (ECU) Mike Mackie (WA Fisheries) Dan Gaughan (WA Fisheries)	Hanson et al. (2006) Gersbach et al. (1999)

APPENDIX B

Details of ecological data sets

Details of ecological datasets used in this report are available from:

Professor Charitha Pattiaratchi
School of Environmental Systems Engineering (Faculty of Engineering, Computing and Mathematics)
Email: chari.pattiaratchi@uwa.edu.au