Long-shelf and cross-shelf transport processes off Perth, Western Australia: the influence of wind, differential cooling and the Leeuwin Current

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Long-shelf and cross-shelf transport processes off Perth, Western Australia: the influence of wind, differential cooling and the Leeuwin Current

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Summary

Winter observations of the dynamic response and transport of stratified shelf waters off Perth, Western Australia are presented and discussed. These observations comprise cross-shelf temperature, salinity and density structure measurements, wind and current time-series data, and satellite imagery from August 1991. Leeuwin Current water was identified over the outer shelf and slope as a thick buoyant layer which was 4°C warmer than near-shore water. Density generally decreased with distance offshore.

The data reveal the responsiveness of the cross-shelf density structure to meso-scale fluctuations of the Leeuwin Current, wind stress, and buoyancy fluxes due to surface heat transfer and freshwater inputs. In particular, two contrasting cross-shelf density structures, separated in time by a typical winter wind cycle, are shown. In one case, cross-shelf transport of coastal water was facilitated and in another it was inhibited. Southward and onshore wind stress assisted the shoreward migration of warm, buoyant Leeuwin Current water in a surface layer, and the associated cross-shelf flushing of denser coastal waters in a bottom layer. In contrast, the water circulation of meso-scale meanders of the Leeuwin Current is anti-cyclonic, and we present a case of one such meander that forced northward flow over the shelf under weak wind conditions. In this case the mid-shelf isopycnals were steeply-inclined due to upwelling, the relaxation of the density structure was opposed and cross-shelf exchange was therefore inhibited.

The satellite imagery revealed strongly coloured plumes of discharged estuarine water, which could be traced over distances of order 100km long-shelf. From the hydrographic data we inferred that the estuarine outflows, initially low in salinity and buoyant, underwent mixing with denser inner-shelf water and eventually became negatively buoyant relative to warmer, more saline outer-shelf water.

1. Introduction

Current oceanographical studies of circulation and mixing processes over the continental shelf off Perth, Western Australia (Hearn, 1991, Pattiaratchi and Backhaus, 1992) are motivated by the need to understand transport pathways of anthropogenic wastes discharged to the near-shore marine environment in order to assess the long-term ecological effects of these discharges (Environmental Protection Authority, 1990, Simpson *et al.*, 1993).

This paper investigates the hydrodynamics and transport characteristics of the Perth coastal waters with reference to an August 1991 winter data set comprising *in situ* measurements and concurrent satellite imagery. These data are used to describe the cross-shelf physical structure extending from shallow inshore waters (< 1km offshore, 10m depth) to beyond the continental shelf (85km offshore) and to document variations in the density structure of the near-shore region (to the 35m contour) at daily intervals over a typical winter meteorological cycle.

In winter, the Leeuwin Current advects warm water along the outer shelf and slope and enhances the cross-shelf temperature and density gradients off Perth (eg Smith *et al.* 1991). Our data illustrate the influence of the Leeuwin Current and wind forcing on the response of the density structure over the shelf, the transport pathways of estuarine plumes, and the exchange between near-shore and offshore waters.

During August 1991 nutrient-rich water draining from rural catchments was stained by tannins during run-off and was then discharged via estuaries to the shelf. This enabled us to use water colour as well as salinity and temperature to interpret the mixing and advection of these discharges over the shelf. It also helped us to trace cross-shelf transport and exchange between near-shore and offshore waters under several meteorological and oceanographical forcing conditions.

In winter, the monthly averaged wind stress vector is predominantly onshore with alternating periods (a few days in duration) of northward and southward long-shore wind stress (Steedman and Craig, 1983, Breckling, 1989). Shallow (< 20m) near-shore waters off the Perth region are strongly wind-driven (Steedman and Associates, 1981, Hearn, 1991, D'Adamo, 1992) and undergo corresponding long-shore reversals in current direction. Since this may favour longer residence times of near-shore waters, it is important to consider the role and significance of cross-shelf transport as a flushing mechanism for near-shore waters.

2. The study area and its winter characteristics

The continental margin off the coast of metropolitan Perth (Figure 1) has four zones:

1. A near-shore inner-shelf zone of shallow (< 20m) basins, lagoons and channels, partially enclosed by reefs and islands.
2. A gently sloping mid-shelf, approximately 30km wide, extending from the outer reefs to the 50m isobath.
3. A more inclined outer shelf, deepening from 50m to 300m over a distance of 30km.
4. A continental slope. Depth contours beyond the inner-shelf are generally smooth and shore-parallel, except about Rottnest Island which extends across the mid-shelf, and a deep submarine canyon which cuts across the continental slope.

The Leeuwin Current (eg Church *et al.* 1989, Smith *et al.* 1991) is a poleward surface flow of warm tropical water which is driven along the edge of the western continental shelf of Australia by a steric height gradient. The current intensifies in autumn and early winter when the opposing mean wind stress is weaker. Drifting buoy tracks (eg Cresswell and Golding, 1980) and satellite imagery (eg Legeckis and Cresswell, 1981, Pearce and Griffiths, 1991) show the common occurrence of meso-scale jets, undulations and meanders of the Leeuwin Current. The

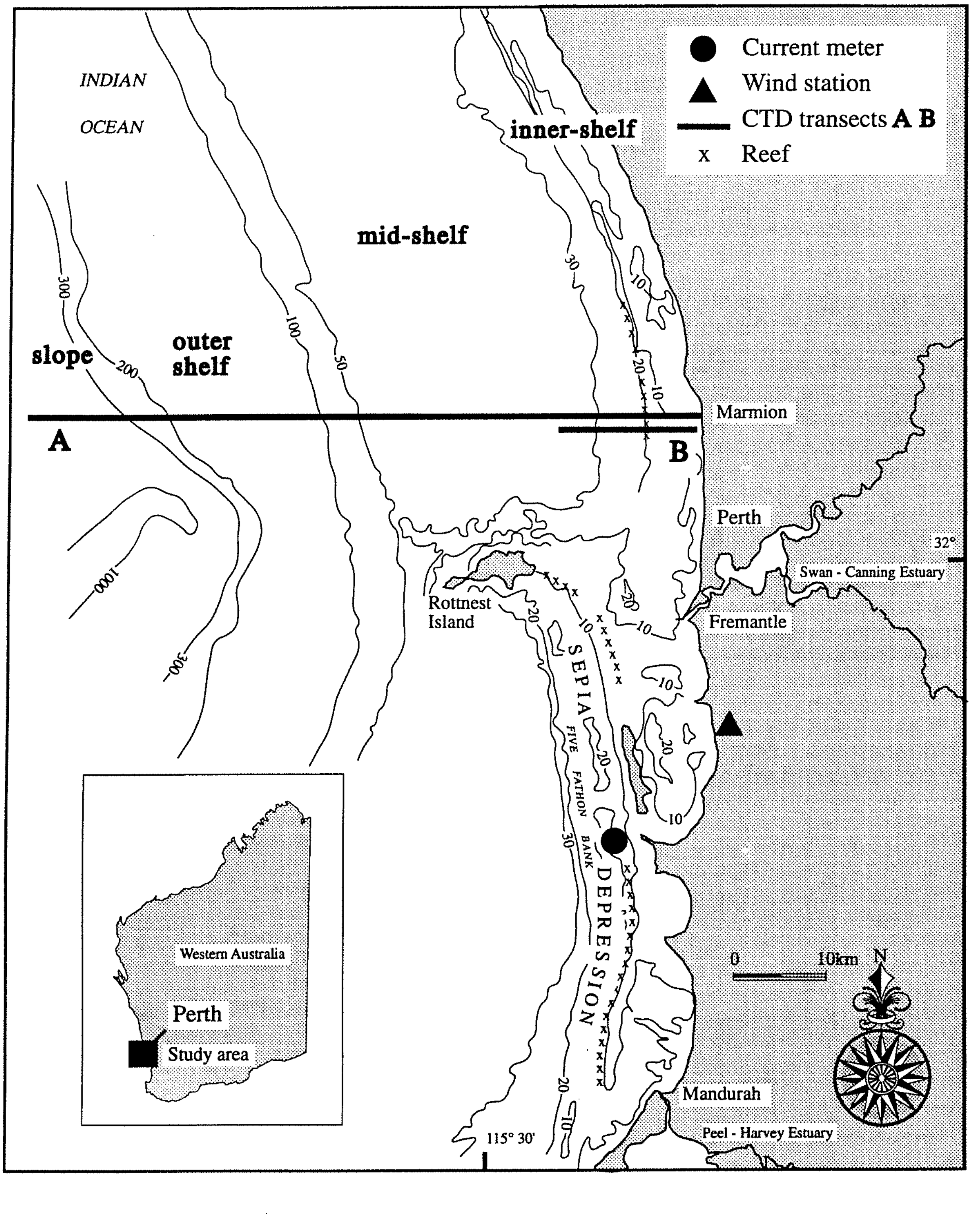

Figure 1. Bathymetry of the study area and the locations of main hydrographic lines and instruments.

warm core meanders have strong anticyclonic circulation around their offshore frontal boundaries and are separated by intervening cold cyclonic gyres. The meanders may grow in offshore amplitude to more than 200km, before pinching off to form detached eddies. On the landward side of some meanders, northward recirculating flow adjacent to the shelf has been documented by Pearce and Griffiths (1991). Pearce *et al.* (1985), Cresswell *et al.* (1989) and Pearce and Church (submitted) have shown that the mid and outer shelf off Perth is influenced by the Leeuwin Current.

In winter, weather systems passing over south-west Australia from the Indian Ocean consist of high pressure anticyclones, separated by cold fronts. Wind records from the study area show cycles, typically of 7 to 8 days, with episodic north-west to south-west winter gales associated with cold fronts, followed by longer periods of moderating and weak winds swinging through the south, east and north with the passing of high pressure systems (Steedman and Craig, 1983, Breckling, 1989).

The near-shore currents on the open shelf have typical speeds of order 0.1ms^{-1} (Steedman and Craig, 1983). They are primarily wind-driven and bathymetrically controlled, with secondary influences from long-shelf pressure gradients and baroclinic effects. In winter, current reversals occur typically at intervals of 3 to 5 days, in association with major wind shifts. The resultant monthly mean along-shore current component in winter is of order 0.01ms^{-1} (Steedman and Associates, 1981).

The water level regime of south-western Australia has been summarised by Hearn (1991). The astronomical tides are mainly diurnal with an annual mean range of 0.5m. Tidal currents are of order 0.01ms^{-1}, with tidal excursions of order 1km. Lower frequency oscillations in the coastal sea level are caused by barometric pressure, wind and oceanographic forcings, which together lead to elevation changes up to 0.5m over a typical time period of seven days. These oscillations are in part a direct sea-level response to variations in the barometric pressure and the associated wind stress fields (eg Harrison, 1983). They may also be due to the propagation of coastally-trapped waves (as suggested by Hamon (1966), Provis and Radok (1979) and Fandry *et al.* (1984)).

In winter freshwater is discharged from the mouths of the Swan-Canning estuary (at Fremantle) and the Peel-Harvey estuary (at Mandurah) as plumes which may be transported along-shelf for up to 100km (Wyllie *et al.*, 1992, Simpson *et al.*, 1993). The volumes of freshwater discharge show strong interannual variation (Finlayson and McMahon, 1988), however, they are not of sufficient magnitude to overcome the dominance of temperature on the density structure at shelf-scales.

3. Environmental data - August 1991

Conductivity-temperature-depth (CTD) transect lines occupied during the period 13-22 August 1991 and the locations of a moored current meter and a wind station are shown in Figure 1. Vertical CTD profiles were taken from less than 1km off the coast at Marmion to 85km offshore (Transect A) on 14 and 21 August. Transect B, approximately 16km long, and extending offshore from the coast at Marmion to the 35m contour, was monitored on 13, 15, 16, 18, 20 and 22 August.

A CSIRO/Yeo-Kal Model 606 CTD meter was used for vertical profiling to a maximum depth of 300m. A vector-averaging Neil Brown Acoustic Current Meter (ACM-2) measured inner-shelf currents at mid-depth in a 20m water column. Wind data (at 12m) were gathered with Unidata sensors and logging system near the coast at Kwinana, approximately 20km south of Perth. LANDSAT Thematic Mapper (TM) and NOAA AVHRR satellite images were acquired and processed using methods discussed in Wyllie *et al* (1992) to complement the *in situ* measurements.

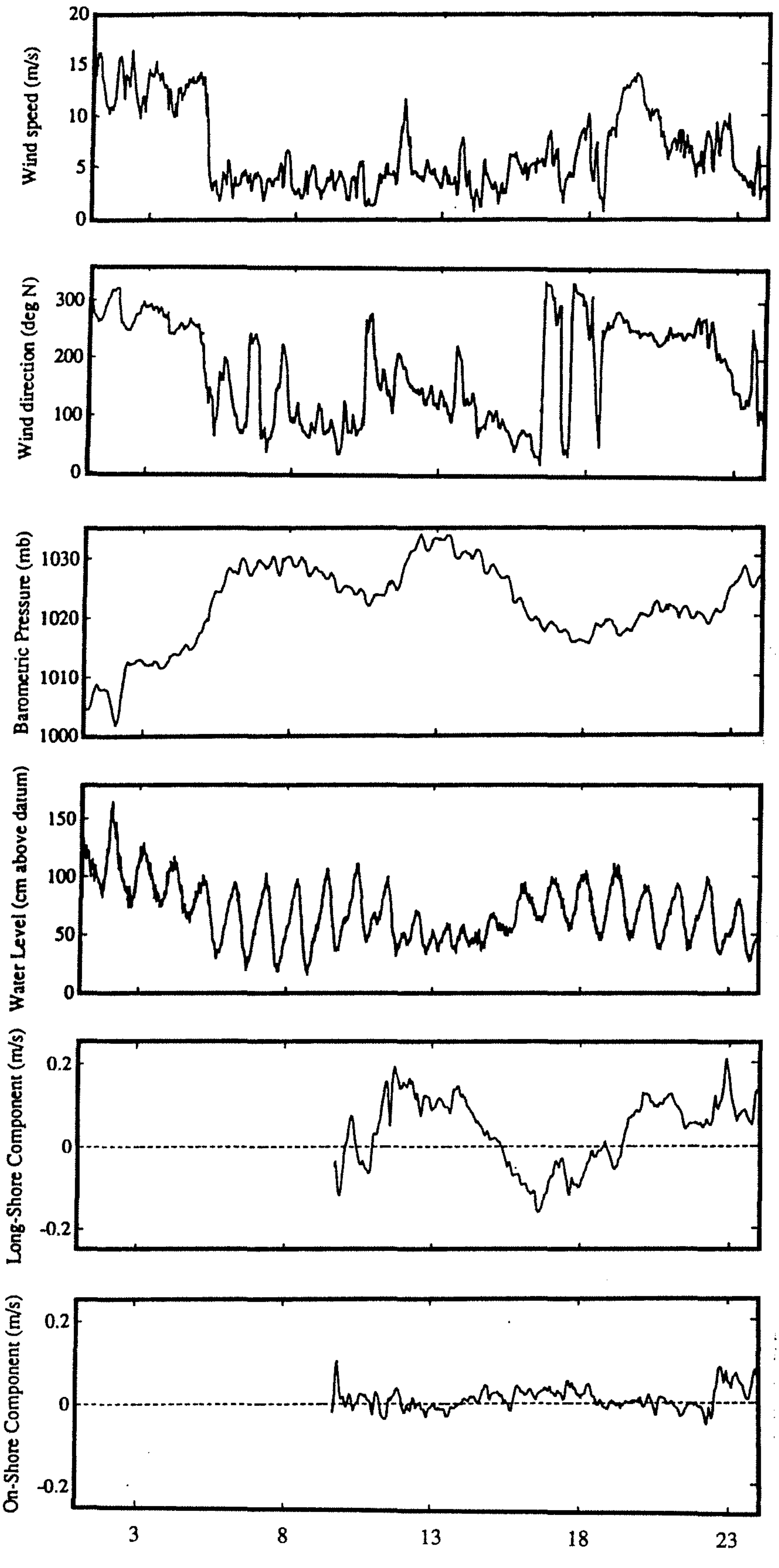

Figure 2. Time-series of wind at 12m height at Kwinana, barometric pressure at Perth, water level at Fremantle, and mid-depth current in Sepia Depression for the period 1-23 August 1991.

Time-series of meteorological, water level and near-shore currents for the period 1 to 23 August leading up to and including the duration of the oceanographic survey, are shown in Figure 2 and may be described as follows:

Wind

Winter gale conditions prevailed from 1 to 4 August. For eight days leading up to the survey (5 to 12 August) and for the first two days of the survey (13 to 14 August) winds were variable and generally less than 5ms^{-1}. From 15 to 17 August the wind swung through north to west, and freshened. 18 August saw the passage of a cold front and the onset of another winter gale, with west to south-west winds which reached a maximum speed of 14ms^{-1} at 1800 hours on 19 August. The wind then subsided to about 7ms^{-1} (south-west) by 21 August. It swung to the south and south-east and weakened further to 3ms^{-1} by 23 August. These wind data are also presented in Figure 3(a) as a progressive vector plot, to illustrate the classical synoptic meteorological winter cycle (Breckling, 1989) experienced in the Perth region during the period of the oceanographic survey.

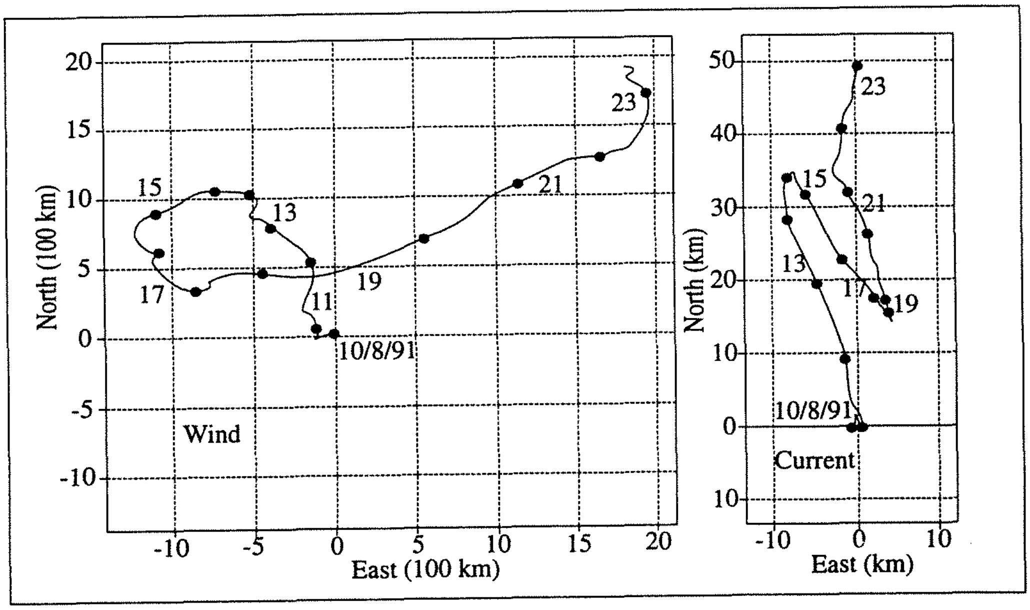

Figure 3. Progressive vector plots of (a) wind (12m) at Kwinana and (b) mid-depth current in Sepia Depression for the period 10-23 August 1991.

Barometric pressure

The barometric pressure time-series (Bureau of Meteorology, Perth) for August 1991 shows the passage of high and low pressure systems over the Perth region with periods of about seven days. These pressure systems drive the meso-scale wind field and influence the water level.

Water level

The water level time-series at Fremantle (Department of Marine and Harbours) exhibited tidal variations characteristic of south-western Australia, ie diurnal components were dominant with an August spring tide range of about 0.8m. Longer period oscillations (including energetic time scales of order seven days) were also evident.

Current

Near-shore currents measured at mid-depth in the Sepia Depression (20m) had a mean speed of $0.09ms^{-1}$. Current direction was predominantly long-shore with alternating northward and southward current runs of about three days duration and about 30km horizontally, subject to bathymetric constraints. As can be seen from the progressive vector diagrams of wind and current (Figures 3(a) and 3(b)) long-shore current reversals at this site responded rapidly to major reversals in the long-shore wind component.

Streamflow data and run-off calculations for ungauged catchment areas were combined to estimate freshwater flux to the coastal waters. The Swan-Canning estuary (pers. comm. F Davies, Water Authority of WA, G Bott, WADEP) and the Peel-Harvey estuary (pers. comm. D Deeley, Waterways Commission) each had mean August 1991 freshwater discharge rates to the ocean of about $60\text{-}70m^3s^{-1}$.

4. Cross-shelf structure - 14 August 1991

Vertical profiles of water temperature, salinity and density were measured across the shelf and slope (Transect A, Figure 1) on 14 August 1991. The cross-shelf structure of water properties was used, together with wind and current time-series data and satellite imagery, to interpret the dynamical response of the shelf waters to meteorological and oceanographical forcings.

4.1 Meso-scale oceanographic conditions

Cloud-free NOAA AVHRR imagery for 15 August (Plates 1(a) and (b)) shows two meso-scale, warm-core meanders of the Leeuwin Current extending to about 200km seaward of the shelf break between the latitudes 30 and 33°S. Offshore, beyond the shelf, these meanders were separated by an elongated cold water gyre. Inshore of this gyre, over the shelf and slope, the meanders were linked together by a short poleward jet (Pearce and Griffiths, 1991) of the Leeuwin Current.

The southern meander was situated directly seaward of the study area and extended 80 to 100km in a longshelf direction. The presence of smaller-scale billows on its western and southern fronts suggest that there was strong cross-frontal shear and anticlockwise circulation about the meander. CTD profiles were obtained from outer shelf and slope stations located within (the eastern side of) this meander. The salinity, temperature and density contours from these stations (Figure 4) indicated a depth scale for the meander of about 150m. The NOAA imagery was used to estimate a horizontal density difference of $1.2kgm^{-3}$ ($\Delta T \sim 5°C$) in 20km across the offshore front of the meander. Hence the baroclinic shear differential was estimated from the thermal wind equation (eg Gill, 1982) to have been of order $1ms^{-1}$.

Plate 1(b) suggests that some of the anticlockwise flow returning shoreward on the southern side of the meander was subsequently recirculated northward over the outer shelf, while the remainder was diverted south as a continuation of the Leeuwin Current. Such behaviour was clearly identified by Pearce and Griffiths (1991) for a similar meander.

4.2 Shelf-scale oceanographic conditions

Plates 1(c) and 1(d) show the visible and thermal band LANDSAT images of continental shelf and slope waters off Perth for 14 August 1991. The thermal band image reveals a sea-surface temperature differential across the shelf of about 3°C, with warmer water (offshore) and cooler water (near the coast) separated by a distinct front. The warmest water (~20°C) was located at the eastern margin of the Leeuwin Current meander discussed in section 4.1. The image also shows a tongue-like incursion of Leeuwin Current water across the mid-shelf, north of Rottnest Island, and as a result of this the temperature front approached to within 15km of the coast.

Plate 1(c), the visible band image, reveals the extent and trajectory of plumes emanating from the Peel-Harvey and the Swan-Canning estuaries. These plumes were strongly coloured by tannins, dissolved during freshwater run-off from the catchments. Upon discharge from the estuary mouths at Fremantle and Mandurah, the plumes initially spread offshore (to the west-north-west). Further away from their respective sources, they moved in a long-shelf (northward) direction. Reference to Plate 1(d) shows that the plumes were bounded offshore by the temperature front. In the case of the Peel-Harvey plume this occurred near the mid-shelf break. In the case of the Swan-Canning plume, it occurred within 15km of the coast. These images indicate that plumes can transport estuarine water alongshelf up to 100km away from source.

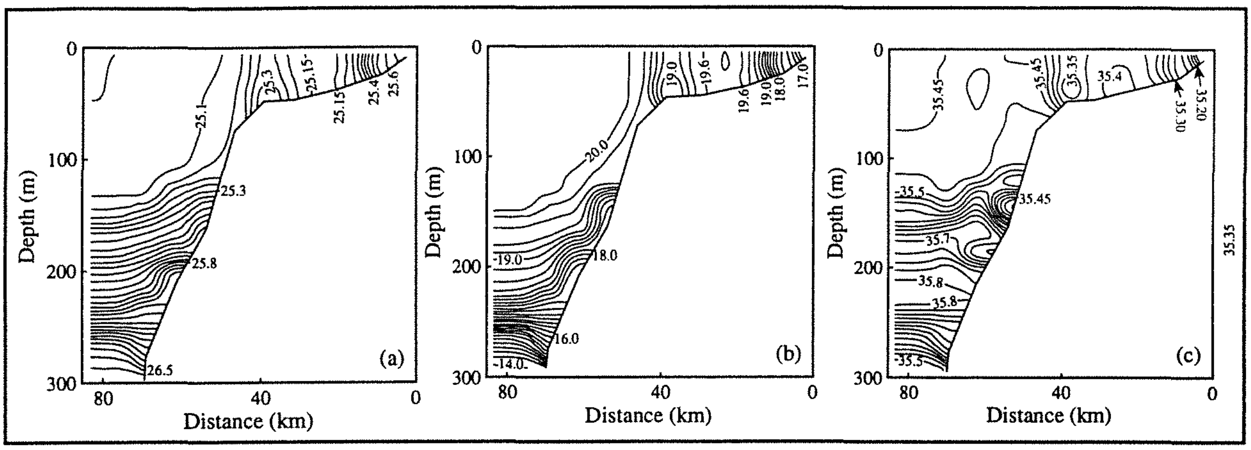

Figure 4. Cross-shelf hydrographic section along Transect A from Marmion to 85km offshore on 14 August 1991, showing (a) density structure (sigma-t contour interval 0.05 kgm^{-3}), (b) temperature structure (contour interval 0.2^{o}C), and (c) salinity structure (contour interval 0.025psu).

4.3 Physical structure over the outer shelf and slope - 14 August 1991

As shown in Figure 4, a warm, well-mixed, 140m deep surface layer was situated over the outer shelf and slope. This has been identified in Section 4.1 as the eastern edge of an anticlockwise circulating meander of the Leeuwin Current. Beneath this surface layer was a zone of strong vertical density stratification ($\Delta\rho$ = 1.6kgm^{-3}). At 245m depth the density, salinity and temperature contours were horizontal, the salinity was maximum (35.85pss) and the water properties were characteristic of South Indian Central Water, as reported by Rochford (1969). Above this level the isopycnals inclined upward toward the continental margin. The horizontal extent of this isopycnal deformation was about 30km. This scales with the baroclinic Rossby radius (R = NH/f) calculated for the shelf slope, where the buoyancy frequency, N ~ 10^{-2} s^{-1}, the total depth, H ~ 300m and the Coriolis parameter, f ~ -7.7 x 10^{-5} s^{-1}. The density structure therefore suggests upwelling supported by vertical shear flow to the north above a level of 245m depth.

Estimates of the baroclinic shear associated with an inclined density structure can be obtained from the thermal wind equation (eg Gill, 1982) as:

$$\Delta v \sim -g\ \Delta\rho\ \Delta z/(\rho\ f\ \Delta x) \qquad (1)$$

where $\Delta v/\Delta z$ characterises the vertical gradient of the current component that is perpendicular to the density section, $\Delta\rho/\Delta x$ characterises the horizontal density gradient, g (= 9.8ms^{-2}) is the gravitational acceleration, ρ (= 1025kgm^{-3}) is a reference density and f (= -7.7 x 10^{-5} s^{-1}) is the Coriolis parameter. Applied to the upwelled density structure over the outer shelf and slope (where $\Delta\rho/\Delta x$ = 0.9 x 10^{-5} kgm^{-4}, Δz = 100m) equation (1) yields a northward flow of about 0.15ms^{-1} near the base of the upper mixed layer (relative to an assumed level of no motion at 245m).

4.4 Physical structure over the mid-shelf – 14 August 1991

The physical structure across the mid-shelf (Transect A, Figure 4) exhibited a significant horizontal density differential (about 0.5kgm^{-3}) and steeply-inclined density contours. Inner-shelf waters, of lower temperature and salinity, were generally denser than surface waters over the outer shelf. The mid-shelf structure of 14 August comprised the following main features:

a a steep density front ($\Delta\rho$ = 0.12kgm^{-3}) situated at the mid-shelf break, which delineated the warm, buoyant surface layer (the Leeuwin Current meander) from mid-shelf waters;

b a dense core of cooler, fresher water (local maximum σ_t = 25.34kgm^{-3}) centred at the 50m depth contour and partially overlain by lighter water, both from inshore and offshore;

c a less dense mid-shelf water mass with properties very similar to Leeuwin Current water;

d a region of strong horizontal temperature and density gradient located about 15km offshore, separating cooler, fresher coastal water from warmer water of off-shore origin.

The main features of the cross-shelf hydrographic structure, listed above, can be identified by inspection of the LANDSAT imagery. Plate 1(c) shows that the darkly coloured estuarine plume from Mandurah travelled in a long-shelf direction and intersected Transect A at the 50m depth contour. The dense but slightly fresh core found at this location in the cross-shelf structure was therefore identified as diluted plume water from the Peel-Harvey estuary, about one week after discharge and 80km from its source. The initially buoyant, estuarine plume had mixed with cool, dense inner-shelf water, reducing its salinity deficit, and had eventually become more dense than the warm, outer-shelf Leeuwin Current water.

The less dense, warm water mass on the mid-shelf was identified from the satellite imagery as part of the tongue-like incursion of Leeuwin Current water, north of Rottnest Island. This warm water tongue was situated between the Peel-Harvey plume (to seaward) and coastal water (to shoreward). The shore-parallel Swan-Canning estuary plume was located immediately inshore of a sharp horizontal temperature gradient zone (Plates 1(c) and 1(d)) which was identified but not finely resolved in the hydrographic structure of 14 August.

The general picture across the mid-shelf is therefore one of adjacent water masses of different density, including estuarine plumes, coastal waters and the Leeuwin Current. Contours were steeply inclined, with strong horizontal gradients and opposing density fronts. These local variations and slope reversals were associated with differential long-shore advection, causing interleaving of distinct water masses, as also inferred from the LANDSAT imagery. Figure 5 provides a schematic representation of the LANDSAT images and the hydrographic section along Transect A for 14 August.

For the nine-day period preceding this cruise, the mean wind speed was 3.7ms^{-1} and winds seldom exceeded 5ms^{-1} (Figure 2). D'Adamo (1992) showed that complete vertical mixing of mid-shelf waters by such weak winds was unlikely under winter hydrographic conditions. The internal Rossby radius of deformation for the mid-shelf ($\Delta\rho$ = 0.5kgm^{-3}, H = 50m) was about 5km, much smaller than the width of the mid-shelf itself. The steeply inclined density structure has therefore been interpreted as an upwelling response consistent with northward flow over the shelf, as recorded by the inshore current meter and indicated by the northward advection of estuarine plumes over the mid-shelf.

Simple long-shelf momentum balance calculations involving wind stress, long-shelf pressure gradient and bottom stress suggest that a 5ms^{-1} southerly wind opposed by a long-shelf sea-surface gradient of order 10^{-7}, typical for the region in winter (Smith *et al.* 1991) would not be able to drive northerly flow of about 0.1ms^{-1} over the mid-shelf. It is therefore proposed that the offshore Leeuwin Current meander (discussed in section 4.1) was mainly responsible for forcing the northward flow over the shelf and slope for several days prior to 14 August. This forcing opposed gravitational relaxation of the inclined density structure and inhibited cross-shelf transport. This probably occurred over a long-shelf distance of about 100km, commensurate with the dimension of the meander. The satellite imagery shows that the dense Peel-Harvey plume was constrained to travel along the mid-shelf for a similar distance.

It is not possible at present to estimate the frequency and duration of events such as described in this section. However, Pearce and Griffiths (1991) showed that meso-scale features of the Leeuwin Current are common and that they tend to migrate only slowly. Smith *et al.* (1991) noted some meso-scale reversals in the long-shelf pressure gradient off the Western Australian continental shelf and suggested that they may have been caused by the presence of meso-scale meanders and eddies of the Leeuwin Current.

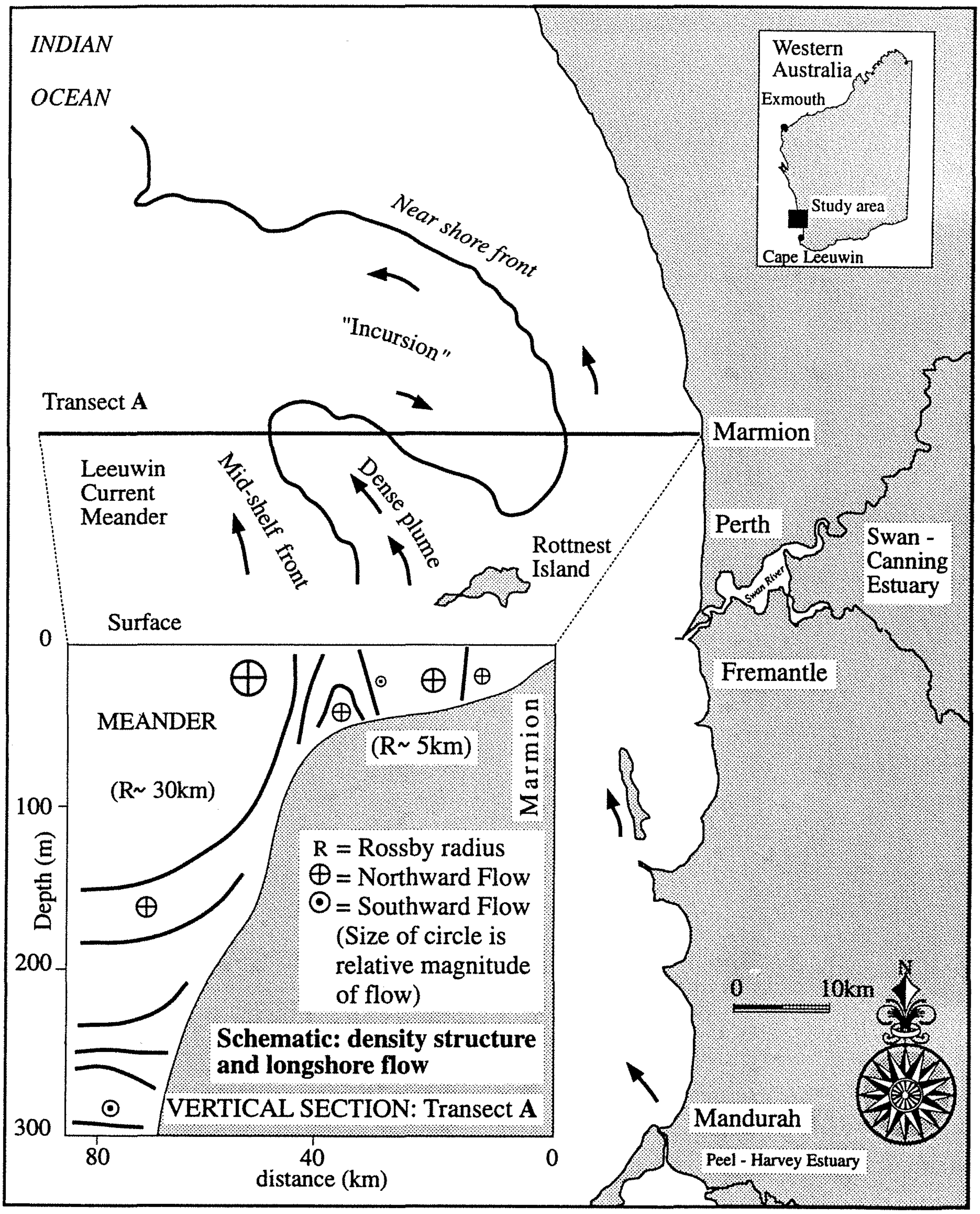

Figure 5. Schematic of the inferred flow structure for 14 August 1991, in the vicinity of Transect A, derived from Landsat TM imagery and the hydrographic section.

5. Cross-shelf structure - 21 August 1991

The physical structure across the shelf and slope (Transect A) was again measured on 21 August 1991 and is discussed here with reference to complementary satellite imagery and available time-series data. This structure was in sharp contrast to that of 14 August 1991.

5.1 Meso-scale oceanographic conditions

A comparison of NOAA AVHRR images for 15 August and 22 August shows (Figure 6) that significant change occurred during this period in the offshore meso-scale features associated with the Leeuwin Current. In particular, the two well-developed meanders, described in section 4.1, migrated southward, and by 22 August the short Leeuwin Current jet linking the meanders was situated directly off the study area (Transect A). Hence it is suggested that the northward flow over the outer shelf on 14 August had given way to southward flow a week later.

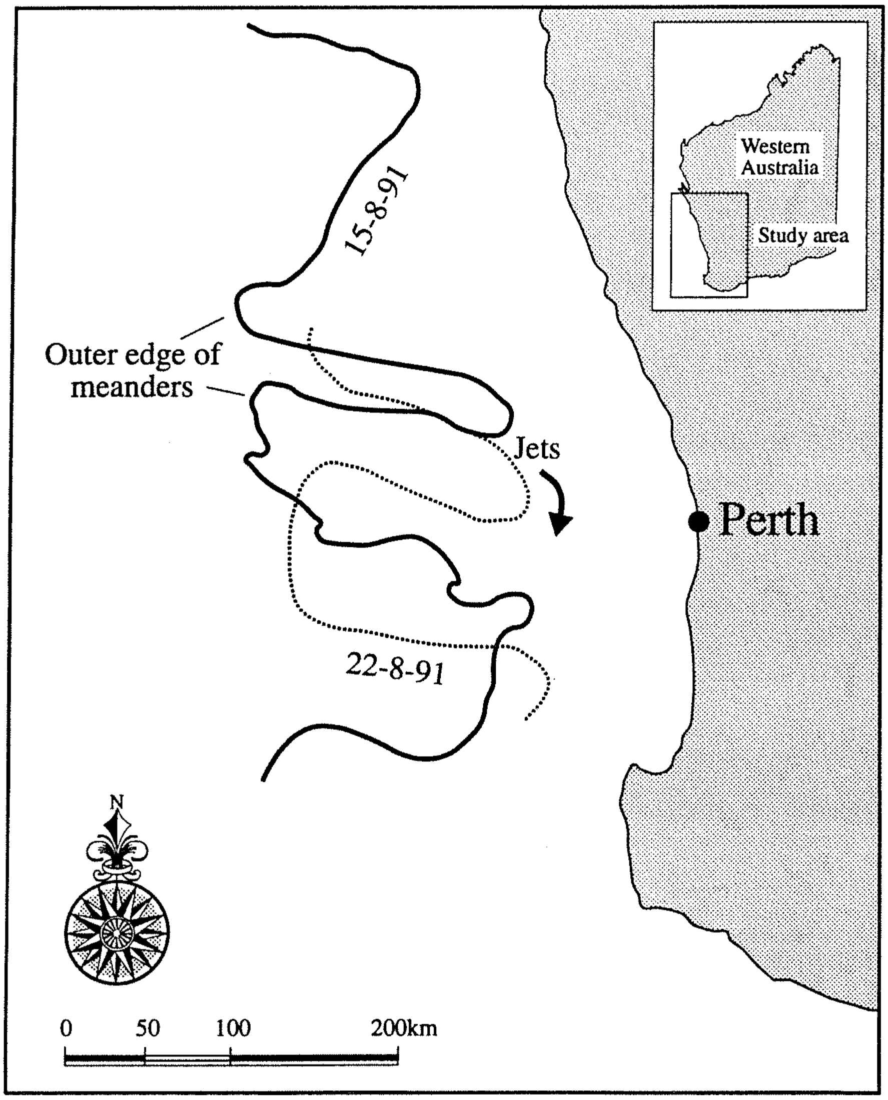

Figure 6. Outer edge of the meso-scale meanders and jets of the Leeuwin Current, showing southward migration over the period 15 to 22 August 1991. Data from NOAA AVHRR satellite imagery.

5.2 Meteorological conditions

This period also saw the passage of cold fronts, which brought first northerly and then strong onshore winds for several days (see Figures 2 and 3). These winds became more southerly and moderated as the next high pressure system approached.

5.3 Physical structure over the outer shelf and slope – 21 August 1991

A warm, well-mixed surface layer (the Leeuwin Current) overlaying a vertically stratified zone was again found on 21 August, as shown in Figure 7. However, the structure was different to that of 14 August in that the contours of the pycnocline either deepened or remained nearly horizontal as they approached the outer shelf and slope. The upwelled structure of 14 August was gone, and replaced by an apparently downwelled structure on 21 August. The onset of downwelling would require a southward flow. Hence, the evidence presented in section 5.1 for a reversal from northward to southward flow over the outer shelf during this period is consistent with the observed change in the density structure.

Figure 7 also reveals a narrow zone of steeply inclined temperature, salinity and density contours adjacent to the outer shelf. This represents a baroclinically-enhanced leakage of cool, relatively fresh (but dense) water off the mid-shelf, and would again be consistent with southward flow, downwelling and offshore Ekman transport in a bottom boundary layer.

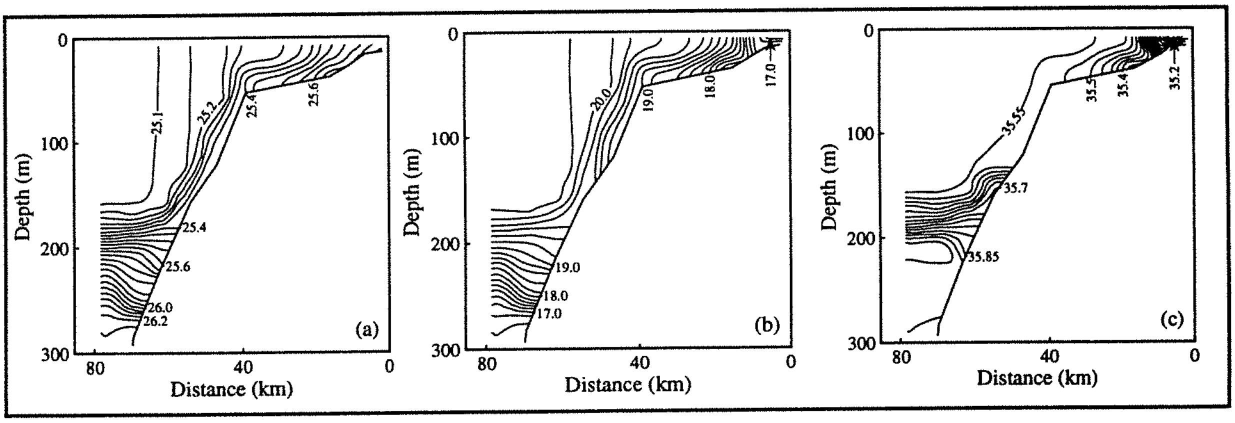

Figure 7. Cross-shelf hydrographic section along Transect A from Marmion to 85km offshore on 21 August 1991, showing (a) density structure (sigma-t contour interval 0.05 kgm^{-3}), (b) temperature structure (contour interval 0.2^{o}C), and (c) salinity structure (contour interval 0.025psu).

5.4 Physical structure over the mid-shelf – 21 August 1991

By 21 August, cooler, fresher, denser coastal water had moved off-shore across the mid-shelf beneath warmer water (see Figure 7). The thermocline, halocline and pycnocline were well-defined and horizontal at a depth of about 25m delineating an upper mixed layer of constant thickness from a lower mixed layer thickening offshore. The horizontal salinity difference in the upper layer was small, indicating that Leeuwin Current water had moved shoreward and cooled, but had undergone minimal mixing with coastal water. In contrast, the lower layer exhibited a marked offshore salinity gradient, possibly the result of entrainment from the upper layer.

5.5 Discussion of factors led to the change in cross-shelf structure

It has been shown that the structure across the mid-shelf changed markedly over the period 14-21 August, from a steeply inclined structure with strong cross-shelf gradients and small vertical stratification to a distinctly two-layered structure. In this section we discuss a range of factors and processes which could have caused the observed structural change.

Interestingly, the steeply-inclined structure of 14 August occurred under very weak wind conditions, whereas the vertically-layered structure of 21 August formed under stronger wind conditions. From this we make two deductions. Firstly, wind-induced vertical mixing was unlikely to have been primarily responsible for the change in the vertical density structure across the mid-shelf, although it may have contributed to the well-mixed nature of the upper layer (Figure 7). Secondly, the change of structure was unlikely to have been primarily due to a baroclinic relaxation, which normally occurs when there has been a reduction in energy available for vertical mixing. The horizontal length scale for baroclinic relaxation is the internal Rossby radius of deformation, which has already been shown to be much smaller than the mid-shelf width. However, the layered structure of 21 August extended right across the mid-shelf.

Enhanced differential cooling, a reduction in freshwater flux, or a change to the density of outer-shelf waters are factors which could have led to an increase in density differential across the mid-shelf and hence to a change in the hydrographic structure. However, the density differential would need to have increased by an order of magnitude for the internal Rossby radius of deformation to scale with the mid-shelf width. Comparison of Figures 4 and 7 shows that this did not happen. It is therefore concluded that the observed change in structure was not primarily in response to a rapid increase in the density differential over the mid-shelf.

The onset of a southward current over the mid and outer shelf during the period 14 to 21 August could possibly explain the development of the two-layered density structure over the mid-shelf. In the absence of outer shelf current meter data, there are two pieces of evidence which suggest a reversion to a southward current:

a comparison of NOAA satellite images from the beginning and end of the period shows (Figure 6) that the short Leeuwin Current jet conveying southward flow between the two meanders had itself migrated southward, to be situated directly off Transect A; and

b comparison of the density distributions for 14 August and 21 August shows the onset of a downwelling structure at about 200m depth over the continental slope that is consistent with a southward flowing Leeuwin Current.

Southward flow would have induced secondary cross-shelf circulation with shoreward transport above a compensating offshore Ekman transport near the sea bed. This circulation would have facilitated an exchange between buoyant Leeuwin Current water (moving landward in a surface layer) and dense coastal water (moving seaward across the mid-shelf in a lower layer) over distances much greater than the local baroclinic Rossby radius of deformation. The following calculations were made to further examine this hypothesis. The Pollard, Rhines and Thompson (1973) expression for the mixed layer depth of a rotating, stratified fluid may be used to estimate the bottom shear velocity (u^*) required to achieve a specified bottom mixed layer depth (h_{max}):

$$u^* = (Nf)^{1/2}\, h_{max}/2^{3/4} \qquad (2)$$

At the 50m depth contour the observed bottom layer depth for 21 August was 25m. For a value of $N \sim 10^{-2}\ s^{-1}$, equation (2) gives $u^* \sim 10^{-2}\ ms^{-1}$, which would require a current speed ~ $0.2ms^{-1}$. A southward current with this bottom shear stress would lead to an offshore bottom Ekman flux of $\tau/\rho f = (u^*)^2/f \sim -1.5\ m^2s^{-1}$. Dividing bottom Ekman flux by bottom mixed-layer thickness gives an offshore velocity estimate for the bottom layer of $0.06ms^{-1}$. For a midshelf width of ~ 20km, this suggests an advective timescale for bottom water to traverse the mid-shelf of about four days, which seems reasonable, given that the change in observed structure across the mid-shelf occurred in less than one week.

Southward and then strong onshore wind stress, and an associated peak in coastal sea level (Figures 2 and 3) occurred in the week between the cross-shelf transects. It is suggested that these forcings would also have driven onshore movement of warmer surface water and offshore underflow of denser coastal water. This will be further examined in section 6.

6. Response of the inner-shelf physical structure to forcings

The two contrasting cross-shelf structures discussed above were separated by seven days. More closely spaced CTD measurements of the inner-shelf physical structure from the coast at Marmion to the 35m depth contour (Transect B, Figure 1) were undertaken on 13, 15, 16, 18, 20 and 22 August. These data are briefly examined here for three reasons:

a they highlight the presence and mobility of a major near-shore temperature/density front;

b they better resolve the transition between inner-shelf and mid-shelf density structure;

c they indicate when the major change in cross-shelf density structure was initiated.

The major near-shore density front was dominated by a sharp temperature gradient and formed the boundary between warm Leeuwin Current water, transported across the shelf, and coastal water. The coastal water was generally cooler, slightly less saline and more dense than the offshore waters. Plumes from the Swan-Canning estuary were sometimes detected as small surface cores in the density structures along Transect B. These plumes overflowed the coastal waters, however they were generally less buoyant than the Leeuwin Current water to seaward of the major front. The cross-shelf migration of the major near-shore front is now described and its response is discussed with reference to the history of wind forcing, the coastal water level and the near-shore flow.

6.1 Northward near-shore flow

On 13 August the front was near vertical, and located at the 30m depth contour, 16km offshore (Figure 8(a)). A similar inclination of density contours and location of the front was noted (Figure 4) in the cross-shelf transect of 14 August, under repeated conditions of northward near-shore flow and weak winds.

6.2 North to south near-shore flow reversal

On 15 August the surface expression of the front was found to be within 8km of the coast (Figure 8(b)). The front was less steeply-inclined than on the preceding two days, but still extended from top to bottom of the water column, meeting the seabed at the 30m depth contour. The long-shore wind component and the near-shore current slowed and reversed direction on 15 August. Warm water was found 8km closer to the coast along Transect B.

6.3 Southward near-shore flow

The southward near-shore current strengthened from 15 to 16 August under the influence of a strengthening southward wind stress component. CTD data from the 16 August transect (Figure 8(c)) show that the surface front had moved a further 2km onshore.

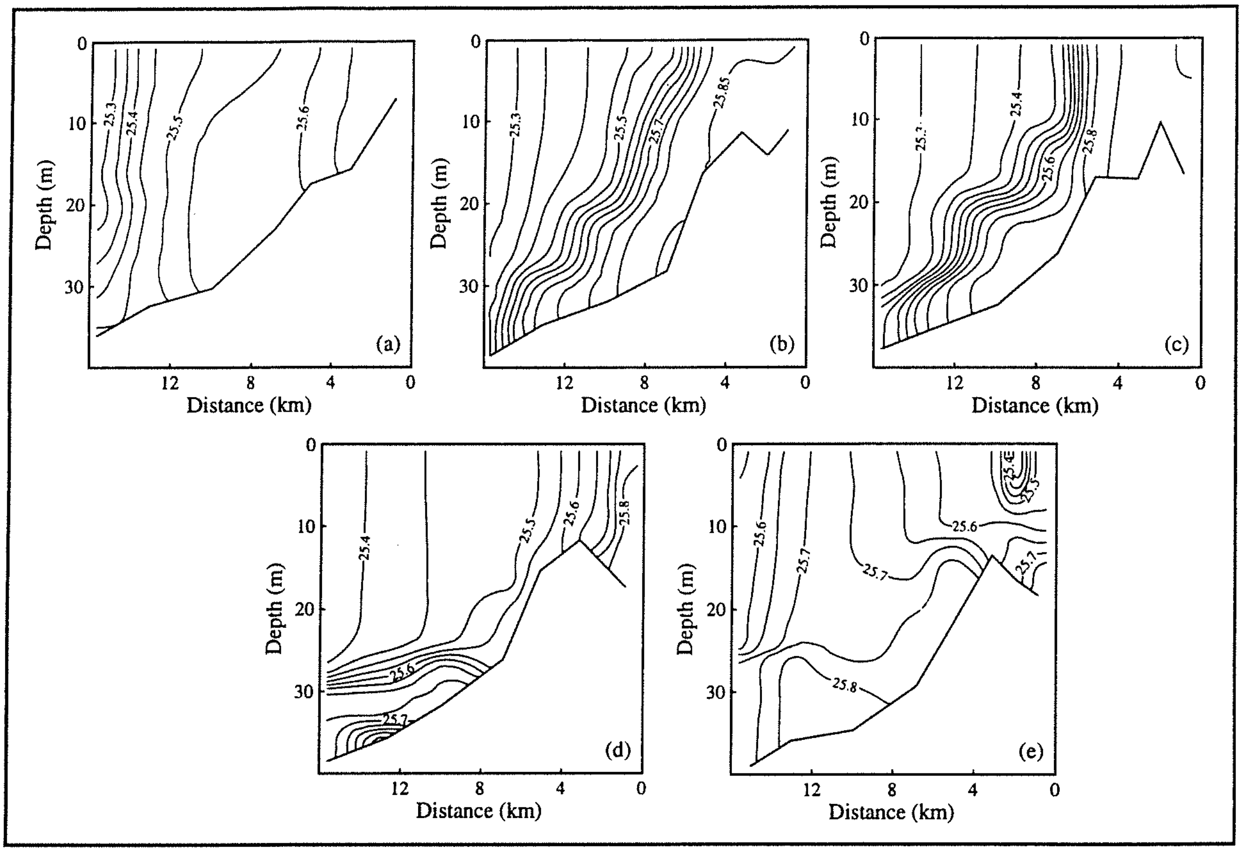

Figure 8. Cross-shelf density sections (sigma-t contour intervals 0.05 kgm^{-3}) along Transect B from Marmion to 16km off-shore, for (a) 13 August, (b) 15 August, (c) 16 August, (d) 18 August, and (e) 22 August 1991.

6.4 South to north flow reversal and strong onshore wind

Figure 8(d) shows that by 18 August a marked structural change had occurred. The surface front had moved to within about 2km of the coast. Further offshore the front had been depressed to a horizontal density interface 25m below the water surface, delineating a lower layer of relatively cool, less saline water which extended offshore beyond the 35m depth contour from a warm upper layer. 18 August saw the cessation of north-westerly winds and the commencement of strong onshore winds (Figure 3). The southward near-shore current decelerated rapidly prior to reversal (on 19 August) from southward to northward flow. The recent history of southward and strong onshore wind stress, and the associated rise in coastal sea level (Figure 3) appears to have combined to force onshore movement of warmer surface water and offshore underflow of denser coastal water.

In addition to the coastal downwelling process just described, wind mixing would also have contributed to producing the observed structure. An estimate of mixing to 20m depth was calculated from the theory of Pollard, Rhines and Thompson (1973) for the 10 hour, 8ms^{-1} wind event (17-18 August) that preceded the CTD measurements. However, the salinity and temperature properties of the density interface at 25m depth remained essentially the same as for the near shore front on preceding days, suggesting that coastal downwelling was the principal process involved in the structural change.

6.5 Northward near-shore flow and onshore wind stress

By 20 August, the wind was still onshore, but with a clear northward component, and the near-shore current was to the north at about $0.1ms^{-1}$ (Figure 3). The surface front had moved offshore more than 10km (water depth >30m) beyond the outer profile station occupied on that day.

The cross-shelf structure measured along Transect A on 21 August has been documented in section 5. The near-shore zone of the transect (to the 20m contour, ~10km offshore) possessed considerably lower salinity due to northward advection of the Swan-Canning estuary plume. Further off the coast, a well defined horizontal density interface at about 25m depth extended from 10km offshore (30m depth contour) across the mid-shelf to the mid-shelf break. This is reminiscent of the feature formed by coastal downwelling on 18 August.

By 22 August the wind was swinging to northward and the near-shore current was also to the north. Figure 8(e) reveals that the surface front was located 14km offshore (35m contour). It was essentially vertical down to 22m, at which depth it became horizontal and extended offshore. This suggests that the lower layer was still present over the mid-shelf. Nearer to the shore is cooler, low salinity water associated with a newly introduced northward flowing Swan River plume. This generated a buoyant structure in the coastal zone, but it was not buoyant enough to override Leeuwin Current water.

Based on the chronology of the front outlined in this section, it is likely that the lower layer cross-shelf transport of coastal water was initiated on 17 or 18 August. A cross-shelf advection of 25km in 3 to 4 days equates to a cross-shelf velocity of order $0.05ms^{-1}$.

7. Conclusions

This paper shows that meso-scale features of the Leeuwin Current, such as meanders and jets, may significantly influence the response of adjacent continental shelf waters. A well-developed anticlockwise circulating meander of the Leeuwin Current was situated off the Perth shelf for several days prior to our measurement period. Winds had been very light and variable for the preceding 10 days. The cross-shelf hydrographic structure of 14 August revealed a transverse baroclinic upwelling response of the pycnocline between 140-240m depth over the outer shelf. Estimates of the vertical shear required to support this upwelled density structure were derived from the thermal wind equation. On this basis a northward flow of about $0.15ms^{-1}$ at the eastern edge of the Leeuwin Current meander was inferred. Pearce and Griffiths (1991) have previously documented northward recirculating flow on the landward side of such meanders. Light, variable winds over the preceding 10 days were considered too weak to have induced the observed upwelling response over the outer-shelf, which we attributed to the recirculating flow of the offshore meander. The mid-shelf structure of 14 August was characterised by steeply-inclined density contours and marked horizontal density gradients, with density decreasing in the offshore direction. The preceding period of light winds suggests that upwelling, rather than vertical wind mixing was responsible for the perturbed mid-shelf density structure.

Strongly coloured plumes of discharged estuarine water were revealed by the satellite imagery. These plumes could be traced over distances up to 100km long-shelf. From the hydrographic data we inferred that the estuarine outflows, initially low in salinity and buoyant, underwent mixing with denser inner-shelf water and eventually became negatively buoyant relative to warmer, more saline outer-shelf water. The upwelled density structure of 14 August inhibited cross-shelf transport of these relatively dense plumes which were advected northward along the shelf and remained shoreward of steeply-inclined density fronts marking the eastern edge of the Leeuwin Current meander. Under these conditions, the plumes mixed slowly, showing low rates of dilution.

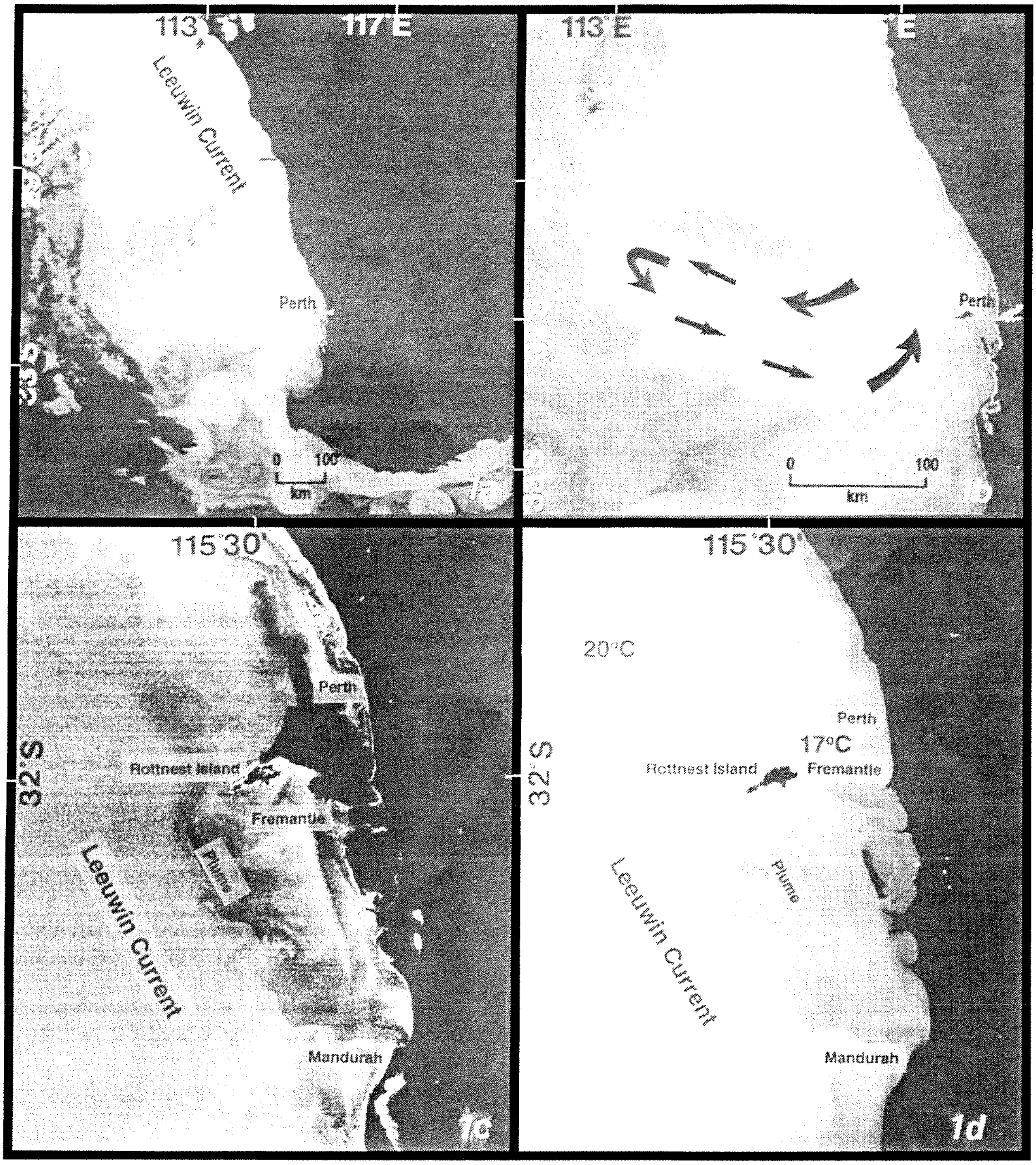

Plate 1(a)	NOAA AVHRR imagery (sea surface temperature) for August 15, 1991 showing mesoscale features of the Leeuwin Current off the West Australian coastline.
Plate 1(b)	NOAA AVHRR imagery (sea surface temperature) for August 15, 1991 showing mesoscale meanders and jets of the Leeuwin Current in relation to the study area.
Plate 1(c)	LANDSAT Thematic Mapper (TM) imagery of the study area for August 14, TM bands 1,2,3 - (Blue, Green, Red).
Plate 1(d)	LANDSAT Thematic Mapper (TM) imagery of the study area for August 14, TM band 6 - Thermal Structure.

Between 14 and 21 August, significant changes occurred both in oceanographical and meteorological conditions. By the end of this period the two well-developed Leeuwin Current meanders had migrated southward and the short section of Leeuwin Current jet flow linking the meanders was situated directly off the study area. Hence it is suggested that the northward flow adjacent to the Perth shelf on 14 August had given way to southward flow a week later. Longshore wind stress was southward from 15 to 17 August and this was followed by onshore wind stress from 18 to 21 August. The movement of a major density front was tracked across the inner-shelf during this week. By 18 August it had approached to within 2km of the coast, and had undergone coastal downwelling, which led to the formation of a dense lower layer of cooler, less saline water, extending offshore beyond the 35m depth contour.

By 21 August the cross-shelf density structure displayed depression of the pycnocline over the outer shelf and slope, and a two-layer vertical structure which extended across the mid-shelf. The formation of the two-layer mid-shelf structure was indicative of cross-shelf exchange, with warm, offshore water moving landward in the surface layer and cooler, fresher water moving seaward in the bottom layer. The estimated time scale of about four days for establishment of the two-layer density structure, observed over the mid-shelf on 21 August, was consistent with the observed formation of the lower layer on 18 August.

The vertically-stratified mid-shelf structure of 21 August evolved in the presence of strong wind forcing, whereas the steeply-inclined structure of 14 August evolved in the presence of weak wind forcing. We have discussed various mechanisms in an attempt to explain the observed changes in mid-shelf structure and the cross-shelf transport of coastal water. Neither vertical wind mixing nor baroclinic relaxation appear to be primary mechanisms. However downwelling associated with a poleward Leeuwin Current jet flow (Thompson, 1987, Smith *et al.*, 1991), Ekman adjustment over the mid-shelf in response to southward wind stress (Csanady, 1982) and direct shoreward wind-driven surface advection due to strong onshore winds appear to have been primary contributors to the observed changes. In the presence of the density differential across the shelf, these mechanisms would explain the observed two-layer structure.

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