Aspects of winter exchange patterns in the coastal waters off Perth, Western Australia — the region between the Shoalwater Islands Marine Park and the Peel-Harvey Estuary

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Aspects of winter exchange patterns in the coastal waters off Perth, Western Australia — the region between the Shoalwater Islands Marine Park and the Peel-Harvey Estuary

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Abstract

This paper describes aspects of winter exchange patterns between the buoyant nutrient-rich outflow of the Peel-Harvey Estuary and the adjacent oligotrophic southern metropolitan coastal waters off Perth. Particular attention is given to the influence of this outflow on the waters of the Shoalwater Islands Marine Park some 25 km to the north of the estuary mouth. Salinity, temperature and density stratification data and contemporaneous current measurements, collected during a typical 10-day synoptic cycle, are utilised in conjunction with numerical modelling to track the outflows and detail the exchange characteristics of these waters.

Under south-southwesterly winds of 5-10 m s^{-1} bouyant plumes from the Peel-Harvey Estuary were transported northward along the coast at speeds in the range of 0.15-0.30 m s^{-1} and traversed the 25 km from Mandurah to Warnbro Sound within 1-2 days. Similar strength winds from the northeast quadrant caused low salinity water originating from the Swan-Canning estuarine outflow, to be transported from southern Cockburn Sound to Warnbro Sound. This flow occurred via the Shoalwater Bay region and traversed this distance within times of order one day. These wind conditions occur cyclically about 3-4 times per month during winter and spring.

Numerical simulations, using the baroclinic Princeton Ocean Model, provided good agreement with the field results. The field and model results also indicated that southward flows from Cockburn Sound into the Shoalwater Islands Marine Park were relatively minor compared with the northward flows from the Peel-Harvey Estuary.

The field studies and model results suggest that the outflow from the Peel-Harvey Estuary has a significant influence on the waters of the Shoalwater Islands Marine Park. This outflow is a significant source of contaminants and should therefore be considered in the management of these waters.

1. Introduction

The Department of Environmental Protection of Western Australia is undertaking an environmental study of the southern metropolitan coastal waters of Perth (Figure 1). The purpose of the Southern Metropolitan Coastal Waters Study (*1991-1994*) is to provide a better technical basis from which to manage the cumulative environmental impacts of contaminants entering these waters (Simpson *et al.* 1993). This paper focuses on nearshore transport processes driven by wind stress and examines the effect of these processes on water exchange between the Shoalwater Islands Marine Park and surrounding nearshore waters. From an environmental management perspective an adequate understanding is required of the transport of nutrients and other contaminants from their main sources, whether local or remote, to areas of high environmental value, such as the coastal embayments.

The Peel-Harvey Estuary in south-west Australia receives large amounts of nutrients (phosphorus and nitrogen) during the winter-spring season from point source discharges and runoff over cleared agricultural land to its main rivers, the Murray, Serpentine and Harvey Rivers (Figure 1). Based on measurements from 1990 to 1992, Deeley *et al.* (1993) estimated a total contribution from these rivers of 80-220 tonnes of total-phosphorus and 700-1600 tonnes of total-nitrogen to the estuary per year. In addition, it has been estimated that the nitrogen-fixing alga *Nodularia spumigena* can introduce a further 2000 tonnes of total nitrogen to the estuary every year (Humphries and Robinson, 1993). After some of the nutrient load is converted to biomass within the estuary, a significant proportion is transported in buoyant outflows to the marine environment in biologically available form (Black *et al.* 1981). Recent estimates (Deeley, 1995) suggest that of the order of 60 tonnes of phosphorus and 500-1000 tonnes of nitrogen are discharged annually to the ocean from the Peel-Harvey Estuary. This paper investigates, by analysis of coastal salinity, temperature and density (S, T and D) data, the potential for nutrients to be transported within buoyant estuarine plumes alongshore into Warnbro Sound and the adjacent waters of the Shoalwater Islands Marine Park by south-southwesterly winds.

We detail the stratification in the region between Mandurah and Fremantle out to the 30 m contour, some 20 km offshore, during a typical 10-day winter synoptic cycle. The Peel-Harvey estuarine outflow plume is tracked by following isohalines from its source at Mandurah to its entry and residence in Warnbro Sound under south-southwesterly wind conditions. The tendency for the plume to remain attached to the shore under these winds is highlighted. The results provide important field evidence regarding the northward transferral of nutrients from a highly eutrophic estuarine system, the Peel-Harvey Estuary, to the oligotrophic coastal waters south of Perth, including the Shoalwater Islands Marine Park.

The data also provide evidence of the entry of relatively low salinity water into Warnbro Sound from the southern Cockburn Sound and Shoalwater Bay regions driven by east-northeasterly winds and deflected to the left of the wind direction by Coriolis forcing. Cockburn Sound is characteristically low in salinity during winter and spring due to the entry of Swan-Canning estuarine plumes under winds from the northern quadrants during 10-day synoptic cycles (D'Adamo *et al.* 1995).

The three-dimensional Princeton Ocean Model (Blumberg and Mellor, 1987) was modified for the Southern Metropolitan Coastal Waters Study (SMCWS) by Mills and Essers (1995) and further developed by Herzfeld (1994). This model was used to simulate the transport of buoyant Peel-Harvey Estuary outflows and low salinity water from the vicinity of the Cockburn Sound southern entrance into the Shoalwater Islands Marine Park and surrounding waters under wind conditions that prevailed during the field survey (Mills and D'Adamo, 1995a; Mills and D'Adamo, 1995b). The model results are compared with the field measurements.

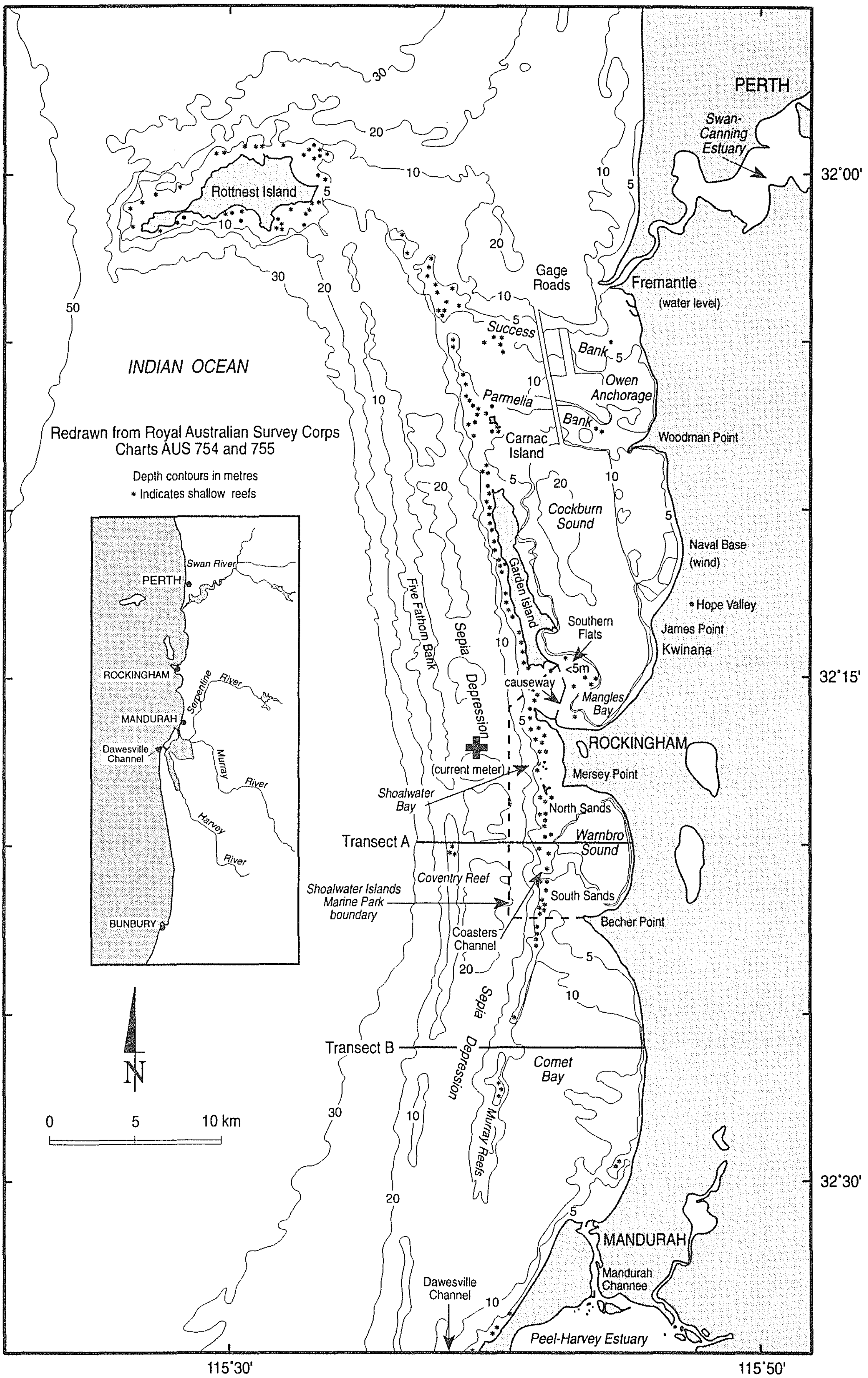

Figure 1. Locality diagram of the metropolitan coastal waters off Perth, Western Australia, bathymetric details, marine park boundary, ST transect paths A and B, wind anemometer and current meter locations.

2. Study area

The site details of the Shoalwater Islands Marine Park and adjacent waters are presented in Figure 1. Warnbro Sound lies approximately 25 km north of Mandurah and 40 km south of Perth, Western Australia. It is bounded by Mersey Point to the north, Becher Point to the south, a reef system to the west and the mainland to the east, and has dimensions approximately 4.5 km by 7 km. Within the Sound a central basin of 15-20 m depth has an area of approximately 15 km^2 or 50 percent of the total area. The northern and southern regions are characterised by shallow depths of less than about 5 m, and are called the North Sands and South Sands, respectively. Coasters Channel provides a central deeper passage 200-300 m wide and 6-10 m deep leading from Sepia Depression into Warnbro Sound through the reef line.

Sepia Depression is about 20 m deep, 5 km wide and partially bounded along its western edge by Five Fathom Bank, which is about 10 m deep on average. Sepia Depression continues southwards as far as the offshore waters west of Mandurah. Another reef line called Murray Reefs, parallel to the shore, runs from 10 km offshore of Mandurah and connects to the north with the Warnbro Sound reef line off Becher Point. The semi-enclosed region between Murray Reefs and the mainland is called Comet Bay. The relatively shallow region connecting Comet Bay and Warnbro Sound over the South Sands is devoid of major reefs.

To the south is the Peel-Harvey Estuary which is relatively shallow (less than about 2 m) and has an area of about 133 km^2. At the time of this study the estuary had one opening to the sea, a 4 km channel at Mandurah. In 1994 the Dawesville Channel was constructed connecting the Harvey Estuary with the sea. The data discussed in this paper were collected in 1991, prior to the existence of the Dawesville Channel.

The bathymetry of Cockburn Sound is characterised by a relatively deep basin (up to approximately 21 m depth) having approximate dimensions of 14 km by 5 km, and a shelf region adjacent to the mainland coast between James Point and Woodman Point having an approximate width of 4 km and a depth less than about 10 m. The northern opening has a mean depth of about 5 m and includes a 15 m deep shipping channel that connects the Sound with Gage Roads. The southern opening comprises two bridge entrances with water depths of about 3 to 4.5 m and a total cross-sectional area of approximately 3800 m^2.

The bathymetry of this coastal region is therefore characterised by partially submerged chains of reefs that protect the nearshore embayments from the full force of oceanic swells and seas, but with relatively narrow channels and openings amongst the reefs.

3. Methods

Within Cockburn Sound and its openings a fine-scale conductivity-temperature-depth (CTD) probe was used to monitor the stratification. The CTD probe returned measurements of salinity, temperature and depth at resolutions of 0.001 pss (practical salinity scale), 0.001 degrees Celsius and 0.001 m, respectively. Between Cockburn Sound and Mandurah salinity-temperature data were collected with a Yeokal Electronics Hamon Model 602 Salinity-Temperature (ST) Bridge. The ST profiles generally had a 1 m vertical spatial resolution. The ST meter is accurate to plus or minus 0.03 pss for salinity and plus or minus 0.1 degrees C for temperature. Regular checks of the meter against inductive salinometers were made and the data were calibrated and adjusted accordingly. Vertical and horizontal ST differences within and across basins during the survey period generally exceeded these accuracies by up to five times. The ST and CTD data therefore provide a good indication of the evolving stratification field, and the transport and mixing of contrasting water masses. Position fixing was achieved by a GPS instrument. The positions of profiling sites are shown in the figures throughout this paper.

A vector-averaging current meter (Neil Brown Acoustic NBIS ACM-2) was moored at a depth of 10 m in Sepia Depression at a site shown in Figure 1. The total depth at the site is approximately 20 m. Wind data were obtained from coastal sites in Kwinana and Fremantle (Figure 1) and Steedman and Craig (1979) have shown that the horizontal wind field is reasonably uniform under typical conditions, that is for 3-15 m s^{-1} speeds.

4. Results

4.1 Meteorology, hydrology and prevailing regional dynamics

The survey period was from 13 to 23 August 1991. The wind field underwent a 10-day synoptic cycle that is typical for local winter conditions (Breckling, 1989). Time series data of the wind velocity for that period are presented in Figure 2. These data show a relatively calm lead-up period prior to a severe west-southwesterly storm (12-14 m s^{-1}) on 19 August, and an ensuing period of moderating winds from the southwest and southeast quadrants. Vector plots of the wind and current runs for the period are shown in Figure 3 (reproduced from Mills *et al.* 1995). As Mills *et al.* (1995) pointed out the currents in Sepia Depression responded primarily to the long-shelf wind component, suggesting that local wind-stress was an important forcing agent for the flows in the nearshore zone encompassing Sepia Depression and the adjacent nearshore embayments of Comet Bay and Warnbro Sound.

The Peel-Harvey Estuary flowed strongly throughout the survey period, at an average rate of about 50 m^3 s^{-1} (Mills *et al.* 1995). Peel-Harvey estuarine outflows had salinities as low as 2.5 pss during ebbs throughout the field survey period (Geoff Bastyan, pers. comm.), suggesting a significant introduction of buoyant water to the local coastal zone. Estimates of typical groundwater flux to Warnbro Sound for winter were obtained from Appleyard (1990) and these estimates indicate that freshwater flux to the coastal zone via groundwater is relatively minor compared to freshwater flows from the estuarine outflows.

Tidal flows in these waters are relatively minor compared to wind-driven and regional currents and estimates for tidal currents in regions not constrained by the bathymetry are of the order of 1 cm s^{-1} (Steedman and Craig, 1979).

4.2 Pre-storm dynamics during weak to moderate winds

STD data collected prior to the storm of 19 August 1991 indicated the transport of coastal waters within and between the nearshore regions of Cockburn Sound, Sepia Depression, Warnbro Sound and Comet Bay. The data are presented in Figures 4 a-f as surface plan contours of salinity structure on days 13 to 18 August, respectively. Density structure reflected that of salinity and therefore the density and temperature structures are not shown here. Solid arrows are inferred flow directions, based on the changing isohaline structure in response to changing wind conditions, and dashed arrows are the measured current directions from mid-depth Sepia Depression (Figure 3) during each day.

Between 13 and 14 August 1991 the wind swung from the southeast to the east (Figure 3). The salinity data from 13 August (Figure 4a) show the low salinity (< 34.5 pss) Peel-Harvey outflow plume region. Figure 4b presents the isohaline (line of constant salinity) structure of 14 August and shows a southward movement of the 34.5 pss isohaline indicating a local change in the position of the north front of the outflow plume. The spatial characteristics of the plume that are shown by the salinity structure in Figure 4b are consistent with the colour Landsat TM satellite image from 14 August, as highlighted in Plate 1a (Mills *et al.* 1995).

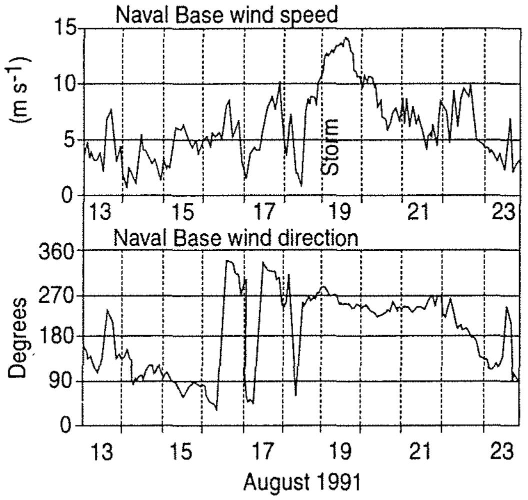

Figure 2. Wind speed and direction time-series plots from the Naval Base station (12 m height) during 13-23 August 1991.

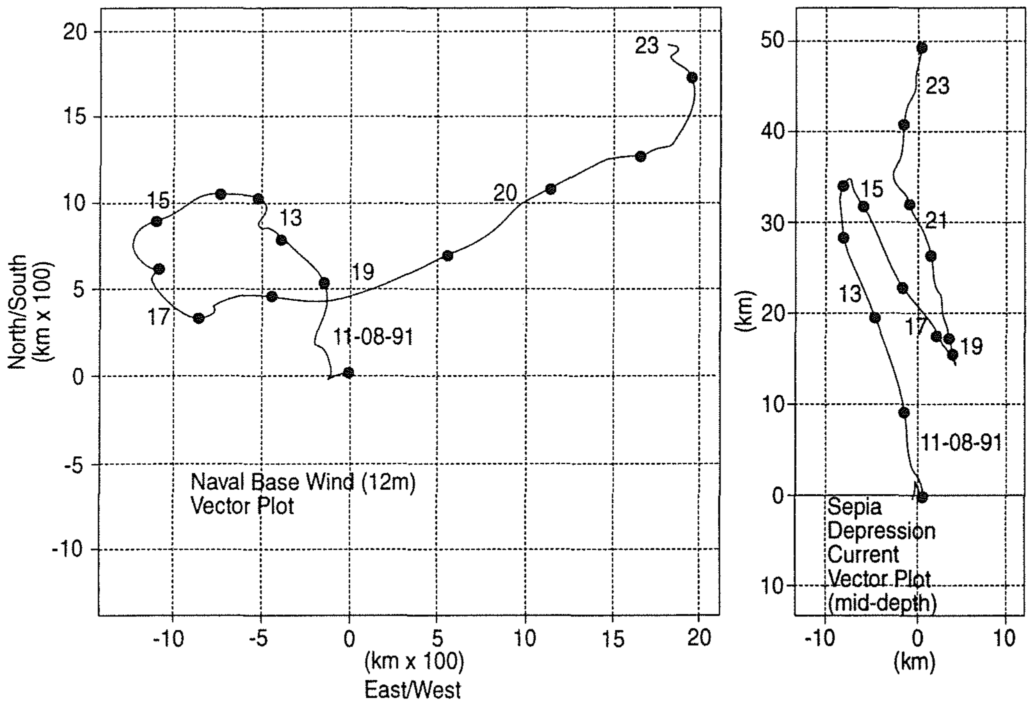

Figure 3. Vector run plots for wind at the Naval Base station (12 m height) and current in Sepia Depression (mid-depth) during 11-23 August 1991.

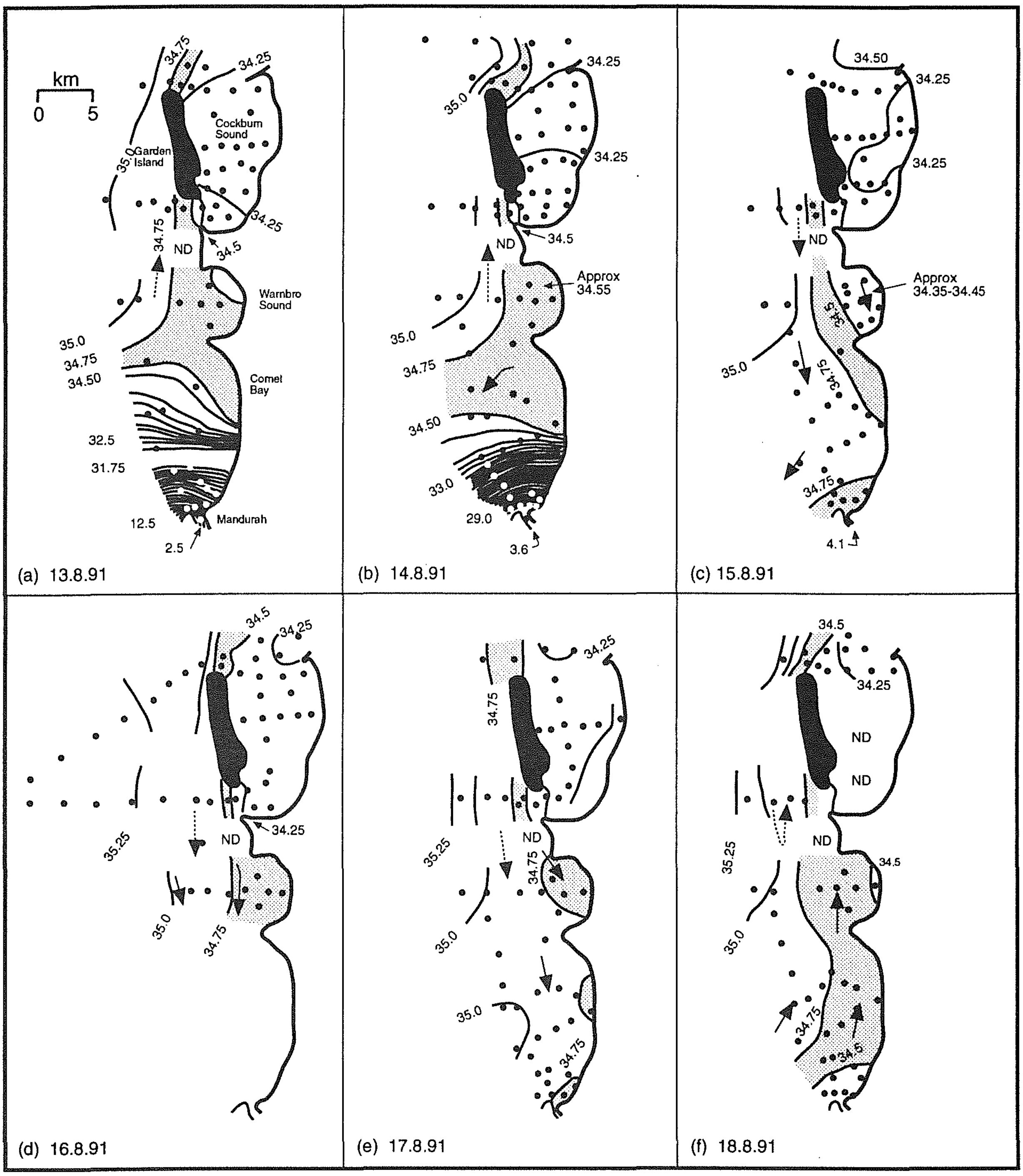

Figure 4. Surface salinity structure between Mandurah and Fremantle from 13 to 18 August 1991. The shaded regions represent water of 34.5-34.75 pss salinity. Diagrams a, b, c, d, e, f, are from 13, 14, 15, 16, 17, 18 August 1991, respectively. Isohaline contours are drawn at intervals of 0.25 pss. Solid arrows are approximate inferred flow patterns and dashed arrows are the approximate mean daily flow direction measured at mid-depth in central Sepia Depression. ND = no data. Dots represent ST or CTD profile sites. Salinities shown in the Mandurah Channel were recorded during ebb tides.

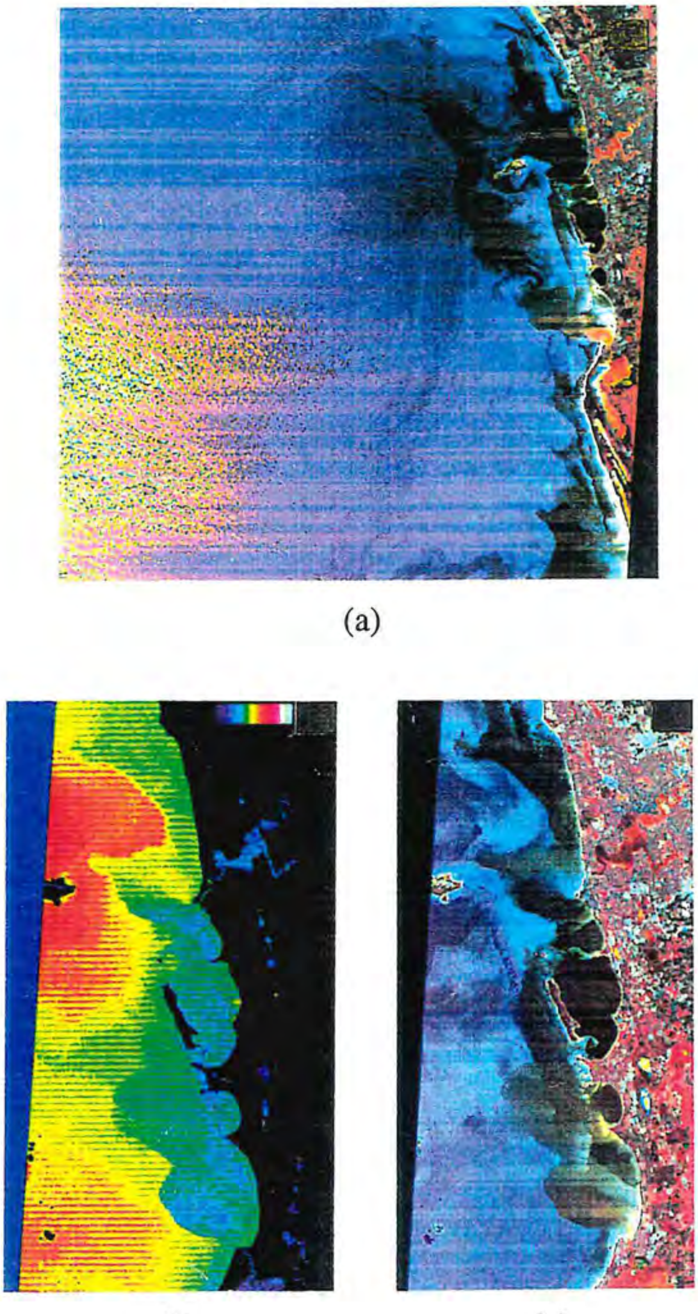

Plate 1. Satellite imagery from Landsat Thematic Mapper: (a) sea colour (visible bands 1, 2 and 3) from 14 August 1991 (0930 hrs) showing darkly stained estuarine plumes (from Mills et al. 1995), (b) pseudo-colour sea-surface temperature (band 6) from 23 August 1991 (0930 hrs) showing colder coastal waters in the plume regions (darker) and warmer Leeuwin Current waters offshore (lighter), (c) sea colour (visible bands 1, 2 and 3) from 23 August 1991 (0930 hrs) showing darkly stained coastal estuarine plumes.

Density contours along Transect A (Figure 1) across Warnbro Sound and Sepia Depression for 13 and 14 August are presented in Figures 5a and b, respectively. Four main features are evident: first, only small changes in the mean density structure occurred, second there was horizontal stratification with lowest densities in Warnbro Sound, third the Sound was vertically stratified, and lastly there was a broad frontal zone in the horizontal density structure through Coasters Channel.

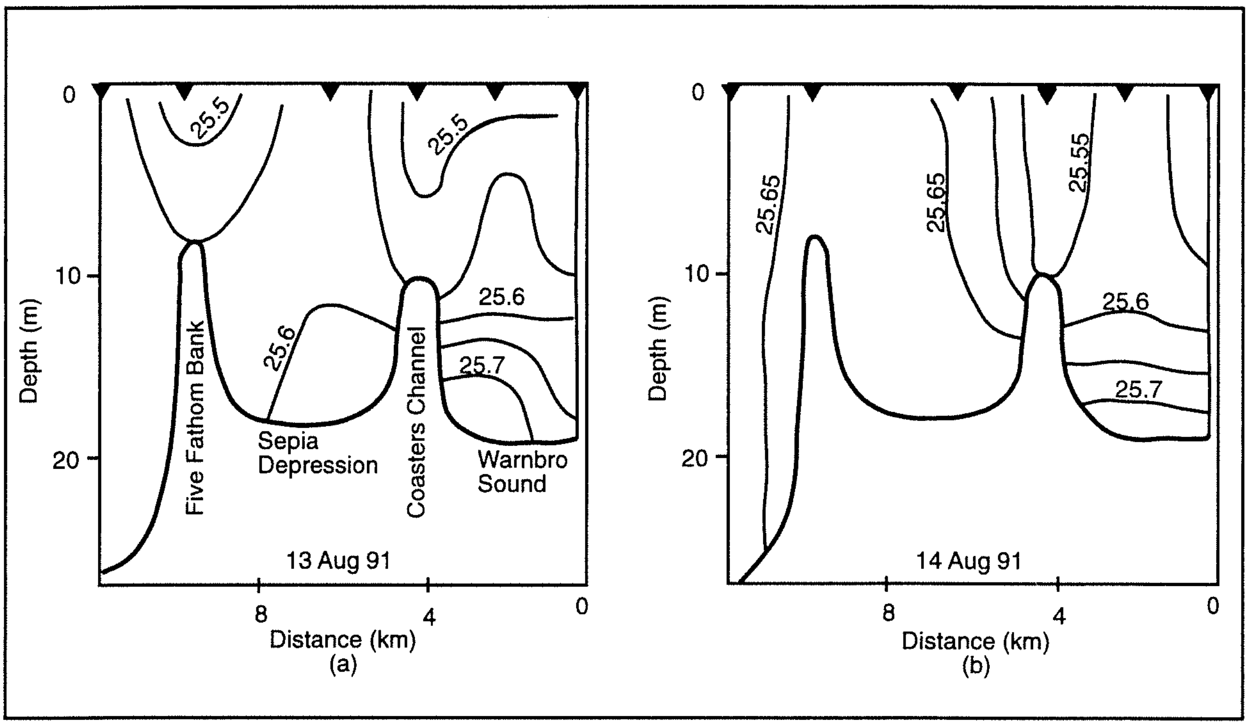

Figure 5. Vertical density structure along Transect A (Warnbro Sound and Sepia Depression) on (a) 13 August 1991 and (b) 14 August 1991. Isopycnal contours are drawn at intervals of 0.05 kg m^{-3}. Profile sites are indicated along the top border of the plots.

On 15 August the wind swung to be from the northeast and the 34.5 pss isohaline of the frontal zone associated with the Peel-Harvey estuarine plume that was present off Comet Bay the day before exited from the study domain (Figure 4c), suggesting a southward advection for the frontal zone of the plume of at least 10 km in the 24 hour period since the previous measurements. Note also the 34.75 pss isohaline that has arrived at the coast in Comet Bay suggesting a strong shoreward advection, from the northwest, into Comet Bay.

The mean surface salinities within Warnbro Sound decreased markedly from about 34.55 to about 34.35-34.45 pss between 14 and 15 August, as seen by comparing Figures 4b and c. The vertical salinity structure along Transect A during 15 August is presented in Figure 6 and shows that there was a significant upper layer of low salinity water in Warnbro Sound and that it was biased towards the eastern shoreline of the Sound. Note also in Figure 4c the presence of low salinity water (< 34.5 pss) in the vicinity of the causeway and within the adjacent southern region of Cockburn Sound. In combination, the temporal change in the surface salinity contours between Warnbro Sound and Cockburn Sound (Figures 4b and c) and the vertical salinity structure within Warnbro Sound (Figure 6) suggests that the east-northeasterly winds led to the southward advection of relatively low salinity water from southern Cockburn Sound into Warnbro Sound via the Sepia Depression region off Shoalwater Bay. The influence of the Earth's rotation would have been to steer the wind-driven flow to the left of the wind vector direction thereby facilitating the southward long-shore advection. This is consistent with a

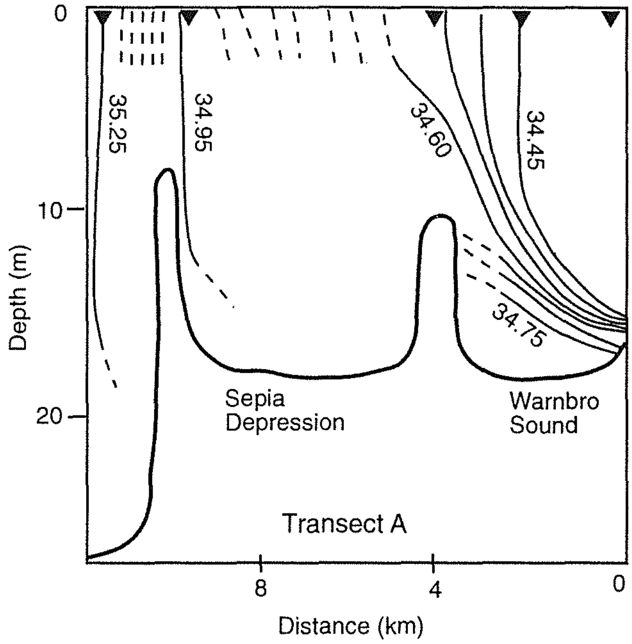

Figure 6. Vertical salinity structure along Transect A (Warnbro Sound and Sepia Depression) on 15 August 1991. Isohaline contours are drawn at intervals of 0.05 pss. Profile sites are indicated along the top border of the plots.

calculation of the Rossby radius of deformation that results in typical values of less than 5 km (see Mills *et al.* 1995).

It is interesting to note here that the primary source of low salinity water in Cockburn Sound during winter is the Swan-Canning Estuary (D'Adamo, 1992; D'Adamo *et al.* 1995). Winds from the northwest quadrant drive Swan-Canning estuarine outflow plumes into Cockburn Sound. These plumes are then distributed and mixed within the sound predominantly by wind mixing and penetrative convection (D'Adamo *et al.* 1995). Hence, it can be inferred that a hydrodynamic connection between the low salinity waters of Cockburn Sound and the Warnbro Sound embayment represents a connection between some component of Swan-Canning estuarine outflow plumes and Warnbro Sound.

The resulting basin-wide structure in Warnbro Sound on 15 August was characterised by relatively strong vertical and horizontal salinity gradients (Figures 4c and 6), suggesting that the inflows occurred as buoyant surface flows.

By 16 August the wind was onshore from the northwest. The return to higher salinities in Warnbro Sound (Figure 4d) suggests that the basin water from 15 August was expelled in one day by a continuing southward coastal advection. No data were collected south of Warnbro Sound on 16 August and so the fate of the expelled water could not be tracked. On the basis of the surface isohaline structure the source of the newly arrived higher salinity water in Warnbro Sound appears to be from Sepia Depression in the region off Shoalwater Bay. On 17 August the wind was from the northwest and the isohaline structure (Figure 4e) and flows (inferred and measured) resemble those of 16 August suggesting a continuing southward advection.

By 18 August the wind was from the west-southwest and the following observations were made (Figure 4f): the recorded Sepia Depression flow returned to be northward, the 35.0 and 34.75 pss isohalines moved offshore, nearshore salinities were lowered and the isohalines suggest a northward coastal flow of buoyant water into the Comet Bay and Warnbro Sound regions from south of Mandurah.

In summary, the pre-storm STD and current meter data suggest significant long-shore displacements of large patches of coastal water in response to a changing wind field. Tracking of isohalines suggests that under weak to moderate south-southwesterly winds in winter (of order 5-8 m s^{-1}) water can be advected into Warnbro Sound from the Mandurah to Comet Bay coastal zone, or under moderate northeasterly to northwesterly winds water can be advected into Warnbro Sound from the region between the southern entrance of Cockburn Sound and Sepia Depression (off Shoalwater Bay) in times of order one day. In summary, the data thus far presented show that the waters within the coastal zone between Fremantle and Mandurah had a significant degree of hydrodynamic communication. Furthermore, buoyant coastal flows were found to lead to vertical stratification in the coastal basins

4.3 Storm mixing

The storm of 19 August led to the pronounced mixing of the stratification in Warnbro Sound. The density contours in Figure 7 are from data collected on 20 August along Transect A through Warnbro Sound and Sepia Depression and show vertical and horizontal density differences of about 0.05 kg m^{-3} or less in these respective regions. The structure is weak compared to before the storm (see Figure 5). The vertical mixing due to wind stress can be estimated on the basis of a one-dimensional model of mixing (as reasoned by D'Adamo *et al.* (1995) for Cockburn Sound for the storm of 19 August 1991), which is based on a vertical integration of the turbulent kinetic energy equations (Spigel, Imberger and Rayner, 1986; Pollard, Rhines and Thompson, 1973; Imberger, 1994). For the case of two well-mixed layers of different density, the rate of deepening is estimated by

$$h(t) = [C_S/(g_o'h_i)]^{0.5}u_*^2t \qquad (1)$$

where $C_S = 0.24$ is a constant that determines the efficiency of energy conversion (Imberger and Patterson, 1990), t is the time since the onset of mixing, $g_o' = \Delta\rho_W . g/\rho_W$ is the effective acceleration due to gravity at the commencement of mixing, $\Delta\rho_W$ is the density difference between the upper and lower layers, g is the acceleration due to gravity (= 9.81 m s^{-2}), ρ_W is the average water density, H is the water depth, h_i the initial depth of the mixed layer, and u_* is the wind shear velocity given by

$$u_* = [(C_D\rho_A/\rho_W)^{0.5}]U \qquad (2)$$

where C_D is a drag coefficient equal to 0.0013 (Fischer *et al.* 1979), ρ_A is the density of air equal to 1.2 kg m^{-3}, U is the wind speed at 10 m height. This mixing law is for shear-dominated mixing due to locally parallel flow at the interface between the upper and lower layers, and is assumed applicable in this case for the duration and strength of the storm winds that occurred on 19 August. The pre-storm vertical density structure that was assumed for the commencement of wind mixing is shown in Figure 8, and this was based on the vertical stratification measured on 18 August 1991. Two homogeneous layers separated by a density difference of 0.2 kg m^{-3} are assumed, with the upper layer starting as 7 m thick. By applying Equation 1 to this case it is estimated that mixing to the bottom of the Warnbro Sound basin would have occurred in 4 hours during winds of 13 m s^{-1}. There are no measurements of the temporal change in the vertical density stratification during the period of the storm on 19 August, however on the basis of the field data before and after the storm and the vertical mixing estimates using Equation 1, it is suggested that the weakly stratified nature of Warnbro Sound after the storm was due to complete vertical mixing by the winds of 13-15 m s^{-1} that occurred on 19 August.

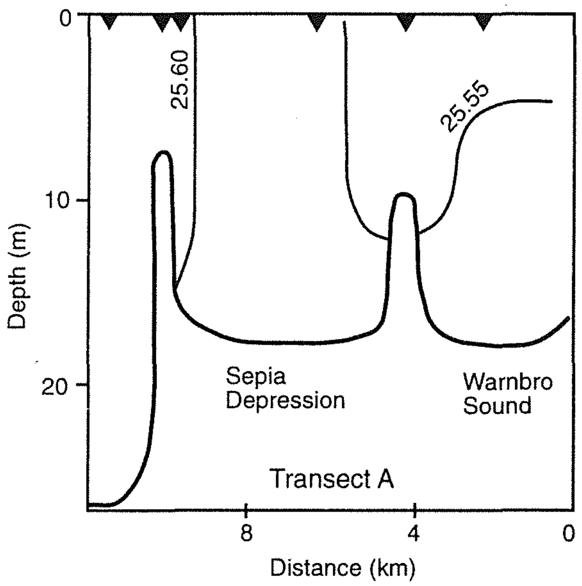

Figure 7. Vertical density structure along Transect A (Warnbro Sound and Sepia Depression) on 20 August 1991. Isopycnal contours are drawn at intervals of 0.05 kg m^{-3}. Profile sites are indicated along the top border of the plots.

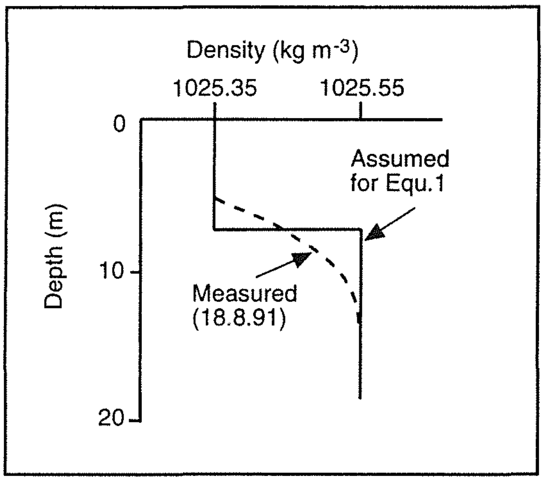

Figure 8. The measured vertical density structure from the eastern end of Transect A in Warnbro Sound on 18 August 1991, and the assumed two-layer structure for the vertical mixing analysis using Equation 1.

4.4 Post-storm restratification due to buoyancy flux from the Peel-Harvey Estuary outflow

Following the storm, the winds blew predominantly from the southwest quadrant, hence having a slightly onshore orientation. Stratification data collected between Mandurah and Cockburn Sound are presented in this section to demonstrate the northward transport of the Peel-Harvey estuarine plume and the potential of the plume to enter the nearshore basins of Comet Bay and Warnbro Sound.

The horizontal surface salinity stratification fields between Mandurah and Fremantle for 20, 21 and 22 August 1991 are presented in the contour plots of Figures 9a, b and c, respectively. Salinity controlled density within the plume, with temperature having a minimal influence on the mean density structure.

On 20 August the Peel-Harvey outflow plume was present as a nearshore feature within Comet Bay although it had not yet reached Warnbro Sound (Figure 9a). Note the low salinity of 13 pss recorded in the Mandurah Channel during the ebb tide at 0900 hours on 20 August 1991 (G Bastyan, pers. comm.). This suggests that the source of the low salinity water in Comet Bay was the Peel-Harvey Estuary. The complementary vertical salinity-density structure of the plume across Comet Bay on 20 August is presented in Figures 10a and b, showing the respective salinity and density contours along Transect B. The buoyant structure and frontal shape is clearly evident. A sharp density gradient zone separates it from the more saline ambient waters. The onshore wind stress component at that time was sufficiently strong to maintain the plume as a nearshore feature.

The ensuing northward progression of this plume is shown by the horizontal plan contours of surface salinity in Figures 9b and c from data collected on 21 and 22 August, respectively. The arrival of the plume into Warnbro Sound on 21 August is clearly evident with the minimum surface salinity in the Sound having been lowered from about 34.65 to 34.0 pss. The further lowering of salinities to 33.8 pss in Warnbro Sound on 22 August (Figure 9c) suggests a continuing northward coastal flow and influx into Warnbro Sound of the Peel-Harvey outflow plume.

The plume's vertical structure on 22 August along transects A and B is presented in Figures 11a and b, respectively, showing the salinity stratification. The buoyant frontal nature of this plume in Comet Bay is again clearly evident. Within Warnbro Sound on 22 August the upper half of the water column was less than 34 pss in salinity, and this is significantly lower than the minimum salinity of approximately 34.6-34.7 pss recorded in Warnbro Sound and adjacent waters on 20 August (Figure 9a). This suggests the introduction of plume water into Warnbro Sound via an alongshore advection through Comet Bay driven by wind-stress during the 5-10 m s^{-1} southwest winds of 20-22 August 1991. On the basis of the elapsed time between the cessation of the storm mixing of 19 August and the first identification of the plume in Warnbro Sound, we estimate a propagation rate of about 25 km in 1-2 days or a mean speed for the buoyant plume of order 0.15-0.30 m s^{-1}. The lower speed in this range compares well with mid-depth currents recorded in Sepia Depression during that period (Mills *et al.* 1995).

Further evidence of the spatial extent of the influence of the Peel-Harvey outflow during the post-storm period is given by the sea-surface temperature and water colour Landsat Thematic Mapper images of 23 August 1993 (approx 0930 hours), presented in Plates 1b and c, respectively. The images show the clear frontal zone between the Leeuwin Current (Pearce and Walker, 1991), shown as the warmest water offshore, and the colder nearshore Peel-Harvey plume water. The south-southwesterly winds that blew between 20 and 22 August were followed by a mild southeasterly wind (of order 3-5 m s^{-1}) during the night of 22/23 August and the influence of the offshore wind is reflected in the northwestward orientation of the

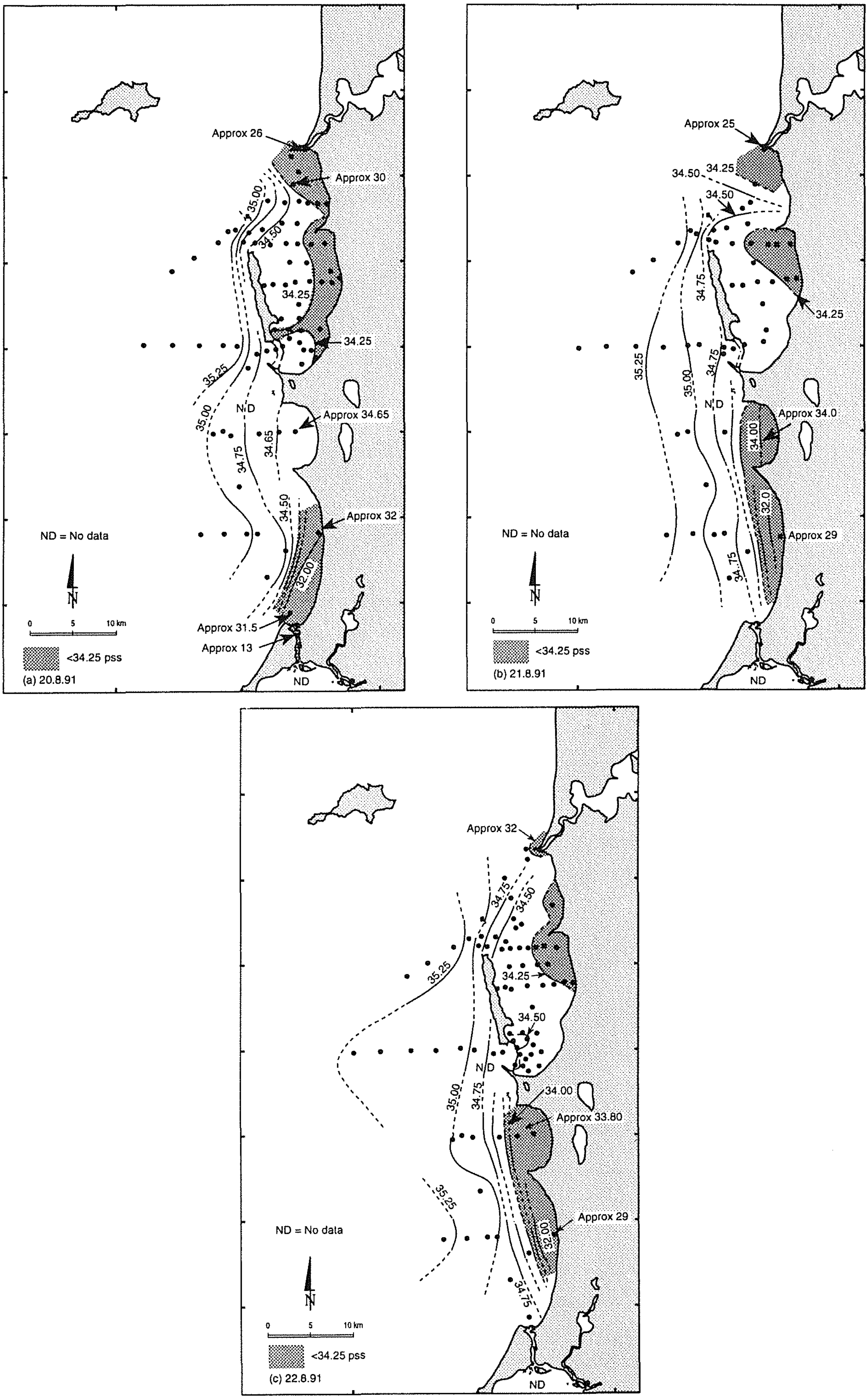

Figure 9. Surface salinity structure between Mandurah and Fremantle from 20 to 22 August 1991. Diagrams a, b, c, are from 20, 21, 22 August 1991, respectively. Isohaline contours are drawn at intervals of 0.25 pss, except where shown. Shaded regions represent water of salinity less than 34.25 pss salinity. Dots represent ST or CTD profile sites.

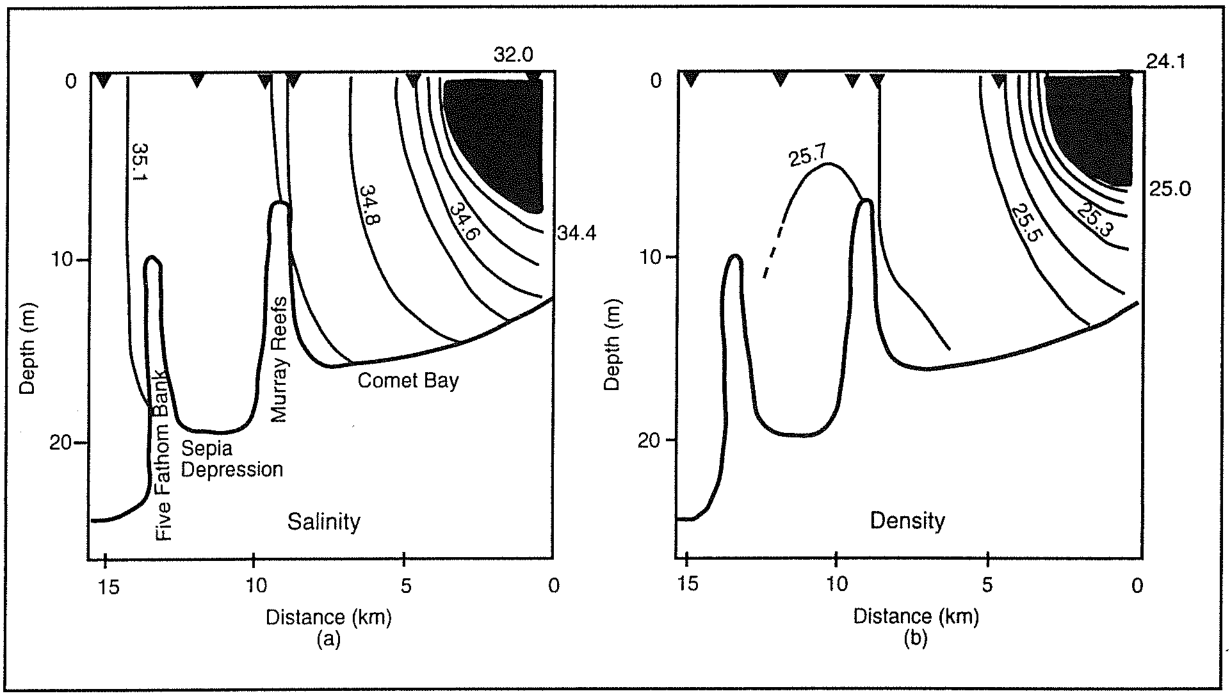

Figure 10. Vertical salinity (a) and density (b) structure along Transect B (Comet Bay and Sepia Depression) on 20 August 1991. Isohaline and isopycnal contours are drawn at intervals of 0.1 pss and 0.1 kg m^{-3}, respectively. Relatively intense salinity or density gradient zones are darkened on the plots. Profile sites are indicated along the top border of the plots.

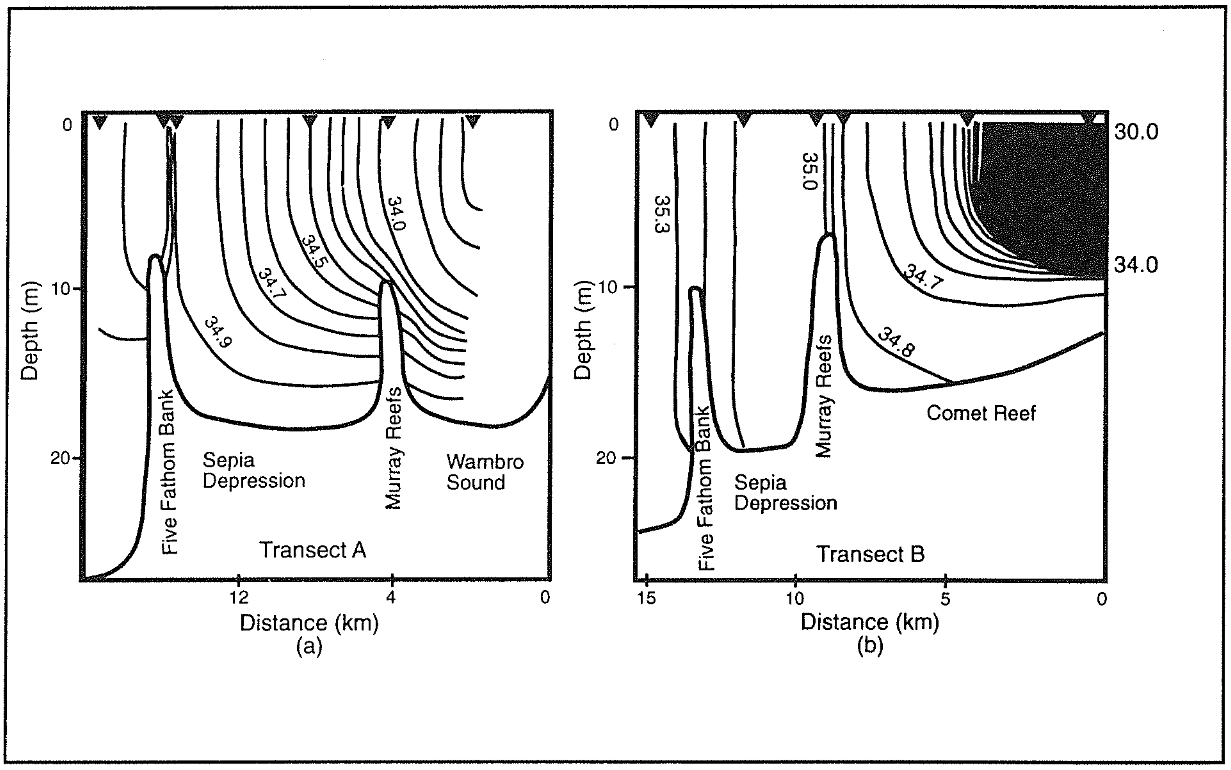

Figure 11. Vertical salinity structure along Transect A (a) and Transect B (b) on 22 August 1991. Isohaline contours are drawn at intervals of 0.1 pss. The relatively intense salinity gradient zone is darkened on the plots. Profile sites are indicated along the top border of the plots.

patches of coloured plume water west of Sepia Depression. The coloured plume water is also clearly evident within Comet Bay, Warnbro Sound and the adjacent Sepia Depression. The presence of the coloured water northwards in Sepia Depression near Carnac Island suggests that the Peel-Harvey outflow was driven northwards within Sepia Depression at rate of about 0.15m s^{-1} between 20 and 23 August, and this is in agreement with the flow speeds recorded during the post-storm period by the Sepia Depression current meter (Mills *et al.* 1995).

5. Discussion

The long-shore transport of Peel-Harvey estuarine outflow water into Comet Bay and the Shoalwater Islands Marine Park during a typical 10-day winter wind cycle in 1991 has been identified. The Peel-Harvey estuarine system exports significant loadings of phosphorus and nitrogen to the nearshore marine waters. The stratification data collected during 13-23 August 1991 indicate a transport mechanism for the flux of buoyant outflow waters from the estuary via the Mandurah Channel to Warnbro Sound. Contemporaneous nutrient data show elevated (above ambient) nutrient concentrations within the low salinity plume region (Cary *et al.* 1995). The conditions that led to the flow of Peel-Harvey estuarine water into Warnbro Sound during the post-storm period were winds of order 7.5 m s^{-1} or stronger, blowing for approximately one day or longer from the southwest quadrant. The wind data in Figure 12 shows that throughout the winter-spring runoff period from June to December 1991 there were an average of about three occurrences per month when outflows from the Peel-Harvey Estuary could have been advected into Warnbro Sound by relatively strong winds from the southwest quadrant. Biological evidence that Peel-Harvey Estuary outflow water can enter Warnbro Sound were the recordings of significant amounts of the nuisance blue-green alga *Nodularia spumigena* in Warnbro Sound during November 1992 (Helleren and John, 1995). Large blooms of this non-marine planktonic alga commonly occur in the Peel-Harvey Estuary during spring and summer (Hodgkin *et al.* 1985).

The Princeton Ocean Model (POM) was used (Mills and D'Adamo, 1995a) to simulate the transport of buoyant Peel-Harvey Estuary outflow for flow and wind conditions that prevailed during the field survey. A net constant flux of 60 m^3 s^{-1} of fresh water was introduced adjacent to the Mandurah Channel entrance and the model was forced by a 7.5 m s^{-1} southwesterly wind. The output from that simulation produced the surface salinity fields shown in Figure 13. The model predicted that the outflow plume would have been driven northwards as a coastal long-shore flow and into the Warnbro Sound basin within 1.5 days since the start of the wind, and this is in general agreement with the field data (Figure 9).

The field survey has also detailed an event where relatively buoyant water from the Cockburn Sound southern entrance and off Shoalwater Bay was transported into the region of the Shoalwater Islands Marine Park. Winds of order 5-10 m s^{-1} or stronger, blowing for approximately one day or longer from the northeast and northwest quadrants led to this southward transport. A hydrodynamic connection between Cockburn Sound and the waters of the marine park, including Warnbro Sound, was also shown by the results of regional aerial photography from 1970 (Environmental Resources of Australia, 1970) that identified southward flowing plumes of Swan River water coloured brown by the estuarine diatom *Melosira Sp.* The primary source of low salinity water in Cockburn Sound during winter is via the southward transport of Swan-Canning Estuary plumes, under the forcing of winds from the northwest quadrant (D'Adamo, 1992; D'Adamo *et al.* 1995). The wind data in Figure 12 shows that throughout the winter-spring runoff period from June to October 1991 there were an average of about four occurrences per month when significant southward flows could have been caused within the marine park waters by relatively strong winds from the northwest quadrant.

The POM was also used to simulate the transport of low salinity water from the southern entrance of Cockburn Sound forced by east-northeasterly winds, as occurred during 14-15 August. The wind data from Naval Base (Figure 3) was used (13 to 15 August 1991) and the

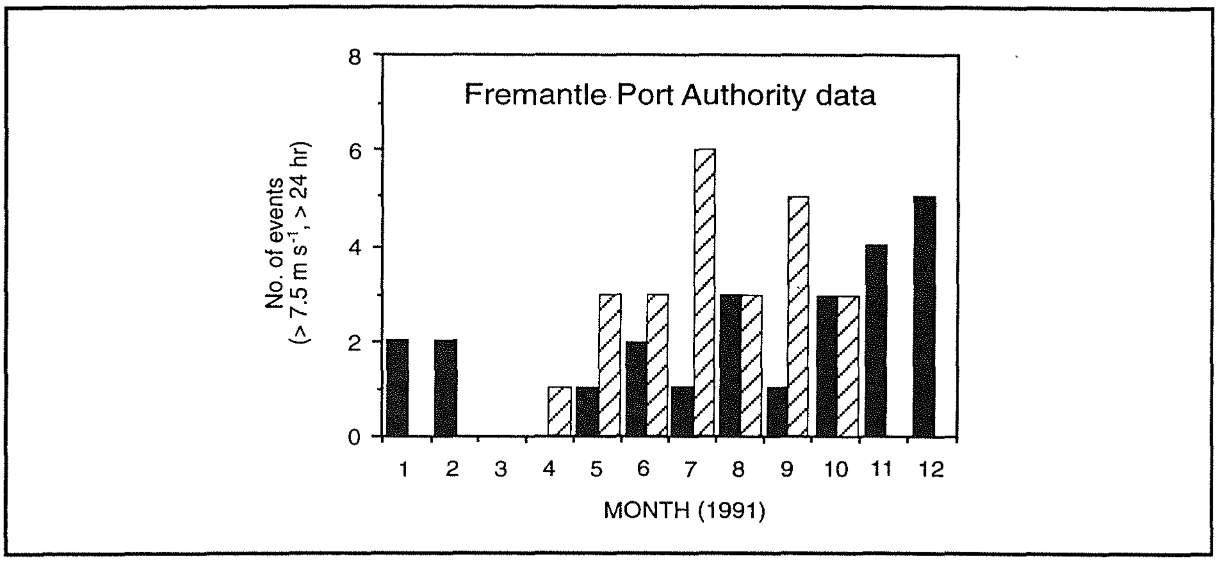

Figure 12. Number of occurrences, during the months of 1991, of wind events with speeds greater than about 7.5 m s^{-1} and durations longer than 24 hours. Solid bars are data for wind events from the southwest quadrant and hatched bars are data for wind events from the northwest quadrant.

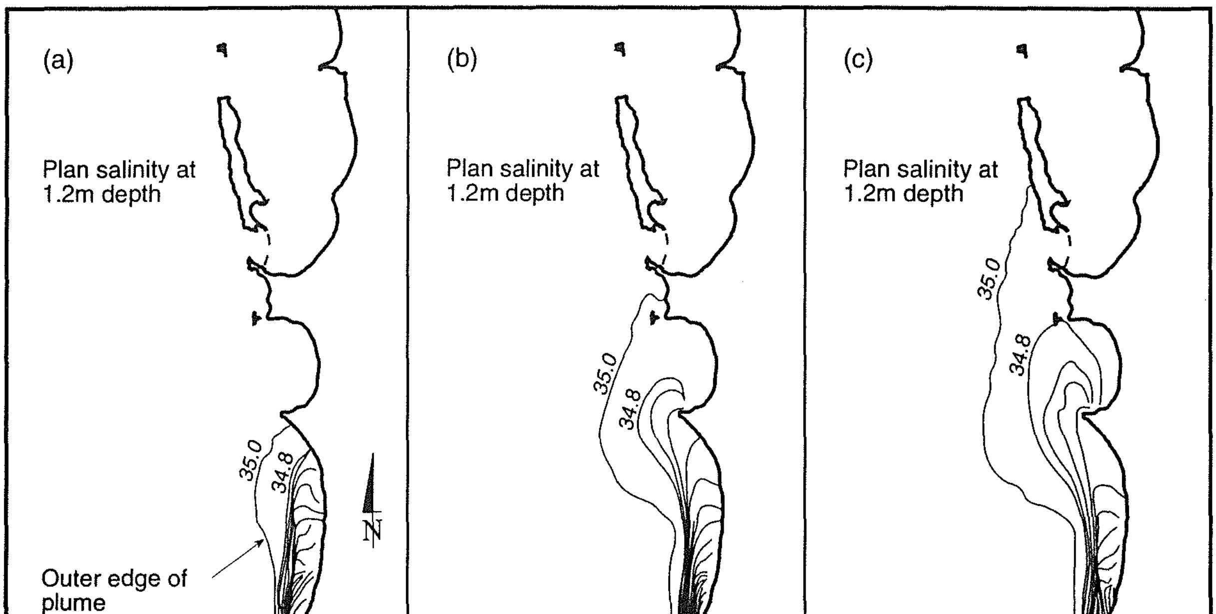

Figure 13. Baroclinic numerical hydrodynamic model simulation of the transport of the Peel-Harvey Estuary plume forced by a constant 7.5 m s^{-1} SW wind (from Mills and D'Adamo, 1995a). A flux of 60 m^3 s^{-1} of 1 pss water was released adjacent to the Mandurah Channel mouth. The ocean salinity was set at 35 pss. Diagrams a, b and c are the predicted near-surface (1.2 m) salinity fields at 0.5, 1.0 and 1.5 days since the beginning of the wind, respectively. The contour plot interval is 0.2 pss.