Field measurements and baroclinic modelling of vertical mixing and exchange during autumn in Cockburn Sound and adjacent waters, Western Australia

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Field measurements and baroclinic modelling of vertical mixing and exchange during autumn in Cockburn Sound and adjacent waters, Western Australia

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Abstract

Cockburn Sound is a semi-enclosed micro-tidal embayment on the southwest coast of Western Australia. Salinity, temperature and density structure in the sound and its surrounding shelf waters was measured during four autumn cruises. These data, in the context of year-round measurements of basin versus shelf water density differences, suggest that the surrounding shelf waters are typically less saline and more buoyant than Cockburn Sound water in autumn. They also suggest that Cockburn Sound is typically vertically stratified in density at this time of the year, due to the entry of buoyant shelf water into the sound, and due to diurnal heating. The field data supported the results of three-dimensional baroclinic modelling, which showed that exchange between the sound and adjacent shelf waters in autumn involves the entry of relatively buoyant shelf water and its circulation about the sound mainly as near-surface flows.

Vertical density differences (top to bottom) of between 0.1 and 0.5 kg m^{-3} were recorded in the sound during typical autumn conditions. Autumn is characterised by periods of low wind stress, and it is of ecological relevance to investigate the rate of deepening of the upper mixed layer, the conditions required for full depth mixing and the number of times that this is likely to occur during autumn.

Using simple wind-mixing and penetrative convection formulae it is estimated that winds greater than 7.5-10 m s^{-1} in association with penetrative convection, due to heat losses of order 300 W m^{-2} or greater, can achieve a fully-mixed water column over a diurnal cycle. From past time-series data it is estimated that this combination of surface forcings and the resultant fully-mixed condition occurs, on average, approximately 4 to 5 times per month in mid-late autumn. The data further indicate that intervening periods, between successive complete mixing events, of up to 3-4 weeks can occur during which the bottom waters remain vertically stratified. This may lead to relatively long residence times of bottom water, and to water quality problems, such as can occur in poorly mixed nutrient-rich waters.

1. Introduction

Cockburn Sound is a semi-enclosed micro-tidal embayment on the southwest coast of Western Australia (Figures 1 and 2). This paper investigates aspects of the exchange, stratification and vertical mixing in the sound during autumn, and assesses the potential for prolonged residence of relatively dense bottom waters in Cockburn Sound during this season. The investigation employs field measurements of water currents and physical structure, and uses a three-dimensional baroclinic model to perform hydrodynamic and transport simulations.

During autumn there is minimal direct or diffuse flux of freshwater to the coastal zone. The cumulative seasonal influences of evaporation and cooling, combined with bathymetrically restricted exchange, cause Cockburn Sound waters to be more saline and/or cooler, and therefore of greater density than shelf waters (D'Adamo and Mills, 1995a). Exchange that takes place between shelf and sound waters therefore has the potential to contribute to vertical stratification within the sound, as does daily warming due to short-wave radiation. Winds are seasonally at their weakest during autumn, and this brings into question the ability of wind stress and the penetrative convection that is associated with surface cooling at night to mix through typical vertical density gradients, and the frequency with which lower basin waters may be replenished by vertical mixing.

Previous investigations of Cockburn Sound's hydrodynamics have not fully addressed these questions. Early numerical model studies of the circulation (Maritime Works Branch, 1977; Steedman and Craig, 1979) employed depth-averaged barotropic models to simulate wind-driven circulation and exchange. These models did not take into account the role of density effects in the hydrodynamics of the sound. More recent oceanographical studies have sought to characterise the spatio-temporal variations of density in Perth's southern coastal waters, in order to gain a more detailed understanding of the circulation, flushing and exchange regimes in this region.

D'Adamo, Mills and Wilkinson (1995) analysed the hydrodynamics during a typical 7-10 day synoptic meteorological cycle in winter. Outflows from the Swan-Canning Estuary formed buoyant plumes that were forced alongshore and into Cockburn Sound under favourable winds. Storm winds led to strong vertical mixing of the plumes, resulting in a lowering of the sound's mean salinity (and density) relative to adjacent shelf waters. Then, for the remainder of the synoptic cycle, dense shelf waters entered the sound, sank to the bottom, spread across the basin and displaced lighter resident basin water upwards, leading to the formation of a main pycnocline. Some of the water above the main pycnocline was transported out of the sound primarily by wind-stress forcing. Early spring warming helps to maintain the excess buoyancy of the sound relative to the open shelf and to prolong the sequence of flushing and exchange processes described above, which are collectively referred to as the 'winter-spring' regime.

Another major hydrodynamic regime described by D'Adamo and Mills (1995b) was the 'summer' regime (from about late spring to early autumn) during which density differences between the basin and open shelf are relatively small. Furthermore, the absence of significant freshwater fluxes and the recurrence of strong sea-breeze winds leads to a typically weak and transient vertical density stratification in Cockburn Sound, and a basin-scale circulation that is essentially barotropic. Water resides at the bottom of the basin only temporarily, as a consequence of full-depth vertical mixing events that generally recur every day or two in association with strong sea-breeze winds.

However, there is a third distinct hydrodynamic regime, named the 'autumn' regime, which occurs from autumn to early winter, and the circulation, mixing and exchange of Cockburn

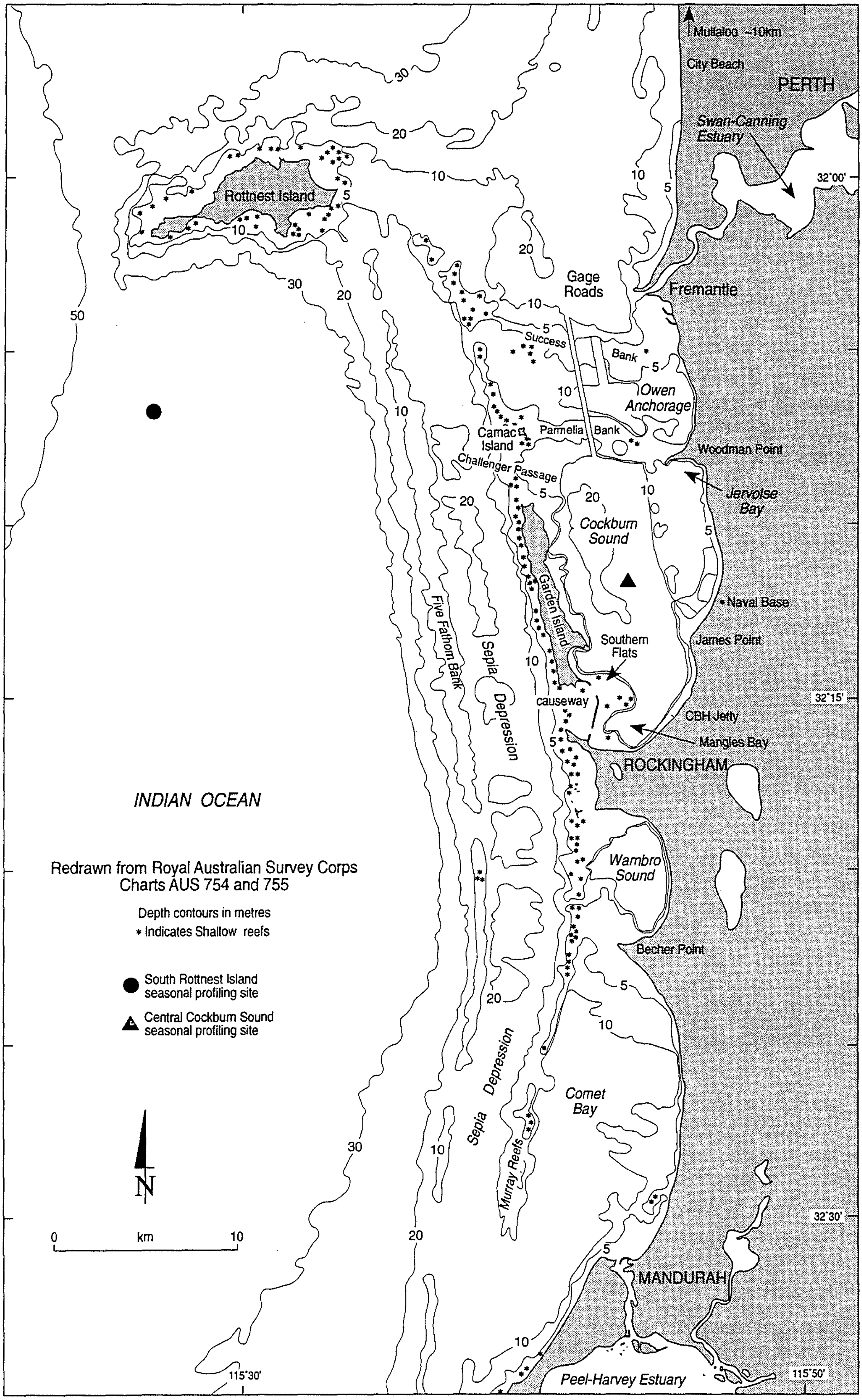

Figure 1. Locality diagram and bathymetric details of the metropolitan coastal waters off Perth, Western Australia.

Figure 2. Oblique perspective plot of the sea-bed of Perth's coastal zone from Hillarys to Mandurah and out to west of Rottnest Island, highlighting the protected nature of the channels and basins east of the major reef lines.

Sound for this period forms the main subject of this paper. During this period the sound is vertically stratified in density and is on average denser than the adjacent shelf water, as was identified from a series of seventeen surveys of the vertical salinity, temperature and density (STD) structure through the sound and mid-shelf waters, conducted between August 1991 and May 1994 (D'Adamo and Mills, 1995a). These data were used to identify an annual cycle in the salinity and temperature *differences* between central Cockburn Sound and a site 10 km south of Rottnest Island. This cycle, reproduced in Figure 3 shows when Cockburn Sound was either denser, more buoyant, or of approximately equal mean density compared to the adjacent shelf waters.

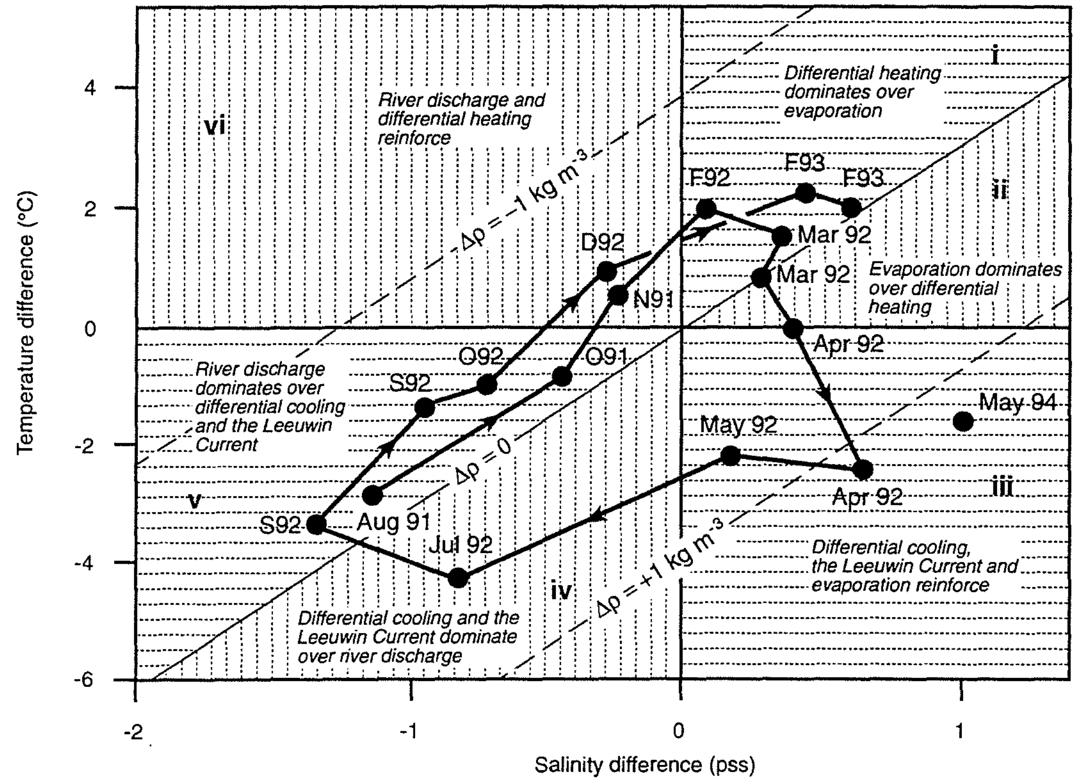

Figure 3. The annual cycle in cross-shelf salinity and temperature differences from a representative depth of 10 m (Cockburn Sound minus mid-shelf water 10 km south of Rottnest Island). Diagonals are lines of constant density difference. The month and year of each survey are shown next to the respective data points. The relative influence of the major forcings on the annual cycle are indicated for six categories (i to vi, as shaded). The cross-shelf density difference cycle falls broadly into three main seasonal regimes: 'summer' (i and ii), 'autumn' (iii and iv) and 'winter-spring' (v and vi). Figure redrawn from D'Adamo and Mills (1995a).

During autumn to early winter, water in Cockburn Sound is typically more saline and/or colder, and is more dense, than water at the offshore site (Figure 3). The nearshore elevation in salinity during autumn is due to the differential effects of evaporation. As autumn progresses, differential cooling lowers the water temperature of Cockburn Sound relative to the deeper offshore site. The temperature difference is accentuated by the passage offshore of relatively warm water from the southward flowing Leeuwin Current, which intensifies from March onwards (Pearce, 1991; Cresswell, 1991). The elevated density in Cockburn Sound is maintained until significant amounts of fresh water from Swan River discharges enter the sound in early winter (D'Adamo, Mills and Wilkinson, 1995).

Because in autumn the basin water is generally stably stratified and denser than the surrounding shelf water (D'Adamo and Mills, 1995a), and the wind field is typically at its weakest on a seasonal basis (Steedman and Craig, 1979), it is important to investigate the potential for prolonged periods of poor vertical mixing of dense bottom waters in Cockburn Sound. Because of Cockburn Sound's history of eutrophication (Department of Conservation and Environment, 1979; Simpson *et al.* 1993; Cary, Simpson and Chase, 1991) and its high rates of pelagic productivity (Helleren and John, 1996), the organic loading to the sediments is enhanced. The possibility of prolonged periods of vertical stability in autumn raises questions about oxygen depletion in bottom waters, which could lead to the inhibition of denitrification, resulting in greater availability of bio-available nitrogen (e.g. ammonium). Masini (1994a) sampled the oxygen climate at the bottom of the Cockburn Sound basin during autumn conditions and he also conducted oxygen demand experiments using sediments from that region (Masini, 1994b). He found that water at 0.2 m above the bottom displayed signs of oxygen depletion during field measurements and that the Cockburn Sound deep basin sediments were net consumers of oxygen during controlled laboratory experiments.

Driven by this ecological motivation, this report reviews recently collected data of the salinity, temperature and density (STD) structure through Cockburn Sound and adjacent waters during the autumns of 1992 and 1994. These data are used to interpret exchange between shelf and sound waters, and to characterise vertical density stratification in the sound for conditions that are representative of the 'autumn' regime (autumn to early winter). Simple wind-mixing and penetrative convection formulae are used to investigate the meteorological conditions required for full-depth mixing, and the number of times that this is likely to occur during autumn. Numerical modelling of circulation and the exchange between the sound and adjacent shelf waters is also conducted to complement the field results.

This work is part of an environmental study of the southern metropolitan coastal waters off Perth (Figure 1), conducted by the Department of Environmental Protection of Western Australia. The purpose of the Southern Metropolitan Coastal Waters Study (1991-1994) is to provide a better technical basis from which to manage the cumulative environmental impacts of contaminants entering these waters (Simpson *et al.* 1993).

The results of this paper assist in the choice, calibration and application of numerical hydrodynamic models of Perth's coastal waters (Simpson *et al.* 1993). The role of the vertical and horizontal density stratification in influencing the nature of mixing and transport is considered in related modelling exercises, based in part on the results of this work.

This analysis complements other investigations from the Southern Metropolitan Coastal Waters Study (SMCWS) of the hydrodynamics of Cockburn Sound and adjacent waters for conditions characteristic of winter (Mills *et al.* 1994; Mills *et al.* 1996; D'Adamo, Mills and Wilkinson, 1995; D'Adamo, Cary and Mills, 1995) and summer (D'Adamo and Mills, 1995b).

2. Site

2.1 Bathymetry and topography of Cockburn Sound and adjacent waters

Cockburn Sound is situated on the southwest coast of Western Australia just south of the city of Perth (Figures 1 and 2). 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 is open-shelf. Five Fathom Bank runs from offshore of Mandurah to Rottnest Island.

Cockburn Sound has a relatively deep central basin (up to approximately 21 m in depth) with approximate horizontal dimensions of 14 km x 5 km, and an eastern margin adjacent to the mainland coast (between James Point and Woodman Point) with an approximate width of 3-4 km and a depth less than about 10m. Mangles Bay lies in the southern end of the sound. The northern opening has a mean depth of about 5 m and is comprised of a reef line between north Garden Island and Carnac Island, a relatively shallow sill called Parmelia Bank, and a narrow 150 m wide shipping channel that cuts northwards through Parmelia Bank, Owen Anchorage and Success Bank with a depth of about 15 m. The cross-sectional area of the northern opening (Garden Island to Carnac Island to Woodman Point) is approximately 2.8 x 10^4 m^2. The causeway, with its two bridge openings, was completed across the southern opening in 1974 and reduced the cross-sectional area of the opening from approximately 1 x 10^4 m^2 to 4 x 10^3 m^2, with water depths of about 3 to 4.5 m under the bridges.

2.2 Climate during autumn

The southwest of Australia has a 'Mediterranean' climate, varying annually between cool wet winters and hot dry summers. Autumn is characteristically mild. Mean monthly rainfall is 45 mm in April and 123 mm in May (Commonwealth of Australia, 1989). However, buoyancy fluxes to Cockburn Sound from Swan River discharges are generally not significant until mid-winter, when stronger rainfall and consequent runoff occurs (D'Adamo, Mills and Wilkinson, 1995). Industrial discharges of freshwater and heat into Cockburn Sound are relatively minor compared to natural surface buoyancy fluxes (D'Adamo, 1992). Mean minimum and maximum daily air temperatures range from 11.6 to 24.6 °C, respectively, and mean evaporation is about 3-4.5 mm per day in April-May (Commonwealth of Australia, 1989).

2.3 Characteristic winds over the Perth coastal zone in autumn

Detailed analyses of the wind patterns for the Perth coastal zone are available in Steedman and Craig (1979), Hearn (1991) and Breckling (1989). With respect to the present discussion, one of the most important characteristics in the meteorology of the coastal zone during autumn, compared to other times of the year, is the relatively weak winds and low frequency of storm events. Figure 4 (from Steedman and Craig, 1979) presents statistical data (based on hourly wind data records from Fremantle) of the percent occurrence of wind speed and direction throughout the year and shows that in April-May the percent occurrence of strong winds is seasonally at its lowest. An evaluation of the occurrence of storm events in autumn is performed in the wind mixing analysis, below.

2.4 Heat flux

The heat flux at the water surface exhibits considerable variation over diurnal, synoptic and seasonal time scales. Pattiaratchi *et al.* (1995) utilised local meteorological data for 1993 and estimated the hourly heat flux at the water surface for a nearshore site approximately 30 km north of Perth (Figure 5). Throughout the year the day-time heat flux into the water reached about 800 W m^{-2} and losses at night reached up to about 500 W m^{-2}. For the autumn period (March to May) the data indicate that night-time losses were typically about 200-400 W m^{-2} and during the day gains via the surface ranged from about 100 to 700 W m^{-2}. For the present analyses the data in Figure 5 can be utilised as a reasonable estimate of the likely range of heat fluxes that occur in Cockburn Sound. A methodology for the estimation of heat fluxes, on the basis of local meteorological and hydrological data, is presented in Fischer *et al.* (1979).

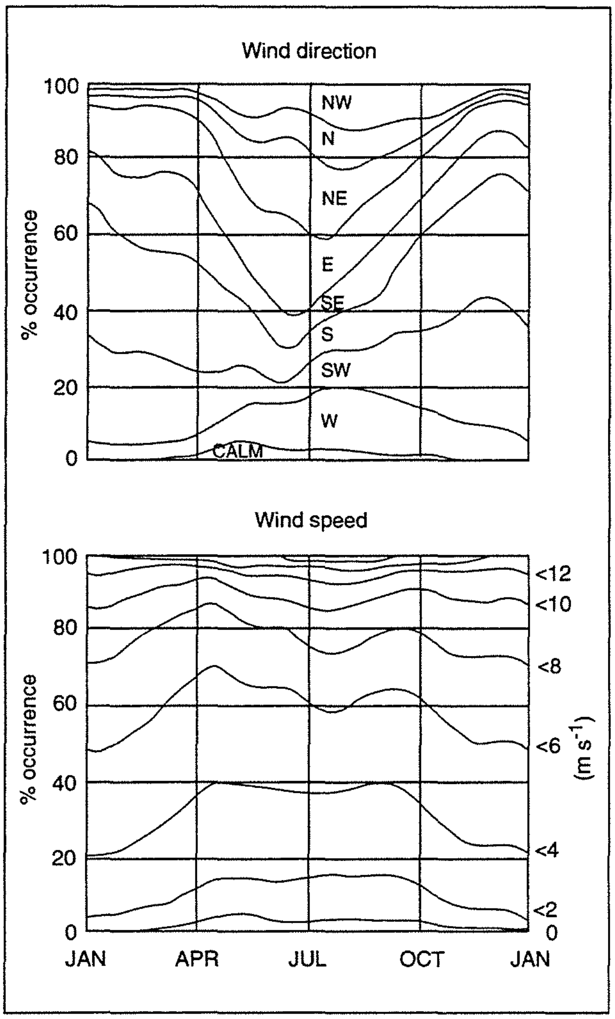

Figure 4. Combined monthly one-hourly averaged wind speed and direction occurrence diagrams - January 1971 to December 1977. Data collected at Fremantle at a height of 50 m. Figure redrawn from Steedman and Craig (1979).

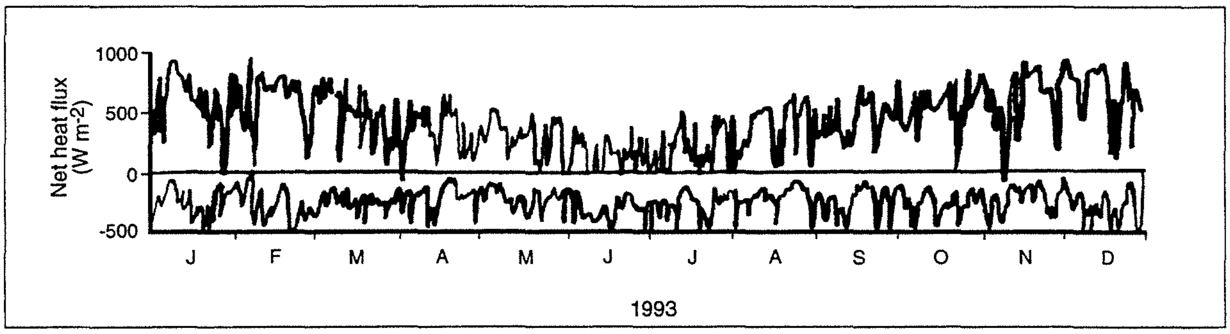

Figure 5. Net heat flux for 1993 at the water surface for the nearshore waters 30 km north of Perth, based on hourly data, and showing variations in maximum day-time gain rates (+ve) and maximum night-time loss rates (-ve). (Derived from Pattiaratchi *et al.* (1995)).

3. Field programme and instrumentation

The vertical salinity, temperature and density (STD) structure in Cockburn Sound and adjacent waters was measured on 30 April 1992, 26 May 1992, 3 May 1994 and 4 May 1994. The 1992 stratification data were collected with a fine-scale conductivity-temperature-depth (CTD) probe. The probe 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 Global Positioning System. The data were retrieved via an electrical cable, processed and stored in an onboard computer. The drop speed of the instrument 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 0.001 m.

The 1994 stratification data were collected with a CSIRO/YEOKAL Model 602 Submersible Data Logger (SDL). The SDL was deployed from a vessel in vertical profiling mode by lowering it at a speed of approximately 0.25 m s^{-1}. At a sampling rate of 4 samples per second this resulted in a recording about every metre. After calibration from laboratory checks, salinity, temperature and density data were returned at resolutions of 0.1 in practical salinity scale (pss), °C and kg m^{-3}, respectively.

4. Results

4.1 Field data

4.1.1 Stratification of Cockburn Sound and adjacent shelf waters: 30 April 1992, 26 May 1992, 3 May 1994 and 4 May 1994

The annual cycling in STD, discussed above and represented by the cyclic plot in Figure 3, has important implications for the hydrodynamic behaviour of the basin, as discussed by D'Adamo and Mills (1995a). During autumn, because the basin water is relatively dense compared to the adjacent shelf water, exchange processes can introduce buoyant shelf waters into the sound. In addition to day-time thermal stratification of the water column due to solar radiation, this introduction results in vertical density stratification within the basin, unless vertical mixing is strong enough to overcome the stratification. A number of regional STD surveys conducted as part of the SMCWS have identified a vertically stratified structure in autumn and the data from 30 March 1992, 26 May 1992, 3 May 1994 and 4 May 1994 are presented in Figures 6a, b, c and d respectively, to exemplify this point. For each day, the vertical density stratification is shown along transect paths that passed through Cockburn Sound and adjacent shelf waters. Figure 6c also contains contour plots of salinity and temperature to accompany the south-north density contours and, in addition, a vertical temperature contour plot from south of Rottnest Island through Challenger Passage, and then on to Jervoise Bay via northern Cockburn Sound. For each day the vertical STD profiles are also plotted from a site in central Cockburn Sound to show the details of the vertical structure.

The data in Figure 6 are examples of cases when the basin was vertically stratified and its mean density was greater than that of the adjacent ocean. On all occasions the basin was both more saline and of a lower temperature than the adjacent ocean and hence both these characteristics

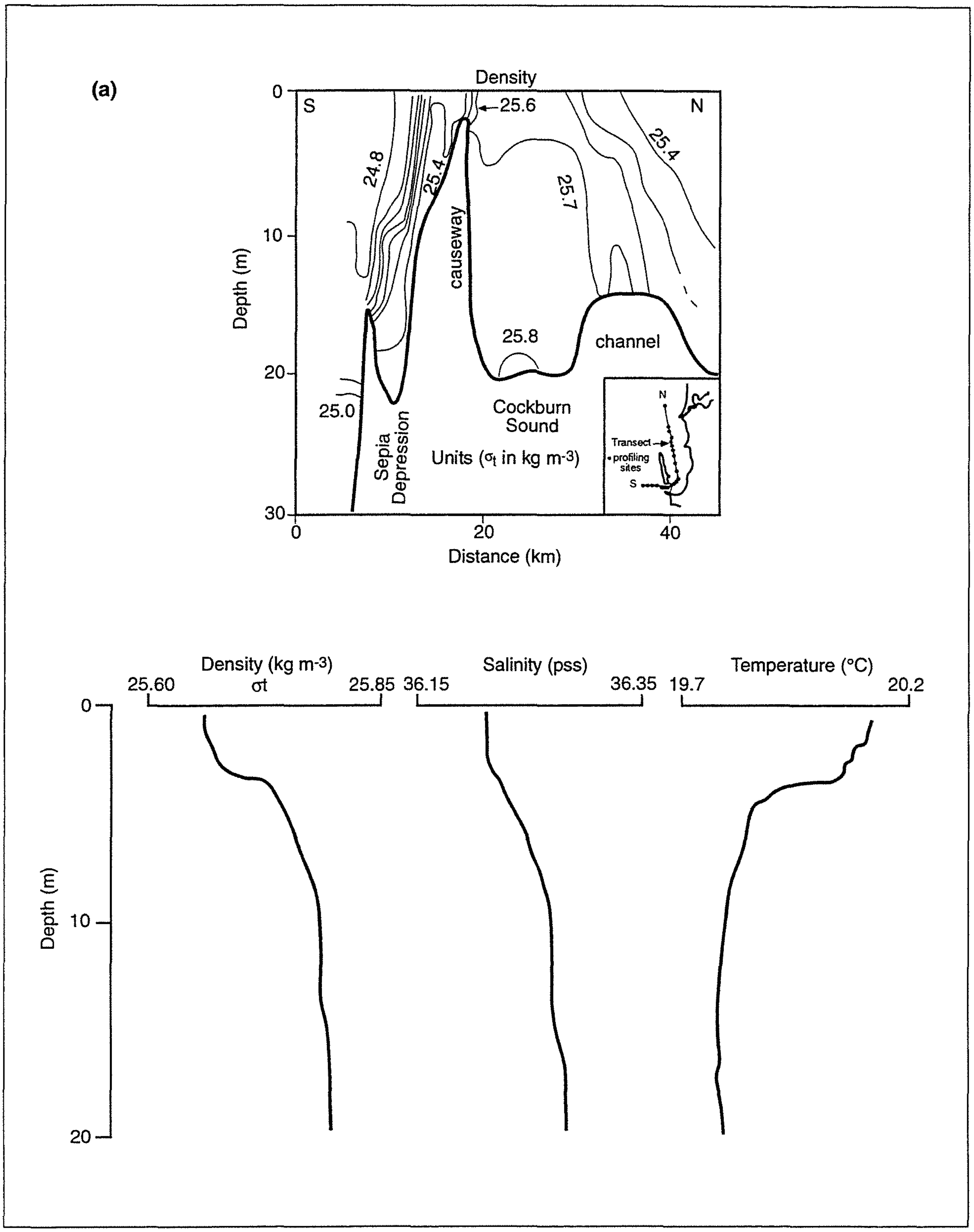

Figure 6. Vertical density contour plots from transects through Cockburn Sound, Owen Anchorage and adjacent shelf waters. Diagrams a, b, c and d are for 30 April 1992, 26 May 1992, 3 May 1994 and 4 May 1994, respectively. In each case the vertical density, salinity and temperature profiles from central Cockburn Sound are also plotted. In Figure 6 c the salinity and temperature contours are added and an additional temperature contour plot is plotted from a W-E transect starting just south of Rottnest Island and progressing to Jervoise Bay.

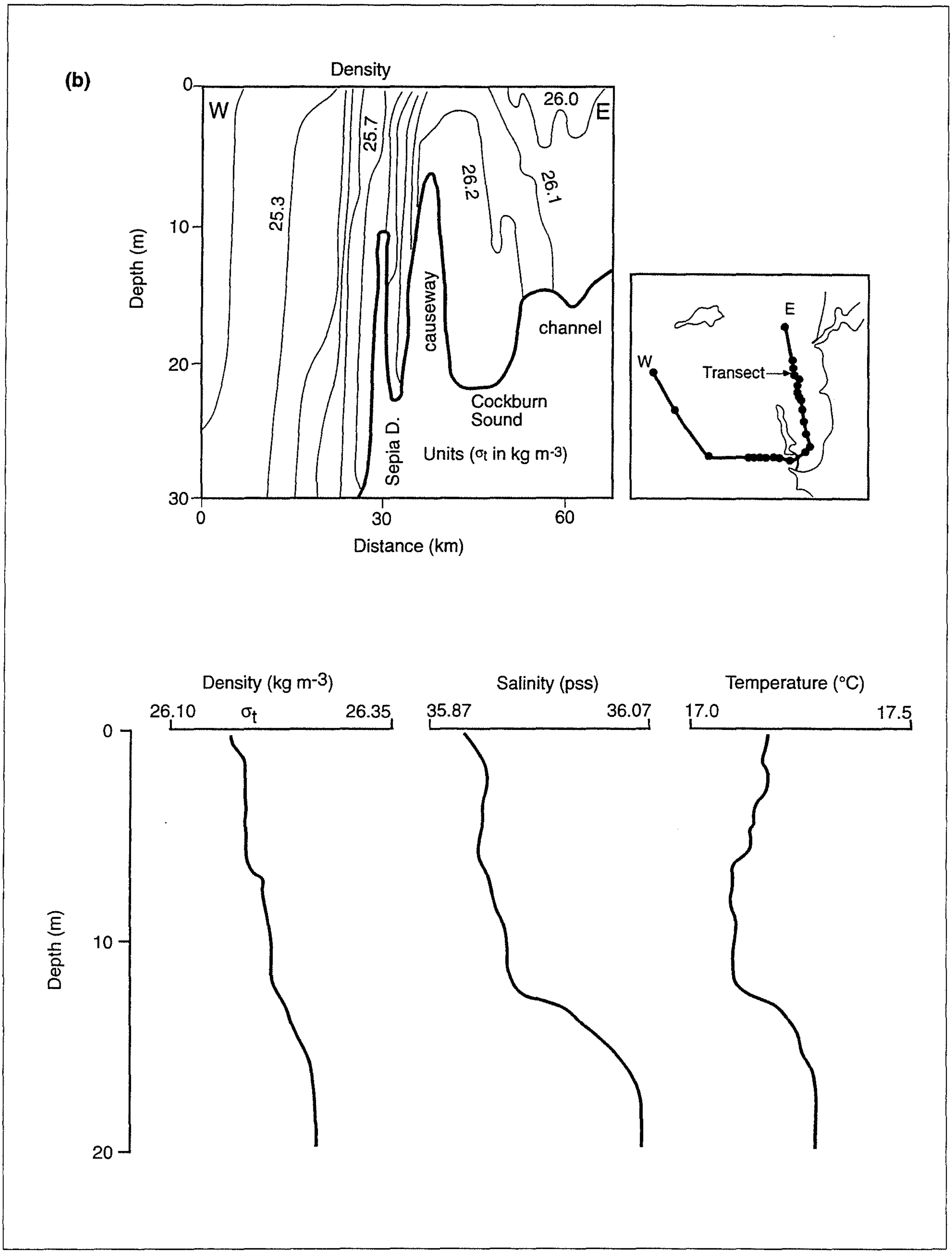
(b)
Density
W
E
26.0
25.7
25.3
26.2
26.1
causeway
channel
Cockburn Sound
Sepia D.
Units (σt in kg m-3)
Depth (m)
Distance (km)
0
10
20
30
0
30
60
E
W
Transect
Density (kg m-3)
26.10
σt
26.35
Salinity (pss)
35.87
36.07
Temperature (°C)
17.0
17.5
Depth (m)
0
10
20

Figure 6b.

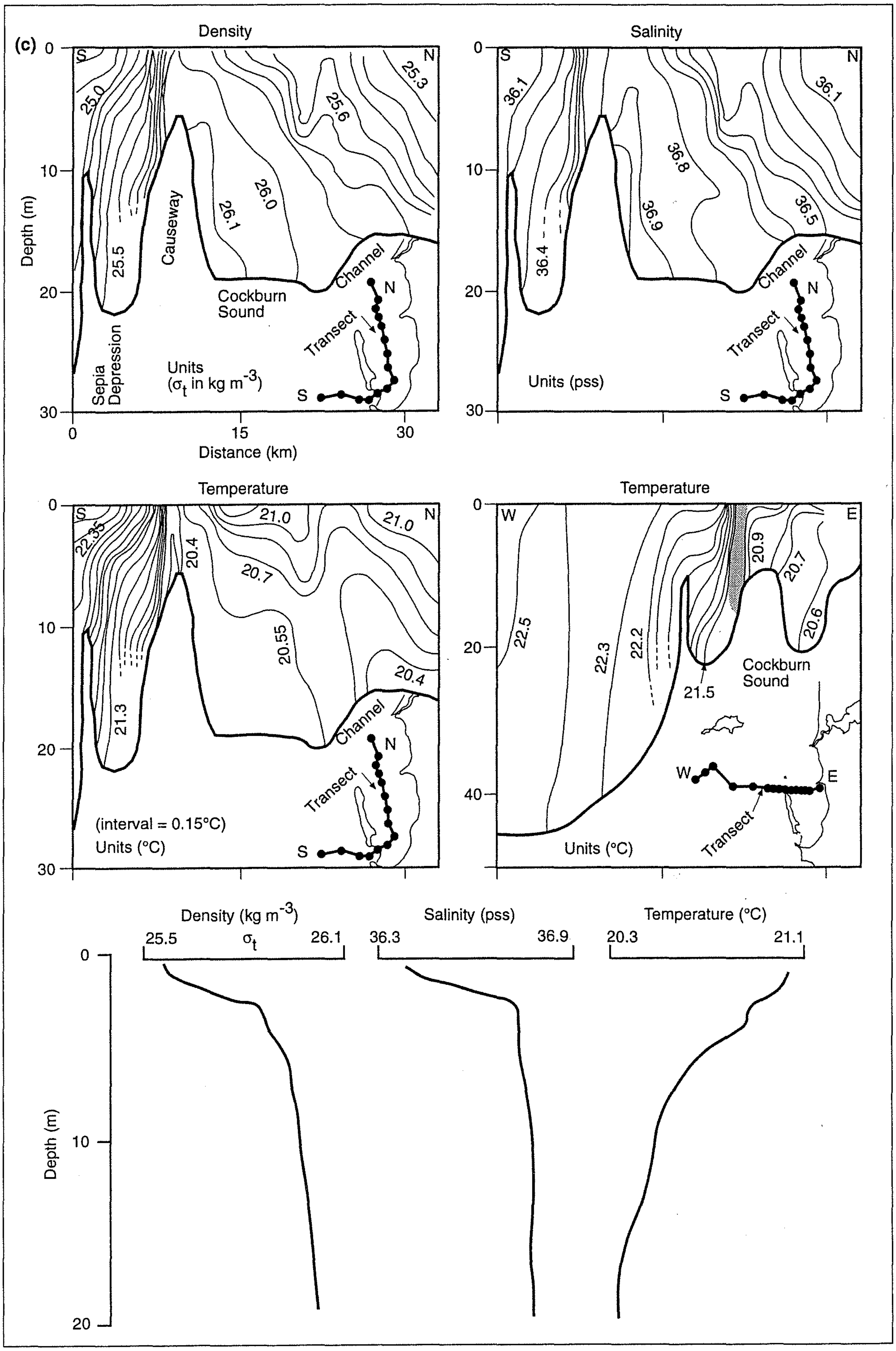
(c)
Density
Salinity
S
N
25.0
25.3
25.6
26.0
26.1
25.5
Causeway
Sepia Depression
Cockburn Sound
Channel
Transect
Units (σ_t in kg m^{-3})
36.1
36.8
36.9
36.5
36.4
Units (pss)
Depth (m)
Distance (km)
0
10
20
30
15
Temperature
21.0
22.35
20.4
20.7
20.55
21.3
(interval = 0.15°C)
Units (°C)
W
E
22.5
22.3
22.2
21.5
20.9
20.7
20.6
40
Density (kg m^{-3})
25.5
σ_t
26.1
Salinity (pss)
36.3
36.9
Temperature (°C)
20.3
21.1

Figure 6c.

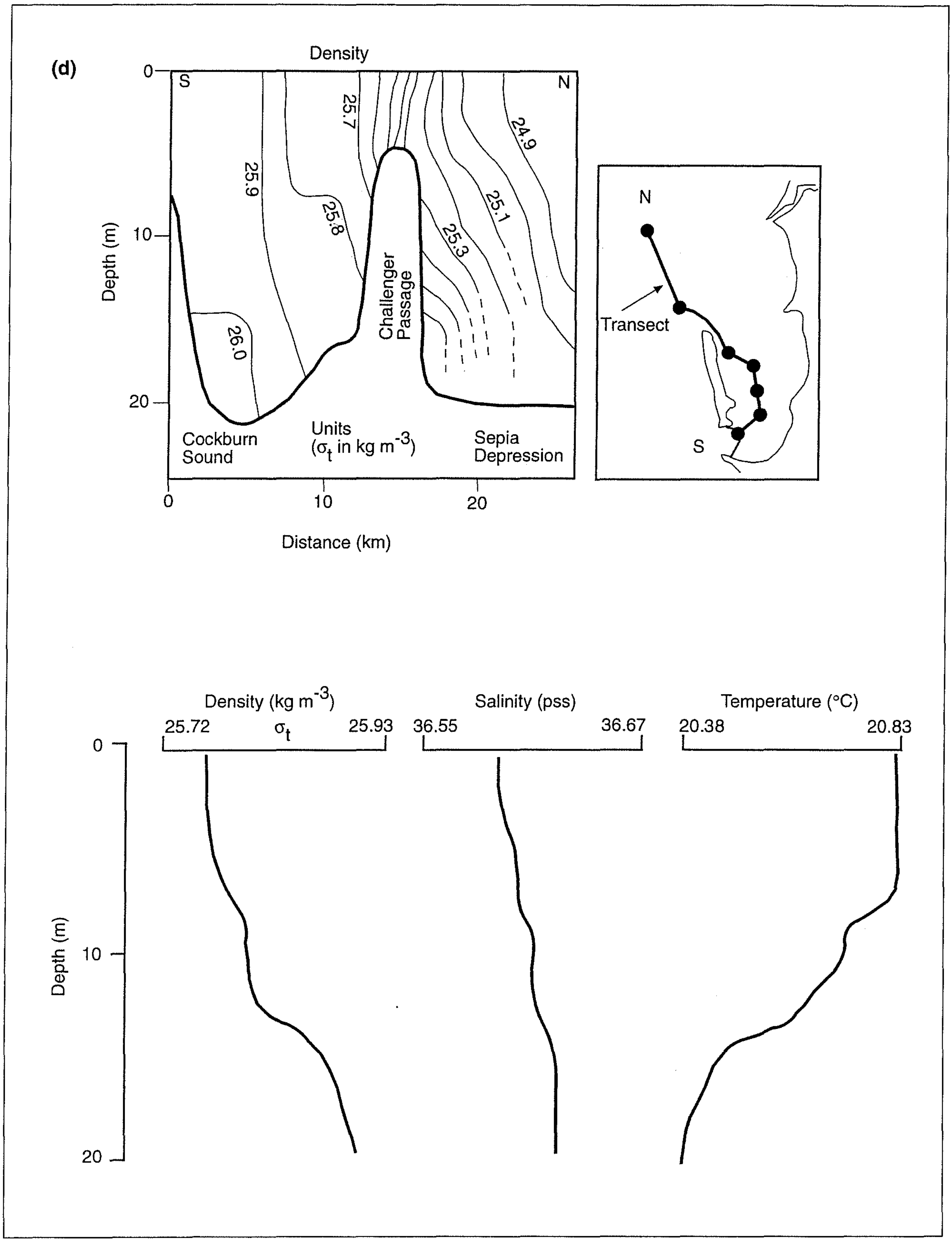
(d)
Density
0
10
20
Depth (m)
S
N
25.9
25.8
25.7
26.0
Challenger Passage
25.3
25.1
24.9
Cockburn Sound
Units
(σ_t in kg m^{-3})
Sepia Depression
0
10
20
Distance (km)
N
Transect
S
Density (kg m^{-3})
25.72
σ_t
25.93
Salinity (pss)
36.55
36.67
Temperature (°C)
20.38
20.83
0
10
20
Depth (m)

Figure 6d.

served to increase the relative density of the basin. In all cases the contours in Figure 6 show that the respective isopycnals (and isohalines and isotherms in Figure 6c) slope upward toward the interior of the basin in such a way as to suggest that shelf water has entered the sound as a buoyant feature in the upper water column. This interpretation is supported by the results of the numerical modelling of the autumn dynamics in Section 4.2.

4.1.2 The presence of the Leeuwin Current west of Cockburn Sound during autumn

The temperature contours in Figure 6c show that the western part of the transect paths were within a relatively high temperature zone, which represented the shoreward edge of the Leeuwin Current, as confirmed by sea-surface temperature (SST) NOAA-AVHRR satellite imagery for each of these days (A Wyllie, personal communication). The SST image from 0915 hrs 3 May 1994 is presented in Plate 1 to illustrate the presence of the Leeuwin Current on that particular day. As shown on the image, the STD transect paths traversed through a sharp temperature front between warm water from the Leeuwin Current and colder water from the nearshore zone. The temperature contour plots from 3 May 1994 (Figure 6c) show the temperature front just outside of the northern and southern openings of Cockburn Sound, and this front is evident on the SST image of Plate 1. During the 'autumn' regime the presence of the relatively buoyant waters of the Leeuwin Current over the mid-outer shelf assists in maintaining the characteristic direction in the cross-shelf density gradient, with the sound remaining relatively dense compared to the adjacent shelf region.

4.2. Numerical modelling

4.2.1. Modelling the exchange and onset of stratification in Cockburn Sound during autumn

A numerical model has been used to simulate exchange processes between Cockburn Sound and surrounding shelf waters and their role in maintaining vertical stratification within the sound during autumn (Mills and D'Adamo, 1995a). The time-dependent, three-dimensional, baroclinic model (Blumberg and Mellor, 1987; Mellor, 1992) is based on the primitive equations of mass, momentum, salt and heat conservation, subject to the hydrostatic assumption and the Boussinesq approximation, an equation of state, and an embedded turbulence closure sub-model (Mellor and Yamada, 1982). The version used here was modified and rewritten in the C programming language by Herzfeld (1994) and further developed by Mills and Essers (1995).

The model domain centres on Cockburn Sound and extends 60 km south to north from Comet Bay to City Beach, and 23 km west to east from the 40 m depth contour to the mainland coast. The domain is gridded at 500 m resolution. The bathymetry was derived from a detailed 100 m resolution bathymetric data base compiled by the Department of Transport of Western Australia. In this paper, the graphical representations of model simulation results are for a sub-domain of the model only.

The aim of the simulation was to see whether the model could, after 4-5 days, reproduce the major features of the measured salinity structure for the period 3-4 May, 1994. If this was the case, then the simulation results could be used to complement the understanding of exchange and stratification processes drawn from the analysis of limited STD field data collected during autumn.

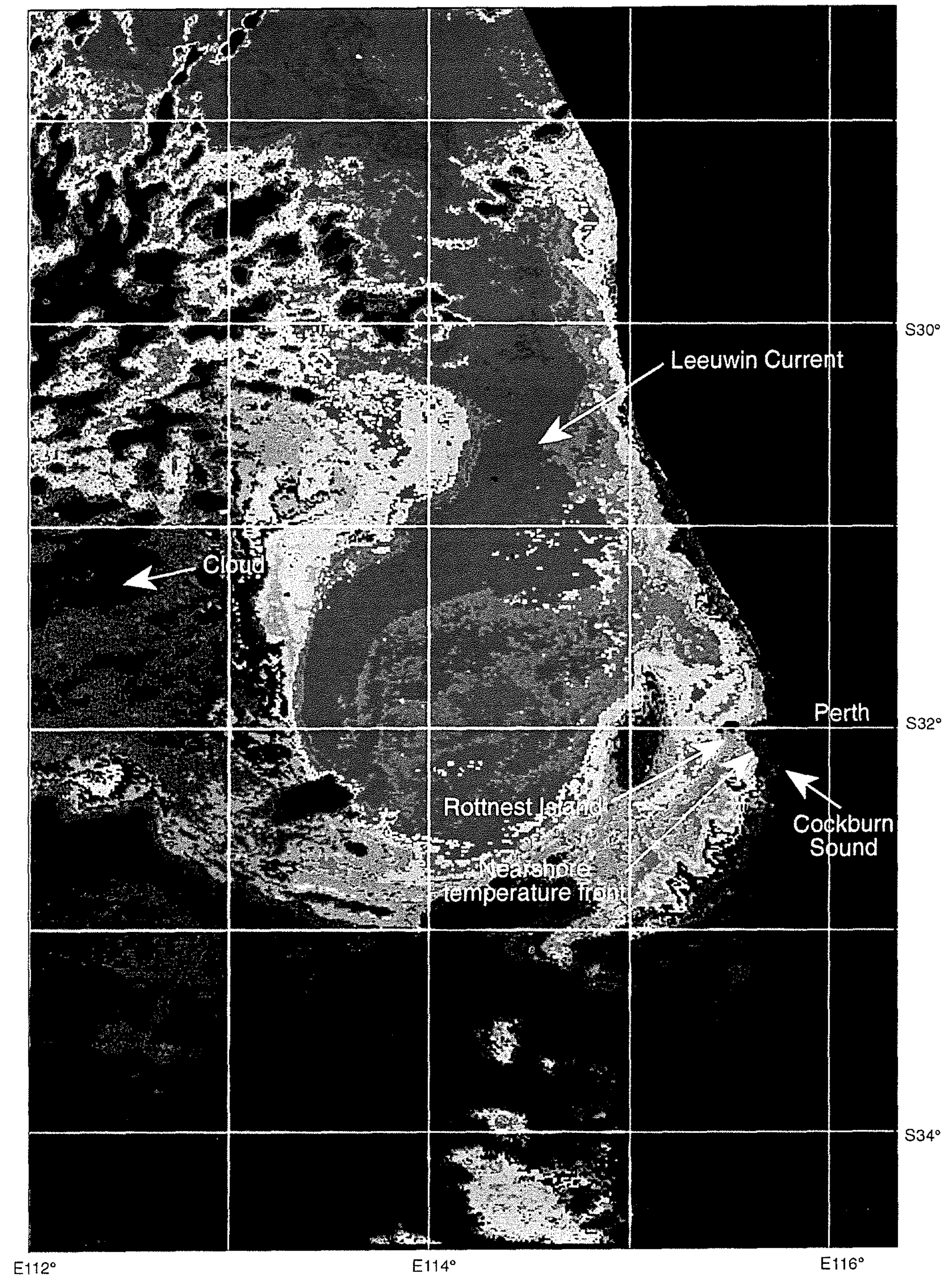

Plate 1. Sea-surface temperature of the southwest Australia coastal zone from the NOAA 11 satellite, showing the Leeuwin Current (red), recorded on 3 May at 0915 hrs Perth time.

The simulation was started from a state of rest and the model forced with half-hourly averaged wind data recorded at Naval Base (at 12 m height) from the period 0000 hrs 29 April to 2400 hrs 7 May 1994. As shown in Figure 7, daily sea-breeze events (8-10 m s^{-1} southwesterly winds lasting 6-12 hours) and intervening periods of weaker southeast to east winds occurred on the first three days. During the following 2.5 days (0000 hrs 2 May to 1200 hrs 4 May 1994) moderate to weak winds (0-6 m s^{-1}) from the south-east to north-east prevailed. A daily pattern of seabreeze followed by weaker southerly to southeasterly winds re-established in the remainder of the simulation period.

The initial salinity field supplied to the model (Figure 8) consisted of two homogeneous water masses, one with 36 pss salinity occupying Cockburn Sound and part of Owen Anchorage, the other with 35 pss salinity occupying the remainder of the model domain, and the initial temperature field in the model was set to be uniform throughout. In this way the dynamic effects of a characteristic shelf-embayment density difference in autumn were incorporated into the model simulation.

For the duration of the model run, there was an underlying salinity difference between the sound and shelf waters and a corresponding density difference of about 0.75 kg m^{-3}, which is within the range of values recorded for the autumn period (D'Adamo and Mills, 1995a). The model simulation was used to investigate the influence of this density difference on the vertical structure of circulation, the onset of vertical stratification and the flushing efficiency of Cockburn Sound under autumn wind conditions.

Knowledge of the initial model salinity distribution and its evolution during the simulation was used to calculate the rates of salt depletion in various pre-determined sub-regions of Cockburn Sound, and hence the corresponding flushing rates of these sub-regions.

Figures 9a-e and 10a-e show near-surface distributions of currents and salinity, respectively, at selected times during the simulation. Figures 11a-e present the complementary vertical salinity structure over a south to north vertical section through Mangles Bay, Cockburn Sound, Owen Anchorage and Gage Roads.

Simulation time 3 days (0000 hrs 2 May 1994) - post sea-breeze

Following sea-breeze winds, the surface circulation (Figure 9a) features include: (i) strong northerly flow (~ 0.2 m s^{-1}) offshore of Garden Island; (ii) water entering the sound under the causeway bridges, flowing north (~ 0.2 m s^{-1}) and then both northwest toward and along the eastern Garden Island shore, and also northward along the eastern margin of Cockburn Sound; (iii) flow passing to the north-east through Challenger Passage, and east to north-east flow across Parmelia Bank (~ 0.25 m s^{-1}).

The corresponding surface salinity distribution (Figure 10a) results from the recent history of water advection and mixing, and shows: (i) low salinity, buoyant shelf water driven into the sound through the causeway openings, and transported to the north and northwest, attaching to the Garden Island coast; (ii) a strong salinity gradient zone extending east-northeast from the northern tip of Garden Island, with salinity contours thence diverging and trending northward over Parmelia Bank and Success Bank; (iii) more saline, denser water driven northward by the sea-breeze along the mainland shore past Woodman Point, over the eastern margin of Owen Anchorage, and toward Fremantle.

The south-north salinity section (Figure 11a) shows that Mangles Bay and the southern end of the main basin are strongly stratified by wind-driven inflow of lower salinity water through the causeway openings. The resultant buoyant structure extends somewhat northward from the Southern Flats and displays its strongest vertical stratification near the surface. A low salinity, buoyant water structure is also found extending several kilometres south of Parmelia Bank,

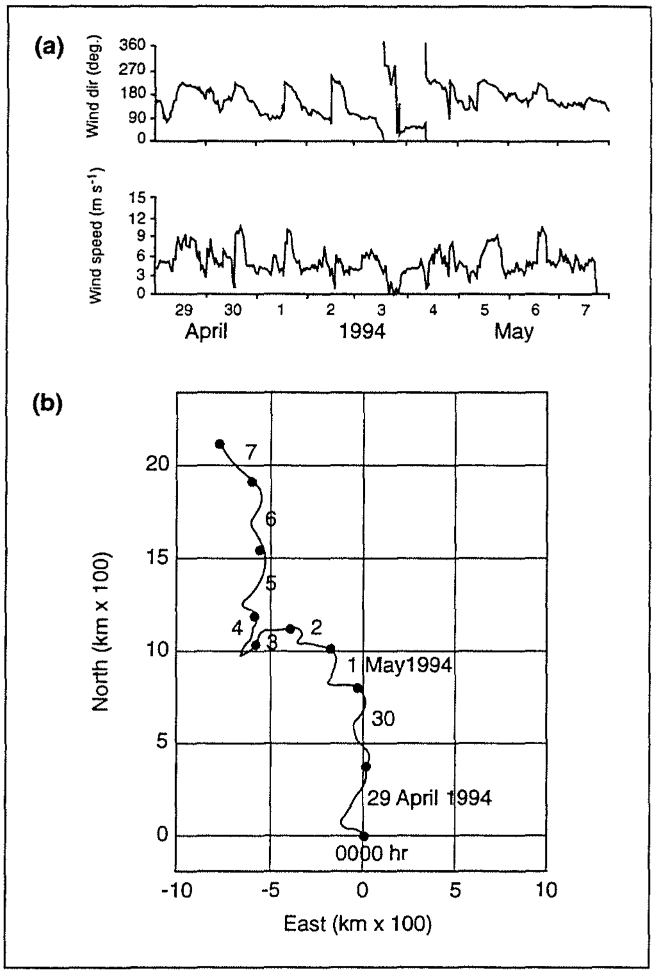

Figure 7. Half-hourly averaged wind speed and direction from Naval Base (12 m) for the period 0000 hrs 29 April to 0000 hrs 8 April 1994, showing (a) time-series plots and (b) the same data as a progressive vector plot.

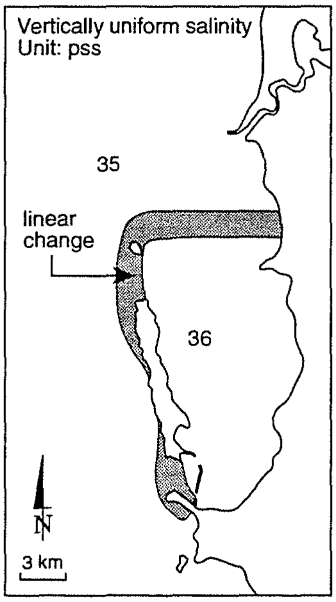

Figure 8. Initial salinity field used to start the numerical model simulation.

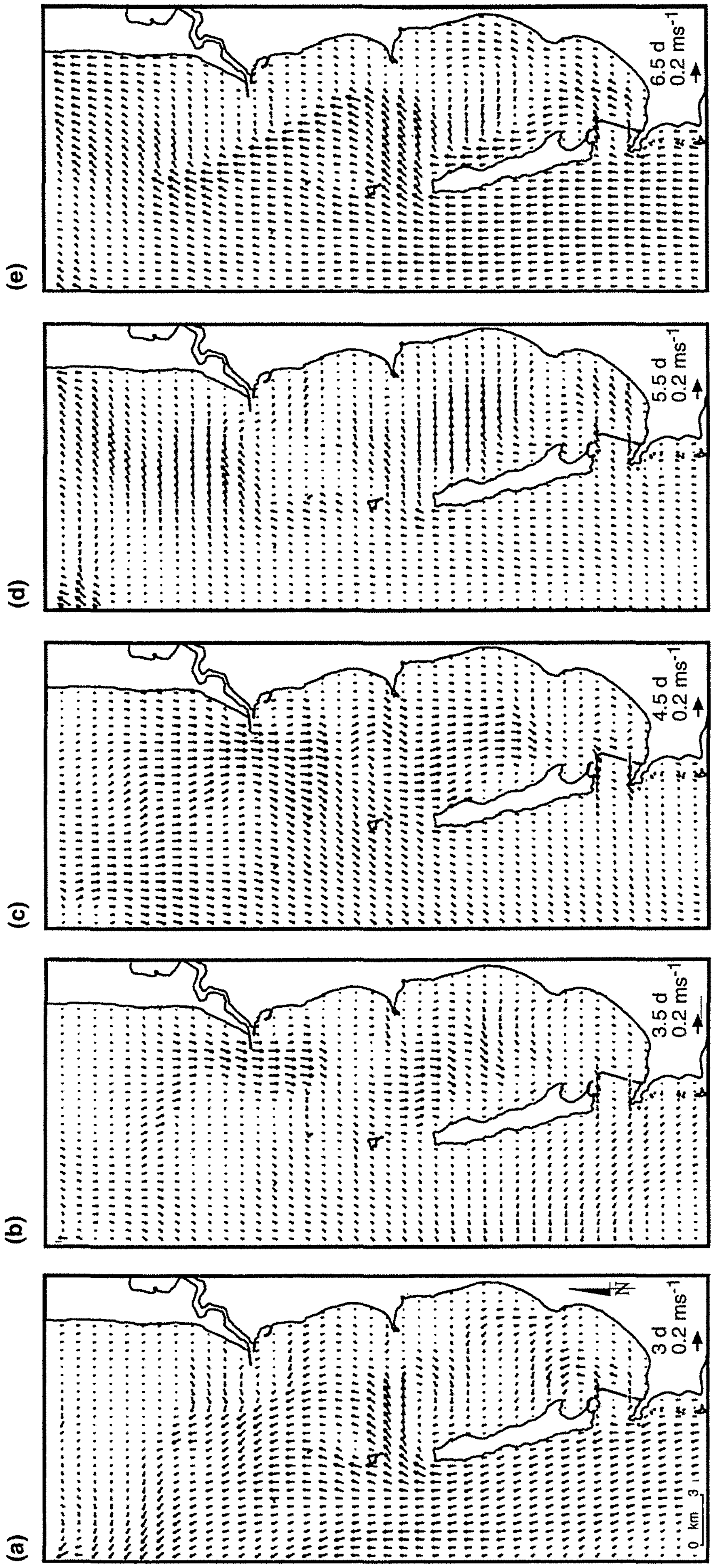

Figure 9. Modelled surface current fields (at 1.1 m depth) for five simulation times: (a) 3 d, (b) 3.5 d, (c) 4.5 d, (d) 5.5 d and (e) 6.5 d. The model was started with the salinity field in Figure 8, and driven by the winds in Figure 7, starting at 0000 hrs 29 April 1994.

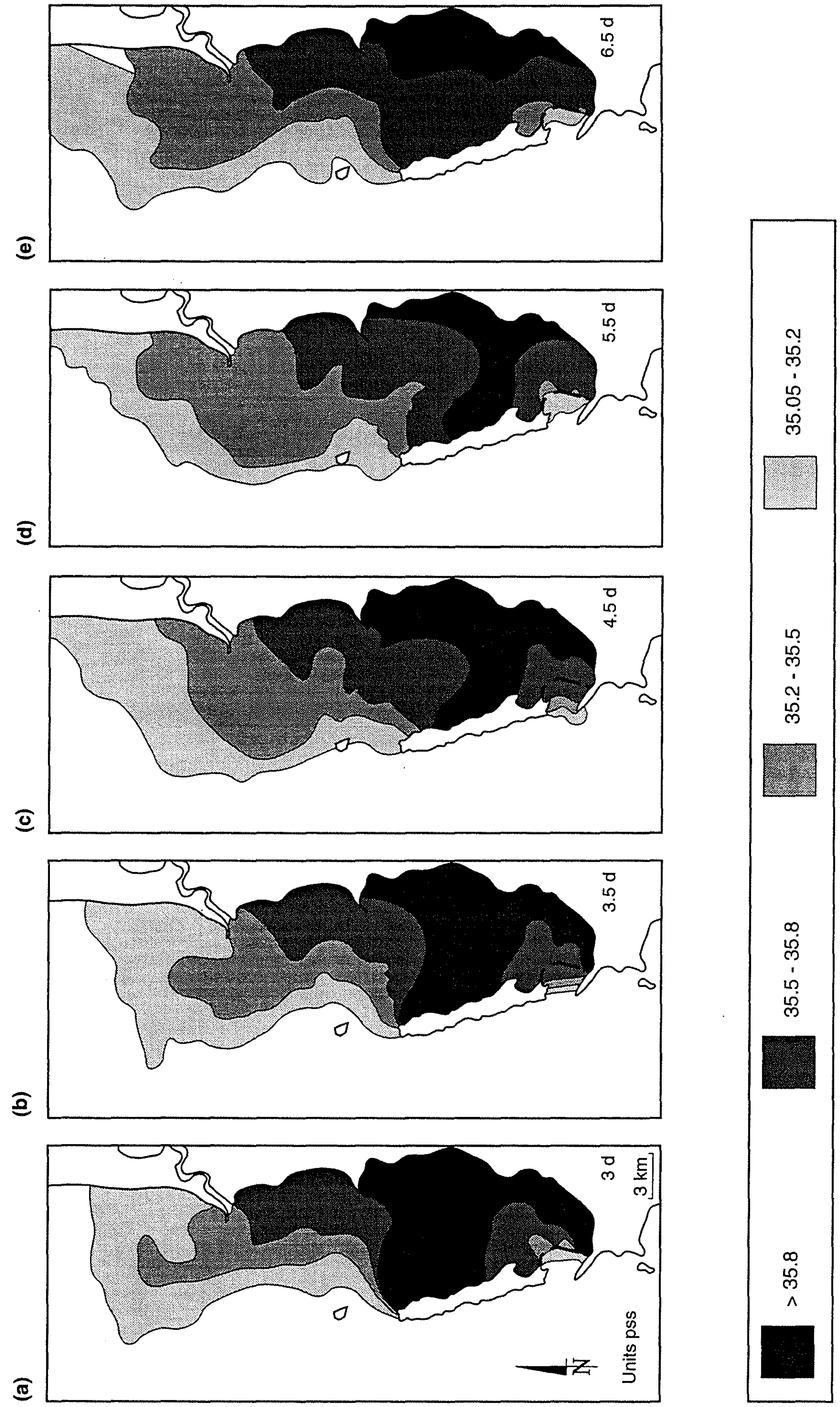

Figure 10. Modelled surface salinity fields (at 1.1 m depth) for five simulation times: (a) 3 d, (b) 3.5 d, (c) 4.5 d, (d) 5.5 d and (e) 6.5 d. The model was started with the salinity field in Figure 8, and driven by the winds in Figure 7, starting at 0000 hrs 29 April 1994.

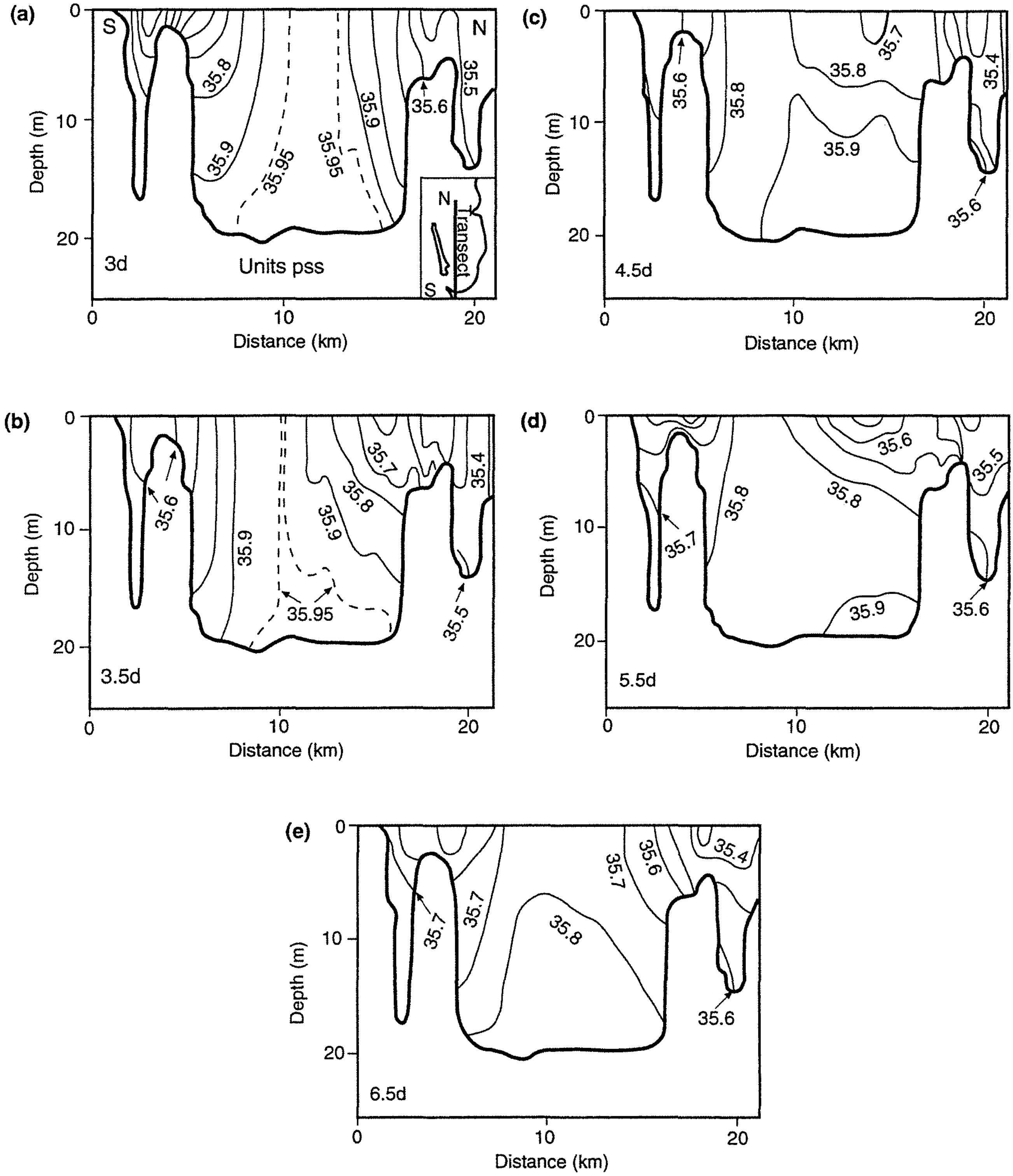

Figure 11. Modelled vertical salinity sections through Cockburn Sound and Owen Anchorage (see inset) for five simulation times: (a) 3 d, (b) 3.5 d, (c) 4.5 d, (d) 5.5 d and (e) 6.5 d. The model was started with the salinity field in Figure 8, and driven by the winds in Figure 7, starting at 0000 hrs 29 April 1994.

however this northern structure has little near-surface stratification because it is more steeply tilted.

Simulation time 3.5 days (1200 hrs 2 May 1994) - intermittent easterly wind

Following intermittent easterly winds (between sea-breezes) the surface currents (Figure 9b) show southward inflow (~ 0.2 m s^{-1}) across the northern opening of Cockburn Sound and outflow under the causeway bridges. Although not shown by the results presented here, the model predicted that there is sub-surface outflow through Challenger Passage and that deep basin flow is weak (~ 0.05 m s^{-1}).

The surface salinity distribution (Figure 10b) shows evidence of outflow through the causeway openings. Because of its higher density, this water sinks and mixes into Sepia Depression, rather than spreading across the surface. Buoyant surface water near the northern opening of Cockburn Sound is transported southward about 2-3 km further into the sound. The areas of highest salinity surface water in the sound are the eastern margin and the central basin. This indicates that these areas are the least flushed by shelf waters to this point in the simulation.

The south-north salinity section (Figure 11b) reflects the entry of less saline water across the northern opening of the sound. The density structure extends southward (note the changed location of the 35.8 pss contour) and vertical stratification increases. The northern and southern structures, initially separated by the length of Cockburn Sound, approach and abutt one another, and the only basin water ($S > 35.95$ pss) along this section still essentially uninfluenced by exchange between the sound and the shelf is below a depth of 15 m. Under easterly winds and inflow from the north, the southern structure becomes more vertical and there is a reduction in its near-surface vertical stratification.

Simulation time 4.5 days (1200 hrs 3 May 1994) - during prevailing easterly wind

Figures 9c, 10c and 11c represent the current and salinity fields 4.5 days after commencement of the simulation, which corresponds to midday on 3 May 1994, about which time the STD transect data shown in Figure 6c were collected. The sea-breeze on the preceding day was weak (< 5 m s^{-1}) and otherwise the winds were consistent easterlies for about 30 hours. Southward surface flow (~ 0.2 m s^{-1}) extends across the whole of the northern entrance to Cockburn Sound, from Woodman Point to the northern tip of Garden Island. Surface currents are mainly south over the whole area of Cockburn Sound, with largest speeds over the central deep basin of the sound. Southward flow also occurs in the vicinity of the Southern Flats and there is outflow under the causeway bridges. Although not shown, near-bottom outflow also occurs through Challenger Passage, and basin flow is to the north at greater depths (12 m and 18 m) within the northern half of the sound.

The surface salinity distribution (Figure 10c) shows further southward penetration of buoyant water into the sound (for example the 35.8 pss salinity contour has migrated a further 2-3 km in one day). Water from Cockburn Sound is expelled through the causeway bridge openings. The least flushed (highest salinity) surface waters in Cockburn Sound are over the eastern margin, the central basin, and a narrow near-shore region between Rockingham and James Point.

The south-north salinity section shown in Figure 11c emphasises the dominant near-surface transport of buoyant water into the sound across the northern opening, and the resultant southward extension of vertical stratification along the basin. By contrast, the southern structure remains more localised within a few kilometres of the Southern Flats. Along the vertical section, essentially unmixed basin water ($S > 35.95$ pss) can be found only below a depth of 15m.

The major features of the modelled sectional salinity structure (Figure 11c) correspond to the measured salinity structure for 3 May 1994 (Figure 6c). The combined velocity and salinity predictions of the model support the suggested interpretation of the field data in relation to circulation and exchange. Comparisons of the fine detail of model predictions and field observations are not appropriate, because the model was started from rest with a simplified salinity distribution (no vertical structure) 4.5 days previously.

Simulation time 5.5 days (1200 hrs 4 May 1994) - at the end of prevailing easterly wind

Figures 9d, 10d and 11d present the current and salinity fields at 5.5 days after commencement of the simulation. This corresponds to midday on 4 May 1994, about the time that the transect data shown in Figure 6d were collected. There had been no sea-breeze event on the previous day and winds remained east to northeast, except for the last hour or two before the time corresponding to this model output, when winds strengthened from the southwest. The modelled surface currents (Figure 9d) appear to have responded rapidly to this recent wind shift, as would be expected. However, the surface salinity distribution (Figure 10d) mainly reflects the preceding influence of the prolonged east and northeast winds. It shows further southward migration of the surface salinity structure into the sound (see for example the displacement of the 35.8 pss contour). Considerably lower salinity water has reached central Cockburn Sound, and the flushing of surface waters in Jervoise Bay has been somewhat enhanced. The highest salinity waters are again found over the eastern margin, central Cockburn Sound and in a thin near-shore strip extending from the CBH jetty to James Point, suggesting that these areas have not been greatly influenced by basin-shelf exchange processes. Comparison of the modelled and field data for 4 May 1994 again shows that the model has been able to reproduce the major features of the basin-scale structure.

Simulation time 6.5 days (0000 hrs 5 May 1994) - post sea-breeze

Figures 9e, 10e and 11e present the current and salinity fields after 6.5 days of the simulation, about one day after the onset of a predominantly southerly wind pattern with moderate sea-breezes, which marked the end of the preceding predominantly easterly wind event. Surface current features characteristic of south to southwesterly winds are again evident. Figure 9e shows strong northerly flow (~ 0.2 m s^{-1}) offshore of Garden Island, inflow through the causeway entrances, northerly flow on either side of Cockburn Sound (stronger on the western side), weaker currents over the central basin, and northeast flow through Challenger Passage.

The surface salinity distribution (Figure 10e) shows that, with the advent of southerly winds, there has been a fresh pulse of lower salinity, buoyant shelf water entering into southern Cockburn Sound through the causeway openings. Northward advection and vertical mixing have eliminated much of the horizontal surface salinity structure over the central and northern portions of the basin. Relatively dense water has been transported farther northward along the Owen Anchorage eastern margin and toward Fremantle. The highest surface salinities are still found over the eastern margin of Cockburn Sound, between James Point and Woodman Point, as well as in a thin nearshore zone between the CBH jetty to James Point, indicating that these are the least flushed near-surface areas under the conditions of the simulation.

The position of the 35.8 pss contour in the south-north salinity transect (Figure 11e) shows that the buoyant structure in southern Cockburn Sound has significantly extended northward. The onset of the southerly wind has caused downwelling and vertical mixing of the density structure at the northern end of the basin, reducing the vertical stratification in that area.

4.2.2 Flushing

For typical variable autumn winds

For the case when Cockburn Sound water is dense relative to the adjacent shelf water, and for typical autumn winds, this simulation has shown that horizontal exchange and moderate to weak vertical mixing processes are capable of developing widespread vertical stratification throughout the basin. After starting with more saline (dense) sound water and less saline (buoyant) shelf water, the model predicted that under typical autumn winds it takes about 3-4 days for the salinity of central surface waters of the basin to be influenced by exchange with the shelf water.

For the estimation of flushing characteristics, two control volumes were defined, comprising the near-surface waters of Cockburn Sound to 5 metres below mean sea level and the deep basin waters of the sound from 15m below mean sea level to the sea bed. Figure 12 shows the predicted rates of flushing for these separate depth zones, calculated on the basis of the replacement of the initial mass of salt in the respective control volumes with less saline water from outside of the sound. The near-surface zone of Cockburn Sound was flushed at a greater rate than the deep basin zone for this 'autumn' simulation. The difference in the modelled flushing rates of these zones appeared to be greatest from about day 2 to day 5 of the simulation, under prevailing moderate easterly wind conditions. After nine days, the near-surface zone was 34 % flushed and the deep basin zone was 25 % flushed. This result is consistent with the introduction of buoyant water into the sound as an upper layer, contributing to the vertical stratification, and inhibiting the vertical mixing and flushing of denser deep basin water.

It should be pointed out that the simulation did not incorporate the effects of surface heat flux and thermal stratification, which would most likely add further stability to the water column. Allowing for this, the Cockburn Sound basin may exhibit an even greater difference in its capability to flush surface and bottom waters during typical autumn conditions.

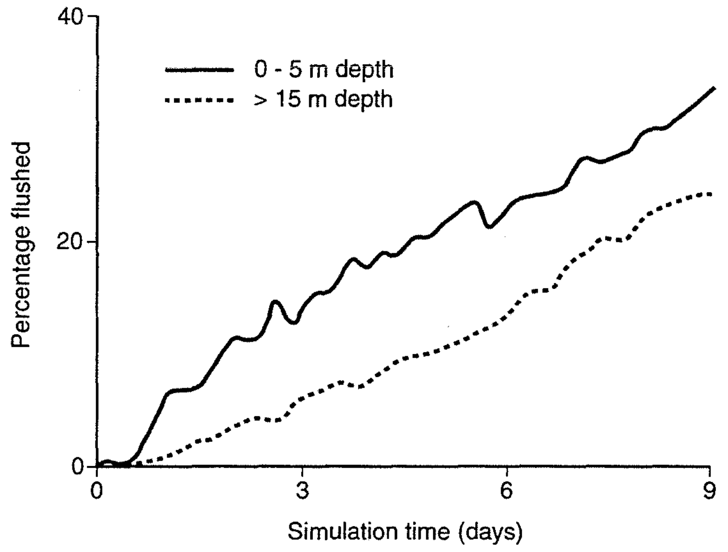

Figure 12. Modelled flushing rates of two control volumes in Cockburn Sound: surface to 5 m depth, and 15 m to the bottom. The model was started with the salinity field in Figure 8, and driven by the winds in Figure 7, starting at 0000 hrs 29 April 1994.

4.2.3 Exchange for prevailing easterly winds

In autumn, prevailing easterly winds last typically for 1-3 days, but on occasions 4-6 days of easterlies are experienced, and a further simulation was run to examine the vertical stratification resulting from such conditions. Figure 13 presents a south-north vertical section of salinity after a five day period of constant 5 m s^{-1} easterly winds, as a result of which the vertical stratification extends over the length of the main Cockburn Sound basin, with larger vertical salinity gradients located in the lower half of the water column.

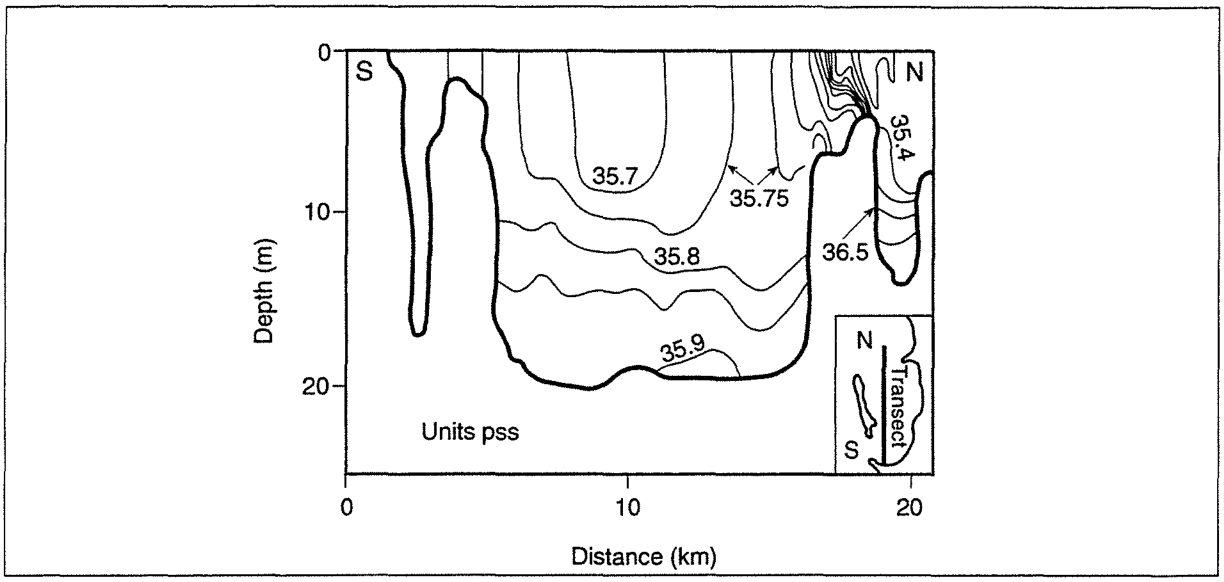

Figure 13. Modelled vertical salinity section through Cockburn Sound and Owen Anchorage (see inset) after a simulation which was forced with 5 days of constant easterly wind at 5 m s^{-1}.

Simulations of the wind-forced buoyant Swan River outflow, conducted by Mills and D'Adamo (1995b), can be used as a guide to determine which other wind directions are favourable to the migration of less dense external surface waters southward across the northern Cockburn Sound opening. The favourable wind directions for this to occur are east, northeast, north and northwest. The ability of westerly winds to drive external water southward into Cockburn Sound needs to be investigated by further modelling. Southwest, south and southeast wind directions will be favourable to the entry of external waters through the causeway openings.

4.2.4 Exchange under calm autumn conditions

Mills and D'Adamo (1995a) carried out a simulation of the hydrodynamic response of the initial salinity (density) field in the absence of wind forcing. They showed that the initial autumn density structure (shown in Figure 8) undergoes baroclinic adjustment, subject to rotational effects, resulting in the entry to the sound of buoyant shelf water. Results from this simulation are reproduced in Figure 14. Inflow from the north forms a buoyant plume attached to the mainland coast, while inflow through the causeway openings propagates northward as a buoyant plume attached to the Garden Island coast. The widths of these plumes are typically several kilometres, which scales with the internal Rossby radius of deformation. It has been shown that the volumetric exchange rates for the baroclinic adjustment simulation are about half those for the simulation with winds (as shown in Figure 7) acting on the same initial salinity structure.

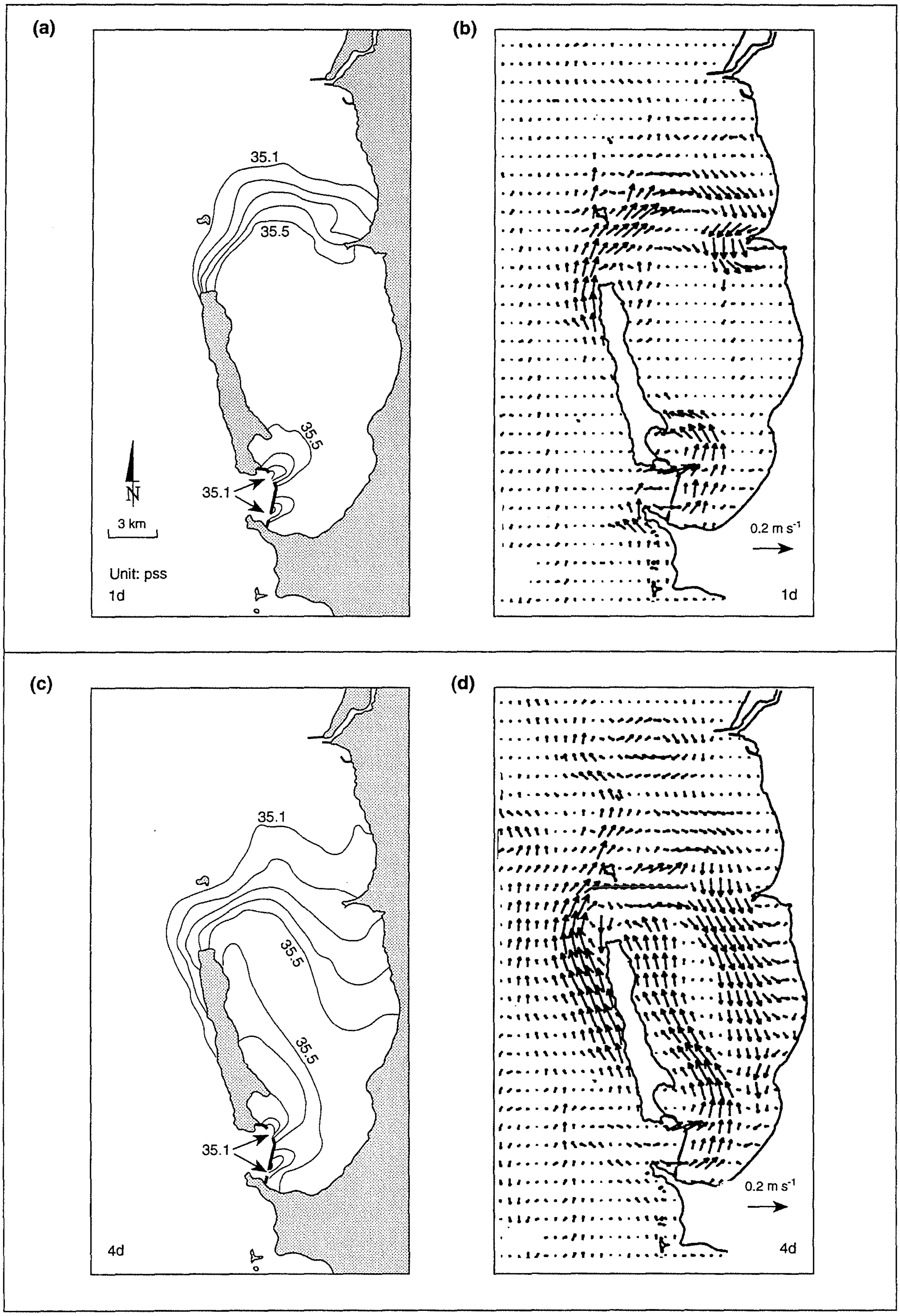

Figure 14. Modelled density-induced exchange between dense Cockburn Sound and buoyant shelf waters during calm autumn conditions showing surface salinity and velocity fields at 1 d (a and b) and 4 d (c and d). The model was started with the salinity field in Figure 8.

4.3 Vertical mixing calculations

Wind stress and penetrative convection are two main mechanisms that could cause vertical mixing. Analytical tools for the prediction of mixing by these mechanisms are reviewed in Imberger (1994). These predictive methodologies, as applicable for the stratified conditions of Cockburn Sound, are summarised below.

4.3.1 Wind-mixing

The vertical mixing due to wind stress can be estimated from a one-dimensional model of mixing which is based on a vertical integration of the turbulent kinetic energy (TKE) equations (Spigel, Imberger and Rayner, 1986; Pollard, Rhines and Thompson, 1973; Imberger and Patterson, 1990; Imberger, 1994). This method has also been applied by D'Adamo, Mills and Wilkinson (1995) for stratified winter conditions in Cockburn Sound.

It is assumed that sufficient time has passed since the start of the wind for the surface layer to have deepened, with shear at the base of the mixed layer being primarily responsible for entrainment. Following Imberger (1994) this time is calculated to be of order 10^3 seconds for the meteorological and stratification conditions typical of those encountered during the autumn surveys (Figures 5 and 6). For the case of a linearly stratified water column the deepening law, as developed by Imberger (1994), is

$$h = 0.5(C_S u_*^4/N^2)^{1/4} t^{1/2}, \qquad (1)$$

where N is the buoyancy frequency given by

$$N = [(g/\rho_w)(d\rho/dz)]^{1/2} \qquad (2)$$

and $d\rho/dz$ is the linear density gradient with z positive downwards, $C_S = 0.20$ is a constant that determines the efficiency of energy conversion (Imberger, 1994), t is the time since the onset of mixing, g is the acceleration due to gravity ($= 9.81$ m s^{-2}), ρ_w is the average water density and u_* is the wind shear velocity given by

$$u_* = [(C_D \rho_A/\rho_w)^{1/2}]U \qquad (3)$$

where C_D is a drag coefficient equal to 0.0013 (Fischer *et al.* 1979), ρ_A is the density of air equal to 1.2 kg m^{-3} and U is the wind speed at 10 m height. The above mixing law is for shear-dominated mixing due to locally parallel flow at the interface between the well-mixed upper layer and the stratified fluid below, and is assumed applicable for the various cases of autumn density stratification shown in Figure 6.

4.3.2 Penetrative convection

Penetrative convection (described, for example, by Fischer *et al.* (1979) and Imberger and Patterson (1990)) is the mixing process whereby cold water forms at the surface as a result of night-time heat loss from the water to the atmosphere and penetrates downwards, with this process gradually deepening the upper mixed layer (UML). A formula for the rate of UML deepening is presented in Imberger (1994), based on the same arguments as those for wind-mixing (Equation 1). For the linearly stratified case the UML depth is given by

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

where $C_F = 0.25$ and $C_E = 1.15$ are coefficients of energy conversion (Imberger, 1994), α is the thermal compressibility of water (= 1.5 x 10^{-4} °C^{-1}), H is the rate at which heat is lost from the water surface in W m^{-2}, and C_p is the specific heat of water (= 200 J kg^{-1} °C^{-1}). Imberger (1994), Spigel, Imberger and Rayner (1986), and Imberger and Patterson (1990) provide a detailed description of the derivation of the above mixing laws.

4.3.3 Competing effects of heat-flux and wind-mixing

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-Oboukhov 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

$$L = (u_*^3 \rho_w C_p C_N^3)/(g \alpha_v H_*) \qquad (5)$$

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).

4.3.4 Potential for destratification of the water column in Cockburn Sound during autumn

We begin by evaluating the value of L (Equation 5) for typical values of heat flux in autumn. Taking typical values of H_* to be in the range 300-500 W m^{-2}, and using Equation 5, the wind speed required to overcome the stabilising effects of such rates of surface heating is calculated to be about 7.5 to 10 m s^{-1}. This forcing would result in vertical mixing to a depth L greater than the depth of the basin (21 m).

An evaluation of the potential for wind-mixing and penetrative convection to mix through typical vertical density gradients in autumn is now performed. We consider a typical diurnal cycle as follows. During the day an initial vertical density stratification is assumed. A day-time wind event (such as an afternoon sea-breeze) then mixes the water column vertically and deepens the upper mixed layer, but with the maximum depth of the UML dependent on the competing effect of the incoming heat flux, as indicated by L. Thereafter, at night, heat losses cause the UML to further deepen by penetrative convection.

The cross-shelf density difference data from Figure 3 and the vertical stratification contours in Figure 6 have been considered together to arrive at two values of N (Equation 2) that are considered to be representative of strong and weak stratification. The first case, for strongly stratified conditions, is derived from Figure 3 and considers the characteristic density differences between the basin and adjacent shelf waters during the autumn periods of the seasonal surveys. If it is assumed that shelf water could enter the sound with minimal mixing, then a potential density difference between incoming buoyant surface waters and resident inner basin water is about 0.5 kg m^{-3} and this could result in $N = 1.5 \times 10^{-2}$ s^{-1}. The second case is for a relatively weak stratification, as was measured on 26 May 1994 (Figure 6b), where the vertical density difference was about 0.1 kg m^{-3} which leads to an approximate value of $N = 7 \times 10^{-3}$ s^{-1}.

For the penetrative convection calculations (Equation 4) a range of heat loss rates from 100 to 500 W m^{-2} are used. The wind mixing calculations (Equation 1) are based on a range of wind speeds from 2.5 to 15 m s^{-1}.

We investigate the potential role of penetrative convection in vertically mixing typical states of vertical density stratification in autumn. On the basis of heat loss rates of 100-500 W m^{-2}, and by application of Equation 4, a series of deepening curves has been constructed and presented in Figures 15 a and b, for the strong and weak cases of stratification, respectively. The results in Figure 15 suggest that for a heat loss of say 300 W m^{-2} a full night of surface cooling would lead to between about 4 and 8 m of mixing by penetrative convection, depending on the initial stratification.

Predictions of deepening of the UML by wind-mixing acting alone are presented in Figures 16 a and b, for the strong and weak cases of stratification, respectively. For a moderate value of stratification (between N=0.015 and 0.007 s^{-1}) it is predicted that a wind speed of 7.5-10 m s^{-1} requires about 8-13 hours to mix to approximately 15 m depth. This UML depth could then be further deepened to the bottom by penetrative convection at night by typical rates of heat loss (H ~ 300 W m^{-2}).

Different values of N will require different combinations of wind speed and penetrative convection to mix the structure to the bottom, and the curves in Figures 15 and 16 can be used to evaluate other cases. However, in summary, if we consider a moderate rate of initial stratification (N ~ 0.01 s^{-1}), and typical short-wave radiation rates and night-time heat loss rates as described above, the application of Equations 1 to 5 suggests that wind events of 7.5-10 m s^{-1} of duration 8-13 hours followed by night-time heat losses of 300 W m^{-2} would mix the water column during typically stratified autumn conditions. We now look to the wind and heat flux observations to check how often this sequence of complete mixing occurs.

Wind velocity data collected at Naval Base (Figure 1) by the Department of Environmental Protection during the autumns of 1993 and 1994 (between the last mixing event prior to 1 April and the first after 31 May) were examined to determine the occurrence of wind events defined as 7.5-10 m s^{-1} for periods greater than 8-13 hours. On the basis of the above predictive calculations these wind events would have mixed the water column sufficiently to allow typical rates of penetrative convection to then complete the mixing to the bottom. The results are presented in Table 1. A total of 9-12 events per analysis period (or about 4 to 5 events per month) would have led to a fully-mixed water column, and the average period between these events ranged from 5.5 to 8.6 days. An important result in Table 1 is that relatively long periods (up to 24 days) of weak winds occurred with wind speeds being less than those predicted to be necessary for full-depth mixing. Unpublished data supplied by WNI Science and Engineering (Steve Buchan, personal communication), and collected at Fremantle (at 50 m height) during the months of April and May of every year from 1983 to 1992, show that wind events defined as having speeds greater than 7.5 m s^{-1} and durations greater than 10 hours occurred on average 3.7 times per month in autumn.

The above analysis, based on 1993 and 1994 wind data, suggests that extended periods (up to 24 days) can occur when typical strength vertical density stratification is not eliminated by the action of vertical mixing by wind-stress and penetrative convection. The analysis used an assumed average initial stratification condition and therefore, for stronger density stratification the potential for extended periods of less than full-depth mixing may be even greater. This analysis supports the conclusion that strong winds capable of leading to fully-mixed conditions in Cockburn Sound occur relatively infrequently during autumn.

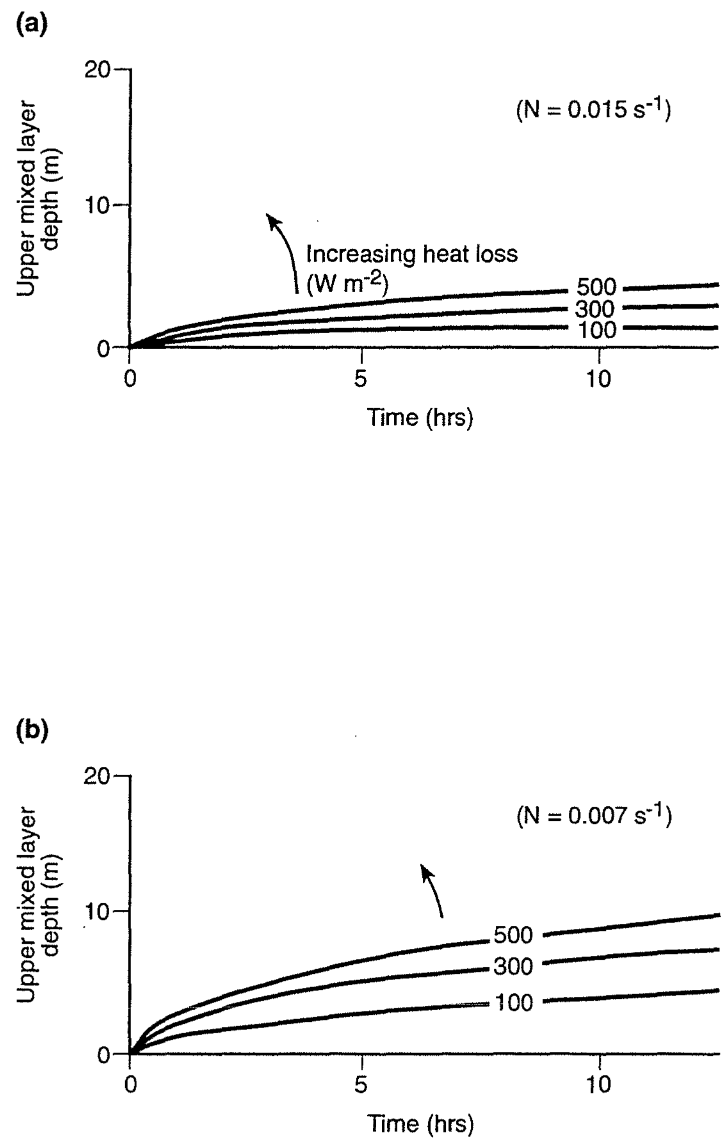

Figure 15. Predicted deepening of the upper mixed layer caused by penetrative convection assuming two cases of initial linear density stratification ((a) strong and (b) weak, for typical autumn conditions) and applying a typical range of heat loss rates to each case.

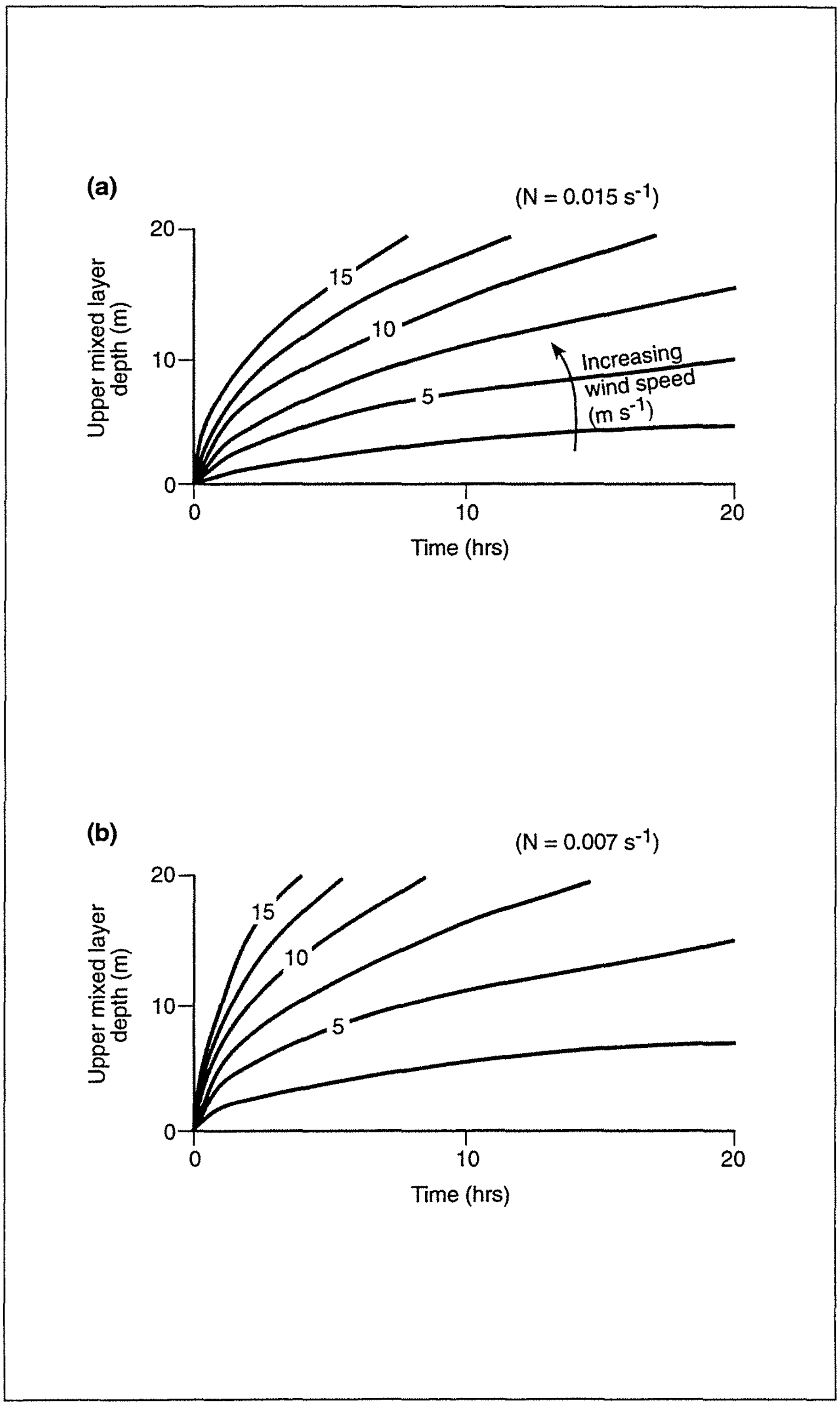

Figure 16. Predicted deepening of the upper mixed layer due to wind-mixing assuming two cases of initial linear density stratification ((a) strong and (b) weak, for typical autumn conditions) and applying a typical range of wind speeds to each case.

Table 1 Wind characteristics predicted to fully mix the water column in central Cockburn Sound for the autumn periods of 1993 and 1994, based on wind data from Naval Base (12 m).

Year and data period	Sample length (days)	Number of events capable of full-depth mixing (considering complementary penetrative convection)	Average period between events (days)	Range of periods between events (days)
1993 31/3-15/6	77	9	8.6	0.8-24.2
1994 30/3-8/6	70	12	5.5	0.7-20.1

5. Discussion

A characteristic density difference between Cockburn Sound and the adjacent shelf was identified in autumn. The differential effects of evaporation raise the salinity within the nearshore zone. Furthermore, during this time of the year differential cooling results in temperatures being lower in nearshore than in offshore waters. The incursion of warm water from the Leeuwin Current onto the mid shelf, north and south of Rottnest Island and west of Garden Island, further enhances the basin-shelf temperature difference. Due to these factors, the density of Cockburn Sound water is greater than shelf water in autumn. Field measurements of STD structure and three-dimensional baroclinic modelling of exchange under typical autumn wind and stratification conditions have been employed to investigate the dynamical role of this density difference.

The mixing analysis of a number of cases of vertically stratified conditions within the basin has indicated that flushing of basin water in Cockburn Sound during autumn is strongly influenced by vertical mixing events, due to both wind and overnight cooling. Typically the combination (rather than just one of these mechanisms in isolation) is required for this mixing to reach the bottom, and this happens relatively infrequently. The results suggest that prolonged periods of vertical stratification of density is a characteristic of the basin structure during the autumn months of April and May.

For typical stratification conditions in Cockburn Sound, a simple mixing analysis showed that full-depth mixing is only predicted to occur when winds, greater than 7.5-10 m s^{-1} for 8-13 hours or more, are followed by typical rates of night-time cooling ($H \sim 300$ W m^{-2}) and associated penetrative convection. The mixing analysis suggested that during April-May there are an average of about 4-5 times per month when this full-depth mixing criterion is satisfied, and that the time between instances of full-depth mixing ranges from about 1 to 24 days. It is suggested that water near the bottom of Cockburn Sound could be subjected to extended periods of poor or negligible vertical mixing at depth before being vertically mixed and eventually flushed across the shallow sills bounding the basin. Long-term monitoring of the stratification climate would be required to further resolve this.

Sediment oxygen demand data and near-bottom oxygen concentration measurements (Masini 1994a and b) suggest that oxygen depletion, and possibly sediment anoxia, can occur in the bottom waters of the deep Cockburn Sound basin in autumn. Our results, indicate that long periods (up to about 24 days) can pass between full-depth mixing events in Cockburn Sound. Hence, it is recommended that detailed field studies be conducted to investigate the relationships between vertical stability of the density structure, the oxygen dynamics of bottom waters and the rates and pathways of nitrogen efflux from the sediments.

Another important factor to consider is the horizontal dynamics and exchange after a strong mixing event. If a period of mixing results in a fully-mixed water column in Cockburn Sound then, because the adjacent shelf waters are characteristically buoyant, it can be expected that subsequent exchange will result in the entry of buoyant shelf water into the basin as surface flows. Because the basin water is relatively dense it can be expected that a relatively slower rate of horizontal exchange would occur below the level of the sills. The role of the intermittent full-depth mixing events is to vertically mix the water column, thereby providing a method to bring some proportion of bottom water into the surface zone, where it can then be driven out of the basin by exchange processes. This would appear to be the principal mechanism for deep-water renewal to occur in this basin during the autumn regime.

The three-dimensional baroclinic Princeton Ocean Model was used to simulate the dynamics of the study area under autumn conditions, starting with a characteristic basin-shelf salinity (density) difference. The simulation utilised real wind data for a 4-5 day period leading up to measurements of the STD structure of 3-4 May 1994. The model results showed the variable dynamic response to preceding wind conditions, including sea-breezes and easterlies, after which it was able to reproduce essential features of the measured basin-scale structure.

The results of this study have important implications for the choice and application of numerical hydrodynamic models for Cockburn Sound and adjacent waters during the autumn regime. The results suggest that baroclinic models are the most appropriate, with the ability to include the hydrodynamic influence of heat fluxes, wind-mixing, and the effect of vertical and horizontal density gradients in opposing vertical mixing and in facilitating horizontal exchange.

6. References

Blumberg A F and Mellor G (1987). A description of a three-dimensional coastal ocean circulation model. In: 'Three-dimensional coastal ocean models. Coastal and Estuarine Sciences' Vol. 4 (ed. N S Heaps). American Geophysical Union, Washington, DC: 1-16.

Breckling J (1989). The analysis of Directional Time Series: Applications to Wind Speed and Direction. In: Lecture Notes in Statistics 61. (eds. J Berger, S Fienberg, J Gani, I Olkin and B Singer). Springer-Verlag.

Cary J L, Simpson C J and Chase S (1991). Water quality in Cockburn Sound: results of the 1989/90 summer monitoring programme. (Environmental Protection Authority, Perth, Western Australia, 6000). Technical Series No. 47. Pp. 14.

Commonwealth of Australia (1989). Western Australian Year Book. No. 26 - 1989. Australian Bureau of Statistics, Western Australian Office.

Cresswell G R (1991). The Leeuwin Current - observations and recent models. In proceedings - The Leeuwin Current: an influence on the coastal climate and marine life of Western Australia. Journal of the Royal Society of Western Australia. 74:1-14.

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

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 nearshore embayment and mid-shelf waters. (Department of Environmental Protection, Perth, Western Australia, 6000). Technical Series No. 69.

D'Adamo N and Mills D A (1995b). 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. (Department of Environmental Protection, Perth, Western Australia., 6000). Technical Series 67.

D'Adamo N, Cary J L and Mills D A (1995). 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. (Department of Environmental Protection of Western Australia, Perth, Western Australia, 6000). Technical Series No. 66.

D'Adamo N, Mills D A and Wilkinson D L (1995). Winter mixing and transport in the stratified coastal embayment of Cockburn Sound, Western Australia. (Department of Environmental Protection, Perth, Western Australia, 6000). Technical Series No. 70.

Department of Conservation and Environment (1979). The Cockburn Sound Environmental Study (1976-1979). (Department of Conservation and Environment, Perth, Western Australia, 6000). Report No. 2. Pp. 102.

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.

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.

Helleren S K R and John J (1996). Phytoplankton and zooplankton and their interactions in the southern metropolitan coastal waters off Perth, Western Australia. School of Environmental Biology, Curtin University of Technology, Perth, Western Australia, 6000.

Herzfeld M (1995). User's guide for the Blumberg-Mellor 3-D numerical ocean model, C version. Flinders Institute for Atmospheric and Marine Sciences, Flinders University of South Australia, Computing Report No 15, Pp. 48.

Imberger J (1994). Transport processes in lakes: A review. Limnology Now: A Paradigm of Planetary Problems. R. Margalef (editor). Elsevier Science B. V.

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

Maritime Works Branch (1977). Western Australia Naval Support Facility. Water movements Cockburn Sound. (Maritime Works Branch, Australian Department of Construction, Perth, Western Australia, 6000). Report MW77.

Masini R J (1994a). Dissolved oxygen concentrations in Cockburn Sound during April and May 1994. (unpublished data report No. SMCWS ECOL-14). Department of Environmental Protection, Perth, Western Australia, 6000.

Masini R J (1994b). Oxygen demand and production rates of marine sediments off Perth, Western Australia during November-December 1993. (unpublished data report No. SMCWS ECOL8). Department of Environmental Protection, Perth, Western Australia, 6000.

Masini R J and van Senden D C (1995). Development, parameterisation and calibration of a nutrient effects benthic ecology model. (Department of Environmental Protection, Perth, Western Australia, 6000). Technical Series 75.

Mellor G L (1992). User's guide for a three-dimensional, primitive equation, numerical ocean model. Unpublished report. Pp. 34.

Mellor G L and Yamada T (1982). Development of a turbulence closure model for geophysical fluid problems. Rev. Geophys. Space Phys., 20, No 4, Pp. 851-875.

Mills D A and D'Adamo N (1995a). The application of a three-dimensional baroclinic model to the hydrodynamics and transport of Cockburn Sound, Western Australia, and surrounding waters. (Department of Environmental Protection, Perth, Western Australia,, 6000). Technical Series 76.

Mills D A and D'Adamo N (1995b). The application of a three-dimensional baroclinic model to the hydrodynamics and transport of coastal waters between Fremantle and Mandurah: the inter-connectedness of the coastal zone. (Department of Environmental Protection, Perth, Western Australia,, 6000). Technical Series 77.

Mills D A, D'Adamo N, Pearce A F and Wylie A (1994). Long-shelf and cross-shelf transport processes off Perth, Western Australia: the influence of wind, differential cooling and the Leeuwin Current. (Department of Environmental Protection, Perth, Western Australia, 6000). Technical Series 58. Pp. 19.

Mills D A, D'Adamo N, Pearce A F and Wyllie A (1996). The response of stratified shelf waters to the Leeuwin Current and wind forcing: winter observations off Perth, Western Australia.. In 'Mixing in Estuaries and Coastal Seas' (ed. C Pattiaratchi). Coastal and Estuarine Studies series, 50, American Geophysical Union, Washington DC: 5-28.

Mills D A and Essers V (1995). User manual for a 3D baroclinic hydrodynamic model adapted from the Princeton Ocean Model. Data Report SMCWS_HYDRO-14.

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: Physical Measurements. Project P2. Unpublished report to the Water Authority of Western Australia. (Water Authority of Western Australia, Leederville, Western Australia, 6007).

Pearce A F (1991). Eastern boundary currents of the southern hemisphere. In proceedings - The Leeuwin Current: an influence on the coastal climate and marine life of Western Australia. Journal of the Royal Society of Western Australia. 74:35-45.

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.

Simpson J H and Rippeth T P (1993). The Clyde Sea: a Model of the Seasonal Cycle of Stratification and Mixing. Estuarine, Coastal and Shelf Science, 37:129-144.

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.

Spigel R H, Imberger J and Rayner K N (1986). Modelling 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.

Vollmer M K (1991). Sharpening and matching response signals for finescale sensors. Centre for Water Research, University of Western Australia, Nedlands, Western Australia, 6009. CWR Reference WP 630 MV.