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The Leeuwin Current south of Western Australia

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Abstract

Two centuries ago Matthew Flinders detected an eastward-flowing current above the continental slope south of WA. A succession of advances in instrumentation, particularly since World War II, has led to a description of that current, the Leeuwin Current: Its tropical low salinity and subtropical high salinity waters arrive at Cape Leeuwin from the north and west in austral autumn and its leading edge progresses eastward at about 20 km day^{-1} into the low salinity subantarctic regime south of WA. The Leeuwin Current meanders on and off the continental shelf as far as the Recherche Archipelago. Off the shelf, its speeds can be as high as 1.8 ms^{-1} and its influence reaches down to 250 m. Beyond the Archipelago, in the Great Australian Bight, it is weaker, with speeds of about 0.3–0.5 ms^{-1} near the shelf edge. The region westward from the Archipelago is rich in eddies that interact with and distort the Leeuwin Current: anticyclonic eddies divert it out to sea and take on some of its waters; cyclonic eddies accelerate it on their northern sides. The current speeds in anticyclonic eddies decrease very little from the surface down to 250–300 m depth. A current meter mooring on the shelf near the Recherche Archipelago indicated that the Leeuwin Current was present most of the time from December 2001 to August 2002. The shelf currents were strongly influenced by winds from passing weather patterns. The results from recent numerical modeling show good agreement with the observations and show subsurface trajectories that would be difficult to capture by observation.

Keywords: Leeuwin Current, Western Australia, salinity, temperature, historical account

Introduction

The Leeuwin Current (LC) is a well-documented current system, of varying intensity, salinity and temperature, deriving in part from extra-Australian sources, and occurring off the coast of Western Australia (Waite *et al*. 2007). In Australian waters the maximum speeds attained by the narrow Leeuwin Current above the upper continental slope of southern Western Australia (WA), are second only to those of the broader East Australian Current, namely ~1.8 ms^{-1} versus 2.5 ms^{-1} (we exclude near shore tidal currents in northern Australia). The LC brings waters of both tropical and subtropical origin around Cape Leeuwin and thence eastward into the subantarctic regime south of WA. This sub-Antarctic regime is rich in eddies that interact with and distort the LC: anti-cyclonic eddies divert it out to sea and take on some of its waters, strengthening in the process; cyclonic eddies accelerate it on their northern sides. The region enjoys considerable biodiversity as a result of the sub-Antarctic, subtropical and tropical waters bringing to it different marine flora and fauna.

In this paper we examine historical work on the currents south of WA as techniques evolved from sailing ship observations in the early 19th century through to the shipboard electrical and acoustical measurements of water properties and current profiles and the satellite measurements of sea surface temperature in the 1980s. Then we examine both published and unpublished observations from 1994 onwards, 1994 being a special year in that there were three voyages by the research vessel *Franklin* – albeit uncoordinated and with vastly different aims – when, for the first time, satellites provided sea surface height measurements. With the near-continuous maps of sea surface topography from satellites one could follow the evolution of currents and eddies and more effectively interpret the sporadic *in situ* ship measurements. Then we examine current records for a nine-month period (December 2001 to August 2002) from on the continental shelf near the Recherche Archipelago. Finally, the results from a numerical model are examined, and they show, among other things, the arrival in autumn of the LC waters south of WA, in agreement with observations.

History

Early 19th century to the 1970s

The charts of Flinders (1814) for his voyages south of WA in December 1801 and May 1803 contain information on the geography of the coast and hinterland, on depths, bottom types, the weather encountered, and the currents experienced. Near the continental shelf between Cape Leeuwin and present-day Albany (118°E), the current was eastward at 1 ¼ knots (about 0.6 ms^{-1}). Farther eastward on the continental shelf of the Great Australian Bight, Flinders reported that *“the water does not seem to run in any constant direction, for is moved according as the* *wind may happen to blow. This was found by admiral D'Entrecasteaux; and is conformable to my experience…"* Flinders described a line "from the north-eastern isles of the Archipelago of the Recherche to Cape Northumberland (near 140°E on the coast of South Australia), we shall have what will commonly be the northern boundary of the current." In other words, he felt that the current that was strong between Cape Leeuwin and Albany may have continued across the Great Australian Bight, but a long way offshore.

Halligan's (1921) remarkable chart of the ocean currents around Australia drew on the observations of, among others, Flinders, King, Wickham, Stokes and Ross – and referred to vessels such as *La Venus, Geographe,* Naturaliste and *Challenger*. The chart showed a warm Indian Ocean stream rounding Cape Leeuwin and flowing eastward. He said that the 62°F (~16.5°C) isotherm lay east-west across the Indian Ocean, but deviated southward near WA, being carried a maximum of 200 miles south of Cape Leeuwin in June. The subsurface temperature measurements from *Challenger* led Halligan to describe what we would now call the Leeuwin Undercurrent going *"as far north as Shark Bay, having dipped below the warm southerly drift"*. Halligan mentioned a cold belt against the WA coast that was due to upwelling, which varied according to the strength and duration of the winds – a feature that we would now describe as the Capes Current (Gersbach *et al*. 1999).

Schott (1935) presented charts of ship drifts, temperature and salinity that suggested the flow of warm water around Cape Leeuwin and eastward towards the Great Australian Bight.

The influence of the Leeuwin Current south of WA is evident in the marine biology of the region: Wood (1954), through observations of subtropical dinoflagellates, postulated that a current flowed eastward from Cape Leeuwin to Tasmania and claimed that this was confirmed by "the finding of warm-water turtles on the west coast of Tasmania".

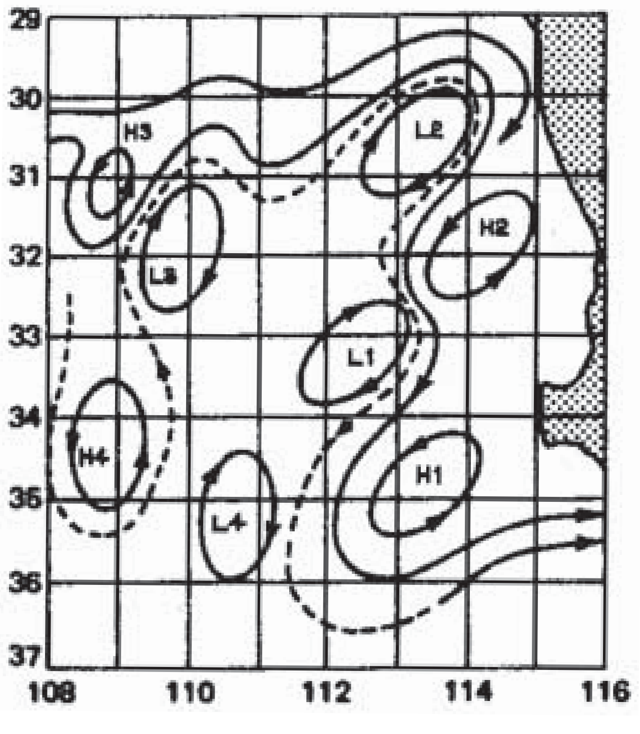

Figure 1. A schematic diagram from ship surveys of the mesoscale features west of WA (Andrews 1977).

Following World War II, Australia's small core of oceanographers used navy frigates for studies around the nation. Hamon's (1965) Nansen bottle observations ("hydrocasts") showed that there was a flow of relatively salty water from the central Indian Ocean towards WA at about 30°S. Andrews (1977) conducted near-synoptic three dimensional temperature mapping with expendable bathythermographs (XBTs), a first for Australian waters. The maps showed that Hamon's inflow was embedded in a field of cyclonic and anticyclonic eddies and that it turned southward at the continental shelf edge and then eastward at Cape Leeuwin, thus entering the study region for this paper (Figure 1).

Satellite tracked drifters in the 1970s

The technology for tracking drifters with satellites first became available in the early 1970s and soon after a dozen drifters built by CSIRO were released off WA. They were important in revealing the LC and prompted its naming. They showed that the LC not only flowed southward near the continental shelf edge to the Cape Leeuwin vicinity, but that it accelerated around the Cape and then flowed eastward at speeds up to 1.8 ms^{-1} towards the Great Australian Bight (Cresswell & Golding 1980). The current had small (~30 km) southward (anticyclonic) meanders separated by ~ 200 km. At the locations of the southward meanders there could be transient offshoots out to sea that took the drifters into cyclonic eddies, where they remained trapped for some weeks. In some instances, the drifter motions showed the cyclonic eddies to drift westward at about 7 km day^{-1}. The drifters decelerated when they entered the cool cyclonic eddies from the LC and accelerated when they re-entered it. The groundings of several drifters along the south coast suggested that the LC could spread in across the continental shelf. Some drifters came from the south to suggest that subantarctic waters were carried northward to interact with the LC.

Satellite sea surface temperature images in the 1980s

While nowadays satellite sea surface temperature images are available several times per day on the internet, the excitement created by the first satellite SST images of the LC south of WA in the early 1980s cannot be overstated. The images showed a number of small offshoots, as had the drifter tracks, with one being linked to an eddy so that it extended over 200 km southward (Legeckis & Cresswell 1981). In addition, and in agreement with the grounded drifters above, images showed that the warm waters of the LC had spread across the shelf to nearshore. Griffiths & Pearce (1985) used satellite imagery to suggest that the offshoots temporarily blocked the flow of the LC and diverted it into unstable baroclinic waves prior to the formation of cyclone-anticyclone eddy pairs. They found the temperature front at the offshore edge of the LC to be as much as 6°C near Cape Leeuwin, but that it was weaker across their images eastward to the Recherche Archipelago.

A sequence of satellite images from 1987 showed that the arrival of the tropical waters of the Leeuwin Current south of WA is a dramatic event: the leading edge of the Leeuwin Current progressed southward to Cape Leeuwin and then eastward at about 20 km day^{-1} between March and April (Cresswell & Peterson 1993). In step with the arrival of the LC there was a decrease in the northward wind stress off the west coast and a decrease in salinity at the Rottnest Island 60 m station at 32°S off Fremantle. At the same time sea level increased at Fremantle and at a pressure recorder on the southern shelf at 116°E. There were some other interesting features in the images: The near shore waters from Cape Leeuwin to 200 km eastward in a March image were cool, probably a result of upwelling from southeasterly winds blowing parallel with the coast and driving the upper waters offshore, to be replaced by a deep onshore flow. The upwelling appeared to feed into what was later named the Capes Current (Gersbach *et al*. 1999). Successive images in April showed a northward intrusion of cold subantarctic water near 118°E to be moving at 0.5 ms^{-1}. The intrusion turned to the east to run alongside the LC. The existence of such intrusions could, in retrospect, be inferred from the tracks and temperatures of the 1970s drifters. Finally, an image in May showed the LC to be interacting with three anticyclonic eddies south of WA.

Thus satellite radiometers and drifters, which respectively monitored the sea surface temperature and the current at the depth of their drogues (20 m), had revealed that the LC reached around Cape Leeuwin and then at least to the Great Australian Bight. The current was strong (up to 1.8 ms^{-1}), it interacted with mesoscale features and subantarctic waters, and part of it spread onto the continental shelf. There was, however, no information on the vertical structure of currents or water properties. For this one would have had to employ research vessels.

Voyages into the LC south of WA in the 1970s and 1980s

In the following paragraphs we discuss the only oceanographic research voyages south of WA in the 1970s and 1980s – by chance all in the same month, June, of each of the years 1971, 1982 and 1987. On each voyage the latest techniques of the time were employed. Hydrocasts at 119°E near Albany in June 1971 by Rochford (1986) from HMAS *Diamantina* showed the LC to flow above the upper continental slope and to have a surface core with temperature exceeding 19.5°C and salinity around 35.7. "Note that salinity is expressed in practical salinity units (International Oceanographic Table, 1981)."

Eleven years later in June 1982 Godfrey *et al.* (1986) ran shipboard and drifter studies of the Leeuwin Current south of WA. The shipboard tools on RV *Sprightly* included a conductivity-temperature-depth profiler (CTD) and XBTs. They mapped a 4°C front at the offshore edge of the LC and found it to be characterized by low Richardson numbers, an indication of considerable interfacial turbulent stresses and overturning. The 15–19°C isotherms at the surface front dipped down to meet the continental shelf edge at about 200 m depth. The front was distorted by an offshoot out to sea that was about 50 km wide and was defined at the surface by the 19°C isotherm, which descended to 90 m on the axis of the offshoot.

In June 1987, the suite of tools to study the Leeuwin Current had expanded to include a hull-mounted Acoustic Doppler Current Profiler (ADCP) on RV *Franklin* and satellite images once or twice per week, within the constraints of cloud cover and the reception range of the Hobart satellite receiving station (Cresswell & Peterson 1993). The LC had a maximum surface speed of over 1.5 ms^{-1} just beyond the shelf edge near 117° E. The trough-shaped near-surface core was 15 km wide between the 0.5 ms^{-1} isotachs and more than 200 m deep. The warm (> 19°C), low salinity (< 35.8) core rode in a U-shaped sheath of higher salinity (> 35.8) subtropical water that had been entrained upstream. Beneath the LC was a reverse flow to the west that probably contributed to the northward flowing LC undercurrent off western WA. A southward offshoot was seen to have strong contrary currents on its western and eastern sides: These ranged up to 0.5 ms^{-1} southward in the west and to 0.5 ms^{-1}northeastward in the east. There was considerable shear in both the horizontal and vertical, with Richardson numbers as low as 0.25. In the course of two days the offshoot pinched off and the remaining anticyclonic bulge on the edge of the LC moved eastward at 0.15 ms^{-1}, faster than similar features observed by Griffiths & Pearce (1985). The current speeds along the curved boundary of the bulge reached 1.5 ms^{-1}. These speeds and the shape of the bulge were similar to those for two anticyclonic meanders travelled by drifters in 1976 (Cresswell & Golding 1980).

These three voyages during the 1970s and 1980s had revealed the vertical structure of the LC, the westward countercurrent that flowed beneath it, and the horizontal and vertical structure of offshoots from it into the open ocean. All three voyages into the study area bounded by Cape Leeuwin and the Recherche Archipelago, the coast and several hundred kilometers southward, were short (less than a week) and the absence of satellite sea surface temperature images for the first two meant that little was known of the larger oceanographic picture. The two images obtained during the period of the third voyage were very useful, but it wasn't until 1994 when data from satellite altimeters, in tandem with daily-updated sea surface temperature images, enabled eddies to be tracked through the study area. Fortuitously, there were three research voyages that year.

Voyages in 1994

As mentioned earlier, 1994 was a special year both because there were three voyages by RV *Franklin* through the study region in July, November and December and because satellite altimeter measurements were available for the first time. Sea surface topography maps (Figures 2A & 2B) derived from measurements by the Topex/ Poseidon and ERS satellites, as well as SST from NOAA satellites, suggested that weak eddies originating east of the Great Australian Bight migrate westward, first encountering the continental slope off the Recherche Archipelago (Cresswell & Griffin 2004). Note that the various eddies shown on Figures 2A and 2B are labelled A, B, C, W, X, and Y. Anticyclonic eddies, labelled A–C on Figure 2, were observed to divert the LC out to sea

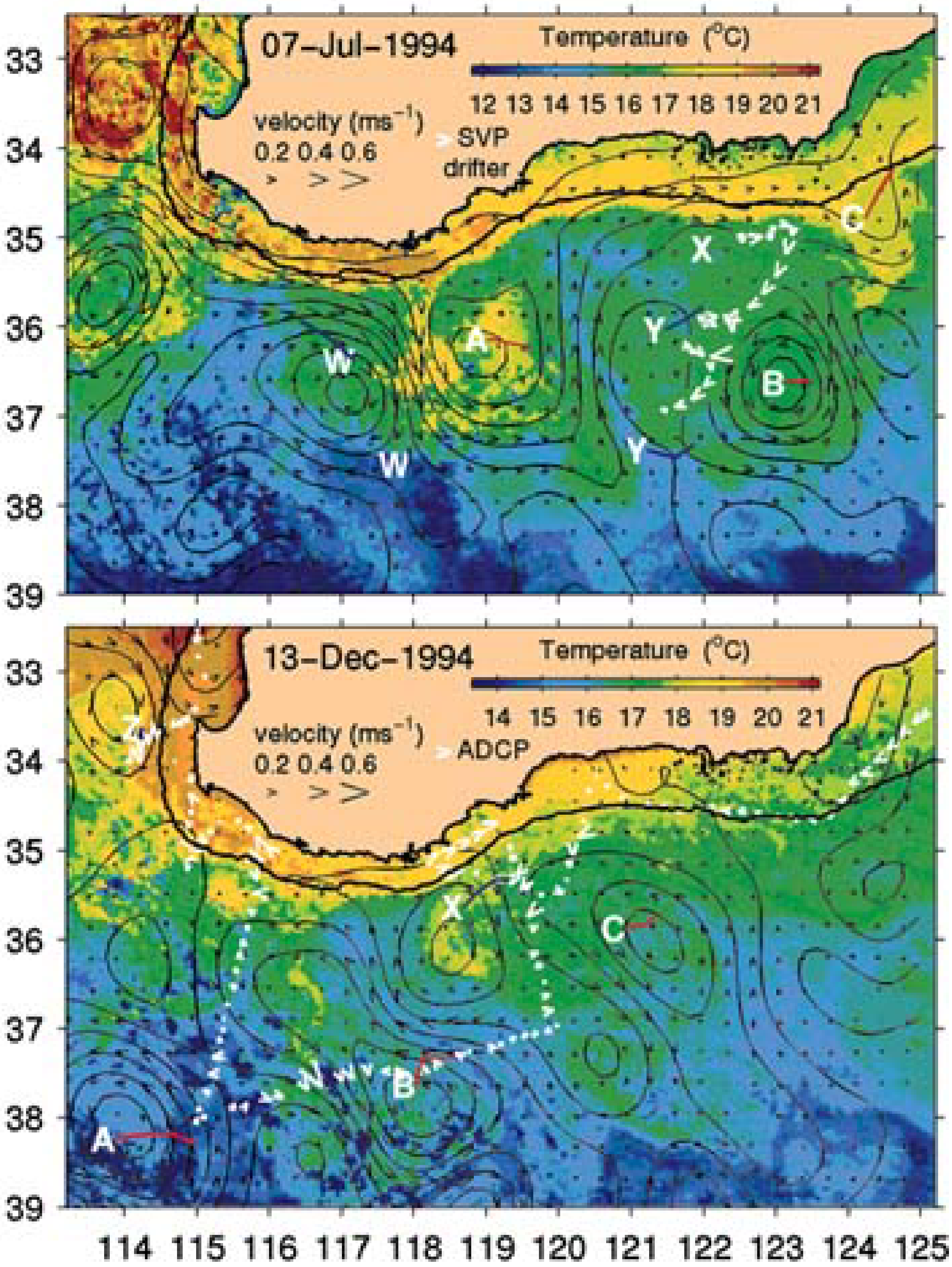

Figure 2a,b. Satellite sea surface altimetry, derived currents and temperature maps for July and December 1994. A, B and C are anticyclonic eddies and W, X and Y are cyclonic. The eddy labeling is automatic and movements of the eddies in the preceding month are marked red /blue for anticyclonic/cyclonic eddies. The white tracks in Figure 2a are the tracks of surface drifters, while in Figure 2b the currents measured by RV *Franklin's* ADCP are marked in white. The shelf edge is marked by a thin black line and a colour scale for the satellite-derived temperatures is shown (Figure kindly provided by David Griffin).

and back again, to capture some of its warm water, and to strengthen as a result. This process was repeated as the eddies drifted westward and occasionally moved near the LC and interacted with it. Cyclonic eddies that moved in against the LC accelerated it eastward along the upper continental slope. Several anticyclonic eddies were followed westward for 18 months as they drifted out into the Indian Ocean at up to 5 km day^{-1}, sometimes splitting, sometimes coalescing. The altimeter data enabled the evolution of oceanographic features to be followed and ship observations to be better understood: For example, we were able to see that the July voyage by chance clipped the NE side of eddy A; the November voyage similarly cut across eddy C; and the December voyage mapped eddy B.

First voyage – July 1994

Franklin voyage FR9407 (Chief Scientist P Petrusevics) from 6–19 July 1994 had been planned to occupy CTD and biology stations along transects from Adelaide to Fremantle. Time ran out near Albany (118°E), but the ship was taken along a zig-zag path to Fremantle and, overall, the voyage yielded an excellent set of current measurements with the vessel's ADCP, which we have processed for this paper. The combined surface topography and temperature image from the time (Figure 2A) shows the LC as a warm stream extending into the Great Australian Bight, along with three anticyclonic

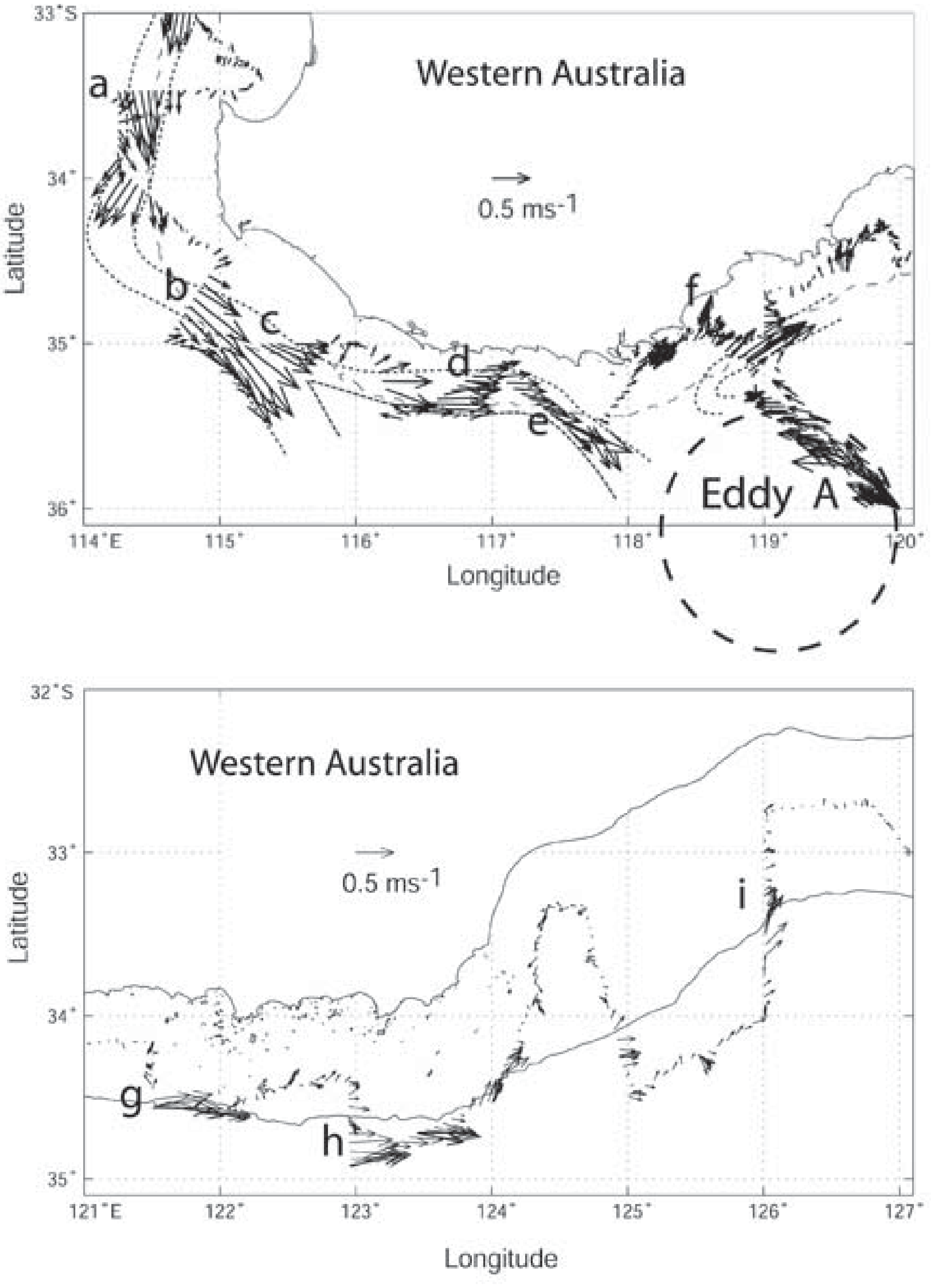

Figure 3. Current vectors at 20 m depth measured by the ADCP on *Franklin* during FR9407, a) from 114 to 120 E and b) from 121 to 127 E. The dotted lines in the former give a conjectured flow path for the LC for speeds greater than 0.5 ms^{-1}. Transects a-i are labeled and the 200 m isobath appears as a thin line.

eddies, labelled A–C, and three cyclonic eddies, labelled W–Y. We note the following features in the image: eddies W and X steepened the sea surface topography from onshore to offshore and thereby accelerated the LC; the edge of the LC bulged seaward across the shelf edge near 115.5°E; the eddy-pair A–W drove a LC offshoot from 118°E out to sea and then around both eddies, more noticeably eddy A; cool subantarctic water flowed northward to the west of eddy W and the east of eddy A; and eddy C was in the process of forming or strengthening in the east of the image. As we will see, voyage FR9407 did not venture sufficiently seaward from the upper continental slope to encounter eddies B and C, but it did cross the NE side of eddy A.

In discussing the ship's ADCP measurements (Figures 3A and 3B, and 4A–4I) we work from west to east – or upstream to downstream with respect to the LC. The LC meandered on and off the outer continental shelf with speeds exceeding 0.7 ms^{-1} from Cape Naturaliste to the Recherche Archipelago. Off the shelf its influence usually reached to 250 m depth, but was sometimes deeper than the depth reached by the ADCP – about 300 m. The LC deviated seaward between Capes Naturaliste and Leeuwin. It was largely on the shelf 100 km farther downstream to the southwest of Cape Leeuwin. It then apparently split, with a major branch heading out to sea – at over 1 ms^{-1} – near 115°E. The other branch moved to be completely on the shelf at 116.5°E, but by 117.7°E this branch deviated offshore. The current speeds on the shelf immediately to the east were very small (0.1 ms^{-1} and smaller), but by 118.5°E the shelf currents had increased to 0.2 ms^{-1} and the LC *per se* ran at 0.8 ms^{-1} right at the shelf edge. It would seem that the seaward offshoot at 117.5°E would have had to have turned back to the shelf for this to be possible – or there was flow from eddy A back into the LC. At 121.5°E the LC was at the shelf edge with a speed in excess of 0.7 ms^{-1}. By 123°E at the Recherche Archipelago the surface core of the LC was 25 km beyond the shelf edge and had a speed again in excess of 0.7 ms^{-1}. At 126°E the LC had a speed of 0.5 ms^{-1} at its core and at longitude of the Head of the Bight, 131°E, 0.3 ms^{-1} (results not shown here). Beyond this it became quite weak and was confused with eddies.

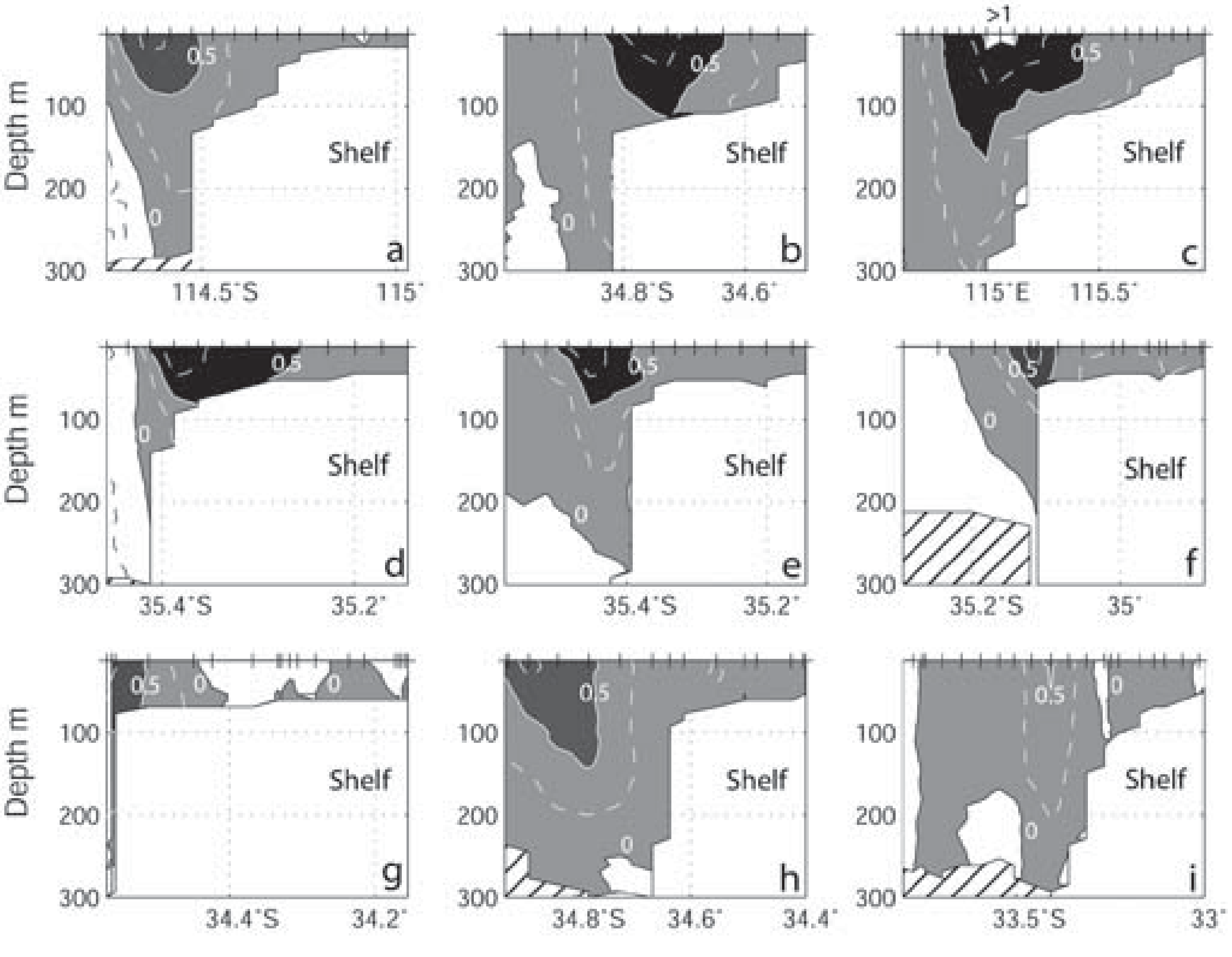

Figure 4. Sections (a-i) showing the downstream (shaded) / upstream (white) current components made with the ADCP on *Franklin* on voyage FR9407 from Cape Naturaliste southward to Cape Leeuwin and then eastward to the western Great Australian Bight. The continental shelf (white) as detected by the instrument is on the right of each panel. The grey shading shows downstream flow of 0-0.5 ms^{-1}; black is for speeds of 0.5-1 ms^{-1} (white near the surface in panel 3 indicates downstream current speeds in excess of 1 ms^{-1}). The contours are separated by 0.25 ms^{-1}. There is noise interference (cross-hatched) near 300 m depth in panels a, d, f, h and i.

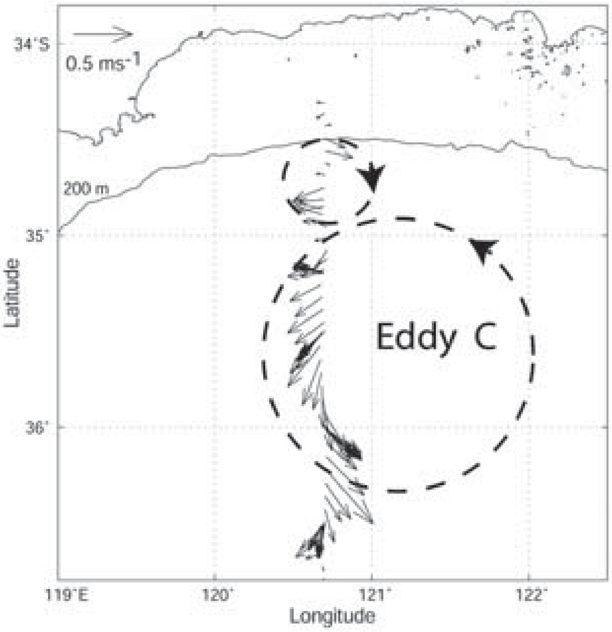

Figure 5. The northern part of a transect made as part of FR9410. The vectors – and satellite sea surface topography from the time – suggest an approximate position of eddy C (dashed line).

Second voyage – November 1994

The second *Franklin* voyage, FR9410, (Chief Scientist M Tomczak) comprised two long transects along 120°E and 132°E to 48 S (Schodlok *et al.* 1997). Here we examine the transect along 120°E, paying attention to the LC and mesoscale features south to 37°S. The transect captured, by chance, the first pass, a chord, across an anticyclonic eddy south of WA. The current speeds in this eddy C reached a maximum of about 0.5 ms^{-1} (Figure 5). The northernmost part of the eddy was at 35.2°S; north of this there appeared to be a small cyclonic cell, with the LC forming its northern side. The LC was weak, with a speed of 0.3 ms^{-1}, but it reached down beyond the outer shelf to more than 300 m (Figure 6A). The current in eddy C decreased very little from the surface to 300 m depth.

CTD stations were occupied only after the ship had moved southward off the shelf (Figure 6B). The surface bowl of eddy C had salinity > 35.5, as did the LC and its cyclonic appendage. Salinity, temperature and other properties are described by Schodlok *et al.* (1997). The SubAntarctic Mode Waters (SAMW) beneath the eddy at 300–700 m depth (salinity and temperature around 34.7 and 9.5°C respectively) can be traced back to the surface at 45°S.

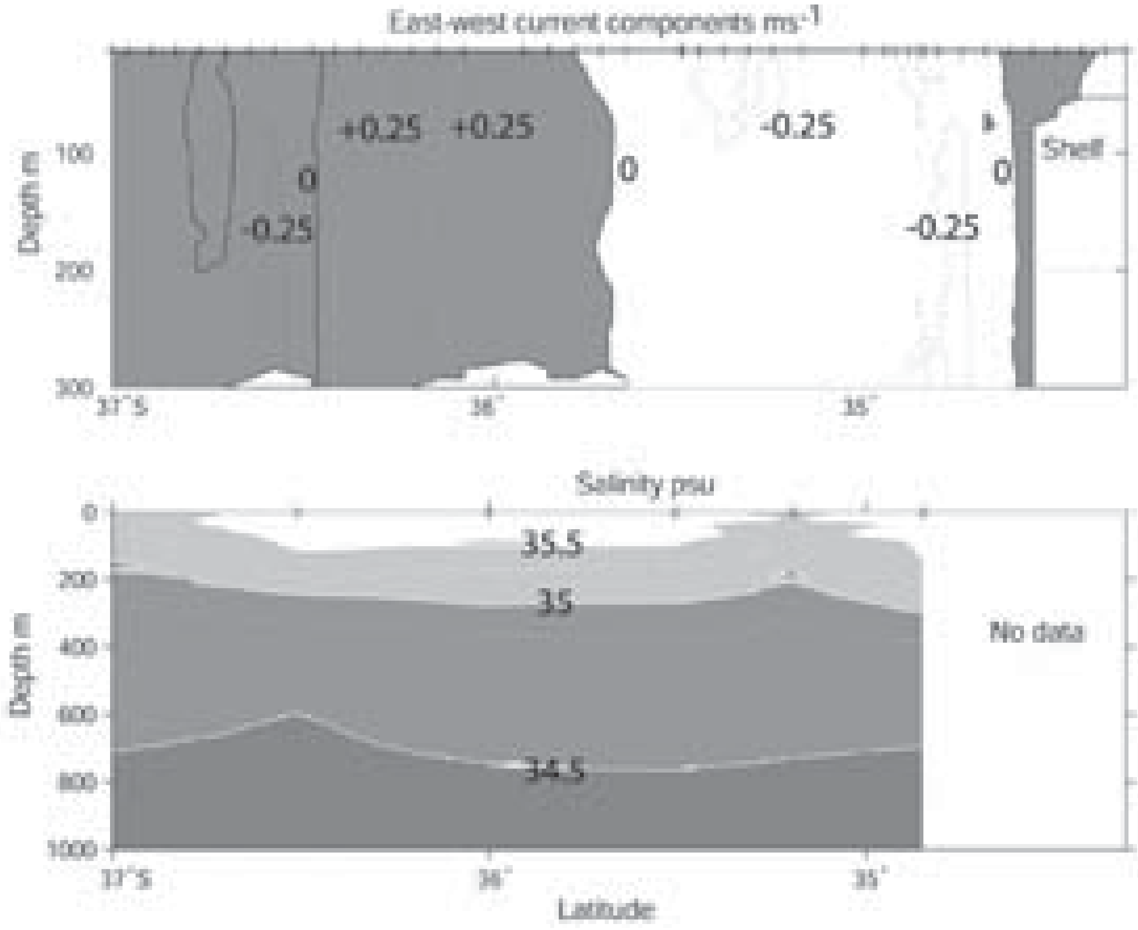

Figure 6. (a) Section made with the ADCP on *Franklin* on voyage FR9407 of the east (grey) and west (white) current component across a chord of eddy C. The continental shelf (white) as detected by the instrument is on the right. The contours are separated by 0.25 ms^{-1}. Thus the eastward component near 36.2°S exceeded 0.25 ms^{-1} as did the westward component near 34.9°S There is noise interference near 300 m depth near 36°S and 36.5°S. (b) The salinity section (to 1000 m) southward from the first station near 34.9°S. The contour spacing is 0.25.

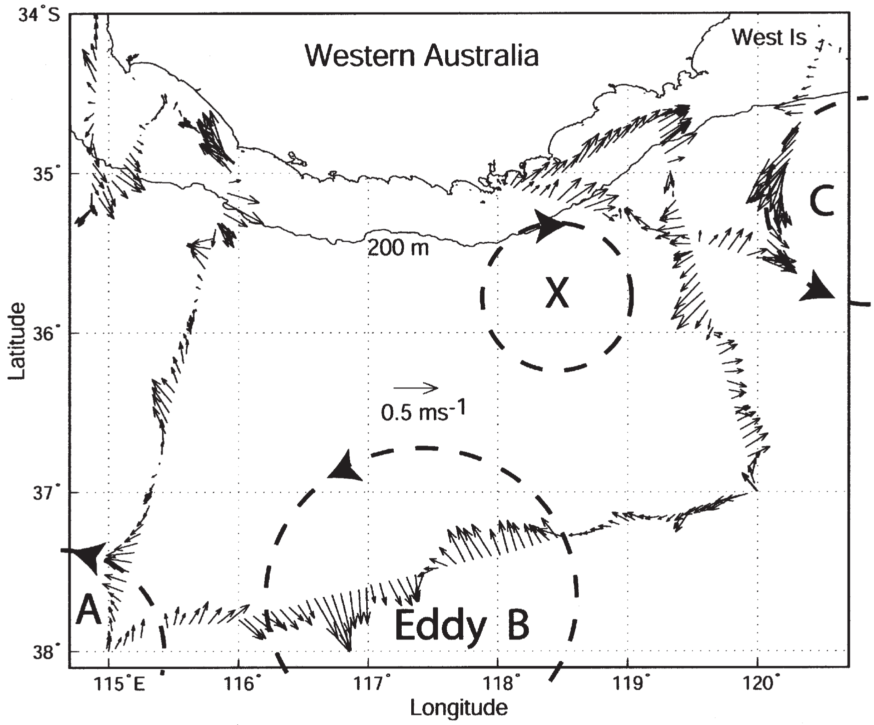

Figure 7. Current vectors at 20 m depth measured by the ADCP on *Franklin* voyage during FR9411. The positions of anticyclonic eddies A-C and cyclonic eddy X, as estimated from both the satellite topography and the vectors measured by the ship, are marked.

Third voyage – December 1994

The third *Franklin* voyage, FR9411 (Chief Scientist G Cresswell), went from Pt Lincoln to Fremantle. A number of findings were presented by Cresswell & Griffin (2004) and we will summarise those, as well as examining the data in a manner that complements the two earlier 1994 voyages. The surface topography and temperature image from the time Fig.2B shows anticyclonic eddies A–C as well as cyclonic eddy X near the shelf edge at 118.5°E; eddy X was in a position to strengthen the LC, whereas eddy C would have weakened it. Cold subantarctic water was driven northwestward on the eastern sides of eddies A and B.

The ship occupied CTD stations along the route and took current and other underway measurements. It crossed Eddy B with the aid of a satellite thermal image and this is obvious in the map of current vectors (Figure 7). The effects of eddies C and X on the current patterns are complex and difficult to interpret. The LC was detected near the shelf edge at 115°, 116° and around 119°E, where cyclonic eddy X may have strengthened the currents and spread them onto the shelf. Just to the east of 120°E the vectors may show the influence of eddy C. On the shelf in the west there was flow, perhaps wind-driven, towards and beyond Cape Leeuwin that contributed to the Capes Current.

Eddy B had a bowl-shaped cross section (Cresswell & Griffin 2004) in temperature and salinity and perturbed the structure down to at least 1000 m. The currents decreased very little from the surface to 300 m. Nutrients and oxygen were low in the centre of the eddy; there was a fluorescence maximum at 80–100 m and this extended up to the surface around the perimeter of the eddy at 116°E and 119.5°E.

Figure 8 shows salinity and temperature profiles and the T–S diagrams from a station nearest the centre of eddy C in November; from one nearest the centre of eddy

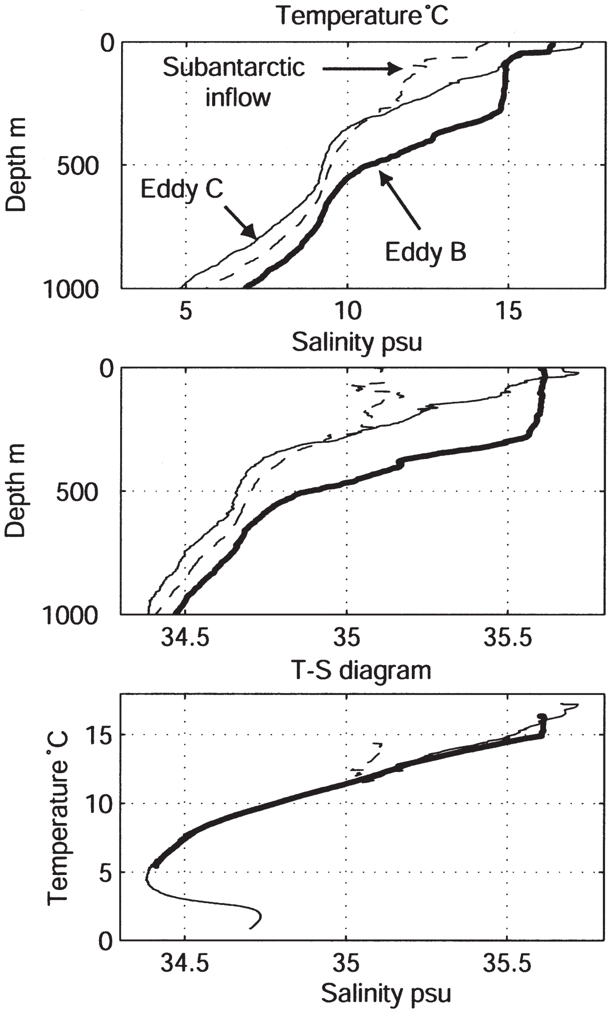

Figure 8. Salinity, temperature and T-S profiles from stations in eddy C in November, eddy B in December, and the subantarctic waters flowing northwestward between eddies A and B in December 1994.

B on December; and from one in the northwestward-flowing subantarctic water between eddies A and B in December. Eddy C showed no evidence for a deep winter mixed layer, probably because it formed off the Recherche Archipelago late in winter (August). Eddy B had a deep winter mixed layer to 290 m with a warm "summer cap" from insolation. Note that salinity was constant through this layer. The subantarctic upper waters can be seen to be relatively cool and fresh. The December stations were only taken to a little over 1000 m and they did not quite reach the salinity minimum of the Antarctic Intermediate Waters, but this can be seen in the T–S profile of the November station that was taken to the bottom. The SubAntarctic Mode Waters formed by deep winter mixing near 45°S are marked by the steeper slopes near 9°C and 34.65 in the temperature and salinity profiles. The temperature and salinity profiles emphasize the 300 m depression of the water structure caused by eddy B.

The observations for 1994 discussed above represent the first example of combining satellite sea surface topography and temperature measurements with research vessel measurements in Australian waters. The observations enabled eddies to be monitored for up to two years and examined in detail as they drifted westward into the region south of WA. They evolved and interacted with the LC and with one another before finally drifting westward into the Indian Ocean. The July 1994 voyage gave the first synoptic picture of the LC as it meandered on and off the shelf between Cape Naturaliste and the Recherche Archipelago. There remained a gap in knowledge about the temporal variability of the currents on the continental shelf, which leads us to the next section.

A mooring at 80 m near the Recherche Archipelago in 2001/02

Until 2001 no current meters had been moored on the shelf or slope south of WA and therefore little was known of the variability of the currents with time. To address this a mooring deployed at 34.125°S, 121.58°E at the 80 m isobath at the mouth of Causeway Channel some 22 nautical miles southwest of Esperance and 15 nautical miles west of the plateau on which stand many of the islands of the Recherche Archipelago (Figure 9).

Aanderaa current meters at 30 and 60 m depth collected data on speed, direction and temperature from November 2001 to August 2002 and here we present for the first time some of the results. The temperature time series (Figure 10A) show that the waters were mainly stratified over summer until mid-March, when they became mixed due to the arrival of the Leeuwin Current and/or the effects of winter heat loss and overturn. The current measurements (Figure 10 b) suggest that the rotor on the lower meter either stuck or fell off after two months. The monthly progressive vector diagrams (Figure 11) showed the current flow to be predominantly in the direction of the Great Australian Bight, apart from November and February, being strongest in May, June,

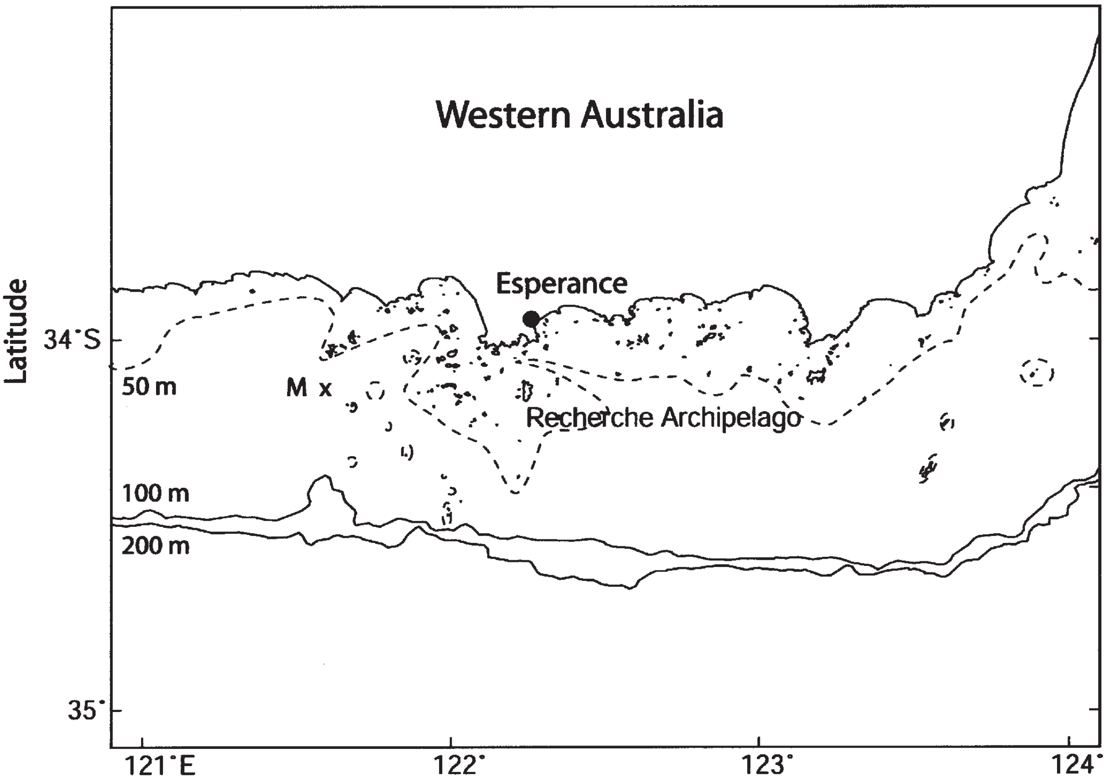

Figure 9. A chart of the location of the mooring (M) showing the coastline and the 50, 100, and 200 m isobaths. The islands form the Recherche Archipelago and the city of Esperance is marked.

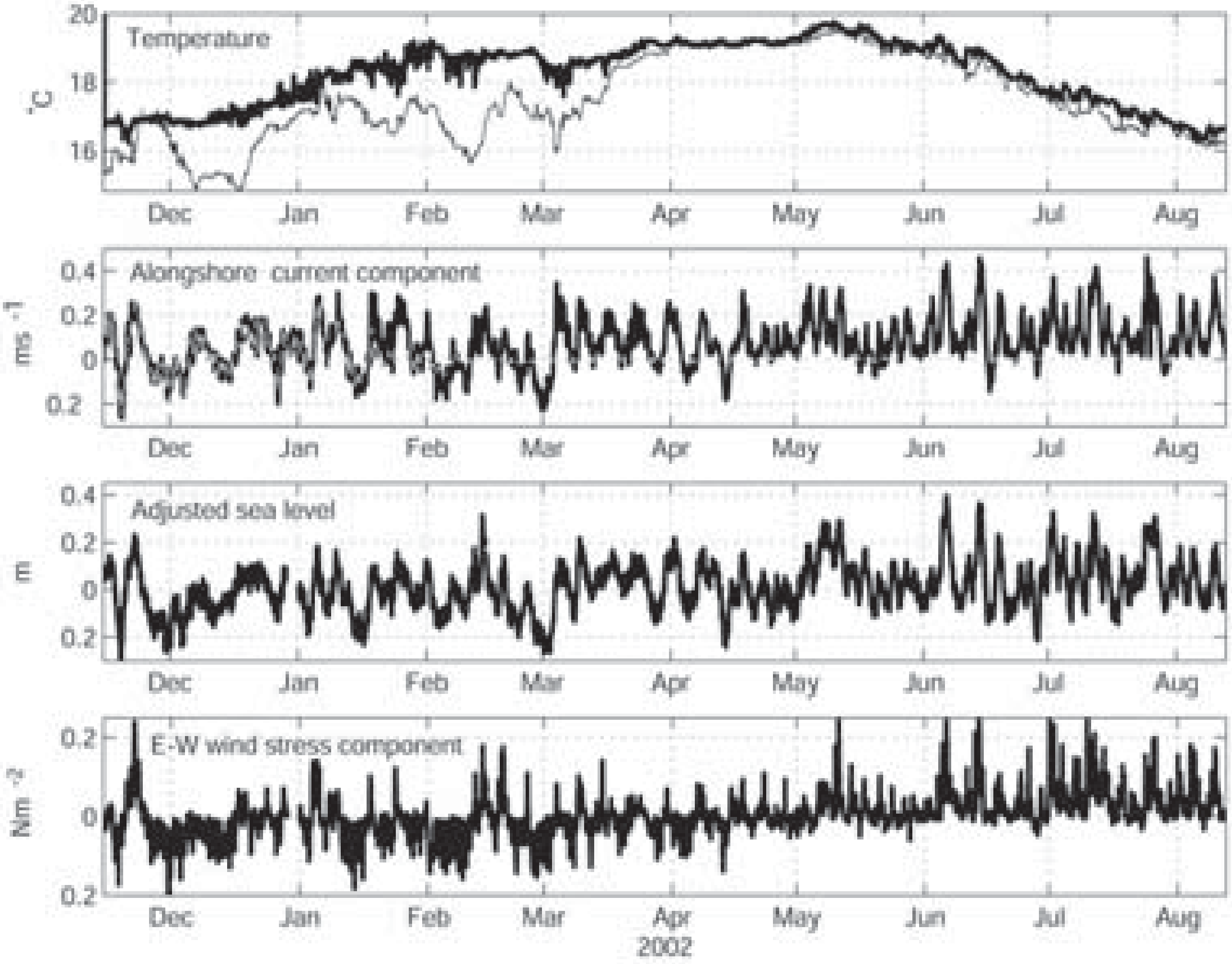

Figure 10. Time series of a) temperature for the upper (thick line) and lower (thin line) current meters; b) alongshore current for the upper meter onto which is superimposed the alongshore current for the lower meter until it failed in early February; c) adjusted sea level at Esperance; and d) the east-west wind stress at Esperance.

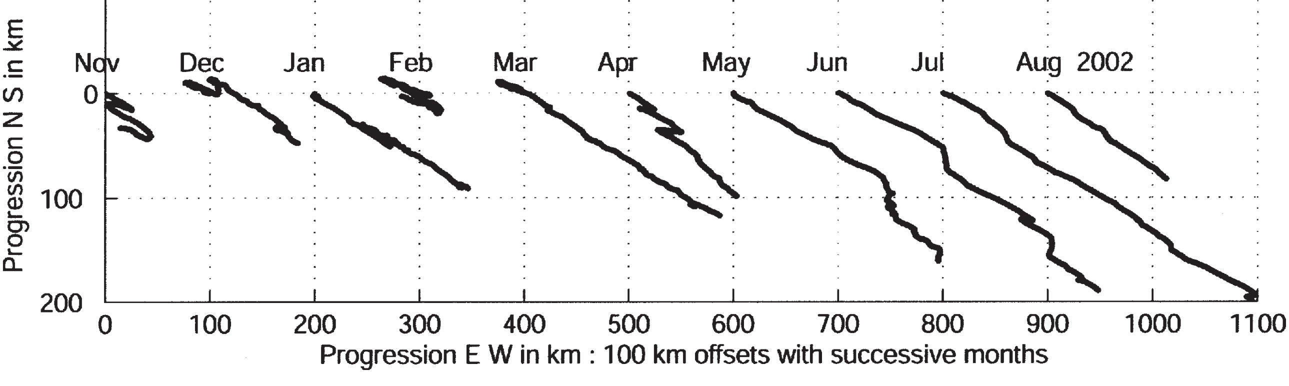

Figure 11. Monthly progressive vector diagrams for the upper meter (30 m depth); November 2001 and August 2002 are not complete months.

July (> 0.1 ms^{-1}, or more than 10 km day^{-1}) and August, and to be diverted to the SSE apparently by the presence of the raised topography of the Recherche Archipelago immediately downstream. Figure 10B shows the flow in the SSE direction and it is referred to as the "Alongshore current component". The strong winter (May/August) flow towards the Great Australian Bight was accompanied by higher sea level (Figure 10C) and stronger eastward wind stress (Figure 10D). The sea level measurements from Esperance were adjusted for the inverse barometer effect (relative to a rough annual average sea level pressure of 1017 hPa).

While there was some agreement between the alongshore current and the eastward wind stress at intervals of several days, there was much better agreement between the current and the adjusted sea level. This was probably due to both parameters responding to passing coastal-trapped waves (Provis & Radok 1979; Church & Freeland 1987) that were generated by weather forcing further west or nearby.

We examine two wind-related events: the oscillating current in November (summer) and a large current pulse in the first week in June. For the former, Figure 12 shows 12 days of the alongshore current components for the two instruments, the adjusted sea level at Esperance, and the east west wind stress component, together with atmospheric pressure maps at times of the extremes of the current oscillations. The current trough, or flow of

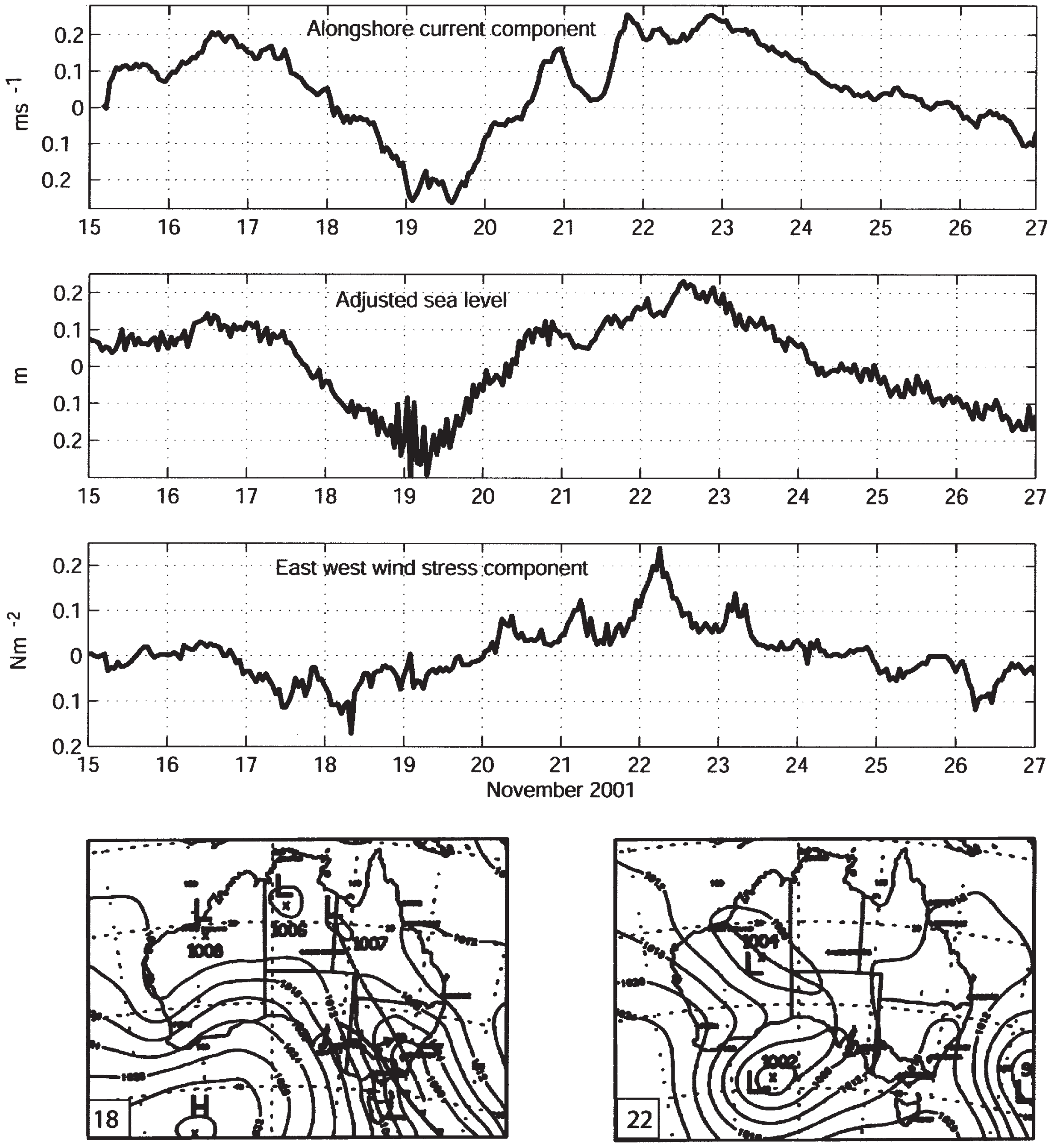

Figure 12. An oscillation in the alongshore current related to the passage of atmospheric pressure features and associated wind forcing: a) alongshore current component 15-27 November 2001; b) adjusted sea level; and c) east-west wind stress. Bottom panels: sea level pressure maps for 18 and 22 November 2001.

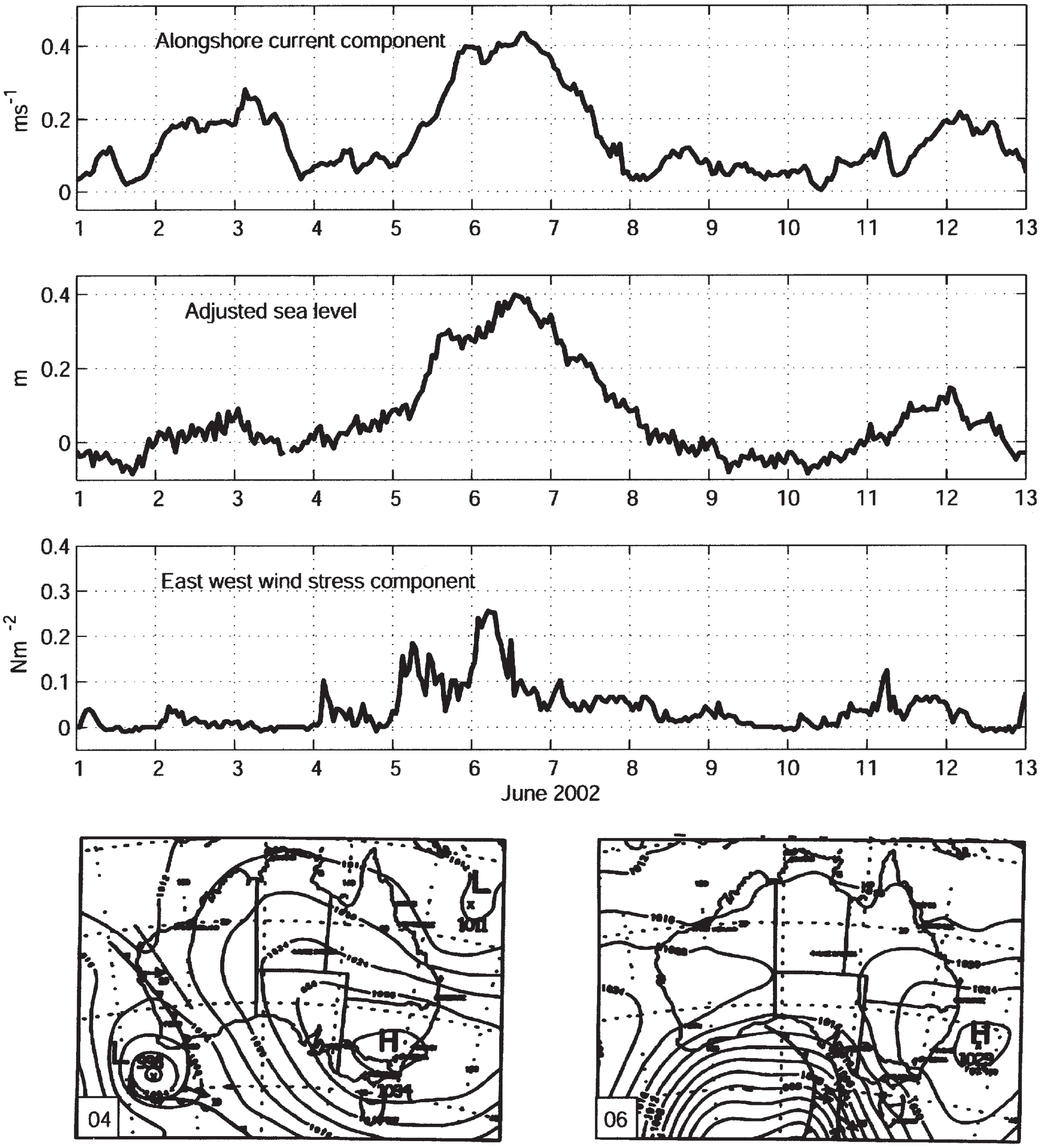

Figure 13. An alongshore current pulse related to the passing of atmospheric low pressure features and associated wind forcing: a) alongshore current component 1-13 June 2002; b) adjusted sea level; and c) east west wind stress. Bottom panels: sea level pressure maps for 4 and 6 June 2002. a) current component time series 3-10 June 2002; b) sea level pressure map for 4 June 2002; c) sea level pressure map for 6 June 2002.

0.25 ms^{-1} towards Cape Leeuwin, followed enhanced westward wind stress from a high pressure cell centred south of the Great Australian Bight. The subsequent current crest, or flow towards the Archipelago, was due to eastward wind stress from a low in the Bight. The current variations were closely related to sea level variations. The wind stress parallel with the coast would have raised/lowered sea level due to the Ekman effect depending on whether it was eastward/westward. The sea level slope across the shelf would have driven the the alongshore currents.

There was a strong (0.4 ms^{-1}) pulse in the alongshore flow towards the Great Australian Bight on 6/7 June 2002 (Figure 13). It was closely related to a crest in the sea level and it followed enhanced eastward wind stress that was due to a deep low pressure cell travelling eastward to south of the continent. The interval, 1–13 June, shown in Figure 13 included two other current pulses on 2/3 June and 12 June. These were related to sea level crests, but the wind stress at the time was not great. Perhaps these current pulses were the result of coastal-trapped waves propagating into the region from the west.

To conclude this section we have seen that the LC usually extends onto the continental shelf and that it is steered seaward by the topography of the Archipelago immediately to the east. Also, passing weather systems and coastal-trapped waves have strong effects on the circulation.

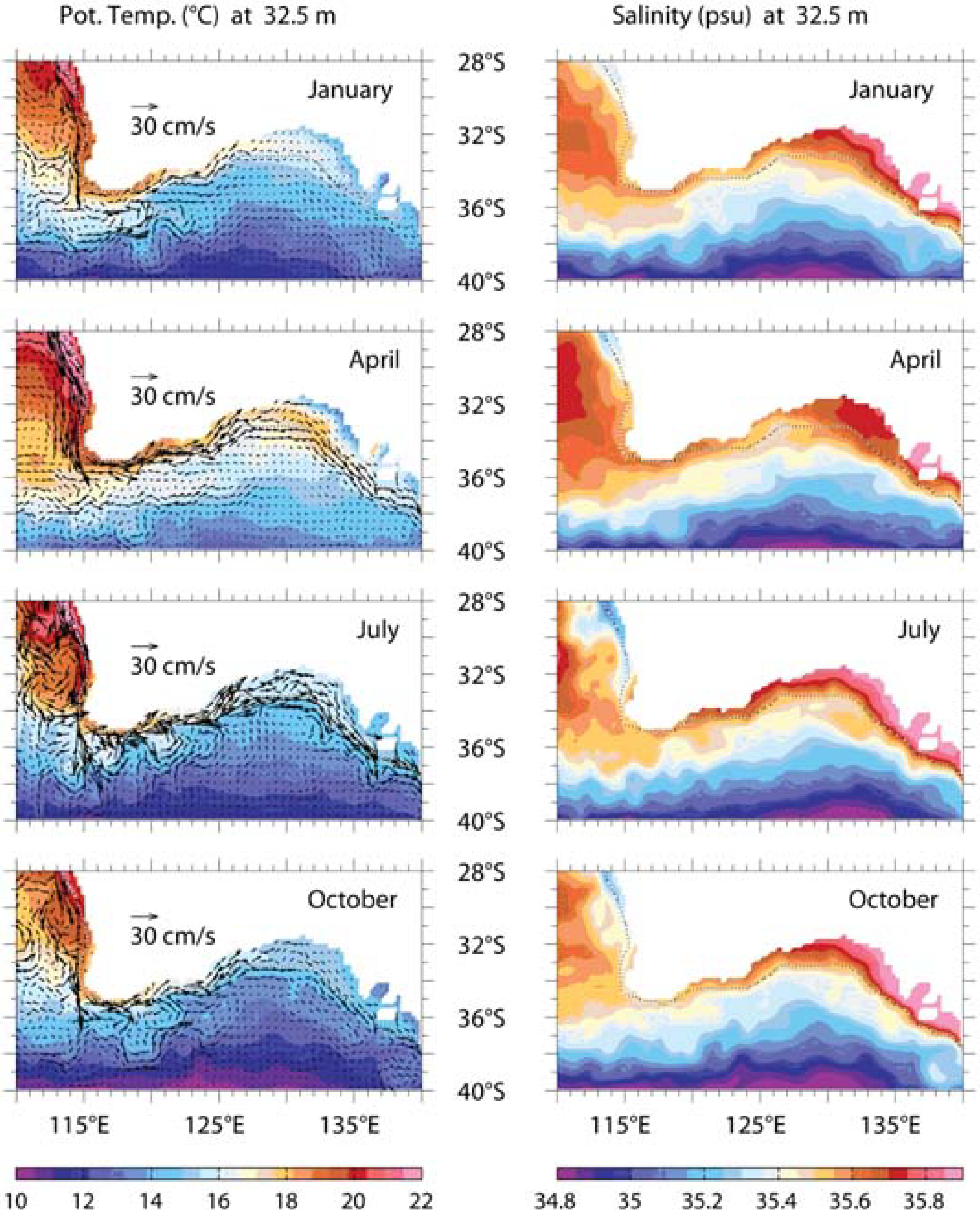

Figure 14. Seasonal variability of the Leeuwin Current in the 0.28º Los Alamos National Laboratory Parallel Ocean Program (POP) ocean model. Potential temperature (lef panels), salinity (right panels) and velocity vectors at 32.5 m (core depth). Velocity vectors were plotted at every other point for clarity.

Model results

We examine the seasonal variability of the Leeuwin Current, along the southern part of the west Australian coast and along the eastern part of the south Australian coast, using 5-year monthly mean simulated fields of near-surface temperature, salinity and velocity from the 0.28° Los Alamos National Laboratory Parallel Ocean Program (POP) ocean model (Maltrud *et al*. 1998; Garfield *et al*. 2001). Qualitatively, this model was shown to reproduce the major components of the observed mean state, low-frequency variability and hydrographic properties of the near-surface circulation associated with the Leeuwin Current and its undercurrent along the

Western Australia coast (Domingues 2006), from North West Cape (22°S) to Cape Leeuwin (34°S).

In agreement with *in situ* observations (*e.g.*, this study) and remotely-sensed observations (*e.g.*, Legeckis & Cresswell 1982; Ridgway & Condie 2004), the simulated fields in Figure 14 illustrate the seasonal progression of the Leeuwin Current into the Great Australian Bight. From December to March, the boundary flow of the Leeuwin Current is quiescent. It suddenly pulses in April and evolves into a vigorous current during austral winter. The eastward flow of the Leeuwin Current in the Great Australian Bight is initially strongest only on the western part of the basin but by July/August it has accelerated along the entire basin. The vigorous flow then becomes unstable and dissipates a large amount of its energy by shedding mesoscale eddies. This energetic winter time eddy variability, along the outer edge of the Leeuwin Current, is clearly manifested in the July panel, even though it represents a 5-year average (1993–1997). From September to November, energy levels gradually decay and the quiescent summertime phase of the Leeuwin Current is restored.

The generation of mesoscale eddies by the vigorous flow of the Leeuwin Current is not only a form of dissipating energy (Feng *et al*. 2005) but also a way of exchanging water properties and other tracers. Domingues *et al*. (2006) found that 70% of the heat advected into the coastal region off Western Australia, by the narrow poleward flow of the Leeuwin Current, is transferred to the adjacent ocean interior through eddy fluxes. This is the primary means by which the Leeuwin Current is cooled along its boundary path (about 5°C over 1350 km). A Lagrangian particle tracking performed during the POP model run (Domingues *et al*. 2007) additionally showed that particles seeded within the Leeuwin Current off Western Australia can be advected as far as the west coast of Tasmania within a 5-year (or less) timescale, and many others can become trapped for prolonged periods in the energetic mesoscale eddies, mostly around Cape Leeuwin. Trapped particles were either seen to gradually subduct and return to Western Australia as part of the equator-ward flow of the Leeuwin Undercurrent or drift westward within the eddies. The latter appeared to be the most common situation.

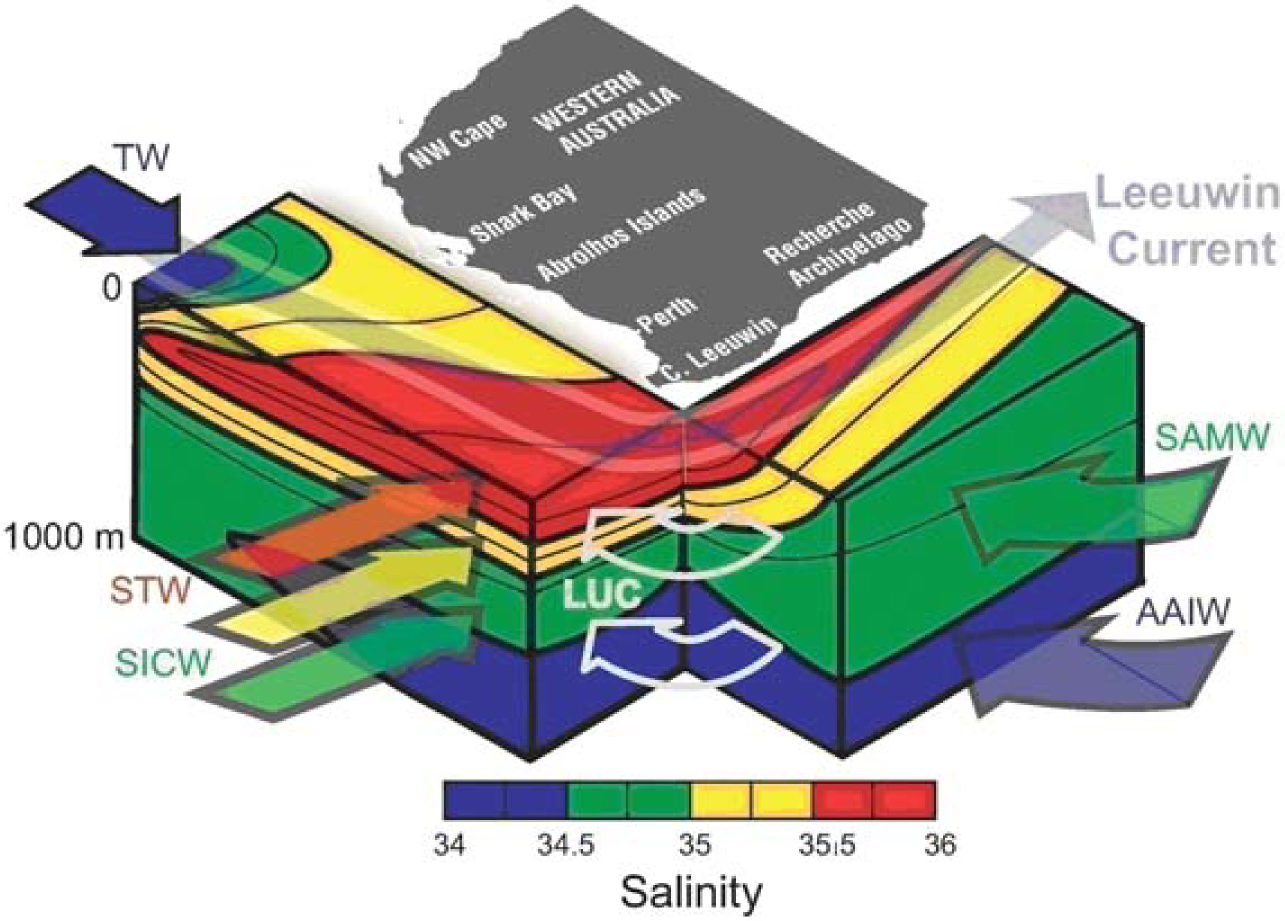

Figure 15. A schematic diagram of the salinity structure down to 1000 m drawn from several ship surveys. The boxes are 1000 m deep and about 200 km wide. The view is from above the southern Indian Ocean and the map is to orient the reader.

Discussion

The interplay of the various water types to the west of WA has been summarized in a schematic diagram by Woo (2005). This inspired Figure 15, which should simplify this discussion. It was drawn from salinity data collected on several voyages by RV *Franklin* in 1987 and 1994; it excludes shelf waters and eddies. The main inputs to the near-surface Leeuwin Current system are the low salinity tropical waters in the north (blue, TW); the salty sub-tropical waters in the west (red, STW); and, to a lesser degree, the relatively fresh subantarctic waters in the south (green). The salty subtropical waters split, with one part moving northward and deepening, while the other moves southward and then eastward around Cape Leeuwin thereby making the Leeuwin Current a relatively salty stream south of WA.

Flowing westward along the southern continental slope to Cape Leeuwin and then northward is the Leeuwin Undercurrent, which Ridgway (2007) has shown to be part of a "supergyre" traversing both the Pacific and Indian Oceans. The other inputs to the depth range from several hundred to one thousand metres are the South Indian Central Water in the west (yellow and green arrows, SICW) and the SubAntarctic Mode Water (green arrow, SAMW) and Antarctic Intermediate Water (blue arrow, AAIW) in the south. Not shown in the east is the Flinders Current (Middleton & Bye 2007) which feeds into the Leeuwin Undercurrent south of WA.

The schematic diagram is expanded for the region south of WA (Figure 16) to show surface currents due to the Leeuwin Current and eddies – one anticyclonic and two cyclonic. As we have seen, there can be several anticyclonic eddies between the longitudes of Cape Leeuwin and the Recherche Archipelago. The diagrams draw on observations taken by Cresswell & Peterson (1993) and Cresswell & Griffin (2004). Sometimes the eddies are too far offshore to influence or interact with the Leeuwin Current, or at other times a bulge may form on the seaward side of the LC adjacent to an anticyclonic eddy. The bulge can develop into an offshoot that will carry LC water out to sea and around the eddy, which then takes on some of the warm salty waters and strengthens. Part of the offshore flow often encircles the adjacent cyclonic eddies, as was revealed by drifters.

The LC attains maximum speeds of 1.8 ms^{-1} between rounding Cape Leeuwin and reaching the Recherche Archipelago as it moves on and off the continental shelf. The offshoots of the LC can have complex structure, with south-going currents of up to 0.5 ms^{-1} on their western sides and north-going ones of similar speeds on the eastern sides. Strong current shear leads to turbulence and overturning. Some of the eddies may propagate into the region from across the Great Australian Bight and then strengthen as a result of interacting with the LC to the south of the Recherche Archipelago. The eddies can be followed with satellite altimetry at least for two years as they drift westward south of WA and then out into the Indian Ocean.

A summer survey of an anticyclonic eddy showed influences of the LC, deep mixing in winter, and summer heating that formed a cap to the temperature structure. This was similar to structures seen in the East Australian Current anticyclonic eddies described by Nilsson & Cresswell (1980). The subantarctic water around the eddy was cooler, fresher, and richer in nutrients and oxygen than both the eddy and the LC. Two of the eddies that were crossed south of WA had maximum surface current speeds of about 0.5 ms^{-1}; these speeds decreased only slightly down to the 250–300 m reached by the Acoustic Doppler Current Profiler.

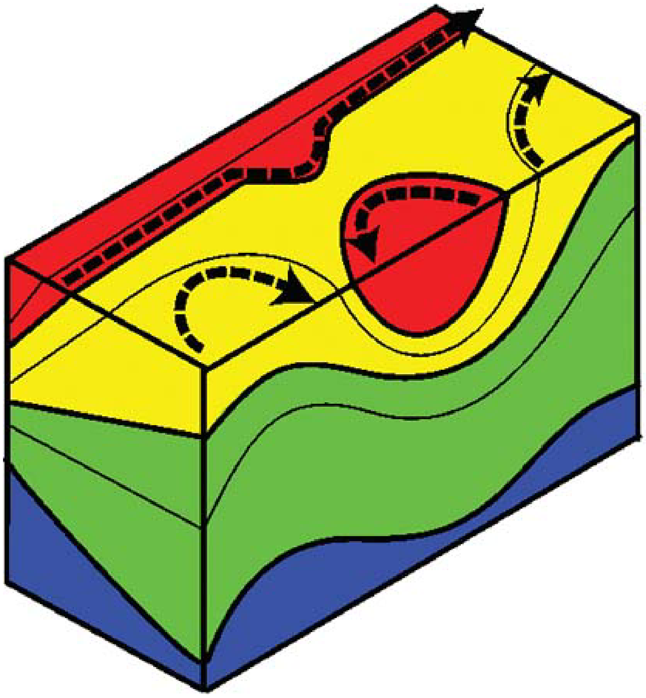

Figure 16. A schematic diagram of the salinity structure down to 1000 m as for Figure 15, but only for the region south of WA, and showing the Leeuwin Current and mesoscale features. The colour scale is as for Fig. 15.

The waters of the Leeuwin Current spread across the southern continental shelf and into the coast. This was suggested by the grounding of two drifters in the 1970s and by satellite images that showed warm waters extending across the shelf with only slight cooling very close to the coast. Midway across the shelf, at a mooring at the 80 m isobath 25 km to the west of the Recherche Archipelago, the LC was the main circulation feature. It was turned seaward there by the downstream proximity of the Archipelago. The other main influence came from the winds from passing weather systems which variously reversed and accelerated the current.

As was mentioned earlier, Wood (1954) suggested that there was an ocean current that flowed from Western Australia to Tasmania. Other support for the idea that the Leeuwin Current could act as a conduit to bring tropical and subtropical marine fauna and flora to southern Australia can be found in Colborn (1975), Krey & Babenerd (1976), Maxwell & Cresswell (1981), Hallegraeff (1984), Wells (1985), and Gaughan & Fletcher (1997). We conclude this discussion with a chronology of the evolution of our understanding of the LC south of WA (Table 1).

Table 1

A chronology of key observational findings in the study area south of WA between Cape Leeuwin and the western Great Australian Bight

Period	Type of study	Key findings
Early 1800s	Navigation with sextant and logline	A 0.6 ms^{-1} current to the east where we would now expect the LC
Early 1900s	As above, plus "Challenger" expedition observations	The flow of warm water southward to Cape Leeuwin and then eastward
1950s	Phytoplankton distribution	An inferred current from Cape Leeuwin to Tasmania
1960s	Hydrocasts	Inflow at 30 S of salty Indian Ocean water towards WA
1970s	Expendable bathythermographs	The southward turning of this inflow through a field of mesoscale eddies to Cape Leeuwin
1970s	Satellite tracked drifters	An energetic southward flow to Cape Leeuwin and then eastward at speeds up to 1.8 ms^{-1}. Interactions with mesoscale eddies and offshoots out to sea. The Leeuwin Current named.
1971	Hydrocasts	Temperature and salinity section shows Leeuwin Current flowing near the upper continental slope near Albany
1980s	Satellite sea surface temperature images	Synoptic images of Leeuwin Current fronts, eddies and offshoots and the spread of the current to the nearshore. Plumes of subantarctic water seen to move northward to interact with the Leeuwin Current. One image showed upwelling near Cape Leeuwin. Other images captured the eastward progression of the Leeuwin Current "nose" at 20 km day^{-1} in autumn.
1982	Expendable bathythermographs, water property profiler (CTD) and drifters	Sections across the Leeuwin Current, a cyclonic eddy and a current offshoot.
1987	Research vessel observations with water property (CTD) and current (ADCP) profilers	Sections across the Leeuwin Current and an offshoot from it. The flow south of WA included both tropical and subtropical waters Speeds exceeded 1.5 ms^{-1} in the Leeuwin Current and there were contrary flows within the offshoot. Beneath the Leeuwin Current there was westward flow at 400–700 m.
1994	Three voyages with CTD and ADCP plus satellite topography images and inferred currents, as well as satellite temperature images	Anticyclonic eddies were followed for as they drifted westward through the study area and beyond into the Indian Ocean. Both anticyclonic and cyclonic eddies interacted with the Leeuwin Current. The properties of the various features were mapped.
2001–02	Current meter mooring at the 80 m isobaths near the Recherche Archipelago	A significant Leeuwin Current influence for all months except November and February, with the winter months being strongest and May having a mean current of 0.13 ms^{-1}. The winds from intense passing weather systems variously reversed and accelerated the current. Coastal-trapped waves also had similar strong effects.

Conclusions and suggestions

Evolving observational techniques over the past two centuries have led to the following conclusions:

The Leeuwin Current south of WA:

- Brings low salinity tropical and high salinity subtropical waters to Cape Leeuwin and thence eastward into the low salinity subantarctic regime south of WA.
- Is present most of the year, but is strongest in autumn/winter following the eastward progression of its leading edge at about 20 km day^{-1} between March and April.
- Meanders on and off the continental shelf from Cape Naturaliste to the Recherche Archipelago with speeds off the continental shelf as high as 1.8 ms^{-1} and a depth penetration to 250m.
- Is weaker (0.3–0.5 ms^{-1}) to the east of the Recherche Archipelago and into the Great Australian Bight
- Is diverted out to sea around anticyclonic eddies that take on some of its waters
- Is accelerated eastward on the northern sides of cyclonic eddies
- Was detected most of the time from December 2001 to August 2002 at a current meter mooring at the 80 m isobath on the continental shelf near the Recherche Archipelago. The shelf currents were also strongly influenced by winds from passing weather patterns and by passing coastal-trapped waves.

The anticyclonic eddies:

- Drift westward across the Great Australian Bight to interact with the Leeuwin Current and strengthen near the Recherche Archipelago
- Interact with the Leeuwin Current, subantarctic waters, and one another as they drift westward to the longitude of Cape Leeuwin and then out into the Indian Ocean.

- Influence the water structure down to at least 1000 m depth
- Have current speeds that decrease very little from the surface down to 250–300 m depth.
- Develop deep mixed layers (to 300 m) if they spent several winter months in the study area
- Are low in nutrients and oxygen.

The tasks that we know to remain include achieving a better understanding of:

- The effects of winds and the LC on the waters across the entire continental shelf south of WA, rather than just at the 80 m isobath near Esperance
- Does upwelling occur to the same degree at the Recherche Archipelago as it does immediately to the east of Cape Leeuwin?
- The effects of the differing bottom topography along the shelf and upper slope – the precipitous shelf edge cliffs, the changing shelf width, the barrier presented by the Recherche Archipelago.
- The responses of living organisms to the dynamic oceanographic features.
- Why the 1970s drifters interchanged with the Leeuwin Current and cyclonic eddies and not with anticyclonic eddies.

These will require observations with research vessels, numerous long-term moorings, gliders, and satellite remote sensing, to name a few.

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