Coastal water transport and vertical mixing during summer in the nearshore zone off Perth, Western Australia — the roles of wind-driven mixing and advection, thermal stratification and penetrative convection

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

Department of Environmental Protection
Perth, Western Australia
Technical Series 67
December 1995

ISBN 0 7309 5723 3
ISSN 1030 - 0600

Coastal water transport and vertical mixing during summer in the nearshore zone off Perth, Western Australia — the roles of wind-driven mixing and advection, thermal stratification and penetrative convection

N. D'Adamo and D. A. Mills

Department of Environmental Protection
Perth, Western Australia, 6000.

Contents

Contents (cont)

Acknowledgments

We are grateful to Dr David Luketina of the University of New South Wales and Dr Greg Ivey of the University of Western Australia for their reviews of this paper. The study was funded by the State Government of Western Australia as part of the Southern Metropolitan Coastal Waters Study (1991-1994) being conducted by the Department of Environmental Protection of Western Australia. The University of Canterbury, New Zealand and University of New South Wales, Australia hosted one of the authors during preparation of parts of this paper. Software for CTD data processing was provided by the Centre for Water Research (University of Western Australia).

Abstract

Dominant mixing and transport processes of the nearshore zone off Perth, Western Australia, are described for a typical summer synoptic period of five consecutive days in March 1992. The long-shore transport off Perth was dominated by wind-driven northward advection of coastal waters due to south-southwesterly sea-breezes, leading to the entry of water into the nearshore semi-enclosed basins of Comet Bay, Sepia Depression, Warnbro Sound, Cockburn Sound, Owen Anchorage and Gage Roads. A long-shore salinity gradient was identified, with highest values to the south. This gradient was due to high salinity outflows from the Peel-Harvey Estuary superimposed upon the normal summer salinity increases observed in the nearshore waters as a result of evaporation.

Inflows of these waters into Cockburn Sound were investigated in detail to discern exchange processes between the coastal waters and the basins. The inflows were of relatively high salinity (and density) and therefore tended to sink to the bottom, and this mechanism, in addition to strong diurnal solar heating, led to vertical stratification of salinity, temperature and therefore density in the basin. The diurnal energetics within the interior of Cockburn Sound was dominated by day-time stratification due to solar radiation, regular mixing by afternoon sea-breezes and penetrative convection due to nightly heat losses. Under typical summer meteorological conditions afternoon sea-breezes generally occur daily. During the diurnal cycles penetrative convection led to upper mixed layer depths of between 5 and 18 m. When the penetrative convection was preceded by sea-breeze winds of greater than about 7-10 m s^{-1} lasting for 5-8 hours or more a fully mixed water column resulted by dawn. Sea-breezes with winds greater than about 10 m s^{-1} with durations of 5-7 hours or more were found to fully mix the water column due to the action of wind-stress alone, a result supported by the application of predictive wind-mixing formulae.

An analysis of long-term wind records indicates that during typical summer synoptic cycles full-depth mixing due to the combined action of afternoon sea-breezes greater than 7.5 m s^{-1} in strength and night-time penetrative convection is likely to occur on average at least every 1 or 2 days. Transport within the nearshore zone, including the basins, is therefore likely to be dominated by barotropic wind-driven circulation, but with intermittent periods of relatively weak vertical stratification in the basins during milder wind periods. Due to the regularity of full-depth mixing, it is concluded that three-dimensional barotropic hydrodynamic models forced by wind stress could, in the first instance, be appropriate for numerical simulations of the main circulation features of this coastal zone (including the nearshore semi-enclosed basins) for typical summer conditions. However, because of the observed diurnal evolution of the stratification by solar radiation and/or advection of high salinity water, baroclinic modelling may be a useful adjunct to account for baroclinic pressure gradients which may be comparable with other forcings, even under vertically well-mixed conditions.

By inference, because the other nearshore basins of Owen Anchorage, Warnbro Sound and Comet Bay are less enclosed and shallower (< 20 m) the potential for vertical density stratification is less. Hence, it can also be expected that they would undergo the same or greater regularity of full-depth mixing during typical summer conditions.

1. Introduction

This paper presents oceanographic data which reveal features of the coastal transport and vertical mixing characteristics of the nearshore zone south of Perth, Western Australia for a typical 5-day summer period (9-13 March 1992). Figure 1 presents the study site and shows a topography characterised by a series of semi-enclosed nearshore embayments adjacent to a gently sloping shelf. Tides and regional currents play minor roles in the hydrodynamics of the site during summer (Steedman and Craig, 1983).

The role of south-southwesterly winds in driving long-shore transport and associated inflows into the semi-enclosed basins within the region is highlighted. The diurnal mixing analysis focusses on the semi-enclosed embayment of Cockburn Sound. In particular, we investigate the relative influences of day-time solar heating and coastal inflows as stratifying agents in Cockburn Sound and the erosion of the stratification by surface mixing due to a combination of wind-stress during typical afternoon sea-breezes and penetrative convection at night.

The oceanographic information is required to assist in the choice, calibration and application of numerical hydrodynamic models for the Department of Environmental Protection of Western Australia's studies (from 1991 to 1994) into the ecology of Perth's southern coastal zone. The Southern Metropolitan Coastal Waters Study (SMCWS) aims to provide a better technical basis from which to manage the cumulative environmental impacts of present and predicted contaminants entering these waters (Simpson *et al.* 1993). This paper complements other literature on the oceanographic results of the SMCWS which describe the winter, autumn and seasonal characteristics of the hydrodynamics of Cockburn Sound and adjacent waters (eg Mills *et al.* 1995; D'Adamo and Mills, 1995a and b; D'Adamo *et al.* 1995a and b). In addition, past hydrodynamic studies of Cockburn Sound and its adjacent waters, which pre-date the SMCWS and go back as far as 1969, are summarised and reviewed in Hearn (1991) and D'Adamo (1992). The oceanography of Warnbro Sound has received attention in recent studies with Gersbach (1993) applying a three-dimensional numerical model to the system forced by a range of wind conditions and Kruh (1994) analysing an intensive 36 hour field data set in autumn of the three-dimensional salinity, temperature and density structure. The first major environmental study of Cockburn Sound and adjacent waters was conducted between 1976 and 1979 by the Department of Conservation and Environment (1979).

Because past studies have identified that density stratification occurs frequently within the basin throughout the year (see Hearn (1991), D'Adamo (1992) and Steedman and Craig (1983)) attention is given in this paper to detailing the influence of stratification on the mixing and transport within Cockburn Sound during a typical summer period. Some of the earlier studies (eg Steedman and Craig, 1983) made reference to the existence of density fronts within the basin under relatively mild wind conditions (of order 5 m s^{-1}) and suggested that their role in the hydrodynamics of the basin required further investigation. D'Adamo (1992) reviewed past oceanographic data sets collected over the four seasons and found that vertical and horizontal stratification was a characteristic of the structure in Cockburn Sound when wind speeds were less than about 5-10 m s^{-1}, which is over 50 percent of the time. The occurrence of fronts in coastal environments and their role in causing spatial variability in the distribution of biological parameters has been reviewed in a recent collection of papers discussing the hydrography, hydrodynamics, sediment dynamics and biological dynamics associated with estuarine, coastal and generic fronts (Largier, 1993 and Vollenweider *et al.* 1992). In view of the propensity for vertical and horizontal density stratification to develop in Cockburn Sound (Steedman and Craig, 1983; Hearn, 1991; D'Adamo, 1992) and then potentially influence the spatial distributions of biological parameters (Chiffings, 1987) the field programme for the summer study was structured to detail the vertical and horizontal stratification and to evaluate the potential of typical strength mixing agents to destroy this stratification.

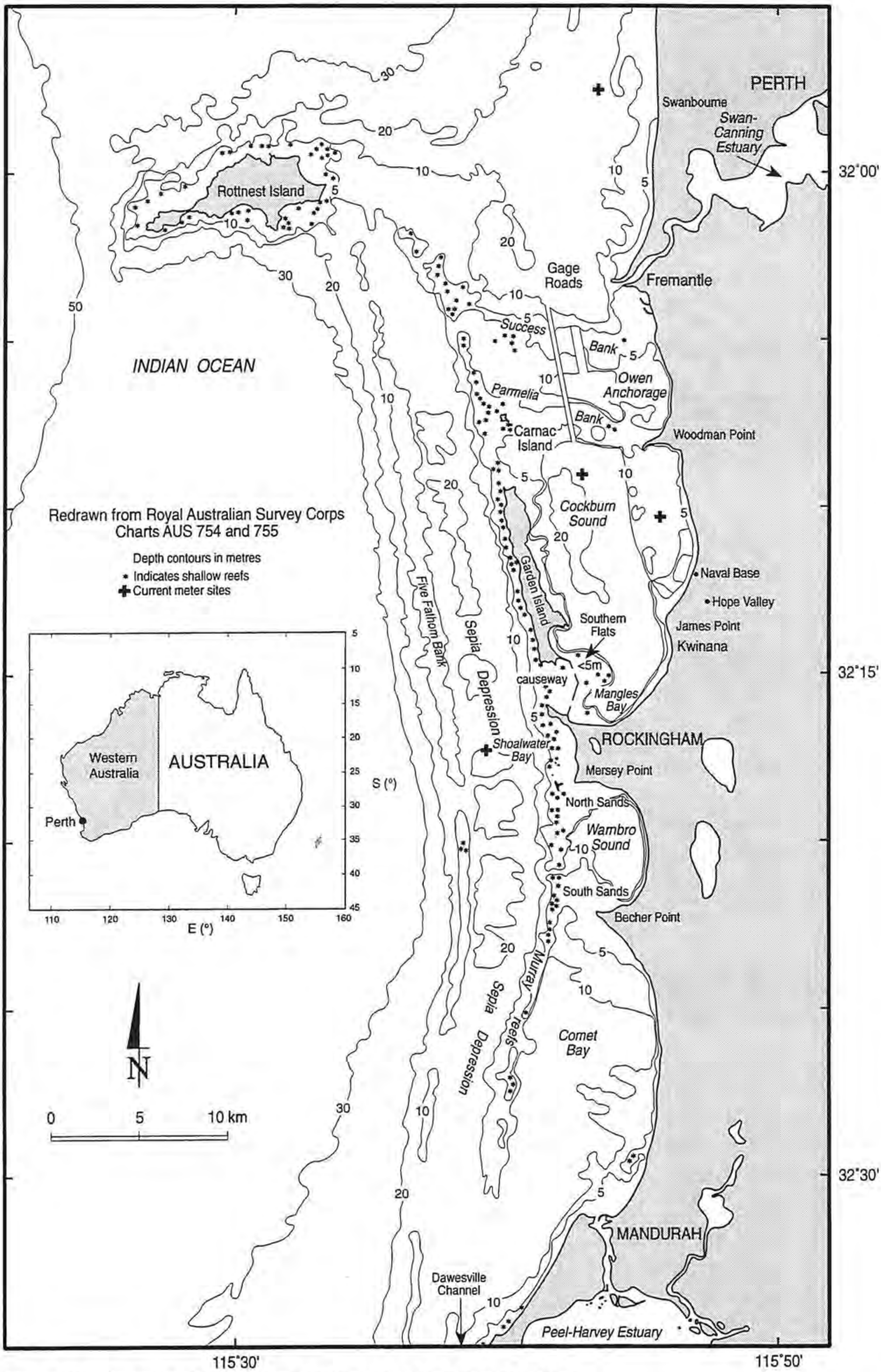


Figure 1. Study region of the Southern Metropolitan Coastal Waters Study.

2. 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 submerged reef line called Five Fathom Bank lies the channel called Sepia Depression, west of which is open shelf. Five Fathom Bank runs from offshore of Becher Point to Rottnest Island (Figure 1) and, in conjunction with reefs, islands and sand banks, shelters Cockburn Sound and adjacent coastal waters from oceanic swells and regional currents. Another shore-parallel reef line, called Murray Reefs, runs from 10 km offshore of Mandurah and connects with the Warnbro Sound reef line off Becher Point. Comet Bay is a relatively shallow basin (< 15 m) between Mandurah and Warnbro Sound. The nearshore zone (including the basins and Sepia Depression) is typically less than 20 m deep and the adjacent mid-shelf region gently slopes to about 50 m depth 20 km west of Sepia Depression.

Within Cockburn Sound the bathymetry is characterised by a deep basin (up to about 21 m depth) having approximate dimensions of 14 km by 5 km, and a shelf region adjacent to the mainland coast between James Point and Woodman Point having a maximum width of about 4 km and a depth less than about 10 m. Mangles Bay forms a more protected pocket of the basin in the southern end of the sound. The northern opening has a depth of about 5 m or less and is comprised of a 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. The causeway with two bridges was completed across the southern opening in 1973 and reduced the cross-sectional area along the alignment of the causeway from approximately 10000 m^2 to 4000 m^2, with water depths of about 3-4.5 m under the bridges.

3. Meteorology

The climate and meteorology of the Perth region is described by the Australian Bureau of Statistics (1989) as being typically Mediterranean. For summer (December, January and February) some of the main characteristics can be summarised as follows. Daily maximum temperatures can reach about 44 degrees Celsius (°C), but with the mean of daily maximums being about 27-30 °C and the mean of daily minimums being about 16-18 °C. During the day-time the daily maximum in the short-wave radiation typically varies from about 500-1000 W m^{-2} with the net heat flux (taking into account all loss terms) into the water body via the water surface varying from about 500 to 800 W m^{-2} for a typical summer day. At night long-wave radiation and latent and sensible heat fluxes typically result in net losses of between 100 and 500 W m^{-2} to the atmosphere via the water surface (Pattiaratchi *et al.* 1995). The proportion of the sky generally covered by cloud (based on the mean of readings at 0900, 1500 and 2100 hrs) is on average about 30 percent, with an average of about 10-11 hours per day of sunshine.

Daily evaporation (based on Class A pan evaporation readings taken at Perth by the Bureau of Meteorology) is on average about 9 mm during summer (Australian Bureau of Statistics, 1989). However, the actual evaporation over a water body is somewhat less than values given by a pan evaporimeter (see Black and Rosher, 1980). For example, Black and Rosher (1980) compared Class A pan evaporation recordings and estimates of evaporation based on contemporaneous field data for the Peel-Harvey Estuary region and suggested that in January and February a factor of about 0.6 needed to be multiplied to the pan evaporimeter recordings and that in December and March this factor needed to be about 0.7.

Relative humidity generally has a diurnal fluctuation, with maxima at night and minima during the day. Data from Department of Environmental Protection instruments positioned at Hope Valley (Figure 1) during the last few years indicate that typical relative humidity values are over 70 percent at night and between 20 to 50 percent during the day. Negligible amounts of rain fall over the Perth coastal plain in summer with the net average for summer being 34 mm, compared to 835 mm for the remainder of the year (Australian Bureau of Statistics, 1989). Hence freshwater buoyancy fluxes to the coastal zone from river discharges are negligible in summer.

Descriptions of the wind regimes over Perth can be found in Steedman and Craig (1979), Breckling (1989) and Hearn (1991). Winds are generally controlled by the largely north-south movement of the anti-cyclonic belt (pressure systems with anti-clockwise winds) which lies across the continent for about six months of the year. With respect to Perth, the belt's axis migrates to the south in summer and to the north in winter. Consequently, prevailing winds are predominantly offshore from the east-southeast in summer and onshore from the northwest and southwest quadrants in winter. Throughout the year, but particularly in late spring and throughout summer, it is common for south-southwesterly sea-breezes to blow in the afternoons. Afternoon sea-breeze winds regularly reach speeds of order 10 m s^{-1} during summer.

The meteorological data set for the study period (9-13 March 1992) is presented in Figure 2. As shown there was strong solar radiation on all days. Class A pan evaporation data from the Commonwealth Bureau of Meteorology indicate that evaporation ranged from 5 to 7 mm per day during 9-13 March. Relative humidity ranged from about 50 to 100 percent and on 10, 11 and 12 March strong afternoon sea-breezes occurred with winds of up to 10-13 m s^{-1}. The progressive wind vector data for the 5 day survey period is plotted in Figure 3 and shows that there was a net northward component in the wind.

4. Field program and instrumentation

The three-dimensional salinity and temperature field in Cockburn Sound and adjacent waters was measured over a comprehensive grid once to twice daily between 9 and 13 March 1992. Outside of the sound vertical profiles of salinity-temperature structure were made at sites between west Garden Island and Warnbro Sound once during each day-time on each of the five days.

A fine-scale conductivity-temperature-depth (CTD) probe was used to monitor the stratification in Cockburn Sound and this instrument comprised a Seabird Electronics SBE-3 thermometer, a Seabird Electronics SBE-4 conductivity meter, a Paroscientific Digiquartz pressure sensor and associated electronics, described in Vollmer (1991). Vertical profiles were obtained by deploying the probe in free-fall mode from a vessel equipped with a Geographical Position Sensor. 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.

Outside of Cockburn Sound manually recorded salinity-temperature data were collected with a Yeokal Electronics Hamon Model 602 Salinity-Temperature bridge. Salinity-temperature (ST) profiles generally had a 1 m vertical spatial resolution and according to manufacturer's specifications the meter is accurate to plus or minus 0.03 parts per thousand (ppt) for salinity and plus or minus 0.1 °C for temperature. Regular checks of the meter against inductive salinometers were made and the data were calibrated and adjusted accordingly. Using the calibration data it is considered that the salinity records are accurate to plus or minus 0.05 ppt. Horizontal ST differences between basins during the survey period generally exceeded these accuracies by up to five times.

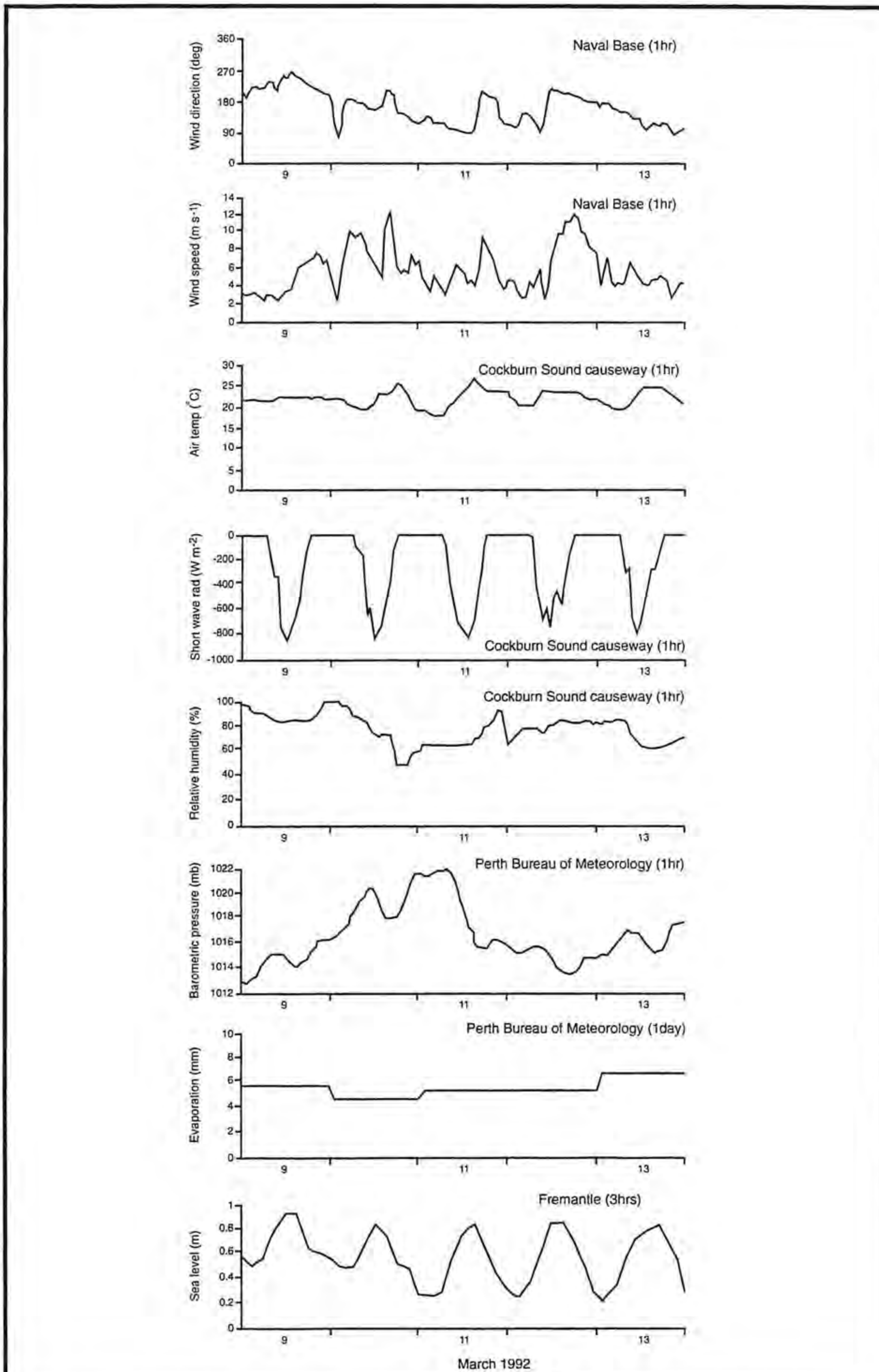


Figure 2. Meteorological data during the study period (9-13 March 1992).

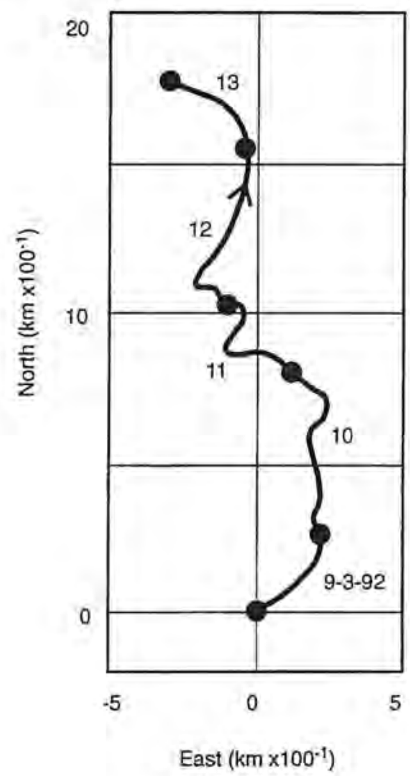


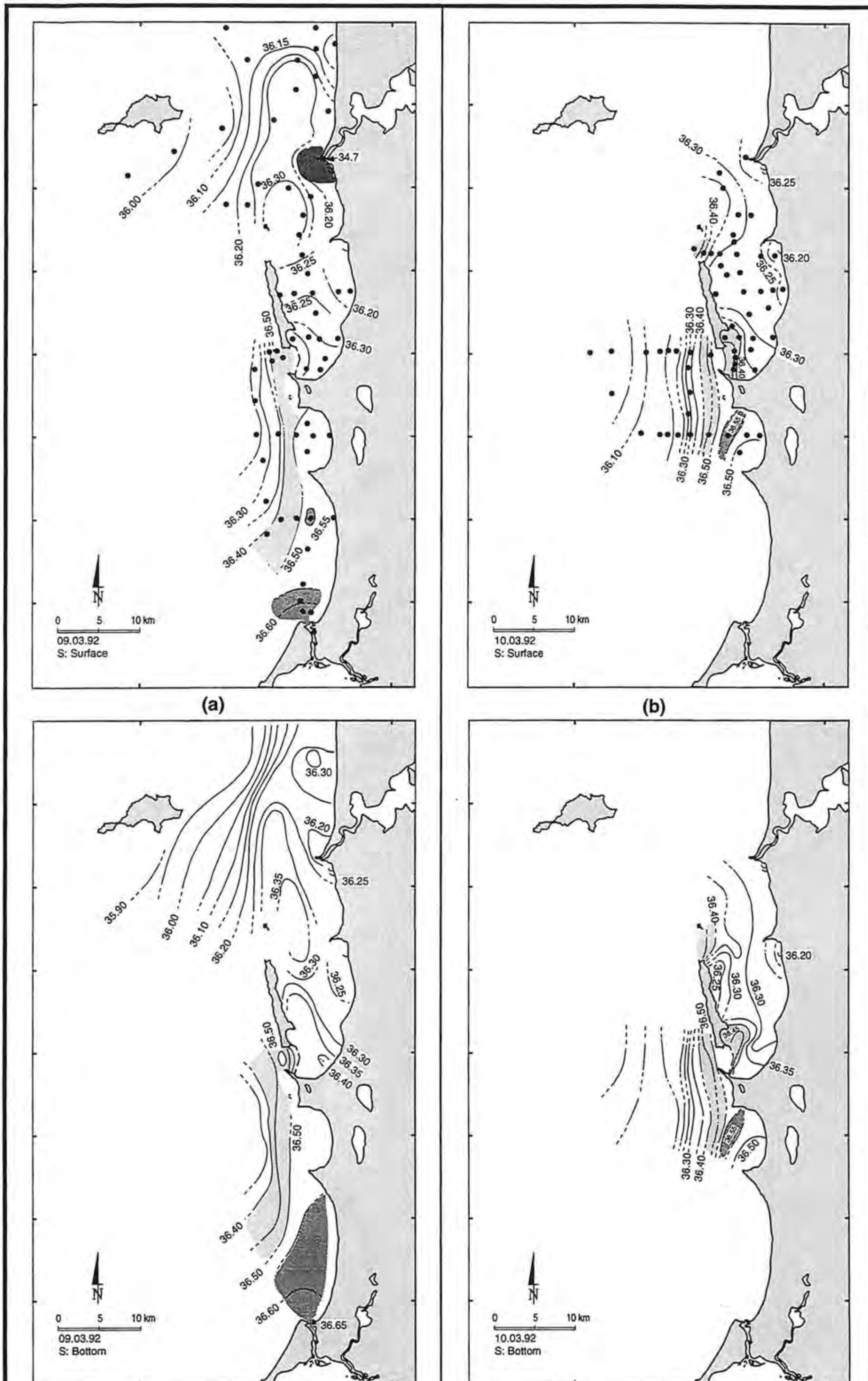
Figure 3. Progressive wind vector plot from Naval Base (12 m) for the period 9-13 March 1992.

Neil-Brown ACM-2 and Steedman Science and Engineering CM-01 vector-averaging acoustic current meters were installed on taut wire moorings at four sites (Figure 1). Data were collected at the near-surface and the near-bottom in Sepia Depression, north-central Cockburn Sound and over the eastern margin of the Sound. In addition, a near-bottom meter was deployed approximately 5 km west of Swanbourne beach. The data were collected at 5 minute intervals and adjusted for calibration errors after laboratory checks. Complementary meteorological data were obtained from coastal sites at Naval Base and Fremantle and from a weather station positioned at the southern end of the causeway (Figure 1).

5. Results

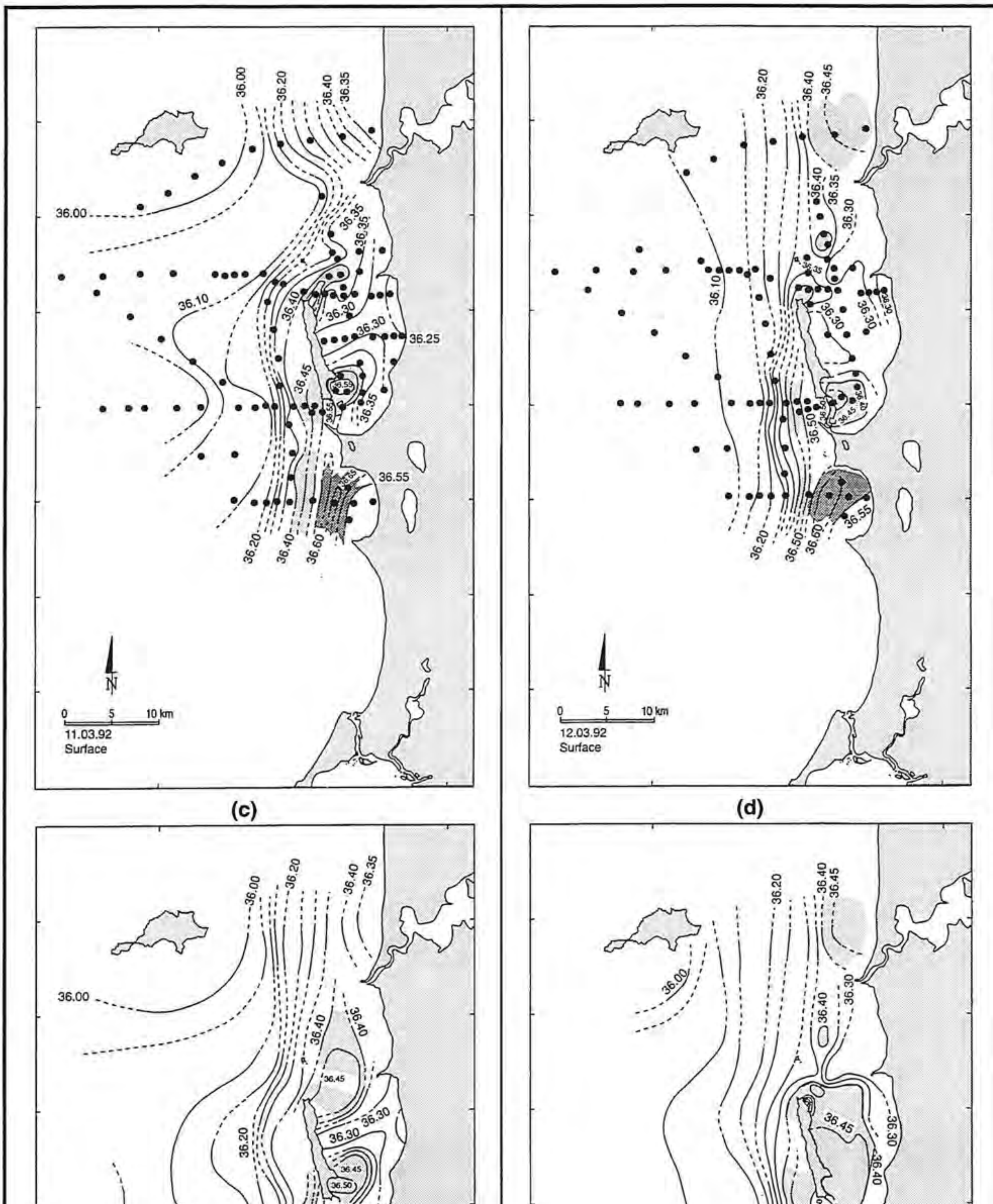
5.1 Wind-driven coastal flow

The salinity and temperature structure of the coastal waters between Mandurah and Fremantle and between the coast and Sepia Depression was monitored during five consecutive days (9-13 March 1992). These data, in conjunction with current meter data were used to infer the causes and patterns of water flow in this coastal region. Figure 4 presents surface and bottom plan contours of salinity to highlight the temporal changes in the horizontal salinity field. As shown, the salinity structure was spatially variable with salinity generally increasing shoreward and to the south. The relatively high coastal salinity is caused in part by the differential effects (with respect to deeper offshore waters) of evaporation over the summer and autumn seasons (Pearce and Church, submitted; Hearn, 1991; D'Adamo, 1992). The Peel-Harvey Estuary develops hypersaline water throughout (up to about 50 pss (practical salinity scale)) due to evaporation during this period (McComb *et al.* 1981; Peel Inlet Management Authority, unpublished data from summer



36.15
34.7
36.30
36.00
36.10
36.20
36.20
36.25
36.25
36.20
36.50
36.30
36.30
36.55
36.40
36.50
36.60
0 5 10 km
09.03.92
S: Surface
(a)
36.30
36.25
36.40
36.20
36.25
36.30
36.40
36.30
36.40
36.10
36.30
36.50
36.50
0 5 10 km
10.03.92
S: Surface
(b)
36.30
36.20
36.35
36.25
35.90
36.00
36.10
36.20
36.30
36.25
36.50
36.30
36.35
36.40
36.50
36.40
36.50
36.60
36.65
0 5 10 km
09.03.92
S: Bottom
36.40
36.20
36.25
36.30
36.30
36.50
36.35
36.50
36.30
36.40
0 5 10 km
10.03.92
S: Bottom

Figure 4.



36.00
36.20
36.40
36.35
36.10
36.30
36.25
36.45
36.55
36.60
0 5 10 km
11.03.92
Surface
12.03.92
Surface
(c)
(d)
36.50
36.65
35.55
11.03.92
Bottom
12.03.92
Bottom

Figure 4.

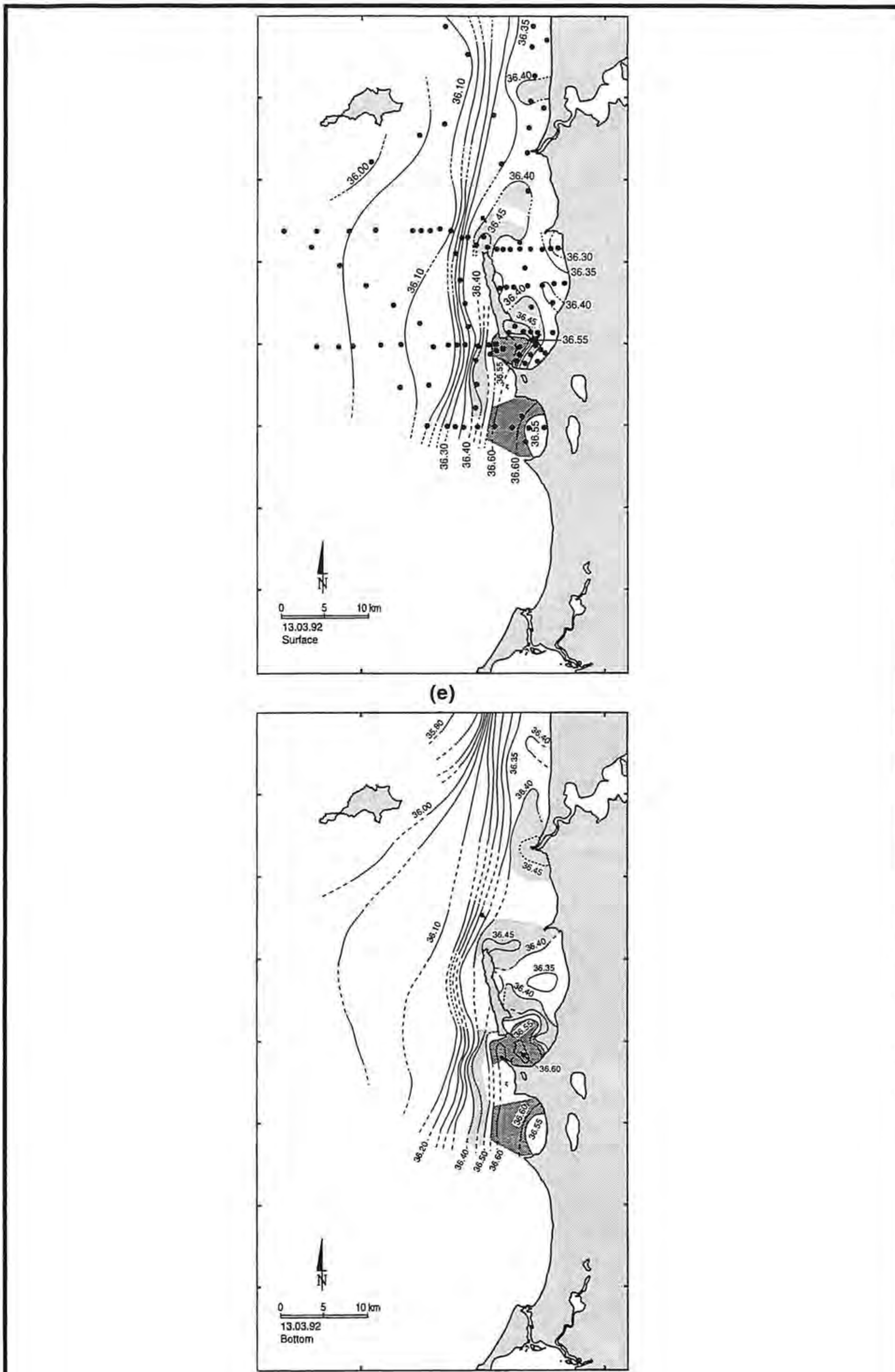


Figure 4. Surface and bottom salinity (in pss) contour plots of the study region during each of the five days (9-13 March 1992) of the field survey. Dashed lines are used to draw contours in regions of either poor data quality or spatial gaps in the survey grid. The grid is shown as dots on the contour plots. The darkest shading indicates water of 36.55-36.65 pss salinity. The lighter shading indicates water of 36.4-36.5 pss salinity.

1994/1995), and hence its summer and autumn outflows provide a source of high salinity water to the nearshore coastal zone. The salinity contours for 9 March 1992 (Figure 4a) indicate that salinity increased southward to a maximum at Mandurah, consistent with the outflow of high salinity water from the Peel-Harvey Estuary via its channel at Mandurah (salinities of up to 38.3 pss were recorded in the Peel-Harvey Estuary on 24 March 1992 (Peel Inlet Management Authority, unpublished data)).

Groundwater fluxes of freshwater are relatively small in summer when considered in the context of their potential influence on the hydrodynamics of the nearshore zone (D'Adamo, 1992; Johannes and Hearn, 1985; Appleyard, 1990; Kruh, 1994). Simple salt budget calculations indicate that daily evaporation during the conditions that occurred from 9 to 13 March (approx 5 mm per day in Cockburn Sound) could have increased the salinity of say a 15 m water column by about 0.01 pss per day. Hence, in considering the temporal changes in the mean salinity of an embayment, increases of up to about 0.01 pss per day could have been due to local evaporative effects. However, if daily salinity changes are significantly greater than this then other factors would have contributed to the changes, such as advective or diffusive exchange with higher salinity waters. The transport of large masses of coastal water can therefore be inferred by tracking the movement of salinity contours between successive days (in conjunction with contemporaneous current meter data), provided that the contouring interval is say 0.05 pss or more.

The transport of two individual patches of water lying within specific salinity ranges are tracked. The 36.55-36.65 pss water (represented by the darkest shading in the contour plots of Figure 4) was present off Comet Bay on 9 March but is evident further northward in Warnbro Sound by 10/11 March. The 36.40-36.50 pss water (represented by the lighter shading in Figure 4) was present as a shore-parallel band in Sepia Depression on 9 March but is evident in the northern and southern regions of Cockburn Sound on 11, 12 and 13 March and in the nearshore region north of Fremantle on 12 and 13 March. Note in Figure 4d that by 12 March the entire basin within Cockburn Sound was layered at the bottom by 36.4-36.5 pss water. This is in contrast to 10 March (Figure 4b) when the salinities were mainly 36.25-36.30 pss. Similarly, over the same 2-day period (10-12 March) the salinity at the bottom of Warnbro Sound rose from about 36.5 pss to about 36.6 pss (compare Figures 4b and d). Such increases in salinity are significantly greater than would be expected by evaporation alone. In conjunction with current meter data collected in Cockburn Sound, Sepia Depression and off Swanbourne (Figure 5), that show a north-northwestward flow within the region, it is inferred that long-shore transport driven by south-southwesterly winds (Figures 2 and 3) was primarily responsible for the observed changes in the basin-scale salinity fields. Past oceanographic surveys have also shown that currents in Sepia Depression are predominantly towards the north during summer due to forcing by typical winds from the southern quadrants (from data collected by Steedman and Associates, presented in Binnie and Partners Pty Ltd in association with G B Hill & Partners (1981)).

As shown by the current meter vector runs in Figure 5, the near-surface, middle and near-bottom meters from Cockburn Sound and the near-bottom meters in Sepia Depression and Swanbourne (no surface data are available from these sites) indicate a net flow towards the north-northwest. The data from the bottom meter in northern Cockburn Sound displays a notably more westward orientation, due probably to bathymetric steering by the nearby shelf of Parmelia Bank. The wind vector data (Figure 3) shows a net northward vector run. To demonstrate more clearly the relationship between wind and current directions, the direction of the wind during the five strong south-southwesterly wind events (9, 10, 11 and 12 March) has been plotted (in Figure 6) against the direction of the currents from the four current meter locations. As indicated by the plots, on these five occasions the flow at the sites was approximately downwind, with some exceptions notable from the near-bottom data at Swanbourne, and northern and eastern Cockburn Sound, where bathymetric effects probably contributed to the poorer relationships.

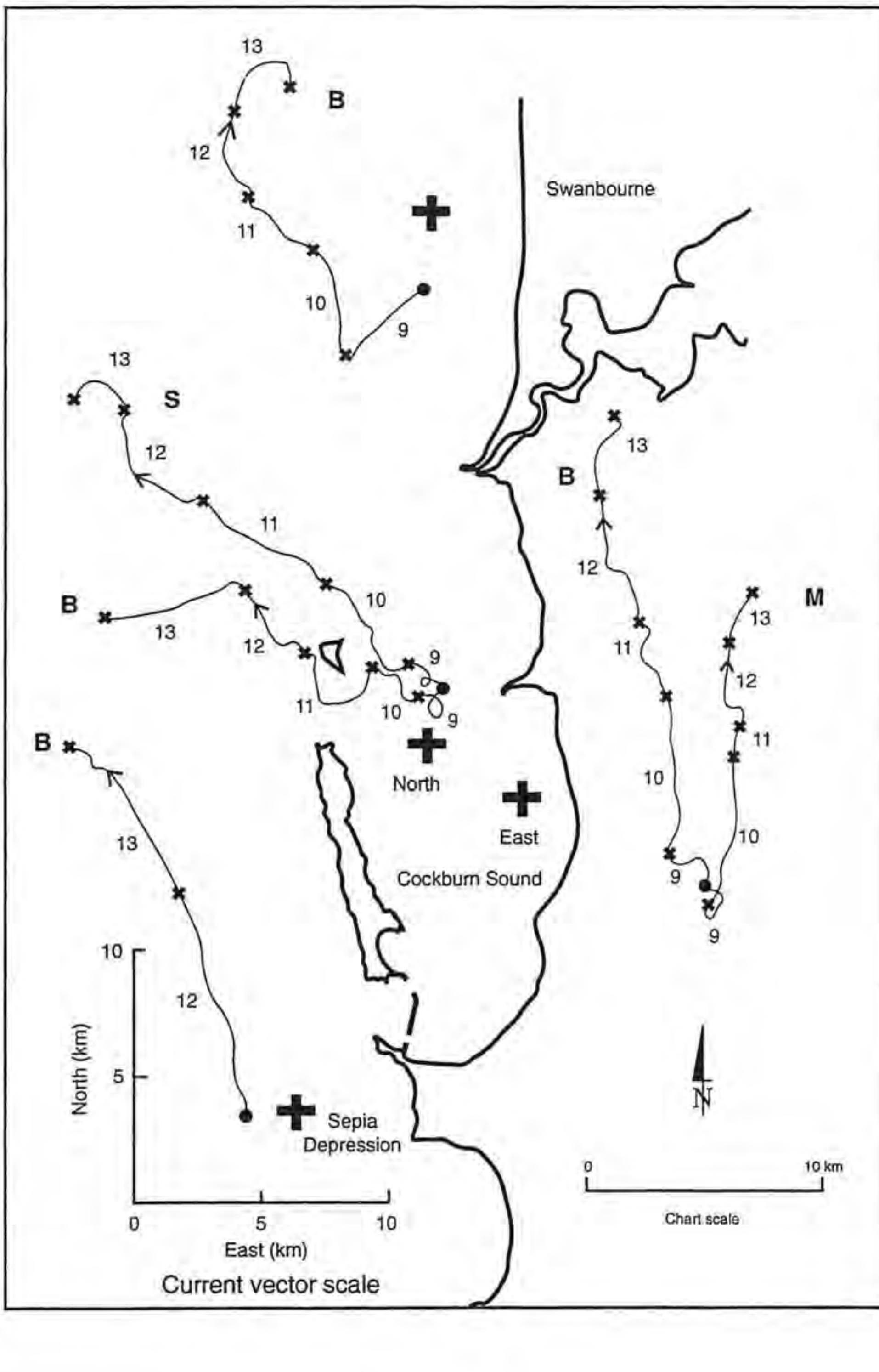


Figure 5. Progressive vector plots of current meter data from Swanbourne, Sepia Depression, northern Cockburn Sound and the eastern shelf of the Sound for the period 0000 hrs 9 March to 2400 hrs 13 March 1992. Meter locations at points marked with a cross, and data for each location are plotted adjacent. S = near-surface, B = near-bottom, M = middle of water column. 0000 hrs of each day is marked with an x on the plots (except for 0000 hrs of the first day of each plot which is marked by a dot).

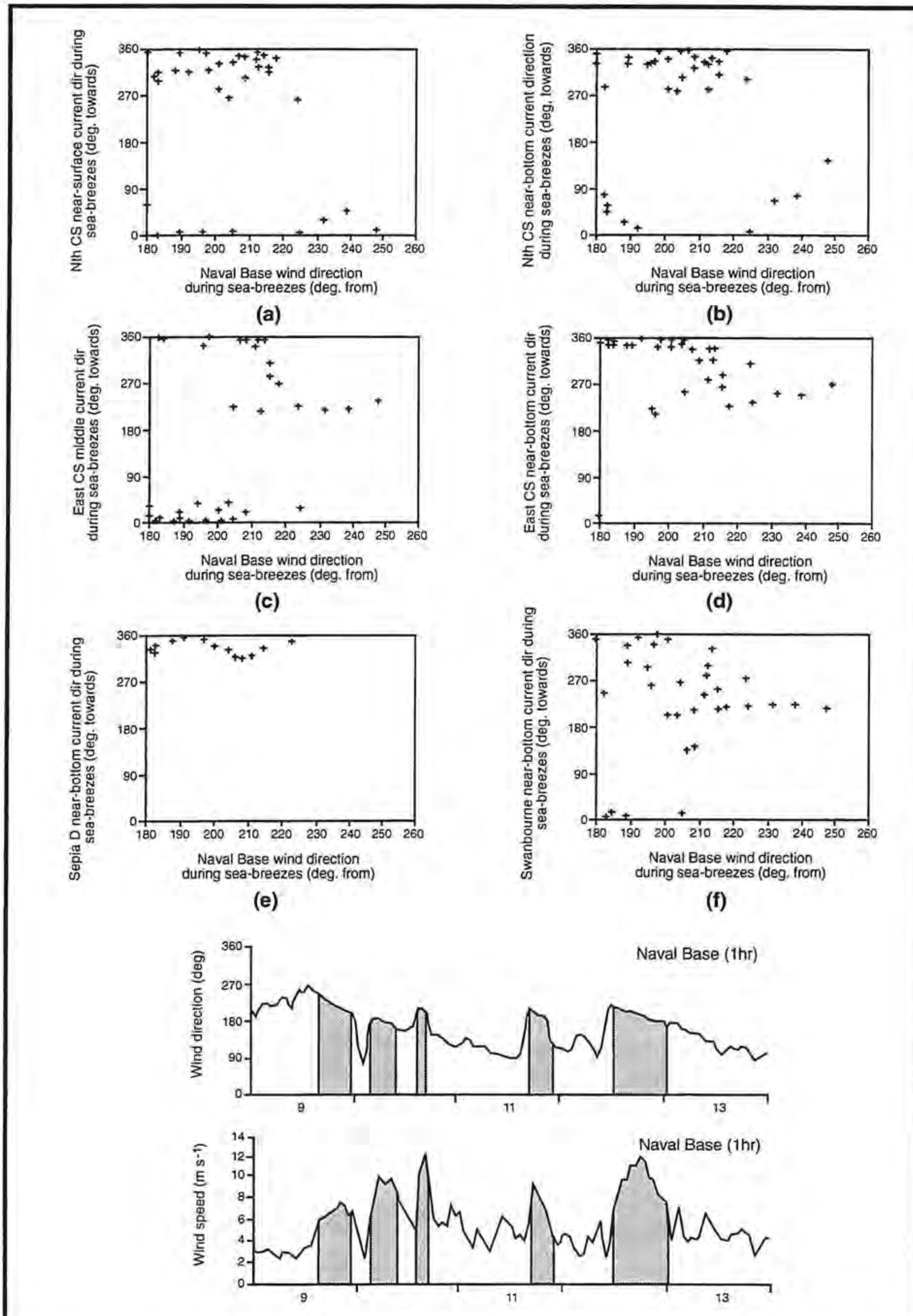


Figure 6. Scatter plots of current direction versus wind direction from data collected during five sea-breeze events (highlighted in the Naval Base wind plots). Plots a and b are for the north Cockburn Sound near-surface and near-bottom meters, respectively. Plots c and d are for the east Cockburn Sound middle and near-bottom meters, respectively. Plot e is for the Sepia Depression near-bottom meter. Plot f is for the Swanbourne near-bottom meter. The current meter sites are shown in Figure 5.

In combination, the temporal changes in the regional salinity distribution and the vector plots of currents and wind suggest that the coastal flow was approximately longshore, towards the northern quadrant and wind-driven during the survey period, resulting in the transport of relatively high-salinity water along and through Comet Bay and Sepia Depression, and then into the semi-enclosed basins of Warnbro Sound and Cockburn Sound.

The mean salinity of Warnbro Sound increased by about 0.10 pss between 9 and 12 March, based on both the surface and bottom salinity data (Figure 4). Evaporation could only explain about 30 percent of this salinity increase, hence it can be inferred that a significant amount of the basin's volume was exchanged in about two days.

On the basis of the regional salinity data and the complementary wind and current information it appears therefore that the flow field was essentially dominated by a wind-driven circulation. The distribution of the coastal water after it entered Cockburn Sound and the subsequent mixing that occurred within that basin is now discussed.

5.2 Influence of density stratification on inflows to Cockburn Sound

The basin scale salinity, temperature and density data are analysed to investigate the influence of density stratification upon the hydrodynamics of inflows in Cockburn Sound. Comparing the surface and bottom salinity contours of 11, 12 and 13 March within Cockburn Sound (Figures 4 c, d and e, respectively) it can be seen that higher salinity water is present and more spread out over the bottom. The corresponding density and temperature distributions for 12 March (Figure 7) show that the surface waters in the Sound were on average warmer and slightly less dense than the adjacent oceanic waters.

The vertically stratified salinity, temperature and density structures of the basin and its adjacent oceanic waters on 12 March (before the establishment of a strong afternoon sea-breeze) are presented in the respective contour plots of Figures 8 a, b and c, constructed from profile data collected along a transect (see inset) which followed a line from west of the causeway, through Sepia Depression, Cockburn Sound, Owen Anchorage and north to Fremantle. The 36.4-36.5 pss water is shaded (as was also done in Figure 4). As shown, the colder high-salinity water that entered the basin was denser than resident basin water. The structure in Figure 8 suggests that once having entered the basin through the openings the water tended to sink to the bottom of the basin due to its relatively high density.

The density difference between central Cockburn Sound and the oceanic waters adjacent to its northern and southern openings during 11-13 March was of order 0.1 kg m^{-3}, as indicated by the time series plots in Figure 9, showing the mean water column density at sites CS1 (central Cockburn Sound), SD1 (the southern opening) and SD2 (the northern opening).

The speed of the baroclinic flow that could occur as a result of density differences such as those encountered during 9 to 13 March, during the periods of weak winds that intervened between the sea-breeze periods, can be estimated by applying a formula for the densimetric velocity scale, as given by Simpson (1982), yielding

$$u = C_1(g'H)^{0.5} \tag{1}$$

where u is the speed of flow, C_1 is a constant based on experimental results, g' (where $g' = \Delta\rho_W g/\rho_W$) is the effective acceleration due to gravity, $\Delta\rho_W$ is the density difference between the flow and the ambient water, g is the acceleration due to gravity (= 9.81 m s^{-2}), ρ_W is the average water density and H is the water depth. For the present case, a baroclinic flow speed of order 0.05 m s^{-1} or less is calculated, however the presence and strength of any baroclinic component in the flow field will depend on the values chosen for the density difference and depth. The spatial

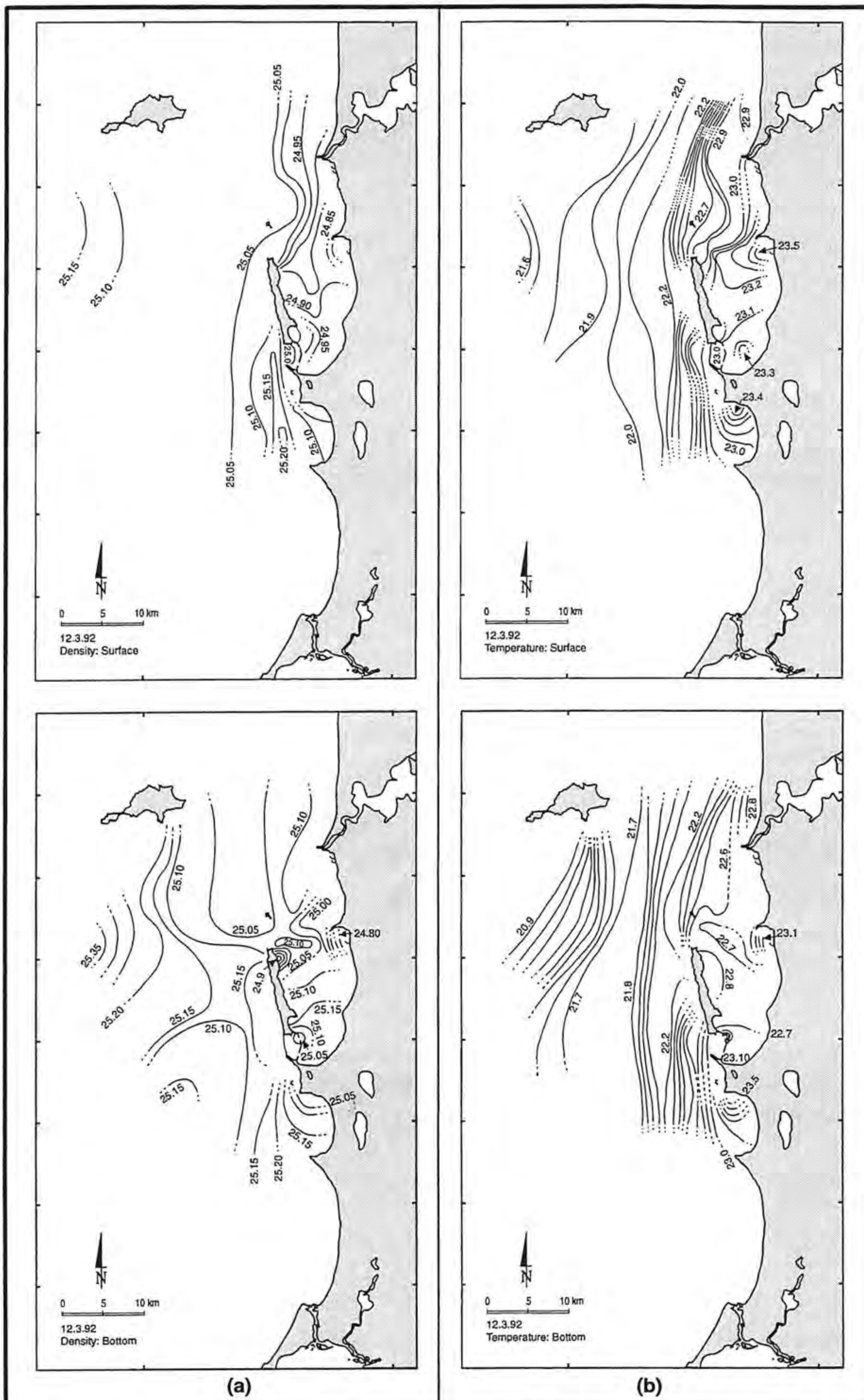


Figure 7. Surface and bottom contours of (a) density (σ_t, in kg m^{-3}) and (b) temperature (in °C) for the study region during 12 March 1992. Dashed lines are used to draw contours in regions of either poor data quality or spatial gaps in the survey grid (the grid is shown in Figure 4).

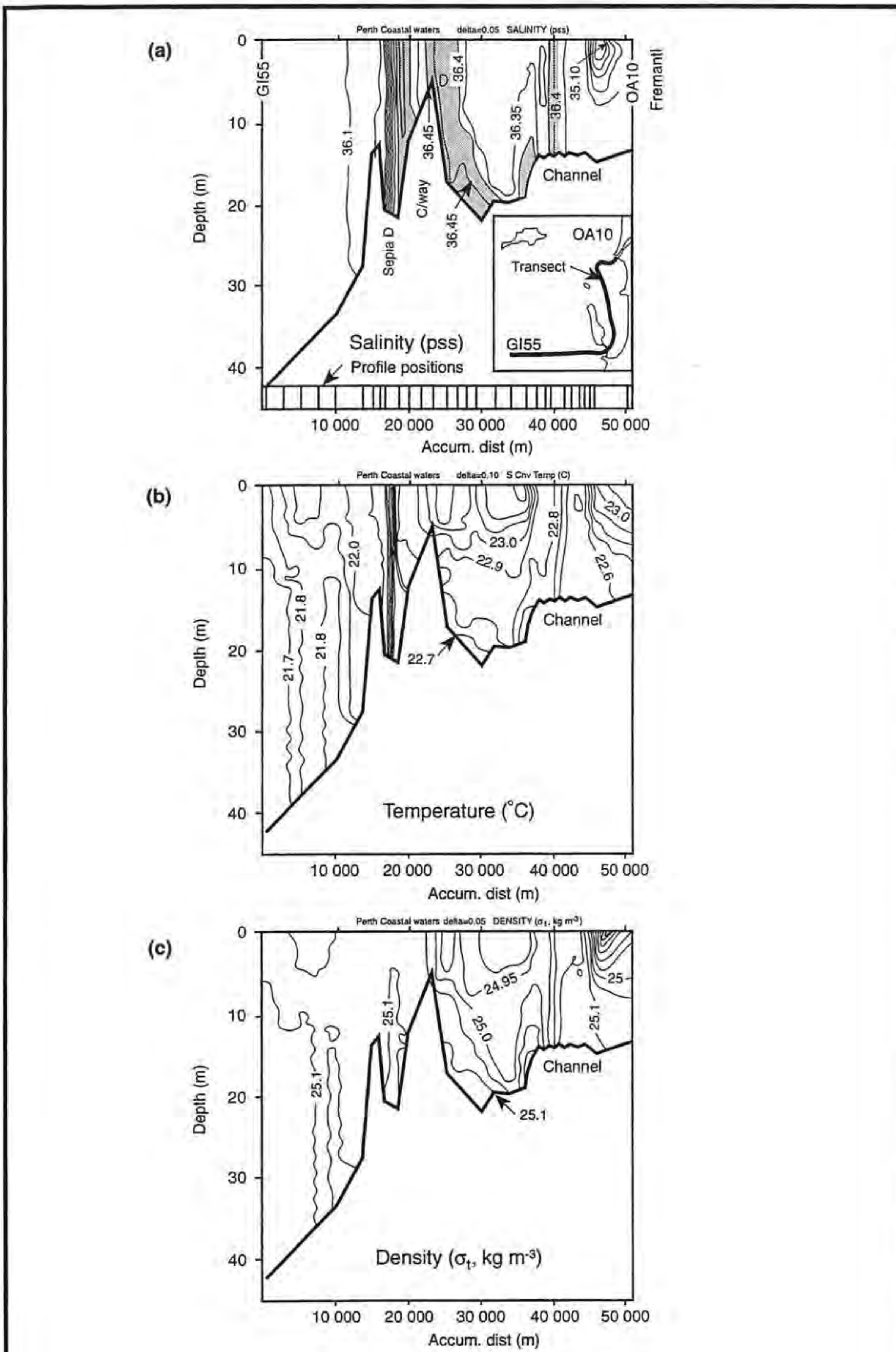


Figure 8. Contour plots of the vertical structure on 12 March 1992 (0723-1420 hrs) along a transect from west of the causeway, through Cockburn Sound and Owen Anchorage, and ending at Fremantle (a: salinity in pss, b: temperature in °C and c: density in sigma-t units (kg m^{-3})). The shading indicates water of 36.4-36.5 pss salinity.

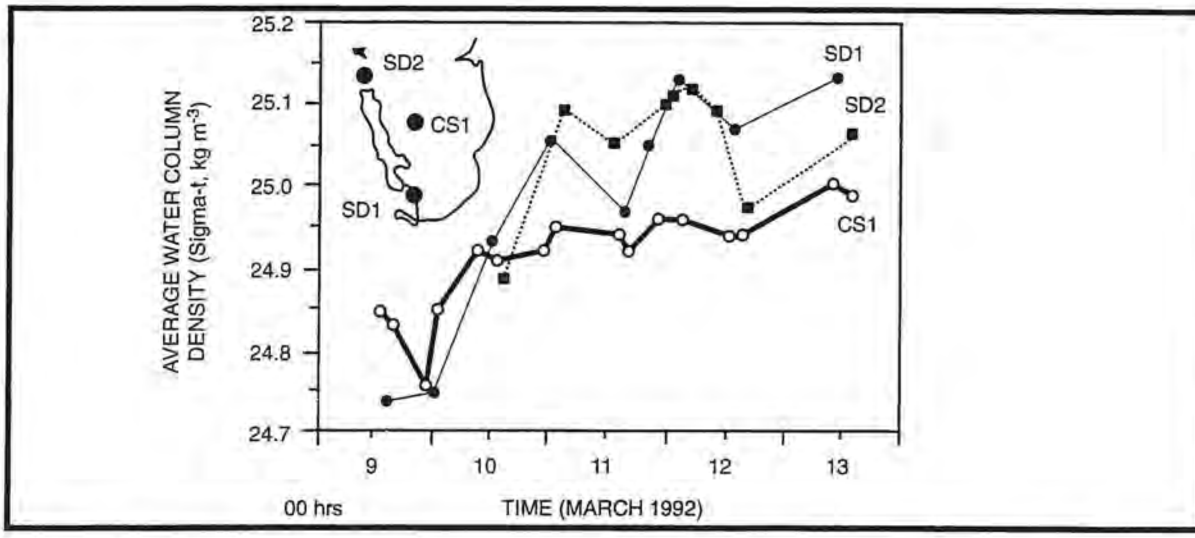


Figure 9. Time series plots of the average water column density from central Cockburn Sound, the north-west gap, and the southern High Level bridge opening (see inset) from CTD data collected between 9 and 13 March 1992.

variability in both the stratification and bathymetry of the site makes a more definitive calculation difficult. In addition, a Rossby radius (~ u/f, where f is the Coriolis parameter) of order 1-2 km is calculated, for $u = 0.05\text{-}0.10$ m s^{-1} and $f = 7.7 \times 10^{-5}$ rad. s^{-1}. Hence the influence of Coriolis force could further complicate the evaluation of density-driven circulation by introducing a significant force perpendicular to the direction of density gradients (Simpson, 1987). The spatial resolution of current measurements precludes any further investigation of this aspect of the dynamics except to conclude that the density difference, albeit weak, appears to have caused inflows to sink to the bottom of the basin, resulting in vertical density stratification.

The stratification could potentially inhibit the vertical mixing of water and any contained biological or chemical substances that may be present at particular depths of the water column. In addition, the formation of fronts between water masses of different density could also result in a horizontal separation of biological or chemical parameters. To assess the temporal persistence of vertical stratification and frontal structure the diurnal energetics of vertical mixing of the stratification within the Cockburn Sound basin during 9-13 March is now investigated.

5.3 Diurnal stratification and vertical mixing in Cockburn Sound

The changing vertical stratification of density, temperature and salinity in central Cockburn Sound at site CS1 is presented as time series contour plots in Figures 10 a, b and c, respectively, with wind data from Naval Base. The density and thermal structures (Figures 10 a and b, respectively) display a clear diurnal variation. Heating of the upper water column due to short-wave radiation, H_{SW}, resulted in vertical temperature stratification during the day-time, with a corresponding density stratification. Vertical density differences across the heated upper layer of up to about 0.15 kg m^{-3} were formed during all afternoons except for 9 March, when a stronger stratification was measured (Figure 10a).

After the establishment of the day-time heated upper layer, a period of surface mixing is shown to have occurred (Figure 10a). The mixing was due primarily to wind-stress in the afternoon and early evening, but would then have been complemented by penetrative convection during the night and early morning. These surface processes are dependent on the respective strengths of the wind-stress and heat fluxes. The short-wave radiation was measured directly (Figure 2) and the other fluxes are determined by the application of bulk aerodynamic formulae (Fischer *et al.* 1979; Tennessee Valley Authority, 1972), given as follows.

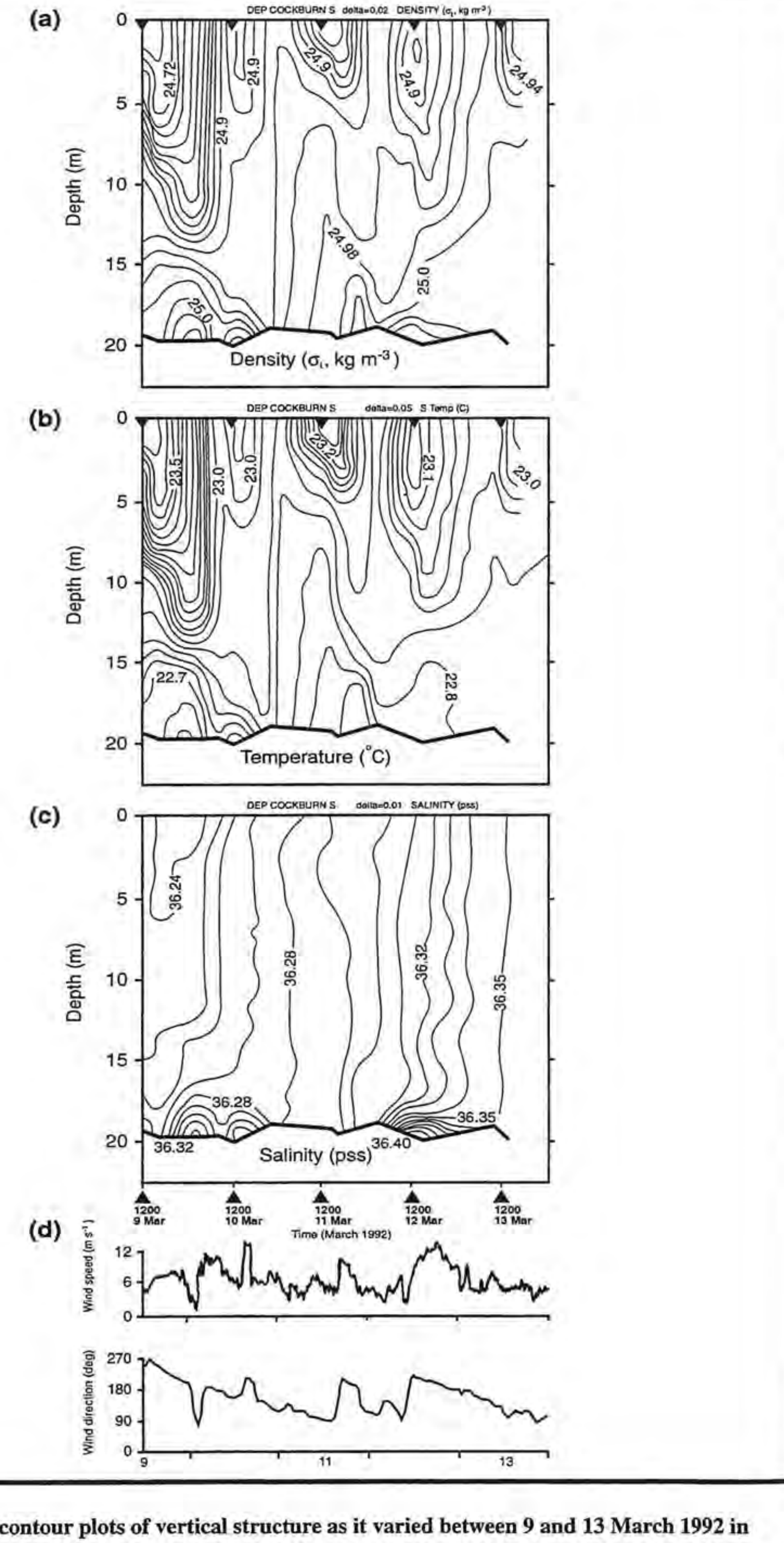


Figure 10. Time series contour plots of vertical structure as it varied between 9 and 13 March 1992 in central Cockburn Sound (site CS1, see inset of Figure 9) and time series plots of wind from Naval Base (a: density in sigma-t units (kg m^{-3}), b: temperature in °C, c: salinity in pss, d: wind velocity).

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

Sensible (conductive) heat flux: $H_S = C_S \rho_A C_P U(T_O - T)$, (3)

Latent (evaporative) heat flux: $H_L = C_L \rho_A L_W U(Q_O - Q)$, (4)

Long-wave radiation from the water vapour in the sky:

$H_1 = -5.18 \times 10^{-13}(1+0.17C^2)(273+T)^6$, (5)

Back radiation lost from the water surface: $H_2 = 5.23 \times 10^{-8}(273+T_O)^4$, (6)

where C_D, C_S and C_L are coefficients, ρ_A and ρ_W the density of air and water respectively, U the wind speed, C_P the specific heat of air, T_O the water surface temperature in °C, T the air temperature in °C, L_W the latent heat of evaporation, Q_O the saturation specific humidity at T_O, Q the specific humidity, and C the fraction of sky covered by cloud. The sign convention adopted is positive for radiation that leaves the surface.

Figure 11 presents time series plots of the various surface flux terms for 9-13 March. As shown, the wind shear velocity (Equ. 2) varied over a wide range, with maximum values occurring during the sea-breeze periods on 10, 11 and 12 March. The net heat flux ranged from strong heat gains during the day (due to solar radiation) to strong heat losses during the night (due to sensible and latent heat transfers, and long-wave radiation, as given by equations 3, 4, 5, and 6).

The basin-wide stratification formed by thermal inputs during the day is typified by the vertical temperature contour plots, presented in Figure 12, from two centreline transects (in the N-S and W-E orientations) taken on 9 March between 1039 and 1637 hrs. The vertical stratification was established by the net heat gain during the day with a heat flux reaching about -700 W m^{-2}, due mainly to short-wave radiation inputs (Figure 11). The temperature structure was primarily responsible for the density structure. Winds were relatively weak (ranging from 3-7 m s^{-1}) and were therefore not able to overcome the stratifying influence of sun's radiation.

We now investigate the diurnal mixing in Cockburn Sound due to wind-stress and penetrative convection by sequentially analysing each of the four diurnal cycles between 9 and 13 March. Both the rate of heat loss and the wind-stress varied over the four cycles, and this enables a characterisation to be made of the potential of these mixing agents to penetrate through the vertical density stratification that was established during each of the afternoons. Because at night there is often the coincident occurrence of wind-stress and heat loss it is difficult to de-couple the relative contributions of either mechanism to the observed mixing during the survey period. However, individual expressions for the mixing potential of these two mechanisms are available from the literature on vertical mixing (see Imberger and Patterson, 1990; Imberger, 1994).

The vertical mixing due to wind stress can be estimated on the basis of a one-dimensional model of mixing (as reasoned by D'Adamo *et al.* 1995b), which is based on a vertical integration of the turbulent kinetic energy equations (see Spigel, Imberger and Rayner, 1986, and Pollard, Rhines and Thompson, 1973). For the case of two uniform layers of different density, the depth of the upper layer is estimated by

$h(t) = [C_S/(g_o' h_i)]^{0.5} u_*^2 t + h_i$ (7)

where $C_S = 0.24$ is a constant that determines the efficiency of energy conversion (Imberger and Patterson, 1990), t is the time since the onset of mixing, g_o' is the value of the effective acceleration due to gravity at the commencement of mixing, and h_i is the initial depth of the mixed layer. This mixing law is for shear-dominated mixing due to locally parallel flow at the interface between the upper and lower layers, and is assumed applicable in this case for the sea-breezes that occurred during 9-13 March. However, for lighter winds (< 5 m s^{-1}) other

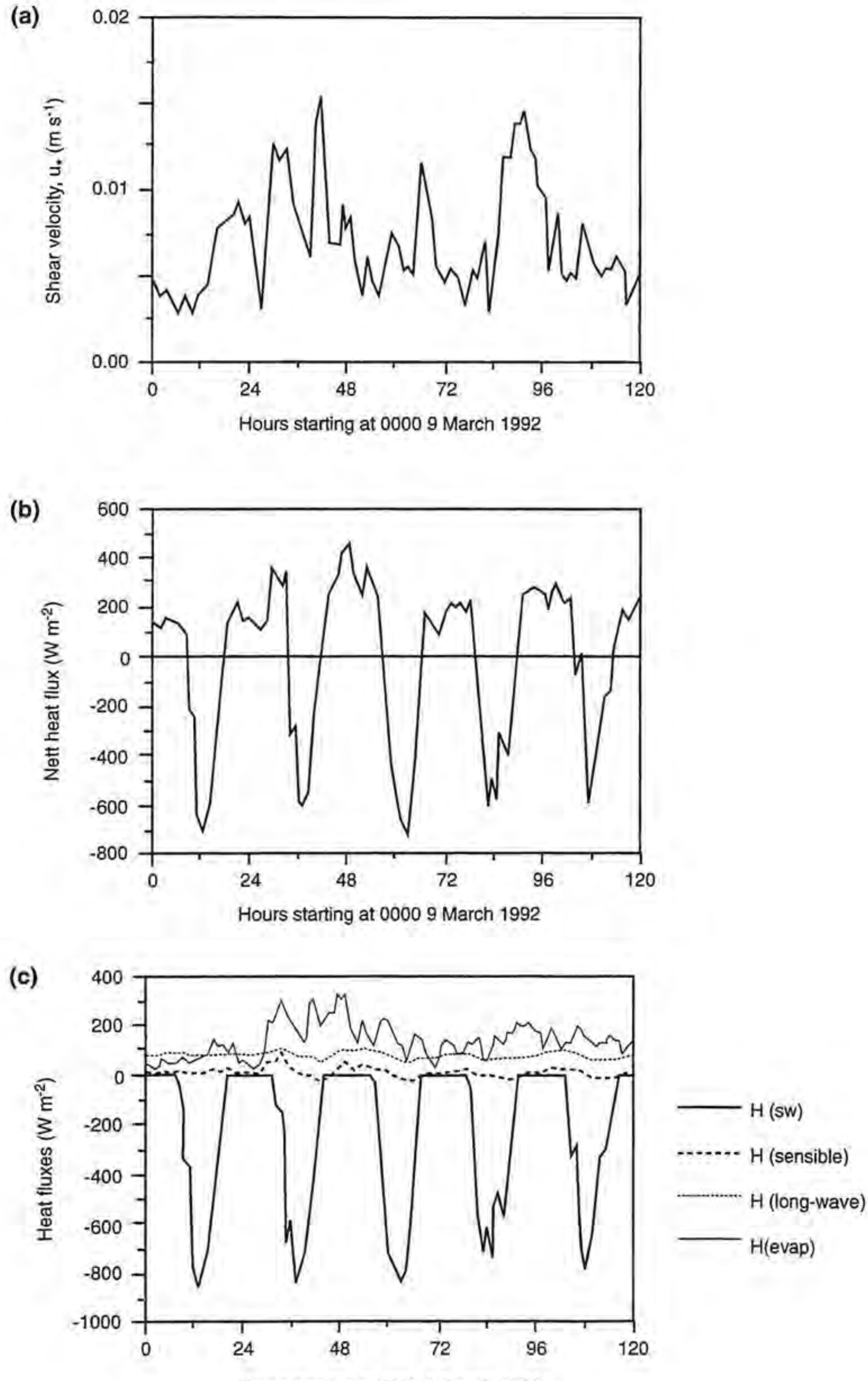


Figure 11. Time series plots of surface fluxes for Cockburn Sound: (a) surface wind shear velocity, (b) net heat flux and (c) individual heat fluxes due to short-wave, sensible, long-wave radiation and evaporative effects.

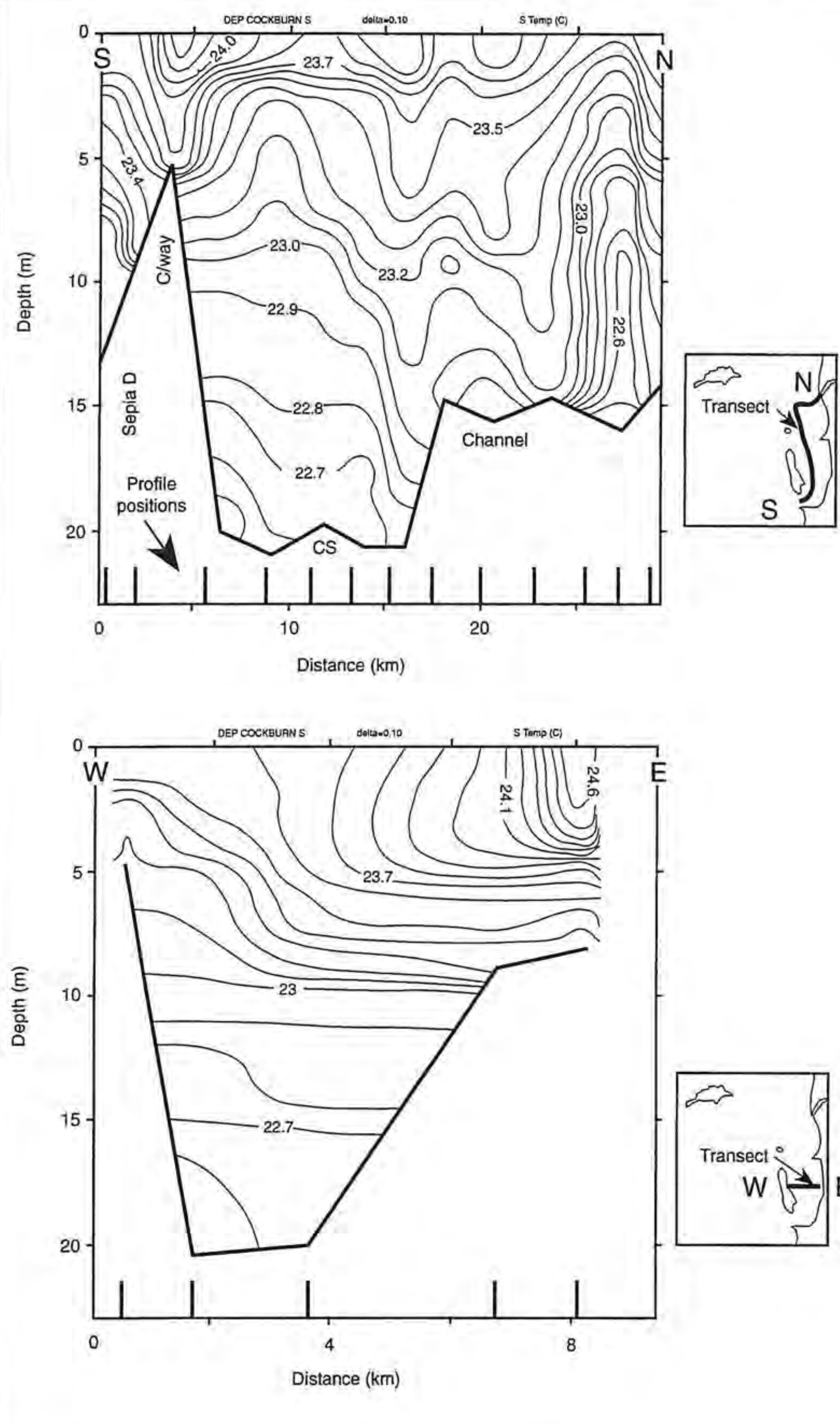


Figure 12. Vertical temperature (°C) contour plots along centreline transects through Cockburn Sound (see insets) showing the stratifying influence of solar radiation between 1039 and 1637 hours, 9 March 1992, before the onset of significant wind-mixing.

laws, which were developed for vertical mixing dominated by vertical stirring processes rather than for shear-dominated mixing, may be more applicable (Imberger, 1994).

Penetrative convection (described by Fischer *et al.* 1979, and Imberger and Patterson, 1990) is the mixing process whereby cold water forms at the surface and is stirred downwards by gravitational instabilities, with this process gradually deepening the upper mixed layer. In the absence of significant vertical salinity gradients the rate of deepening is related to the rate of loss of heat in the upper heated layer. This can be simply estimated on the basis of the one-dimensional heat conservation equation where the heat lost via the surface cools the water column with the rate of mean temperature change approximated as (Fischer *et al.* 1979)

$$\Delta T_O/\Delta t = -HA_S/(C_P\rho_W V) \qquad (8)$$

where t is the time in seconds, H is the rate of heat loss, A_S is the surface area for the heat escape and V the volume being considered.

A useful analytical tool that can be used to investigate the ability of solar radiation to maintain a vertical temperature structure in the presence of wind, is a length scale similar to the Monin-Obukhov length (described for example in Mortimer, 1974 and Imberger and Patterson, 1990), which yields a scale for the potential depth of the upper mixed layer, given a wind speed and a heat influx, and was derived by Rayner (1980) as

$$L = (u_*^3\rho_w C_p C_N^3)/(g\alpha_v H_*) \qquad (9)$$

where C_p is the specific heat of the water, C_N is a coefficient (= 1.33) for the efficiency of energy conversion (Imberger, 1994), α_v (=1.5 x 10^{-4} °C^{-1}) is the volumetric coefficient of thermal expansion, and H_* is the heat flux term as described by Rayner (1980) and takes account of the distribution of incoming heat flux as a function of depth throughout the surface layer (for example short-wave radiation decays exponentially with depth).

We now analyse the diurnal energetics of the mixed layer over the four diurnal cycles of the survey period. Starting with each afternoon's vertical stratification, as measured by the CTD profiling at about 1200 hrs (see Figure 10), the ensuing vertical mixing due to wind-mixing and penetrative convection, in isolation, have been calculated on the basis of equations 7 and 8, respectively. The results are presented in Table 1, which shows the resulting depth of mixing when both mechanisms were considered in the analysis of each diurnal cycle.

For the first diurnal cycle (9/10 March) a strong thermal structure was developed by the mid-afternoon of 9 March (see Figure 10). This structure was superposed on a salinity structure which contained a weak vertical salinity difference (bottom minus surface) of about 0.1 pss. As shown, by mid-afternoon a vertical density difference of about 0.3 kg m^{-3} was established. The strong stratification persisted during the afternoon even though a moderate sea-breeze (5-7 m s^{-1}) blew from about 1300-1700 hrs onwards. This is consistent with a calculated upper mixed layer depth limit, L, (Equ. 9) of 4-8 m for this period. Heat began to be lost from the water surface at about 1800 hrs (Figure 11) and a south-southwest wind with speeds of 5-7 m s^{-1} continued to blow from about 1800 to 2200 hrs. The results in Table 1 suggest that the combined effect of mixing by both penetrative convection and wind-stress would have produced an 11.5 m upper mixed layer by about about 0100 hrs (10 March), and this is in good agreement with the measured vertical

Table 1. Predicted upper mixed layer (UML) deepening for each of the four diurnal cycles from 9 to 13 March 1992 in central Cockburn Sound due to penetrative convection alone (Equ. 8), wind mixing alone (Equ. 7), and the net total mixing due to both mechanisms.

Date (1992)	Time	Initial UML depth (m) in central Cockburn (i)	Increase in UML depth (m): due to penetrative convection alone (Equation 8) (ii)	due to wind mixing alone (Equation 7) (iii)	Predicted net UML depth (m) due to both mechanisms (i) + (ii) + (iii)
9/3	1614	~ 5			
10/3	0100		~ 2.5	~ 4	~ 11.5
10/3	0100	~11.5			
10/3	1000		0	~ 6	~ 17.5
10/3	1325	~ 2.5			
10/3	2400		~ 16	>21	> 21 (full-depth)
11/3	1609	~ 4			
12/3	0800		~ 6	~ 15	~ 21 (full-depth)
12/3	1310	~ 4			
13/3	0800		~ 7	~21	> 21 (full-depth)

structure of site CS1 at 0111 hrs 10 March, as shown in Figure 13a. A stronger southerly wind then blew from 0300 onwards (speeds 6-9 m s^{-1}) and the wind mixing calculations suggest that a further deepening of about 6 m would have resulted in a final mixed layer depth of about 17.5 m by about 1000 hrs 10 March. Again, this estimate is in reasonable agreement with the measured structure of site CS1 at 0921 hrs 10 March, as shown in Figure 13b.

The mixing calculations suggest that for the next three diurnal cycles (10/11, 11/12, 12/13 March) the vertical mixing due to the combined actions of wind-stress and penetrative convection would have led to full-depth mixing of the stratification that was developed by solar heating during the respective mornings on all three occasions (see Table 1). The application of Equation 9 for each of the three afternoon sea-breezes results in a predicted upper mixed layer depth limit, L, of more than 20 m suggesting that the strength of thermal inputs would have been insufficient to withstand the mixing influence of the wind-stress. These estimates of full-depth mixing are supported by the measurements of vertical structure, as presented in Figure 10, which show a vertically homogeneous, or very weakly stratified, water column after each of the three sea-breeze events.

A representative example of the basin-wide nature of the mixing that was caused by the sea-breezes was captured immediately after the sea-breeze of the afternoon of 10 March by the CTD profiling. The wind blew from the south-southwest at 10-15 m s^{-1} between about 1300 and 1700 hrs (Figure 2). The resulting vertical structure of the basin is presented in Figure 14 showing the density contours from transects in the N-S and W-E alignments, collected between 1957 and 0218 hrs 10/11 March. As is evident by the data, the mixing penetrated to the bottom in Cockburn Sound and Owen Anchorage along the basin-wide transect paths shown (which is in contrast to the stratification measured at the end of the previous day, as was indicated by Figure 10). At the time of these transects (Figure 14) no data were collected in the more protected Mangles Bay hence we cannot conclude on whether the full-depth mixing also occurred in Mangles Bay.

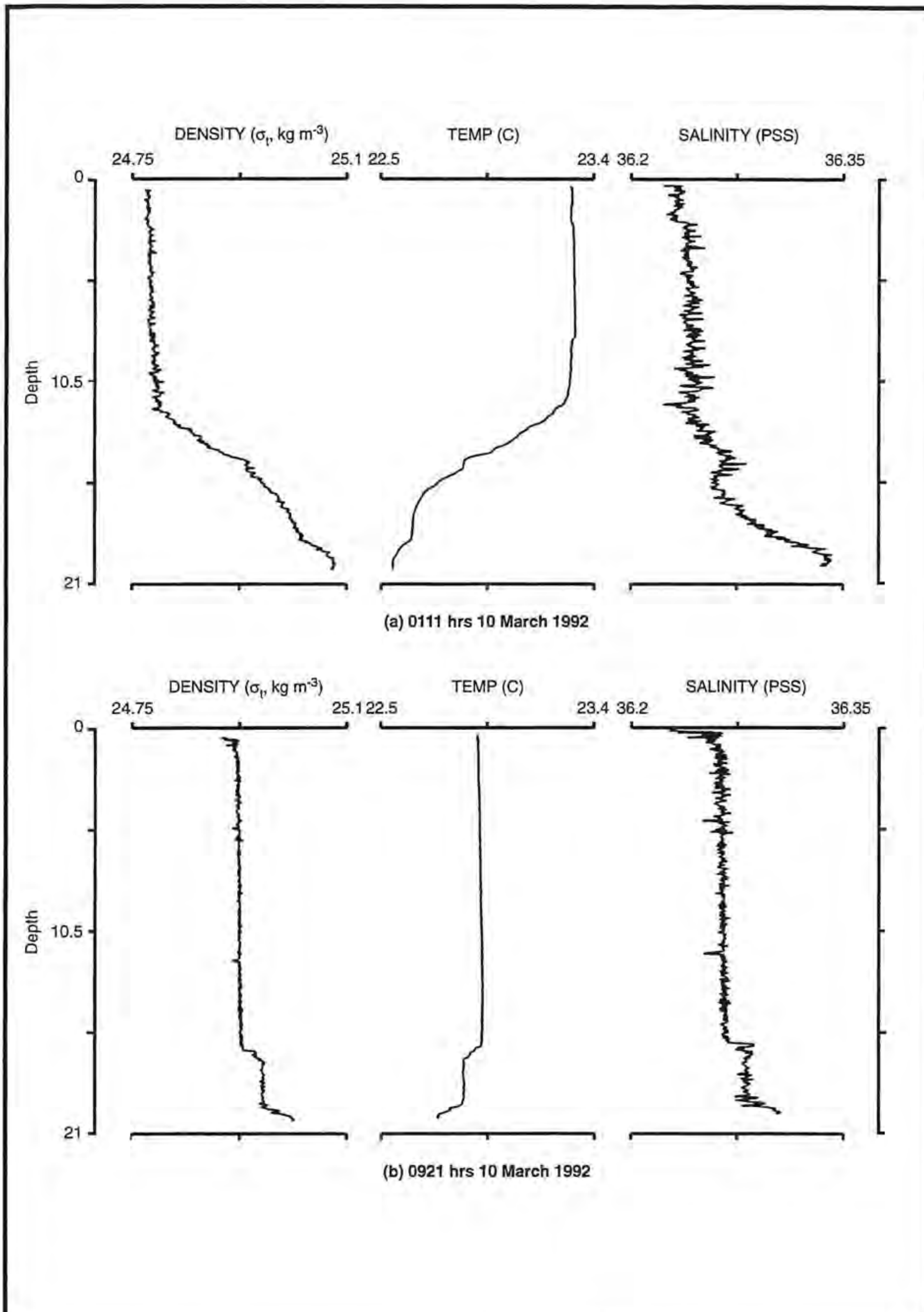


Figure 13. Vertical profiles of density in sigma-t units (kg m^{-3}), temperature in °C and salinity in pss from central Cockburn Sound (site CS1, see Figure 9) at (a) 0111 hours and (b) 0921 hours on 10 March 1992.

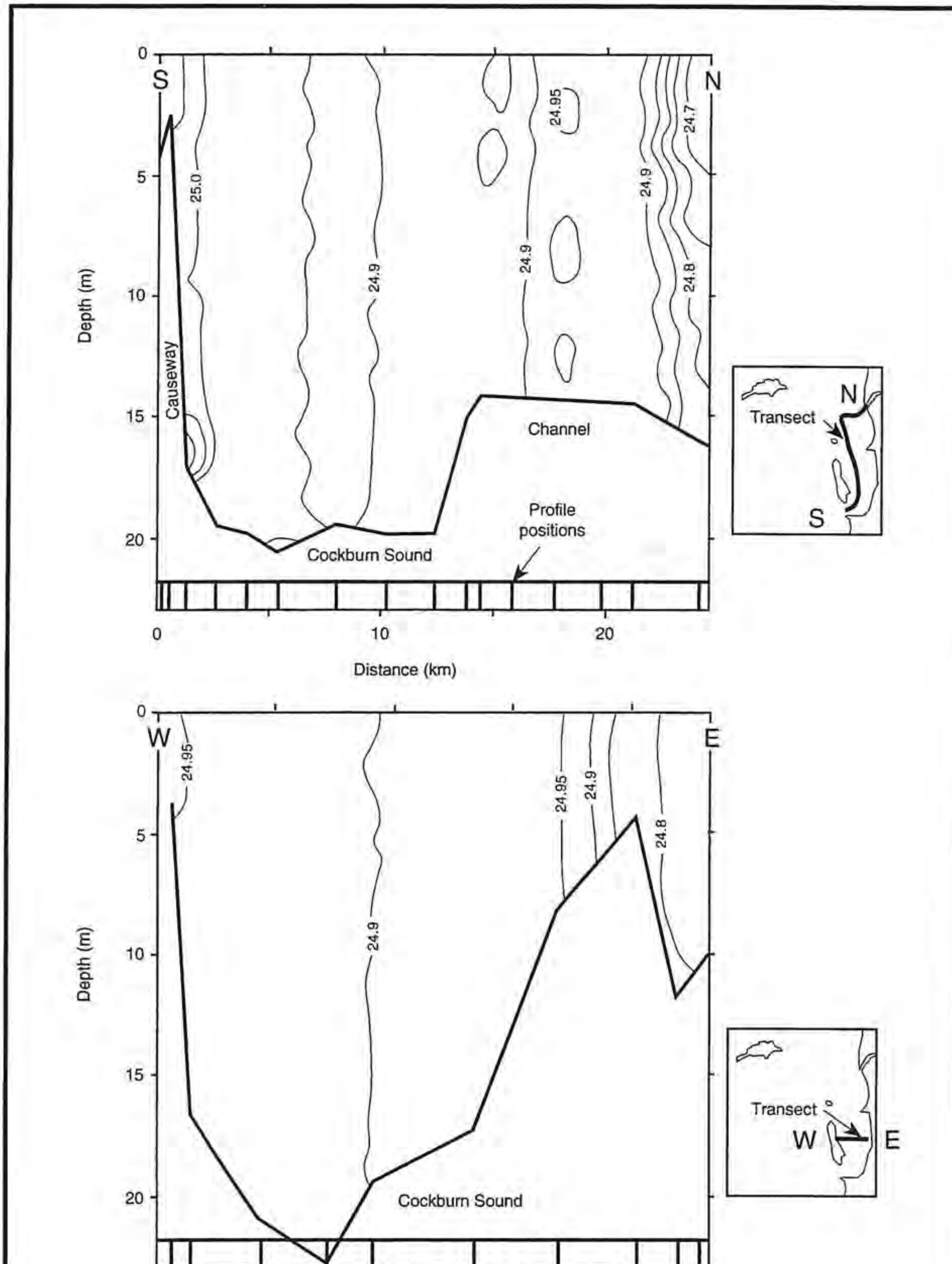


Figure 14. Vertical density contour plots (in sigma-t units (kg m^{-3})) along centreline transects through Cockburn Sound (see insets) from CTD data collected between 1937 hours 10 March and 0218 hours 11 March 1992 indicating the well-mixed character of the basin after strong afternoon wind-mixing.

5.4 Mixing of inflows in Cockburn Sound

As discussed earlier, the long-shore coastal flow during the survey period entered Cockburn Sound as a relatively dense inflow which sank to the bottom of the deep basin and spread horizontally (refer back to Figure 4). For example, the slight vertical salinity stratification that was set up during the morning of 10 March, prior to that afternoon's wind-mixing, was indicated by the time series contours of Figure 10c. The vertical mixing due to the combined actions of wind-stress and penetrative convection during the afternoons and evenings of 10, 11 and 12 March was strong enough to eliminate any prior vertical structure that was set up by the high salinity inflows, as indicated by the calculations in Table 1.

Figure 10c also clearly exemplified the progressive increase during 9-13 March in the depth-averaged salinity of central Cockburn Sound from about 36.25 pss to 36.35 pss with a maximum recording of about 36.40 pss at the bottom on 12 March. As previously discussed, the local evaporation in Cockburn Sound is estimated to have been responsible for 30-40 percent of this salinity increase, and therefore it is inferred that the remainder was due to exchange with higher salinity water from outside of the Sound. The intermittent presence of the high salinity layer at the bottom is indicative of the advection of relatively dense water from the north and south regions of the Sound (refer to Figure 4). The salinity rise occurred even though the salinity was essentially well-mixed vertically by the wind events and is consistent with an inflow of high salinity water that underwent regular vertical mixing. Hence, even though inflows may have led to the establishment of slight vertical stratification, typical strength vertical mixing due to wind-stress and heat loss was shown to be able to destroy the structure on a diurnal basis.

6. Discussion

The long-shore transport of coastal water has been detailed for the period 9-13 March 1992, representing typical summer conditions when the dominant winds were daily south-southwesterly sea-breezes. The wind caused the transport of relatively high salinity water northwards as a coastal flow, originating from the south of the study region. This flow was driven into the nearshore basins of Comet Bay, Warnbro Sound, Sepia Depression and Cockburn Sound. Patches of water, identified by salinity, were tracked to move, under the wind forcing, at rates of the order 10 km per day, in reasonable agreement with contemporaneous current meter records (Figure 5). Detailed basin-wide measurements of the stratification within Cockburn Sound revealed that the high salinity inflows were slightly more dense (by 0.05-0.10 kg m^{-3}) compared to resident sound water, and as a result tended to sink to the bottom of the basin. A weak vertical salinity stratification was consequently set up, adding to the daily vertical thermal stratification of the water column due to heat inputs via short-wave solar radiation. Vertical density differences of up to 0.15 kg m^{-3} were established on most days, with one exception occurring on 9 March when a difference of about 0.3 kg m^{-3} was measured.

A mixing analysis over the four consecutive diurnal cycles of the survey period (9-13 March) demonstrated that the combined effect of sea-breezes and night-time heat losses was sufficient to have led to full-depth vertical mixing in the Cockburn Sound basin during all but one of the diurnal cycles. The exception was during the first cycle (9/10 March) because the winds were relatively weak (of order 5-7 m s^{-1}) and the afternoon stratification on 9 March was relatively strong. During the other diurnal cycles the sea-breezes had speeds of order 10 m s^{-1} or more and hence the wind-stress was sufficient to cause either complete or near-complete vertical mixing. The mixing analysis suggests that for summer conditions full-depth mixing could be expected as a result of the combined effects of typical sea-breezes with speeds of greater than about 7.5 m s^{-1} and penetrative convection due to heat loss rates of 100-300 W m^{-2} or greater, when the vertical stratification is relatively weak (with vertical density differences of less than 0.2 kg m^{-3}).

Theoretical rates of deepening due to wind stress are calculated using Equation 7 for a wide range of wind speeds and for two cases of initial density structure. Case I is based on the afternoon structure of 9 March (approximated as two uniform layers with a $h_i = 5$ m and $\Delta\rho_W = 0.3$ kg m^{-3}), representing the most strongly stratified period of the survey. Case II is based on the afternoon structures of 10-13 March (approximated as two uniform layers with a $h_i = 5$ m and $\Delta\rho_W = 0.15$ kg m^{-3}), representing the more commonly occurring afternoon stratification measured during the survey. The deepening curves that were constructed using Equation 7 for Cases I and II are presented in Figures 15 a and b, respectively.

The results in Figure 15 suggest that a 7.5 m s^{-1} wind would, in isolation, have to blow for about 12 hours to fully-mix the water column given a strong initial stratification, as presented for Case I. However, if the additional mixing due to penetrative convection during a heat loss of 200 W m^{-2} is also considered then a wind event of only 8 hours is required. If we repeat this calculation for the alternative Case II, then it is estimated that given a 200 W m^{-2} heat loss a 7.5 m s^{-1} wind blowing for only 5 hours is required to fully-mix the water column. Under stronger sea-breezes (> 10 m s^{-1}) the calculations suggest that full-depth mixing would be achieved within about 5 to 7 hours by the action of wind stress alone.

The regularity with which typical sea-breezes and accompanying night-time heat losses can fully mix the water column during typical summer conditions in Cockburn Sound is now assessed.

Heat losses during summer over Perth's coastal waters can be characterised by considering typical values of the relevant parameters embedded in the heat loss Equations (3-6). During summer the mean minimum air temperatures range from 16 °C in December to 18 °C in February (Australian Bureau of Statistics, 1989) and in the nearshore zone surface water temperatures range from about 21 to 25 °C (D'Adamo, 1992). From our surveys we adopt typical values of specific humidity difference (Equation 4) of order 0.01 kg per kg of dry air. From historical data (eg Steedman and Craig, 1979) wind speeds of order 5 m s^{-1} can be assumed.

On the basis of these assumptions heat loss rates at night of the order of 200 W m^{-2} are estimated to be typical for the nearshore zone. As calculated earlier, by application of Equations 3 to 6, such heat losses at night would typically generate upper mixed layer deepening of the order of 10 m.

Statistical information on seasonal wind patterns for the Perth coastal region indicates that sea-breezes with speeds equal to or greater than 7.5 m s^{-1} and durations greater than 5-8 hours occur about 15 times per month in summer (Steedman Science and Engineering Pty Ltd, unpublished data). For example, hourly wind data for 1992 collected at Fremantle (Figure 1) have been inspected for the occurrence of sea-breezes with speeds greater than 7.5 m s^{-1} for durations in excess 12 hours, and the results are presented in Figure 16. As shown, over the summer months (January, February and December) 43 such sea-breezes occurred, at an average of about one every two days.

On the basis of the wind data in Figure 16 it could therefore be expected that full depth mixing due to wind-stress alone would occur, on average, about every 2 days during the summer periods in the Cockburn Sound basin. If we also consider the predicted occurrence of regular night-time deepening of order 10 m due to penetrative convection, then it can be concluded that full-depth mixing is likely to occur in Cockburn Sound at least every day or two during typical summer conditions.

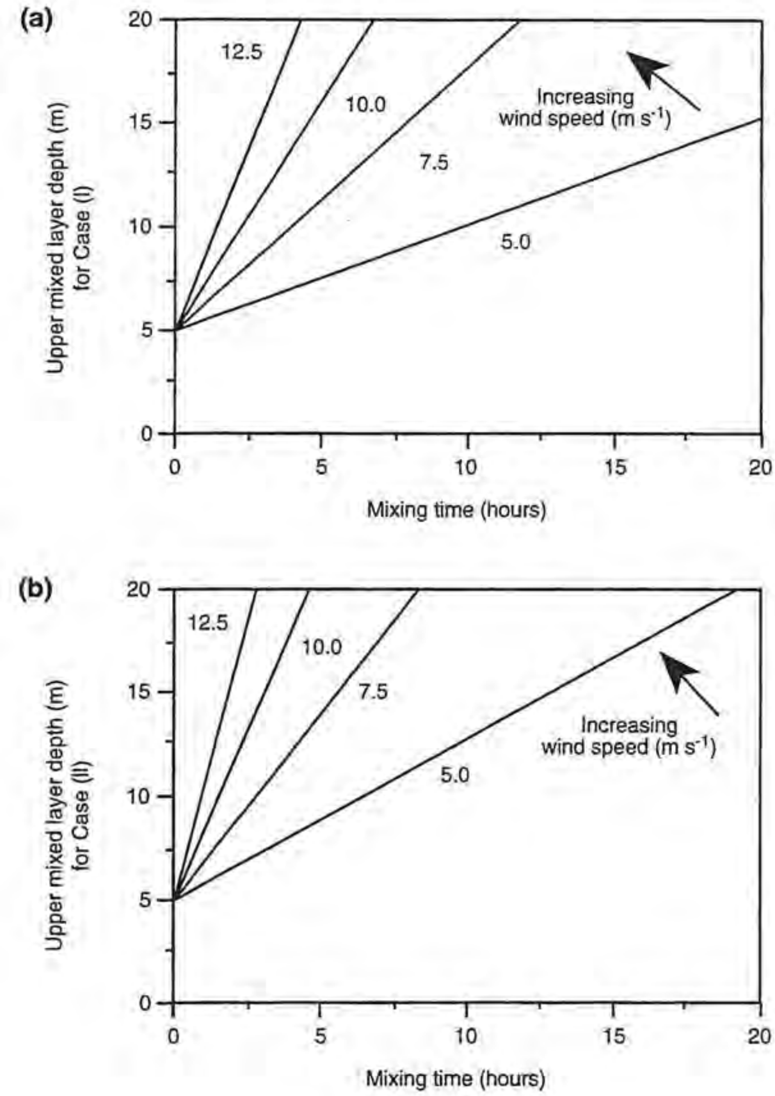


Figure 15. Predicted deepening of the upper mixed layer in central Cockburn Sound (CS1, see Figure 9) for two cases of initial starting stratification (a: Case I is based on the relatively strong afternoon density structure of 9 March and b: Case II is based on the weaker density structures prior to the sea-breezes of 10-12 March 1992, see Figure 10). The deepening rates are calculated for a wide range of wind speeds.

An assessment of the relative importance of various terms in the horizontal momentum balance is now made. The wind forcing term is of order t/H where t is the wind stress and H a typical water depth. For a wind stress of 0.1 Pa (corresponding to a wind speed of about 7 m s^{-1}) and a water depth of 20 m, this term is of order 5 x 10^{-3}. A typical basin-scale horizontal gradient of surface elevation ($\Delta h/\Delta x$) is $5x10^{-7}$. This was derived directly from model results (Mills and D'Adamo, 1995) for times of moderate south to south-westerly winds. The corresponding barotropic pressure gradient is $\rho_w g(\Delta h/\Delta x)$ = 5 x 10^{-3}. The coriolis term is $\rho_w fu$, f is the coriolis parameter and u is current speed. For f = -8 x 10^{-5} s^{-1}, u = 0.1 m s^{-1}, this term is of order 8 x 10^{-3}. Data for the 1992 summer intensive field period shows that horizontal density gradients ($\Delta\rho_w/\Delta x$) are of order 10^{-5} kg m^{-4} even under vertically mixed conditions. Baroclinic pressure gradients at water depth H are given by $gH(\Delta\rho_w/\Delta x)$. For H = 20 m, these pressure gradients are of order 2 x 10^{-3}. Hence it can be seen that these forcing terms, including the baroclinic pressure gradient term, are of comparable magnitude.

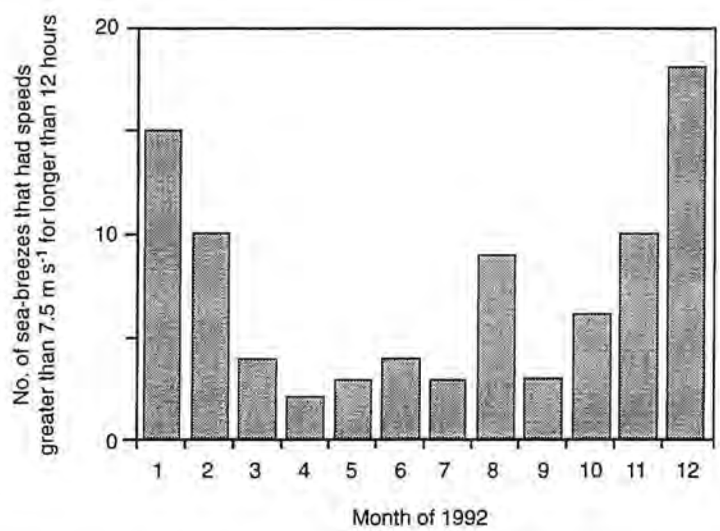


Figure 16. The number of occurrences of sea-breeze events for each of the months of 1992 from data collected at Fremantle by the Fremantle Port Authority of Western Australia. The events are defined as sea-breezes that had wind speeds greater than 7.5 m s^{-1} blowing for 12 hours or more.

The above results lead us to conclude that three-dimensional baroclinic models would be required to most accurately simulate summer conditions, including the diurnal evolution of the stratification by solar radiation and/or advection of high salinity water, and to account for baroclinic pressure gradients which may be comparable with other forcings, even under vertically well-mixed conditions. Galperin *et al.* (1992) present a case study of the application of a three-dimensional model to a vertically well-mixed estuary. The use of such a modelling approach for routine assessment of stratification, flushing and water quality in our study area would require extensive calibration and validation work and ongoing data acquisition to update boundary information and refine ocean climatology.

However, three-dimensional barotropic hydrodynamic models forced by wind stress could, in the first instance, be appropriate for numerical simulations of the main circulation features of this coastal zone (including the nearshore semi-enclosed basins) for typical summer conditions. This has been confirmed by Mills and D'Adamo (1995) who found close agreement between current meter time-series data and corresponding simulated time-series at most sites, using the Princeton Ocean Model (Blumberg and Mellor, 1987; Mellor, 1992) without baroclinic forcing. It is recommended that comparisons be made between these two approaches to assess the benefits of the more detailed approach.

By inference, because the other nearshore basins of Owen Anchorage, Warnbro Sound and Comet Bay are less enclosed and shallower (< 20 m) the potential for vertical density stratification is less. Hence, it can also be expected that they would undergo the same or greater regularity of full-depth mixing during typical summer conditions.

7. References

Appleyard S J (1990). The flux of nitrogen and phosphorus from groundwater to the ocean in the Perth metropolitan region. Hydrogeology Report No. 1990/64. Western Australian Geological Society, Perth, Western Australia, 6000. Pp. 19.

Australian Bureau of Statistics (1989). Western Australian Year Book. No. 26 - 1989. Australian Bureau of Statistics, Western Australian Office, Perth, 6000. Pp. 316.

Binnie and Partners Pty Ltd in association with G B Hill & Partners (1981). Cape Peron Ocean Outlet. Feasibility Study - physical oceanographic data. Report to the Metropolitan Water Supply Sewerage and Drainage Board, Perth, Western Australia, 6000.

Black R E and Rosher J E (1980). The Peel Inlet and Harvey Estuary System Hydrology and Meteorology. A Technical Report to The Peel-Harvey Estuarine System Study (1976-1980), Bulletin No. 89, Department of Conservation and Environment, Western Australia, 6000.

Blumberg A F and Mellor G L (1987). A description of a three-dimensional coastal ocean circulation model. *Three-Dimensional Coastal Ocean Models, Vol. 4* (N. Heaps, Ed.) 208pp, American Geophysical Union, Washington, D.C: 1-16.

Breckling J (1989). The analysis of directional time series: applications to wind speed and direction. In: Lecture Notes in Statistics 61. Springer-Valeg. Pp. 231.

Chiffings A W (1987). Nutrient enrichment and phytoplankton response in Cockburn Sound, Western Australia. PhD Thesis. The University of Western Australia, Nedlands, Western Australia, 6009. Pp. 215.

D'Adamo N (1992). Hydrodynamics and recommendations for further studies in Cockburn Sound and adjacent waters. Technical Series No. 41. Environmental Protection Authority of Western Australia, Perth, Western Australia, 6000. Pp. 107.

D'Adamo N and Mills D A (1995a). 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. (in preparation). Technical Series 69. Department of Environmental Protection of Western Australia, Perth, Western Australia, 6000.

D'Adamo N and Mills D A (1995b). Field measurements and baroclinic modelling of vertical mixing and exchange during autumn in Cockburn Sound and adjacent waters, Western Australia. (in preparation). Technical Series 71. Department of Environmental Protection of Western Australia, Perth, Western Australia, 6000.

D'Adamo N, Cary J L and Mills D A (1995a). Aspects of winter exchange patterns in the coastal waters off Perth, Western Australia - the region between the Shoalwater Islands Marine Park and the Peel-Harvey Estuary. Technical Series No. 66. Department of Environmental Protection of Western Australia, Perth, Western Australia, 6000. Pp. 20.

D'Adamo N, Mills D A and Wilkinson D L (1995b). Winter mixing and transport in the stratified coastal embayment of Cockburn Sound, Western Australia. (in preparation). Technical Series 70. Department of Environmental Protection of Western Australia, Perth, Western Australia, 6000.

Fischer H B, List E J, Koh R C Y, Imberger J and Brooks N B (1979). Mixing in Inland and Coastal Waters. Academic Press. New York. Pp. 483.

Galperin B, Blumberg A F and Weisberg H (1992). The importance of density driven circulation in well-mixed estuaries: the Tampa Bay experience. Estuarine and Coastal Modelling: proceedings of the 2nd international conference sponsored by the Waterway, Port, Coastal and Ocean Division of the American Society of Civil Engineers, Tampa, Florida. November 13-15, 1992; edited by Malcolm L Spalding *et al.* Pp. 332-343.

Gersbach G (1993). Physical oceanography of Warnbro Sound. Honours Thesis. Department of Environmental Engineering, University of Western Australia, Nedlands, Western Australia, 6009. Pp. 52.

Hearn C J (1991). A review of past studies of the hydrodynamics of Cockburn Sound and surrounding waters with an appraisal of physical processes and recommendations for future data collection and modelling. Australian Defence Force Academy. Campbell, Australian Capital Territory, 2600. Pp. 75.

Imberger J (1994). Transport processes in lakes: A review. In: Limnology Now: A Paradigm of Planetary Problems. R. Margalef, Editor. Elsevier Science, B. V. Pp. 99-193.

Imberger J and Patterson J C (1990). Physical Limnology. In: Advances in Applied Mechanics. T. Wu., Editor. Academic Press, Boston. Vol. 27. Pp. 303-475.

Johannes R E and Hearn C J (1985). The effect of submarine groundwater discharge on nutrients and salinity in a coastal region off Perth, Western Australia. Estuarine, Coastal and Shelf Science, 21:789-800.

Kruh H (1994). Diurnal hydrodynamics of Warnbro Sound during Autumn 1994. Honours Thesis. Department of Environmental Engineering, University of Western Australia, Nedlands, Western Australia, 6009. Pp. 86.

Largier J L (1993). Estuaries. Symposium Papers from the Eleventh Bienniel International Estuarine Research Conference (Ed., L J Largier). Journal of the Estuarine Research Federation, Vol. 16, No. 1 - March 1993. Pp. 159.

McComb A J, Atkins R P, Birch P B, Gordon D M and Lukatelich R J (1981). Eutrophication in the Peel-Harvey Estuarine System, Western Australia. In: Estuaries and Nutrients. (Ed., Neilson B J and Cronin L E). Humana Press, Clifton, New Jersey. Pp. 323-342.

Mellor G L (1992). User's guide for a three-dimensional, primitive equation, numerical ocean model. Unpublished report. Atmospheric and Ocean Sciences Program. Princeton University, Princeton, NJ, 08540. Pp. 34.

Mills D A and D'Adamo N (1995). Three-dimensional modelling of Cockburn Sound and surrounding waters. A comparison of model and current meter data for March 1992. Southern Metropolitan Coastal Waters Study (1991-1994). Data Report SMCWS HYDRO-15.2. Department of Environmental Protection, Perth, Western Australia, 6000.

Mills D A, D'Adamo N, Pearce A F and Wyllie A (1995). The response of stratified shelf waters to the Leeuwin Current and wind forcing: winter observations off Perth, Western Australia. American Geophysical Union, Coastal and Estuarine Shelf Series. (in press).

Mortimer C H (1974). Lake Hydrodynamics. Mitt. Int. Ver. Limnol., 20:124-197.

Pattiaratchi C, Imberger J, Zaker N and Svenson T (1995). Perth Coastal Waters Study Project P2: Physical Measurements. Unpublished draft report No. WP 947 CP. Centre for Water Research, University of Western Australia, Nedlands, Western Australia, 6009. Pp. 57.

Pearce A F and Church J A (submitted). A coastal heat and salt budget using seasonal temperature and salinity data off Perth, Western Australia. (submitted to Continental Shelf Research).

Pollard R T, Rhines P B and Thompson R O R Y (1973). The deepening of the wind-mixed layer. Geophys. Fluid Dyn., 3:381-404.

Rayner K N (1980). Diurnal energetics of a surface reservoir layer. Rep. No. ED-80-005. University of Western Australia, Nedlands, 6000. Pp. 227.

Simpson C J, Burt J S, Cary J L, D'Adamo N, Masini R J and Mills D A (1993). Southern Metropolitan Coastal Waters Study (1991-1994) Progress Report 1993. Technical Series 53. Environmental Protection Authority of Western Australia, Perth, Western Australia, 6000. Pp. 65.

Simpson J E (1982). Gravity currents in the laboratory, atmosphere and ocean. Ann. Rev. Fluid. Mech., 14:213-234.

Simpson J E (1987). Gravity Currents: In the Environment and the Laboratory. Ellis Horwood Limited, Chichester. Pp. 244.

Spigel R H, Imberger J and Rayner K N (1986). Modeling of the diurnal mixed layer. Limnol. Oceanogr., 31(3):533-556.

Steedman R K and Craig P D (1979). Numerical model study of circulation and other oceanographic aspects of Cockburn Sound. R K Steedman and Associates Report No. 64. A report to the Department of Conservation and Environment of Western Australia, Perth, Western Australia, 6000. Pp. 206.

Steedman R K and Craig P D (1983). Wind-driven circulation of Cockburn Sound. Aust. J. Mar. Freshw. Res., 34:187-212.

Tennessee Valley Authority (1972). Heat and Mass Transfer between a Water Surface and the Atmosphere. T.V.A. Report No. 0-6803.

Vollenweider R A, Marchetti R and Viviani R (1992). Marine Coastal Eutrophication. Proceedings of an International Conference, Bologna, Italy, 21-24 March 1990. (Ed., Vollenweider R A, Marchetti R and Viviani R). Elsevier Science Publishers B. V. Pp. 1310.

Vollmer M K (1991). Sharpening and matching response signals for finescale sensors. Centre for Water Research, University of Western Australia, Nedlands, Western Australia, 6009. Report No. WP 630 MV.