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Current measurements at a year-long continental shelf mooring near Perth, Western Australia

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Abstract

An acoustic Doppler current profiler moored near the bottom at the 71 m isobath on the outer continental shelf 50 km northwest of Perth recorded currents at 13 levels between mid-November 2000 and late November2001. The main features were the poleward Leeuwin Current, which was strongest in winter with a maximum speed of ~0.6 ms^{-1}, and the wind-driven, equatorward Capes Current in summer with a maximum speed of ~0.9 ms^{-1}. The currents varied continuously, occasionally reversing, due to wind forcing and sometimes due to features off the shelf. Averaged over a month the Leeuwin Current was strongest nearest the bottom and it was directed off the shelf by almost 45°. Independently, there were intervals of several days when the instrument revealed that the equivalent of several tens of km of flow had passed it in a cross-shelf direction. The sea-land breeze cycle generated baroclinic inertial waves with the associated shallow and deep flows being out of phase. These flows moved water across the shelf by several kilometres. There was also a wave like phenomenon with a time scale of 15–45 hours that produced loops in the flow that were as much as 10 km across. When the Leeuwin Current was strong these loops were stretched into cusps.

Keywords: Leeuwin Current, current movements, current variability, continental shelf flows, seasonal variability, wind stress.

Introduction

The continental shelf waters north and south of Perth, Western Australia (Figure 1) are influenced by, *inter alia,* the southward-flowing Leeuwin Current (LC) that is strongest above the upper continental slope, by the northward-flowing Capes Current (CC) driven by summer southerly winds, and by passing weather systems (Cresswell *et al.* 1989; Mills *et al.* 1996; Pearce & Pattiaratchi 1999; Gersbach *et al.* 1999). The rapidly growing population of the coastal region has meant a growth of shipping, naval activities, professional and recreational fishing, coastal developments, tourism, waste management, *etc*., There have been, however, very few long-term moored current measurements.

CSIRO had a succession of month-long deployments of single current meters 10 m above the bottom for depths of ~40–60 m south of the Abrolhos Islands over two years in the mid-1970s and near Rottnest Island for several months in that period (Cresswell *et al*. 1989). Steedman & Associates (1981) reported on current measurements that were related to the proposed Point Peron sewage disposal site and Pearce & Pattiaratchi (1999) presented plots of these. The Leeuwin Current Interdisciplinary Experiment (LUCIE) included an extensive array of moorings from NW Cape southward and then eastward to Cliffy Head (Boland *et al*. 1988; Smith *et al.* 1991). The depths at the mooring sites ranged from mid-shelf (roughly 50 m), to the shelf edge (roughly 100 m), and out to 700 m on the continental slope. The moorings comprised up to four current meters and data were collected from September 1986 to August 1987. The D2 site at the 108 m isobath at 29°33'S out from Dongara obtained an excellent set of records from four depths. The Perth Coastal Waters Study (PCWS) maintained current meters at mid depth at the 200 m, 110 m and 27 m isobaths at intervals during 1992 to 1994 (Lord & Hillman 1995) and Pearce *et al*. (2006) presented the mean monthly north-south current components for these. There was a short (two-week) mooring deployment in the Sepia Depression near Point Peron by Mills *et al*. (1996). From June 2004 to July 2005 three moorings were maintained at the 100 m, 40 m and 20 m isobaths along a line out from Two Rocks at 31°30'S north of Perth. The instruments were rotated every three months and included ADCPs, CTDs and bottom-mounted pressure gauges. Preliminary findings appear in Fandry *et al*. (2006).

Most of the continental shelf current meter records showed the northward-flowing CC in summer and the southward-flowing LC in winter. The Abrolhos and Rottnest current meters revealed current reversals related to forcing by weather systems throughout the year. In *summer*, strong southeasterly wind events on the western sides of atmospheric highs passing from west to east drove northward current pulses of up to 0.4 ms^{-1} and lowered coastal sea level by about 0.3 m. Between these events atmospheric lows reduced the southeasterly winds and there was southward current of about 0.1 ms^{-1}. In *winter* northwesterly storms from passing lows drove southward current pulses of as much as 0.6 ms^{-1} and raised coastal sea level by up to 0.8 m. Northward flow sometimes occurred at times between these events. Not all current events could be related to weather forcing and some may have been due to the incursions of mesoscale features of the LC.

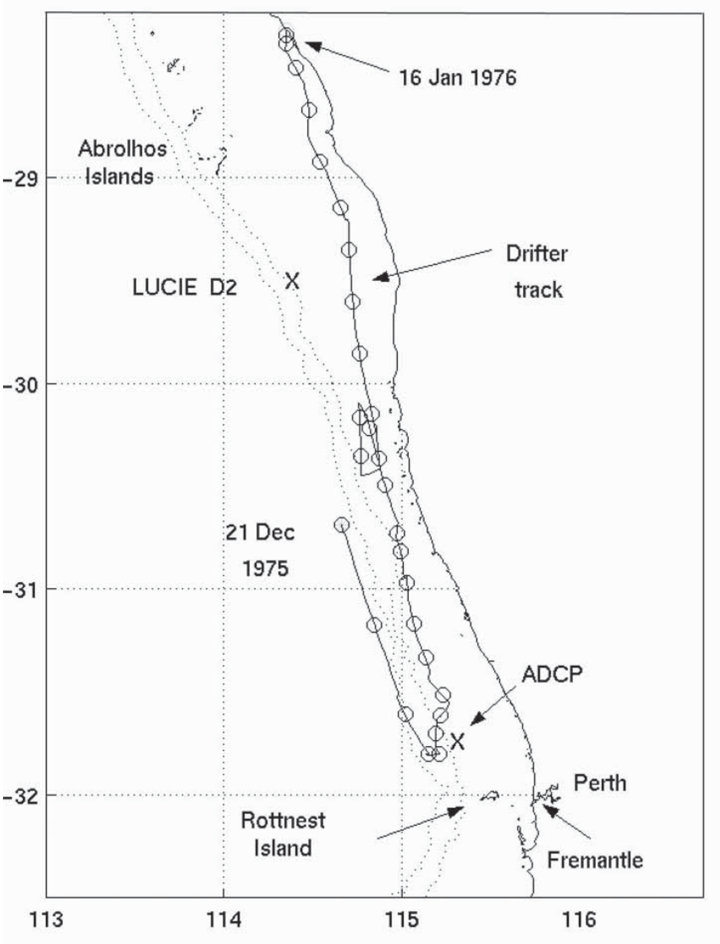


Figure 1. The location of the ADCP mooring, the Lucie D2 mooring, and the track of a drifter showing daily positions showing both the southward Leeuwin Current off the continental shelf and the northward Capes Current on the shelf. The 100 and 200 m isobaths are marked with dotted lines.

The important role of weather systems in winter was also reported by Mills *et al.* (1996): in one case southward and onshore wind stress moved buoyant LC water shoreward, while at the same time there was an offshore flow near the bottom. In another case, the winds were weak and an anticyclonic meander of the LC drove northward flow over the shelf. However, steeply-inclined isopycnals at the mid-shelf opposed any cross-shelf exchange of water.

The seasonal current pattern due to the Leeuwin and Capes Currents is also evident in satellite imagery (Pearce & Pattiaratchi 1999), as well as in Lagrangian data, such as the drift card releases of Rochford (1969) and the satellite tracked drifters of Cresswell & Golding (1980): a drifter in summer interchanged between the southward LC moving at ~0.7 ms^{-1} above the upper continental shelf and the northward CC flow moving at ~0.2 ms^{-1} on the outer shelf (Figure 1). The drifters on the shelf reversed their northward flow as weather systems passed over (Cresswell *et al.* 1989).

Monthly time series data from a transect off Hillarys 20 km north of Perth showed that the cross-shelf exchange, which has important marine ecological implications, is affected by three dominant mechanisms: mesoscale meanders of the LC, smaller-scale tongues of LC water penetrating across the continental shelf, and high density nearshore waters episodically cascading offshore down the seabed (Pearce *et al*. 2006).

In this paper, in order to examine some of the phenomena identified above, we discuss hourly data from an Acoustic Doppler Current Profiler, ADCP, that was moored for a little over a year a few metres above the bottom at the 71 m isobath out from the northern suburbs of Perth (Figure 1). Unlike current meters at discrete depths, the ADCP collected data from 4 m-thick bins up through the water column, albeit losing the top 15% because of side lobes from the ADCP transducers. The ADCP was put at this location so that it would come under the influence of both the CC in the summer and perhaps incursions by the LC in all seasons. The record shows both these currents and it is rich with the effects of other phenomena including flows off and onto the continental shelf, sea/land breezes, summer and winter storms, and wave-like perturbations with periods up to several days. We complement the ADCP data with wind and sea level data.

Methods

The ADCP was housed within a syntactic foam float and moored 3 m above the bottom at the 71 m isobath for a total of 54 weeks. The attachment to the anchor was via two acoustic releases mounted in parallel. When our technicians returned to mooring after one year neither of the releases functioned. Three more days were spent over two weeks working with highly skilled divers from the Perth Diving Academy who eventually recovered the instrument. Both releases were heavily encrusted with corals. The mooring and the instrument were serviced and redeployed and recovered after another year. The instrument did not work on the second deployment. The ocean does not willingly volunteer its secrets.

With the present data set the centre of the first 4 m-thick ADCP bin was at 65 m. Hourly data were acquired up through the water to bin 13 at 17 m depth. Shallower than this, side lobes from the instrument's four acoustic beams, each directed 30°C away from the vertical, introduced noise and the data from those bins had to be ignored. The Doppler shifts of the returned signals for bins 1–13 were processed with the manufacturer's software and yielded profiles of current speed and direction. The instrument recorded temperature. The current data from the ADCP were resolved into cross-shelf and along-shelf components – the shelf edge is aligned roughly 27° west of north. On-shelf flow (positive) is to the ENE and off-shelf flow (negative) is to the WSW. The along-shelf components are NNW (positive) and SSE (negative).

A simple calculation of wind stress was made from the hourly meteorological data collected by the Bureau of Meteorology at Rottnest Island, namely 1.2x0.0013xs^2 Nm^{-2}, where s is the wind speed. The stress was resolved in north-south and east-west components, as much of the forcing was north-south.

Hourly sea level measurements from Fremantle were adjusted for the inverse barometer effect at 0.01 m per hPa from an arbitrary baseline of 1020 hPa with the Rottnest Island atmospheric pressure measurements.

Results

Annual signal

The along and cross-shelf current-depth-time plots (Figure 2A, B) hint at the complexity of the water movements on the shelf, as does the time series of sea level at Fremantle, wind stress at Rottnest Island, and

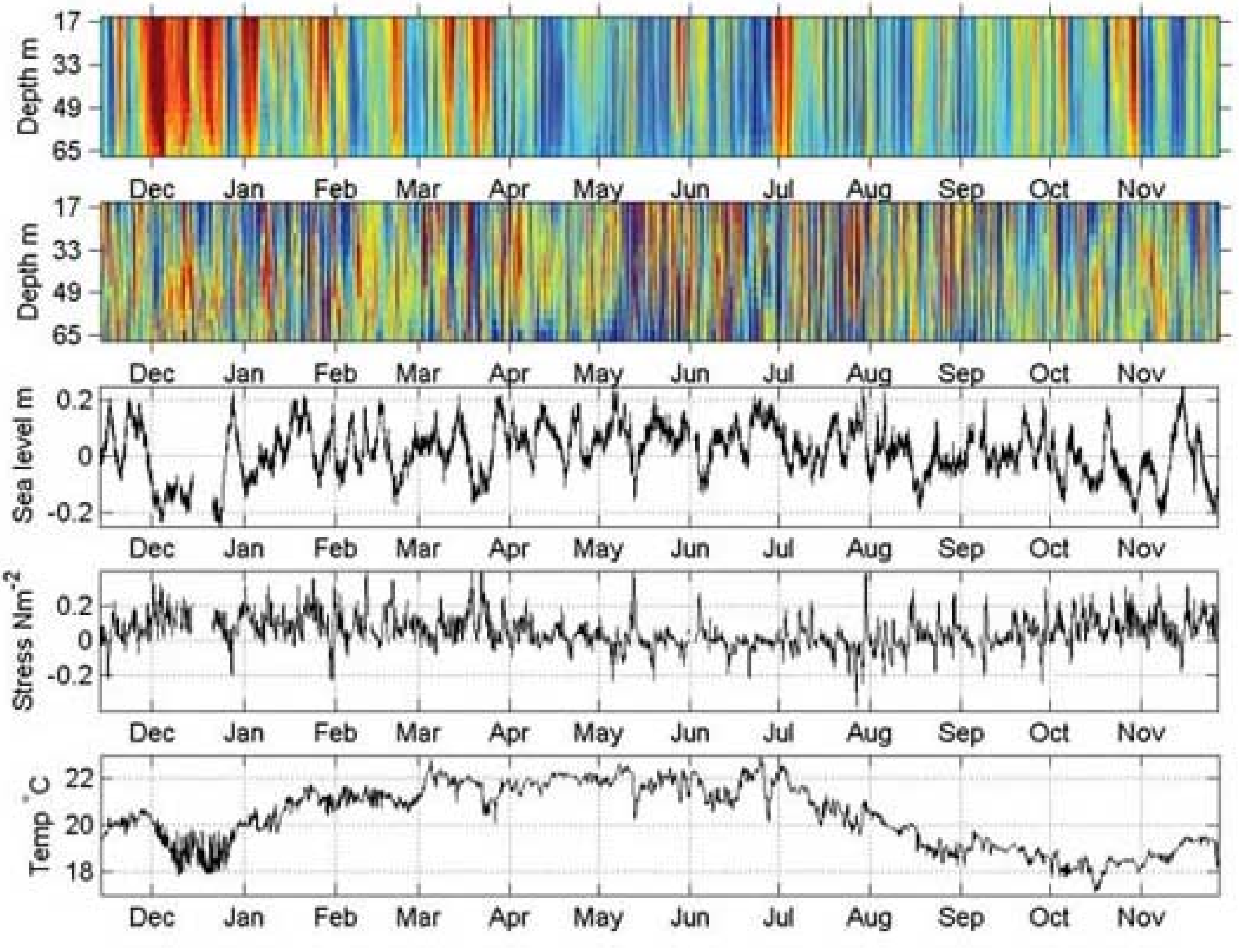


Figure 2. A) The along-shelf and **B**) the cross-shelf currents measured by the ADCP and presented in a component strength-depth-time format. The scales, with the ranges (-0.4 to 0.4 and -0.15 to 0.15 ms^{-1} respectively) were chosen to emphasize the variability in the record. In A) red is along the shelf to the NNW and blue is to the SSE. In B) red is flow onto the shelf and blue is flow off. C) Adjusted sea level at Fremantle. D) The along-shelf wind stress calculated from the Rottnest Island wind measurements. E) The temperature measured at four metres above the bottom by the ADCP. The period covered is 13 November 2000 to 27 November 2001. All values are hourly, but the wind stress has been smoothed slightly (5-hour running mean).

temperature recorded at the instrument (Figure 3C–E). The along-shelf current component showed that there were intervals of LC flow (blue) at times of decreased positive wind stress and increased sea level in November 2000. For the first three weeks of December 2000 the winds of temperate WA were controlled by a large high (>1020 hPa) centred near 90°E, more than 2000 km west of Perth. This drove northward wind stress greater than 0.1 Nm^{-2}, and up to 0.3 Nm^{-2}, a strong CC (red in Figure 2A), and low sea level. The mooring experienced low temperatures with a daily variability of more than 1°C that was related to cycles of the sea and land breezes – to be discussed later. The CC had a peak speed of 0.9 ms^{-1}.

From January through late March there were intervals of positive and negative along-shelf flow and then the LC arrived and drove predominantly ESE (blue) flow through to near the end of the record. Sea level became positive for over four months after the arrival of the LC and the wind stress tended towards zero, only becoming northward again, with low sea level, in October. One might have expected the LC to cease then, but this was not the case. The LC held the temperature at the ADCP above 21°C from early March until early July – in other words, contrary to the normal seasonal signal because of the supply of warm tropical waters. In late June the flow reversed for ten days (red) and reached surface speeds of 0.4 ms^{-1}. The LC had been quite strong immediately prior to this, reaching speeds of 0.6 ms^{-1}. There were many other shorter intervals of WNW (reverse) flow while the LC was flowing. The cross-shelf flow showed similar variability, together with vertical shear, such that on-shelf flow (red) occurred at mid-depth in December and off-shelf flow (blue) occurred in the lower water in the winter months April to August. The lowest temperature of 17.1°C occurred in October.

The monthly progressive vector diagrams (PVDs) for three selected depths: 17 m; 41 m; and 65 m, reveal a little more about the currents (Figure 3). If the ocean was infinite with unchanging bottom topography where individual depth strata moved as if they were solid, then PVDs would show the trajectories of particles from the mooring site. At the continental shelf mooring site the situation is, obviously, more complex, with shoaling to the east and deepening to the west, where the LC is found. Even so, we suggest that PVDs serve as "signatures" of behaviour that are sometimes more readily recognizable than in time series.

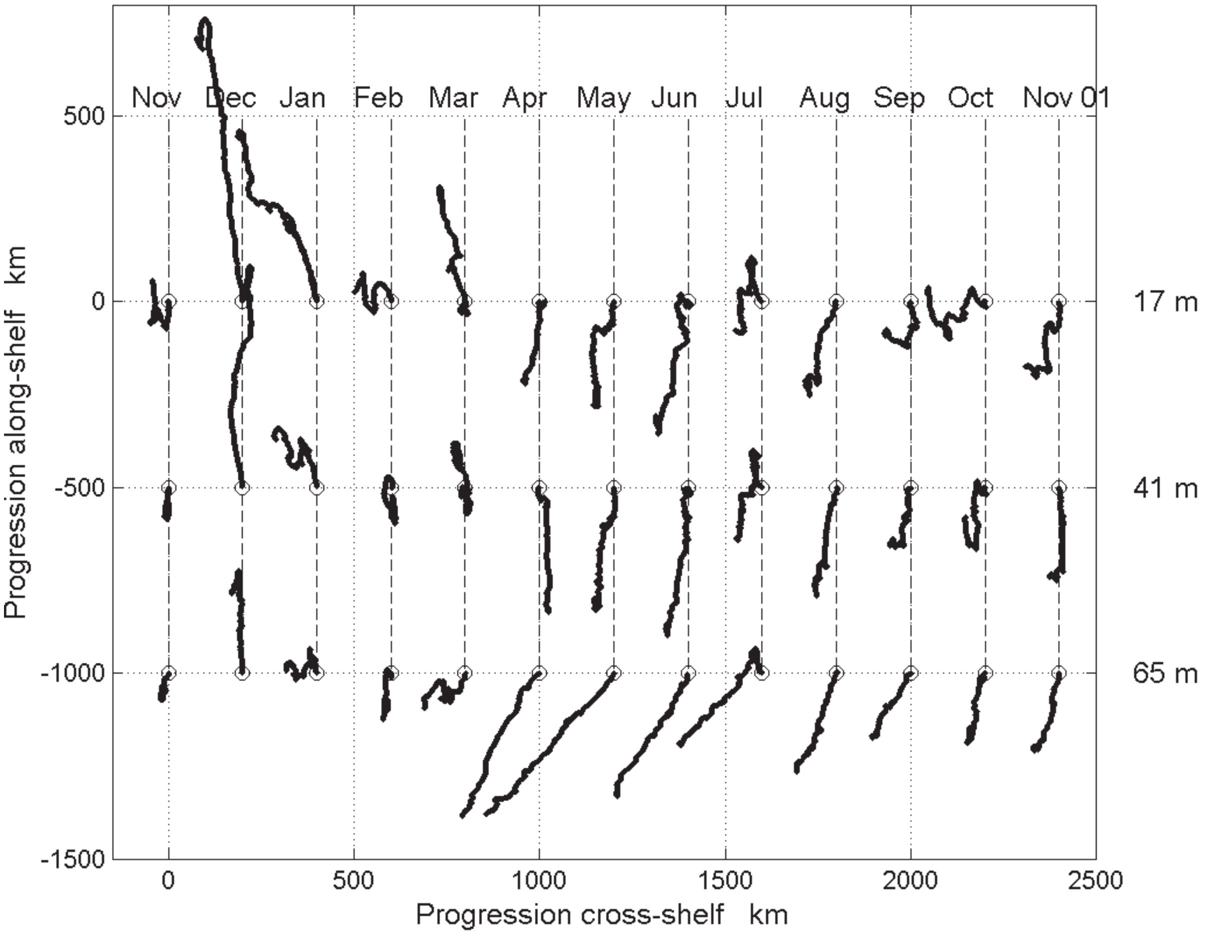


Figure 3. Monthly progressive vector diagrams (PVDs) for water depths 17 m (bin 13), 41 m (bin 7) and 65 m (bin 1). The PVDs are arranged by row for the different depths, and by column for the months, with successive months being offset by 200 km. The November 2000 PVD is short because the record started on 13 November. The November 2001 PVD only extends to 26 November, when the instrument was recovered. The axes are across and along the bottom topography.

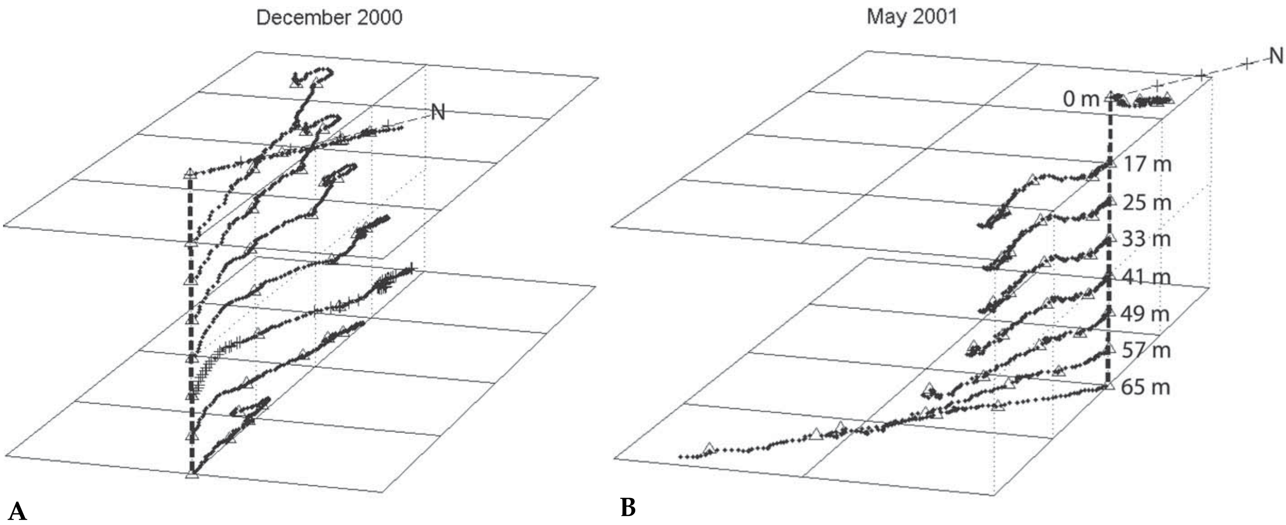


Figure 4A. Progressive vector diagrams plotted six-hourly for the wind stress (top) and every second ADCP bin (depths 17, 25,…65 m; dots) for December 2000 when the CC was strongest. All the motions are horizontal. The triangles mark successive weeks of progression. The pluses on the PVD for 49 m depth (bin 5) indicate when the temperature measured by the ADCP exceeded 19.2°C. The horizontal meshes are made up of 200 km squares with the upper one being at 17 m depth and the lower one at 65 m depth. The vertical grid (dotted) is aligned parallel with the shelf edge. The top of the thick vertical dashed line is the sea surface and the angled dashed line from there towards the upper right indicates north, with the plus signs being a scale showing the wind stress progression at 0.1 Nm^{-2} for one week. The view is out across the shelf towards the northwest.
Figure 4B. As for Figure 4A, but for May 2001 when the LC was strongest.

The wind-driven CC in December was strongest at the uppermost bin at 17 m depth, with an overall apparent drift component along the shelf of 700 km, equivalent to a mean speed of 0.25 ms^{-1}. The waters moved off-shelf by 100 km during the month. The current was also quite strong at mid-depth, with an on-shelf component in the second half of the month. The CC was present, but weaker, in January and March, again with components of off-shelf flow. At 65 m shows in March the flow had components both off-shelf and poleward, the flow direction of the LC. Late March appears to have been the onset of the LC that continued throughout the record and was generally strongest near the bottom, usually with a strong off-shelf component. The LC flow near the bottom reached a maximum in May with over 500 km of water going past the mooring with an along-shelf component of -0.14 ms^{-1} and a cross-shelf component of -0.12 ms^{-1}. The surface flow of the LC was weaker, perhaps due to those waters being more susceptible to northward wind forcing from passing storms, and it was more aligned with the shelf. The 10-day pulse of reverse flow that was seen in the time series can be seen in the upper two PVDs at the end of June/start of July.

A perspective 3D view of the PVDs for December 2000 (Figure 4A) when the along-shelf CC was at its peak strength showed on-shelf flow at mid-depths, but not near the bottom, in the middle two weeks of the month. The on-shelf flow coincided with temperatures at the ADCP decreasing by 2°C, albeit with daily oscillations for much of the month (Figure 2), so possibly this was due to intrusions of cold continental slope water that was associated with the strong CC. It is puzzling that the flow at 65 m – closest to the ADCP and its temperature sensor – did not register an on-shelf component. The on-shelf flow was strongest at bin 5 (49 m) and it corresponded with low temperatures being measured at the ADCP: the PVD is marked by dots rather than plus signs. The wind stress PVD for the month was strongly northward apparently averaging more than 0.1 Nm^{-2}, but note that eight days were missing from the Rottnest wind data, so it would have been stronger than shown.

A similar perspective view of the PVDs for May 2001 (Figure 4B) when the LC was strongest showed a smooth transition from the mainly along-shelf (SSE) flow near the surface that progressively turns off-shelf and increases in strength with depth. As compared with December, the wind stress PVD was small.

Two significant current reversals

Leeuwin Current in summer 2000/2001

Two instances of summer flows of the LC in November 2000 have already been mentioned. Here we discuss an interval in late December 2000 (Figure 5) when the wind stress, which had reached 0.3 Nm^{-2} earlier in the month under the influence of a 1020+ hPa high at about 90°E, decreased to less than 0.1 Nm^{-2} northward and reversed to 0.2 Nm^{-2} southward on 27/28 December. The interruption to the northward wind flow from the high near 90°E came from the combined effects of a small 1004 hPa low over Perth and a 1024 hPa high centred south of the Great Australian Bight at 40°S, 130°E. During this time the current ran southward as a LC, peaking at 0.4 ms^{-1}, and sea level rose (as is the case when the LC flows), by 0.4 m. The current reversal commenced with off-shelf flow of 0.1 ms^{-1}, but this was somewhat masked in the time series in Figure 5 by a daily oscillation of amplitude as much as 0.15 ms^{-1}.

Perspective views of PVDs covering respectively four days from prior to the event to its peak, and four days from the peak until after the event appear in Figure 6A, B. The first, 24–27 December, shows how particles that

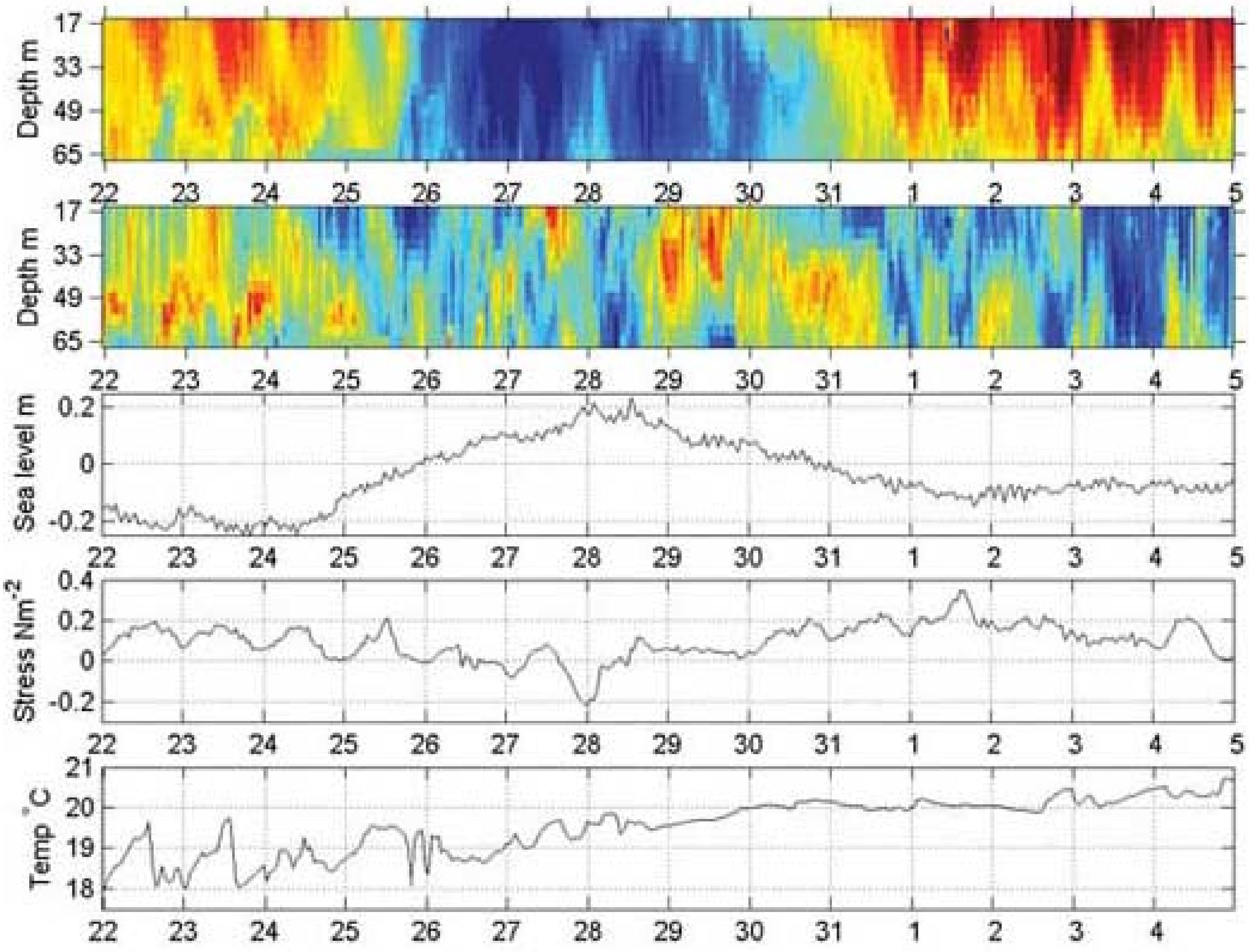
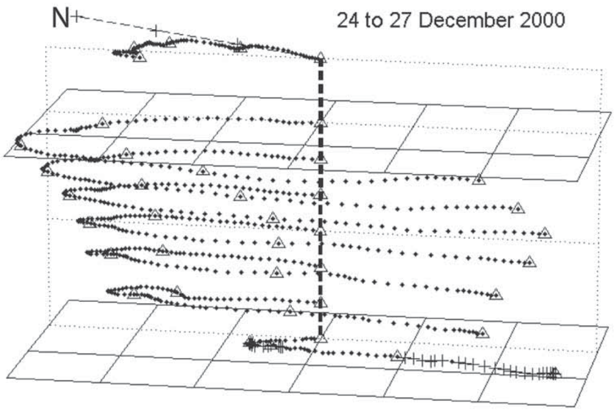
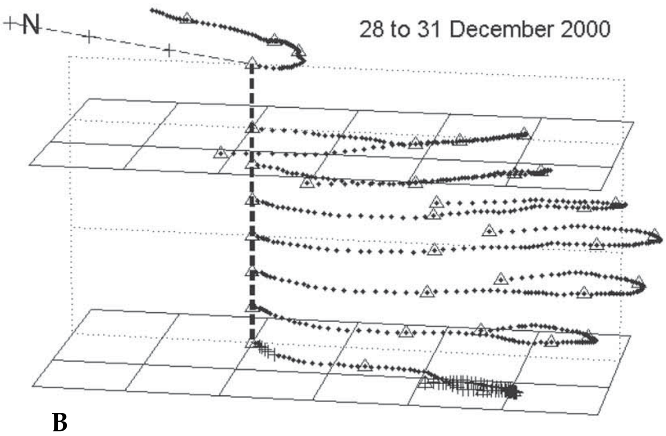


Figure 5. As for Figure 2, but from 22 December 2000 to 5 January 2001 with the ranges for A and B as -0.35 to 0.5 and -0.25 to 0.25 ms^{-1} respectively.



A



B

Figure 6A. Progressive vector diagrams plotted hourly for the wind stress (top) and every second ADCP bin (depths 17, 25,…65 m) for UTC 24 to 27 December 2000inclusive. All the motions are horizontal. The horizontal meshes are made up of 10 km squares with the upper one being at 17 m depth and the lower one at 65 m depth. The vertical grid(dotted) is aligned parallel with the shelf edge. The top of the thick vertical dashed line is the sea surface and the angled dashed line from there indicates north. The '+' signs along it are a scale for the wind stress, showing the progressions that would be made in 24 hours at 0.1, 0.2 and 0.3 Nm^{-2}. The pluses on the 65 m depth PVD indicate when the temperature exceeded 19°C. The triangles on all PVDs are one day apart.

Figure 6B. As for Figure 6A, but for UTC 28 to 31 December 2000 inclusive, with the pluses on the 65 m PVD being for temperatures greater than 19.8°C.

left the mooring under the influence of the CC turned off-shelf as the wind stress PVD weakened and were then carried in a LC. The second, 28–31 December, shows the wind stress to reverse once again and to become strongly northward. The current, however, did not reverse for two more days until the northward wind stress exceeded 0.1 Nm^{-2}. The reversal at 17 m (bin 13) preceded those at 41 and 65 m by 18 hours. A linear fit to a scatter plot of the along-shelf current at 17 m with the north-south wind stress for this interval showed that zero current occurred when the northward wind stress was ~0.06 Nm^{-2} and that when the wind stress was zero the current became southward at ~0.27 ms^{-1}.

Reversal of the Leeuwin Current in late June 2001

There was a sudden reversal of the LC in late June (Figures 7 and 8) that initiated the longest period, one week, of NNW flow between April and November, with speeds at 17 m depth reaching 0.5 ms^{-1}. Immediately prior to this the LC was unusual in that it was strongest at the surface (up to 0.5 ms^{-1}) and progressively weakened with increasing depth to 0.2 ms^{-1} at the lowest level. The weak on-shelf wind stress is unlikely to be the cause of the reversal. The temperature, which had been over 22°C, dropped 2°C prior to the reversal and then increased. Sea level fell by 0.2 m, but this occurred about 2 days after the northward current was strongese. The recovery of the LC was quite slow and faltering, taking about one week and is not treated in detail here.

What was the cause of the strengthening of the LC and then the reversal? Figure 9 shows satellite sea surface temperature images for 21, 26 and 28 June and 5 July 2001. (There were numerous cloud-free images between the first and third images, but none between the last two). The first three images showed a meander of the LC to develop into an anticyclonic eddy that moved southward above the continental slope. On 26 June the LC south of the eddy had moved eastward to be entirely on the continental shelf, thereby explaining the stronger currents detected by the ADCP. The eddy continued to move southward and then it spread across the shelf into the mooring site, which seems to explain the current reversal. From 29 June to 5 July the eddy apparently moved back to the north and the effects of the LC were then felt again at the mooring.

Cross-shelf flows both near the surface and near the bottom

28 to 30 May 2001 – off-shelf flow at depth

The wind stress was weak and variable, so it was unlikely to have been the driving force for the positive

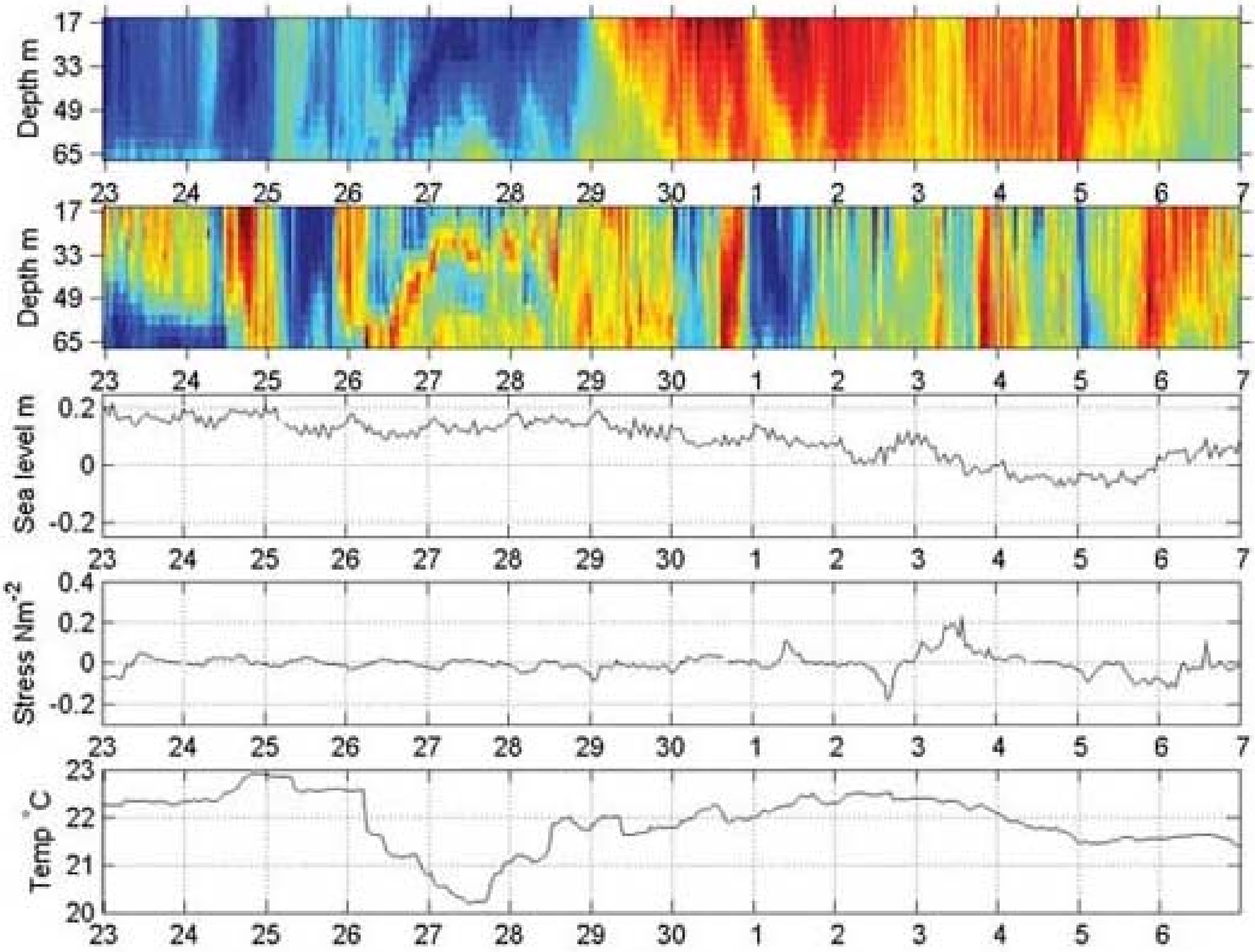


Figure 7. As for Figure 2, but for UTC 23 June to 6 July 2001 inclusive, with the ranges for A and B as -0.5 to 0.45 and -0.3 to 0.2 ms^{-1} respectively.

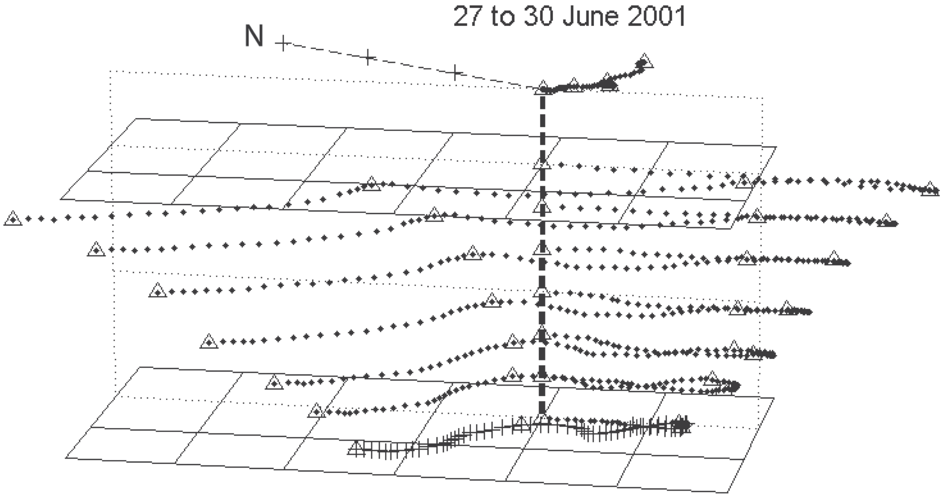


Figure 8. As for Figure 6A, but for UTC 27 June to 30 June 2001 inclusive; the pluses on the 65 m depth PVD indicate when the temperature exceeded 21.8°C.

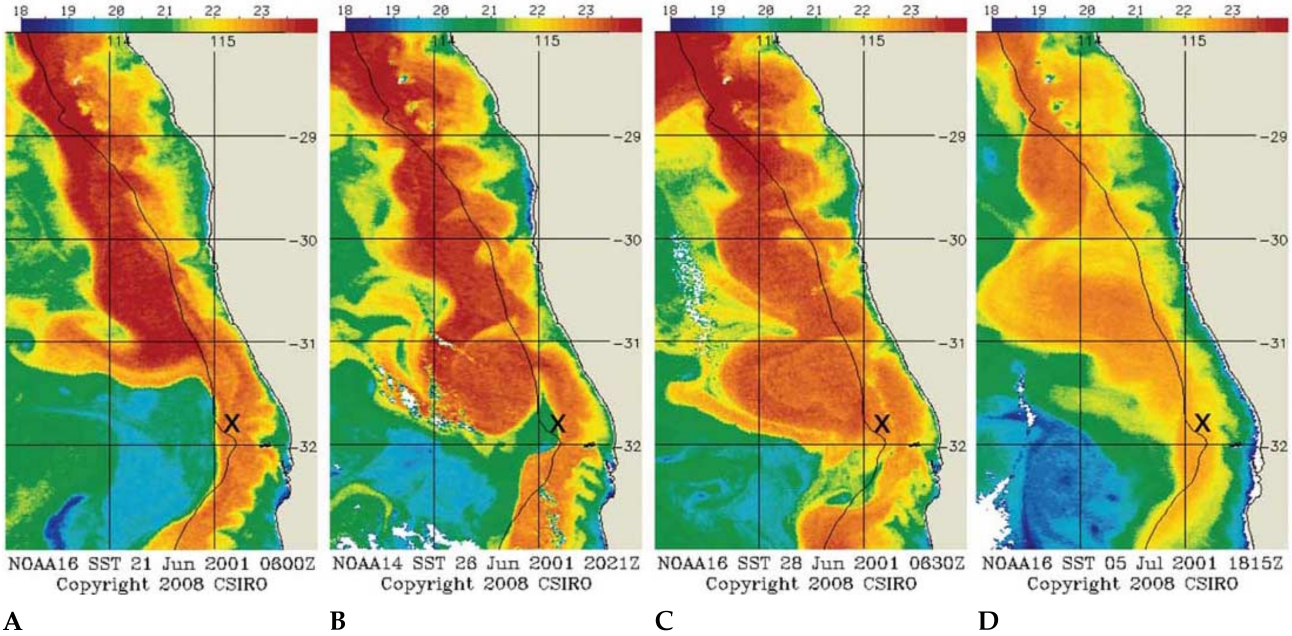


Figure 9. A–D: Satellite images of sea surface temperature for 21, 26 and 28 June and 5 July 2001 during which time the LC as monitored at the mooring, marked "X", initially strengthened, then reversed (due to the anticyclonic eddy seen in Figure 9C), and then recovered. The colour scale for temperature is at the top of the images and the edge of the continental shelf is marked by a thin line.

along-shelf currents that exceeded 0.3 ms^{-1} NNW in the upper part of the water column (Figure 10A). From mid-depth to the bottom there was a rotation in the flow direction, with relatively cool water flowing off-shelf at the bottom. This flow ceased with a right-angled turn to the SSE as the upper currents reversed to flow in the same direction. The temperature at the bottom increased from 21°C to 22°C in six hours, perhaps due to LC water reaching the mooring. A similar cycle of events was repeated in the next three days, but is not shown here.

14 to 18 October 2001 – off-shelf flow near the surface

The coldest water during the one-year record was recorded at this time. The wind stress showed a sea-land breeze cycle with magnitudes up to 0.2 Nm^{-2} and this had an influence on the along-shelf flow of 0.3 ms^{-1} peak-trough with a delay of about 4 hours. The flow at 17 m (top bin) was off-shelf and about 30° positive along-shelf (Figure 10B). At the mid-depths the flow was in the opposite direction. This was the case for the first day at the bottom, but the flow then turned to flow to negative along-shelf (SSE). The temperature at the ADCP was initially 18.2°C but then the on-shelf flow apparently brought colder water (17.2°C) to the ADCP over the course of one day, and then the temperature recovered two days later to 18°C.

Rotary flows

Progressive vector diagrams made from the records showed many cases of anticyclonic rotations with time

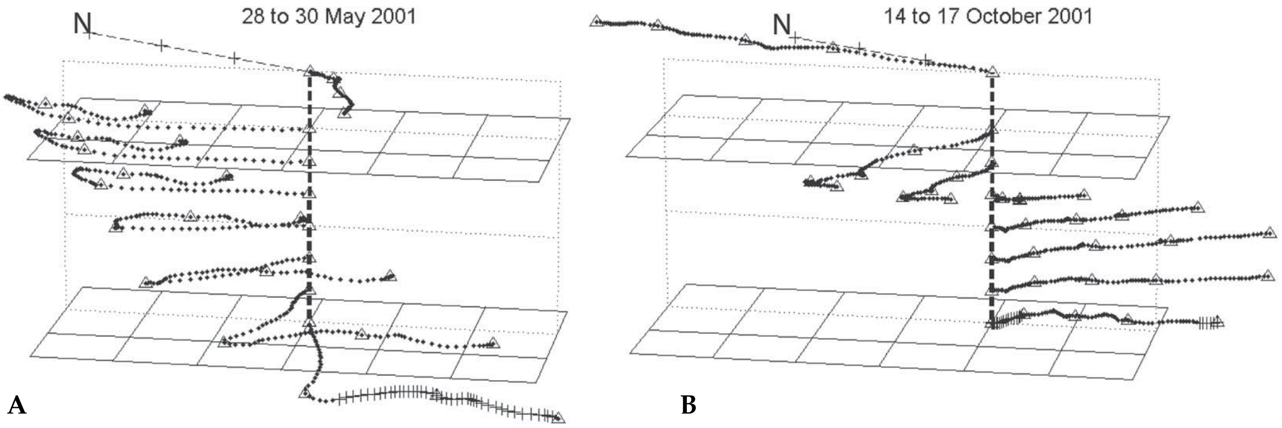


Figure 10A. As for Figure 6A, but for UTC 28 to 30 May 2001 inclusive, with pluses on the 65 m depth PVD indicating when the temperature exceeded 21.8°C.
Figure 10B. UTC 14 to 17 October 2001 inclusive, with pluses on the 65 m depth PVD indicating when the temperature exceeded 17.7°C.

scales from about 15–45 hours (the inertial period at the latitude of the ADCP mooring is 22.6 hours). If the LC was too strong then the loops were stretched to become cusp-like oscillations. We cannot discuss all of the cases here. Rather, we will examine six examples of several days duration. In some of the other instances the “orbits” followed by water particles at different depths were grossly complicated by strong vertical shear.

9 to 12 January 2001

The northward wind stress from a 1030 hPa high at 95°E exceeded 0.3 Nm^{-2} on the first day and this apparently drove the upper waters along the shelf to the NNW. The effect of the wind forcing rapidly decreased with depth and apparently had no effect in the lower half of the water column (Figure 11A). The alongshore current measured at 17 m lagged behind the northward wind stress by about 5 hours. The PVDs in the lower half of the water column revealed the signature of a wave that was masked or not present nearer the surface. The wave arrived at all these depths at about the same time and brought warmer water to the instrument.

12 to 14 June 2001

The wind stress was near-zero for two days before this interval and then for two days into it, so wind was unlikely to have been the trigger for any unusual water movements. The LC was strong near the bottom where it had an off-shelf component as compared with the shallower levels (Figure 11B). A significant influence came from a wave-like motion that produced anticyclonic loops through the water column; these were in phase and were described in about 30 hours at ~0.4 ms^{-1}. This was followed by an on-shelf meander at all depths. The temperature at the mooring was coldest when the flow was off-shelf, perhaps due to cool shelf waters reaching the mooring, and warmest at other times, perhaps when the edge of the LC had migrated shoreward.

19 to 21 July 2001

The wind stress was very small and unlikely to be a driving force for the currents. The current PVDs suggest that two waves passed the mooring (Figure 11C). Perhaps the LC was too strong for the anticyclonic loops to be described (the maximum speeds along the trajectories were 0.4 ms^{-1}. The cusps were separated by about 35 hours. The deep flow had a strong off-shelf component, but nearer the surface the flow was more aligned with the topography. The onshore excursions due to the waves brought slightly warmer (0.5°C) water to the mooring.

24 to 26 July 2001

The PVDs for the currents (Figure 11D) are reminiscent of those for June 12 to 15. The translation due to the LC in this case was stronger throughout the water column, possibly because winter cooling and convection led to a deep surface mixed layer. There was a current loop at most depths due to a wave and at 17 m (the uppermost bin) this was described in about 24 hours at ~0.2 ms^{-1}. Nearer the bottom the loop appeared to have been stretched into a cusp. The wind stress was southward for half a day at up to 0.2 Nm^{-2}, then it decreased to near-zero for almost a day, and finally reached 0.25 Nm^{-2} over the course of the last half day. The upper currents appeared to respond to these two intervals of strong southward wind forcing, reaching 0.3 ms^{-1}. The temperature behaviour was more complicated than in the June example.

27 to 29 July 2001

The wind stress had southward spikes of exceeding 0.4 Nm^{-2} and 0.3 Nm^{-2} around hours 12 and 60 of the 3-day interval. These were associated with atmospheric lows southwest and south of Perth respectively. Between and after these spikes the stress was near-zero. The LC was strongest near the bottom, where it flowed at an angle off the shelf (Figure 11E). At mid-depth it ran parallel to the shelf edge and nearer the surface it had a small onshore component. Three waves appear to have passed by the mooring, with the second producing anticlockwise loops in the upper part of the water column. The timings between the first and second and the second and third perturbations were about 20 hours.

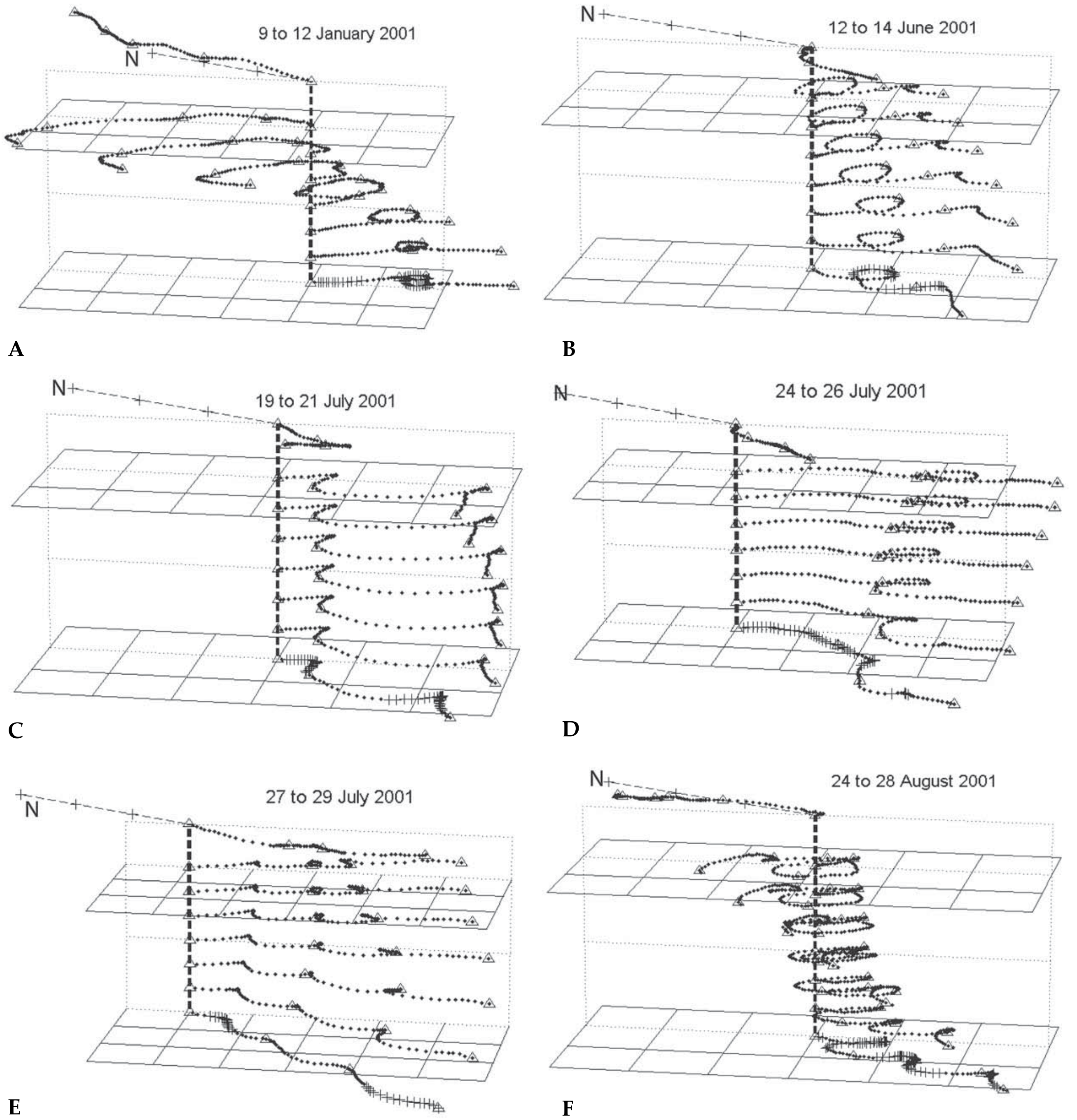


Figure 11A. As for Figure 6A, but for UTC 9 to 12 January 2001 inclusive, with pluses on the 65 m depth PVD indicating when the temperature exceeded 21.2°C; **B**) for UTC 12 June to 14 June 2001 inclusive, with pluses indicating when the temperature exceeded 21.2°C; **C**) for UTC 19 to 22 July 2001inclusive, with pluses indicating when the temperature exceeded 20.8°C; **D**) for UTC 24 to 26 July 2001 inclusive, with pluses indicating when the temperature exceeded 20°C; **E**) for UTC 27 to 29 July 2001 inclusive, with pluses indicating when the temperature exceeded 20.2°C; **F**) for UTC 24 to 28 August 2001 inclusive, with pluses indicating when the temperature exceeded 18.8°C.

The speeds along the trajectories ranged from 0.05 to 0.5 ms^{-1}. The temperature at the ADCP varied between 19.5°C and 20.5°C, but its variation was too slow to be related to the individual perturbations.

23 to 28 August 2001

A cold front passed over some ten hours before the interval covered for the diagram (Figure 11F) and it drove a southeastward pulse in the wind stress for about six hours that reached 0.2 Nm^{-2}. Twenty hours later a high centred at 90°E drove northward wind stress that exceeded 0.2 Nm^{-2} for half a day. After that it was near-zero. The LC was present only in the deeper part of the water column, as if the wind stress may have retarded it nearer the surface. There appeared to be no net movement at mid-depth. There were three oscillations

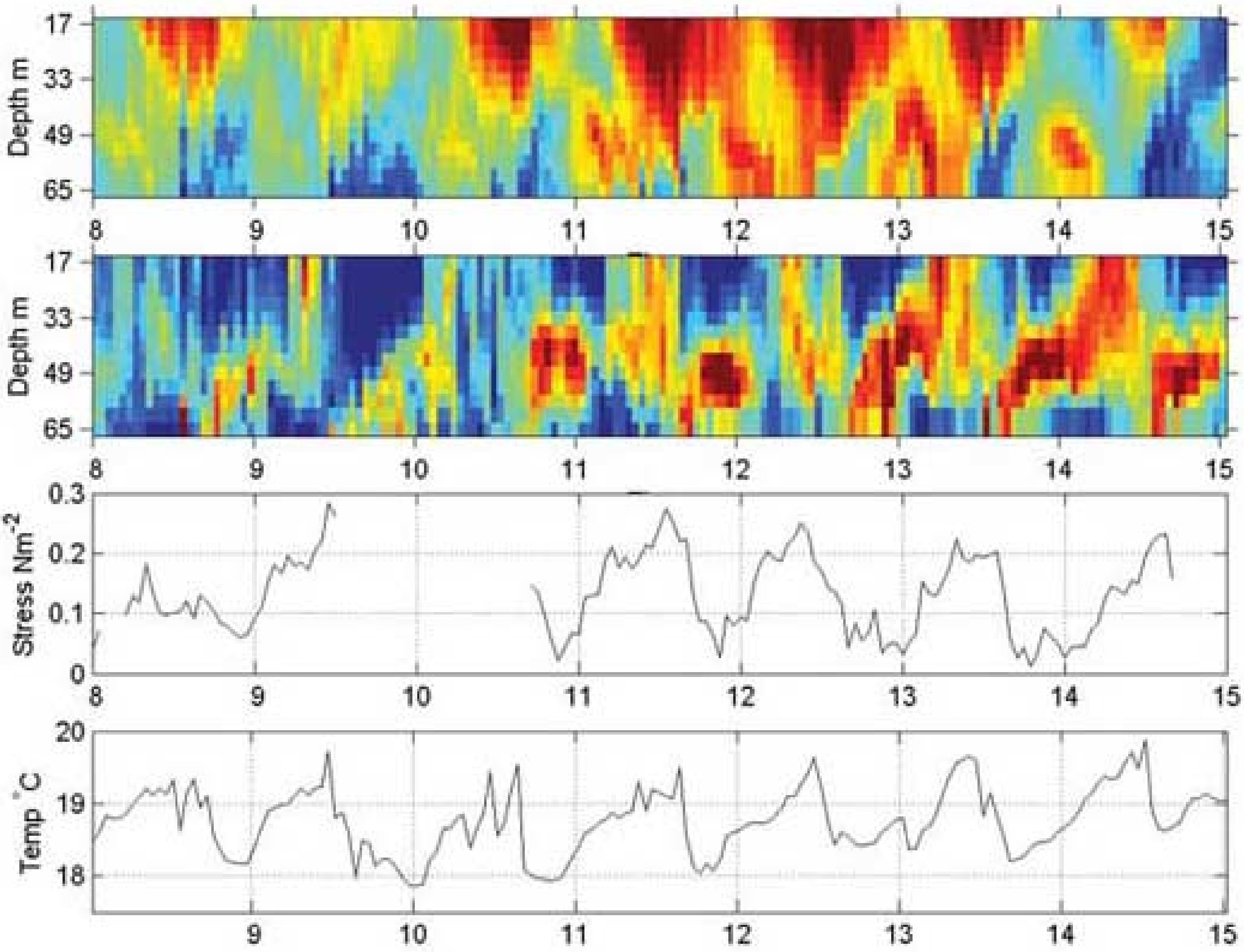


Figure 12. As for Figure 2, but from 8 to 14 December 2000 with the ranges for A (along shelf) -0.1 to 0.5 (blue to red) and B (across shelf) -0.1 to 0.2 ms^{-1} (blue to red) respectively. The Rottnest Island wind data had gaps on 10 and 14 December. Sea level was steady and was omitted from the Figure.

that in some cases drove the current in anticyclonic loops and they were separated by roughly 43 and 36 hours. The associated speeds reached 0.3 ms^{-1}.There was warming associated with each of the oscillations: for the first it was 1°C peak to trough; then 0.7°C for the second; and 0.3°C for the third.

Sea-land breeze effects

The daily oscillations in temperature in December 2000 noted earlier are seen in Figure 12 to be closely tied to northward wind stress and the along-shelf and cross-shelf current components. The current components show considerable complexity, with contrary flows at different depths being quite common. What are the links between the daily cycles of wind stress, currents and temperature at the instrument?

To address this we have selected a one-day interval and drawn PVDs for the currents and also a PVD for the Rottnest Island wind stress (Figure 13A), since that is likely to be the force driving the daily oscillations. The wind stress PVD "progressed" roughly northward, due to strong sea breeze forcing from about 1100 to 2300 local time, together with a weaker land breeze for the remainder of the time. Similar behavior was seen on other days. While there was strong positive along-shelf flow at all depths, the cross-shelf flows were noticeably oscillatory and apparently out of phase at different depths. The daily warm half cycle occurred during the sea breeze.

To examine the daily-varying currents we calculated the steady hourly flows from the daily progressions and subtracted these from the observed currents and prepared new PVDs (Figure 13B). These were closed loops around which the progressions were anticlockwise. The "hour hands" from the origins to midway around the perimeters show how the upper waters were out of phase with the lower waters: compare the top and bottom PVDs at 17 and 65 m. The phase difference would explain the contrary flows seen in the upper and lower waters in Figure 13A. There was also a phase difference between the wind stress and the current, with the stress leading the current at 17 m by about 4 hours. The temperature information on the deepest PVD – circles indicating the warm half cycle of the temperature fluctuation — suggests the possibility that warm water from the shelf moved offshore past the mooring for a half cycle and then cool water moved inshore past it for the other half cycle. For comparison, the same temperature information has been added to the PVD for 17 m depth.

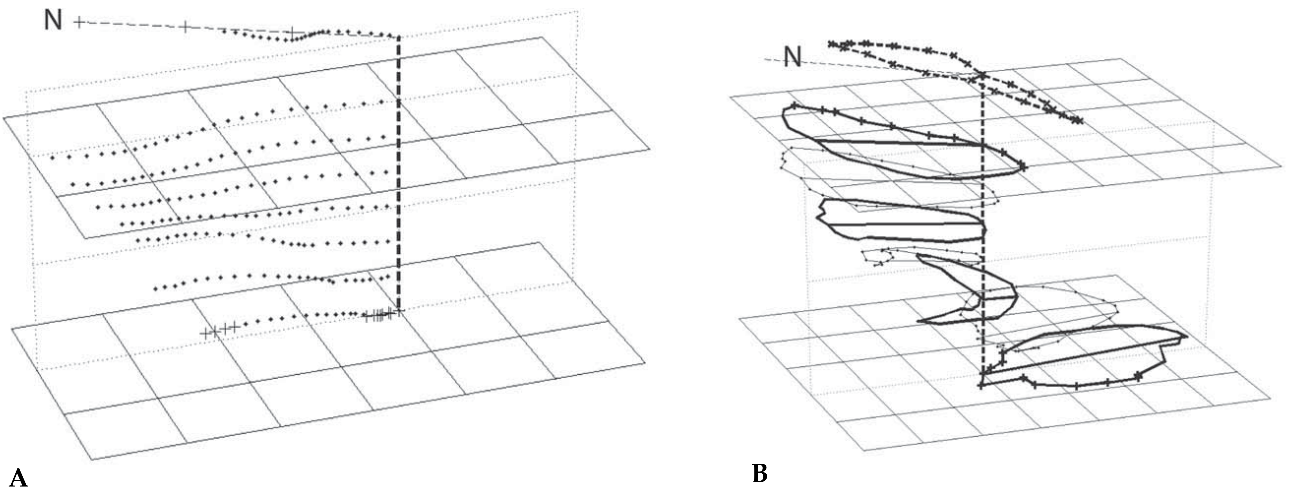


Figure 13A. As for Figure 6A, but for one day from 1000 UTC (1800 WAST) 11 December 2000 to 0900 UTC (1700 WAST) 12 December 2000 and with pluses on the lowest PVD (65 m depth) PVD indicating when the temperature exceeded 18.7°C.
Figure 13B. As for Figure 13A, except that the steady translations over the one day period have been removed and the mesh size is 1x1 km. The daily warm half cycle (T>18.7°C) is marked by the pluses on the PVDs for 17 and 65 m depth and the "hour hands" on each path go from the origin to the 12 hour point. The angled dashed line at the top indicates north.

Discussion

This is the first uninterrupted year-long record of currents on the continental shelf of temperate Western Australia. It covers 13 x 4 m depth intervals (3/4 of the water column at the 70 m isobath) and temperature was measured at the instrument. Prior to this the best record is that from mooring site D2 at the 108 m isobath off Dongara as part of the LC Interdisciplinary Experiment, LUCIE (The Lucie Group, 1988). That mooring had four current meters at different depths and with two deployments covered the period September 1986 to August 1987, albeit with a 2 ½ week gap. We will refer to the results in this discussion. The three moorings along the Two Rocks line in 2004/05 also yielded important information (Fandry et al., 2006).

As expected, the dominant seasonal features of the present ADCP record are the LC in winter and the CC in summer. These currents were at times highly variable due to wind and other forcing; they reached speeds of 0.9 ms^{-1} and 0.6 ms^{-1}, respectively. The wind-driven CC ceased at times of diminished northward wind forcing: if this forcing became smaller than ~0.06 Nm^{-2} then it seems as if the background north to south pressure gradient drove an unseasonal LC. On one occasion in winter the LC (at the mooring) ceased and there was a week-long northward flow that could not be related to wind forcing. It is possible that an anticyclonic eddy from the open ocean was having an effect on the shelf currents. Such interactions have been studied by Moore et al. (2007) with anticyclonic eddies being found to entrain shelf waters with relatively high concentrations of chlorophyll *a*.

The flow of the CC is known from satellite imagery (Pearce and Pattiaratchi, 1999) to be associated with the appearance of cool upwelled water on the continental shelf. Progressive vector diagrams, which tend to smooth over current variability, did show onshore flow and cool water at the ADCP in December 2000. However, there was no persistent onshore flow at 65 m nearest the bottom. It was only further up in the water column that steady onshore flow was experienced: it was strongest at the 49 m depth bin where the flow made an angle of 17° with the shelf edge. With decreasing depth the angle decreased, became zero at 33 m and 7° offshore at 17 m depth (the shallowest bin). The 1°C temperature oscillation experienced each day may have been due to forcing from the sea-land breeze cycle and the close proximity of a front between warm shelf and cold slope water. This will be discussed below.

The annual temperature range measured at the ADCP was 18–22°C, with brief excursion above and below. At the LUCIE D2 site, almost 40 m deeper and at the shelf edge, the range was 19–22°C. In both cases the presence of the tropical LC waters served to counteract seasonal cooling and held the water temperature at 22°C from March until July.

Monthly progressive vector diagrams showed, somewhat surprisingly, that the LC, from March, was strongest at depth where it was directed as much as 40° off the shelf. Since there was no compensating flow nearer the surface – unless it was in roughly the upper 15 m – there must have been on-shelf flow somewhere north of the site, perhaps even related to the geometry of the Abrolhos Islands. The LUCIE D2 measurements also showed increasing off-shelf flow with increasing depth, but the current speed decreased with depth.

The currents throughout the record changed continuously on time scales up to several days, as can be seen in the cross-shelf current plot in Figure 2. By restricting our time "window" to several days and selecting a number of examples we were able to observe effects due to changes in wind forcing, shear and rotation with changing depth, a type of oscillation with a time scale 15–45 hours that at times created anticyclonic loops as much as 10 km across, and shear due to the sea-land breeze cycle.

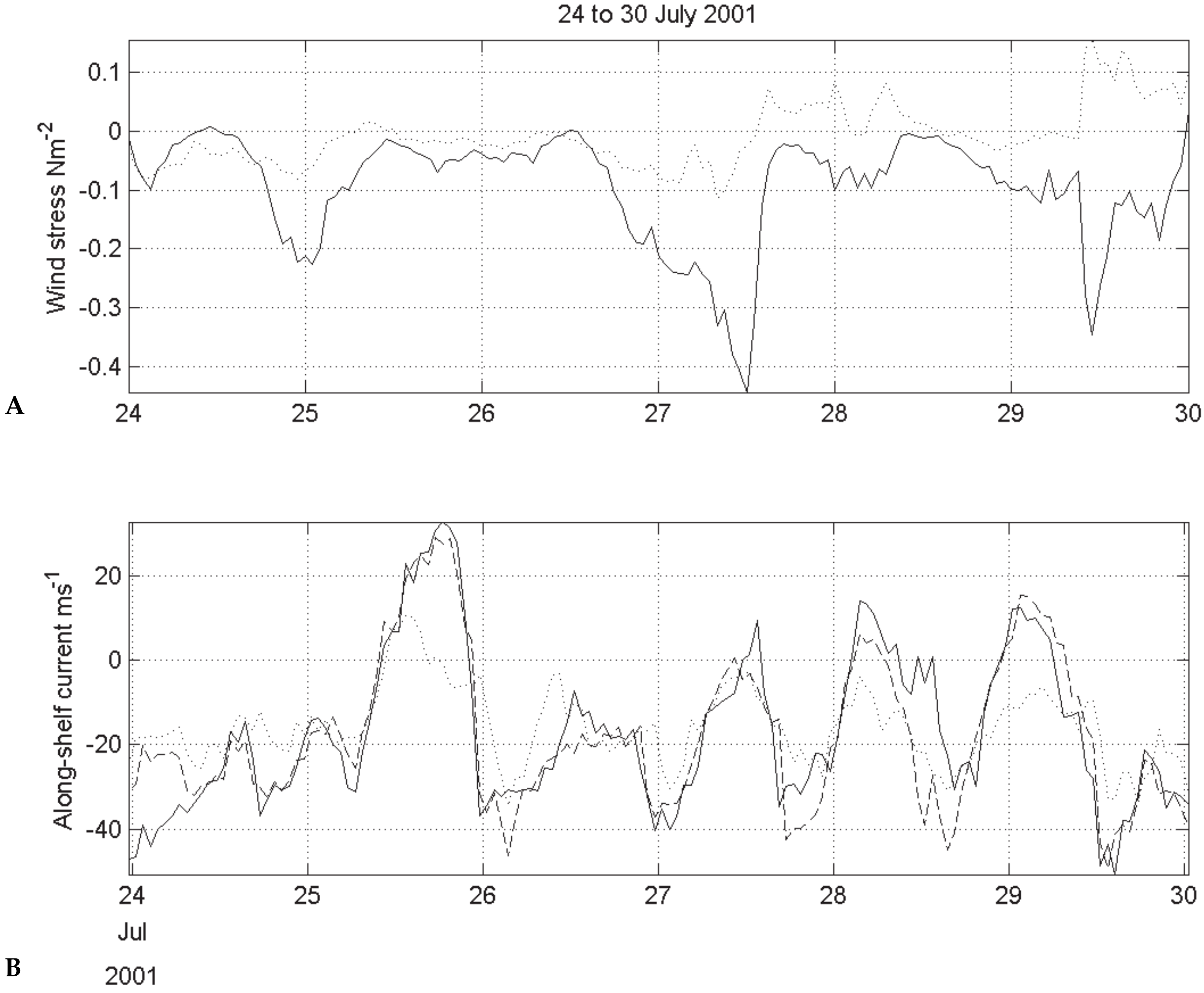


Figure 14. Time series of, **A**) wind stress showing north-south (full line) and east-west (dashed line) components and, **B**) along-shelf current at 17 m (full line), 41 m (dashed line), and 65 m (dotted line) depth.

The 1–2 day oscillations and loops are difficult to interpret with data from only a single point. Figure 14, the time series for 24–30 July 2001 to accompany Figures 11C and D, shows that the strong southward wind pulses that punctuated calm conditions bore little relationship with the current oscillations marked by the loops and cusps seen in the PVDs. The generation region and mechanism and the propagation direction and speed for these "waves" will have to await further observations from mooring arrays.

The sea-land breeze cycle generated anticlockwise motion through the water column – seen when the steady translation was removed from the motion – with the lower waters being out of phase with the upper ones. The loops that were generated were up to several kilometres across. It would seem that the 24-hour period wind forcing, which was also anticlockwise, served to drive baroclinic inertial waves, since at this latitude the inertial period is about 24 hours.

These inertial oscillations, the larger cross-shelf movements associated with the ~15–45 hour waves discussed earlier, and episodic cross-shelf motions will be important in the life cycles of marine creatures.

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