Winter mixing and transport in the stratified coastal embayment of Cockburn Sound, Western Australia.

A contribution to the Southern Metropolitan Coastal Waters Study (1991-1994)

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Abstract

The exchange between Cockburn Sound and adjacent shelf waters during mid winter and early spring is strongly influenced by outflows of low salinity Swan-Canning Estuary water and by the passage of winter synoptic weather patterns every 7-10 days, bringing storm events with intervening periods of weak to moderate winds.

A typical sequence of exchange and mixing processes begins with the southward advection of low salinity plume water from the mouth of the Swan-Canning Estuary, through Owen Anchorage and into the sound, driven by northeasterly-northwesterly winds that precede winter storms. Observations and analysis of vertical mixing showed that the buoyant estuarine plume water can be mixed with Cockburn Sound water by storm winds (> 10 m s^{-1}) which normally accompany low pressure systems as they cross the coast. Repeated plume incursions and mixing events result in a characteristic horizontal density difference between Cockburn Sound and the adjacent shelf region.

After a storm which results in full-depth mixing in the basin, moderating southerly winds advect surface waters out of the sound, leading to replacement inflows of relatively high salinity (and therefore denser) offshore water into Cockburn Sound via the openings. These inflows then sink to the bottom and are transported across the interior of the basin. The major inflow, from the north, appears to be spatially biased towards the eastern side of the central basin, consistent with a response to the earth's rotation. It takes 2-3 days after cessation of the storm for the sea bed of the deep basin to be entirely covered by a lower layer of higher salinity, higher temperature water. The dense water inflows and formation of this lower layer result in the upward displacement of more buoyant water which had been mixed to the bottom of the Cockburn Sound basin during the storm. This displaced water then becomes part of the diurnal mixed layer (0-15 m depth) where it is regularly mixed during moderate wind and penetrative convection events. However the strong pycnocline (due to sharp salinity gradients) separating the diurnal mixed layer and the bottom layer is able to withstand all but the strongest mixing events (those which are associated with the periodical winter storms). Near-surface waters are transported northward out of the sound by wind-driven advection caused by the moderating southerly winds which generally prevail after the storm has passed.

These findings were drawn from winter oceanographic surveys and supported by numerical simulations. On the basis of long-term wind records and the frequency of occurrence of storms, it is concluded that this dynamical sequence is repeated on average every synoptic cycle (7-10 days) throughout the winter-spring regime.

The action of wind stress also causes upwelling and downwelling of the density structure in Cockburn Sound. The field measurements and baroclinic modelling results both suggest this dynamical response to wind stress and also indicate that, in Cockburn Sound, the Coriolis effect causes tilting of the density structure transverse to the direction of the wind.

It appears that exchange in Cockburn Sound during winter-spring conditions occurs more rapidly than has been suggested by earlier studies whose deductions were based on depth-averaged numerical modelling and assumed that flows were primarily barotropic. This paper shows that the presence in winter of horizontal density stratification between the near-shore basin zone and the open shelf waters promotes a layered component of circulation in Cockburn Sound. The role of density effects in modifying the circulation in Cockburn Sound and thereby significantly adding to the flushing efficiency of wind-driven exchange has been highlighted.

1. Introduction

1.1 General

This paper presents the findings of an oceanographic study of the winter hydrodynamics of Cockburn Sound, a semi-enclosed stratified basin on the southwest coast of Western Australia (Figures 1 and 2). The main aim of the investigation was to clarify the influence that density stratification has on mixing and circulation within the sound, and on water exchange between the sound and the surrounding shelf. Cockburn Sound is approximately 15 km x 8 km in horizontal dimensions and is one of a series of semi-enclosed coastal embayments which run parallel to the coast, and which are protected from the full force of oceanic swells and currents by reefs, banks and islands. The sound communicates with the adjacent shelf region via relatively shallow openings at its northern and southern ends. Tides in the region are predominantly diurnal and have a small (< 1 m) range (Hodgkin and Di Lollo, 1958). Hence, except for the most restricted areas within the sound, tidal currents are weak and of order 0.01 m s^{-1}. Regional currents (Steedman and Craig, 1979; 1983) and wave motions (Pattiaratchi *et al.* 1995) are reported to cause only relatively minor flows within the protected basins in this region. Wind and density effects, however, are considered to be significant to the overall dynamics of the sound (Steedman and Craig, 1983).

The analysis builds on the results of past oceanographic studies of Cockburn Sound and adjacent waters (e.g. Maritime Works Branch, 1977a and b; Steedman and Craig, 1979 and 1983; and other studies reviewed by Hearn, 1991 and D'Adamo, 1992). It investigates the winter hydrodynamics based on the results of a field survey, which spanned a typical 7-10 day winter synoptic meteorological period (Breckling, 1989). The field work included basin-wide conductivity-temperature-depth (CTD) profiling, current metering and drogue tracking. Other routinely collected hydrological and meteorological data were also used in the analysis. The roles of wind, density effects and rotation on the mixing and transport were evaluated. Past studies have indicated that the major sources of buoyancy to the sound in winter are low salinity plumes from the nearby Swan-Canning Estuary and day-time heating due to short-wave radiation (D'Adamo, 1992; Hearn, 1991). The stratifying potential of these sources is investigated more fully in this study, as is the potential for vertical mixing by wind-stress and penetrative convection. Use is also made of results from numerical simulations of the wind-driven transport of low salinity plumes from the Swan-Canning Estuary (Mills and D'Adamo, 1995a), for which the three-dimensional Princeton Ocean Model (Blumberg and Mellor, 1987; Herzfeld, 1995) was applied. The winter dynamics of exchange between Cockburn Sound and shelf waters, and the role of density effects, have also been modelled (Mills and D'Adamo, 1995b), and selected results are presented.

The field data revealed important aspects of the hydrodynamics of Cockburn Sound and surrounding waters during three distinct phases of a typical winter synoptic wind cycle.

The first phase of the wind cycle was characterised by moderate northeasterly-northwesterly winds (5-10 m s^{-1}) which preceded the arrival at the coast of a low pressure storm front. For this phase of the cycle, we investigated the wind-driven transport of Swan-Canning estuarine plumes into Cockburn Sound, and wind-forced upwelling and downwelling of the mean density structure of the sound, considering the influence of rotation.

As the front crossed the coast, winds swung through west to west-southwest and increased in strength (10-15 m s^{-1}). Field data on vertical mixing due to winds associated with a storm were

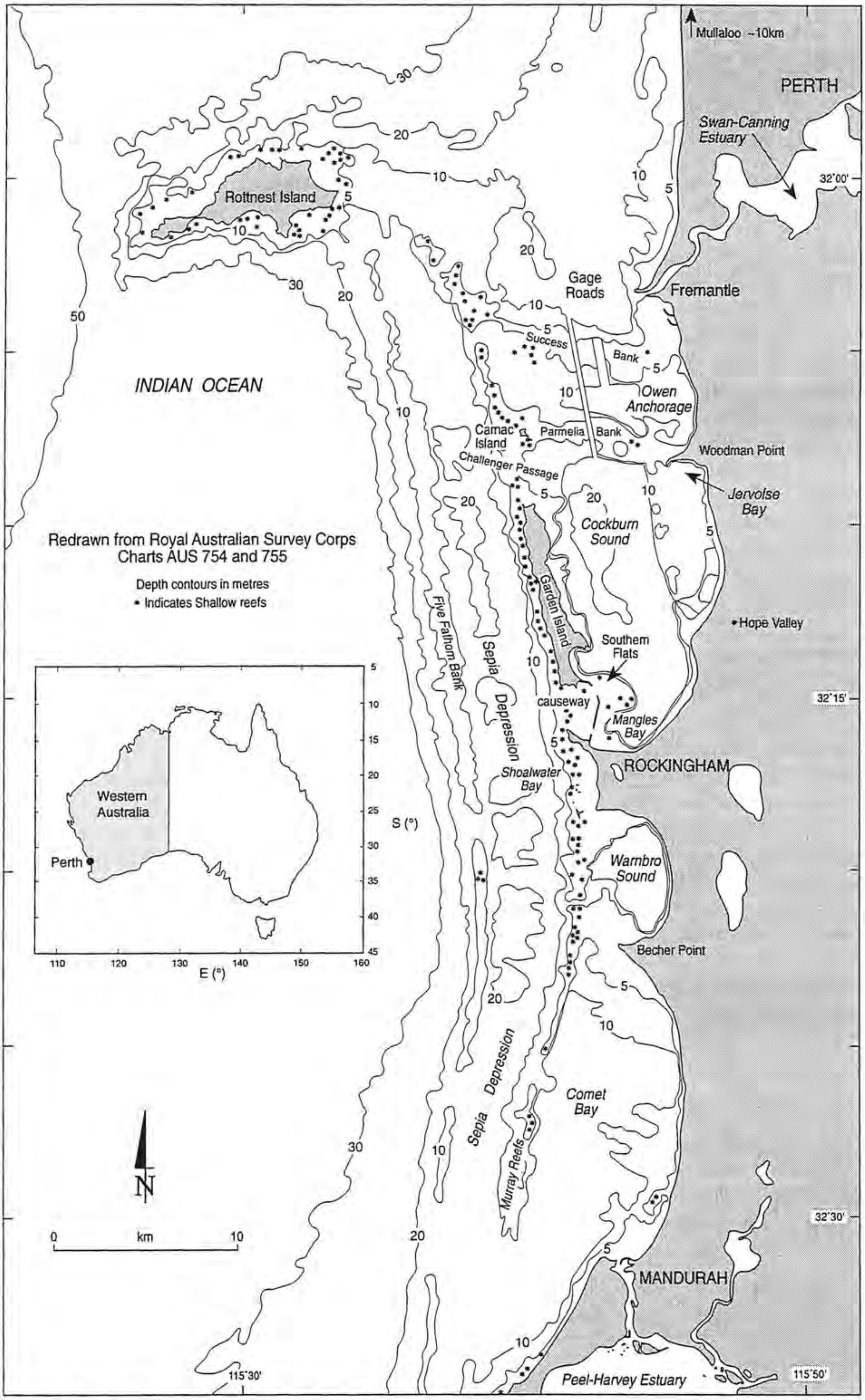


Figure 1. Study region of the Southern Metropolitan Coastal Waters Study.

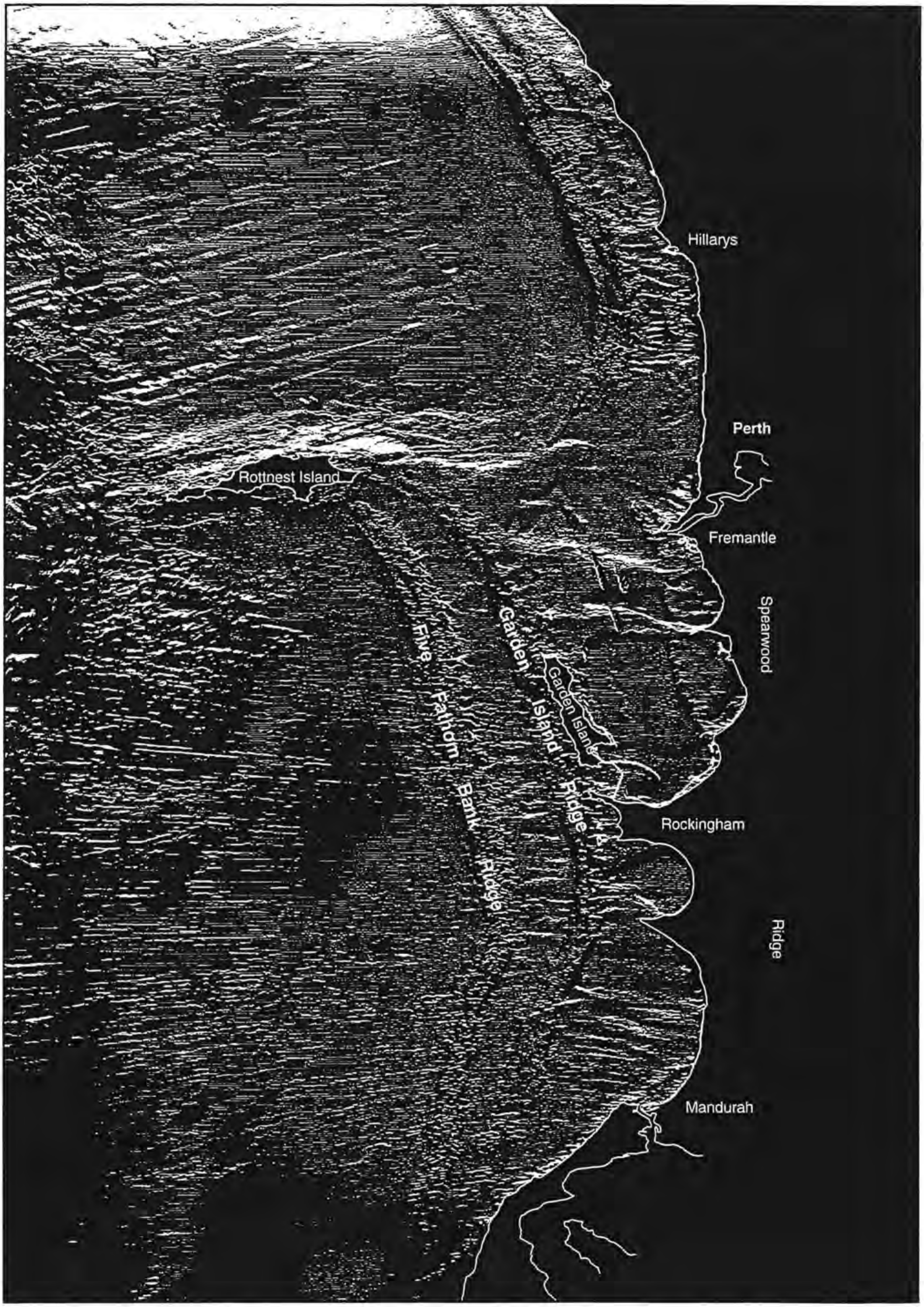


Figure 2. Three-dimensional perspective plot of the bathymetry of Perth's coastal zone from Hillarys to Tim's Thicket and out to west of Rottnest Island.

analysed for this second phase of the wind cycle, and a predictive methodology was applied to estimate the potential for winds of varying strengths to vertically mix through typical winter density gradients.

Finally, after the storm front had passed through the region, winds moderated (< 10 m s^{-1}) from the south-southwest. For this third phase, wind-driven advection of surface water out of the sound and deep-water renewal by the inflow of relatively high salinity (and therefore denser) oceanic water into the basin via the openings was investigated.

The cycling in day-time stratification due to solar radiation and night-time mixing due to cooling and resultant penetrative convection was examined by analysing closely-spaced time-series measurements of the vertical structure throughout the survey period.

From a hydrodynamic perspective, the importance of buoyancy fluxes to a coastal zone from estuarine discharges of low salinity water has been highlighted in recent investigations of other *Regions of Freshwater Influence* (ROFI) such as the Clyde Sea ROFI on the west coast of Scotland (Simpson and Rippeth, 1993) and the Rhine River ROFI in the North Sea (Simpson *et al.* 1993a). Those studies have defined a ROFI as the region where the vertical and horizontal density gradients arising from freshwater discharge to the coastal zone have significant influences on vertical mixing and exchange patterns. Vertical density structure can inhibit turbulent mixing of the water column, and horizontal gradients can either lead to trapping of relatively dense bottom waters in a basin or facilitate deep-water renewal by density-enhanced exchange, depending on the sign of the relative density difference between the basin and shelf waters. We investigated these influences for Cockburn Sound during winter conditions.

The investigation formed a component of the Southern Metropolitan Coastal Waters Study (SMCWS) (1991-1994), conducted by the Department of Environmental Protection of Western Australia (DEP). The objective of the SMCWS was to provide a better technical basis from which to manage the cumulative environmental impacts of contaminants entering these coastal waters (Simpson *et al.* 1993b). As part of the SMCWS ecological models (Masini *et al.* 1993) were developed to assist in formulating strategies for the management of these waters. To facilitate these objectives, a better understanding of the seasonal characteristics of the hydrodynamics of the nearshore embayments was required. This paper addresses the winter period, and complements other technical reports on the oceanography of the southern metropolitan coastal waters for winter (D'Adamo *et al.* 1995; Mills *et al.* 1996), summer (D'Adamo and Mills, 1995a), autumn (D'Adamo and Mills, 1995b) and seasonal (D'Adamo and Mills, 1995c) hydrodynamic processes.

1.2 Overview of past local environmental and oceanographic studies

Over the past 30-40 years the growth in major industrial activity and urbanisation in the vicinity of Cockburn Sound has seen it become increasingly utilised as a receiving water body for toxic substances and nutrients via outfalls, channels and groundwater. As a result, toxic contamination of the sediments and biota occurred and nutrient inputs promoted the excessive growth of nuisance phytoplankton and macroalgae (Department of Conservation and Environment, 1979; Cary *et al.* 1991; Simpson *et al.* 1993b) with the consequent loss of large areas of seagrasses due to light limitation. These problems, in conjunction with the construction of a causeway in 1973, which partially blocked throughflow at the southern opening of the sound (Chittleborough, 1970; Crook, 1971), provided the motivation for many environmental studies during the 1970's to 1990's (summarised in Simpson *et al.* 1993b), with the SMCWS being the most recent.

Intensive oceanographic studies were conducted from 1969 to 1977 due to concern that the causeway could restrict flushing of contaminants from the sound. These studies included basin-scale salinity-temperature profiling, current metering, meteorological and hydrological data collection and numerical modelling (reviewed by Hearn, 1991 and D'Adamo, 1992). Based on basin-wide isohaline tracking, flux measurements through the openings and numerical modelling studies, it was concluded that the causeway would reduce flows through the southern opening, thereby reducing the combined rate of volume exchange across the northern and southern openings of the sound (Maritime Works Branch, 1977a). The modelling was two-dimensional (depth-averaged) and did not account for the effects of density gradients. Although the field data indicated the presence of vertical and horizontal density gradients, their effect on circulation and mixing inside the sound could not be fully addressed by numerical models that were available at that time.

Steedman and Craig (1979, 1983) conducted further oceanographic field studies and hydrodynamic scaling analyses. They concluded that density gradients could significantly affect the hydrodynamics of the sound when winds were less than about 5 m s^{-1}. For stronger winds they suggested that the hydrodynamic behaviour of the system would be dominated by wind stress. Based on this conclusion, the circulation of Cockburn Sound was simulated with a two-dimensional vertically-averaged numerical model which predicted basin-scale topographic gyres (Steedman and Craig, 1983). Limitations in the accuracy of field instrumentation, computing power and numerical modelling techniques precluded a more detailed understanding of the hydrodynamic influence of density stratification. Steedman and Craig (1983) pointed out the need for further work to investigate this issue. Hearn (1991) and D'Adamo (1992) reviewed past efforts to model Cockburn Sound and adjacent coastal waters and re-analysed many of the oceanographic data sets collected between 1969 and 1991, arriving at a similar conclusion.

D'Adamo (1992) found that throughout the year vertical density differences (top to bottom) through the water column in central Cockburn Sound were in the range 0.1-0.5 kg m^{-3}, typically, and suggested that erosion of the pycnocline to the bottom would only be achieved by wind-stress when wind speeds exceeded 5-10 m s^{-1} for periods of 5-10 hours or more. Horizontal salinity, temperature and density stratification in the basin was found to be common with very few recorded instances of complete homogenisation of salinity or temperature at a basin scale. D'Adamo (1992) suggested that density effects could be expected to influence the circulation and mixing in Cockburn Sound for a significant percentage of the time (greater than 50 % at least), and that barotropic circulation would be dominant only when winds are particularly strong (of order 10 m s^{-1}), such as during strong summer sea-breezes or winter storm fronts.

Furthermore, D'Adamo (1992) suggested that, because the basin is largely land-locked and currents (~ 0.1 m s^{-1}) are typically weak (Steedman and Craig, 1983), the vertical mixing in the centre of the basin could be represented, for short time scales (< 0.5 day), by analytical tools developed for closed basins such as lakes and reservoirs (see Mortimer, 1974, Csanady, 1975; Spigel *et al.* 1986; Imberger and Patterson, 1990). It was reasoned that if the time scale of a storm was small enough so that horizontal advection could be ignored as a means of introducing buoyancy flux to the centre of the basin, then simple one-dimensional models could be employed to model the vertical mixing in that area, and this approach is adopted in the analysis of wind-mixing presented in this paper.

2. Site

2.1 Bathymetry and topography

Cockburn Sound is situated in the southwest coastal waters of Western Australia, just south of the city of Perth (Figure 1). The western side of the sound is bordered by Garden Island. Between Garden Island and the Five Fathom Bank lies the channel called Sepia Depression, west of which the open continental shelf slopes gently to the 50 m depth contour. Five Fathom Bank runs from offshore of Becher Point to Rottnest Island and, in conjunction with reefs, islands and other sand banks, helps to protect the coast from the full force of swell waves and regional currents.

Cockburn Sound has a relatively deep central basin (up to 21 m) with approximate horizontal dimensions of 14 km x 5 km. Adjacent to the mainland coast between James Point and Woodman Point is a shallower margin having a width of up to 4 km and depths less than about 10m. Mangles Bay lies in the southern end of the sound. The northern opening has depths generally of about 5 m or less and is comprised of an irregular reef line between north Garden Island and Carnac Island, a relatively shallow seagrass-dominated sill called Parmelia Bank, and a narrow 15 m deep shipping channel that cuts northwards through Parmelia Bank, Owen Anchorage and Success Bank. The cross-sectional area of the northern opening (Garden Island - Carnac Island - Woodman Point) is approximately 28000 m^2. Across the southern opening, the causeway with two bridges was complete in 1974 and reduced the cross-sectional area along its alignment from approximately 10000 m^2 to 4000 m^2, with water depths of about 3-4.5 m under the bridges.

2.2 Climate

The southwest of Australia has a 'Mediterranean' climate characterised by cool wet winters and hot dry summers (Australian Bureau of Statistics, 1989). In winter, mean minimum daily temperatures range from 5-10 ^{o}C and mean maximum daily temperatures from 15-20 ^{o}C. Relative humidity exhibits a diurnal fluctuation in response to wind and air temperature variations, with maxima at night and minima during the day. Typical values of relative humidity are over 70 percent at night and between 20 to 50 percent during the day. Most rainfall occurs from May to October and Perth's average is approximately 870 mm per year. The Swan-Canning Estuary freshwater flow regime responds to this rainfall pattern and Figure 3 presents monthly averages of Perth rainfall and Swan-Canning freshwater discharge, respectively. Average daily evaporation is about 2-3 mm in winter and the average yearly evaporation at Perth is approximately 1700 mm.

The heat flux at the water surface exhibits considerable variation over diurnal and seasonal time scales. Pattiaratchi *et al.* (1995) utilised local meteorological data from 1993 and estimated the hourly heat flux at the water surface for a nearshore site off Mullaloo, approximately 30 km north of Perth (Figure 4). For the winter period (June-August) the data indicate that heat gains via the surface during the day-time ranged from about 100 to 500 W m^{-2} and at night losses were typically about 200-400 W m^{-2}. There is sufficient similarity in the meteorological and hydrological conditions of the nearshore basins to enable the data in Figure 4 to provide reasonable estimates for the Cockburn Sound region. A methodology for the estimation of heat fluxes, on the basis of local meteorological and hydrological data, is presented in Fischer *et al.* (1979).

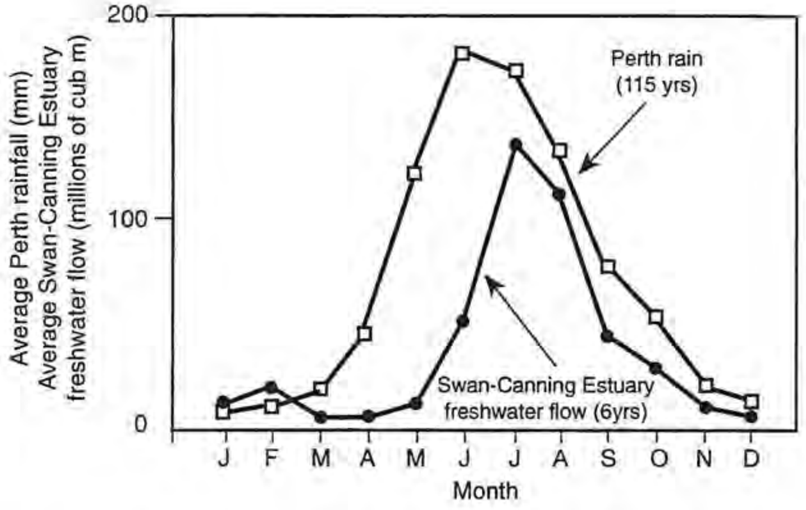


Figure 3. Average total monthly Perth rainfall (based on 115 years of data) and Swan-Canning Estuary freshwater flow (based on 6 years of data). Sources: Rainfall data from Australian Bureau of Statistics (1989); flow data from Deeley (in preparation).

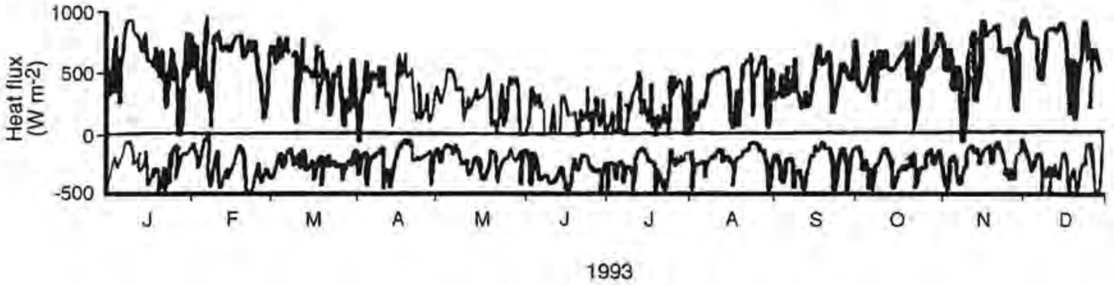


Figure 4. Net heat fluxes for 1993 at the water surface for the nearshore waters 30 km north of Perth, based on hourly data, and showing variations in maximum day-time gain rates (+ve) and maximum night-time loss rates (-ve). (Derived from Pattiaratchi *et al.* (1995)).

The seasonal weather patterns, and hence winds, of the region are controlled by the migration of the anticyclonic belt from about 30 °S in July to 40 °S in January. Thus, in winter, southwest Australia lies in the high pressure region. 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 (Breckling, 1989; Steedman and Craig, 1979).

During winter the high pressure cells within the anti-cyclonic belt produce predominantly west-southwesterly winds (the roaring forties) over southwest Australia. These cells become periodically displaced by low pressure cyclonic cells that move rapidly eastwards bringing cold fronts, rain and strong storm winds (~ 10-20 m s^{-1}) from the northwest to southwest. On a seasonal basis, the wind field is relatively weak and variable in winter, except during the passage of the low pressure cells. Further details of the seasonal characteristics of wind patterns for the Perth coastal region can be found in Steedman and Craig (1979), Breckling (1989) and Hearn (1991). Steedman and Craig (1979) analysed a comprehensive set of wind velocity data comprising approximately 7 years of hourly averages from Fremantle (Figure 5) and found that winds were less than 5 m s^{-1} for about 50 percent of the time and less than 10 m s^{-1} for about 90 percent of the time in winter.

During the study period of 13-23 August 1991 winds were associated with a typical winter synoptic cycle, the details of which are presented as part of the meteorological data set in Figure 6. The data show the changing wind vector including a west-southwesterly storm (10-15 m s^{-1}) on 19 August 1991.

3. Field programme and instrumentation

The three-dimensional salinity, temperature and density field in Cockburn Sound and adjacent waters was measured along selected transects by profiling with a CTD (conductivity-temperature-depth) probe once to twice daily between 13 and 23 August 1991. Certain sites and transects were visited up to 5 times in one day. The transect paths and locations at which instruments were deployed (including current meters, drogues and meteorological stations) are shown in Figure 7.

The fine-scale CTD probe used to monitor the stratification comprised a Seabird Electronics SBE-3 thermometer, a Seabird Electronics SBE-4 conductivity meter, a Paroscientific Digiquartz pressure sensor and associated electronics. Vertical profiles were obtained by deploying the probe in free-fall mode from a vessel equipped with a Global Positioning System (GPS). The data were retrieved via an electrical cable, processed and stored in an onboard computer. The drop speed was about 1 m s^{-1} and the CTD data were collected at a rate of 50 Hz yielding a spatial resolution of approximately 0.02 m. In combination, these sensors yielded density measurements accurate to 0.005 kg m^{-3}, and depth was accurate to 0.002 m. Details of the probe can be found in Vollmer (1991).

Neil-Brown ACM-2 and Steedman Science and Engineering CM-01 vector-averaging acoustic current meters were calibrated and then installed near the surface and bottom on taut wire moorings at three sites within Cockburn Sound and at mid-depth in Sepia Depression (Figure 7). Drogues with an underwater sail area of 2 m^2 and minimal windage were released along the transects shown in Figure 7.

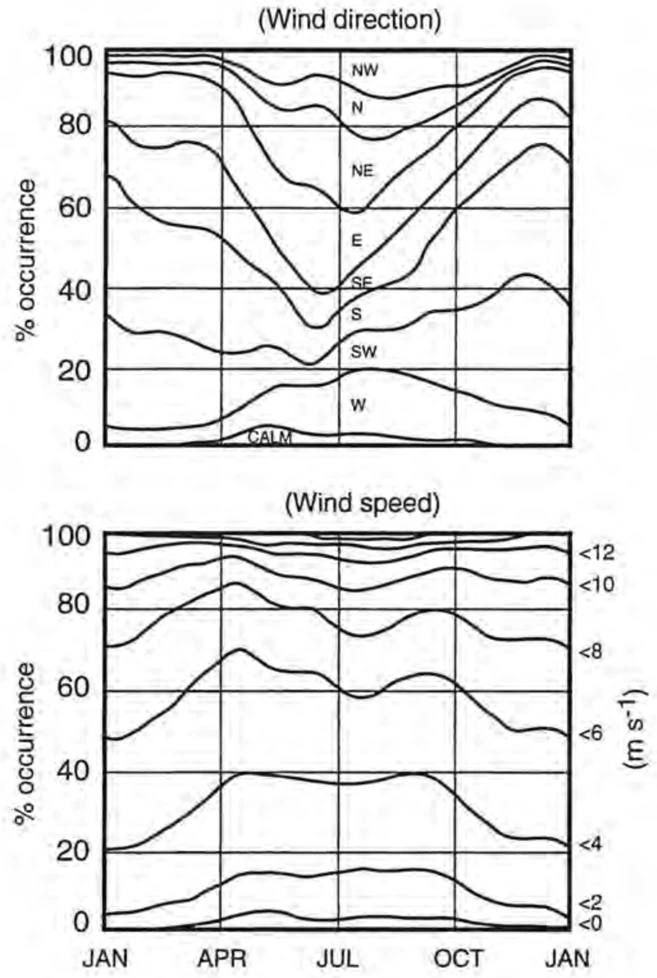


Figure 5. Combined monthly one-hourly averaged wind speed and direction occurrence diagrams - January 1971 to December 1977, Fremantle. Calculation were based on hourly data. Re-drawn from Steedman and Associates (1979).

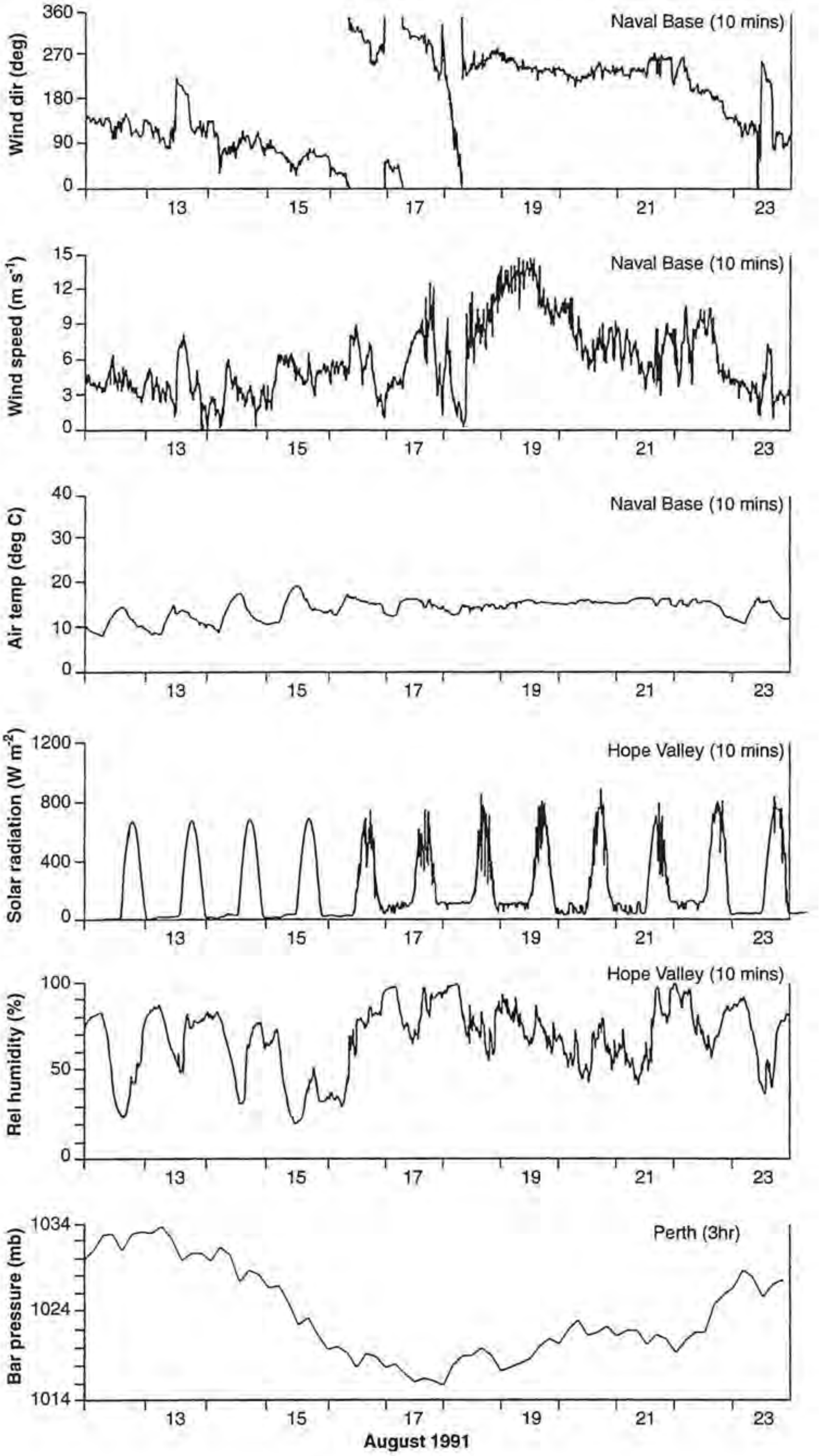


Figure 6. Meteorological data collected in the Kwinana and Perth region during the period 12-23 August 1991.

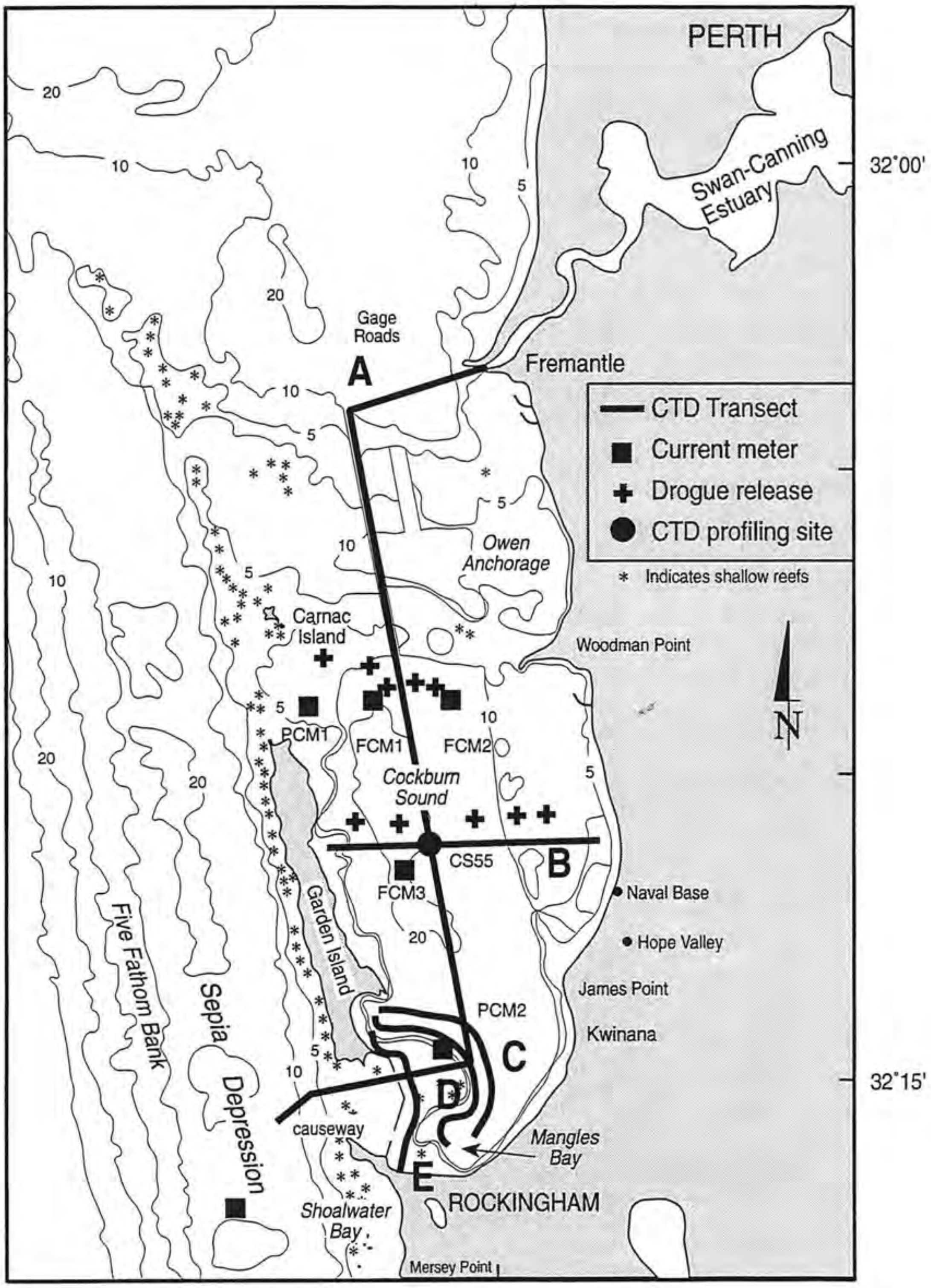
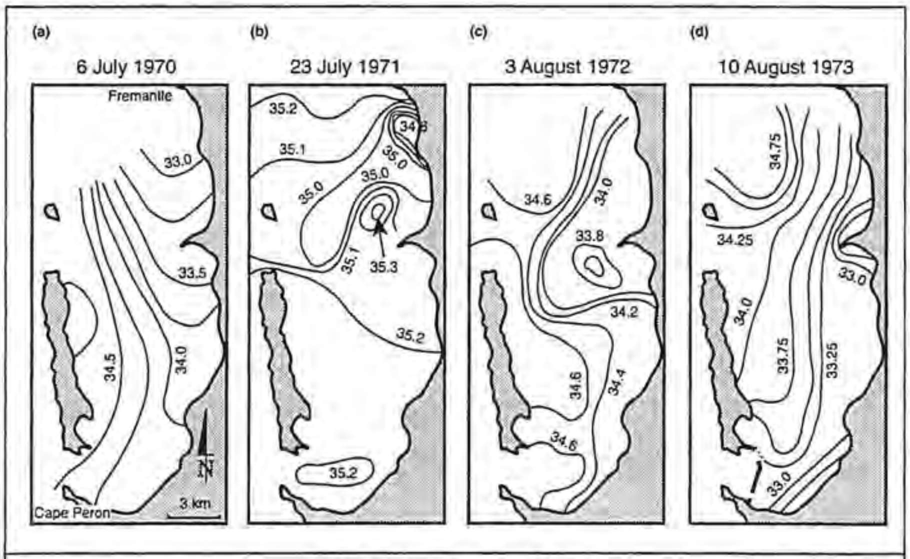


Figure 7. Transect paths and site locations of data collection for the field survey of 13-23 August 1991.

4. Results

4.1 Seasonal development of a Region of Freshwater Influence (ROFI)

Past oceanographic surveys have measured the salinity structure of Perth's southern coastal waters (summarised in D'Adamo, 1992 and Hearn, 1991). These surveys have shown that, in winter, the nearshore zone between Fremantle and Cape Peron, east of the Garden Island Ridge (see Figure 2), is of lower salinity than the adjacent shelf region. This is due to coastal discharges of low salinity estuarine water, mainly from the Swan-Canning Estuary. During typical winter synoptic cycles, approaching low pressure systems result in northeasterly-northwesterly winds that drive buoyant estuarine plumes southward from the Swan-Canning Estuary mouth into Cockburn Sound. A representative set of surface salinity fields resulting from such events is presented in Figure 8 (from Environmental Resources of Australia, 1970, 1971, 1972 and 1973), and these data exemplify the broad spatial influence of this process. The 48-hour average rates of freshwater discharge prior to these four surveys ranged from 4 to 125 $m^3\ s^{-1}$ and long-term records of freshwater discharge to the estuary (obtained from Water Authority of Western Australia archives, Surface Water Branch) indicate that values of 10-50 $m^3\ s^{-1}$ within a range of about 5-100 $m^3\ s^{-1}$ are typical for winter. As shown, apart from the weak discharge period in July 1971, the low salinity region extended well into Cockburn Sound. Additional historical field evidence relating to this mechanism was provided by aerial tracking of darkly coloured (due to the estuarine diatom *Melosira* Sp.) estuarine plumes by Environmental Resources of Australia (1970) which showed that ebb pulses were driven southwards into Cockburn Sound and/or around Garden Island into Sepia Depression under northeasterly to northwesterly winds (Figure 9).



Winds during preceding 48 hours

(a)	(b)	(c)	(d)
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 ($m^3\ s^{-1}$)

(a)	(b)	(c)	(d)
55	4	20	125

Figure 8. Time series of surface salinity structures between Fremantle and Cape Peron during the winters of (a) 1970, (b) 1971, (c) 1972 and (d) 1973, showing the result of southward coastal 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. Units for isohaline contours are in parts per thousand. Figures (a), (b), (c) and (d) are re-drawn from Environmental Resources of Australia (1970, 1971, 1972 and 1973, respectively).

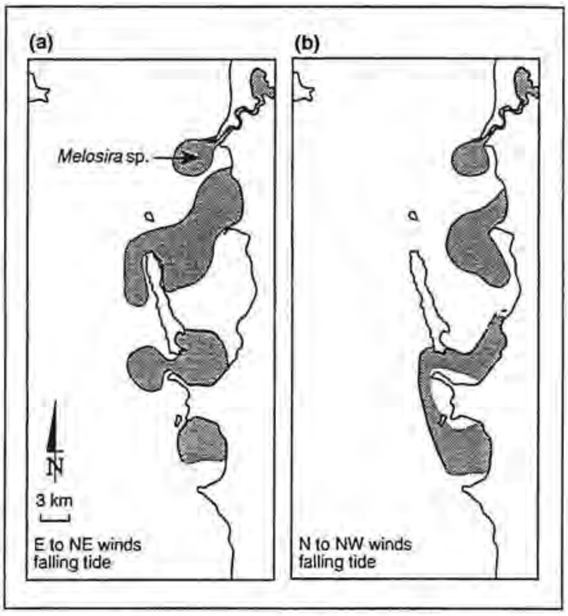


Figure 9. Observed positions of successive tidal ebb pulses of Swan-Canning estuarine water (coloured brown by the estuarine diatom *Melosira* Sp.) under (a) east-northeasterly winds and (b) north-northwesterly winds. Re-drawn from Environmental Resources of Australia (1970).

The field evidence on the southward transport of Swan-Canning estuarine plumes is strengthened by recent baroclinic numerical model simulations of the SMCWS (Mills and D'Adamo, 1995a). The modelling of the wind-driven transport of low salinity Swan-Canning estuarine plumes under typical winter discharge and wind conditions predicted that winds of 5-7.5 m s^{-1} from the northeast and northwest quadrants would advect the buoyant plumes well into Cockburn Sound within 1.5 days (Figure 10). Such winds typically occur 3-4 times per month during winter and into spring, as part of synoptic wind cycles (Breckling, 1989) and so the results of the modelling, in conjunction with the field evidence, suggest that low salinity plumes regularly enter Cockburn Sound in this period, driven by wind stress. It is therefore likely that this is a characteristic mechanism which lowers the mean density of the sound during winter and spring, thereby creating a *Region of Freshwater Influence* (ROFI), a descriptive term for such regions attributable to Simpson *et al.* (1993a). In contrast, the nearshore waters to the north of the sound, for example in the Marmion Lagoon (situated off Hillarys, 30-40 km north of Fremantle), do not exhibit the same degree of salinity decrease during winter and spring, despite the fact that there are about as many strong northward wind periods as there are southward wind periods during these seasons (Breckling, 1989). D'Adamo and Mills (1995c) compared the annual cycle of salinity for Cockburn Sound with that of Marmion Lagoon (data from Pearce and Church, submitted). They found that, during winter and spring, the mean salinity of Cockburn Sound is significantly altered by Swan-Canning estuarine plumes, whereas Marmion Lagoon has its salinity only slightly altered. In fact, during this period, whilst Cockburn Sound has its mean density lowered to below that of the adjacent shelf region due to the wind-driven entry of low salinity Swan-Canning estuarine plumes, the Marmion Lagoon has its mean density increased as a result of differential cooling of near-coastal waters, resulting in lowered temperatures, which dominate over any slight salinity decreases in terms of their effect on density. The southern opening of Marmion Lagoon is 30 km from Fremantle compared to the distance of 15 km between the northern opening of Cockburn Sound and Fremantle. The Marmion Lagoon is less physically enclosed than Cockburn Sound. For these

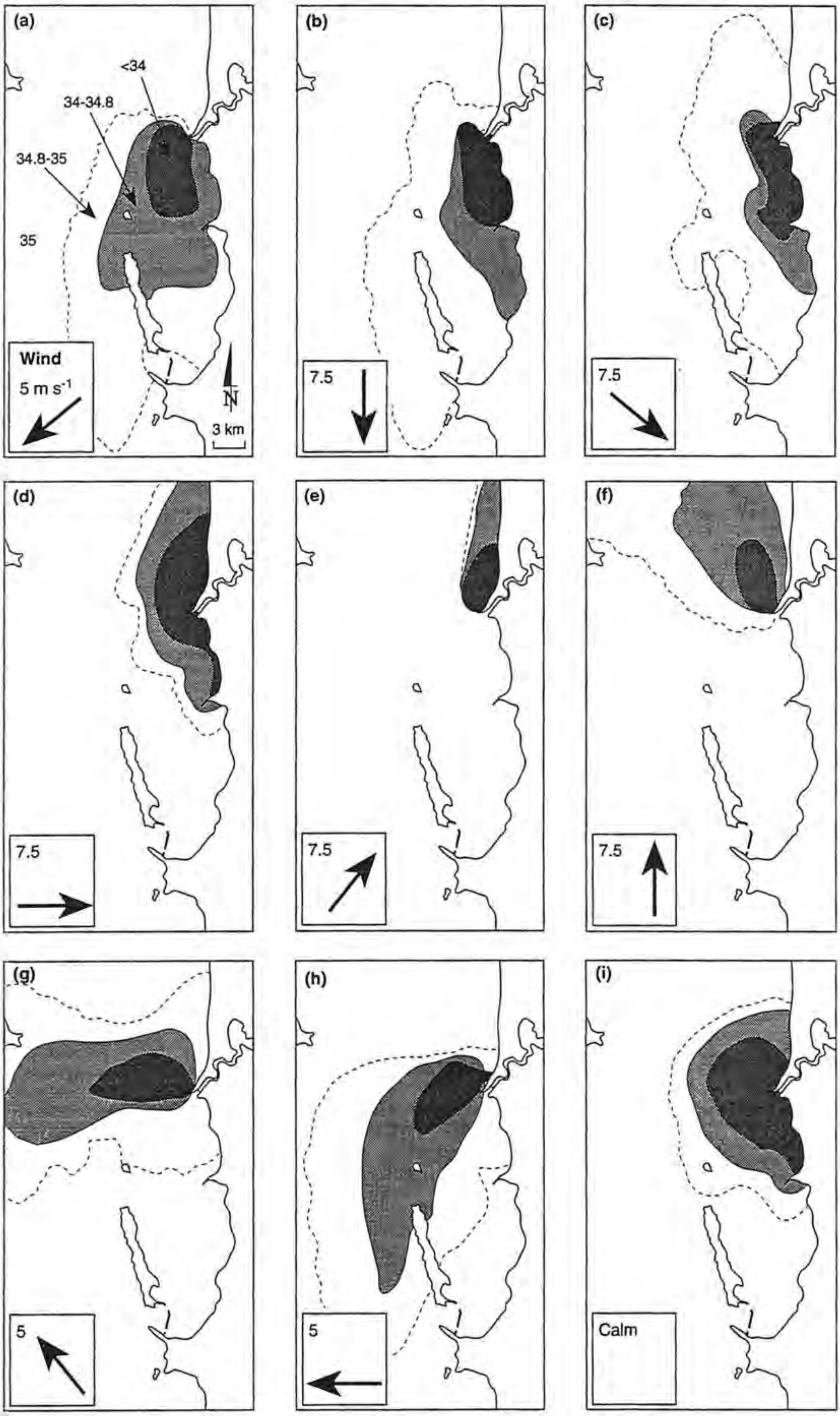


Figure 10. Baroclinically modelled surface salinity fields representing the transport of Swan-Canning estuarine plumes after 1.5 days under (a to h) eight constant wind conditions and (i) calm conditions. Re-drawn from Mills and D'Adamo (1995a). The surface buoyant plume is enveloped by the 34.8 pss contour.

reasons estuarine plumes are more readily dispersed and mixed with shelf waters after leaving the Swan-Canning Estuary and travelling northwards than is the case for southward travelling plumes into Cockburn Sound.

The seasonal lowering of the salinity and density in Cockburn Sound was confirmed by cross-shelf CTD data collected during a series of 17 surveys, transecting Cockburn Sound and adjacent shelf waters, from August 1991 to February 1993, and during May 1994 (D'Adamo and Mills, 1995c). These data provided the basis for determining the annual patterns in the cross-shelf salinity, temperature and density differences between central Cockburn Sound and shelf waters south of Rottnest Island, as shown in Figure 11. This cyclic plot was used by D'Adamo and Mills (1995c) to identify three important hydrodynamic regimes for these waters, namely the 'winter-spring', 'summer' and 'autumn' regimes, respectively. The onset and duration of the 'winter-spring' regime varies somewhat from year to year, depending on the timing and magnitude of freshwater discharge from rivers, and on the strength of the warming of nearshore waters in spring. During this regime nearshore basin waters are relatively buoyant in comparison to offshore waters, because of these two factors.

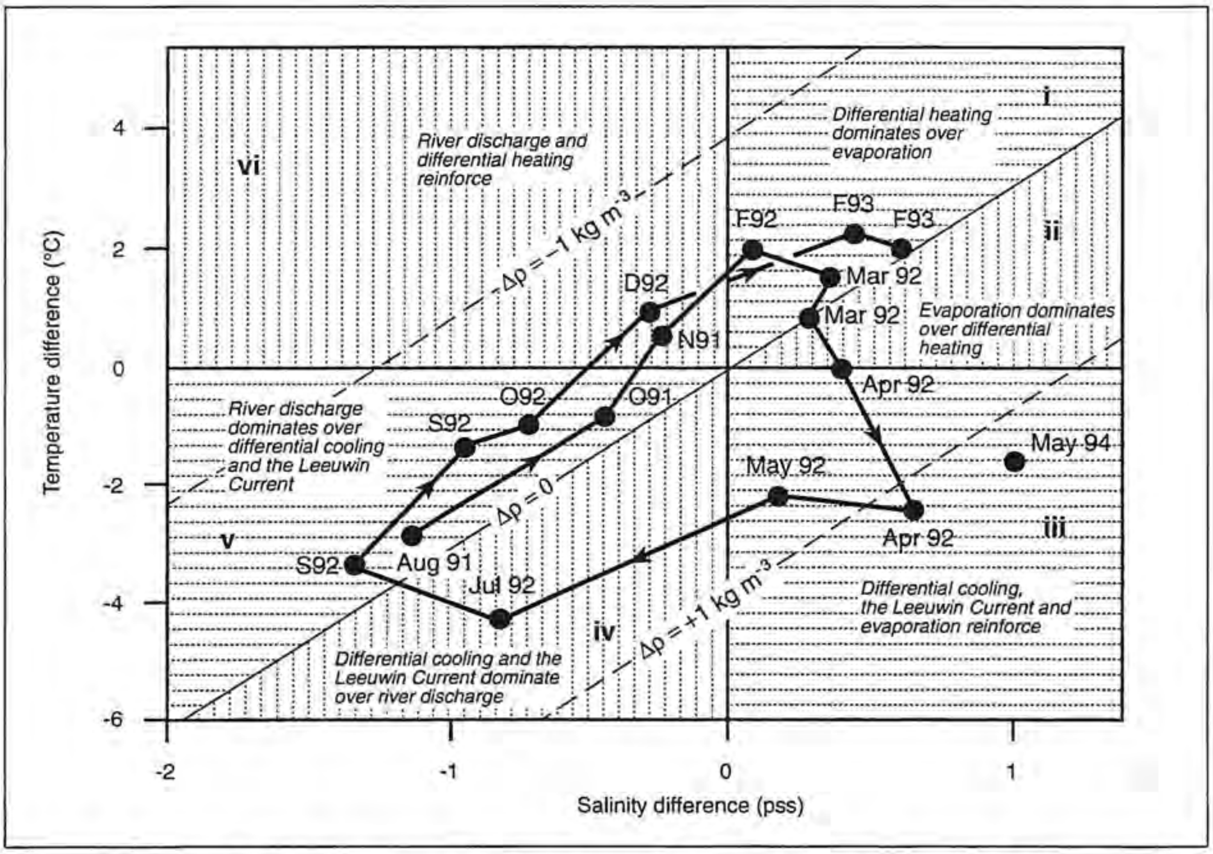


Figure 11. Annual cycle in cross-shelf salinity and temperature differences between central Cockburn Sound and mid-shelf waters approximately 10 km southwest of Rottnest Island, based on representative data at 10 m depth. The timing of each individual survey is indicated. Data above the central diagonal indicate that Cockburn Sound water was buoyant compared to mid-shelf water, and data below the central diagonal indicate that Cockburn Sound water was dense compared to mid-shelf water. The relative influence of the major forcings is differentiated into six categories (i to vi). The three main seasonal regimes and their categories are: 'summer' (i, ii) 'autumn' (iii, iv) and 'winter-spring' (v, vi). Re-drawn from D'Adamo and Mills (1995c).

With respect to the vertical structure of the region, estuarine discharges result in vertical salinity, and therefore density, stratification (Hearn, 1991; D'Adamo, 1992; Mills *et al.* 1996). D'Adamo and Mills (1995c) have shown that throughout the year vertical density differences in Cockburn Sound are typically 0.1-0.5 kg m^{-3}, but that the strongest vertical gradients usually occur in winter and spring, reflecting the stratifying influence of buoyant estuarine discharges and solar heating (Figure 12). Vertical density differences of over 1 kg m^{-3} have been recorded in the sound as a result of low salinity plumes entering from the Swan-Canning Estuary during the winter-spring period (D'Adamo and Mills, 1995c).

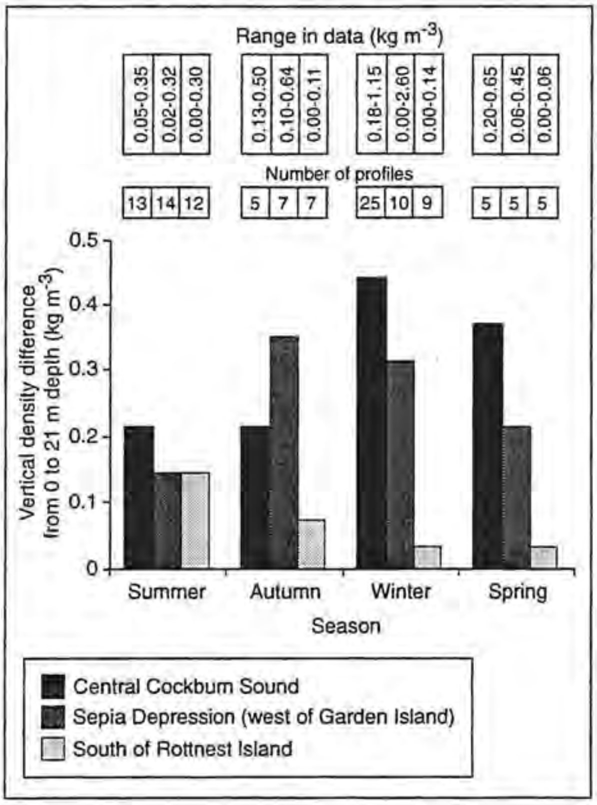


Figure 12. Seasonal mean vertical density differences in central Cockburn Sound, central Sepia Depression (west of Garden Island) and mid-shelf waters south of Rottnest Island. Re-drawn from D'Adamo and Mills (1995c).

Questions arise concerning the influence of vertical and horizontal density gradients on the vertical mixing within the basin, the horizontal exchange between the basin and adjacent shelf waters, and the flushing rates and pathways of materials discharged to the basin. In addition, the passage of synoptic meteorological features and the influence of the resultant wind cycles on the hydrodynamics of the sound in the presence of strong density gradients requires investigation.

The intensive field survey data from 13-23 August 1991 are used to help address these questions. These data provide a record of the dynamic response of the sound during different phases of the synoptic wind cycle during 13-23 August 1991. The cyclic nature of the wind field for that period is highlighted by the progressive wind vector plot in Figure 13. In broad terms, the observed cycle can be considered in three phases: firstly, moderate (5-10 m s^{-1}) northeasterly-northwesterly winds; secondly, a low pressure front which crossed the coast and brought strong (10-15 m s^{-1}) west-southwesterly storm winds on 19 August; and thirdly, moderating (5-10 m s^{-1}) south-southwesterlies after the front passed through the region. The following analysis of the dynamics is structured according to these three wind phases.

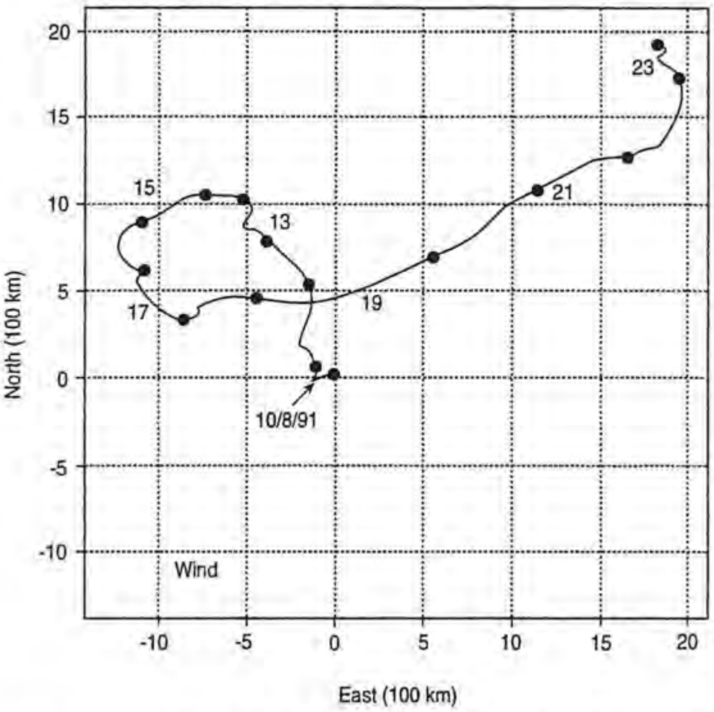


Figure 13. Progressive vector plot of wind at Naval Base (at 12 m height) during 10-23 August 1991.

4.2 Pre-storm dynamics: northeasterly-northwesterly winds at 5-10 m s^{-1}

As discussed above, winds of greater than about 5 m s^{-1} from the northerly quadrants can drive buoyant Swan-Canning estuarine discharges into Cockburn Sound within about 1-2 days. On 17-18 August CTD profiling between Fremantle and Cape Peron revealed one such occurrence (Figure 14). Northeasterly-northwesterly winds of about 5-10 m s^{-1} had been blowing since 16 August and, as shown by the surface salinity field, low salinity water was advected into northern Cockburn Sound. The plume can be seen to have increased in salinity with distance from the mouth, suggesting that mixing with the ambient higher salinity water was occurring. However, the plume was still of low enough salinity within the sound to suggest a significant introduction of buoyancy flux.

The predominantly southward directed wind stress resulted in significant changes to the basin-scale density structure within the sound. Before 16 August the sound was vertically stratified in density due to basin-wide vertical stratification in salinity, with a vertical zone of relatively buoyant water between the surface and about 15 m depth, as exemplified by the density stratification for 15 August in Figure 15. The winds were relatively weak (< 5 m s^{-1}) and large changes in vertical density structure were not observed prior to 16 August (D'Adamo and Mills, 1995d). However, the ensuing strengthening northeasterly-northwesterly winds perturbed this structure by advecting buoyant low salinity water into the sound (D'Adamo and Mills, 1995d) and by causing a tilting (downwelling) of the longitudinal density structure. This change in the vertical structure is indicated by the stratification shown in the vertical contour plot for 17 August in Figure 16. This resulted in relatively low density water near the bottom at the southern end and relatively dense water near the bottom at the northern end.

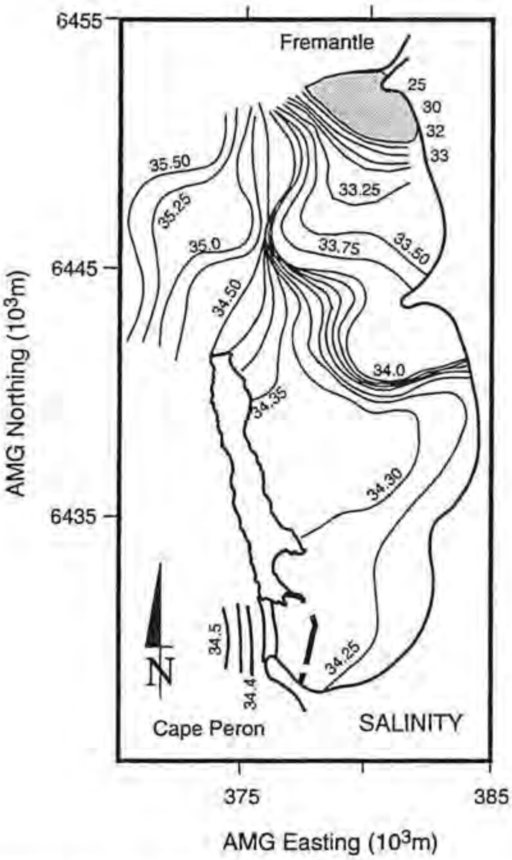


Figure 14. Salinity contours of the horizontal stratification at 0.25 m depth south of Fremantle during a strong Swan-Canning Estuary discharge period: 0823 hrs 17 August to 1231 hrs 18 August 1991. The discharge was about 50 m^3 s^{-1} (Mills *et al.* 1996). Units are practical salinity scale (pss) and contours are drawn at either 0.05 or 0.25 pss intervals.

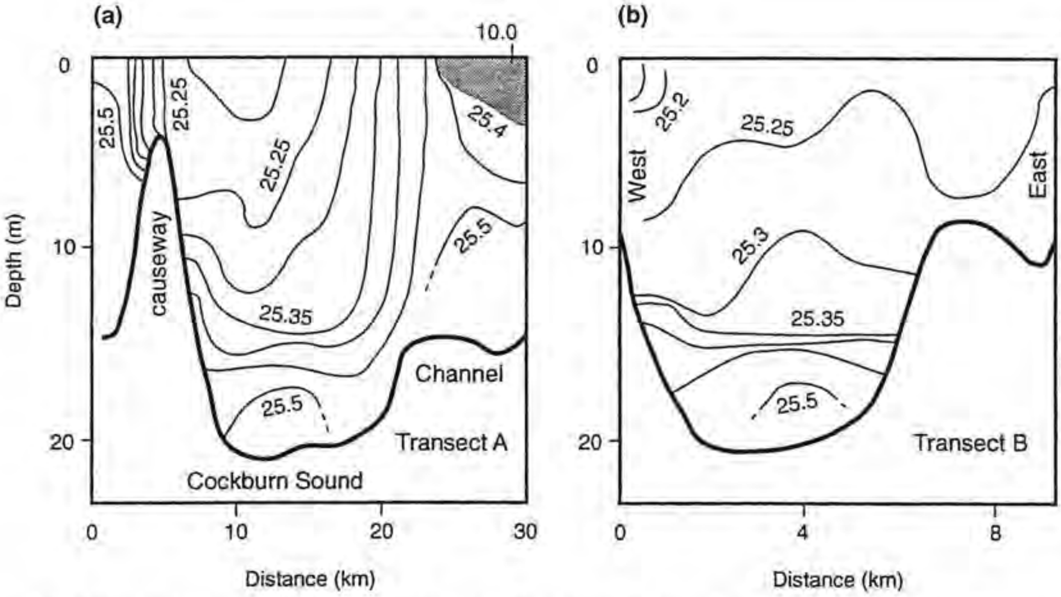


Figure 15. Vertical density stratification in Cockburn Sound and adjacent waters on 15 August 1991 along (a) Transect A (0802-1549 hrs) and (b) Transect B (1146-1241 hrs). Contours are in sigma-t units at an interval of 0.05 kg m^{-3}. Shading indicates a Swan-Canning estuarine plume of density less than 25.4 kg m^{-3} (sigma-t units).

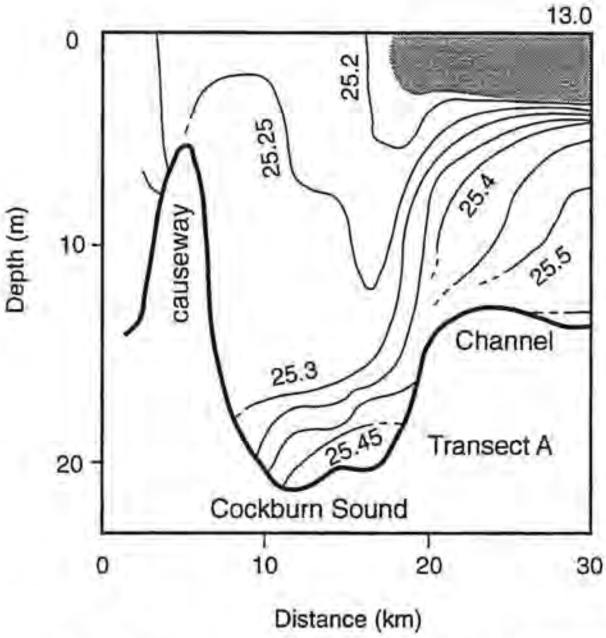


Figure 16. Vertical density stratification in Cockburn Sound and adjacent waters during 17 August 1991 along Transect A (0745-1150 hrs). Contours are in sigma-t units at an interval of 0.05 kg m^{-3}. Shading indicates a Swan-Canning estuarine plume of density less than about 25.0 kg m^{-3} (sigma-t units).

An indication of the potential for along-basin tilting of the density structure in a two-layered basin can be obtained by determining the Wedderburn number (Imberger and Hamblin, 1982; Imberger, 1994) and for the pre-storm conditions of 16-17 August 1991 ($U \sim 7.5$ m s^{-1}, $\Delta\rho \sim 0.25$ kg m^{-3}) W was 0.4 in Cockburn Sound, suggestive of basin-scale tilting of the density structure in the along-basin (north-south) alignment, as observed.

The Wedderburn Number is a non-dimensional number that was initially derived for a two-layered rectangular closed basin and essentially describes the balance between the perturbing force due to wind-stress and the restoring force due to the basin-wide vertical density difference between the upper and lower density layers (Imberger and Hamblin, 1982; Imberger, 1994). One of the mechanisms it describes is the ability of wind-stress to set-up the free surface against the downwind end wall, thereby causing the interface between the upper and lower layers to move downwards towards the bottom, resulting in an upwind flow in the lower layer. The Wedderburn Number is defined as $W = (g'h/u^{*2})h/L$, where $g' = g\Delta\rho/\rho$ is the effective acceleration due to gravity, g is the acceleration due to gravity, $\Delta\rho$ is the density jump between the upper and lower layers, ρ is the average water density, h is the upper mixed layer depth, $u^* = (\rho_a C_d/\rho)^{1/2}U$ is the wind shear stress, $\rho_a = 1.2$ kg m^{-3} is the density of air, C_d a drag coefficient equal to 0.0013 (Fisher *et al.* 1979), U is the wind speed at 10 m height and L is the distance along the basin in the direction of the wind. A value of $W < O(1)$ suggests that the wind-stress dominates the force balance and can be used to indicate that the pycnocline will surface at the upwind end, with downwelling at the downwind end. A value of W greater than 1 suggests minimal vertical motions of the pycnocline.

If the earth's rotation is important, then this adds another force (i.e. the Coriolis force) perpendicular to the wind direction and induces an associated tilt in the pycnocline perpendicular to the wind (Imberger and Hamblin, 1982). Rotational effects will be significant if two conditions are met: first, the elapsed time for the flow is equal to or greater than the inertial period, which is approximately 1 day, as given by $2\pi/f$ (f is the Coriolis parameter and equals 7.7×10^{-5} for Perth's latitude); and second, if the Rossby number, R, (Csanady, 1982) is less than 1 ($R = u/fL$, where u is the speed of the current and L is the width of the basin).

For current speeds typical of Cockburn Sound (i.e. of order 0.1 m s^{-1}) $R < 1$ is calculated. This indicates that rotational effects should be significant in Cockburn Sound for time-scales of about 1 day (the inertial period) or more. This is most probably why the west-east density structure across the centre of the sound displayed a significant slope on 16/17 August, as shown in Figure 17, in response to relatively strong north-northwesterly winds (5-10 m s^{-1}), with a downwelling to the eastern side of the basin and an associated upwelling along the western margin. The eastward component of the wind vector was of order 5 m s^{-1} for about 10 hours during 16 August, and the value of W for this situation is calculated to be about 2, and hence the force due to the eastward wind vector alone is unlikely to have made a significant contribution to the across basin motion of the density structure (shown in Figure 17). This leaves the across-basin (west-east) influence of the earth's rotation as the most likely reason for the upwelling along the western margin of Cockburn Sound. This is a dynamical situation similar to that described by Cushman-Roisin *et al.* (1994) for the two-layered structure of the Porsangerfjord, Norway, which was monitored as it was acted upon by a surface wind-stress in the along-fjord direction. Mortimer (1974) has also discussed the occurrence of this phenomenon for the stratified Lake Michigan being acted upon by along-basin winds.

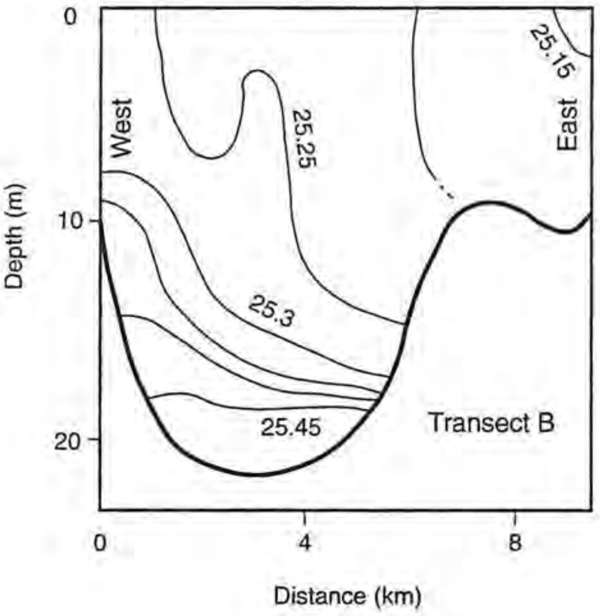


Figure 17. Vertical density stratification in Cockburn Sound and adjacent waters during 16/17 August 1991 along Transect B (2358-0108 hrs). Contours are in sigma-t units at an interval of 0.05 kg m^{-3}.

4.3 Storm dynamics: west-southwesterly winds at 10-15 m s^{-1}

The passing of the low pressure storm front on 19 August brought with it strong 10-15 m s^{-1} west-southwesterly winds (Figure 6). Leading up to the storm CTD measurements revealed that there was strong basin-wide vertical density stratification due to salinity stratification (Section 4.2, above and Figure 27, to follow in Section 4.5), with a relatively strong halocline (which formed a pycnocline) at about 15 m depth throughout the basin. Temperature was of minor importance in its influence on the vertical density structure within the pycnocline. After the storm, monitoring of the vertical salinity structure during the morning and early afternoon of 20 August indicated that full-depth mixing had occurred during the storm throughout most of the sound (Figure 18). The application of vertical wind-mixing formulae from Imberger (1994) can be used to retrospectively predict the extent of vertical mixing of a given vertical density structure over a range of wind speeds, including the strong speeds encountered during the storm.

Strong wind events in the region generally last of order 5-10 hours, and this is a relatively short time compared to the time taken for water to be advected to central Cockburn Sound from the openings, given current speeds (of order 0.1 m s^{-1}) that are typical in Cockburn Sound (D'Adamo, 1992). Under these short wind forcing events the initial stratification in central Cockburn Sound will not be significantly affected by horizontal advection of water from the northern or southern ends. It is therefore assumed that the rate of deepening due to wind mixing in the central region of the sound can be reasonably simulated using the vertical one-dimensional mixing laws developed and described for lake scenarios (Imberger and Patterson, 1990; Imberger, 1994). The duration of these wind events is also short compared with the inertial period of about 1 day, and so rotational effects can be expected to have a relatively minor influence at these time-scales.

Under the conditions just described, the Wedderburn Number may be used to classify the dynamical response of the upper mixed layer to wind stress (see Imberger and Patterson, 1990), and in general $W < O(1)$ suggests shear-dominated mixing (Pollard, Rhines and Thompson, 1973) with significant horizontal transport and associated upwelling of the pycnocline, whereas a $W > O(1)$ suggests that vertical stirring processes (Kraus and Turner, 1967) dominate mixing, with little horizontal transport.

Upper mixed layer deepening laws for stirring and shear-dominated mixing in lakes have been developed by Sherman *et al.* (1978), Rayner (1980), Spigel *et al.* (1986), Imberger and Patterson (1990) and Imberger (1994). For the two-layer case the stirring-dominated deepening law is $h(t) = (C_k h^3 u^{*3} t)/(g_o' h_i)$ and the shear-dominated law is $h(t) = (C_s/g_o' h_i)^{1/2} u^{*2} t$, where $C_k = 0.13$, $h = 1.23$ and $C_s = 0.24$ are constants that determine the efficiency of energy conversion (Imberger and Patterson, 1990), t is the time since the onset of mixing, g_o' is the value of effective gravitation at the commencement of mixing, and h_i is the initial depth of the upper mixed layer. These laws can be easily re-derived for other cases of initial vertical stratification, including linearly varying density profiles. The approach adopted provides approximate estimates of dh/dt, the rate of deepening due to wind stress.

D'Adamo (1992) used this method to predict that vertical density differences of 1 kg m^{-3}, due to an upper layer of 5 m thickness over a lower layer of 15 m thickness, would be eliminated by storm winds of 10 - 12.5 m s^{-1} lasting for about 12 hours.

In Figure 19 we utilise the data from the field survey and the deepening laws described above to estimate the approximate rate of vertical mixing for a range of wind speeds in central Cockburn Sound. The density profile shown in Figure 19 is assumed as the simplified stratification at the onset of wind-mixing and was based on CTD data collected in central Cockburn Sound at 1421 hrs, 14 August 1991. This profile is adopted as being representative of mid-afternoon stratification during the weak to moderate winds (of order 5 m s^{-1}) that occurred during the pre-storm period.

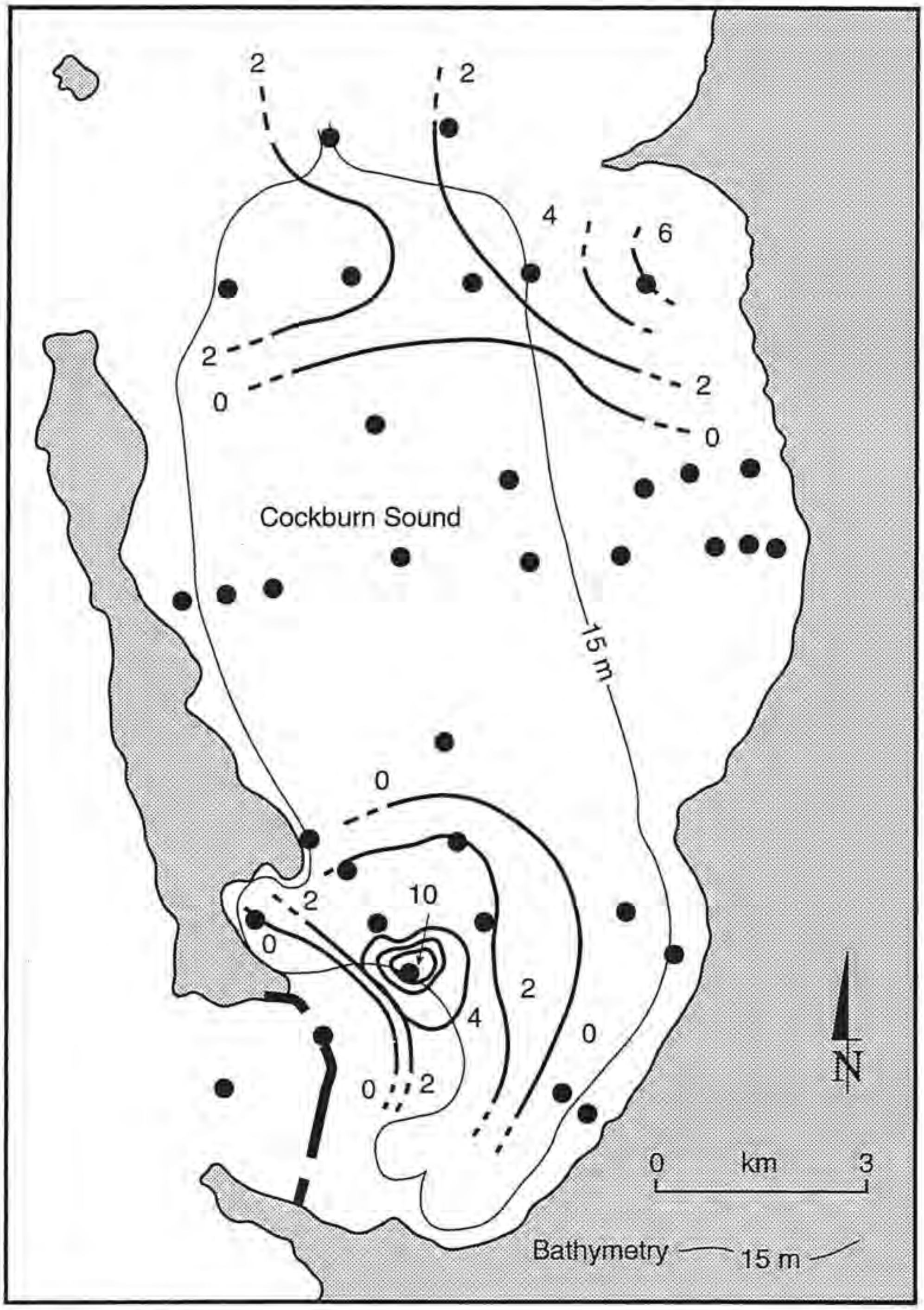


Figure 18. Horizontal contour plot of the distance (in metres) from the bottom to the main halocline (where the vertical salinity structure changed markedly, in the form of a step) during 20 August 1991 (0824-1415 hrs). Dots show positions of CTD monitoring sites.

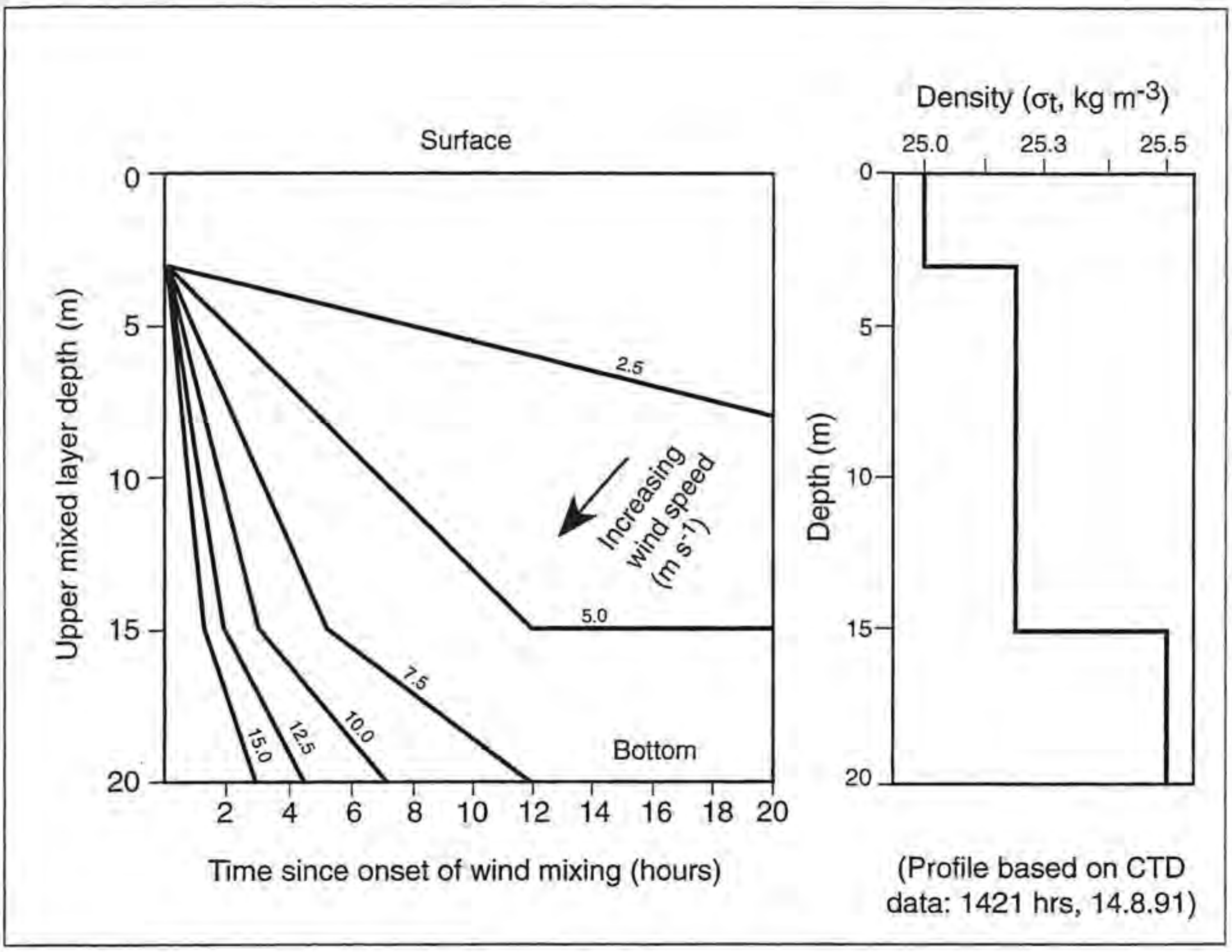


Figure 19. Predicted rates of vertical mixing due to wind-stress for central Cockburn Sound over a range of wind speeds. The initial density profile was based on CTD data collected in central Cockburn Sound at 1421 hrs, 14 August 1991.

The value of W varies in response to a changing wind stress and to changes in the value of the density difference across the eroding interface. Hence, W changes abruptly when the upper mixed layer reaches the main pycnocline, at 15 m depth. The curves in Figure 19 have been constructed on the basis of the mixing laws described above and take account of changes in W. As shown, it is predicted that the vertical stratification would be completely eliminated by vertical mixing in times of less than about 7 hours for wind speeds greater than 10 m s^{-1}. The storm winds were greater than 10 m s^{-1} from about 0000 hrs 19 August to 0600 hrs 20 August, a period of 30 hours. Hence it is predicted that full-depth mixing would have occurred in central Cockburn Sound. This result is in agreement with the observed fully-mixed nature of the central region of Cockburn Sound after the storm (Figure 18). As will be detailed in the next section, the vertical stratification near the northern and southern openings of the sound included a relatively dense lower layer on 20 August. This was due either to incomplete vertical mixing at these sites during the storm, a relaxation of the longitudinally stratified density structure or a rapid plunging inflow of relatively dense high salinity water into the basin via the openings after the storm. In view of the strength and long durations of the storm winds of 19 August it is probable that they would have completely mixed the vertical structure throughout the basin, as would be suggested by the curves in Figure 19. However, since these data were collected 6-12 hours after the peak of the storm, the predictions of vertical mixing could not be verified for these regions. The ensuing exchange that occurred between relatively buoyant Cockburn Sound water and relatively dense shelf water is the subject of the following section.

4.4 Post-storm dynamics: south-southwesterly winds at < 10 m s^{-1}

CTD profile data collected during a sequence of three surveys between 20 and 23 August were analysed to investigate the re-stratification of the sound after the storm. Figure 20 illustrates the three successive states of salinity stratification as represented on a north-south-vertical section, and along surfaces 0.5 m above the sea bed and 0.5 m below the sea surface, respectively. The northward flow of low salinity (and therefore buoyant) near-surface water out of the sound and the complementary inflow of relatively high salinity (and therefore dense) shelf water into the sound via the openings can be seen. In Figure 20 the 34.5 pss isohaline is darkened and the lowest salinity water (<34.3 pss) is shaded to highlight these processes.

The data in Figure 20 indicate that the central region of Cockburn Sound was re-stratified vertically by the bottom flow of high salinity (and therefore high density) water by 21 August 1991, some 1-2 days after the storm. The propagation of end waters across the basin therefore occurred at a speed of order 0.1 m s^{-1}. The near-bottom salinity fields suggest that high salinity waters that had flowed in through the narrow causeway openings were limited to the southern end of the sound, whereas the southward, high salinity inflow from the broader northern opening was able to traverse most of the length of the deep basin. This southward bottom inflow tended to be biased toward the eastern side of the basin, presumably in response to the effect of the earth's rotation. A Rossby number less than 1 is calculated for this situation (using a current speed of 0.1 m s^{-1} and a basin width of 5 km) confirming the significance of rotational effects to the flow field.

Figure 20 also shows that by the night of 22/23 August 1991 the high salinity water (>34.5 pss) that was only present at both ends on 20 August 1991 had traversed and covered the entire sea bed of the deep basin, vertically displacing lower salinity water that had been mixed down to the sea bed during the storm.

By 22 August 1991 the winds had moderated and were south-southwesterly at speeds less than about 10 m s^{-1}. As shown by the flow data in Figure 21 all near-surface current meters and drogues deployed across the northern opening recorded predominantly northward flow, indicating wind-driven advection out of the sound at speeds up to 0.15 m s^{-1}. The 14 m deep drogues just north of FCM1 and FCM2 and the near-bottom meters at FCM1 and FCM2 displayed east-southeastward currents, suggestive of flow into the deep basin via the deeper parts of the northern opening.

At the southern end of the sound, the current meter data in Figure 21 indicated a flow into the basin at PCM2 of order 0.06-0.08 m s^{-1} at about 1200 on 22 August 1991. In conjunction with the stratification data in Figure 20, these data suggest that an inflow of shelf water was occurring over the Southern Flats via the southern bridge openings of the causeway. This is further supported by density data collected later that day in the southern end of the sound, plotted in Figure 22, which presents contours of the density field at 0.5 m above the sea bed. The tide had been in flood since about 1800 hrs and there was a south-southwesterly wind blowing. The density field suggests an inflow of dense ocean water into the sound via the two bridge openings, a continuation of these inflows over the Southern Flats and their subsequent plunging as two bottom flows. The vertical structure perpendicular to these inflows is illustrated by the density, salinity and temperature structure along transect D, which skirted around the southern flats, plotted in Figures 23 a, b and c, respectively. Two dense slugs are evident, having the relatively high salinity and high temperature characteristics of oceanic water under the bridges.

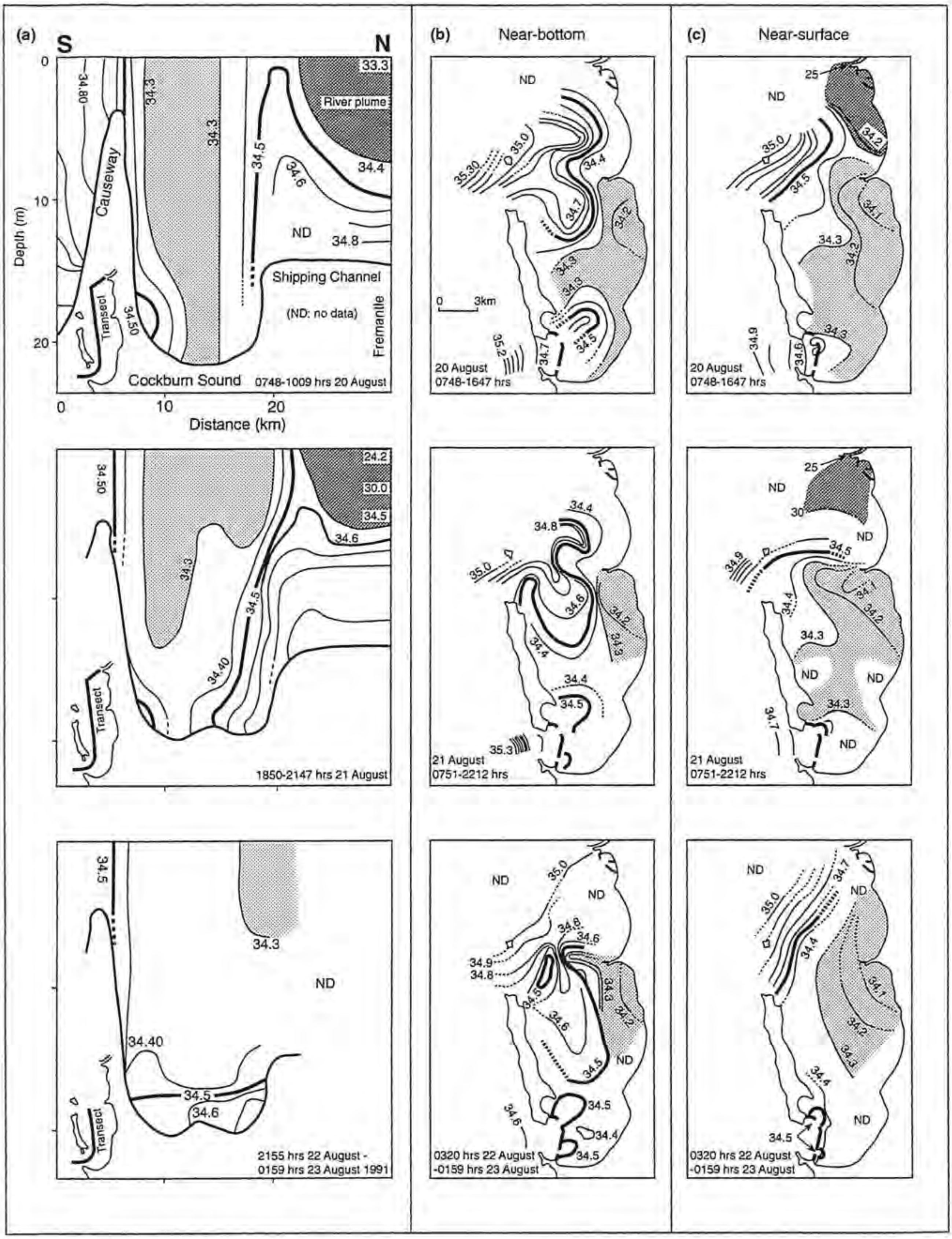


Figure 20. Time series of (a) vertical, (b) plan near-bottom and (c) plan near-surface salinity structure in Cockburn Sound showing deep-water renewal of high salinity shelf water and surface exit of low salinity basin water between 20 and 23 August 1991, after the storm of 19 August. Vertical contours are along Transect A. Units are in practical salinity scale (pss). Contour interval is 0.1 pss. The river plume regions are shaded dark and water less than 34.3 pss within the basin in shaded light.

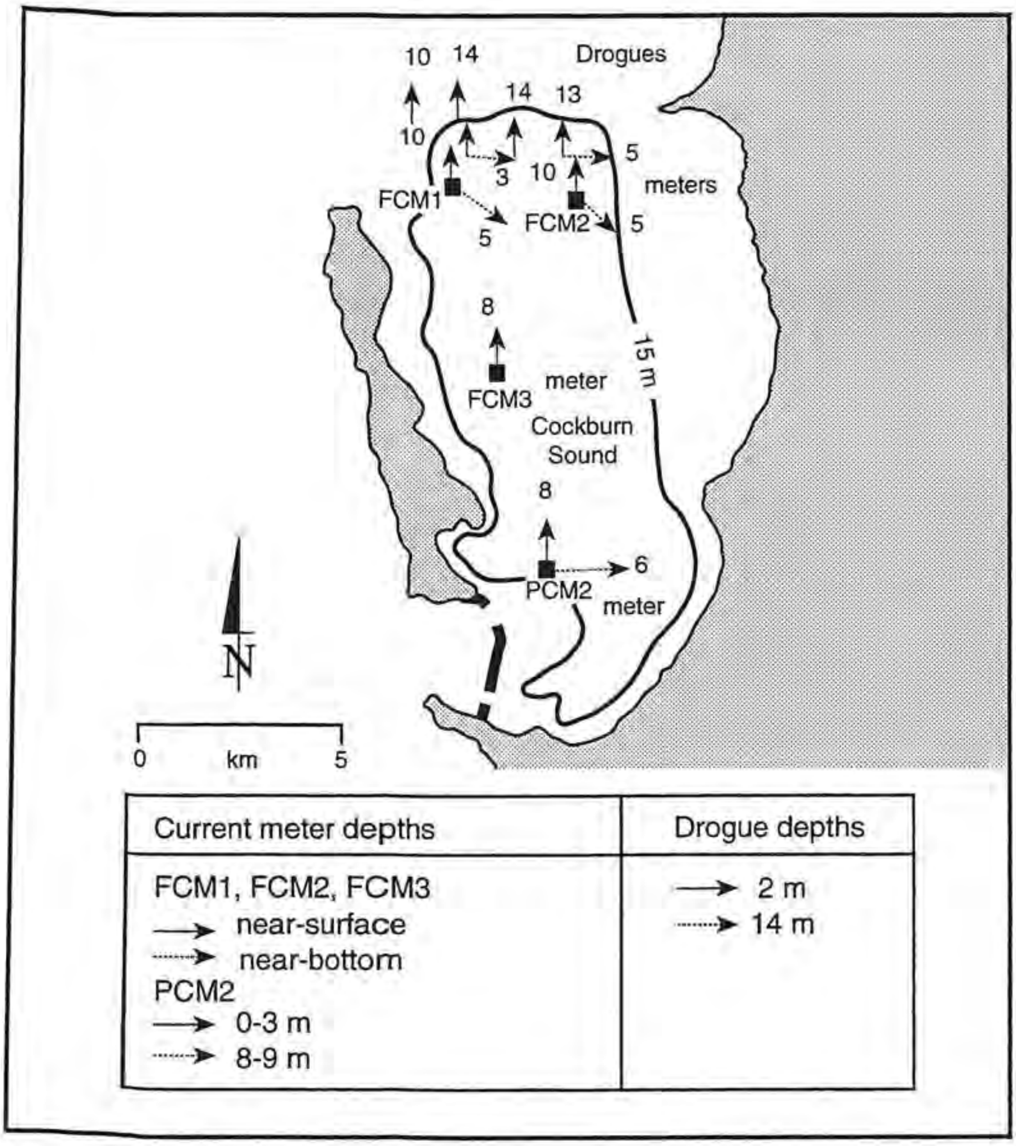


Figure 21. The approximate directions (arrows) and speeds (in cm s^{-1}) of flows recorded with current meters and drogues at approximately 1200 hrs 22 August 1991.

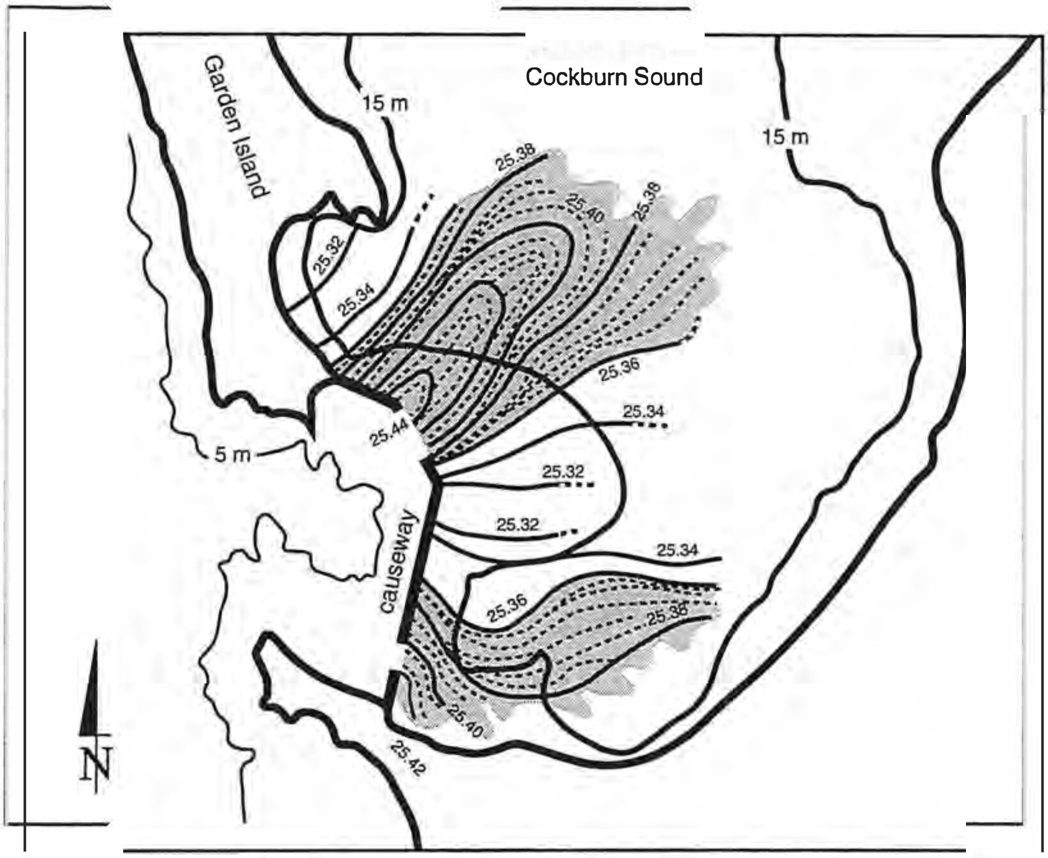
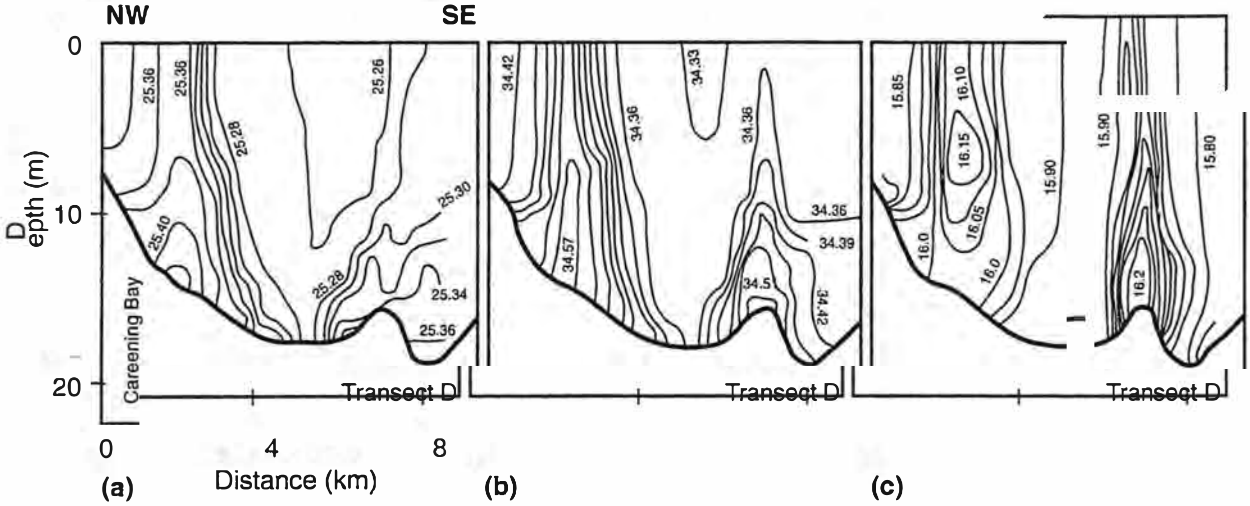


Figure 22. Contours of density, in sigma-t units (kg m^{-3}), on a bottom-following surface 0.5 m above the sea bed, between the causeway and the region skirting around the southern flats. The CTD data were collected between 2114 hrs 22 August and 0024 hrs 23 August 1991 along Transects C, D and E (see Figure 7). The shaded region represents water of density greater than 25.36 kg m^{-3}, in sigma-t units.



(a) (b) (c)

Figure 23. Contour plots of the vertical stratification along Transect D during 2114 hrs 22 August and 0019 hrs 23 August 1991: (a) density in sigma-t units (kg m^{-3}), (b) salinity (practical salinity scale), (c) temperature (°C). The stratification indicates two intrusions of oceanic water having relatively high densities, salinities and temperatures.

This suggests an inflow of oceanic water via the causeway openings, driven by a combination of tide, wind-stress and density difference. The vertical position of the inflowing intrusions is along the bottom due to their relatively high density compared to the receiving water in the sound (Figure 20).

The Princeton Ocean Model (modified by Herzfeld, 1995) was used to simulate re-stratification in the sound after a winter storm (Mills and D'Adamo, 1995b). The model run was started with a vertically uniform basin salinity that was 0.6-0.8 pss lower than adjacent shelf water salinity, resulting in initial horizontal density differences in the model similar to those observed between Cockburn Sound and the open shelf following the storm (Figure 20b). The model was forced by wind data from 18 August onward (see Figure 6) and by baroclinic forces arising from horizontal density gradients in the model domain. The influence of the earth's rotation was included. However the model did not include the effects of day-time heating and night-time cooling. The resulting comparison between measured and modelled changes to the north-south structure of the basin in the post-storm period are presented in Figure 24 as a time-series of north-south-vertical salinity sections. As is evident, the model has reproduced the essential behaviour of the post-storm exchange between the sound and the adjacent shelf region by predicting the entry of high salinity (i.e. relatively dense) shelf water into the sound and its subsequent transport across the bottom of the central basin.

The relative importance of density-driven exchange compared to wind-driven exchange during the re-stratification of the sound after the storm is difficult to quantify on the basis of the field data alone. However, further numerical baroclinic modelling has been conducted (Mills and D'Adamo, 1995b) to examine this question. To represent the density field at the end of the storm, the model salinity structure was again initialised (as shown in Figure 24(h)) with the sound vertically uniform and of lower salinity (by 0.6-0.8 pss) than the adjacent shelf region. The only model forcings for this simulation were the horizontal pressure gradients induced by the density field and the Coriolis force. The tide was neglected because it is a relatively minor agent in the flushing of the sound (Steedman and Craig, 1983) and wind forcing was not applied in this case. The model results are presented in Figure 25, showing the surface salinity fields, and the velocity vector and salinity fields near the bottom (18 m) at 1, 3 and 6 days since the start of the simulation. In this model run, the intrusion of dense shelf water into Cockburn Sound and the renewal of the deep basin (Figure 25) is the result of baroclinic relaxation of the density structure under the influence of the earth's rotation. As shown, the high salinity (high density) water has intruded about 10 km southwards into the basin as a bottom gravity current within 6 days. However, the flow field is significantly influenced by the Coriolis force, because $R < 1$, and this is evident in the bottom velocity vectors which are strongly steered counterclockwise, but bathymetrically constrained by the edges of the deep basin. The simulation suggests that density differences in winter between the sound and shelf can, in their own right, induce significant renewal of deep-basin waters, after a typical winter storm which leaves the basin well-mixed vertically but with a horizontal density difference between it and the adjacent shelf region. The baroclinic current speeds in the simulated velocity fields are up to about 0.05 m s^{-1}, which is significant when compared with the measured wind-driven currents of about 0.1-0.15 m s^{-1} (Figure 21).

Excluding rotational effects, a theoretical and laboratory derived estimate of the speed of a density driven flow is given by the simple formula $u \sim 0.5(g'H)^{1/2}$ (Simpson, 1982), where H is the depth of the water column. Using a basin depth of 21 m and a $\Delta\rho$ of 0.15 kg m^{-3} (an approximate density difference between the centre and ends of the basin on 20 August), a speed of about 0.08 m s^{-1} is predicted. Given that the influence of rotation is likely to slow the rate of

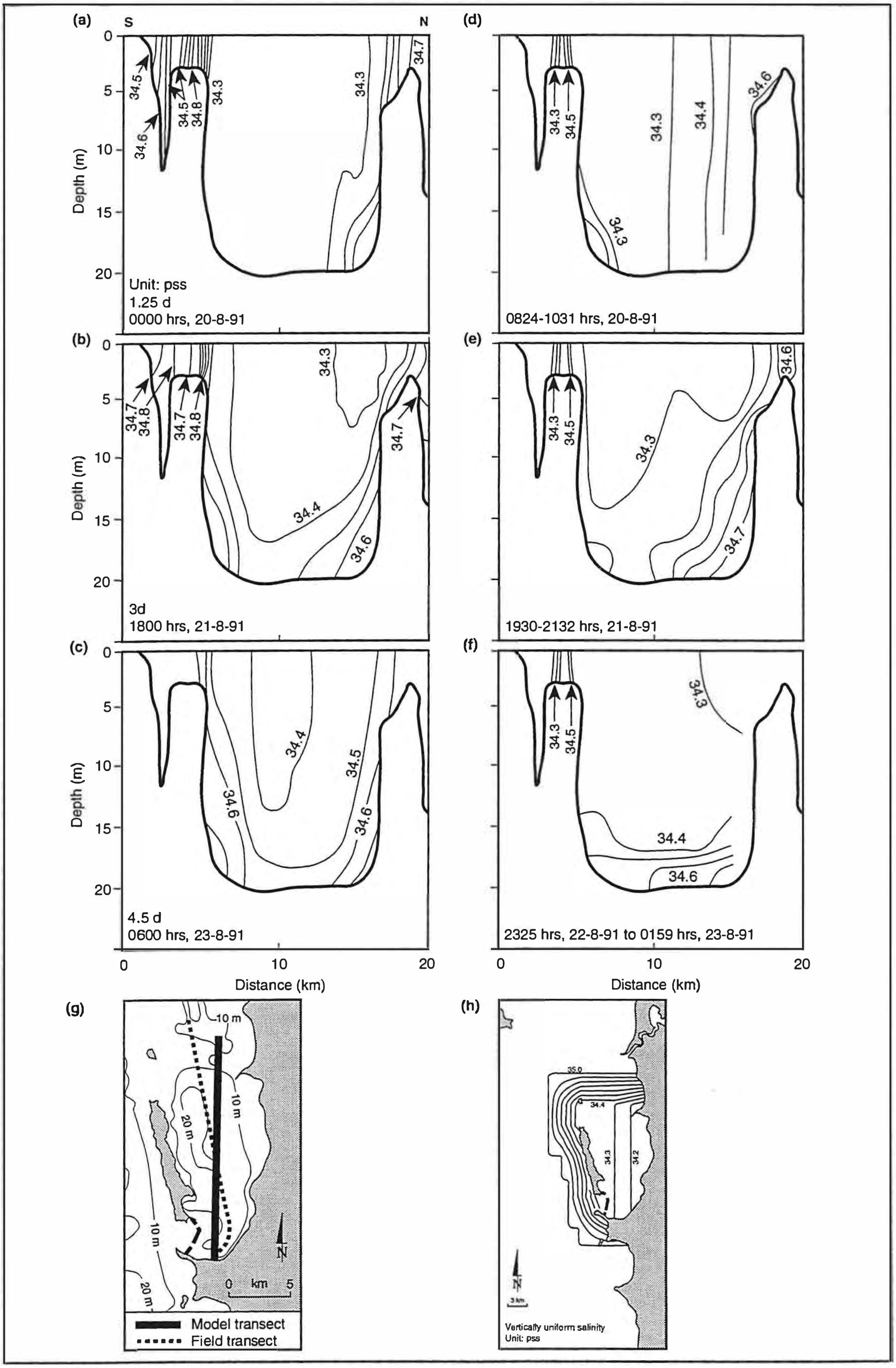


Figure 24. Vertical salinity sections along Transect A showing deep-water renewal in Cockburn Sound during the post-storm period of 20-23 August 1991 from (a-c) baroclinic model simulations (Mills and D'Adamo, 1995b) and (d-f) field measurements. Measured salinity was projected onto the model salinity transect path (g). For the model the recorded winds (Figure 6) were used, and the model was started at 1800 hrs 18 August 1991. The initial salinity field for the model was as shown in (h).

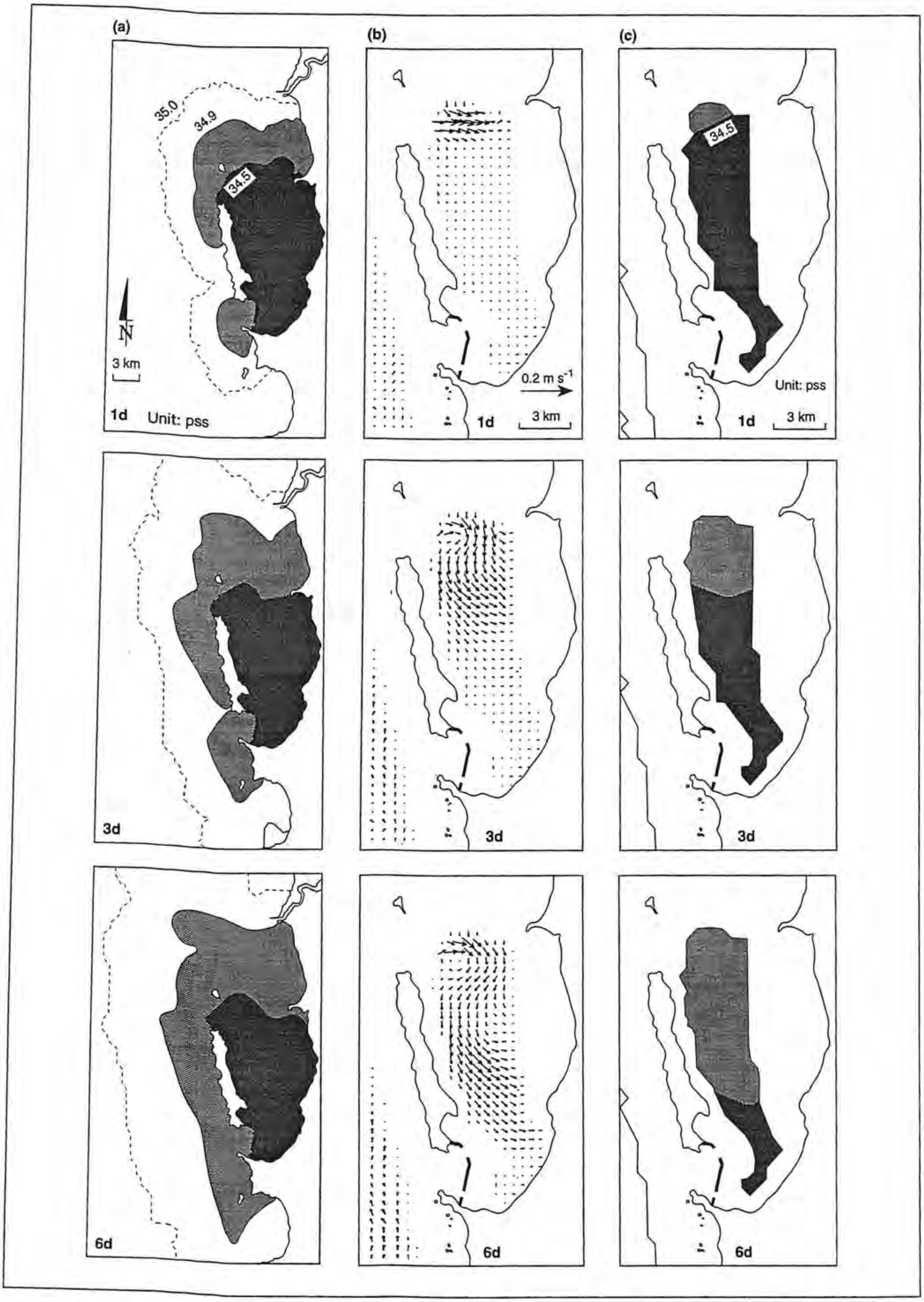


Figure 25. Baroclinic model simulation (Mills and D'Adamo, 1995b) of density-induced exchange (with no wind forcing) between buoyant Cockburn Sound water (set to be homogeneous at 34.4 pss) and dense shelf water (set to be homogeneous at 35.0 pss) after 1, 3 and 6 days, showing (a) surface salinity, (b) bottom velocity and (c) bottom salinity. The surface buoyant plume is enveloped by the 34.9 pss contour.

intrusion and density-driven exchange between the shelf and Cockburn Sound, this estimate is in reasonable agreement with the model results.

Mills and D'Adamo (1995b) compared the results of these 'winter' simulations and showed that the exchange rates for the case which included wind forcing were about three times greater than for the case of baroclinic relaxation (with no wind forcing).

The measured lateral density structure of the sound (in the west-east direction) underwent large changes in its inclination during the post-storm period of the field survey. Vertical density stratification measured across the centre of the sound (Transect B) during 20 August and 22/23 August, are presented in Figure 26 to highlight this. As shown, the initial structure on 20 August, about 0.5 day after the storm, was horizontally stratified, with the densest water in the west of the basin. However, by midnight of 22 August the inclination of the mean density structure was reversed with the densest water now in the east of the basin. The intervening winds were south-southwesterly and the wind-stress advected basin water towards the northern end of the sound. As previously discussed (Section 4.2) the Rossby number for such situations is less than 1, suggesting that the Coriolis force should exert a significant influence on the circulation. There was no westward component in the wind vector and hence direct wind-forced set up of the free surface could not have occurred along the western margin. The observed change in the basin-wide slope of the isopycnals was therefore most likely due to an across-basin adjustment of the density structure due to Coriolis force during the northward wind-driven flow.

The general picture that emerges for the post-storm dynamics is as follows. At the end of the storm the basin is left vertically well-mixed but horizontally stratified. After the storm, the overall circulation is influenced mainly by wind-driven advection, density effects, including basin-scale baroclinic forcings, and Coriolis effects. Relatively dense oceanic water flows in through the openings, sinks to the bottom and flows to the centre of the basin within 1-2 days, displacing lighter central basin water upwards. The vertically transported water can then be mixed within the upper layer and exported out of the sound within near-surface wind-driven flows via the northern opening by south-southwesterly winds.

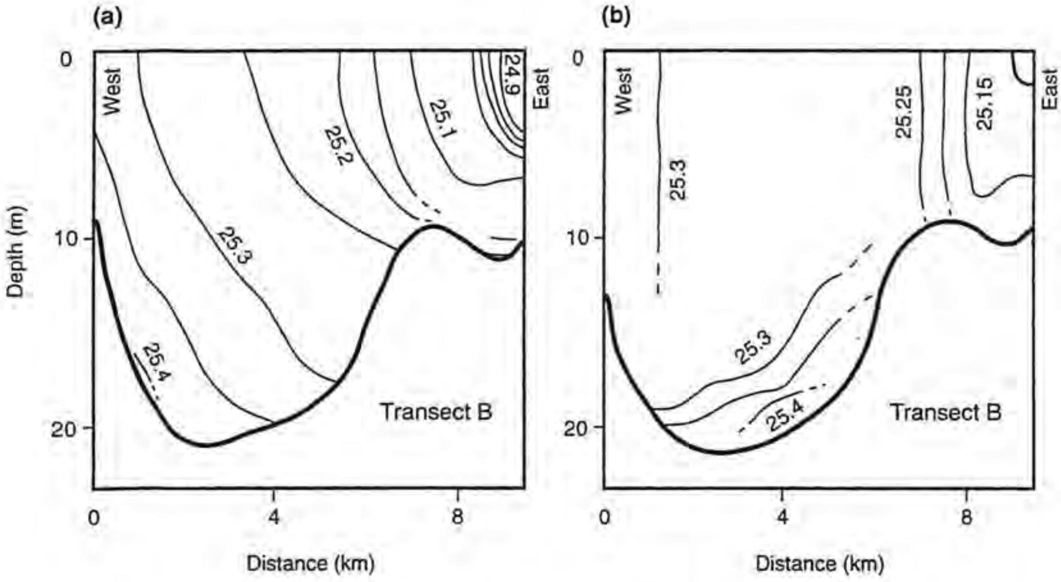


Figure 26. Contour plots of the vertical density stratification along Transect B during (a) 1205-1249 hrs 20 August 1991 and (b) 0052-0138 hrs 23 August 1991. Contours are in sigma-t units at an interval of 0.05 kg m^{-3}.

This sequence describes an effective flushing scenario for central Cockburn Sound waters, which are mixed, uplifted and subsequently advected out, predominantly through the northern opening of the sound. The basin-scale stratification and flow data suggest that under this series of processes a significant fraction of central Cockburn Sound water can be driven out of the sound in 2-3 days after a storm. Based on wind statistics, storms sufficiently strong to mix to the bottom of the sound occur on average about 5 times per month (WNI Science and Engineering, unpublished data), and we therefore conclude that the associated mixing and flushing sequence could occur up to 15 times per winter.

4.5 Diurnal heating, penetrative convection and vertical mixing during weak to moderate winds

The above analysis has concentrated on basin-scale advection and on the ability of strong storm winds to vertically mix through typical density gradients. Except during the storm of 19 August, the sound was found to be vertically stratified in salinity, temperature and therefore density. It was established that inflows of high salinity shelf water, as bottom flows, into Cockburn Sound resulted in a characteristic pycnocline at approximately 15 m. This section now investigates the diurnal energetics above the level of the main pycnocline.

The actions of solar radiation and vertical mixing (by wind stress and penetrative convection) were found to be important to the vertical cycling of mass throughout Cockburn Sound. Measurements of the diurnal variation in the basin-wide stratification revealed that there was daily warming of the upper layer followed by mixing due to penetrative convection down to about the level of the main pycnocline on most nights. This is exemplified by vertical CTD data collected at the centre of the basin and which have been used to plot the time history of vertical stratification for the 10-day survey period (Figure 27). These data are broadly representative of the entire basin in terms of the diurnal cycling in the vertical stratification (D'Adamo and Mills, 1995d).

As shown in Figure 27, there were up to three prominent vertical layers; a buoyant heated upper layer of approximately 3-5 m thickness that persisted during the day-time, a relatively dense bottom layer resident below about 15 m (the level of the main pycnocline, where salinity increased by about 0.5 pss) and a central layer that was present during the day-time, but became part of a well mixed upper layer, due to penetrative convection between the surface and main pycnocline, during the night. The main thermocline was situated within the main pycnocline where temperature increased sharply with depth. Hence, the temperature stratification was not responsible for density structure within the main pycnocline; rather it was the strong salinity variation that dominated density.

The basin-wide effects of diurnal heating and penetrative convection were captured by the CTD measurements. It was found that a day-time upper heated layer developed over the whole basin and at night the upper layer became well-mixed due to penetrative convection. This feature is illustrated in Figure 28 which presents the isotherm contour plots along the north-south and west-east transects (A and B, respectively) during the day-time of 14 August and night-time of 14/15 August. During the day a warm surface layer is evident to a depth of about 3-5 m. Winds during the day-time were relatively weak (2-4 m s^{-1}) and not strong enough to mix the heated layer (Figure 27). The wind-mixing predictions in Section 4.2 indicated that, in the days leading up to the storm, afternoon winds of less than about 5 m s^{-1} would not have been able to mix the typical day-time stratification to below about 8 m (Figure 19).

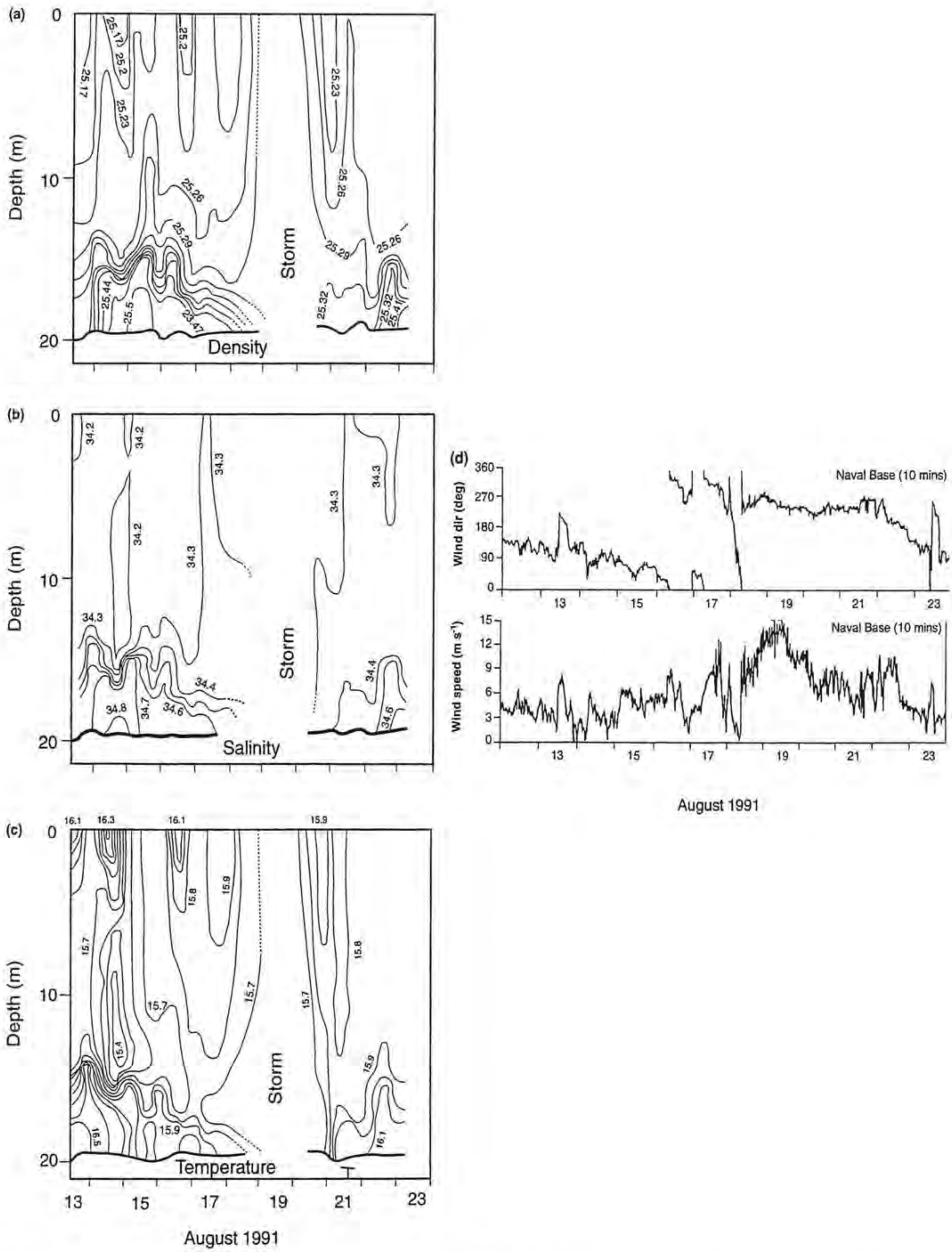


Figure 27. Time series contour plots of the vertical stratification in (a) density (in sigma-t units at an interval of 0.03 kg m^{-3}), (b) salinity (practical salinity scale (pss) at an interval of 0.1 pss) and (c) temperature (°C) at an interval of 0.1 °C) in central Cockburn Sound. Wind data from Naval Base (12m height) are shown in (d). Note the changes in the stratification due to heating, cooling and strong storm winds.

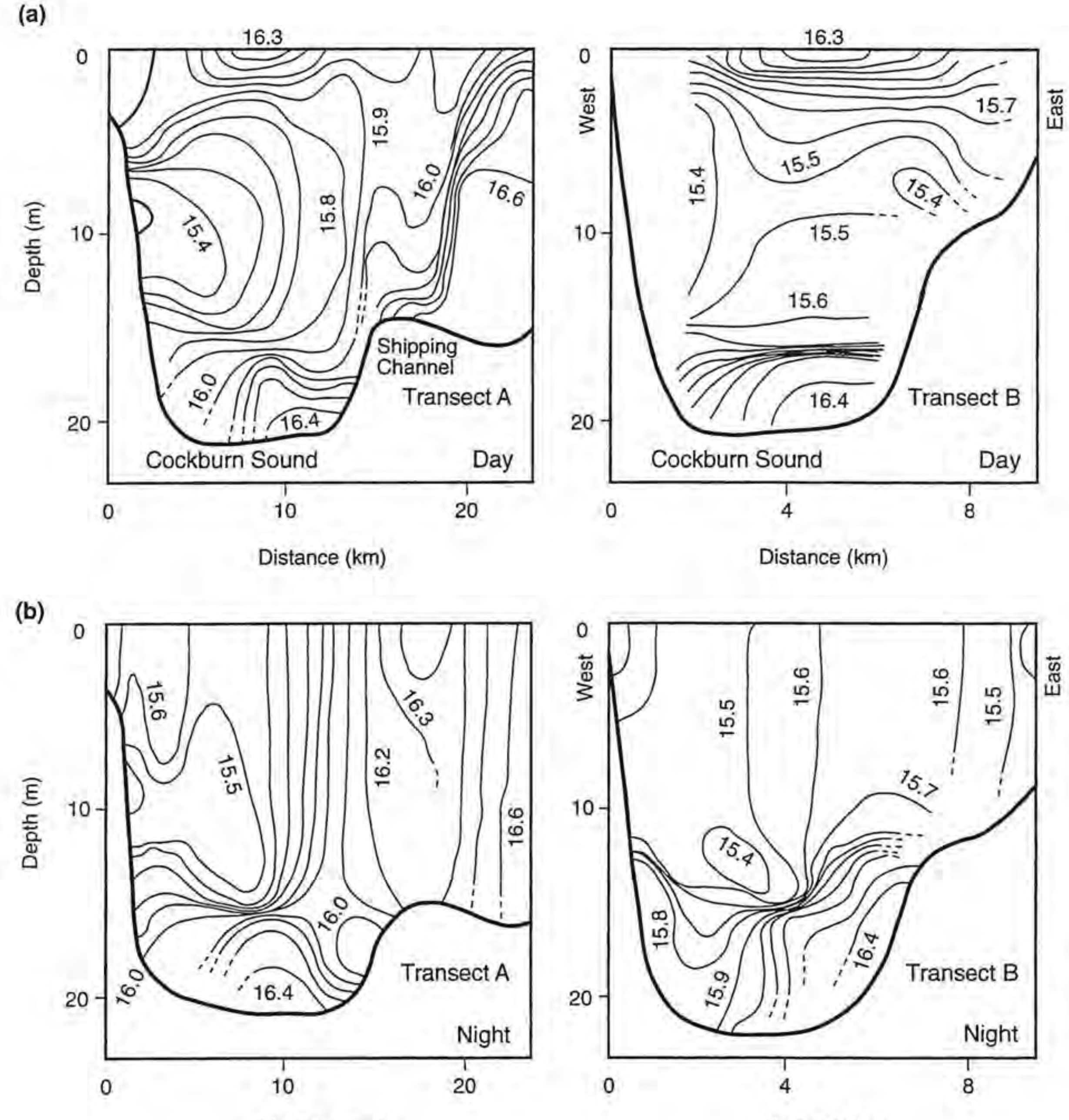


Figure 28. Vertical temperature stratification along Transects A and B during (a) the day-time of 14 August (1150-1553 hrs) and (b) the night-time of 14/15 August (2116-0249 hrs). Temperature contour intervals are 0.1°C.

However, at night penetrative convection was found to mix the day-time stratification to the level of the main pycnocline. A formula for the prediction of upper mixed layer deepening due to penetrative convection is given in Imberger (1994) and was derived following the same methodology as that for vertical wind mixing, discussed in Section 4.2. An initially linearly stratified water column is adopted as an approximation for the vertical structure of the upper heated layer during the day-time. For this case the formula for penetrative convection is (Imberger, 1994)

$$h = [(4C_F\alpha gH^*)/(N^2(C_F+C_E)C_p\rho_w)]^{1/2}t^{1/2}$$

where N is the buoyancy frequency given by $N = [(g/\rho_w)(d\rho/dz)]^{1/2}$, ρ_w is the mean water density, $d\rho/dz$ is the linear density gradient with z positive downwards, $C_F = 0.25$, and $C_E = 1.15$ are coefficients of energy conversion (Imberger, 1994), α is the thermal compressibility of water (= $1.5 \times 10^{-4}\ {}^oC^{-1}$), H* is the rate at which heat is lost through the water surface in W m^{-2}, and has been estimated to typically range from 200 to 400 W m^{-2} at night during winter (Figure 4) and C_p is the specific heat of water (= 200 J $kg^{-1}\ {}^oC^{-1}$). By applying this formula for the given case, a maximum depth of mixing to about 15 m is predicted after 6 hours during which the heat loss rate was set at 300 W m^{-2}, an estimated average H* for winter. Upon reaching 15 m depth the penetrative convection would have encountered a density gradient zone separating the upper and lower layers that was more step-like than linear (Figure 27). Allowing for this new density gradient the prediction is that minimal further deepening (about 1 m) would have ensued during the remainder of the night, and this is consistent with the recorded vertical density stratification data in Figure 27.

The analysis suggests that for the typical winter stratification, when the upper layer of Cockburn Sound is diluted with buoyant outflow from the Swan River and subjected to a diurnal heating (and hence stratification) cycle, vertical mixing by wind-stress is confined to the upper 15 m of the water column provided that wind speeds remain below about 7.5 m s^{-1}. The diurnal thermal stratification is overcome at night by penetrative convection typically to the level of the main pycnocline, which was at about 15 m during the field survey. Hence, it is probable that the water above the level of the main pycnocline undergoes regular mixing in winter, but that mixing below that level only occurs during storms when winds are stronger than 10 m s^{-1}. Vertical stratification data collected during past oceanographic studies (as reviewed by D'Adamo, 1992) suggest that the vertical salinity gradients encountered during our survey were typical for winter conditions.

5. Discussion

In mid-winter and early spring the mean density of Cockburn Sound is typically lower than that of adjacent shelf waters. The relative buoyancy of the sound results from the wind-driven advection of buoyant Swan River plumes into Cockburn Sound, where they are mixed with resident water by wind-stress and penetrative convection. This process results in horizontal density differences both within the sound and between it and adjacent waters. Density effects and, to a small extent, tidal advection complement wind stress in driving circulation and flushing of the basin.

During winter the wind regimes are characterised by 7-10 day cycles (Breckling, 1989) where the wind starts as weak to moderate (<10 m s^{-1}) and blows from the southwest-southeast quadrants. It then swings counterclockwise through north, eventually strengthening to greater than 10 m s^{-1} from either the northwest or southwest quadrants. The cycle ends with winds moderating to be again from the southwest or southeast quadrants. The hydrodynamic behaviour can be described for the various dominant wind regimes, as follows.

Mixing by weak-moderate winds and penetrative convection

In general, if winds are less than about 7.5 m s^{-1} then neither wind-shear nor penetrative convection appear to be able to mix the water column fully to the bottom on a regular basis. Penetrative convection at night can achieve upper mixed layer deepening to about the level of the main pycnocline (15 m). The main pycnocline is associated with a strong vertical salinity gradient at a depth of about 15 m which forms as a result of the inflows of relatively high salinity, and therefore denser, shelf water. The inflows occur as bottom currents from the northern and southern openings of Cockburn Sound, with the major influx through the northern opening, due to its comparatively large cross-sectional area.

Circulation under moderate northerly winds

Under typical strength northeasterly-northwesterly winds (5-7.5 m s^{-1}) lasting for 1-2 days, buoyant estuarine plume water is driven into the sound through the northern opening and basin-scale downwelling occurs, causing depression of the main pycnocline at the southern end. In addition, there is a lateral (east-west) tilting of the density structure in response to the southward wind-stress and the earth's rotation, which deflects the southward moving plume and deepens it against the east coast of the sound, and causes an upwelling of the density (salinity) contours against the west coast.

Storm-mixing

Stronger winds (>10 m s^{-1}) blowing for more than about 10 hours are required to fully mix the water column vertically, and during these winds the circulation appears to be dominated by wind-driven advection. For example, complete vertical mixing was achieved by the 10-15 m s^{-1} winds of the storm of 19 August 1991. However, these storm winds were not able to completely eliminate horizontal stratification, and the basin was left characteristically stratified with densest waters at either end.

Wind and density-driven exchange following storms

After a winter storm, moderate (<10 m s^{-1}) southerly winds cause surface transport northward out of the sound, and dense inflows through the small causeway openings in the south. In addition, both the density differential, and the water level gradient due to the northward wind stress, drive flows into the sound through the deeper parts of the northern opening, and these dense inflows plunge to form bottom currents. Within about 1-2 days after the cessation of the storm, the denser waters from the northern and southern regions are transported across Cockburn Sound as bottom currents, and the vertical stratification is re-established. The Rossby number for typical flows in Cockburn Sound is less than unity and, after about 1 day (the inertial period), discernable rotational effects appear.

The stratification data throughout such periods indicate that a parent pycnocline (due to salinity gradients) is characteristically re-established at about 15 m depth within about 1-2 days after a storm, and is maintained under weak to moderate winds (< 10 m s^{-1}). The central basin water previously mixed down to the sea bed during a storm is subsequently displaced upward by the denser inflows following the storm.

During the intensive winter survey of August 1991, the upper 15 m zone was found to undergo regular diurnal mixing by penetrative convection and wind mixing by normal strength winds. Once in this zone, therefore, water is available to be exported out of the sound via the northern opening within near-surface wind-driven flows under moderate (5-10 m s^{-1}) south-westerly winds which typically occur after a winter storm. The northward transport of low salinity near-surface water was reflected in the movement of isohalines from the centre of the basin to the northern opening in 2-3 days during post-storm south-southwesterly winds of 5-10 m s^{-1}.

Frequency of occurrence and confirmation of flushing mechanism

The sequence discussed above provides a flushing mechanism for Cockburn Sound during typical winter and spring conditions. There are, on average, 15 storm events per winter (defined as winds greater than about 10 m s^{-1} of duration 5-10 hours or more). Hence, this sequence of plume incursion, complete vertical mixing, deep water renewal, upward displacement and partial flushing of basin waters, probably occurs up to about 15 times per winter.

Numerical hydrodynamic modelling also confirms that the transport of relatively dense shelf water to central Cockburn Sound as a bottom flow is a characteristic mechanism which operates under winds up to about 10 m s^{-1}. This density-induced mechanism enhances the efficiency of flushing between Cockburn Sound and the open shelf beyond that which would otherwise be provided by wind-stress alone.

6. Conclusions

There are two key factors which govern the exchange mechanism detailed in this paper. The first is that the sound must be buoyant relative to the adjacent ocean. D'Adamo and Mills (1995c) suggest that this is typically the case from about July to December due to buoyancy fluxes from river discharge in winter to early spring and then solar radiation in spring to early summer. Whilst river discharges decline in spring (September to November), differential heating of the shallower nearshore basins tends to maintain the direction of the buoyancy gradient between the sound and ocean. The second factor is that strong mixing events, such as storm winds (> 10 m s^{-1}) which can mix to the bottom of Cockburn Sound, must be separated in time by weaker mixing conditions for long enough to enable basin-scale penetration of dense shelf water inflows. Adjacent high density shelf waters enter the basin during wind-driven exchange as near-bottom flows and cover the whole of the basin seabed within 2-3 days. These two factors generally coincide from about July to October, prior to the strengthening of the diurnal sea-breeze cycle.

Our results suggest that volume exchange between Cockburn Sound and surrounding shelf water in winter-spring conditions occurs more rapidly than has been suggested by earlier studies whose deductions were based on two-dimensional depth-averaged numerical modelling and assumed that flows were primarily barotropic.

Due to the presence of strong vertical and horizontal density stratification, it is suggested that numerical models which include baroclinic processes are appropriate for the simulation of the hydrodynamics of Cockburn Sound during winter and spring.

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