Seasonal variation in the physical structure of the coastal zone off Perth, Western Australia — implications for exchange between the nearshore embayments and mid-shelf waters

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Seasonal variation in the physical structure of the coastal zone off Perth, Western Australia — implications for exchange between the nearshore embayments and mid-shelf waters

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Acknowledgments

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Abstract

Between 1991 and 1994 repeated salinity and temperature surveys were conducted in the marine waters off the coast of Perth, Western Australia. These data were used to determine the annual cycles in salinity, temperature and density differences between Cockburn Sound, a semi-enclosed nearshore basin, and the more exposed, open mid-shelf waters. The basin-shelf density difference cycle was found to be an important factor determining the seasonal influence of density effects on the circulation and exchange of Cockburn Sound. Particular phases of the annual density difference cycle were found to be associated with distinctive regimes of circulation and exchange, named the 'autumn', 'winter-spring' and 'summer' regimes. The 'autumn' regime, which begins in autumn and extends into early winter, occurs when basin waters are relatively dense, due firstly to high salinities caused by evaporation over summer and autumn, and secondly to differential cooling from late autumn to early winter. The 'winter-spring' regime, from about mid-winter to spring, occurs when basin waters are relatively buoyant in comparison to offshore waters due at first to the introduction of buoyant estuarine plumes from the Swan-Canning Estuary and then due to spring warming of nearshore waters. The 'summer' regime, during late spring to early autumn, occurs when there is a small cross-shelf density difference because the nearshore zone gradually increases in salinity due to evaporation while at the same time it gradually warms due to increasing solar radiation.

The results of mixing analyses from complementary oceanographical studies conducted as part of the Southern Metropolitan Coastal Waters Study suggest that full-depth vertical mixing in Cockburn Sound, due primarily to wind stress and penetrative convection, can be expected at least 10-15 times per month in the 'summer' regime, and this is in contrast to about 4-6 times per month in the 'autumn' and 'winter-spring' regimes. In 'summer' strong winds occur regularly, basin-shelf density differences are small and vertical gradients are regularly eliminated by mixing. Under these conditions circulation and exchange is essentially wind-driven and barotropic. In 'autumn', the winds are generally weaker. The few full-depth mixing events that do occur as a result of strong sea-breezes or storms in 'autumn' are followed by significant periods of moderate to weak winds during which near-surface waters in the basin are renewed by relatively buoyant shelf waters that are driven in as surface flows. In 'winter-spring', the wind field remains weak except for 1-2 days of each 7-10 day synoptic cycle when strong storms occur and fully mix the basin. These storm events are typically followed by the renewal of deep basin waters by plunging inflows of surrounding denser shelf water. These dense inflows form a distinct lower layer and displace upward more buoyant water which had been mixed down to the sea bed during the preceding storm event. The displaced water, as part of the diurnal mixed layer, is subject to regular vertical mixing by moderate wind-stress and penetrative convection. It therefore can be transported out of the Sound, principally by wind-driven exchange.

The importance of density effects for much of the year indicates that three-dimensional, baroclinic numerical models are generally required to simulate hydrodynamic transport in Cockburn Sound. However, barotropic models may suffice when the basin is predominantly well-mixed and being forced by strong winds (of order 10 m s^{-1} or more), such as during storms and periods of regular sea-breezes.

1. Introduction

This paper reports on one of a series of oceanographic investigations for the Southern Metropolitan Coastal Waters Study *1991-1994* (SMCWS). The SMCWS was undertaken by the Department of Environmental Protection of Western Australia in order to provide a better technical basis for managing the cumulative environmental impacts of contaminants entering the coastal waters off Perth, Western Australia (Figures 1 and 2) (Simpson *et al.* 1993a).

This study focuses on the seasonal characteristics of horizontal and vertical density gradients in the region and on the seasonal variation in the energetics responsible for vertical mixing and horizontal exchange. It also summarises the key aspects of the other complementary oceanographic studies of the SMCWS which investigated shorter time scale processes, from diurnal to synoptic scales, for winter (D'Adamo *et al.* 1995a and b; Mills *et al.* 1995), summer (D'Adamo and Mills, 1995a) and autumn (D'Adamo and Mills, 1995b).

Cross-shelf measurements of the physical water structure were conducted from 1991 to 1994 to describe the annual cycle in the salinity, temperature and density stratification of the nearshore and mid-shelf waters. The influences of differential heating and cooling, evaporation, river flow, wind-stress and regional currents on the vertical and horizontal stratification of these waters were examined. The work furthers the understanding of the hydrodynamics of Cockburn Sound and adjacent waters acquired during earlier field, numerical modelling and analytical studies of the 1960's to 1980's (Maritime Works Branch, 1977a and b; Department of Conservation and Environment, 1979; Steedman and Craig, 1979 and 1983).

An important issue related to the ecology of these coastal waters is that of the transport and biological conversion of nutrients that enter the coastal zone via point discharges, rivers and groundwater flux. Hence, the characterisation and numerical modelling of key hydrodynamic transport and mixing processes are intrinsic inputs to the ecological work (Simpson *et al.* 1993a), and the results presented here provide guidance for the choice of appropriate numerical models for the simulation of the hydrodynamics (Mills and D'Adamo, 1995a, b, c and d).

Numerical modelling efforts in the late 1970's to early 1980's (Maritime Works Branch, 1977a and b; Steedman and Craig, 1983) simulated the hydrodynamic behaviour of Cockburn Sound and adjacent waters with two-dimensional (vertically averaged) barotropic models, forced by winds and external currents. These models did not account for the influence of density effects on the hydrodynamics. Steedman and Craig (1979) suggested that barotropic modelling was likely to be inappropriate for wind speeds less than about 5 m s^{-1} due to the influence of density stratification on the hydrodynamics of Cockburn Sound. Reviews of hydrodynamic data and studies from the period 1969 to 1991 are given in Hearn (1991) and D'Adamo (1992) and these have confirmed the importance of the local wind field in driving mixing and transport. Additionally, these reviews suggested that vertical and horizontal density gradients are a common trait of the water structure throughout the year and that the stratification significantly influences the overall hydrodynamic behaviour at wind speeds less than 10 m s^{-1}.

D'Adamo (1992) suggested that vertical density gradients in the nearshore basins precluded full-depth vertical mixing for a significant percentage of time during the year. He also suggested that density effects could have an important influence on transport within and between the nearshore basins. Both Hearn (1991) and D'Adamo (1992) recommended that further field and modelling work be carried out to determine the importance of density-effects and the relative influence of other physical forcings (regional currents, wind stress, atmospheric heating and cooling) to the mixing and transport characteristics of the site throughout the year.

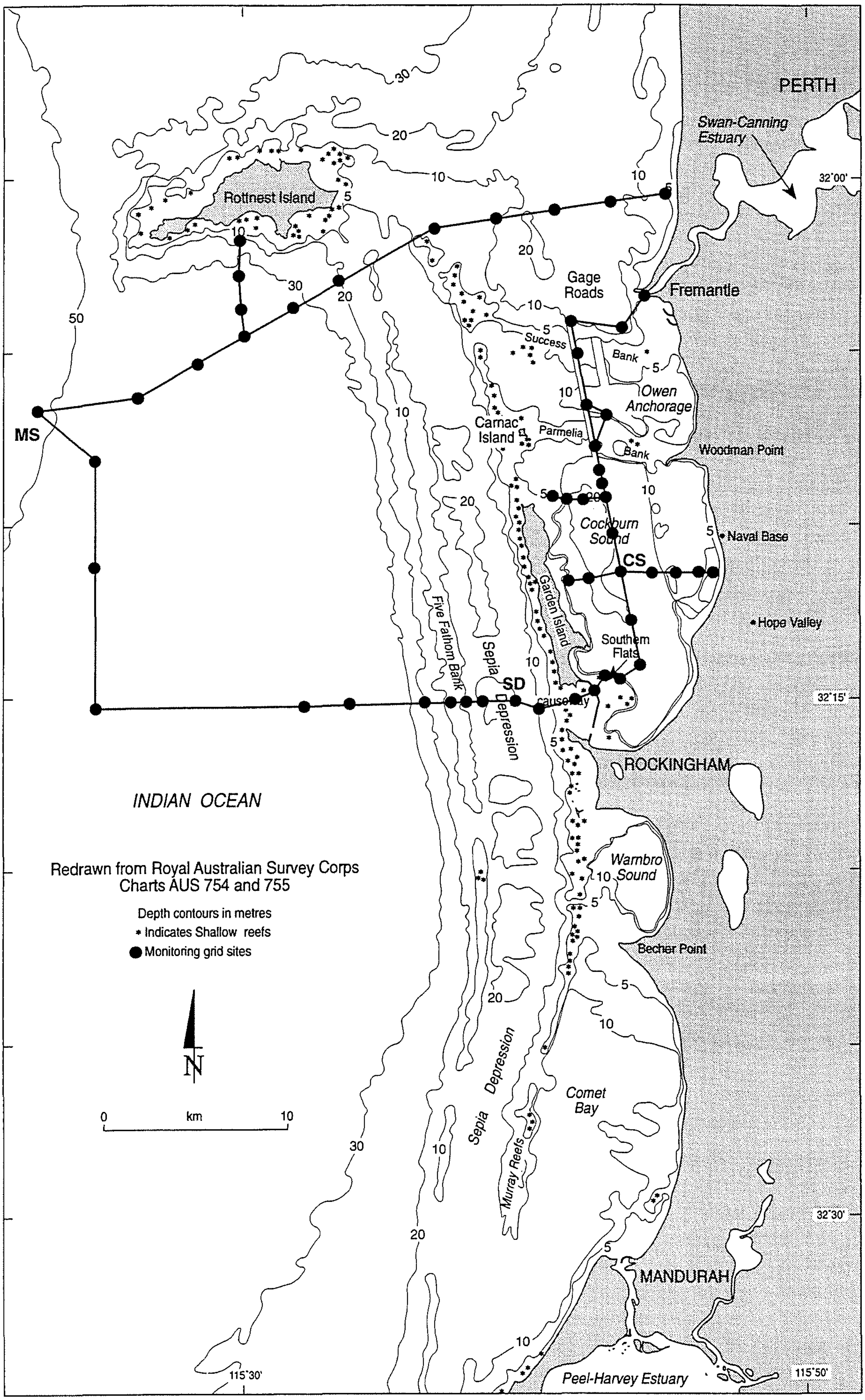


Figure 1. Study region of the Southern Metropolitan Coastal Waters Study and transect paths for the seasonal oceanographic surveys.

Figure 2. Three-dimensional perspective plot of the bathymetry of Perth's coastal zone from Hillarys to Tim's Thicket and out to west of Rottnest Island. (Source: Western Australian Department of Transport.)

Following from these recommendations a series of salinity-temperature surveys was conducted, detailing the vertical and horizontal stratification of the nearshore and shelf areas throughout the year. These data were used to assess the relative roles of barotropic processes and density effects on mixing and transport.

2. Study area

Bathymetry

The nearshore zone consists of an inter-connected series of semi-enclosed embayments, basins and channels of 15-20 m depth between the coast and 20 km offshore. Further west is a gently sloping mid-shelf area which reaches 50 m depth at about 40 km offshore, beyond Rottnest Island (Figures 1 and 2).

Cockburn Sound and Owen Anchorage are separated by Parmelia Bank (of depth less than about 5 m) which has a shipping channel 15 m deep cutting through it. The channel continues north through Success Bank and opens out into Gage Roads, west of Fremantle. Challenger Passage lies between Garden Island and Carnac Island and forms a major hydraulic link between Cockburn Sound and Sepia Depression. Cockburn Sound has overall dimensions of approximately 15 km by 8 km and a central basin with a maximum depth of about 21 m. Along the eastern margin of the Sound is a 3 km wide shelf of less than 10 m depth. The northern opening of Cockburn Sound has a cross-sectional area of about 2×10^4 m^2 and its southern opening, partially blocked by a solid rock-fill causeway, has a total cross-sectional area under its two bridges of about 4×10^3 m^2. A line of reefs and islands runs parallel to the coast between the embayments and the 20 m deep Sepia Depression. Another shore-parallel reef line called Five Fathom Bank (approximately 5-15 m deep) separates Sepia Depression from the mid-shelf zone.

Climate

The southwest of Australia has a 'mediterranean' climate characterised by hot dry summers and cool wet winters (Australian Bureau of Statistics, 1989). The synoptic-scale weather patterns of the region are controlled by the migration of the anticyclonic belt from about 40 °S in January to 30 °S in July. Thus, in summer, southwest Australia lies in the tropical low pressure region and in winter it is within the high pressure belt. This belt rotates eastward around the globe and results in synoptic variations in the barometric pressure field at periods of about 7-10 days, with synoptic weather patterns broadly reflecting this periodicity.

From about October to March stable anticyclonic pressure cells produce a predominantly easterly airflow over southwest Australia. From June to September the anticyclonic pressure systems and accompanying westerly winds (the roaring forties) are periodically displaced by low pressure cyclonic systems that move rapidly eastwards bringing strong winds (~ 20 $m\ s^{-1}$) and rain. Through much of the year local diurnal heating and cooling along the coastline results in a land-sea breeze cycle which is superimposed on the regional pattern, particularly in summer. Wind speeds in the Perth region are generally between about 5 and 15 $m\ s^{-1}$. South-southwesterly onshore sea-breeze winds occur on over 250 days each year although the strongest sea-breezes (10-15 $m\ s^{-1}$) occur mainly during the mid-spring to summer period (Hearn, 1983). Apart from during storms (> 10 $m\ s^{-1}$), the wind field becomes weaker and more variable throughout autumn and winter. The annual characteristics of the wind at Fremantle and Naval Base, in close proximity to our study site, are presented by the data in Figures 3 and 4, respectively.

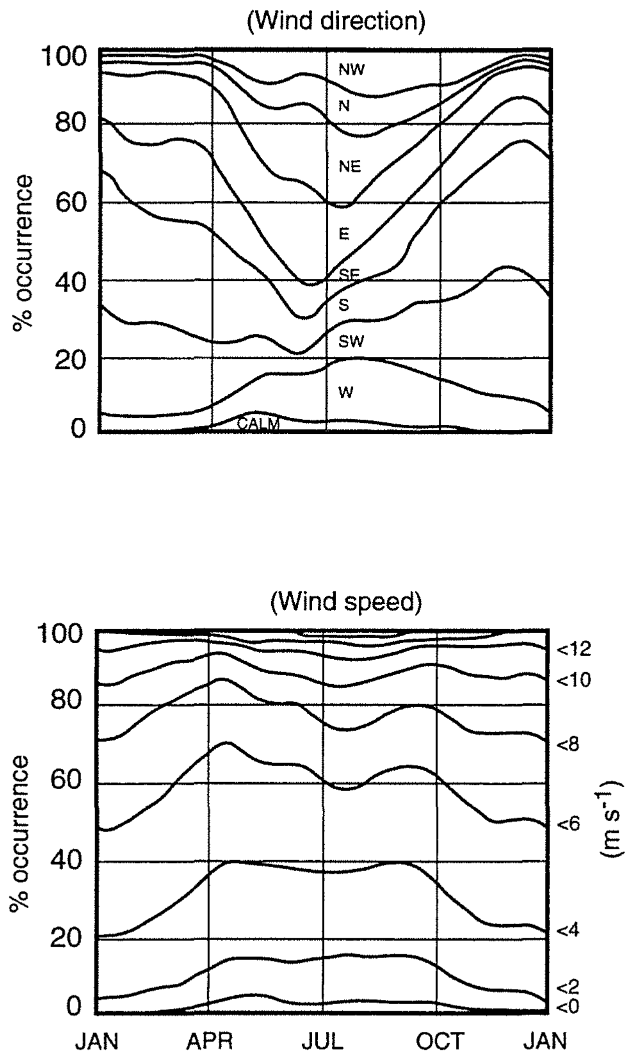


Figure 3. Daily percentage occurrence of wind speeds and directions at Fremantle, based on hourly data from 1971 to 1979. Re-drawn from Steedman and Craig (1979).

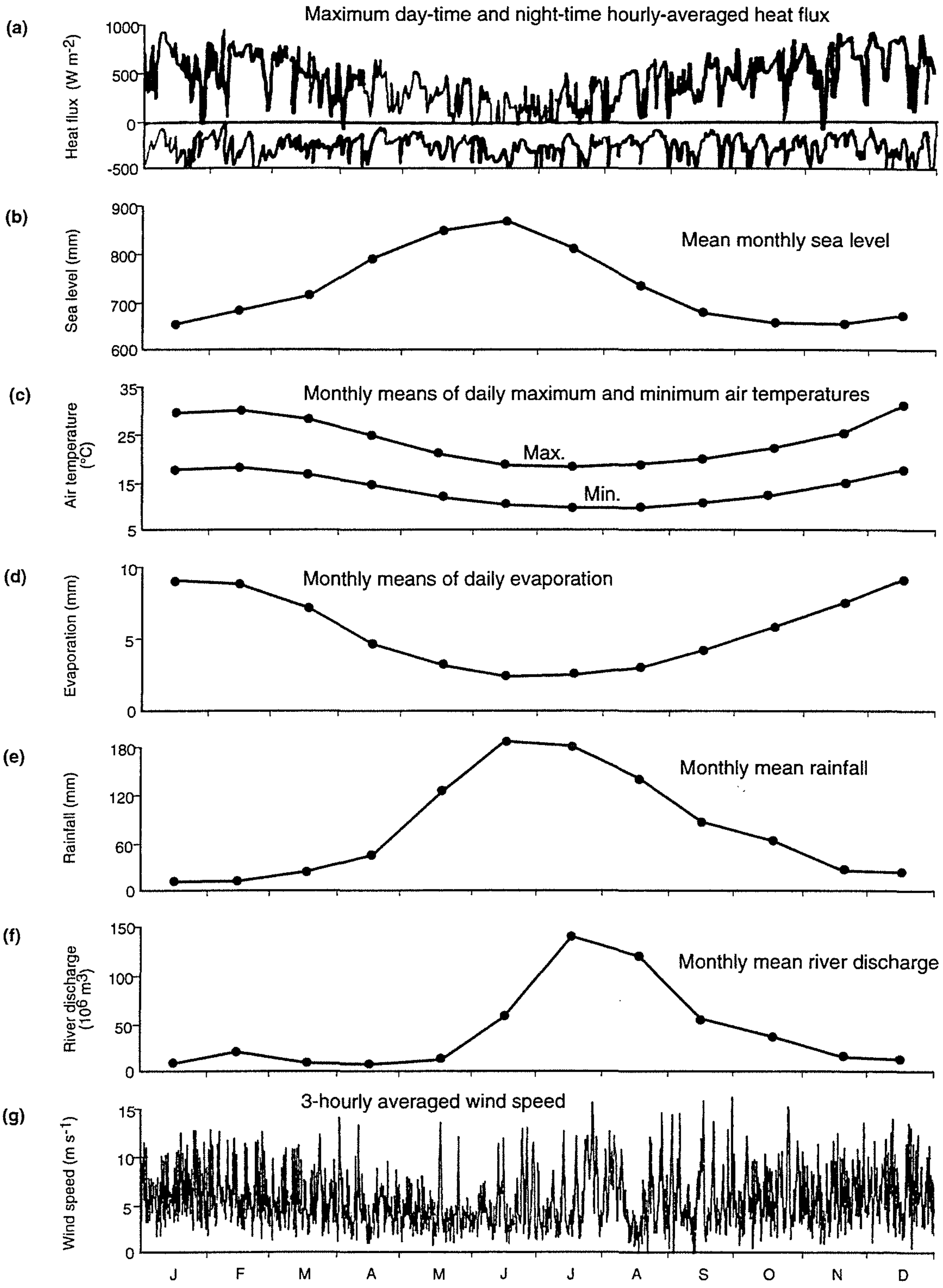


Figure 4. Annual time series of hydrological and meteorological parameters for the Perth coastal region: (a) net heat flux, showing the maximum rates of day-time (+ve) gains and night-time (-ve) losses for 1993 at the sea surface 30 km north of Fremantle, based on hourly data (modified from Pattiaratchi *et al.* (1995)), (b) mean monthly sea level at Fremantle (re-drawn from Pattiaratchi and Buchan (1991), data period 1959-1989, data from Tidal Laboratory, Flinders Institute for Atmospheric and Marine Science), (c) monthly averages of daily maximum and minimum air temperatures for Perth (Australian Bureau of Statistics, 1989), (d) monthly average of daily evaporation at Perth (Australian Bureau of Statistics, 1989), (e) mean monthly rainfall at Perth (Australian Bureau of Statistics, 1989), (f) mean monthly freshwater discharge from the Swan-Canning Estuary, data period 1987-1992, estimated by Deeley (in preparation) and (g) 3-hourly averaged wind speed from Naval Base (12 m height) for 1993 (data from the Department of Environmental Protection).

Figure 4 presents annual time series data of heat flux at the water surface, sea level, air temperature, evaporation, rainfall, river discharge and wind speed for the Perth coastal region. These factors have been shown to be related to the seasonal nature of the hydrodynamics of Cockburn Sound and adjacent waters (Hearn, 1991; D'Adamo, 1992; Steedman and Craig, 1979, 1983). The annual average rainfall for the Perth region is about 900 mm with over 80 % occurring from May to September. The Swan-Canning Estuary freshwater discharge pattern follows that of rainfall, but with a lag of about 1 month. The annual average evaporation is about 1700 mm with maximum and minimum rates of about 9 mm d^{-1} and 2 mm d^{-1} occurring in January and June, respectively. Extreme air temperatures at Perth range from about 44 ^{o}C in summer to about 1 ^{o}C in winter, with monthly means of the daily maximum and daily minimum air temperatures being respectively up to 30.0 ^{o}C and down to 16.2 ^{o}C in summer, and similarly up to 18.2 ^{o}C and down to 9.0 ^{o}C in winter. Cloud cover varies from about 30 percent in January to 60 percent in June. Maximum daily short-wave radiation ranges typically from about 750-1000 W m^{-2} in summer and 250-500 W m^{-2} in winter. Night-time heat losses at the water surface range from about 100-500 W m^{-2} during the year.

Tides, barometrically forced water level variations and waves

The tides of southwest Australia are relatively small and mainly diurnal. The predicted astronomical tidal range at Fremantle varies from about 0.1 to 0.9 m (Australian National Tide Tables, 1995) and the annual mean range is about 0.5 m (Hearn, 1991). Tidal currents for the Perth shelf are typically less than about 0.02 m s^{-1} (Steedman and Craig, 1983; Hearn *et al.* 1985; van Senden, 1991; Pattiaratchi *et al.* 1995).

Variations from predicted astronomical tide heights are mainly due to barometric pressure variations and wind effects. The *inverse barometer effect*, where an increase (or decrease) in local barometric pressure of 1 mbar causes a lowering (or raising) of mean sea level by about 0.01 m, can lead to about 0.1-0.2 m changes in sea level over typical synoptic meteorological cycles (Hamon, 1966). Storm winds can produce changes in sea level along the coast which may be of order 0.1 m (Hearn, 1991; Hodgkin and Di Lollo, 1958). Hence, in combination these meteorological effects can alter the water level by up to about 0.3 m during synoptic cycles. However, during the more infrequent passage (usually less than once per year) of tropical cyclonic depressions down the southwest coast the relatively strong pressure changes and winds can alter the coastal water level by up to about 1-2 m (Fandry *et al.* 1984; Hodgkin and Di Lollo, 1958).

Low frequency oscillations of water level along the coast of Western Australia have characteristic periods of 5-10 days and ranges of 0.1-0.3 m (see Webster, 1983; Hamon, 1966; Harrison, 1983). These may be associated with propagating coastally trapped waves such as continental shelf waves and Kelvin waves or may be directly forced by the passage of synoptic meteorological systems. It is believed that low frequency oscillations could cause currents of order 0.01-0.1 m s^{-1} in the shelf zone off Perth (Hearn, 1991; van Senden, 1991), however the understanding of these processes off the coast of southwest Australia is at an early stage.

The wave climate is comprised of oceanic swell and locally generated sea waves. The swell develops in the Southern and Indian Oceans and arrives predominantly from the south-southwest. Wave rider buoy records from south-southwest of Rottnest Island show that the swell has a mean significant period of about 12 seconds and significant heights typically in the range 0.5-5 m, with a mean annual value of 1.75 m (Department of Transport, unpublished data). Local winds generate sea waves with significant periods of less than 8 seconds and significant wave heights typically in the range 0.3-3.3 m, with a mean annual value of 1.3 m (Department of Transport, unpublished data). Wave induced currents are believed to be relatively minor compared to wind-driven currents in the embayments and on the shelf (Pattiaratchi *et al.* 1995).

Local and regional scale wind-driven circulation and the influence of the Leeuwin Current

Traditional atlases show a mean northward oceanic current off Western Australia which is the eastern portion of the large Indian Ocean anti-clockwise gyre. However, closer to the coast (within about 500 km) of Western Australia the Leeuwin Current flows strongly southward for much of the year.

The Leeuwin Current typically flows over the continental shelf and slope as a warm, low salinity tropical mass, driven by a north to south steric height gradient (Godfrey and Ridgway, 1985) which is typically of order 55 cm from about 10 °S to 35 °S. It has maximum core speeds of order 0.5 to 1.5 m s^{-1} just beyond the shelf edge (Pearce and Griffiths, 1991; Cresswell, 1991; Pearce, 1991). The Current is of order 50-100 km wide and about 200 m deep off the southwest coast in winter. It is strongest from about March to October, but is weakened in spring/summer primarily in response to the strength of opposing south-southwesterly winds, as suggested by Smith *et al.* (1991). The Leeuwin Current is believed to be the primary reason for the absence of significant upwelling along the west coast, despite the prominence of equatorward winds during the year that would otherwise favour upwelling, as is the case along the west coasts of South America and South Africa (Pearce, 1991).

The eastern edge of the Leeuwin Current water mass can approach the nearshore zone as a strong temperature/density front and influence the hydrodynamics of the shelf waters (Mills *et al.* 1996). The mean sea level has been proposed to be a good indicator of the strength of the Leeuwin Current throughout the year by Pearce and Phillips (1988) and Figure 4b was presented by Pattiaratchi and Buchan (1991) to indicate the changing seasonal strength of the Current. According to this criterion the Leeuwin Current flows most strongly from about April to September. During El Nino-Southern Oscillation (ENSO) events (Bureau of Meteorology, 1994; Philander, 1990) annual variations in mean coastal sea levels along the west coast of Australia are lower and the waters along the outer shelf are cooler and more saline (Pearce and Phillips, 1988). These features are considered to be indicative of a weaker Leeuwin Current that is perhaps associated with a weaker flow through the Indonesian Archipelago during these events (Pearce, 1991).

Past studies have shown that the mean wind-driven transport within the nearshore zone is predominantly shore-parallel with speeds typically of order 0.1 m s^{-1} within a range of about 0-0.25 m s^{-1} (see Hearn, 1991; Steedman and Associates, in Binnie and Partners, 1981; Pattiaratchi *et al.* 1995). However, the effect of the complex bathymetry, such as the reefs, islands and semi-enclosed embayments, results in bathymetric steering of wind-driven flows. In addition, the presence of sills restricts the flushing of the embayments.

The dynamical influence of the earth's rotation is equivalent to an additional force acting perpendicularly to the direction of water movement. If this 'force' is not balanced, the flow direction will be significantly deviated in the anti-clockwise sense (in the southern hemisphere) after a time equivalent to the inertial period which, at the latitude of Perth, is approximately one day. For water current speeds of order 0.1 m s^{-1}, typical of the study area, rotational effects become significant in unstratified water bodies which have horizontal dimensions of several km or more. In such cases the Rossby number (Csanady, 1982) is less than one.

The combined presence of vertical density stratification and rotation introduces another dynamical length scale, the baroclinic radius of deformation (Csanady, 1982). As will be shown in this report, the embayments, channels and inner-shelf areas of Perth's southern coastal waters have typical vertical density differences of 0.1-0.5 kg m^{-3} in the upper 20 m of the water column, and this corresponds to a baroclinic radius of deformation in the range 1-3 km. Cockburn Sound is about 15 km long and up to 10 km wide. The basins of Warnbro Sound, Mangles Bay and Owen Anchorage, although smaller than Cockburn Sound, nonetheless have horizontal dimensions which scale with the baroclinic radius of deformation. Hence, the effects of rotation on the response of the density structure are expected to be significant.

3. Methods

A series of seventeen regional salinity-temperature-depth (STD) surveys were conducted at intervals of about 1-2 months between 1991 and 1993, and in May 1994, between Fremantle, Rottnest Island, southern Garden Island and through Cockburn Sound, to detail the annual variation in the three-dimensional stratification of the coastal waters. Table 1 lists the dates of surveys. The surveys were conducted between about 0700 and 1500 hours on each of the individual days. Each day's survey followed the same general path (shown in Figure 1), with alterations in some instances due to logistical constraints.

Table 1. Dates of the seventeen surveys of the Southern Metropolitan Coastal Waters Study 'routine' oceanographic programme from 1991 to 1994.

Survey Number	Date
1	15 August 1991
2	1-3 October 1991
3	19-20 November 1991
4	11 February 1992
5	12 March 1992
6	26 March 1992
7	15 April 1992
8	30 April 1992
9	26 May 1992
10	24 July 1992
11	9 September 1992
12	17 September 1992
13	21 October 1992
14	17 December 1992
15	8 February 1993
16	16 February 1993
17	3-5 May 1994

Depending on instrument availability, data were collected either with fine-scale conductivity-temperature-depth (CTD) probes (described in Vollmer, 1991) or Yeokal Electronics HAMON Model 602 salinity-temperature bridges. The CTD probe comprised Seabird Electronics conductivity and temperature sensors and a Digiquartz pressure transducer with accuracies of $\pm$ 0.001 Siemens m^{-1}, 0.01 degrees Celsius and 0.015 %, respectively. The CTD probe was deployed in free fall mode, and the data were collected at 50 Hz yielding a vertical resolution of approximately 0.02 m. During collection, the data were viewed via an onboard computer and stored electronically. As a back-up to the CTD probe, the Yeokal salinity-temperature bridges were deployed manually with depths taken from a scaled cable, generally at 0.5-1 m intervals. Calibrations of the Yeokal meter data during the field programme suggest that salinity and temperature can be accepted as accurate to ± 0.10 parts per thousand and ± 0.1 degrees Celsius, respectively. Regular checks of the meters against more accurate sensors were conducted and the data were adjusted accordingly.

4. Results

4.1 Annual cycles in cross-shelf salinity, temperature and density gradients

Time series of salinity, temperature and density monitored at 10 m depth in central Cockburn Sound, Sepia Depression and the mid-shelf region south of Rottnest Island are presented in Figure 5. The monitoring sites (CS, SD and MS, respectively) are shown in Figure 1. The nearshore region (Cockburn Sound) undergoes the greatest changes in all three parameters from one season to the next. In particular, salinities in Cockburn Sound rise above mid-shelf salinities in summer, due mainly to evaporation, and fall below mid-shelf salinities in winter, due mainly to the influx of river discharge via nearby estuaries. The Sepia Depression curves are generally enveloped within the curves for the shelf and Cockburn Sound sites. Figure 5(c) shows that, as a result of the annual cycling in salinity and temperature and the combined influence of these parameters on water density, the year can be divided into two main periods, depending on whether the density of Cockburn Sound water is less than or greater than the density of mid-shelf water. There are two times in the year when the nearshore-offshore density difference reverses sign. Other studies of the annual cycling in these parameters for Perth's nearshore and shelf waters have been conducted by Pearce and Church (unpublished), D'Adamo (1992), Rochford (1969) and Hodgkin and Phillips (1969).

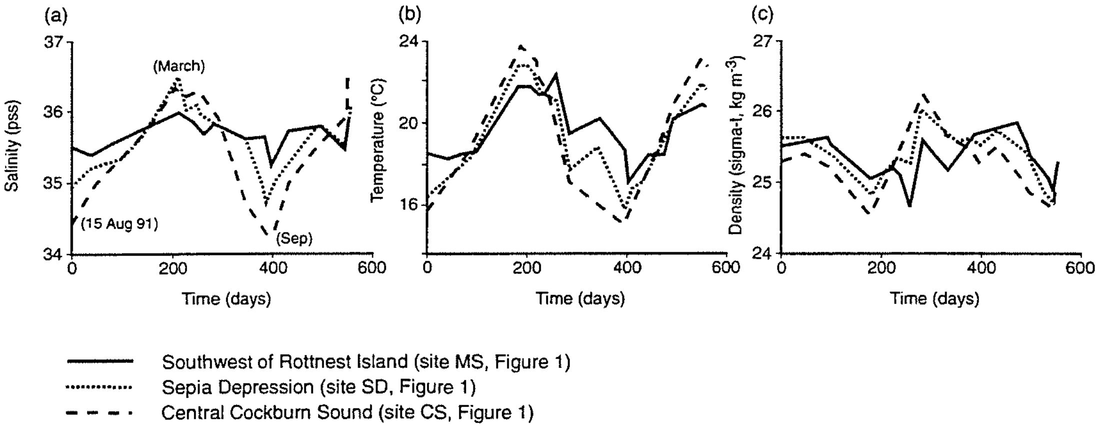


Figure 5. Annual time series of (a) salinity (pss), (b) temperature (°C) and (c) density (sigma-t units, kg m^{-3}) at 10 m depth from central Cockburn Sound, central Sepia Depression west of Garden Island and over the shelf approximately 10km southwest of the west end of Rottnest Island. Data period: 15 August 1991 — 16 February 1993.

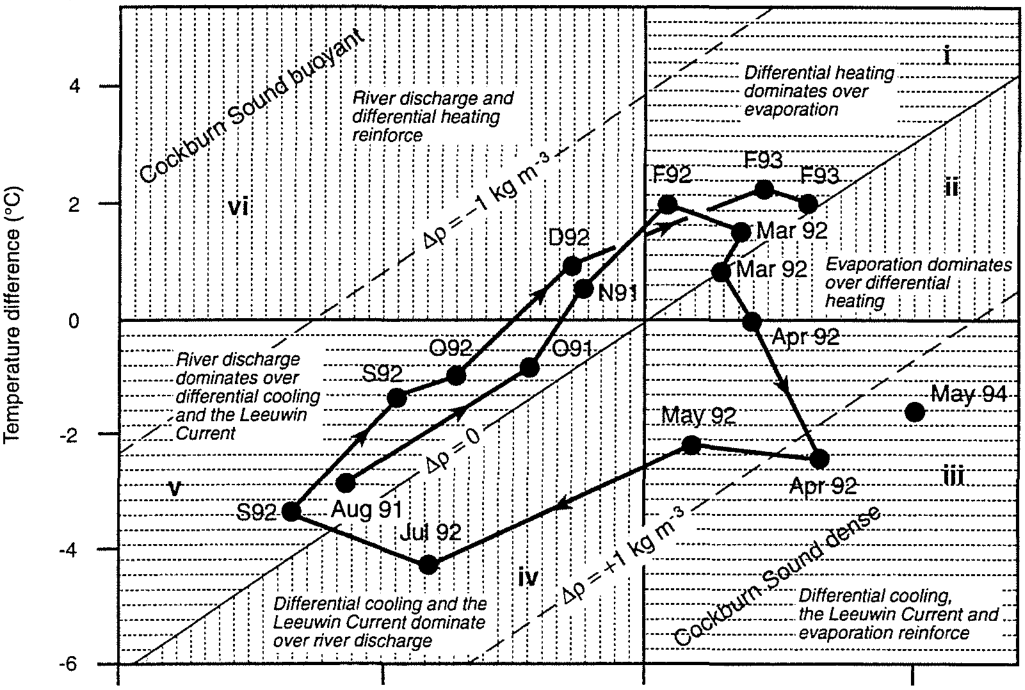
Figure 6a presents a plot of the temperature difference versus salinity difference, from a representative depth of 10 m, between central Cockburn Sound (site CS, Figure 1) and the mid-shelf region southwest of Rottnest Island (site MS, Figure 1) for the series of regional surveys conducted between 1991 and 1994. Figure 6a displays an annual cycle in cross-shelf density difference. All differences are computed as the value in Cockburn Sound minus the value over the mid-shelf. Beginning with the data from August 1991, and then joining each subsequent data point in a chronological progression, a cycle emerges which crosses the zero density difference contour line twice in one year. This indicates that the cross-shelf density difference reverses twice each year, once at about the end of summer and once during winter. As shown, Cockburn Sound was less dense than the offshore waters between about August and February and the Sound was more dense than the offshore waters between about April and July. Pearce and Church (unpublished) investigated the annual cycling in surface salinity, temperature and density from data collected monthly over 3 years from the nearshore waters of Marmion Lagoon (offshore of Waterman, approximately 40 km north of Perth) and shelf waters (approximately 5 km west of the western end of Rottnest Island at the CSIRO long term water quality monitoring station (Johannes *et al.* (1994)). Pearce and Church's data are used to produce the curve in Figure 6b enabling a comparison to be made with the SMCWS data in Figure 6a. As shown, the two curves (Figures 6a and 6b) display the same general cycle in cross-shelf density difference, but with a substantial contrast in the relative position of the data points, particularly from within the late winter-early spring period. The cycle from the 'Marmion Lagoon minus mid-shelf' data (Figure 6b) indicate that during August-September the nearshore Marmion Lagoon site was more dense than the shelf site. In contrast, the cycle from the 'Cockburn Sound minus mid-shelf' data (Figure 6a) indicate that the Cockburn Sound site was less dense than the shelf site during August-September. In both cases the temperature data indicate that the nearshore sites were colder than the shelf sites during this period, however the salinity of Cockburn Sound was substantially lower than that of the shelf site whereas the salinity of the Marmion Lagoon was approximately equal to that of the shelf site.

The main reason for the differences in the relative positions of the late winter-early spring data along the cycles of Figures 6a and b, respectively, is that significant amounts of low salinity water flowing from the Swan-Canning Estuary are forced to reside in Cockburn Sound under typical wind conditions during winter and spring. D'Adamo *et al.* (1995a) have shown that plumes of estuarine water are driven into the interior of Cockburn Sound by northeasterly-northwesterly winds that typically occur as part of 7-10 day synoptic meteorological cycles. Once these waters enter the relatively enclosed Cockburn Sound they tend to reside there for longer times than is the case for the more exposed and open Marmion Lagoon. Flushing times (defined as waterbody volume divided by volumetric influxes through the open boundaries) for the Marmion Lagoon have been estimated to be of order 1 day for typical oceanographic and meteorological conditions by Pattiaratchi *et al.* (1995), and this compares with estimates of order 10 days or more for Cockburn Sound (see Steedman and Craig, 1979 and 1983; Hearn, 1991 and D'Adamo, 1992). Furthermore, the mouth of the Swan-Canning Estuary at Fremantle is only about 15 km from northern Cockburn Sound but approximately 40 km from Marmion Lagoon. Hence, there is a greater potential for dilution and offshore transport of estuarine plumes en route to Marmion Lagoon as compared to those moving toward Cockburn Sound.

4.2 Main factors influencing cross-shelf salinity, temperature and density gradients

The annual cycle in Figure 6a falls into a number of distinct *categories*, labelled on the diagram as I, II, III, IV, V and VI. Within each category the temperature difference (ΔT) and salinity

(a) Cockburn Sound minus Mid-shelf



(b) Marmion Lagoon minus Mid-shelf

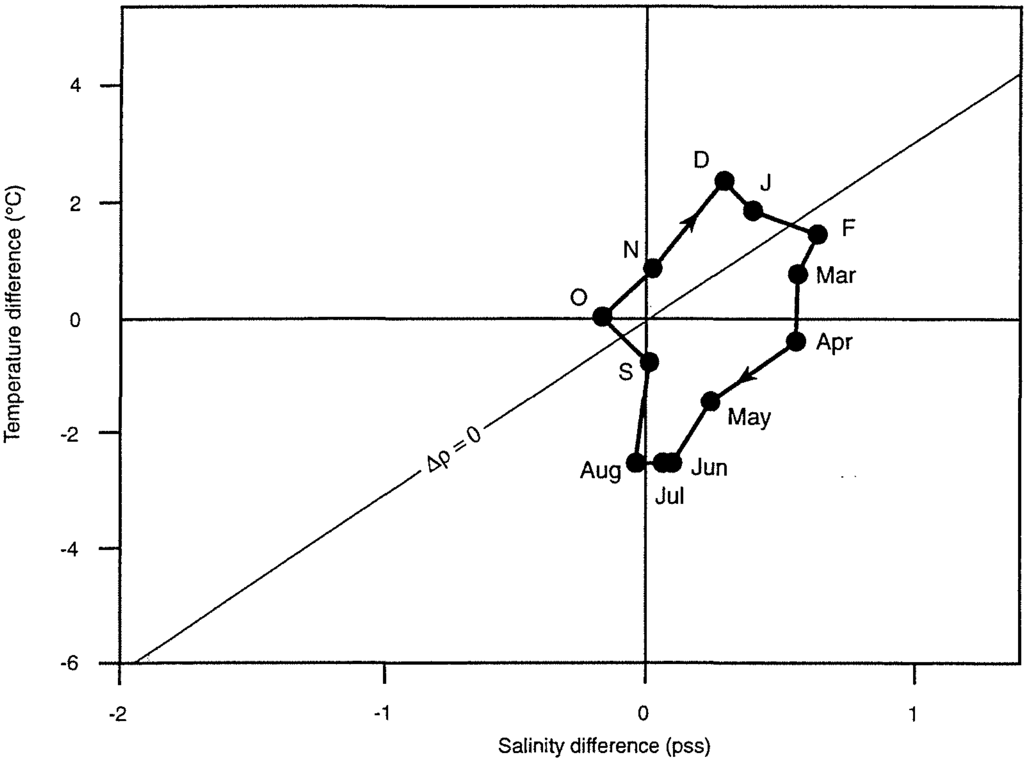


Figure 6. The annual cycle in the salinity (pss) and temperature (°C) differences (ΔS and ΔT, respectively) (a) between central Cockburn Sound (CS) and over the shelf approximately 10 km southwest of the west end of Rottnest Island (MS) at 10 m depth and (b) between Marmion Lagoon off Waterman and 5 km southwest of Rottnest Island at the surface. The diagonal lines are contours of constant density difference, Δρ, (kg m^{-3}). In each plot data above the central contour indicate that the nearshore site is less dense than the offshore site, and the opposite for data below the central diagonal. In (a) the influence of river discharge, differential heating, differential cooling, evaporation and the Leeuwin Current on the cross-shelf differences are indicated on the diagram, and according to these influences the annual cycle in ΔS and ΔT falls into six categories, I to VI, as shaded, and in terms of the cross-shelf density difference, the annual cycle falls into three main temporal regimes: 'summer' (I and II), 'autumn' (III and IV) and 'winter-spring' (V and VI). Data in (a) are from this study and data in (b) were taken from Pearce and Church (unpublished) and represent monthly averages of data collected over three years.

difference (ΔS) either reinforce or oppose one another in their effect on the density difference ($\Delta\rho$). In situations where they oppose one another, either one of ΔT or ΔS can dominate in determining whether $\Delta\rho$ is positive or negative. Along the contour line of zero density differential ΔT and ΔS are either both zero or effectively cancel one another in terms of their respective effects on the density difference. Throughout the year there are a number of seasonally varying factors that contribute to the changes in ΔT and ΔS, and therefore $\Delta\rho$. The main factors are: estuarine discharge of low salinity water which lowers the mean density of the nearshore zone; differential heating (described in Imberger and Patterson, 1990) where the temperature of the relatively shallow nearshore zone increases at a greater rate than deeper offshore waters thereby reducing the relative density of the nearshore zone; differential cooling (described in Imberger and Patterson, 1990) where the temperature of the relatively shallow nearshore zone falls at a greater rate than deeper offshore waters thereby increasing the relative density of the nearshore zone; evaporation which, because of the relatively shallow nature of the nearshore zone, causes the salinity (and thus density) to increase at a greater rate in the nearshore zone relative to deeper offshore waters; and finally the Leeuwin Current (Cresswell and Golding, 1980; Cresswell, 1991; Pearce, 1991) which introduces relatively warm, low salinity, (and thus relatively buoyant) tropical water over the mid-outer shelf, particularly during autumn to spring. The relative influence of these various factors on ΔT and ΔS within each of these six categories of Figure 6a has been indicated on the diagram, and can be related to the seasonal changes in the major meteorological and hydrological factors highlighted in the time series curves of Figure 4.

Beginning in Category I, during December-February the salinity of Cockburn Sound becomes greater than that of mid-shelf waters because of diminishing freshwater flux from the Swan-Canning Estuary and evaporative effects. However, as a result of differential heating the nearshore zone warms at a greater rate than shelf waters and this effect dominates over the opposing cross-shelf salinity difference in terms of its influence on the density difference.

At the boundary between Categories I and II (February-March) the opposing effects of evaporation and differential heating cancel. As a result the horizontal density difference between the Sound and the shelf reduces to zero.

Progressing into Category II of the annual cycle, the density difference reverses sign and Cockburn Sound becomes more dense than shelf waters. The cross-shelf salinity difference dominates over an opposing temperature difference in its effect on density. The temperature difference declines due to a reducing net heat flux into the water.

As the cycle moves into Category III (April and May) evaporation increases the salinity of the Sound thereby increasing its mean density. For example, a maximum horizontal density difference of order 1 kg m^{-3} was recorded on 30 April 1992 (Figure 6a). Heat losses continue to lower the water temperature in the Sound, thereby increasing its density relative to the shelf. In addition, the Leeuwin Current generally strengthens, moves southwards and is found over the outer shelf off the Perth coast by this time of the year as a buoyant flow (Cresswell, 1991; Pearce, 1991; Pearce and Phillips, 1988; Pattiaratchi and Buchan, 1991), further increasing the cross-shelf density difference.

In Category IV (June-July) increasing rainfall and river discharge (Figure 4) results in the introduction of positive buoyancy flux to the coastal zone via estuarine outflow. Winds from the northeast and northwest quadrants have been shown to drive plumes of low salinity water, emanating from the Swan-Canning Estuary, as southward coastal flows into Cockburn Sound (D'Adamo, 1992; Hearn, 1991; D'Adamo *et al.* 1995a). As a consequence, the mean salinity of

Cockburn Sound is reduced as these plumes are mixed with resident basin water by wind-stress and penetrative convection. However, the effect of this on the cross-shelf density gradient is opposed by the temperature difference due to the presence of the Leeuwin Current over the mid-outer shelf and the greater rate of cooling of nearshore Cockburn Sound waters. Cockburn Sound continues to be cooled during this period and nearshore temperatures are much lower (by up to 4 °C) than those south of Rottnest Island. As a result the nearshore zone remains relatively dense.

As the cycle enters Category V it passes through the contour of zero density difference. None of the surveys yielded data points near this line and basin-scale data of higher temporal resolution would be required to further resolve the timing and duration of this 'transition' period.

Within Category V (August to October) the relatively low salinity of Cockburn Sound dominates in its effect on the cross-shelf density gradient compared to other factors, despite the Sound being colder than shelf waters. D'Adamo *et al.* (1995a and b) and D'Adamo (1992) have shown that during the winter-spring rainfall period estuarine discharges enter the semi-enclosed embayments between Perth and Mandurah as along-shore coastal plumes driven by winds with an onshore component.

Within Category VI (November-December) Cockburn Sound was both warmer and less saline and therefore relatively less dense than the adjacent shelf waters. The role of differential heating assumes greater importance during this period (spring-early summer) as air temperatures and solar radiation increase. Because the nearshore zone is shallower than offshore waters a greater degree of heating per unit volume results within this zone, leading to differential heating. In this period positive buoyancy fluxes from diminishing estuarine discharges and increasingly stronger solar radiation superpose in the nearshore zone, and dominate together over other effects in the establishment of regional horizontal stratification. The Leeuwin Current is known to still maintain a presence over the mid-outer shelf during this period but is weaker due to the strengthening prevailing southerly winds (Cresswell, 1991; Pearce, 1991; Smith *et al.* 1991).

4.3 Relevance of cross-shelf density difference to the circulation and flushing of Cockburn Sound

In the remainder of this paper we consider the relevance of the annual cycle of shelf versus embayment density difference (illustrated in Figures 5 and 6a) to the nature of the circulation and exchange between Cockburn Sound and adjacent shelf waters. Exchange between embayment and shelf water masses of different densities will result in vertical stratification of the basin unless the energy available for mixing is sufficient to overcome that stratification.

Other factors contributing to the vertical stratification of the basin will include surface heating and the wind-driven transport of estuarine plumes into the basin. Factors contributing to the vertical mixing (destratification) of the basin include wind and penetrative convection due to evaporation and night-time cooling.

However, in the absence of mixing and the other stratifying factors, it might (on the basis of Figure 6a) be expected that, from about August to February, denser shelf water transported into Cockburn Sound would gravitate to the bottom of the enclosed deep basin, displacing lighter basin water. Likewise, from about March to July, when the adjacent shelf water is lighter than Sound water, it would be expected that shelf water transported into the Sound would tend to remain near the surface. When internal and external waters were of the same density, there would be no such tendency for incoming waters to seek a preferred vertical level in the basin.

It will be shown that these simple considerations provide the foundation for defining three major seasonal 'regimes' of circulation and water exchange between Cockburn Sound and its adjacent waters. However, in order to describe and identify these 'regimes' more realistically an examination was performed of the seasonal variation in the strengths of vertical salinity, temperature and density gradients in response to the seasonal variability in the stratifying influences and strength of vertical mixing processes.

4.4 Vertical stratification and vertical mixing events

Vertical profile data from central Cockburn Sound, Sepia Depression (west of Garden Island) and the mid-shelf (south of Rottnest Island) have been used in Figure 7 to plot characteristic vertical density differences between the surface and 21 m depth for the different seasons. The profiles were collected during the field surveys of this and other selected studies since 1981.

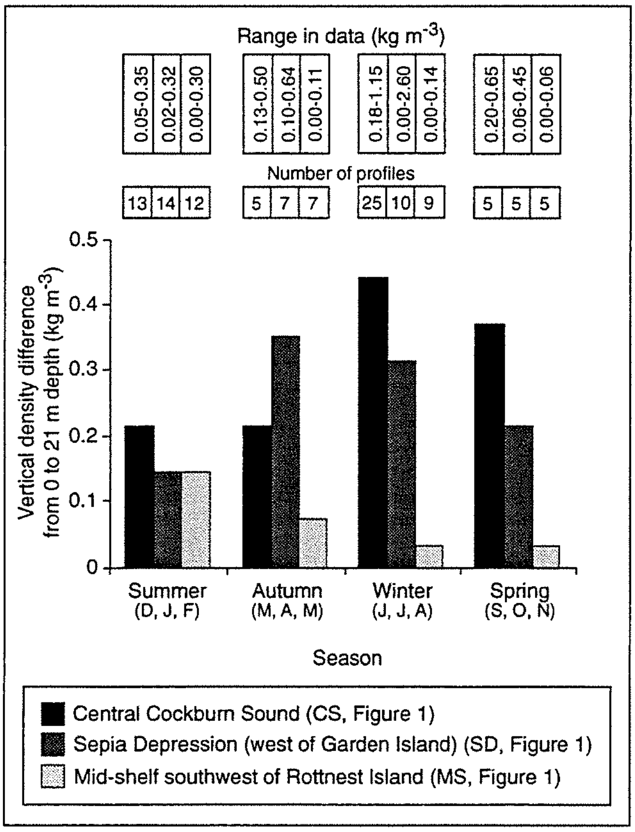


Figure 7. Seasonal mean vertical density differences (kg m^{-3}) for central Cockburn Sound, central Sepia Depression (west of Garden Island) and over the shelf (approximately 10 km southwest of the west end of Rottnest Island). Data were obtained from SMCWS surveys, Steedman and Associates, in Binnie and Partners (1981) and data collected during the Cockburn Sound Environmental Study 1976-1979 (Department of Conservation and Environment, 1979).

The data were generally collected between mid-morning and mid-afternoon prior to normal times of strong mixing events, and thereby represent the strength of vertical density stratification that vertical mixing processes have to overcome in order to fully mix the upper 21 m of the water column (which is the maximum depth in the nearshore basins). The strongest vertical gradients in Cockburn Sound occurred in winter and spring, reflecting the stratifying influence of buoyant estuarine discharges and solar heating. Interestingly, Sepia Depression is strongly stratified in autumn, and this is in part due to the fronts that can form between nearshore cooler water and warmer buoyant water that spreads over the mid-shelf region from the Leeuwin Current. In summer vertical gradients are relatively weak due to the absence of significant sources of low salinity water and due to the regularity of strong vertical mixing, discussed below. The results for the shelf region to the southwest of Rottnest Island indicated weaker vertical density stratification of the upper 21 m of the water column compared to nearshore waters.

Throughout the year, vertical mixing is due primarily to wind-stress, with assistance from penetrative convection caused by surface heat losses at night. The results of mixing analyses from complementary studies of the SMCWS (D'Adamo and Mills, 1995a and b; D'Adamo *et al.* 1995a) suggest that vertical mixing to the bottom of the Sound (21 m) due to strong winds (>7-10 m s^{-1}) lasting for 5-8 hours or more, in association with typical rates of penetrative convection, can be expected to occur at least 10-15 times per month during the period December-March (D'Adamo and Mills, 1995a). In contrast, during April-July, when the basin is relatively dense and typically vertically stratified, full depth vertical mixing can be expected only 4-6 times per month (D'Adamo and Mills, 1995b) as a result of strong winds and penetrative convection. During August-November, when the basin is relatively buoyant and typically vertically stratified, full depth vertical mixing due to these agents can also be expected only 4-6 times per month (D'Adamo *et al.* 1995a). The action of strong vertical mixing events is to remove vertical density gradients, however they also tend to sharpen the horizontal density gradient between basin and shelf waters.

4.5 Identification of three main 'regimes' in the circulation and exchange between Cockburn Sound and adjacent shelf waters

From late spring to early autumn the density difference between Cockburn Sound and adjacent shelf waters is relatively small or zero (Figure 6). From Figure 7 it can be seen that vertical density differences in the Sound are typically about 0.2 kg m^{-3} prior to strong mixing events. Strong sea-breeze winds generally occur every day or two and full-depth vertical mixing is therefore regular enough to eliminate vertical density gradients that may form within the basin due either to the introduction of slightly differing density water from outside or due to thermal stratification. The regularity of strong wind events which force horizontal water movement and (in conjunction with penetrative convection) full-depth vertical mixing, combined with the weakness and transience of vertical stratification, suggests that the circulation during this period is primarily governed by barotropic processes, as described by D'Adamo and Mills (1995a). This period is referred to as the 'summer' regime.

From mid-autumn to early winter the basin is significantly denser than shelf waters and vertical density stratification is moderate and similar to 'summer' (Figure 7). Strong wind events are relatively infrequent, however, occurring only about 4-5 times per month on average, and as a consequence full-depth vertical mixing is also relatively infrequent. During this period, referred to as the 'autumn' regime, the circulation is governed primarily by wind and density effects with relatively buoyant shelf waters entering as upper layers and preferentially renewing the near-surface waters of the Sound, as described by D'Adamo and Mills (1995b).

From about mid-winter to spring the basin is relatively buoyant with respect to shelf waters and vertical stratification in Cockburn Sound is relatively strong (Figure 7). Strong wind events are relatively infrequent, occurring only about 4-5 times per month on average, and as a consequence full-depth vertical mixing is also relatively infrequent. During this period, referred to as the 'winter-spring' regime, the circulation is again governed primarily by wind and density effects, leading to layered exchange with relatively dense shelf waters entering the Sound, plunging into the deep basin, and renewing its bottom waters, as described by D'Adamo *et al.* (1995a).

The exact timing of the various regimes associated with the annual $\Delta\rho$ cycle depends on the timing of the factors that influence the cross-shelf salinity and temperature differences. For the purposes of the present discussion the periods for each of the regimes have been defined according to the data in Figure 6a, collected during the field surveys. Future studies may add to the data set thereby producing a greater sample number from which to better define the periods of the individual regimes.

A selection of the cross-shelf CTD surveys, conducted during 1991 to 1994, have been presented in Figure 8 as vertical sections of the density, salinity and temperature structure. These provide examples of the basin and cross-shelf stratification considered to be characteristic of the three main hydrodynamic regimes and of the transition periods that occur between regimes.

4.6 Basin dynamics, cross-shelf structure and implications for numerical modelling during the three main 'regimes' in the annual cross-shelf density difference cycle

4.6.1 'Summer' regime

Throughout the 'summer' regime, regular strong sea-breezes in the Perth region drive predominantly northward long-shore currents and these flows enter the nearshore basins (Figure 9). The wind stress, in conjunction with nightly episodes of penetrative convection, results in regular full-depth mixing in Cockburn Sound during meteorological conditions typical of this regime (D'Adamo and Mills, 1995a). D'Adamo and Mills (1995a) investigated the potential for vertical mixing in Cockburn Sound during 'summer' by sea-breeze winds and penetrative convection and concluded that full-depth mixing of typical day-time vertical density gradients occurs at least 10-15 times per month. A characteristic example of the resulting basin-scale structure after full-depth mixing during typical 'summer' conditions was recorded during 10/11 March 1992 (Figure 8a). As shown, Cockburn Sound was well-mixed vertically throughout most of the basin and this was caused by winds of order 10 m s^{-1} or stronger. These data also highlight the counterbalancing effect that salinity and temperature gradients can have in producing a relatively weak cross-shelf density gradient.

It should be noted that full-depth mixing occurs relatively regularly during the 'summer' regime in spite of the diurnal evolution of vertical stratification due to thermal inputs via short wave radiation (D'Adamo and Mills, 1995a). For example Figure 10, taken from D'Adamo and Mills (1995a), shows a sequence of diurnal heating and mixing cycles from central Cockburn Sound during typical summer conditions, when daily heating stratified the water column in temperature (and hence also density) but afternoon sea-breezes (> 7.5 m s^{-1} in strength) in conjunction with night-time penetrative convection (due to heat loss rates of greater than about 200 W m^{-2}) mixed the water column to the bottom.

The wind patterns during summer are dominated by the eastward passage of synoptic scale high pressure systems at approximately weekly cycles (Breckling, 1989). Afternoon sea-breezes are common and occur nearly every day. However, within each synoptic cycle the sea-breezes vary in strength. Hence, there are intervening periods (between strong sea-breezes) when the wind strength is relatively weak (< 7.5 m s^{-1}). For one of these intervening periods D'Adamo and Mills (1995a) analysed salinity, temperature and density stratification data collected over the inner shelf and semi-enclosed basins on several successive days (see Figure 9). This figure

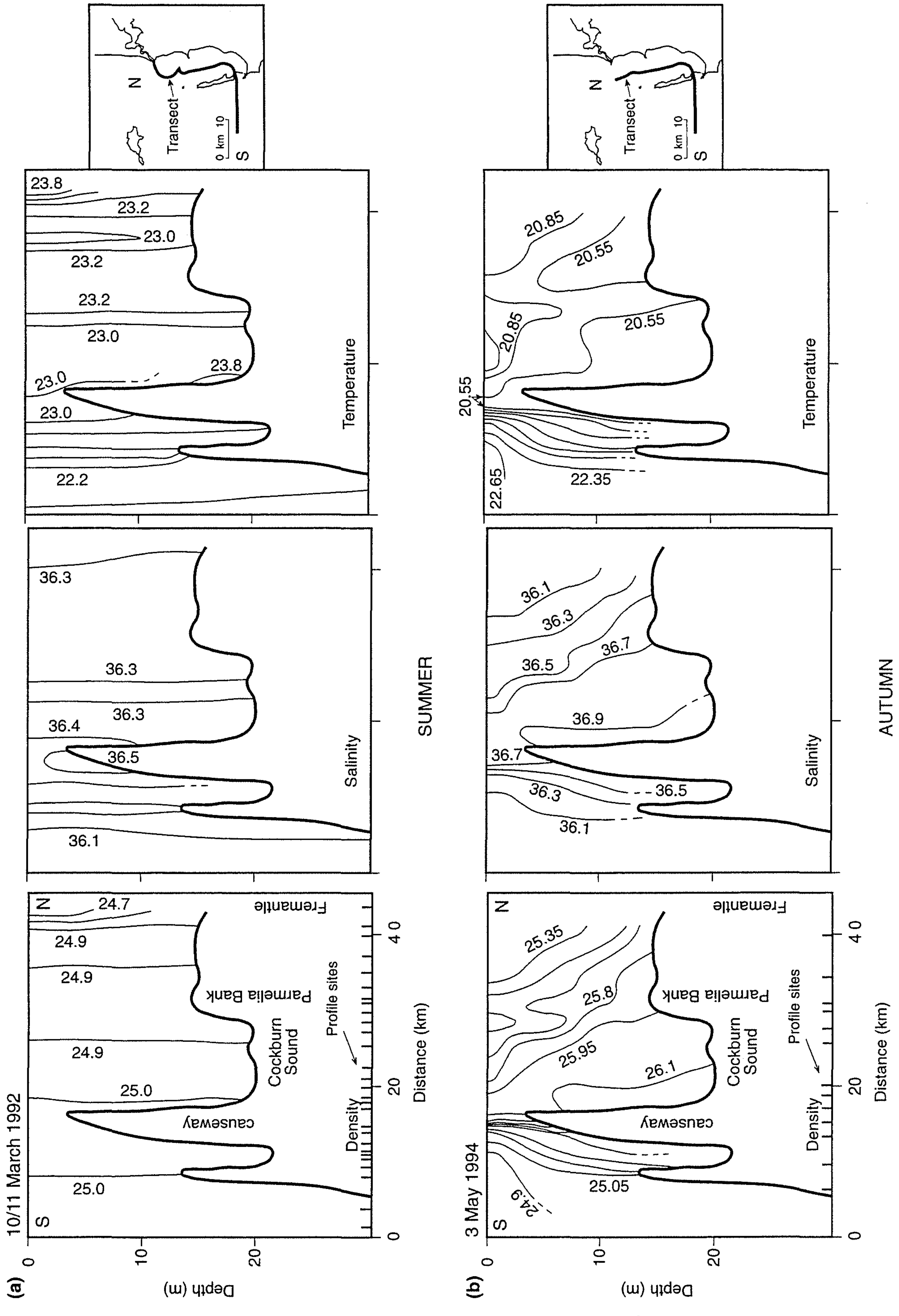
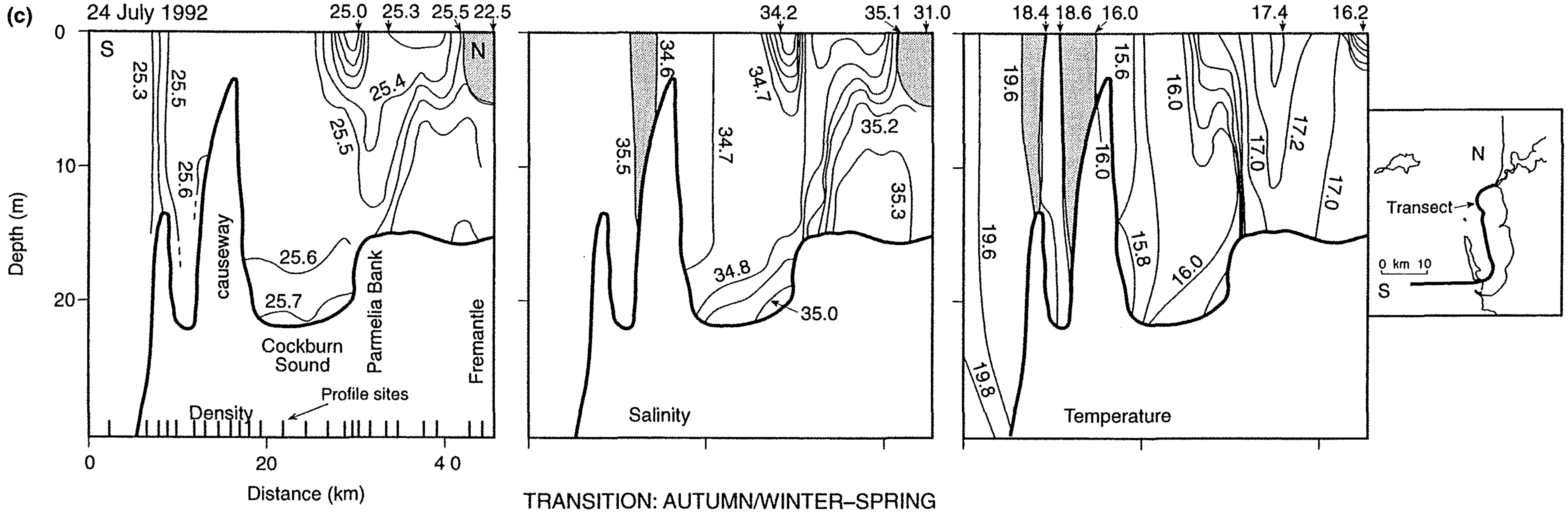
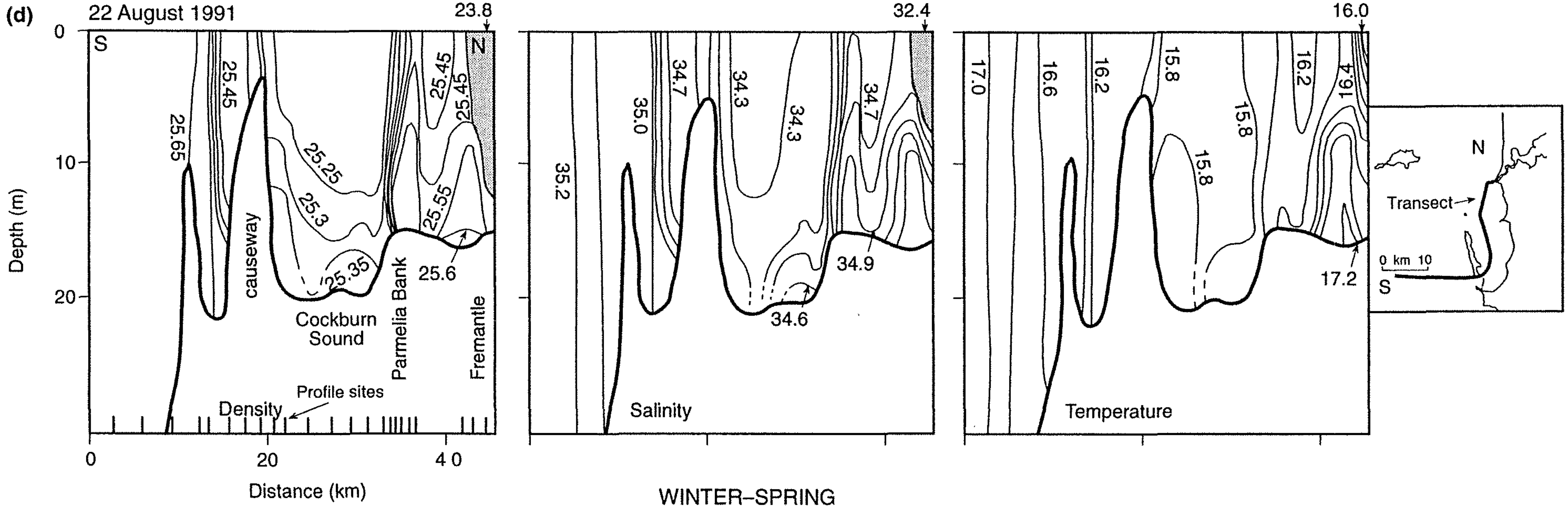


Figure 8. Typical examples of cross-shelf sections of density (sigma-t units, kg m^{-3}), salinity (pss) and temperature (°C) stratification for (a) the 'summer' regime, (b) the 'autumn' regime, (c) the transition period between the 'autumn' and 'winter-spring' regimes, (d and e) the 'winter-spring' regime and (f) the transition period between the 'winter-spring' and 'summer' regimes. Intense gradient zones, where individual contour lines would merge, are shown as shaded areas.



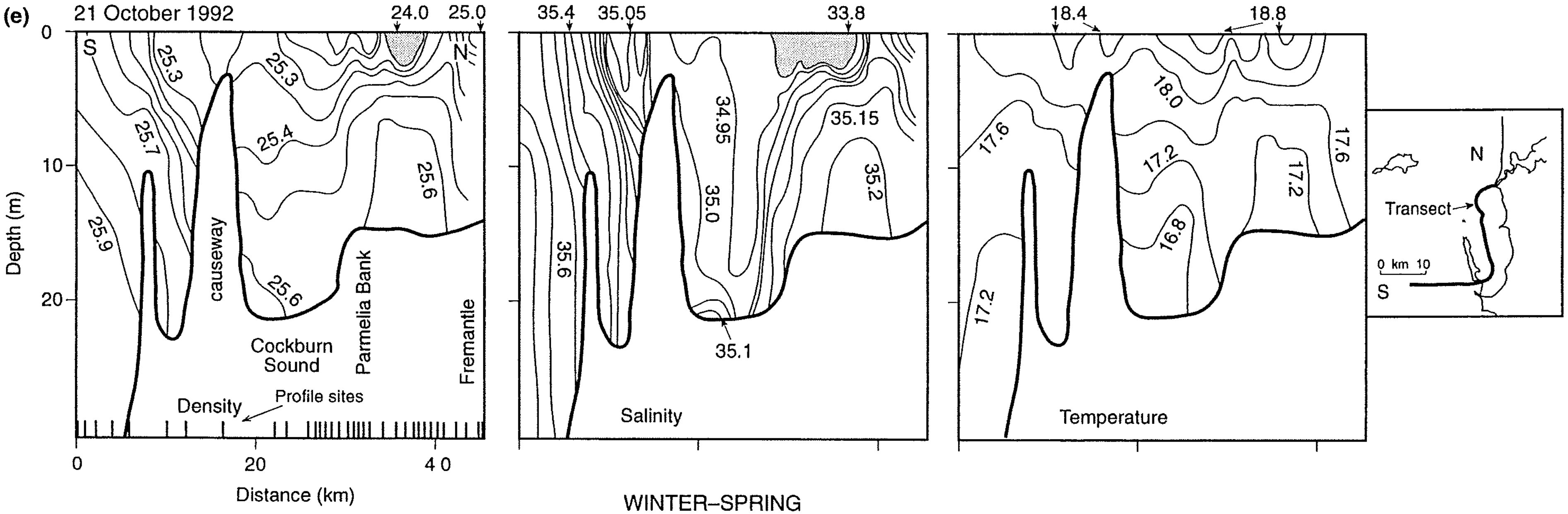
TRANSITION: AUTUMN/WINTER–SPRING



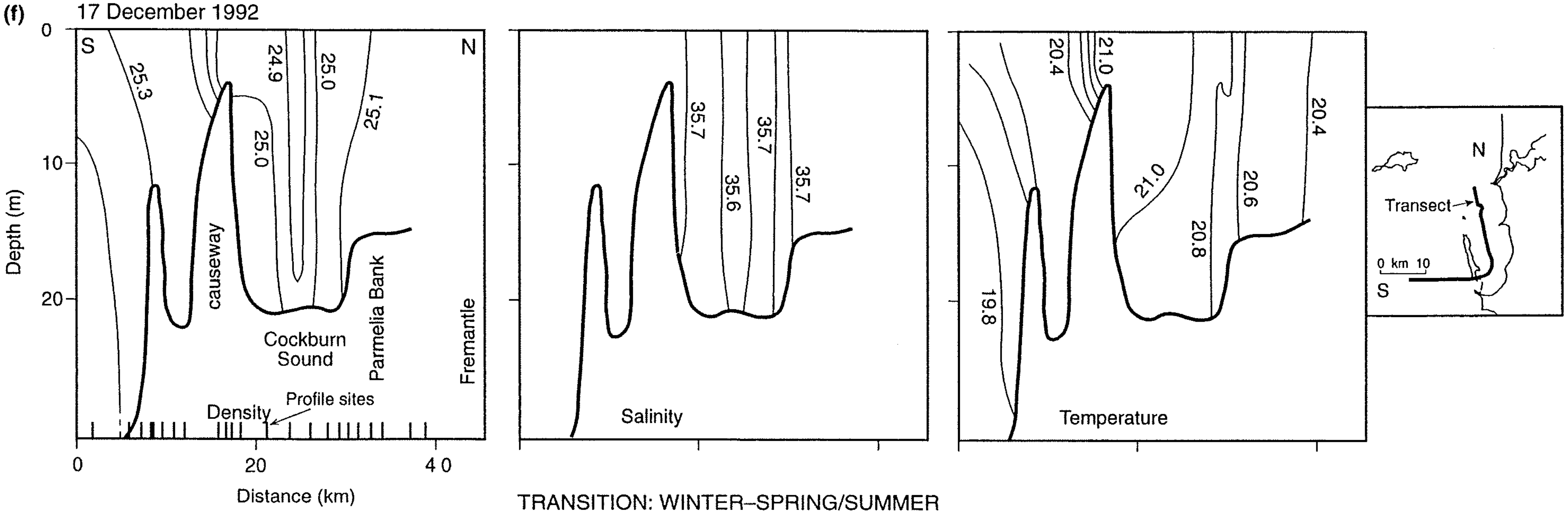
WINTER–SPRING

Figure 8. continued.

Figure 8. Continued.



WINTER–SPRING



TRANSITION: WINTER–SPRING/SUMMER

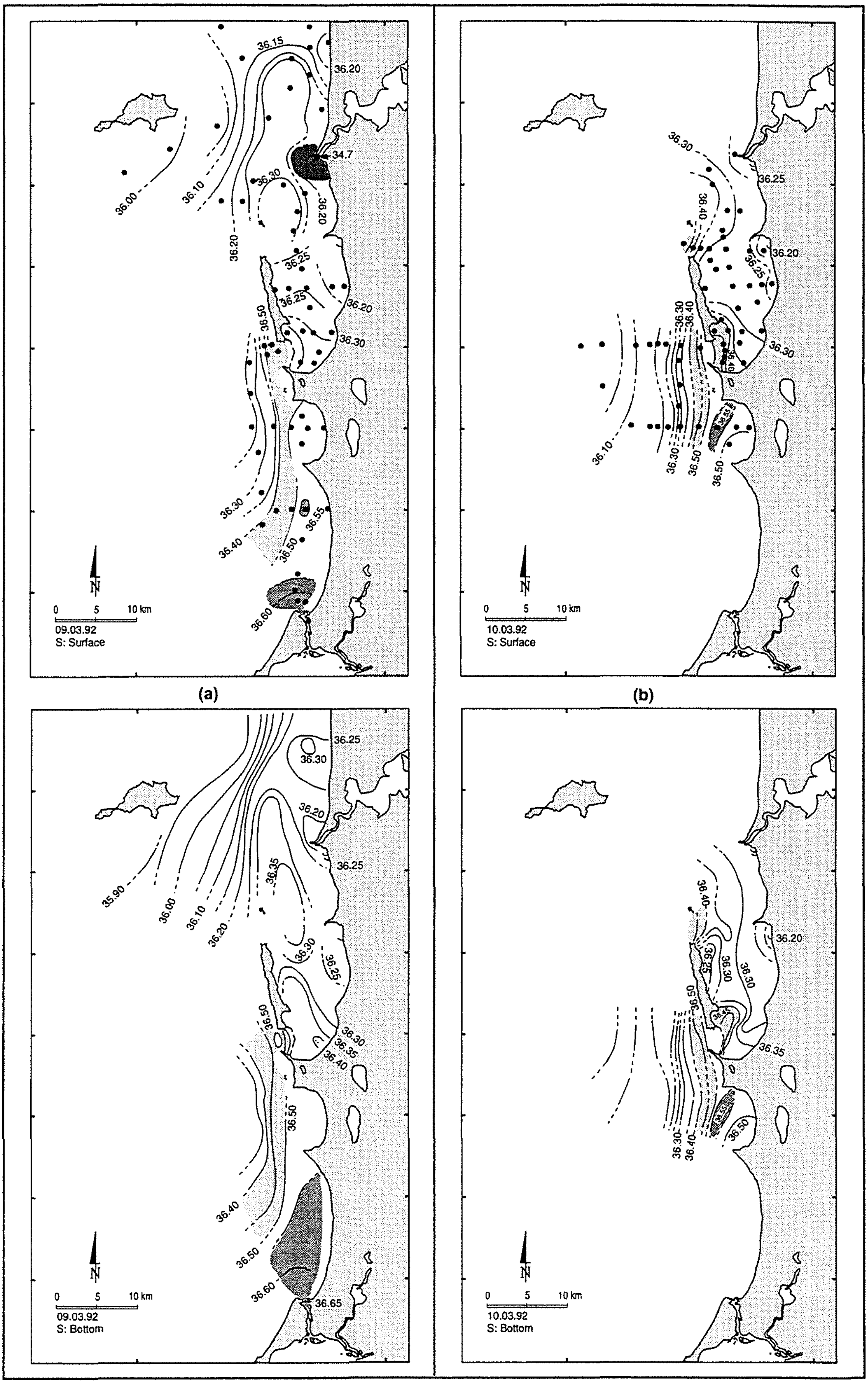


Figure 9. Contour plots of surface and bottom salinity (in pss) south of Perth on 5 successive days during 9-13 March 1992. Dark shading indicates 36.55-36.65 pss and light shading indicates 36.4-36.5 pss. Note the northward progression of patches of water with these salinity ranges and their entry into the basins. Source: D'Adamo and Mills (1995a). Dashed lines indicate poor quality data or gaps in the survey grid.

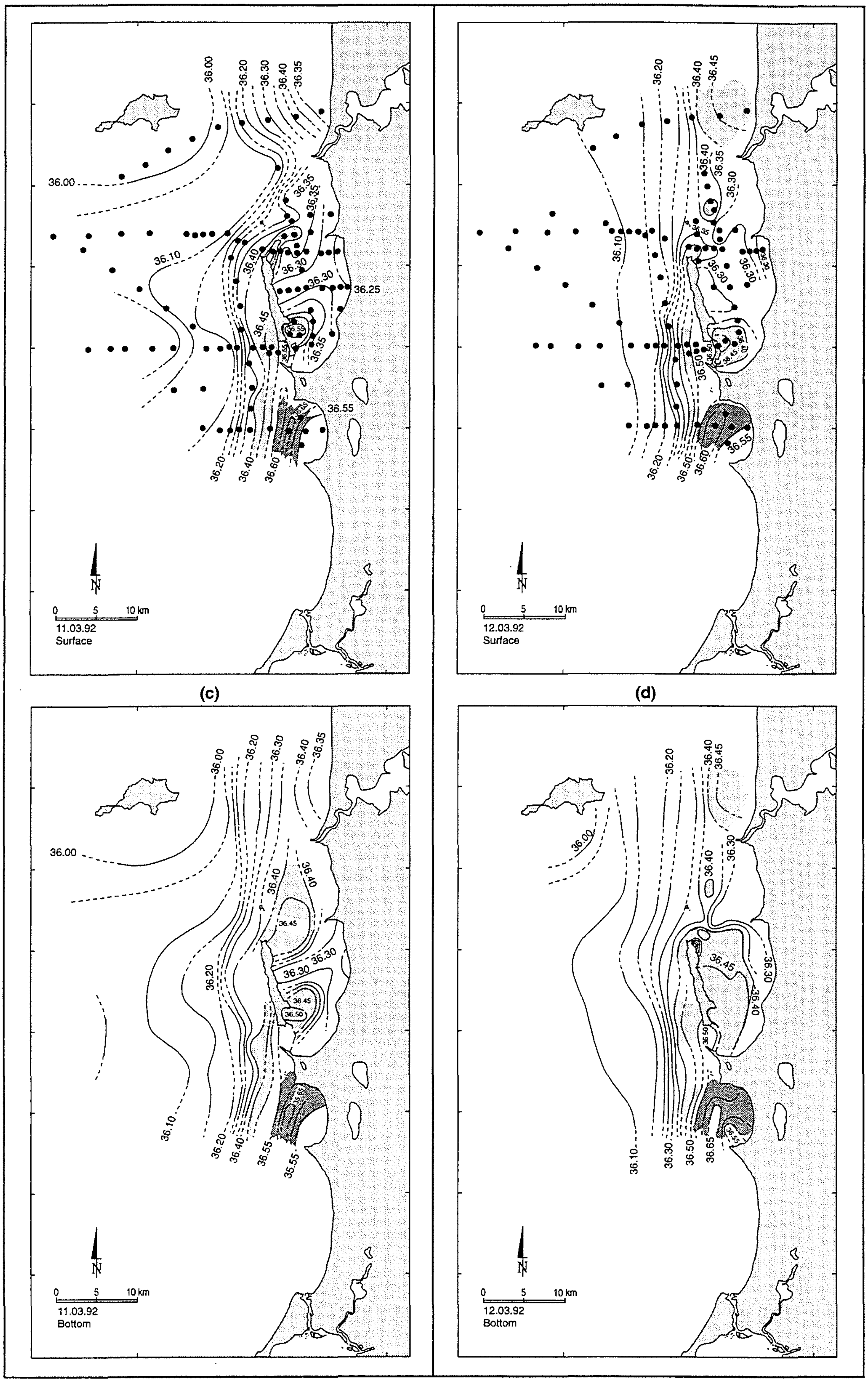


Figure 9 continued.

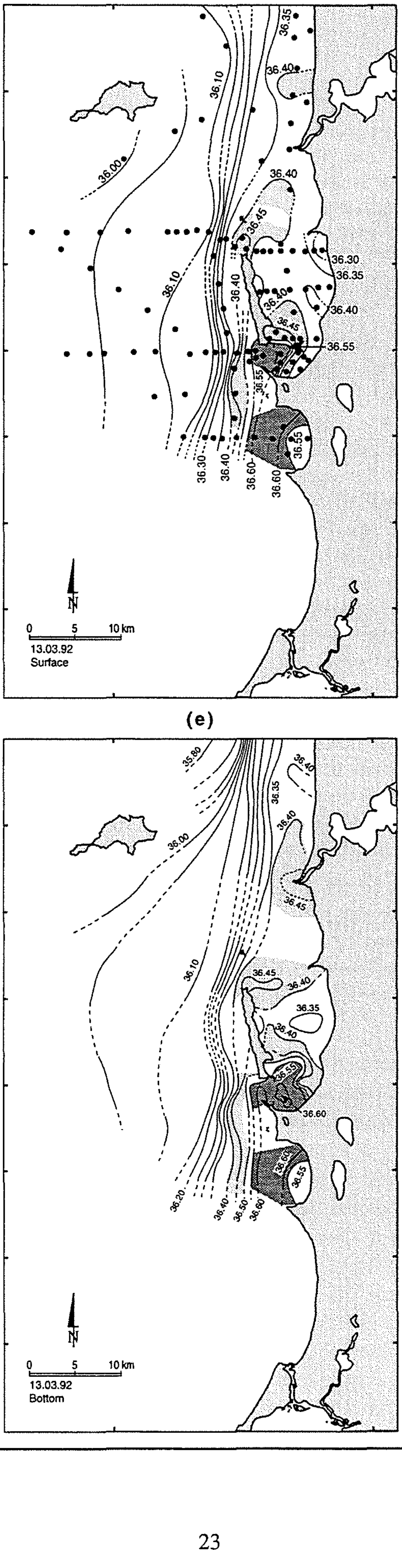


Figure 9 continued.

suggests that outflows from the hypersaline Peel-Harvey estuary enhanced by the effects of evaporation in shallow water contributed to a salinity and density elevation of the nearshore waters. Furthermore, it was concluded that this nearshore water mass was advected northward and intruded as bottom flows into Warnbro Sound and Cockburn Sound. While some evidence of high salinity water intrusions near the sea bed of Cockburn Sound can be seen in the time-series of vertical salinity stratification (Figure 10) (c)), these appear to be transitory features, and it is clear that the combined mixing by wind and penetrative convection was usually energetic enough to remove them.

4.6.2 'Autumn' regime

During the 'autumn' regime relatively strong density differences were recorded between the Sound and the shelf (Figure 6a), particularly before the commencement of significant estuarine outflows and consequent freshening of Cockburn Sound. In addition, moderate vertical density stratification was recorded within the Sound (Figure 7) (D'Adamo and Mills, 1995b). D'Adamo and Mills (1995b) concluded that the cross-shelf density structure led to inflows of buoyant water from the adjacent shelf zone over resident Sound water that was both colder and more saline, resulting in a stratified structure characterised by inclined isotherms, isohalines and hence isopycnals between the shelf and Sound. A typical example of the resulting cross-shelf structure is presented in Figure 8b, from the CTD survey of 3 May 1994, representative of the early to middle phase of the 'autumn' regime. As indicated by the contours, the basin was vertically stratified in density by buoyant inflows of adjacent shelf waters, with both the vertical salinity and temperature structure contributing to the density stratification. During the 'autumn' regime the winds are relatively weak compared to other times of the year and therefore mixing between surface and bottom waters by either wind-stress or penetrative convection can be absent for extended periods of time (D'Adamo and Mills, 1995b). D'Adamo and Mills (1995b) performed mixing analyses for this period and concluded that for typical strengths of vertical density stratification recorded in the Sound, complete vertical mixing probably only occurs about 4-6 times per month, and they suggested that extended periods of up to about 3 weeks could occur when the energy available for vertical mixing was insufficient to eliminate typical vertical gradients throughout the full depth of the water column.

An application of the studies of the hydrodynamics during the 'autumn' regime has been to highlight the potential for prolonged vertical stability in the water column to lead to de-oxygenation in the bottom waters. De-oxygenation can influence the recycling pathways of nitrogen derived from organic loadings to the sediments by inhibiting denitrification, resulting in greater availability of bio-available nitrogen (D'Adamo and Mills, 1995b; Masini, 1995; Barry, 1995; Coleman, 1995).

In the transitionary period between the 'autumn' and 'winter-spring' regimes the Sound was found to be of comparable density to the adjacent waters of Sepia Depression, however, the basin and Sepia Depression were relatively dense compared to the mid-shelf region south of Rottnest Island. The contours of cross-shelf STD structure from 24 July 1992, presented in Figure 8c, highlight these main features of the horizontal structure. These data represent the period approaching the reversal ('autumn' to 'winter-spring') in the cross-shelf density gradient between Cockburn Sound and shelf waters south of Rottnest Island. The salinity structure indicates that estuarine water had begun to enter the Sound sufficiently to reduce its salinity to below that of mid-shelf waters, and shows the low salinity plume emanating from the Swan-Canning Estuary (Figure 8c). However, when comparing the mean density of the basin to that of mid-shelf waters it can be seen (Figure 8c) that the basin is still relatively dense, due to the large cross-shelf temperature differential. This situation changes as winter progresses, when further inputs of low salinity plumes into the Sound result in its salinity being considerably less than both Sepia Depression and the shelf waters, as will be discussed below in Section 4.6.3. Further data surveys would be required to better resolve the characteristics of the cross-shelf

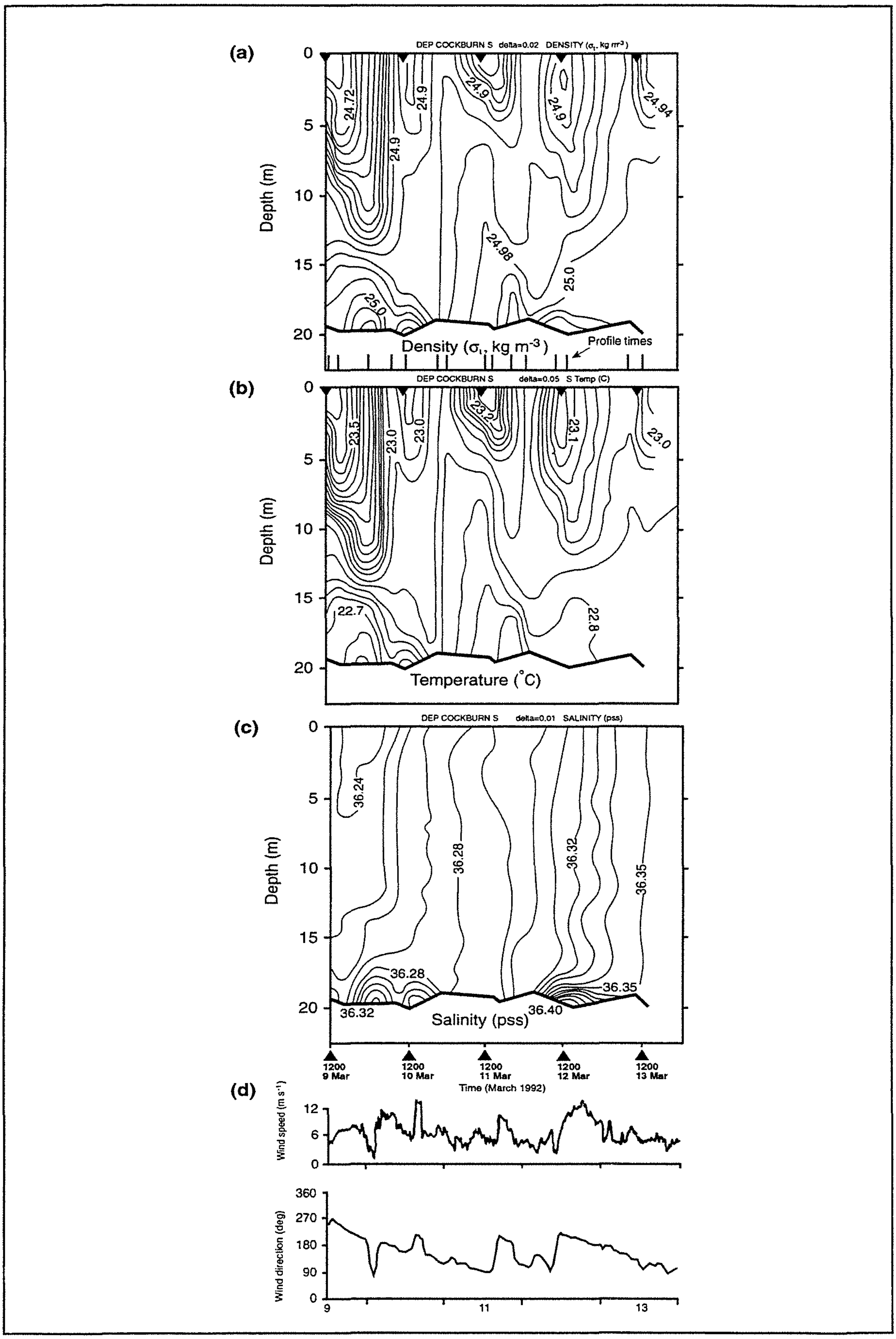
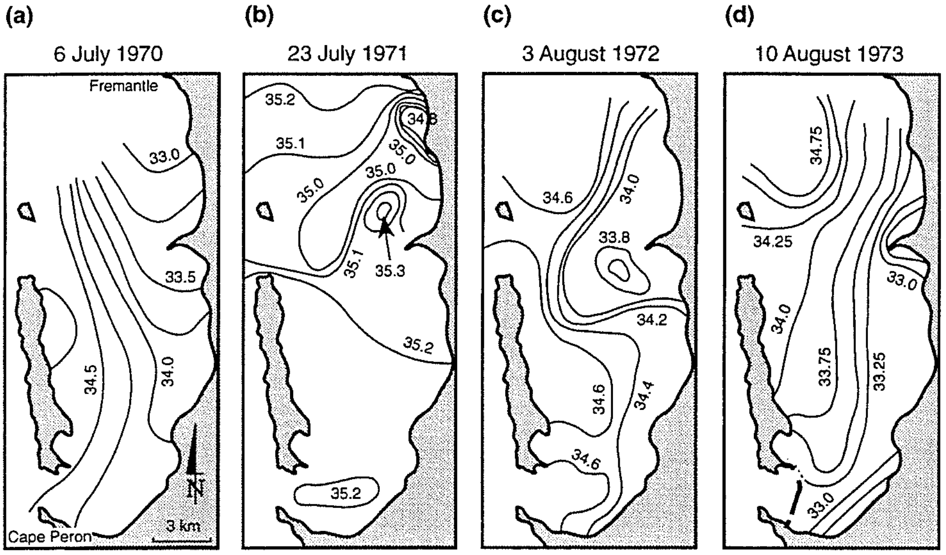


Figure 10. Time series contour plots of vertical structure as it varied between 9 and 13 March 1992 in central Cockburn Sound and time series plots of wind velocity at Naval Base (a: density in sigma-t units (kg m^{-3}), b: temperature in °C, and c: salinity in pss). Source: D'Adamo and Mills (1995a).

salinity, temperature and density gradients during the transition from the 'autumn' to 'winter-spring' regimes.

4.6.3 'Winter-spring' regime

During the 'winter-spring' regime the Sound is characteristically less dense than shelf waters. D'Adamo *et al.* (1995a) have shown that the principal mechanism which causes this is the southward long-shore advection of low salinity plumes from the Swan-Canning Estuary into the Sound under the forcing of winds from the northern quadrants. These winds typically occur during 1-2 days of each synoptic (7-10 day) meteorological cycle during winter and early spring (Breckling, 1989). The resulting horizontal salinity field is exemplified by the surface salinity data in Figure 11 (Environmental Resources of Australia, 1970, 1971, 1972 and 1973), collected over a typical range of winter estuarine outflow conditions. Later in the 'winter-spring' regime the cross-shelf density difference is reinforced by differential heating, where the temperature of the shallower nearshore zone increases at a greater rate compared to the adjacent deeper shelf waters. Throughout this regime the buoyancy fluxes into the basin lead to relatively strong vertical density stratification (Figure 7). D'Adamo *et al.* (1995a) analysed the density structure and concluded that density effects have a strong influence on the vertical mixing behaviour and the circulation patterns of the Sound and adjacent waters. During this regime the nearshore region between Fremantle and Cape Peron can therefore be described as a *Region of Freshwater Influence* (ROFI, a term attributable to Simpson *et al.* 1993b).



Winds during preceding 48 hours

W-NW, 5-7.5 ms^{-1}	E-NE-N, 0-7.5 ms^{-1}	NE-NW, 10-15 ms^{-1}	N-NE, 7-13 ms^{-1}

Swan-Canning Estuary freshwater discharge during preceding 48 hours (m^3 s^{-1})

55	4	20	125

Figure 11. Surface salinity fields (ppt) between Fremantle and Cape Peron during the four successive winters of (a) 1970, (b) 1971, (c) 1972 and (d) 1973, showing the result of southward wind-driven transport of low salinity water from the Swan-Canning Estuary into Owen Anchorage and Cockburn Sound after winds from the northeast and northwest quadrants. Re-drawn from Environmental Resources of Australia (1970, 1971, 1972 and 1973, respectively).

The cross-shelf density, salinity and temperature contour plots from the cross-shelf CTD surveys of 22 August 1991 and 21 October 1992 are presented in Figures 8d and e, respectively, to exemplify the vertical and cross-shelf stratification that is typical for the early and late phases of the 'winter-spring' regime, respectively (D'Adamo *et al.* 1995a). There is an appreciable horizontal density difference between the waters of the shelf and Sound and also a pronounced vertical density structure within the Sound.

In the early to mid 'winter-spring' regime the relatively low salinity of the inner Sound renders it less dense than adjacent shelf waters, and this is despite the fact that at this time the Sound water is relatively cold with respect to shelf waters. The salinity difference therefore dominates in its effect on density difference. Figure 8d, from the cross-shelf survey of 22 August 1991, exemplifies these traits.

After low salinity estuarine plumes enter the Sound they are typically mixed with Cockburn Sound water by storm winds (> 10 m s^{-1}) which normally accompany low pressure systems as they cross the coast (D'Adamo *et al.* 1995a).

One such storm occurred on 19 August 1991 during an intensive 10-day field survey of the winter hydrodynamics of Cockburn Sound (D'Adamo *et al.* 1995a). That particular storm caused complete vertical mixing of the Sound. After the storm, moderating southerly winds were found to advect buoyant water out of the Sound, leading to replacement flows into Cockburn Sound, particularly through the larger northern opening, of denser shelf water which then sank to the bottom under gravity (Figure 12). The plunging inflow from the north was found to be deflected to the eastern side of the central basin, presumably in response to the earth's rotation. Within 2-3 days after the storm, the entire deep basin was covered by dense inflow and a near-bottom pycnocline was reformed between the more saline, and therefore denser, inflowing shelf water and resident basin water. By inference, most of the water which was adjacent to the bottom of the deep basin in Cockburn Sound following full-depth mixing by the storm was displaced vertically, entered the diurnal mixed layer (0-15 m depth) where it was subject to regular mixing during diurnal wind-mixing and penetrative convection cycles. Water from the diurnal mixed layer is driven out of the Sound through the northern opening by wind stress associated with moderating southerly winds which occur after the 'front' has crossed the coast. D'Adamo *et al.* (1995a) concluded that this dynamical sequence is repeated on average every synoptic cycle (7-10 days) throughout the 'winter-spring' regime.

Another important feature of the 'winter-spring' dynamics in the Sound is that throughout a synoptic cycle the water column is subjected to the diurnal forcings of heating and cooling, and also to occasional weak wind-mixing. As a result, the water column goes through repeated cycles of vertical density stratification and mixing above the level of the main pycnocline, which is the vertical zone across which the most intense density stratification occurs, due to salinity stratification. The time series contour plots in Figure 13 from central Cockburn Sound during the winter survey of 13-23 August 1991 (from D'Adamo *et al.* 1995a) exemplify these features. During the day-time the upper layer is heated and stratified, whilst at night it is cooled and mixed by penetrative convection to the level of the main pycnocline, which was at about 15 m depth during the 10-day survey. Hence, the upper portion of the water column is regularly mixed in winter. The storm of 19 August is shown to have eliminated the vertical structure. After this, the reformation of the vertical structure was due to the relatively dense inflows of shelf water into the basin following the storm, as discussed above. Interestingly, the strong vertical stratification of the parent pycnocline is as a result of renewal of bottom basin water

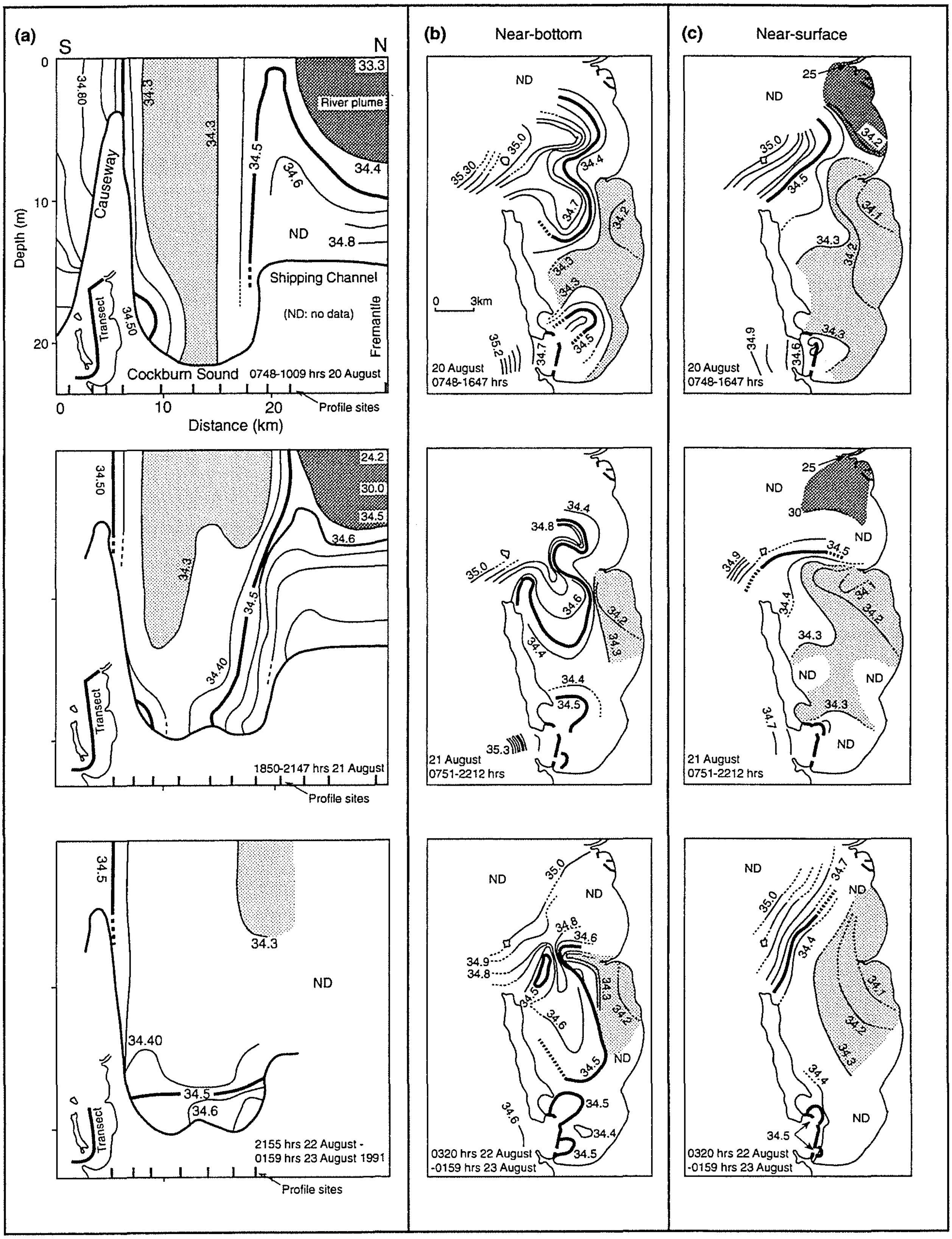


Figure 12. Time series of (a) vertical sections, (b) near-bottom plan and (c) near-surface plan sections of salinity structure (pss) in Cockburn Sound showing deep-water renewal of high salinity shelf water and surface exit of low salinity basin water between 20 and 23 August 1991, after a storm on 19 August which left the Sound fully-mixed vertically but with denser water at its northern and southern regions. Contour interval is 0.1 pss. The river plume regions are shaded dark and water less than 34.3 pss within the basin is shaded light. All profiling site locations are shown in Appendix A.

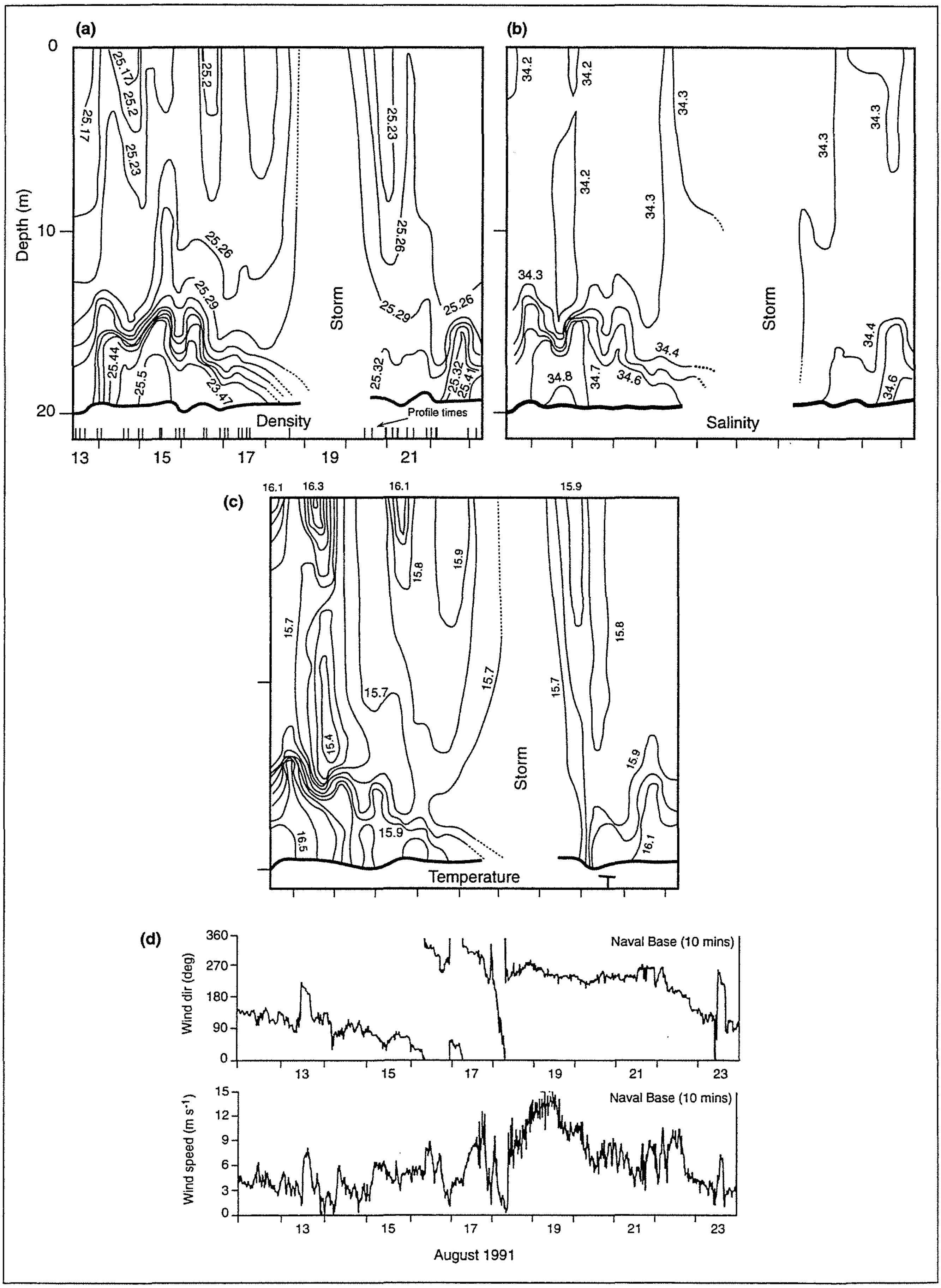


Figure 13. Time series contour plots of the vertical stratification in (a) density (in sigma-t units at an interval of 0.03 kg m^{-3}), (b) salinity (practical salinity scale (pss) at an interval of 0.1 pss) and (c) temperature (°C at an interval of 0.1 °C) in central Cockburn Sound. Wind data from Naval Base (12m height) is shown in (d). Note the changes in the stratification due to heating, cooling and strong storm winds.

with denser shelf water. The flushing process has therefore promoted the re-establishment of vertical stratification.

The action of wind stress also resulted in upwelling and downwelling of the density structure in Cockburn Sound during the strongly stratified winter period, and in addition, Coriolis effect was suggested to be primarily responsible for observed oscillations of the density structure transverse to the direction of the wind (D'Adamo *et al.* 1995a).

As the cycle enters the spring season the Sound warms due to the increasing air temperatures and increasing inputs of solar radiation (Figure 4). River discharge weakens in this period and hence buoyancy flux due to freshwater inputs reduces. However, the relative warming of the Sound maintains its relatively low density with respect to adjacent mid-shelf waters. The solar heating also produces strong vertical temperature (and thus density) stratification in Cockburn Sound (see also D'Adamo, 1992). Figure 8e, from the cross-shelf survey of 22 October 1992, exemplifies these traits. Hence, in this period even though the salinity difference decreases, the enhanced warming of the Sound results in a maintenance of a cross-shelf density difference (the Sound being buoyant) and hence the likely dynamics after storm events can be expected to be essentially similar to that described for the mid-winter period above, namely exchange in which relatively dense shelf water enters and sinks to the bottom of the basin during deep-water renewal events.

It appears that exchange in Cockburn Sound during the 'winter-spring' regime occurs more rapidly than has been suggested by earlier studies which assumed that flows were primarily barotropic. The role of density effects (arising largely from the basin-shelf horizontal density differences) combined with wind forcing leads to a layered circulation and exchange that favours efficient flushing of the Cockburn Sound basin.

In the transitionary period between 'winter-spring' and 'summer' the Sound remains relatively buoyant with respect to the shelf (Figure 6a), but daily winds begin to strengthen significantly due to the onset of regularly occurring strong sea-breezes (Breckling, 1989). D'Adamo and Mills (1995a) investigated the vertical mixing characteristics of the Sound during typical summer conditions, when sea-breezes with winds greater than about 10 m s^{-1} occur, and they suggest that from about December onwards winds are strong enough to regularly eliminate vertical stratification in the Sound. The field survey of 17 December 1992 captured one such occasion when the Sound was relatively well-mixed after winds with speeds of greater than 10 m s^{-1}, as characterised by the cross-shelf vertical stratification data from that day (Figure 8f).

5. Conclusions

Repeated measurements of the salinity, temperature and density characteristics in the waters between Cockburn Sound and the mid-shelf between 1991 and 1994 provided the basis for determining the annual cycles in cross-shelf salinity, temperature and density differences. The cross-shelf density difference has been identified as an important factor influencing the nature of the major hydrodynamic regimes in Cockburn Sound, named the 'summer', 'autumn' and 'winter-spring' regimes, respectively. The key elements of these regimes are summarised in Table 2.

The 'summer' regime occurs from late spring to early autumn. The hydrodynamics during this regime was also investigated by the complementary study of D'Adamo and Mills (1995a). In 'summer' evaporation increases the salinity and solar radiation increases the temperature of the nearshore zone. Freshwater buoyancy fluxes from local and remote sources are small. Two

Table 2. Summary of the seasonal hydrodynamic regimes for Cockburn Sound.

	SUMMER REGIME	AUTUMN REGIME	WINTER-SPRING REGIME
DRIVERS			
• **Evaporation**	• Evaporation maintains a higher salinity in the basin than in the shelf zone	• Evaporation maintains a higher salinity in the basin than in the shelf zone	• Evaporation rates are relatively small
• **Surface heat flux and Leeuwin Current**	• Solar radiation maintains a higher temperature in the basin than in the shelf zone	• Solar radiation diminishes, Leeuwin Current strengthens offshore, and basin temperature falls below shelf temperature	• Lower solar radiation/ air temperatures and strong offshore Leeuwin Current maintains lower temperature in the basin than in the shelf zone
• **Freshwater inflows**	• Freshwater inflows are insignificant compared to other buoyancy fluxes	• Freshwater inflows are insignificant compared to other buoyancy fluxes	• Brackish water plumes of river origin are driven into Cockburn Sound by winds from the northeast and northwest quadrants reducing the salinity of the Sound to less than the shelf zone
• **Wind regime**	• Strong sea breezes (> 20 knots) occur on average 10-15 times per month	• Wind fields are relatively weak but interrupted by occasional strong storms (~ 4-6 times per month)	• Wind fields are relatively weak but interrupted by occasional strong storms (~ 4-6 times per month)
EFFECTS	• Regular full-depth mixing (10-15 times per month) • Basin and shelf waters of similar density • Circulation mainly as wind-driven surface layer overlying topographic gyres	• Persistent vertical salinity and temperature stratification • Basin density typically greater than shelf density • Oceanic inflows enter the basin as buoyant surface flows • Full-depth mixing occurs only during storms (on average 4-6 times per month) but storms can be separated by up to 3 weeks during autumn • Limited vertical mixing due to penetrative convection (surface cooling) occurs nightly but is generally restricted to 10-15 m depth	• Buoyant brackish plumes cause vertical salinity stratification • Basin density typically less than shelf density • Vertical mixing by penetrative convection nightly but limited to 15 m depth • Periodic full-depth mixing by storms (~4-6 times per month) • Following full-depth mixing shelf water enters the basin via the north and south openings and covers the bottom in the form of plunging bottom flows • Weak surface mixing and winds drive uplifted water out of the basin via the openings
OUTCOMES	• Predominantly barotropic circulation dominated by wind-driven mechanisms • Barotropic models (which do not consider density effects) are likely to capture the main features of circulation and mixing	• Density effects have a significant influence on circulation and mixing • Bottom water in the basin has a relatively long residence time • Baroclinic modelling required to capture the influence of density effects	• Density effects have a significant influence on circulation and mixing • Bottom water is regularly replaced by deep water renewal following full-depth mixing by storms • Baroclinic modelling required to capture the influence of density effects

characteristics are noted. Firstly, cross-shelf density differences are relatively small or insignificant in terms of their influence on the mean hydrodynamic behaviour of Cockburn Sound. Secondly, although there is a characteristic diurnal cycle of day-time heating through the water surface, the prevalence of strong sea-breezes and the complementary mixing strength of nightly episodes of penetrative convection causes full-depth mixing in the Cockburn Sound basin at least 10-15 times per month. From these two factors it is concluded that the circulation of Cockburn Sound and adjacent waters is predominantly controlled by barotropic mechanisms, driven by wind stress and it is suggested that barotropic numerical hydrodynamic models are adequate to simulate the essential features of the mean hydrodynamics. However, during periods of milder winds it is to be noted that relatively weak vertical and horizontal density gradients can form and hence during such periods the effects of density gradients may need to be considered by baroclinic numerical hydrodynamic models.

The 'autumn' regime occurs from autumn to early winter. The hydrodynamics of this regime was also investigated by the complementary study of D'Adamo and Mills (1995b). In 'autumn' evaporation and cooling of the nearshore zone results in Cockburn Sound being more dense than shelf waters. Solar radiation and the introduction of relatively buoyant low salinity water from the adjacent shelf region into the Sound sets up relatively strong vertical stratification in the Sound. Winds are relatively weak during 'autumn' and wind-mixing and penetrative convection typically mix to no further than about 10-15 m depth in the Sound. The vertical stratification is eliminated throughout the full water depth only when winds are stronger than about 7.5-10 m s^{-1} for about 8-13 hours, during storms for example, but this only occurs on average 4-6 times per month with periods between full-depth mixing events lasting up to about 3 weeks. The relatively high density of the Sound and relatively infrequent occurrence of full-depth mixing therefore results in bottom waters having longer residence times than waters nearer the surface. The importance of vertical and horizontal density gradients to the structure in 'autumn' suggests that the effects of density gradients need to be considered by the application of baroclinic numerical hydrodynamic models.

The 'winter-spring' regime occurs from mid-winter to spring. The hydrodynamics of this regime were also investigated by the complementary studies of D'Adamo *et al.* (1995a and b). In 'winter-spring' flows of low salinity estuarine water from the Swan-Canning Estuary result in the coastal zone immediately south of Fremantle becoming a *Region of Freshwater Influence*, similar to other such regions from around the world (see, for example, Simpson *et al.* 1993b; Simpson and Rippeth, 1993). The estuarine outflows begin to flow strongly after the first significant runoff in early-mid winter. Then northwesterly winds that occur as part of synoptic (7-10 day) winter meteorological cycles transport buoyant plumes from the Swan-Canning Estuary into the Sound. Ensuing storms (part of the same synoptic cycles) then mix the buoyant plume waters throughout the entire depth of the Sound. Eventually, when a sufficient number of estuarine plumes have been driven into the Sound, its resident waters become appreciably less dense than the shelf waters. This density difference is important to the basin-scale flushing: in the moderate to weak wind periods between winter storms, water exchange occurs, and the relatively saline, dense water which flows into the Sound sinks to the bottom of the basin. Hence, resident basin water is displaced and transported upward from the bottom to become part of the diurnally-mixed layer of the water column, where gentler wind mixing and penetrative convection mixes the water column. Water from this diurnally-mixed upper layer (above the parent pycnocline and the bottom layer) is driven across the openings of Cockburn Sound under the influence of wind forcing. In terms of the choice and application of models for Cockburn Sound and adjacent waters, the importance of vertical and horizontal density gradients to the structure in 'winter-spring' suggests that the effects of density gradients need to be considered by the application of baroclinic numerical hydrodynamic models.

In general, it is concluded that the influence of horizontal and vertical density gradients on the hydrodynamic behaviour of the Sound, including the vertical mixing and flushing characteristics, is more important than previously thought. These results assist in the choice and application of hydrodynamic models to southern metropolitan coastal waters off Perth.

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Appendix A

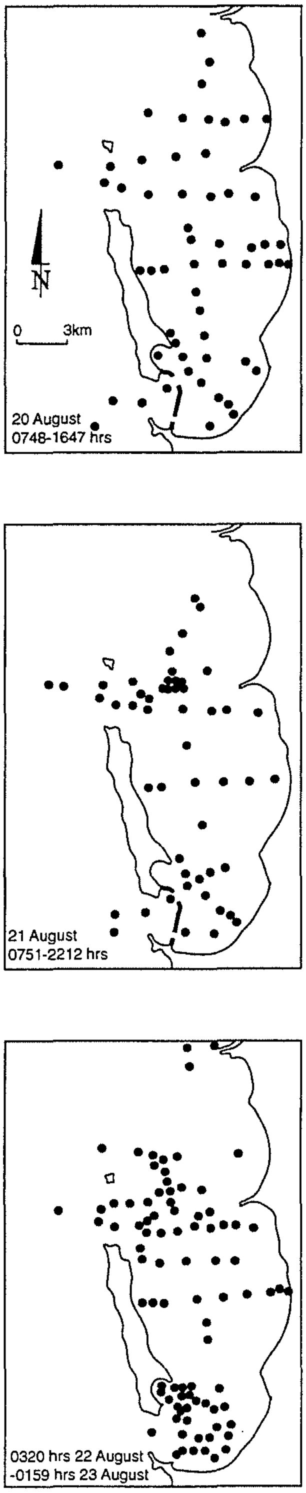

Figure A1. The locations of all conductivity-temperature-depth (CTD) profiling sites at which data were used to derive the contours in Figure 12.