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Hydrodynamics and recommendations for further studies in Cockburn Sound and adjacent waters

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Summary

This report reviews past studies of the hydrodynamics of Cockburn Sound and adjacent waters and complements related studies by Hearn (1991) and Mills (in prep.). Data were drawn from reports and archives dating back to 1969. The relative importance of barotropic and baroclinic mechanisms has been investigated and the results have been used to assist in planning the oceanographic program (1991-1994) of the Southern Metropolitan Coastal Waters Study (SMCWS), being conducted by the Environmental Protection Authority of Western Australia (WAEPA) . The overall study site comprises the region from Fremantle to Warnbro Sound and out to the 40 m contour approximately 30 km offshore. In the analyses greatest emphasis focusses on the nearshore basins of Cockburn Sound, Owen Anchorage, Sepia Depression and Warnbro Sound.

Pollutant sources can be introduced at various levels of the water column, and the internal biological and chemical cycling of mass in the coastal waters will be strongly influenced by vertical and horizontal mixing rates, light attenuation, horizontal advection, surface and bottom boundary fluxes, and general circulation patterns. An understanding of the stratification is important because this feature of the water structure can have a controlling influence on the characteristics of these hydrodynamic properties.

Wind stress is the most significant forcing that drives currents at the surface but vertical density stratification will influence the nature in which wind transports mass horizontally and vertically within and between basins. Vertical stratification will confine direct wind-driven advection to the upper mixed layer, until such time that this layer deepens to the bottom. Adjustment flows in the lower layer will occur, but their characteristics will be influenced by the vertical stratification and the bathymetry. The influence of winds on the hydrodynamics will depend on their strengths and duration and on their ability to overcome the potential energy inherent in an initially stratified water column.

A first order mixing analysis was performed and indicates that vertical mixing in the 15-20 m deep basins is unlikely to penetrate through typical density gradients, or to the bottom sediments, unless winds climb above 5-10 m s^{-1} for sustained periods (greater than about 5 hours). The strongest vertical salinity and density gradients occur in winter and early spring due to freshwater inputs from the Swan River, and vertical stratification is most resistant to wind mixing during that period. Summer stratification is weaker relative to that which occurs in winter, and typical strength winds (such as sea-breezes) appear to be more effective in mixing the water column vertically. The data reviewed suggest that typical sea-breezes (from the south-southwest) and winter storms (predominantly from the north and west quadrants) are able to fully mix the water column. In between individual wind events however, vertical stratification is likely to be established by solar heating, evaporation, and freshwater buoyancy sources, and be resistant to complete mixing to the bottom. Further field work is required to detail more accurately the spatial and temporal characteristics of wind mixing through vertical density gradients during the year.

The nearshore waters are characteristically more saline and warmer than offshore waters in summer, and the reverse is true for winter. These gradients undergo reversal during the spring and autumn periods. Evaporation, differential heating and cooling, buoyancy inputs from river discharge such as from the Swan River, and the intrinsic relative differences in the densities of regional currents with respect to nearshore waters, all help to set up vertical and horizontal salinity, temperature and density gradients in the southern metropolitan waters. Hearn (1991) suggested that the typically occurring onshore-offshore density gradients could drive offshore baroclinic flows, that are rotated counterclockwise by the force due to the earth's rotation, thus producing longshore advection. But this mechanism requires further modelling and field investigation.

Apart from within bathymetrically constricted regions, tides are likely to have only a weak influence on transport and mixing in the region. Sea and swell waves, and low frequency oscillations of coastal water level associated with coastally trapped waves and meso-scale pressure variations are likely to be important in their effect on longshore coastal transport. However, the quantitative characteristics of such motions are yet to be fully explored for this coastal region.

Because it appears that stratification is a characteristic of the structure of Cockburn Sound and adjacent waters for an average of probably 50 percent of the time or more, and from the point of view of predicting the hydrodynamic behaviour of the individual basins and lagoons and of the entire region of the southern metropolitan waters, it appears that analytical or numerical models will need to address transport due to both baroclinic and barotropic hydrodynamic processes in order to adequately represent the governing mean-scale mixing and circulation patterns. Field measurements are required in order to compile a relevant set of sufficiently temporally and spatially resolute data from which dominant baroclinic and barotropic processes can be identified and quantified, and in turn be used to develop and calibrate appropriate numerical hydrodynamic models.

A field study addressing the issues raised in this and other recent reviews has now been initiated by the Environmental Protection Authority of Western Australia.

1. Introduction

1.1 Water quality

The most comprehensive synthesis of past studies of the ecological characteristics and water quality of Cockburn Sound and Owen Anchorage was the Cockburn Sound Environmental Study, (DCE, 1979). That study spanned over four years from 1976 to 1979. It drew together a wide range of information from a multi-disciplinary field and had the following principle objectives (DCE, 1979):

i Monitoring of industrial discharges;

ii assessment of the causes of the death of seagrass;

iii assessment of the causes and possible cures for the algal blooms which can and do degrade the Rockingham swimming domains;

iv analysis of the social and recreational issues of the Sound and its tourist and recreational value;

v assessment of the fisheries production and potential for professional and amateur fishermen;

vi appraisal of water movements to re-assess flushing of effluents and to provide alternative options to treatment on land by discharge of effluents into well-flushed areas; and

vii beach movement studies to assess the role of seagrass naturally or the need for artificial devices to control beach erosion.

The Cockburn Sound Environmental Study (CSES) concluded that nutrient loadings up to the time of the study had led to excessive growths of phytoplankton, particularly along the eastern edge of the Sound. This led to increased turbidity of the water and affected the seagrasses adversely by increasing direct shading and promoting epiphytic algal growth on seagrass leaves. Excessive growth of epiphytes on the seagrass leaves leads to stress on the plants by smothering and shading effects. This was cited as the main cause of the wide-spread dieback of the seagrass meadows in Cockburn Sound and over Parmelia Bank.

This general type of ecological degradation is now seen as the major threat to a sustained acceptable environmental quality of Perth's metropolitan waters (EPA, 1991; Pearce, 1990)). The threat can be described as a decline in the ecological viability of coastal ecosystems due to shading of benthic flora by excessive phytoplankton or macroalgal growth stimulated by excessive loadings of nutrients (nitrogen and phosphorus compounds) derived from urban (such as wastewater outfalls and septic tank leachates in groundwater), industrial (outfalls) and non-specific sources (such as river runoff and aerial inputs). The important role that the benthic floral communities have in driving the food chain is therefore accorded paramount importance from the point of view of sustaining marine ecosystems of the Perth metropolitan coastal zone (EPA, 1991).

In the CSES the contamination of the groundwater and the fish and shellfish also resulted in great concern for the health of people who utilised such resources.

From an aesthetic point of view both nutrient induced algal growth and discolouration of the water by industrial discharges were major causes for concern for the recreational areas of the waters of Cockburn Sound and Owen Anchorage.

From about 1955 to the time of the CSES, total nitrogen inputs by industry into Cockburn Sound progressively rose to about 5000 kg d^{-1}. It was established by the CSES that regional seagrass loss occurred at a time when total nitrogen loadings into the Sound were about 2000 kg d^{-1} and nuisance algal blooms were first recorded when total nitrogen loadings had reached about 4000 kg d^{-1}. Figure 1.1, reproduced from DCE (1979), illustrates the temporal correlation between nitrogen loading and water quality deterioration for Cockburn Sound from 1955 to 1979. Since that time nitrogen loadings have been progressively reduced by industry to levels of approximately 1500 kg d^{-1} in 1990 and now even further to between 200-500 kg d^{-1}. This has led to an overall improvement of water quality in the Sound but not to the complete elimination of algal blooms. Expansive algal blooms were recorded in Mangles Bay in late autumn during 1988 and 1989, and unacceptable high levels of chlorophyll **a** are

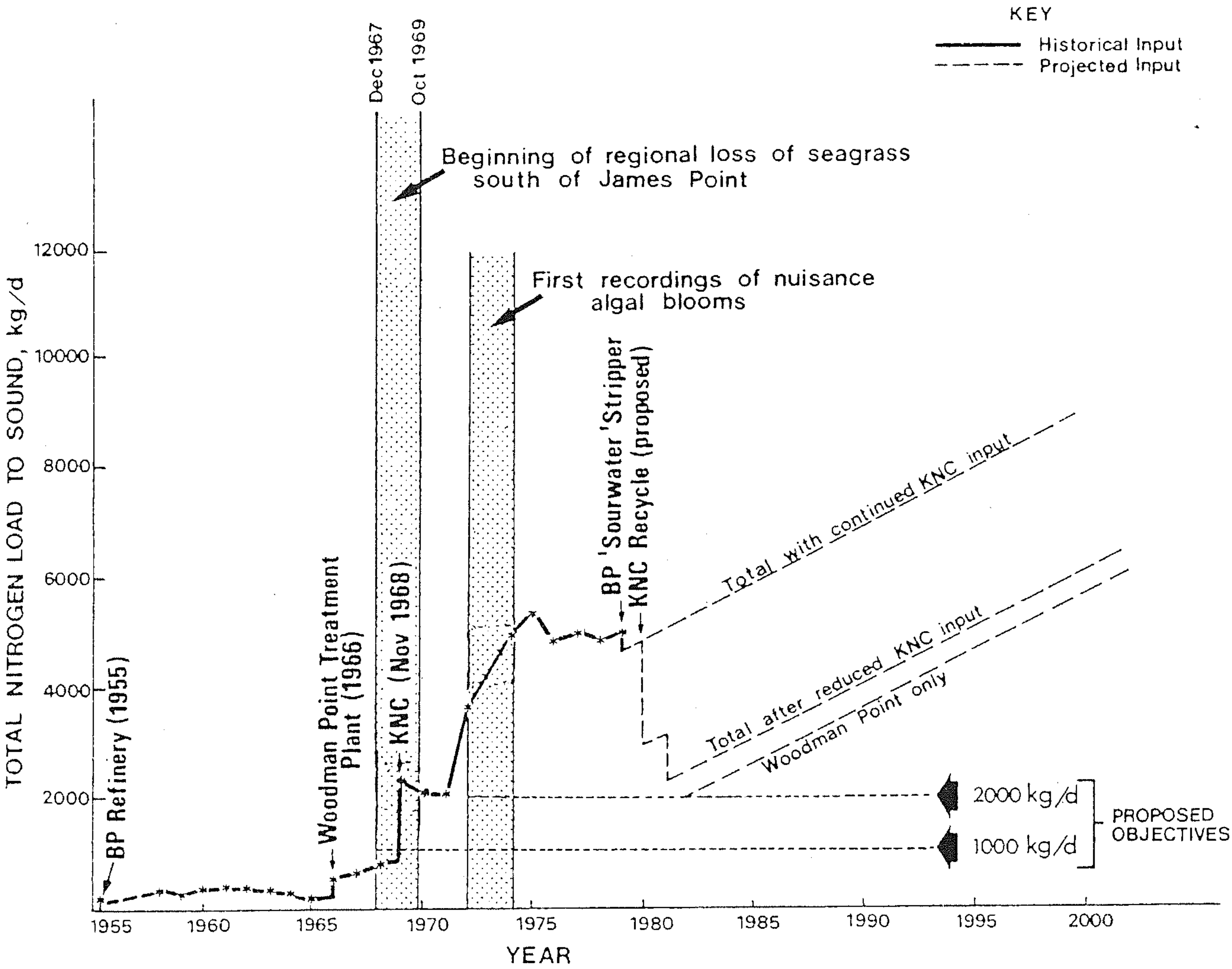


Figure 1.1 Historical and projected nitrogen loading into Cockburn Sound as at 1979 and accompanying information on sea-grass dieback and algal bloom formation (from DCE, 1979).

still found in Cockburn Sound (Cary et al, 1991). For example, a recent a field survey during the summer of 1989/1990 (December 1989 to February 1990) of water quality in Cockburn Sound (Cary et al, 1991) has shown that chlorophyll "a" levels, which were high in the late 1970's and then fell in the mid-1980's as a result of pollutant reductions motivated by the recommendations of the CSES, have again reached levels as high as 13 $\mu g\ l^{-1}$.

It is now thought that Cockburn Sound is placed in a delicate state of ecological balance, with regards to nutrient loadings, phytoplankton productivity and stress on seagrasses. The question of the present state of health of flora and fauna in the Sound and of the Sound's assimilative capacity to both present levels and potential increases in pollutant loads must now be addressed. In addition, the desire to avoid ecological degradation, of the type that Cockburn Sound suffers, in other coastal embayments necessitates that similar questions be also addressed in studies aimed at determining the capacity of these other waters to accept continued and increasing levels of nutrient loadings.

1.2 Mixing and transport

Critical factors in any understanding of the assimilative capacities of the coastal basins of the southern metropolitan coastal waters to continued pollutant loadings are their vertical mixing and internal circulation characteristics, and their exchange patterns with open waters. The flushing characteristics of individual basins must be understood. It is necessary to quantify the likely transport and dispersion of effluent discharges, drainage and river discharges, groundwater inputs and other point or diffuse sources of pollution. Further, the efficiency of mixing and replacement of nearshore waters by the exchange processes must also be quantified.

Since 1969 a number of major fundamental studies have addressed the need to understand, in detail, the hydrodynamic characteristics of Cockburn Sound and surrounding waters. These studies are reviewed in this report.

More recently, Hearn (1991) has undertaken a review for the EPA of past studies on the hydrodynamics of the Perth metropolitan coastal zone from Yanchep to Mandurah and out to the continental shelf. The present report complements that review and much of the historical data and information gathered to produce the present analysis was also incorporated by Hearn (1991). This report concerns itself primarily with the nearshore hydrodynamic processes and addresses a fundamental question of the relative importance of barotropic as compared to baroclinic hydrodynamic mechanisms to vertical and horizontal mass transport within nearshore basins of the southern metropolitan coastline and on exchange between them and the offshore waters.

This issue is intrinsic to the choice of an appropriate numerical model, or suite of models, for the prediction of hydrodynamic characteristics as they relate to management of the ecology. In the past, modelling efforts for the hydrodynamics of Cockburn Sound and surrounding waters have assumed that circulation is governed by barotropic processes. However, as will be shown in this report, past field surveys of the basin-scale three-dimensional salinity, temperature and density structure of Cockburn Sound and Owen Anchorage, conducted prior to the past modelling exercises, returned evidence that relatively strong vertical and horizontal stratification occurred in these basins for prolonged periods throughout the year, especially when winds were relatively weak or when the Swan River flowed relatively strongly.

This report attempts to determine areas in the understanding of the hydrodynamics of the nearshore basins that still need to be addressed in order to resolve important issues regarding their assimilative capacities to continued and increased nutrient loadings. A method is outlined of a scheme to make a first order estimation of the wind velocity required to fully mix a typically stratified water column, thereby yielding a critical wind speed for transition from baroclinic to barotropic hydrodynamic behaviour. Where it is obvious that further information, in the form of field surveys, are still required to resolve outstanding questions related to the hydrodynamics, then recommendations for such are given.

Chapter 2 describes the topography and bathymetry of the southern metropolitan waters.

Chapter 3 contains an overview of past studies of the hydrodynamics of the study region.

Hydrodynamic analyses of mixing and transport, based on existing data, are conducted for Cockburn Sound in Chapter 4, Owen Anchorage in Chapter 5, and the combined area of Warnbro Sound and Sepia Depression in Chapter 6.

The mixing and transport properties of these individual basins are compared in Chapter 7.

Conclusions and recommendations are presented in Chapters 8 and 9, respectively.

Supportive data and analytical developments are presented in Appendices A1 to A8.

2. Topography and bathymetry

Overall study site

The general study region extends from Fremantle down to Becher Point and out to west of Five Fathom Bank, which is aligned approximately parallel to the Western Australian mainland. Figure 2.1 presents the major topographical and bathymetric characteristics.

Five Fathom Bank and Sepia Depression

Five Fathom Bank is approximately 15 km offshore from Fremantle and this distance gradually decreases to approximately 10 km offshore from the central Warnbro Sound shoreline. Parallel and to the east is a reef line which forms the eastward boundary of Sepia Depression, a natural channel approximately 5 km wide and 20 m deep.

The reef line runs roughly parallel to the mainland shore between Five Fathom Bank and the mainland through the entire study region. The reef varies in depth with a maximum of approximately 10 m. Rocky islands (such as Carnac Island, Penguin Island and the Sisters) and deeper gaps and channels (such as the Carnac-Garden Island gap and Coasters Channel west of Warnbro Sound) occur along its extent. Generally, this reef structure is sufficiently shallow to act as a physical barrier to the full force of oceanic swells and as a consequence the inshore basins (Owen Anchorage, Cockburn Sound and Warnbro Sound) have a milder wave and swell climate than the offshore waters.

Owen Anchorage and surrounding features

Owen Anchorage lies between Cockburn Sound and Gage Roads, off Fremantle. It has a central basin region and is bordered to the north by Success bank (2-5 m in depth), to the south by Parmelia Bank (2-5 m in depth), to the west by the reef system and to the east by the main coast line. The inner basin region of Owen Anchorage has a depth range of 10-20 m and an area of approximately 9 square km.

The relatively shallow Parmelia Bank extends from the Woodman Point headland and groin on the east to Carnac Island on the west. Parmelia Bank has a depth range of about 2 to 5 m and is extensively covered in seagrass meadows. Challanger Passage lies in the gap between Carnac Island and northern Garden Island. This gap has a minimum depth of about 5 m, and serves as an important hydraulic connection through which Cockburn Sound and the Ocean communicate via the northern opening. A 15 m deep shipping channel cuts through Parmelia and Success Banks connecting Cockburn Sound hydraulically to the northern oceanic waters of Gage Roads. A shorter shipping channel cutting through Success Bank runs parallel and to the east of the major channel.

Garden Island

Garden Island forms a major physical barrier between the open ocean and the mainland, and together these land masses help to encompass the semi-enclosed basin of Cockburn Sound. Garden Island has approximate dimensions 1.5 km x 10 km and is aligned approximately 15 degrees west of north.

Cockburn Sound

Cockburn Sound varies in width from approximately 9 km at its northern end to 6 km at its southern end. Its area is approximately 80 square km. Within the Sound there is a central basin of approximately 20 m depth which occupies approximately 60 percent of the Sound's total area. Peripheral shallower regions (0-10 m depth) occupy the remaining 40 percent mainly in the north-east sector of the Sound. At one stage, before the industrialisation of the 1950's, almost the entire region between the shoreline and the 10 m contour was extensively covered in seagrass meadows. At last estimate this coverage had been reduced to less than or equal to about 10 percent of the original area (Cambridge and McComb, 1984).

Northern opening of Cockburn Sound

Figure 2.2 is a rough cross sectional view of the bottom contour from the northern tip of Garden Island to Carnac Island, and then across from Carnac Island to Woodman Point. The cross-sectional area through the Garden Island - Carnac Island gap is approximately 9500 m^2 and that through the Carnac Island - Woodman Point gap is approximately 18600 m^2.

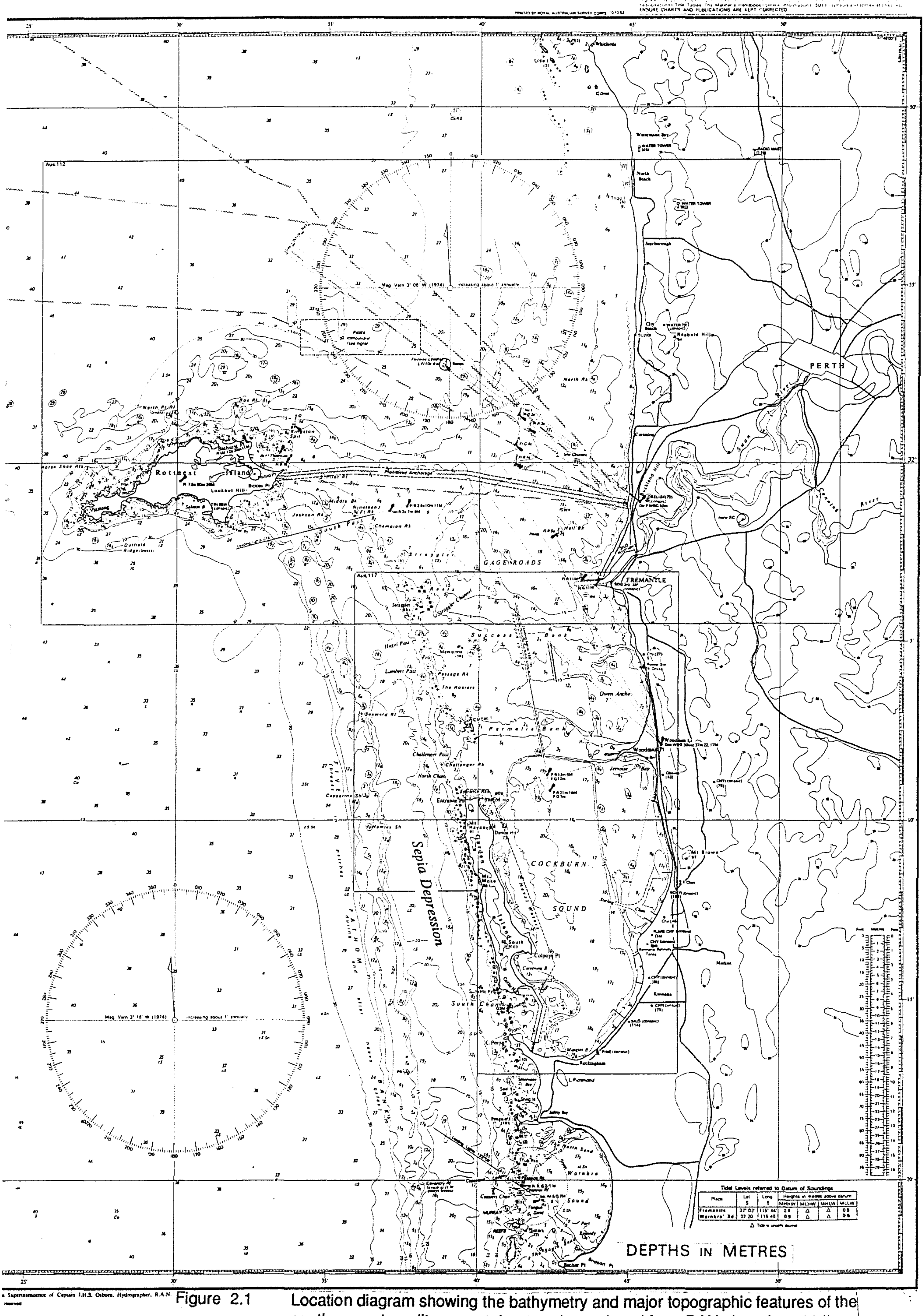


Figure 2.1 Location diagram showing the bathymetry and major topographic features of the southern metropolitan coastal waters (reproduced from RAN chart Aus. 114).

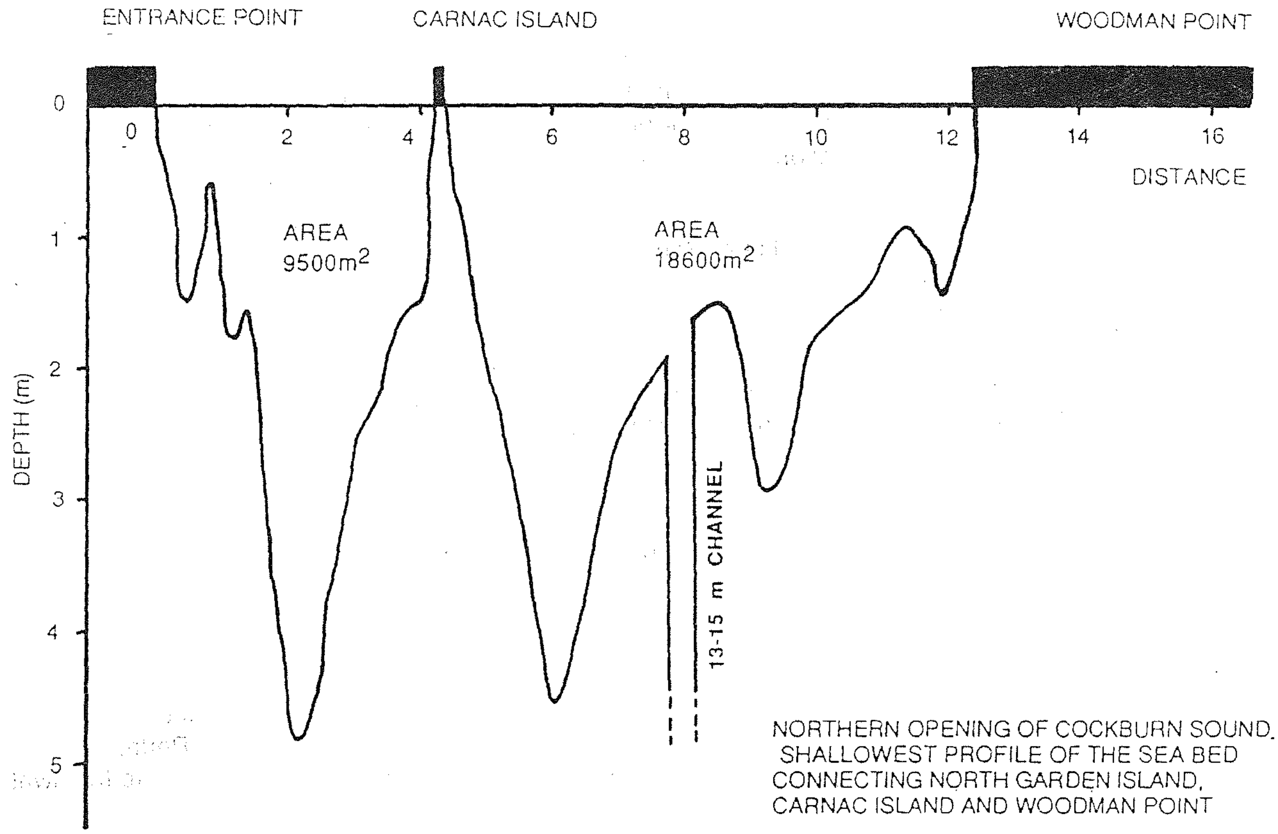


Figure 2.2 Bottom profile from North Garden Island to Carnac Island to Woodman Point.

Southern opening of Cockburn Sound

The natural 2 km wide southern opening of Cockburn Sound was modified by the construction of the Causeway in 1972, linking the mainland at Rockingham to the southern end of Garden Island at Parkin Point. The Causeway serves as a communicating transport link between the mainland and the Garden Island Department of Defence naval facilities at HMAS Stirling in Careening Bay. The Causeway is of solid rock construction with pylon type bridge openings to the north (High Level Bridge) and south (Trestle Bridge). The effective hydraulic exchange area between the Sound and ocean through the southern opening was reduced to about 25 percent of original by the construction of the Causeway. The original cross-sectional area of the southern opening was approximately 5000 m^2 across its shallowest profile (from Collie Head to John Point) and approximately 10000 m^2 along the alignment of the now existing Causeway. At present, the total area under the bridges is approximately 3800 m^2 with the area under the High Level Bridge being 2900 m^2 and that under the Trestle Bridge being 900 m^2 for average tidal conditions.

Warnbro Sound

Warnbro Sound lies south of Cockburn Sound. It is bounded by Penguin Island to the north, Becher Point to the south, the reef system to the west and the mainland to the east. This broad area has approximate dimensions 4.5 km by 7 km, and an area of approximately 30 km^2.

Within Warnbro Sound an inner basin of 10-20 m depth occupies an area of about 15 km^2, representing approximately 50 percent of the total area of the Sound. Extensive shallow flats of depth less than 5 m characterise the bathymetry of the northern area (off Mersey Point) and southern area (off Becher Point). These shallow flats have a combined area of about 15 km^2.

Swan River

The Swan-Canning estuarine system drains directly into the study area, and has its mouth at Fremantle.

Other freshwater sources

The Peel-Harvey estuarine system discharges significant amounts of freshwater via the Mandurah Channel, approximately 17 km south of Becher Point. Freshwater could be advected into the study from this source during northward longshore flows. Approximately 90 km north of Perth, the Moore River discharges appreciable amounts of freshwater during winter and this may contribute freshwater to the study region during southward longshore flows.

Minor municipal storm water drains are scattered along the metropolitan coastline and contribute minor amounts of freshwater to the coast during rainfall and runoff periods.

3. Past studies

This section summarises past investigations of hydrodynamic processes in the nearshore coastal basins of Cockburn Sound, Owen Anchorage, Sepia Depression and Warnbro Sound. Where local work on particular coastal mechanisms has not been carried out reference to the general oceanographic literature is made. Local studies on biological, zoological or chemical issues are not specifically reviewed.

3.1 Shelf-scale processes

A number of shelf-scale mechanisms will influence the circulation of the study region. These are divided into the following general categories; the Earth's rotation, coastal boundary currents, wind-driven currents, tidal flows, low frequency oscillations, sea and swell waves and density effects. A brief review of past studies is given and a simple estimate of the relative potential of individual mechanisms to drive coastal transport is made.

3.1.1 Definition of barotropic and baroclinic flow

Many oceanographic field studies have been conducted in the study region over the last 25 years. They have all had a common objective of characterising the hydrodynamic response of the waters to environmental forcings. These studies have investigated both barotropic and baroclinic circulation mechanisms, with these terms defined as (Gill, 1982):

Barotropic - "...pressure is constant on surfaces of constant density".

Baroclinic - "...pressure is not constant on surfaces of constant density".

Another way of describing barotropic flow is that which occurs within a fluid that has pressure and density surfaces parallel. Examples of barotropic flows are wind-driven currents and tidal currents in waters that are homogeneous in density.

Another way of describing baroclinic flow is that which occurs due to pressure surfaces and density surfaces not being in parallel. Baroclinic circulation is often simply described as density-driven, due to the fact that a horizontal density gradient can set up an associated horizontal pressure gradient which in turn drives a horizontal current. Examples of baroclinic flows are lock-exchange circulation between two fluids of different density, and salt-wedge intrusion of sea-water into a river of relatively low salinity and therefore low density.

3.1.2 The earth's rotation (Coriolis force)

The influence of the Earth's rotation upon flows is to deflect them anticlockwise in the southern hemisphere under the action of Coriolis force. Looking downstream this acts to the left of the flow. For small water bodies the Coriolis force has a relatively minor effect on the nature of barotropic or baroclinic currents. Csanady (1982) presents a theoretical treatise on this subject.

The Rossby number, R, is a non-dimensional number that is used to indicate the potential of the earth's rotation to deflect currents, and is given by

$$R = u/(Lf) \qquad 3.1$$

where u is the speed of the current, L is the width of the basin and

$$f = 2\Omega \sin\Phi \qquad 3.2$$

is the Coriolis parameter, with Ω being the frequency of the earth's rotation (=7.3 x 10^{-5} rad. s^{-1}) and Φ the latitude, in degrees, of the point in question. The Coriolis parameter, f, has a value of approximately 7.7 x 10^{-5} rad. s^{-1} for the Perth region (Φ = approximately 32 degrees). When $R < 1$

rotational effects are important and the current will be appreciably deflected by the force of the earth's rotation. When R > 1 rotational effects are overcome by the fluid's momentum (Fischer et al, 1979).

An inertial period is defined as $T_i = 2\Pi/f$, which is of the order of 1 day for the Perth region. This period is a guide to the time scales required for rotational effects to be of significance to the general flow pattern. For example if R <1, a current that has been in motion for times that scale with $2\Pi/f$ or more will undergo significant tendency to rotation.

Nunes (1988) has found that Coriolis force is important in its effect on basin scale re-adjustments of the density field for Spencer Gulf, South Australia. Evaporation leads to appreciable salinity increases at the head of the Gulf and a strong longitudinal density stratification develops as a consequence. During neap tides the density structure tends to relax by baroclinic readjustment. However, the influence of Coriolis force is to turn the current vectors accordingly anti-clockwise until this adjustment to geostrophic equilibrium actually halts the process at an intermediate stage. Hence, rotation can turn an initially vertically sheared transverse circulation into a horizontally sheared longitudinal circulation. In other words a "geostrophic balance" is reached between the pressure field due to the density gradient and that due to the earths rotation.

Hearn (1991) suggests that rotation of cross-shelf baroclinic flows is likely to be an important mechanism in transport for Perth's coastal waters and this is discussed below (3.1.8). The influence of rotation on nearshore currents for the nearshore shelf zone of Perth's coastal waters requires further field investigation.

3.1.3 Coastal boundary currents

The alongshore advection of a warm tropical water mass southwards in autumn and winter is called the Leeuwin Current (Cresswell and Golding, 1980). It has been described (Pearce and Cresswell, 1985; Church et al (1989)) as a band of warm, low salinity water of tropical origin about 200 km wide and 50 m deep in the north and 50-100 km wide and 200 m deep in the south, that flows southward with speeds in its core of up to 1.5 m s^{-1}, mainly above the continental slope from Exmouth to Cape Leeuwin. Coriolis force deflects the Leeuwin Current towards the east and causes it to maintain its preferred structure as a poleward boundary current along the Western Australian continental slope.

It is generally accepted that the main driving force for the Leeuwin Current is the sea level gradient between the waters of the northwest shelf area and the southwest of Western Australia, the sea level being about 55 cm higher in the north during autumn and winter due to a build-up of tropical water, perhaps being fed also by a flow of warm, low-salinity water from the Western Pacific Ocean (see Pearce (1991) and Cresswell (1991) for recent reviews of past studies and fundamental characteristics of the Leeuwin Current). As Pearce and Cresswell (1985) point out, in summer the north-south sea level gradient weakens and the mean wind stress along much of the coast is strongly northwards resulting in a weakening of the Leeuwin Current.

Andrews (1977) has described another Western Australian boundary current that occurs as a summer feature and he referred to it as the "Western Australian Current". It is a relatively cool, saline zone of southern Indian Ocean water that flows eastwards between the 30^{o} and 32^{o} latitudes, thereby being deflected southward along the southwest Australian continental shelf. The flow is dominated by migrating eddies and mean southward propagation. Pearce (1991) has also discussed the origin of this current, and points out that it is most likely a clockwise offshoot of the traditional northwards current of the same name which forms the eastern limb of the Indian Ocean Gyre.

Satellite images (Pearce and Cresswell, 1985; Pearce and Griffiths, 1991; Pearce and Church, 1992) and satellite tracked drifter-buoys (Cresswell and Golding, 1980) have revealed that during winter the Leeuwin Current can have associated meanders, with both warm-core (anticlockwise) and cool (clockwise) eddies evident, particularly south of Shark Bay. The warm-core meanders have diameters up to 300 km. The schematic taken from Pearce and Griffiths (1991) and reproduced here in Figure 3.1 illustrates these features. Past studies have shown that the Leeuwin Current sometimes propagates westward onto the nearshore shelf regions in the form of smaller-scale meanders of order 20 km with characteristic speeds of the order of 0.1-0.3 m s^{-1} (Pearce and Griffiths, 1991). The spatial and temporal characteristics of such events are not well understood at present.

Over the shelf the dynamics are controlled by a balance between the longshore and cross-shore pressure gradients (associated with the Leeuwin Current and its associated meanders), bottom friction

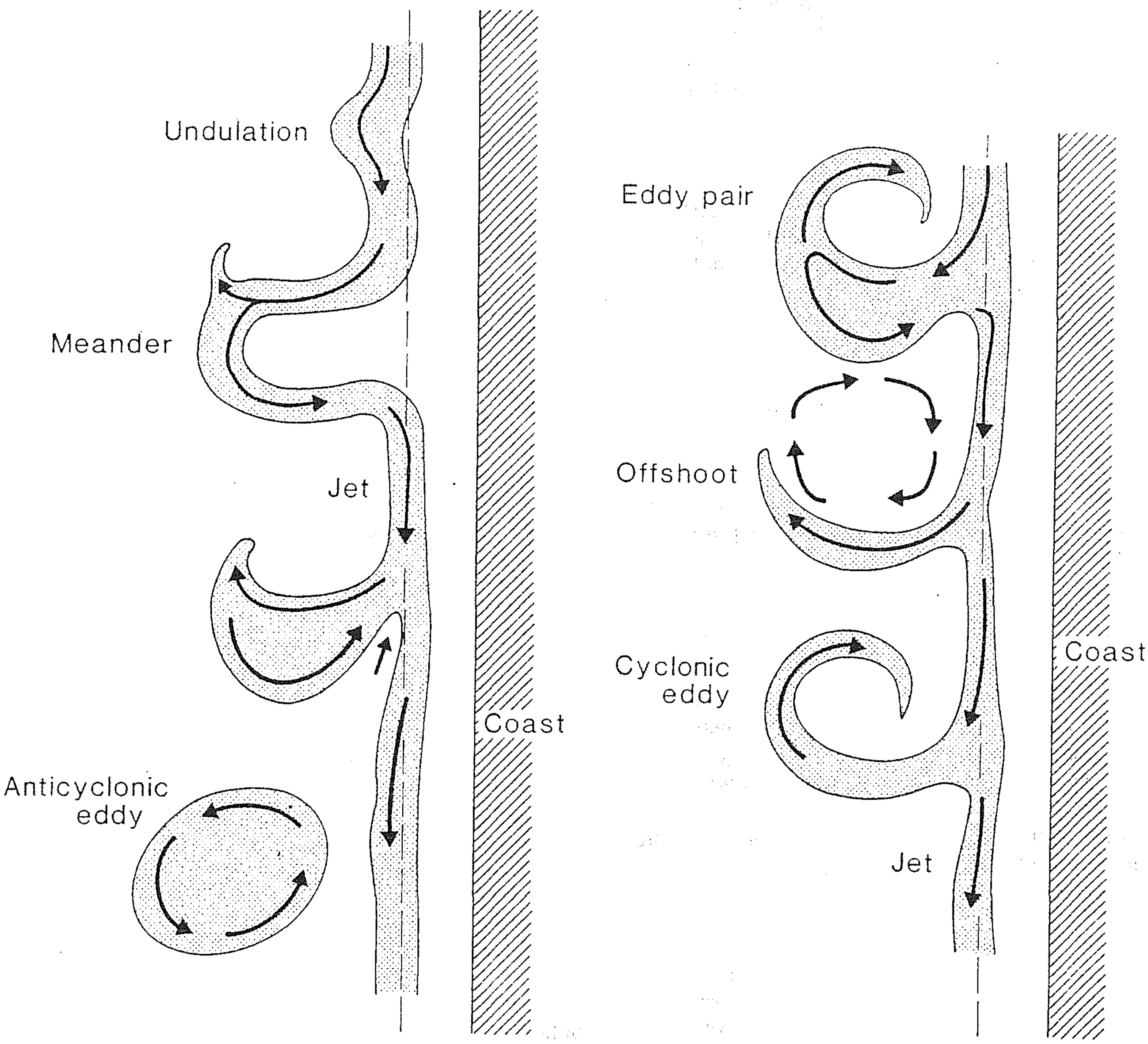


Figure 3.1 A reproduction of Pearce and Griffith's (1991) schematic showing typical meso-scale features of the Leeuwin Current as it propagates along the continental shelf break off the west coast of Western Australia. As Pearce and Griffiths (1991) describe: Figure 3.1a represents the evolution from a jet flow along the shelf break through a fully developed meander (or wave) to a free anticyclonic eddy; 3.1b represents an eddy pair, an offshoot, and a cyclonic eddy. In each case, the coast is shaded and the shelf break is indicated by the dashed line.

and wind stress. Thompson (1987) has modelled this interplay analytically. The influence of vertical and horizontal density stratification in this force balance is as yet not well understood.

Little work exists on the spatial and temporal characteristics of the nearshore occurrence of the Leeuwin Current along the southwest Australian coastline, or of the dynamical interactions between the Leeuwin Current and other forcings (eg wind, tide, density effects, Coriolis force) over the nearshore continental shelf regions. The influence of the Leeuwin Current, either directly or indirectly, on circulation within the nearshore basins requires further study.

3.1.4 Wind-driven currents

Ekman drift

Ekman drift describes transport of the surface layer subjected to both wind stress and the Coriolis force. Csanady (1982) reviewed the characteristics of Ekman drift in homogeneous water columns, and describes how the influence of Coriolis force induces rotation (counterclockwise in the southern hemisphere) of wind-driven currents in oceans away from the influence of side or bottom boundaries. For such cases the depth of the turbulent Ekman boundary layer (Csanady, (1982) is given by

$$D = 0.1\, u^* f^{-1} \qquad 3.3$$

where u^* is the friction velocity (in ms^{-1}) given by

$$u^* = (\rho_A C_d/\rho)^{1/2}\, U_{10} \qquad 3.4$$

and, ρ_A is the density of air, approximately equal to 1.2 kg m^{-3}, ρ is the density of the water, C_d is a drag coefficient that depends on atmospheric conditions and sea-surface roughness but can be approximated as 0.0013 (Fischer *et al*, 1979), and U_{10} is the wind speed at 10 m height. Ekman boundary layer depths of order 10 m are typical at mid-latitudes for winds of 5-10 m s^{-1}.

Ekman transport and geostrophic balance

For times that scale with the inertial period ($2\Pi/f$ = of order 1 day for the Perth coastal zone) a geostrophic balance (Csanady, 1982) will occur in longshore Ekman transport, with southward longshore flows rotated towards the coast, thereby causing set up of water level and surface Ekman drift towards the coast with a subsequent net offshore flow reversal near the bottom due to the resulting offshore directed pressure gradient. Northward wind-driven flows will be rotated away from the coast, the geostrophic balance causing the water level to be depressed near the coast, with consequent upwelling of bottom waters in towards the coast. Near coastlines wind drift is also strongly influenced by the steering influence of the coastal boundary and local topography, and by the stress due to bottom friction.

Langmuir circulation

Adjacent and oppositely rotating circulation cells in the Ekman layer lateral to the direction of the wind are known to occur and are called Langmuir circulations (Langmuir, 1938; Faller and Auer, 1988). Langmuir Circulation is usually evidenced by streaks of floating surface scum, foam, or detritus, in the direction of the wind, along zones of convergence between oppositely rotating "cells". Where the lower boundary (base of the upper mixed layer, or sea-bed) is the controlling factor, the scale for the cross-wind wave length of the circulation cell field, L, is given by $2.5<L/H<3.5$, where H is the depth to the lower boundary (Faller, 1969). Hence, for a typical H for coastal shelfs of order 10-30 m, L will be of order 25-100 m. Set-up time scales for Langmuir circulation will scale with L/0.03 s (Faller and Auer, 1988), or 10^3 s for most coastal situations.

The effect of Langmuir circulation on dispersion is discussed by Csanady (1970, 1974) and McLeish (1968). Csanady (1970) described the dispersive effect of Langmuir circulation as follows "...as a cloud (of discrete floating tracers) is released it rapidly forms itself into a number of windrows. Given a typical lifetime of 10^3 s each windrow acts as a new source with about this frequency, redistributing its load over a few successor windrows". However, Faller and Auer (1988) introduce a note of caution in adopting predictive formulae (Csanady, 1974) of lateral dispersion due to Langmuir circulation. Faller and Auer's (1988) modelling of Langmuir circulation suggested the row splitting in the overall cell field should occur infrequently, and that the principle mechanism of dispersion will be due to the stochastic wandering of rows in time and space, somewhat like a random walk. They argue that the wide variability in natural conditions requires that analytical estimates of dispersion should be taken to describe no more than the gross effects of Langmuir circulations.

The influence of Langmuir circulation on the hydrodynamics of Perth's coastal waters is poorly understood at present.

Wind-driven currents in the Perth coastal zone

The seasonal characteristics of southwest coastal winds have been analysed by Steedman and Craig (1979, 1983) and Steedman and Associates (in Binnie and Partners, 1981). A detailed summary of that work is presented in Appendix A1. The results of past studies (Binnie and Partners, 1981) showing the relatedness of longshore winds and associated coastal currents west of Garden Island are presented in Appendix A2. Those investigations indicated that mean longshore regional currents off the south-west coast have speeds (averaged over periods of weeks) of order 5-10 cm s^{-1}, lying within a range of approximately 0-25 cm s^{-1}. They also suggest that vertically averaged currents in Sepia Depression (west of Garden Island) are channelled in the longshore directions and flow predominantly northwards in summer and predominantly southwards in winter with speeds typically of the order of 5-10 cm s^{-1}, but sometimes reaching 40 cm s^{-1} during strong storms and sea-breezes. The direction of these coastal currents was found to be generally in the direction of the predominant longshore wind vector. For example, sea-breezes blow towards the northern quadrants and were found to invariably lead to northward flow in Sepia Depression.

In view of the fact that these records were relatively gap free and that complimentary tide, wind and barometric pressure data are available, a further analysis of the data involving spectral and cross-correlation techniques is recommended as future work for the SMCWS.

3.1.5 Tidal flows

There are a number of summaries and descriptions of the tidal characteristics of Perth's coastal waters available in the literature (see for example, Easton, 1970; Hodgkin and Di Lollo, 1958; D'Adamo, 1985, van Senden, 1991; Hearn, 1991). The tides are mainly diurnal with semi-diurnal tides only occurring for 3-4 days at a time when both the lunar and solar semi-diurnal components are near their maximum (Hodgkin and Di Lollo, 1958).

Typically, the maximum daily range in the water level of Perth's coastal zone is approximately 1.0 m during spring tides and the minimum is approximately 0.1 - 0.3 m during neaps (Hodgkin and Di Lollo, 1958 and D'Adamo, 1985). This contains about a 0.7 m maximum contribution from the dominant astronomic tidal constituents, and the remainder is due to remote or locally forced barometric pressure and wind effects. Analyses of long-term water level records for the south-west coast show that rare events, such as onshore gales associated with cyclonic depressions, have caused a range in water level of up to 1.8 m over the duration of the event (Hodgkin and Di Lollo, 1958; Fandry et al, 1984). Other non-tidal effects are discussed below.

Maximum tidal current speeds for Perth's coastal waters are estimated to be of the order of 1 cm s^{-1} (Steedman and Craig, 1983; Hearn et al, 1985, van Senden, 1991). In comparison to other mechanisms, the influence of tides on the mean circulation of Perth's coastal waters is probably negligible, unless in regions of bathymetric constrictions such as a shipping channel or a natural connection between a basin and the sea.

3.1.6 Low frequency oscillations

Local wind-set up and isostatic response due to meso-scale barometric pressure fluctuations, and low frequency oscillations associated with remotely or locally forced propagating coastally trapped waves (eg, continental shelf waves and Kelvin waves) can cause long-period water level variations in Perth's coastal waters (Hodgkin and Di Lollo, 1958; Hamon, 1962 and 1966; Adams and Buckwald, 1969; Provis and Radok, 1979; Fandry et al, 1984; Harrison, 1983; Webster, 1983). The literature suggests that for the southwest Australian coast low frequency oscillations have characteristic periods of the order of 5-10 days or more , ranges of the order of 0.1-0.3 m, and southward celerities of 3-6 m s^{-1}.

Simple estimates of longshore transport rates due to these low frequency oscillations can be made using simple wave propagation theory for coastally trapped waves (see for example, Mortimer, 1974; Csanady, 1982; Gill 1982). Longshore velocities of the order of 1-10 cm s-1 with corresponding longshore excursions of up 5-40 km are calculated (see also van Senden, 1991). It is to be noted that the nature of these flows is cyclic, and hence would lead to alternating southward and northward excursions during respective crests and troughs as they pass through the system.

The transport or flushing of coastal waters by low frequency oscillations is not sufficiently understood for the Perth coastal zone at present. The influence of local bathymetric variations, or topographic features (such as the sloping shelf, islands, reef lines, basin shapes) in directing such motions requires further study. The potential for such flows to cause appreciable transport exists and should be considered in general oceanographic studies of mean circulation for this coastal region.

3.1.7 Sea and swell waves

On the southwest coast the prevailing wave climate exhibits regularity on seasonal time-scales.

Waves at any particular oceanic location are due to a combination of sea and swell waves. Sea describes waves generated locally by wind, and have characteristically short periods for Perth's coastal waters (less than 8 seconds, Binnie and Partners, Dec 1981) and their direction is governed by the direction of the wind. Swell refers to longer period waves (8-12 seconds) that are generated by storm winds in the deep ocean .

A number of wave-rider buoy deployments have been conducted over the last decade by local oceanographic groups. R.K. Steedman and Associates (in Binnie and Partners, Dec 1981) performed comprehensive qualitative and quantitative analysis of waves impinging on the southern metropolitan coast by using records from wave rider buoys deployed for long periods of time. Figures 3.2 and 3.3 show the resulting distributions of direction of sea and swell waves for two discrete periods: summer, defined as October to March and winter, defined as April to September. As shown, sea and swell in summer arrives predominantly from the south-southwest, however in winter there is much more 'west' in the direction of sea and swells.

Past studies on the attenuating effect of the local reefs and sandbanks on incoming sea and swell are reviewed in van Senden (1991), where data (unpublished) from the Department of Marine Harbours (Ref: Mr Grant Ryan) collected off Guilderton were discussed (one site was in 33m depth offshore of the reef and another inshore of the reef in 10m depth). As van Senden (1991) points out, the reefs cause an attenuation of the order of 50 percent, but the exact figure varies according to wave height, wave period, and mean water level. In addition, van Senden (1991) compared the relative occurrence of sea and swell periodicities in the wave field, and found the for the Guilderton data the smaller period sea waves were more prominent at the inner reef site than at the outer reef site. Similar results have been reported (Hearn, 1991) for wave data from west Garden Island, and inner Cockburn Sound, where it was found that the attenuation reduced wave heights by up to 85 percent in Cockburn Sound relative to the more exposed waters west of garden Island.

The persistent action of a wave field normal to a shallowing coastal zone over prolonged periods will result in a 'wave set-up' due to the transfer of momentum from the wave to the water by radiation stress (Longuet-Higgins and Stewart, 1964; Gill, 1982). Pattiaratchi and Imberger (1991) referred to the action of this mechanism for the Marmion Lagoon as "wave-pumping' and provide an appraisal of the potential of this and other wave effects to drive horizontal transport, particularly shoreward of shoals and reef lines. A small residual transport can be expected and this mechanism is generally included in wave circulation models. Pattiaratchi and Imberger's (1991) analysis indicates that 'wave-pumping' could be important as a flushing mechanism, particularly in nearshore regions of the Perth coastal zone.

Past studies have not fully investigated the influence of swell and local wind waves on circulation and flushing patterns of the nearshore semi-enclosed embayments such as Cockburn Sound and Warnbro Sound. However, this should form a part of future hydrodynamic studies of the SMCWS.

3.1.8 Density effects

In addition to the above mechanisms horizontal density gradients could drive circulation in coastal waters. Vertical density stratification will influence the manner in which mass is transported vertically and horizontally, as described above in 3.1.2 and also in Appendix A3. Various possibilities that may produce baroclinic transport are discussed below.

<u>Nearshore wind-induced circulation in the presence of stratification</u>

Csanady (1982) describes how vertical stratification near coasts can strongly influence the circulation patterns of wind-induced currents by leading to the formation of a "coastal jet" in the coastal boundary

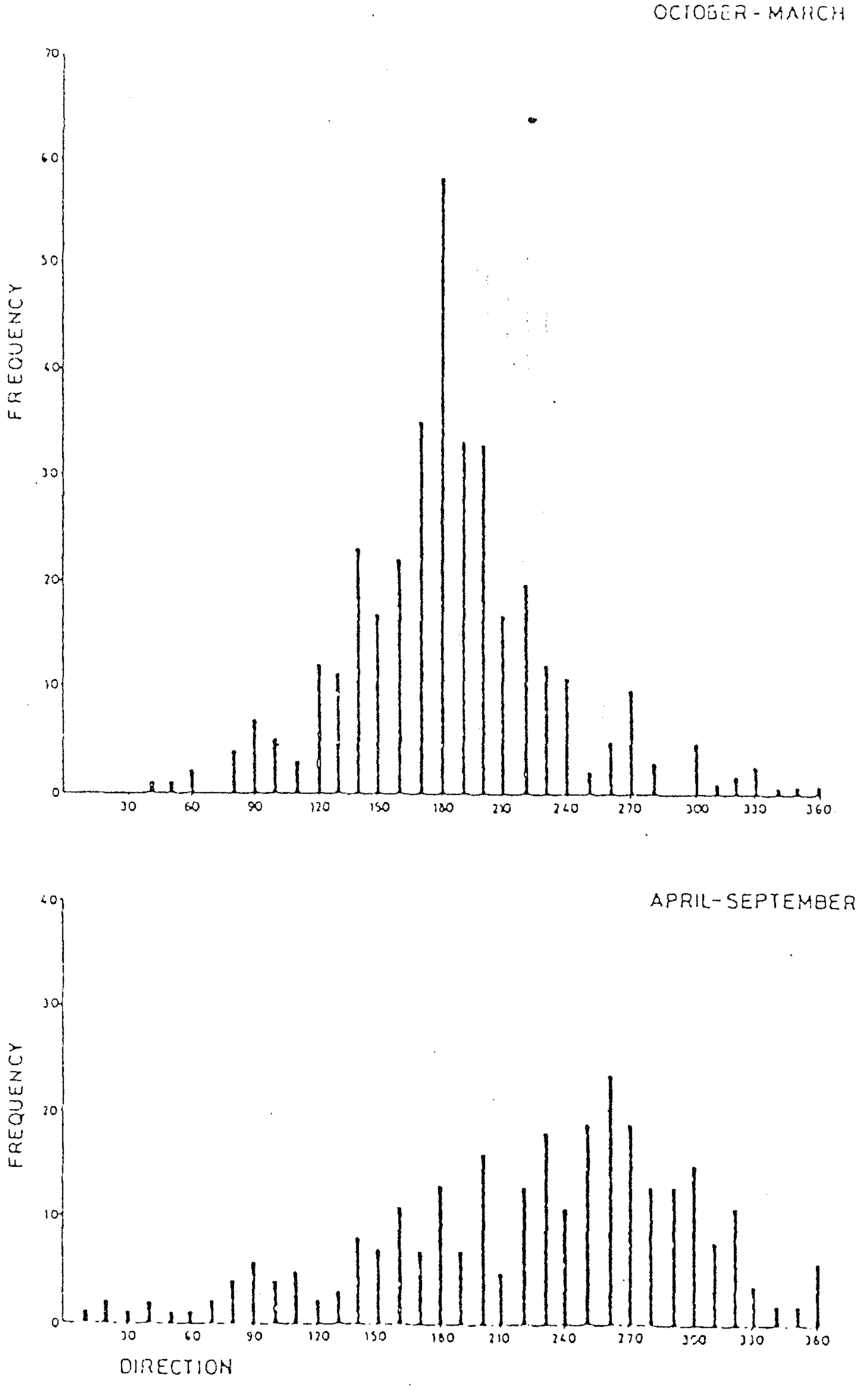


Figure 3.2 Typical frequency distribution of sea (wind-wave) directions of the southern metropolitan coastal waters for Oct-Mar and Apr-Sep (from R K Steedman and Associates, in Binnie and Partners (1981)).

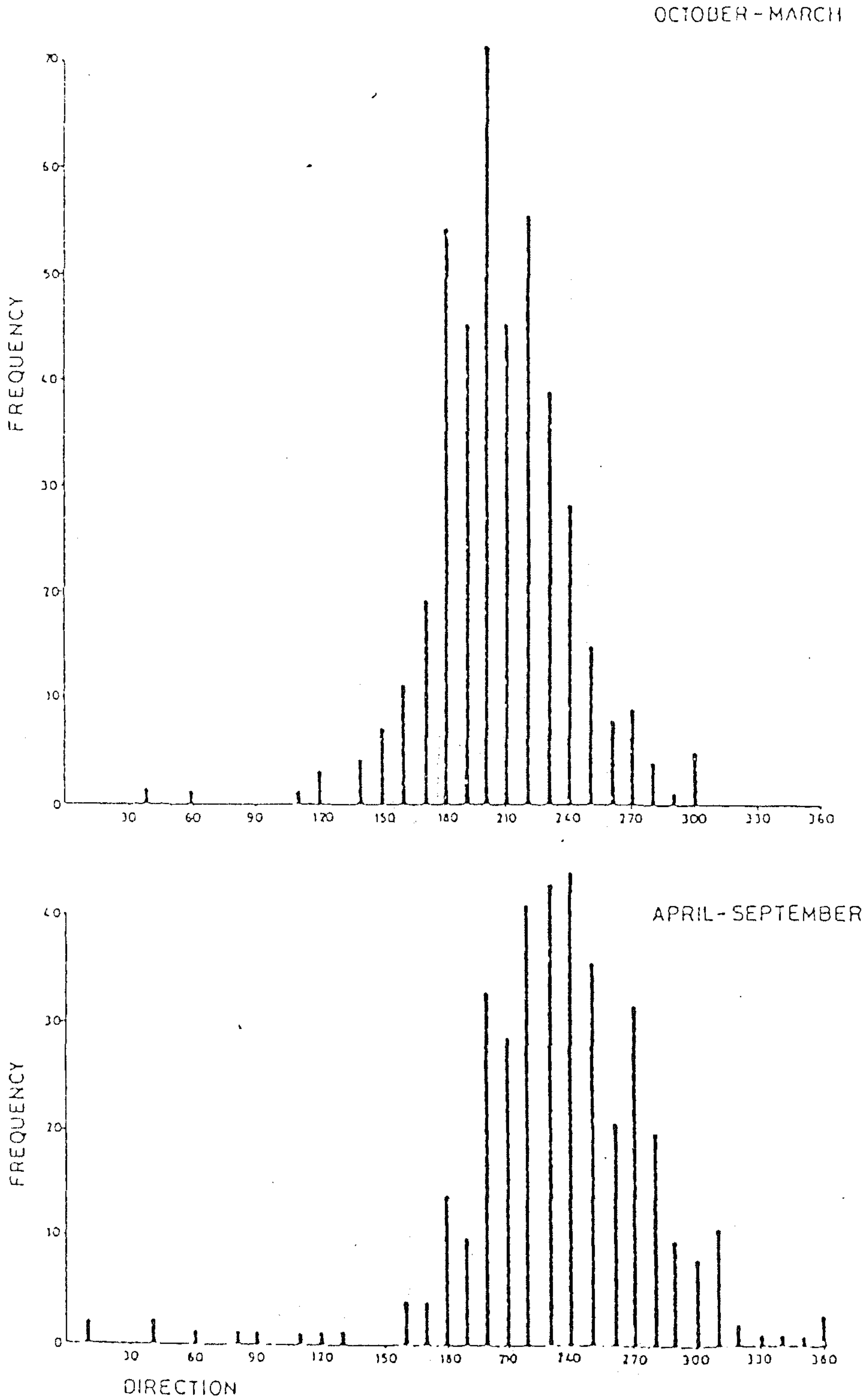


Figure 3.3 Typical frequency distribution of swell directions of the southern metropolitan coastal waters for Oct-Mar and Apr-Sep (from R K Steedman and Associates, in Binnie and Partners (1981).

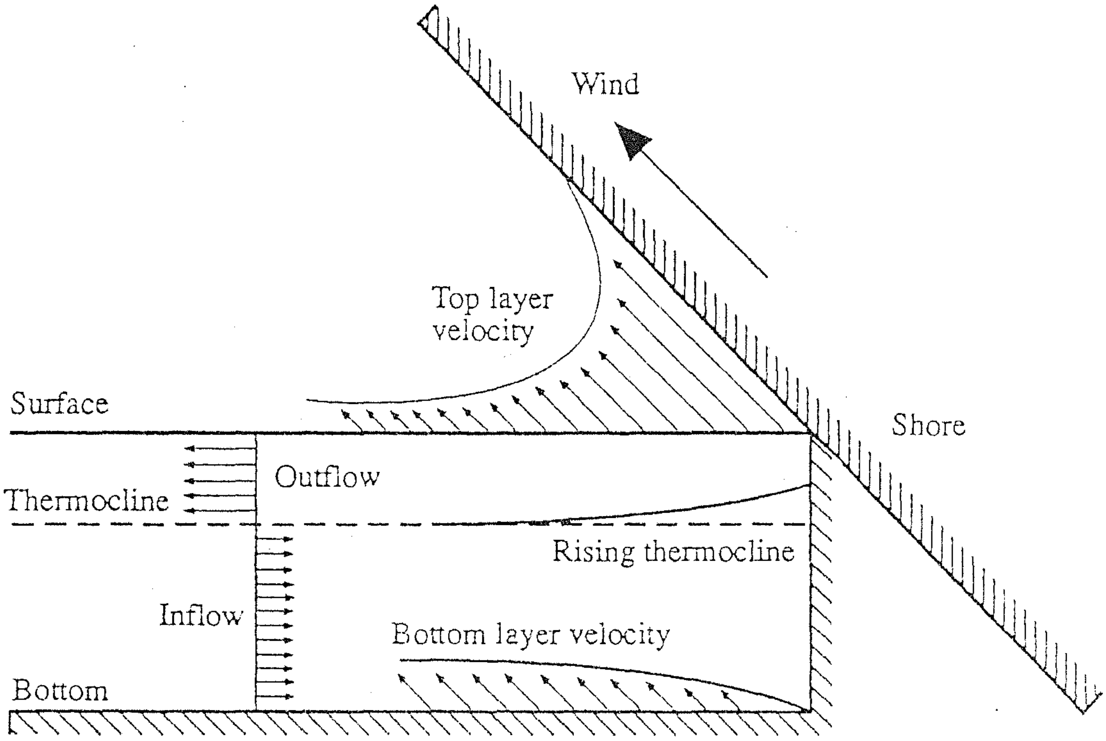


Figure 3.4 Schematic diagram of coastal jet development in a two-layer fluid without bottom topography (modified by Pattiaratchi and Imberger (1991) from Csanady (1977)).

layer, the width of which scales with the internal radius of deformation (u/f). For an idealised two-layered coastal system with an assumed frictionless flat bottom, forced by longshore wind, and influenced by Coriolis force (i.e., for times > the inertial period), the tendency to geostrophic balance will result in Ekman transport towards (or away) from the coast in the surface layer, and a corresponding adjustment flow away (or towards) the coast in the bottom layer. In the southern hemisphere for example, northward winds along say the Perth coastal zone would result in Ekman transport away from the coast of surface water above the pycnocline, and an associated flow of bottom waters towards the coast in an upwelling manner. Figure 3.4 (modified by Pattiaratchi and Imberger (1991) from Csanady (1977)), represents this flow field schematically. Csanady (1982) presents illustrative data on this effect collected in Lake Ontario.

Submarine Groundwater Discharge

Hearn (1991) has described and analysed coastal submarine groundwater discharge of freshwater as a potential mechanism that could force baroclinic flow. He postulated that this source could lower the average salinity, and therefore density, of nearshore waters and create an offshore directed pressure gradient which would drive an offshore directed baroclinic density current of relatively less dense surface coastal water. Initially ($T < T_i$) the speed of such density currents will scale with that given by the densimetric velocity (of order $0.5(g'H)^{1/2}$, as defined in Appendix A3).

The influence of the earth's rotation would then be to induce a counterclockwise rotation of this baroclinic flow, thus leading to a net drift southwards in a band within a few kilometres of the coast (which scales with the Rossby radius of deformation, given by u/f, where u is the current speed). The fundamental factor required for this dynamical adjustment to occur is therefore an offshore directed pressure gradient driving an offshore directed baroclinic current. By assuming typical submarine discharge rates of 4 m^3 per day per m of coastline along the metropolitan coast Hearn (1991) calculated that this mechanism could induce a southward flowing geostrophically adjusted coastal boundary current of the order of 5 cm s^{-1} or less.

As part of the SMCWS Appleyard (1990) reviewed existing hydrogeological data on submarine groundwater discharge rates from Yanchep to Becher Point and that work indicates that average discharge rates are of the order of 4.5 m^3 per day per m of coastline between Yanchep and Mullaloo, 2.5 m^3 per day per m of coastline between Mullaloo and Fremantle, 2 m^3 per day per m of coastline along the Owen Anchorage coast, 2.5 m^3 per day per m of coastline between Woodman Point and James Point in Cockburn Sound, and 0.5 m^3 per day per m of coastline along the Mangles Bay and Warnbro Sound coasts.

Hence, it could be expected that the strength of any alongshore buoyancy boundary current would be greatest in the northern metropolitan waters, and that it would be less pronounced but still significant in the southern metropolitan waters.

No definitive hydrodynamic field data exists to verify the importance of this potential flow mechanism. However, studies by Schwartz and Imberger (1988) and Johannes and Hearn (1985) have shown clearly that nearshore waters (within a few hundred meters of the coast) can have their salinities significantly decreased by submarine groundwater discharge and that density fronts parallel to the coast (Johannes and Hearn, 1985) and offshore directed baroclinic flushing of semi-enclosed embayments (Schwartz and Imberger, 1988) can result as a consequence. Hence, the limited amount of field data suggests the existence of the fundamental requirements for the setting up of alongshore baroclinic transport due to submarine groundwater discharge.

Evaporation

Hearn (1991) also introduced the possibility of nearshore evaporation as a forcing mechanism that could lead to this alongshore transport. Evaporation would lead to the formation of more saline, and therefore denser, nearshore waters and in turn this would drive an offshore baroclinic current at the bottom. The effect of evaporation is enhanced in shallow waters because there is less ambient water available in the water column with which the evaporated water can mix, hence mean salinities are relatively high in shallower waters as compared to deeper waters.

Monthly vertical salinity profiles were collected in central Warnbro Sound and central Sepia Depression west of the Causeway from June 1979 to August 1981 by the then Department of Conservation and

Environment of Western Australia (DCE). Figure 3.5 presents the surface and bottom salinity time series of these data. Figure 3.5 indicates a clear seasonal trend in salinity; in summer nearshore salinities (Warnbro Sound) are higher than those further offshore (Sepia Depression) and in winter this difference has reversed, with the nearshore data exhibiting lower relative salinities. The differences in salinities between the two sites were greatest in the summer and winter periods and ranged typically from 0.5-1.5 ppt. These results are consistent with Pearce and Church's (1992) analysis of ST time series data from CSIRO's Waterman Bay and Rottnest sites.

One possible cause of the observed variation in summer is the differential evaporative effect leading to relatively high salinities in shallower waters. The Leeuwin Current could also lead to cross-shelf gradients. In winter, reduced evaporation rates, submarine groundwater discharge (discussed above) and river flows can cause nearshore waters to decrease in salinity. The specific influence of the Swan River on nearshore salinity is discussed in Chapter 4.

Differential heating and cooling

Differential heating would lead to the formation of warmer and therefore less dense nearshore waters and in turn this would drive an offshore directed baroclinic current at the surface. On the other hand, differential cooling would lead to the formation colder, and therefore denser, nearshore waters and in turn this would drive an offshore baroclinic current at the bottom.

Temperature data were collected in conjunction with the salinity data discussed above and time series plots of temperature variation at the surface and bottom of Warnbro Sound and Sepia Depression are presented in Figure 3.6. As shown, Warnbro Sound was generally warmer than Sepia Depression in summer but colder in winter. This characteristic is attributed to differential heating and cooling. In summer shallower nearshore waters undergo greater heating than deeper waters, whereas in winter the reverse occurs, with shallowest waters cooling the most (see Section 4.1.8 in the proceeding Chapter).

River discharge

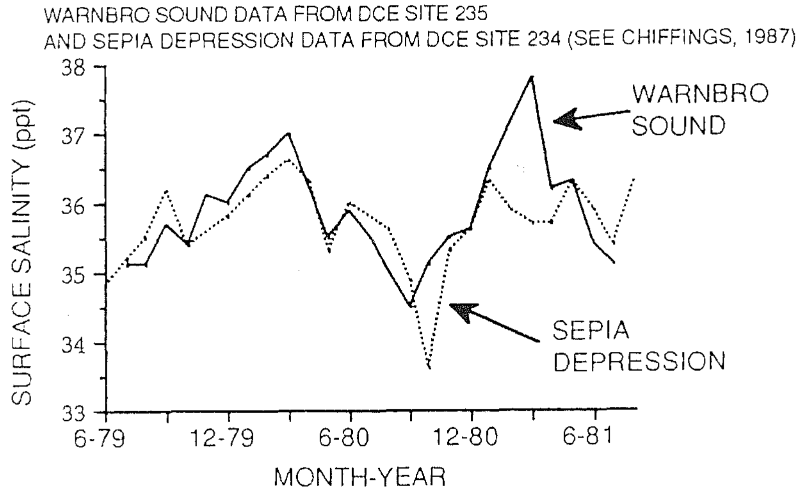
Rivers will discharge significant amounts of freshwater into the coastal zone. Longshore winds will advect the low density water along the coast, with some offshore turbulent spreading. Hence, there will be a cross-shelf density field set up and the potential for cross-shelf baroclinic exchange will be present. In addition, longshore Ekman transport will be away from the coast for northward flows, thereby leading to offshore movement of low salinity water, and upwelling of deeper more saline water in the nearshore coastal zone. For southward flows, Ekman transport will drive the buoyant river discharges towards the coast, with downwelling there. The net result of these circulation patterns is to cause the cross-shelf density structure to be tilted from horizontal, thereby causing horizontal pressure gradients. Upon cessation of the wind, for periods less than the inertial period (~ 1 day), the density structure will relax and tend to gravitational equilibrium via a baroclinic flow field. Rotational influences will then influence the flow patterns as described above. The influence of coastal discharges on the shelf-scale dynamics requires further field investigation.

3.1.9 Summary

A review of shelf-scale mechanisms has been performed and their transport potential investigated. The following listing summarises the main results of the above analysis.

PROCESSES INFLUENCING THE HYDRODYNAMICS OF THE SHELF-REGION

Process	Potential influence on transport and mixing	Temporal characteristics	Spatial characteristics	Comments
Coriolis force	Important	Frequent (inertial period of order 1 day).	Entire region	Will influence all flows with time scales > approx. 1 day. Field work needed.



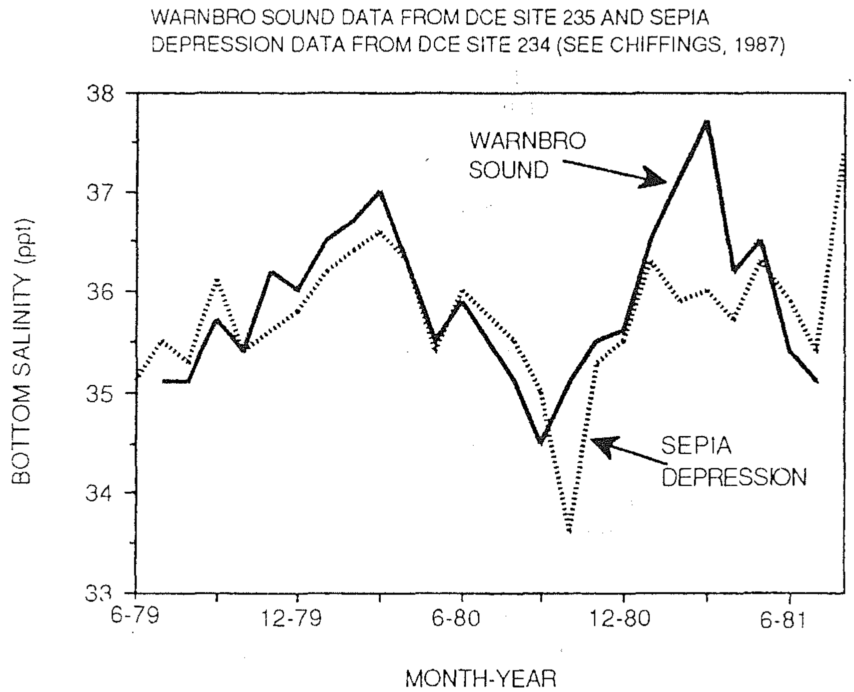
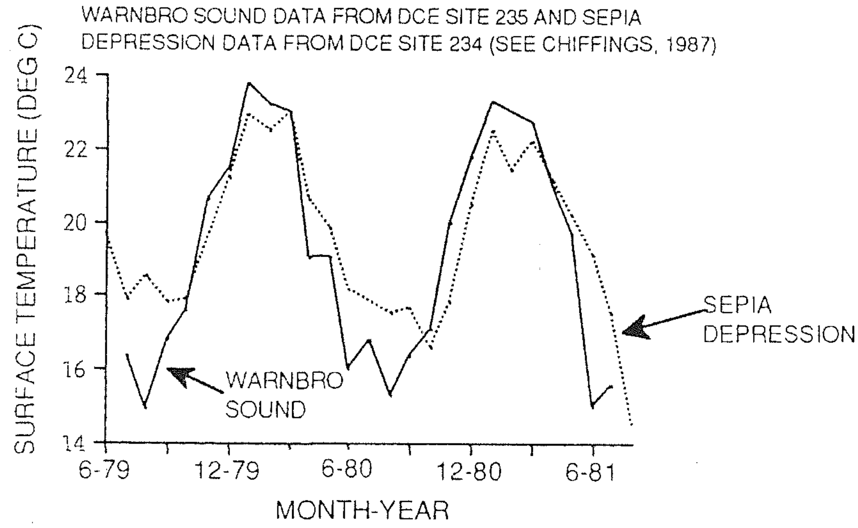
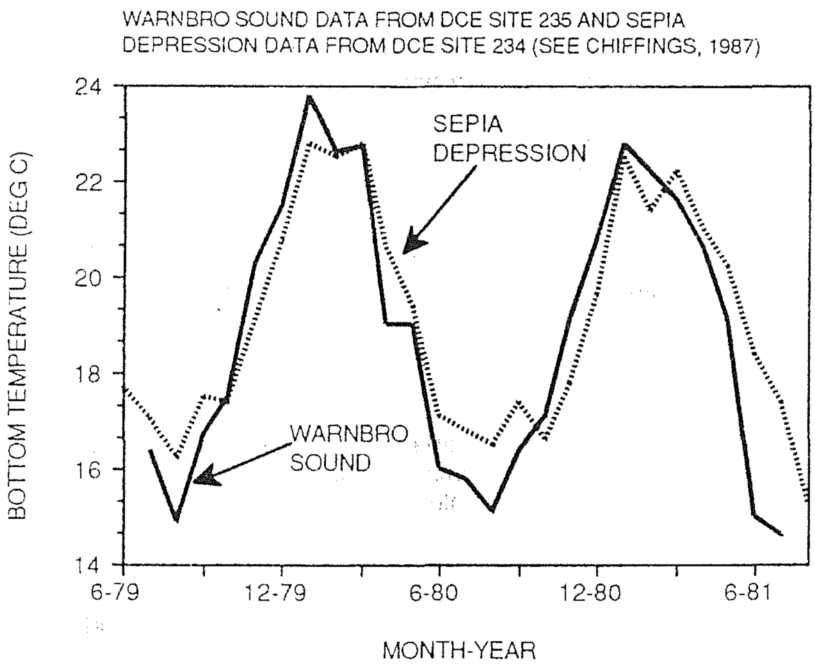


Figure 3.5 Surface and bottom salinity time series plots for central Warnbro Sound and central Sepia Depression (west of the causeway). Data from monthly DCE ST surveys during 1979-1981 (station locations presented in Figure 4.18, Chapter 4).


WARNBRO SOUND DATA FROM DCE SITE 235 AND SEPIA
DEPRESSION DATA FROM DCE SITE 234 (SEE CHIFFINGS, 1987)
SURFACE TEMPERATURE (DEG C)
24
22
20
18
16
14
6-79
12-79
6-80
12-80
6-81
MONTH-YEAR
SEPIA
DEPRESSION
WARNBRO
SOUND


WARNBRO SOUND DATA FROM DCE SITE 235 AND SEPIA
DEPRESSION DATA FROM DCE SITE 234 (SEE CHIFFINGS, 1987)
BOTTOM TEMPERATURE (DEG C)
24
22
20
18
16
14
6-79
12-79
6-80
12-80
6-81
MONTH-YEAR
SEPIA
DEPRESSION
WARNBRO
SOUND

Wind-driven flow	Strong: (horiz. transport up to 20 km d^{-1})	Frequent. Periodic, 1-10 day periods. All year.	Entire region	Important mechanism. Occurs in events of order 5-10 hours duration, within longer term variations with periods of order 1-10 days. Field work needed (esp. to characterise vertical shear in presence of stratification).
Vertical density stratification	Strong	Frequent. All year.	Entire region	Most important in basins. Also important elsewhere. Field work needed to assess influence on vertical mixing, benthic re-suspension, and horizontal transport.
Wind-mixing	Strong	Intermittent. All year.	Entire region	Speeds > approx 5-10 ms^{-1} (occur 50 % of time, on average) needed to break down typical vertical density stratification. Appears to be most effective in summer, when vertical density stratification seems to be at its weakest.
Horizontal stratification and density-driven flow	Medium: (up to 10 km d^{-1})	Unknown (probably frequent, all year).	Unknown (probably extensive)	Important. Field work needed to quantify and detail interaction with rotation.
Low frequency oscillations	Strong: (5-40 km d^{-1})	Unknown (probably intermittent, cyclic with 10 day periods).	Unknown (probably entire region)	Could be important. Theoretical and field investigation needed. Net transport could be small due to cyclic nature in direction of flow.
Leeuwin Current	Strong: (up to 30 km d^{-1})	Probably autumn to spring.	Probably shelf-scale	Likely to be important. Influence on nearshore basins unknown. Field work needed.
Wave pumping	Weak: (up to 5 km d^{-1})	Probably all year.	Unknown (probably primarily basin-scale)	Could be important, particularly in constricted regions (eg lagoons). Field work needed.
Tidal flows	Weak: (up to 2 km d^{-1})	All year.	Entire region	Probably most important through gaps and openings. Field work needed.

3.2 Numerical modelling of the nearshore regions

A brief summary of the results of past numerical modelling studies for Cockburn Sound and surrounding waters is given here.

Previous models of the circulation of Cockburn Sound and surrounding waters have been based on the assumption that the circulation is barotropic. The major basin-scale models that have been applied to the study region, or individual basins of the study region, were those of the Danish Hydraulics Institute, named the " System 21 - Jupiter" (Commonwealth Department of Construction, 1977), and Steedman and Craig (1979, 1983).

Both models were finite difference and two-dimensional, and the driving environmental forcings included surface wind stress, tidal forcing and external forcing from regional currents and atmospheric pressure gradients. The grid cells for these models ranged in scale from about 200 m to about 1850 m. They were able to reproduce measured flow patterns, as inferred from the tracking of drifter drogues, for strong wind situations (greater than 5 m s^{-1}). However, the reliability of the results of drogue-tracking in accurately representing depth-averaged current patterns comes into question due to the likely effects of surface drag on the floats of the drogues utilised, and this is discussed in Chapter 4.

For wind situations where speeds were less than 5 m s^{-1} the models were either not run (Commonwealth Department of Construction, 1977) or were unable to reproduce current patterns or speeds with any acceptable degree of confidence (Steedman and Craig, 1979 and 1983).

Steedman and Craig (1979) suggested that their model could only be applied for winds greater than 5 m s^{-1}. They performed theoretical calculations and relevant field measurements of salinity, temperature and current velocity structure to suggest that wind currents could be balanced by finer scale baroclinic flow structures when winds fall below about 5 m s^{-1}. If correct, then the same limitations would therefore have applied to the System 21 - Jupiter model.

Smaller areas and coastal embayments of the study region have been modelled by Hearn and Hunter (see the review by Hearn, 1991). They have applied barotropic models with grid sizes as small as 50 m and the details of these applications are summarised in Hearn (1991).

Hearn (1991) has presented a detailed review of past modelling efforts of the hydrodynamics of Cockburn Sound, surrounding waters and the wider metropolitan coastal zone. The reader is referred to that report for a comprehensive treatise of past modelling studies.

3.3 Field studies of the nearshore regions

3.3.1 Overview

The above discussion has investigated the known or likely role of various shelf-scale mechanisms to mixing and transport of Perth's coastal waters. The nearshore basins are hydraulically connected to the shelf zone and hence shelf-scale processes will influence both their internal hydrodynamics and flushing behaviour. The hydrodynamic behaviour within basins will also be strongly influenced by their three-dimensional density stratification (see for example Imberger and Patterson, 1990; Csanady, 1982). This property will depend both on local influences (eg solar heating, local wind-mixing) and on remote mechanisms (eg advection of buoyant river plumes from distant sources). The circulation will be driven by barotropic and baroclinic processes, with the relative prominence of either depending on the state of the stratification, and the nature and strength of the forcing mechanisms.

Past studies of Cockburn Sound (eg, Steedman and Craig, 1983) suggest that baroclinic processes will assume importance over barotropic processes when winds are less than order 5 m s^{-1}. This conclusion was based on analyses of limited basin-scale stratification data in conjunction with data of environmental forcings (eg wind and tide). As mentioned above, Steedman and Craig (1983) modelled the circulation of Cockburn Sound with a barotropic model, stating that the results were not valid for winds less than about 5 $m\ s^{-1}$. That study was the first to raise a most important issue in relation to predicting circulation and flushing of Cockburn Sound. That is under what physical conditions is the mixing and transport of the nearshore basins governed by barotropic processes, baroclinic processes, or by a combination of both? A sufficiently detailed appraisal of this issue was not found in the literature, and the following part of this report addresses this need by an evaluation and analysis of existing oceanographic and meteorological data from the following sources.

3.3.2 Data references

Environmental Resources of Australia Pty Ltd (a series of studies from 1969-1976)

Intensive hydrodynamic investigations were conducted before, during and after the causeway construction by the environmental consultants, Environmental Resources of Australia Pty Ltd (ERA). That consultant group performed its studies in the period 1969 to 1976, under commission by the then Commonwealth Department of Construction (now known as Australian Construction Services), motivated by a need to understand the hydrodynamic, and in turn water quality, implications of the causeway to the waters of Cockburn Sound.

Their study region comprised Cockburn Sound, Owen Anchorage and central Sepia Depression (west of the causeway).

The ERA studies involved intensive field measurements of currents, and salinity and temperature structure at temporal resolutions that captured short (of order hours and days), medium (of order weeks) and long (of order months and years) time-scale dynamical responses of the basin to environmental forcings. The field techniques of basin-scale salinity and temperature profiling, current metering, drogue tracking, dye tracking and meteorological data collection were employed, often with many of the parameters being monitored coincident in time.

Many of these measurements were conducted during periods when the nearshore waters were strongly stratified both vertically and horizontally and also during periods when the basin was essentially devoid of significant stratification, with circulation therefore governed by barotropic transport processes.

Of particular use are some repeated salinity-temperature profile runs around the entire study region where up to 33 stations were visited, morning and evening, continually over periods ranging from 3 to 15 days during different seasons of the year. In many of the reports the stratification data were presented as basin-scale contour plots of salinity and temperature along vertical and/or horizontal planes. Numerous drogue tracking studies were conducted that captured barotropic wind driven currents. Current metering was performed at many sites of the study region including some periods of very intensive flow monitoring under the causeway bridges. These studies provide an important insight into the hydrodynamic characteristics of Cockburn Sound and Owen Anchorage over a range of time scales, comprising hours, days, weeks and months

Steedman and Craig (1979, 1983)

Steedman and Craig (1979, 1983) collected detailed salinity, temperature and current measurements from local regions of Cockburn Sound and surrounding waters. They identified baroclinic structures and also measured currents during periods of intense winds when currents were barotropic. Steedman and Craig (1979) also performed a comprehensive statistical treatment of wind data from the 60 m station at the Fremantle Port Authority building.

Chiffings (1987)

Chiffings (1987) studied the ecology of Cockburn Sound and Owen Anchorage and investigated the response of phytoplankton to nutrient enrichment. In that study Chiffings (1987) had cause to analyse physical measurements of salinity and temperature structure and perform correlations between chlorophyll "a" distributions and salinity and temperature distributions.

R. K. Steedman and Associates (a series of studies during 1975, 1976 and 1981)

R. K.Steedman and Associates conducted a series of current metering studies in Cockburn Sound and Sepia Depression during 1975, 1976 and 1981. Currents were recorded throughout the year near the bottom at sites in central Sepia Depression. In addition a comprehensive statistical analysis of winds was made.

As part of the Cape Peron Outfall Study program, Steedman and Associates (in Binnie and Partners, Dec 1981) conducted salinity-temperature profile runs monthly during 1981 along a transect path from the west shore in Owen Anchorage out through the Carnac Island - Garden Island gap to the 40 m contour then down to directly offshore of either the causeway or central Warnbro Sound and then directly in towards shore. This data was used to indicate a seasonal pattern of onshore/offshore salinity, temperature and therefore density distribution to be established for the wider southern metropolitan waters based on monthly measurements.

Clark and Penrose (1981)

Clark and Penrose (1981) deployed current meters close to the bottom in Sepia Depression, just west of the causeway, from December 1979 to December 1980.

Department of Conservation and Environment of Western Australia (1978-1981)

The Department of Conservation and Environment of Western Australia (DCE), now known as the EPA, performed basin-scale salinity-temperature profiles at over 20 stations in Cockburn Sound and Owen Anchorage periodically (generally monthly) from 1978 to 1981. The stations were roughly equally spaced around these basins to provide broad coverage. In addition, two control stations were visited in central Warnbro Sound and central Sepia Depression west of the causeway. Some temporally intensive profiles were conducted at stations along the eastern margin of Cockburn Sound, such as diurnal work off the CBH jetty in Mangles Bay.

Environmental Protection Authority of Western Australia (1990-1991)

More recently, the EPA has conducted two summer surveys of the basin-scale salinity and temperature structure of Cockburn Sound and Warnbro Sound. In the 1989/90 summer 8 sites were monitored weekly in Cockburn Sound. In the 1990/91 summer 8 sites were monitored weekly in Warnbro Sound, with additional measurements of salinity and temperature profiles taken in central Sepia Depression on some occasions.

The following chapters make use of this comprehensive historical data set and investigate individual hydrodynamic mechanisms for Cockburn Sound and adjacent nearshore regions. The primary aim is to identify under what conditions the system is stratified (vertically or horizontally) and to then determine what are the likely dominant hydrodynamic mechanisms operating to mix and transport the water (and contained substances) under the range of physical regimes.

4 Mixing and transport in Cockburn Sound

4.1 Summer

4.1.1 Basin scale stratification under weak and strong wind conditions

The primary aim of this section is to demonstrate the characteristics of stratification in Cockburn Sound on a basin-wide scale as a function of wind strength. Investigations of structure on smaller vertical and horizontal spatial scales are conducted in proceeding sections.

Environmental Resources of Australia Pty Ltd conducted comprehensive three-dimensional ST surveys of Cockburn Sound over continuous 10 to 13 day periods during the summers of 1971 (ERA, April 1972) and 1972 (ERA, March 1973). The surveys encompassed both Owen Anchorage and Cockburn Sound and contained up to 30 stations. Generally, the complete grid of stations were visited twice daily.

The ST surveys utilised manually operated ST meters (Electronic Switchgear, and Yeo-Kal Autolab Model 602). These meters are specified to be accurate to within 0.03 ppt salinity and 0.1 ^{o}C. Most of the principal investigators were contacted by the author and it was stated that in general, calibrations of the meters were conducted with sufficient regularity that measurements were accurate to within 0.05 ppt and 0.1 ^{o}C. On days when instrument calibrations revealed unacceptable errors the results of the particular survey were rejected and the exercise in question was repeated.

Generally, temperature data were not presented by ERA (April, 1972,; March, 1973)) in the reports and the original records are no longer available. Hence, most of the discussion of the ERA data is restricted to interpretations based on salinity and meteorological information only.

At the time of the 1971 survey only the southern one third of the causeway was constructed. The length of the causeway was increased up to and including the High Level bridge by the time of the 1972 summer survey.

Both the 1971 and 1972 data sets show that the basin was vertically and horizontally stratified in salinity for various periods. Generally, in 1971 vertical salinity gradients were weaker than in 1972. As an explanation for this it is noteworthy that average wind velocities were much higher in 1971 compared to 1972, and their dynamical effect is is now investigated.

<u>Strong sea-breezes: 29 Nov - 10 Dec 1971</u>

Figure 4.1 presents the grid layout used for the surveys of 29-11 to 10-12-71. The winds during the 1971 survey (ERA, April 1972) displayed the typical local characteristics associated with strong afternoon sea breezes, with directions from the south-southwest and speeds generally greater than 5 m s^{-1} and often reaching 10 m s^{-1} by early afternoon. Table 4.1 presents a summary of the wind and air temperature characteristics for the period 29 Nov to 10 Dec 1971.

Table 4.1 General wind and air temperature characteristics of the Cockburn Sound region for the period 29 Nov to 10 Dec 1971. The data were collected by the Fremantle Port Authority (FPA), Fremantle, at the top of the FPA tower (height = approximately 70 m). Time series of these data are also presented in ERA (April, 1972).

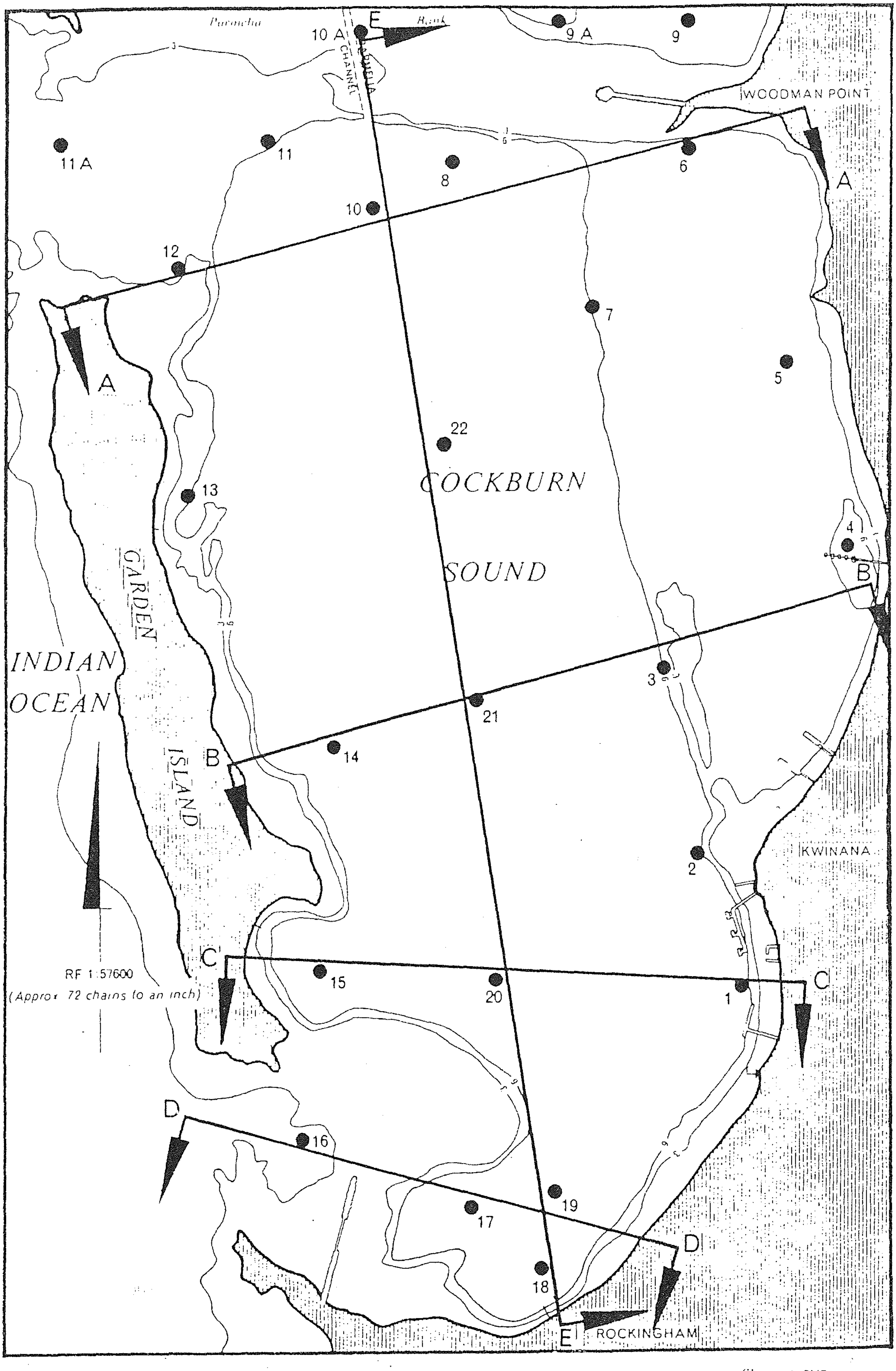


Figure 4.1 Grid layout and station numbers for the ERA salinity-temperature profile surveys conducted in Cockburn Sound during 29-11 to 10-12-71 (ERA, April 1972).

Date and approximate period of the day (AM or PM) 1971		General characteristics of the wind direction	Approximate range in the speed of the wind (m s^{-1})	Daily air temperature Max (°C)	Min
29 Nov	AM	predominantly SW	7-9	22.8	17.8
	PM	predominantly SW	7-9		
30 Nov	AM	SE	5	20.8	13.8
	PM	SW	7-10		
1 Dec	AM	E/SE	0-3	23.9	12.5
	PM	SW	5-10		
2 Dec	AM	S	3-5	23.2	12.1
	PM	SW	5-10		
3 Dec	AM	SE	3-5	22.6	12.6
	PM	SW	5-10		
4 Dec	AM	S	5-7	23.9	13.8
	PM	SW	5-12		
5 Dec	AM	S/SE	3-4	26.5	16.2
	PM	SW	10		
6 Dec	AM	E/SE	4-7	30.3	15.9
	PM	SW	7-10		
7 Dec	AM	S/SW	3-5	27.3	20.3
	PM	SW	5-10		
8 Dec	AM	SW	8-11	20.9	17.4
	PM	W/SW	8-11		
9 Dec	AM	W/SW	5-10	21.2	14.8
	PM	SW	5		
10 Dec	AM	SE	0-1	22.2	14.2
	PM	SW	5-7		

The maximum air temperatures ranged from about 20 to 35 °C throughout the period, and minimums ranged between about 13 and 20 °C (see Table 4.1).

The salinity stratification in the basin was generally weak, both in the vertical and horizontal throughout the 13 day period and can be described as follows:

- The basin was generally vertically isohaline after winds that were of the order of 5-10 m s^{-1} for extended periods. Vertical salinity differences (top-bottom) rarely exceeded 0.1 ppt and occurred sparsely around the Sound. Figure 4.2 presents the vertical salinity variation for the north, centre and south areas of the Sound and highlights this point. The relatively strong vertical salinity variation of 10 December is discussed below.
- The horizontal salinity structure was characterised by large patches of isohaline water having dimensions of 1-5 km with salinity variations between adjacent patches of the order of 0.1-0.3 ppt. Figure 4.3 is taken from ERA (April, 1972) and shows the above mentioned structure for 8 December 1971. Winds had been WSW at 8-11 m s^{-1} throughout the entire afternoon and morning. Figure 4.4 is a time series plot showing the maximum and minimum salinities recorded in the Sound for every day of the survey period. There was horizontal salinity variation on all days.
- Assuming temperature structure reflected salinity structure it can be concluded that the basin was mixed by winds of order 5-10 m s^{-1} but horizontal stratification was found to persist.
- During the summer 1971 survey fronts of relatively high salinity water were measured to enter the Sound via the northern and southern openings, as indicated by the plan contour plots of salinity structure from 6, 8 and 10 December in Figure 4.5.
- Originally, at the beginning of the field survey, the Sound was almost exclusively of 35.0 ppt salinity. It took about 6-12 days for the changing salinity structure to show clearly that new oceanic water had entered the Sound to the extent that all original water had been replaced. The total volume of water in the Sound was therefore estimated to have been exchanged with

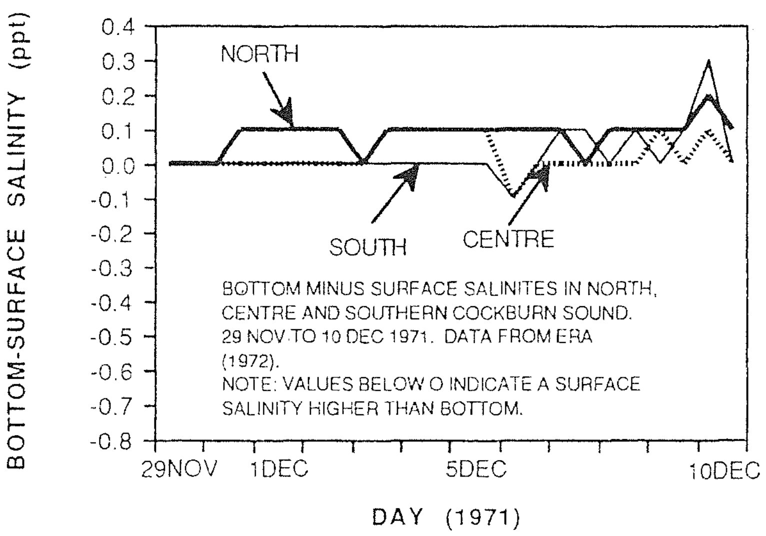


Figure 4.2 Bottom minus surface salinity variation during 29-11 to 10-12-71 in north, centre and south Cockburn Sound (data from ERA, April 1972).

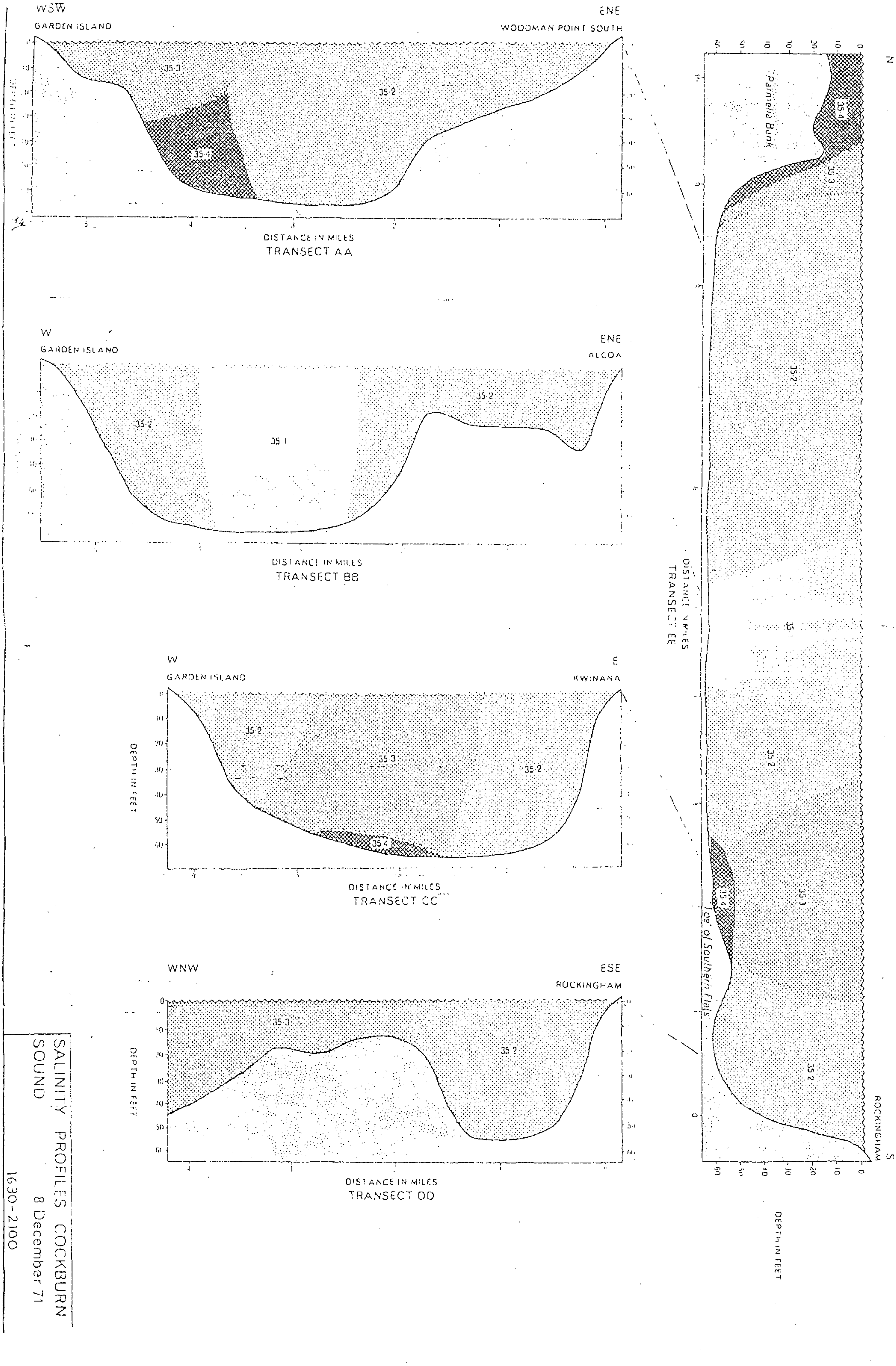


Figure 4.3 Vertical salinity structure of Cockburn Sound: 1630-2100, 8-12-71. See Figure 4.1 for grid details. Data from ERA (Apr, 1972).

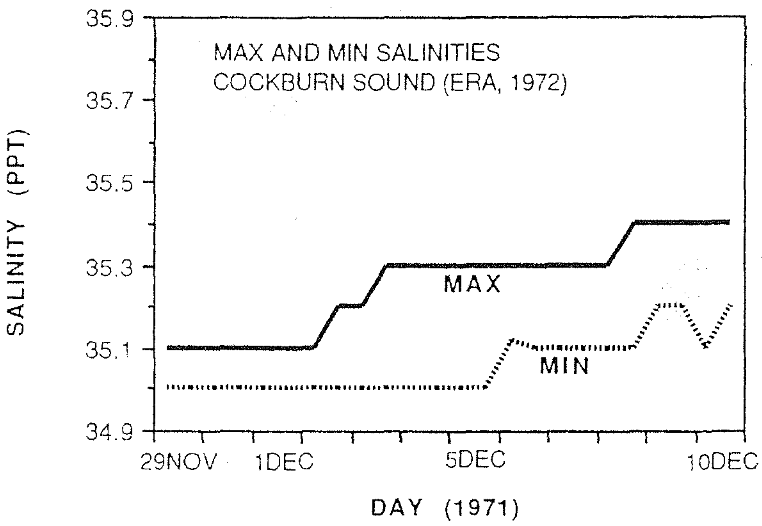


Figure 4.4 Time series of maximum and minimum salinities in Cockburn Sound from 29-11 to 10-12-71. Data from ERA (Apr, 1972).

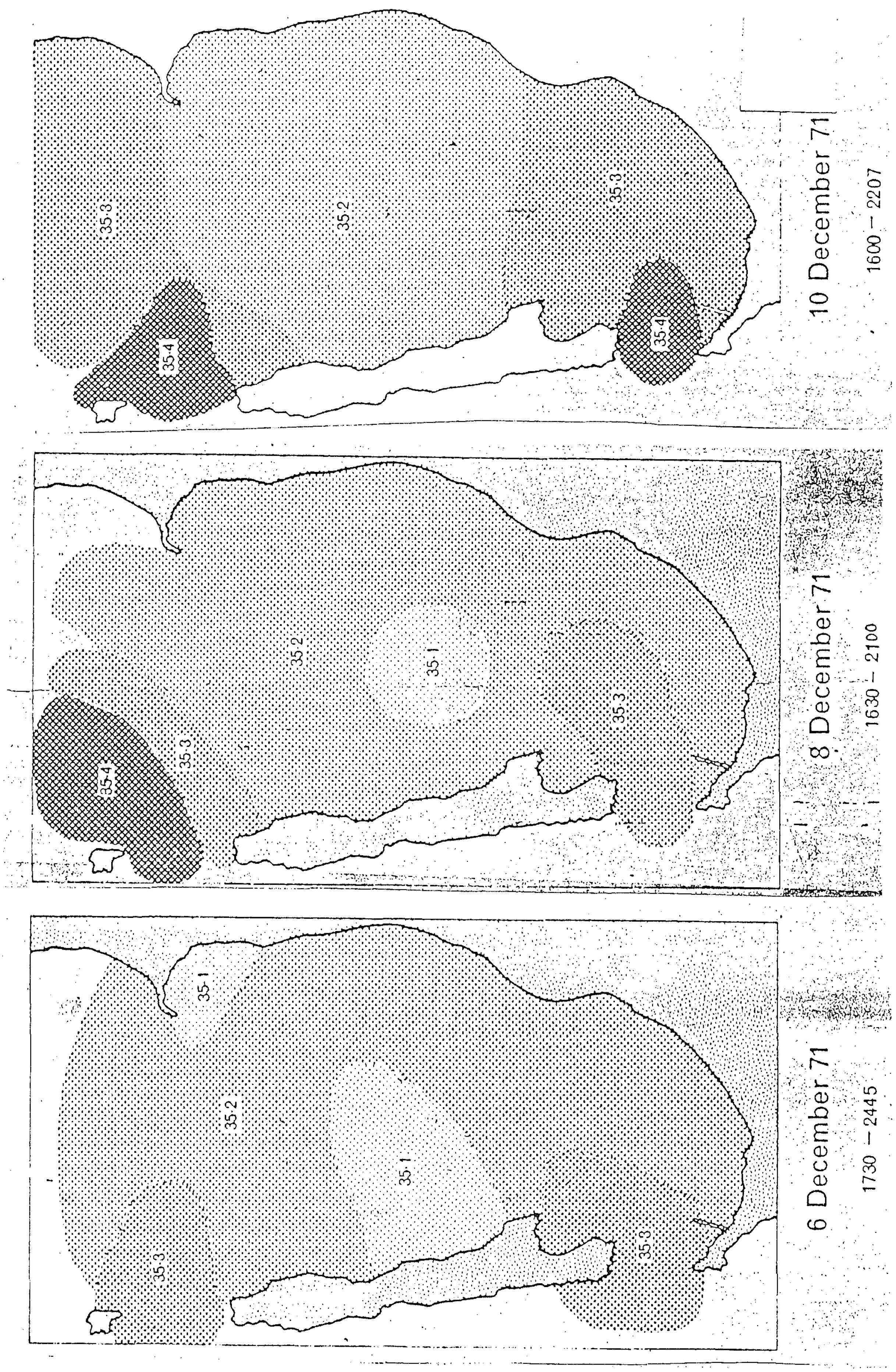


Figure 4.5 Surface salinity structure of Cockburn Sound: 6-12-71 (1730-2445), 8-12-71 (1630-2100), 10-12-71 (1600-2207). See Figure 4.1 for grid details. Data from ERA (Apr, 1972).

oceanic water in a time of 6-12 days. Figure 4.4 also supports this conclusion, by showing that after 6 days no evidence of the original salinity range (35.0-35.1 ppt) could be found in the Sound.

- Winds weakened to be of order 0-5 m s^{-1} on 10 December and the resulting salinity structure shows relatively stronger vertical and horizontal stratification (see Figure 4.6). It would appear that the density structure was both allowed to relax baroclinically and be strengthened by the intrusion of more saline oceanic waters as bottom gravity currents.

This final point leads into a discussion of the alternate wind scenario, that is when winds are relatively weak for prolonged periods in summer. This was the case during the 1972 ST survey (ERA, March 1973) and the associated basin-scale stratification characteristics are discussed below.

Mild hot summer periods: 6-15 dec 1972

The wind climate during the period 6-15 December 1972 was significantly milder than that for the summer field survey of 29 Nov - 10 Dec 1971. Table 4.2 presents wind and air temperature data for that period.

Table 4.2 General wind and temperature characteristics of the Cockburn Sound region for the period 6 Dec to 15 Dec 1972. The data were collected by the Fremantle Port Authority (FPA), Fremantle, at the top of the FPA tower (height = approximately 70 m). Time series of these data are also presented in ERA (March. 1973).

Date and approximate period of the day (AM or PM) 1972		General characteristics of the wind direction	Approximate range in the speed of the wind (m s^{-1})	Daily air temperature Max (^{o}C)	Min
6 Dec	AM	SE	4	33.7	18.2
	PM	SW	7		
7 Dec	AM	SE	7	34.6	17.7
	PM	SW	5		
8 Dec	AM	NW/NE	4	38.2	22.3
	PM	SE	2.5		
9 Dec	AM	E/NE	2-4	39.7	23.2
	PM	W/NW	3		
10 Dec	AM	E/SE	2-5	36.2	23.6
	PM	SW	4-5		
11 Dec	AM	E/SE	3-5	40.1	23.6
	PM	SW	4-5		
12 Dec	AM	NW-NE	0-3	29.9	20.5
	PM	W	3-5		
13 Dec	AM	E/SW	3-4	26.5	20.8
	PM	SW	9		
14 Dec	AM	SE	3-7	27.0	17.4
	PM	SW	3-5		
15 Dec	AM	SE	2-5	31.4	17.4
	PM	S/SW	6-8		

The winds during 6-15 Dec 1972 displayed typical summer characteristics, being morning offshore ESE breezes (less than 5 m s^{-1}) followed by afternoon SSW sea breezes (3-7 m s^{-1}). The meteorological conditions were strongly influenced by an intense high pressure system. As a result air temperatures were very high and winds generally relatively weak. Maximum air temperatures for the period ranged from about 25-40 ^{o}C and minimums from about 18-25 ^{o}C.

The salinity stratification was consequently allowed to develop with much stronger vertical and horizontal gradients than those recorded for the summer 1971 period, above. The salinity structure throughout the period is described in summary as follows. Figure 4.7 presents the grid of ST profile stations used throughout the exercise.

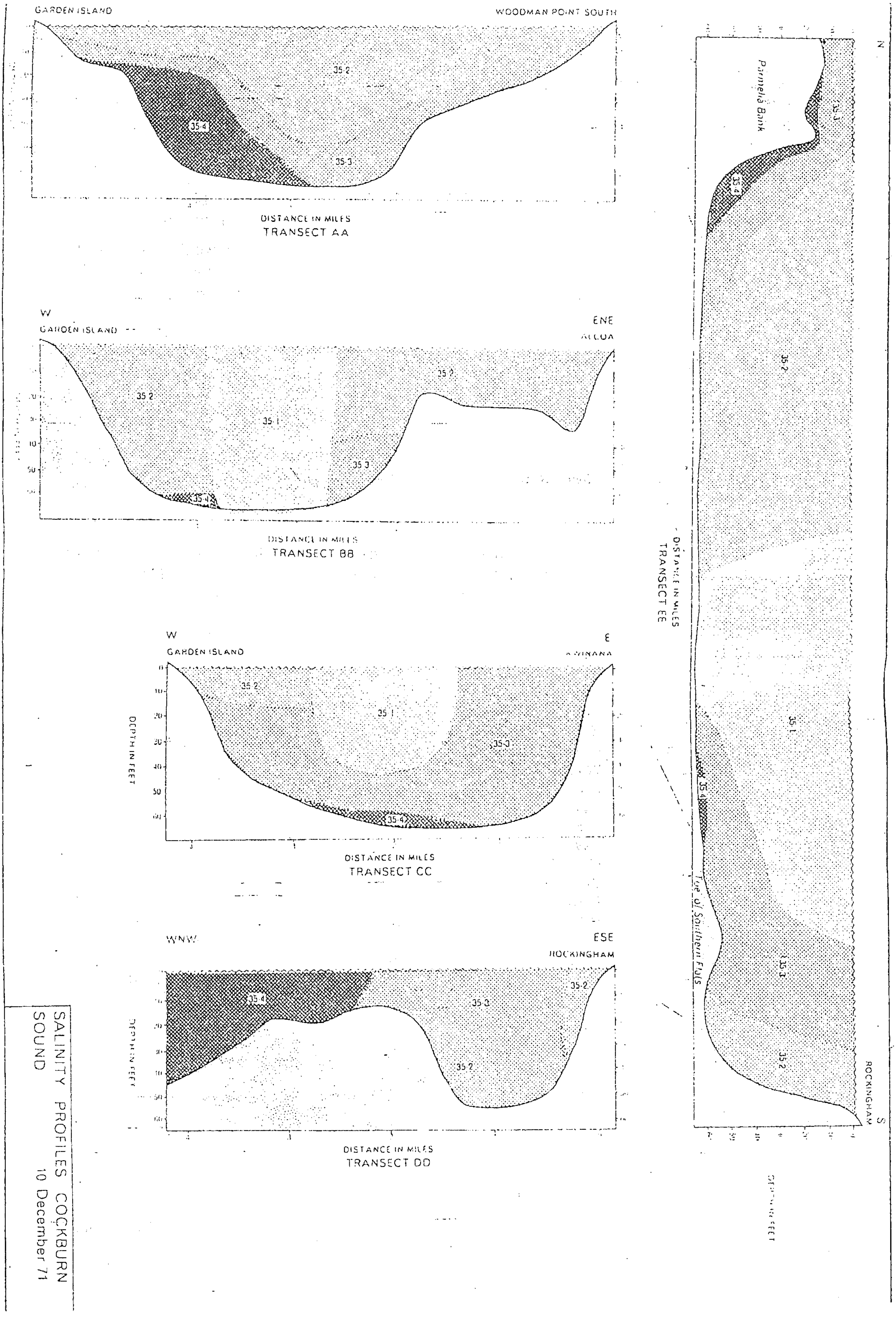


Figure 4.6 Vertical salinity structure of Cockburn Sound: 1600-2207, 10-12-71. See Figure 4.1 for grid details. Data from ERA (Apr, 1972).

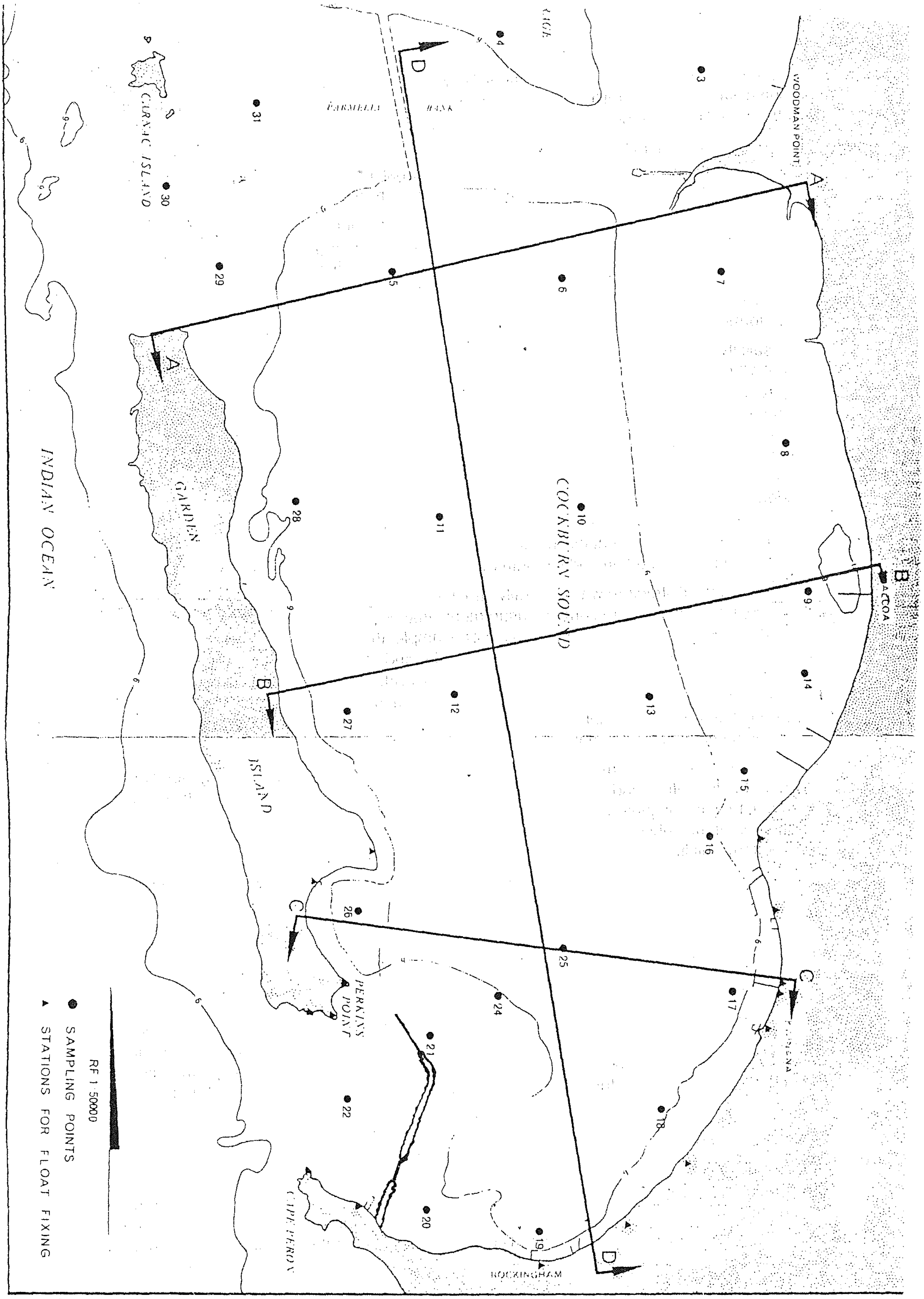


Figure 4.7 Grid layout and station numbers for the ERA salinity-temperature profile surveys conducted in Cockburn Sound during 6-15 Dec 1971 (ERA, March 1973).

- Figure 4.8 shows the general rise in the salinity of the Sound, and also shows that the water column was vertically stratified in salinity, with surface salinity generally greater than that at the bottom. Salinities ranged from 35.1-35.7 ppt on 6-12-72 to 35.4-35.9 ppt on 14-12-72.

- The basin was generally vertically and horizontally stratified in salinity throughout, with the horizontal surface salinity structure characterised by patches with spatial scales of order 1-7 km, and salinity differences between patches ranging from 0.1-0.3 ppt (see Figure 4.9).

- Daily temperatures rose sharply during the same period (Table 4.2), and this therefore suggests one possible explanation for the rather rapid rise in regional salinities, namely evaporation of nearshore waters during very hot conditions. It is estimated in Section 4.1.9 that evaporation rates could have been sufficient to produce such salinity increases. However, it is not possible from the data set to determine whether the observed salinity rises were formed insitu or due to the arrival of higher salinity waters in regional currents.

- The salinity data are also presented as basin-scale vertical contour plots in Figures 4.10, 4.11 and 4.12 for the days of 6, 9 and 13 December, respectively. The transect paths are shown in Figure 4.7. These plots indicated that vertical salinity gradients were in general monotonically decreasing with depth from the surface down. This would in general be a gravitationally unstable profile, unless stabilised by strong vertical heating of the water column. It can be inferred that vertical temperature differences must therefore have reached about 1-2 ^{o}C. Lateral and longitudinal gradients in salinity were common with frontal structures evident (see in particular the front at the northern boundary on 6 December in Figure 4.10). These data suggest there was significant baroclinic structure in the Sound throughout the entire survey period and that this mean characteristic was able to persist through various wind events, ranging in direction and strength (up to about 7 m s^{-1}).

- While the vertical structure was generally stratified in salinity throughout the period 6-15 December 1972 there were some measurements that displayed a vertically isohaline nature in response to increasing wind strengths. For example, the strong vertical salinity gradients that were allowed to establish during relatively mild wind conditions of the morning of 6 December were almost completely eliminated by relatively strong SW winds (at 7 m s^{-1}) later that day. The vertical contour plots in Figure 4.13 from the period 1800-2400 on 6 December show this feature. It is also interesting to note in Figure 4.13 that while the basin was vertically isohaline some horizontal variability in salinity persisted.

- The data set also gives some indication on the rate of restratification of a vertically isohaline salinity structure after winds subside. For example the vertically isohaline nature shown in Figure 4.13 was completely replaced by vertical salinity gradients throughout the whole basin by the end of the subsequent ST profile run (1300 7 December), as shown in Figure 4.14. The bottom salinities in the contours of Figure 4.14 are as low as 35.1 ppt, whereas the minimum salinity the previous evening was 35.4 ppt, and this indicates the relatively rapid intrusion of a bottom current of low salinity water during the intervening period. The most probable mechanism that could have led to this new salinity structure was bottom baroclinic intrusions of low salinity, but relatively cold and therefore denser, oceanic waters via the northern and southern openings. For bottom waters to have penetrated into the basin to the regions shown in Figure 4.14 in 12 hours they must have travelled at mean rates of the order of 8 cm s^{-1}. Calculating a baroclinic velocity, by using Equation A3.2, for such bottom currents, using a depth of say 10 m and density difference of say 0.2 kg results in a speed of the order of 5-10 cm s^{-1}, and this is roughly consistent with the measured rates. The inertial period is of order 1 day, and hence while rotational effects would have been important after this period, the mean structure could have been produced by the baroclinic exchange within 1 day.

Summary

For a mild hot summer period (air temperatures 20-40 ^{o}C, winds less than about 7 m s^{-1}) the basin exhibited vertical stratification of salinity, and probably density. Wind events greater than 7 m s^{-1} mixed the basin vertically but not horizontally. Baroclinic relaxation of the density structure then re-

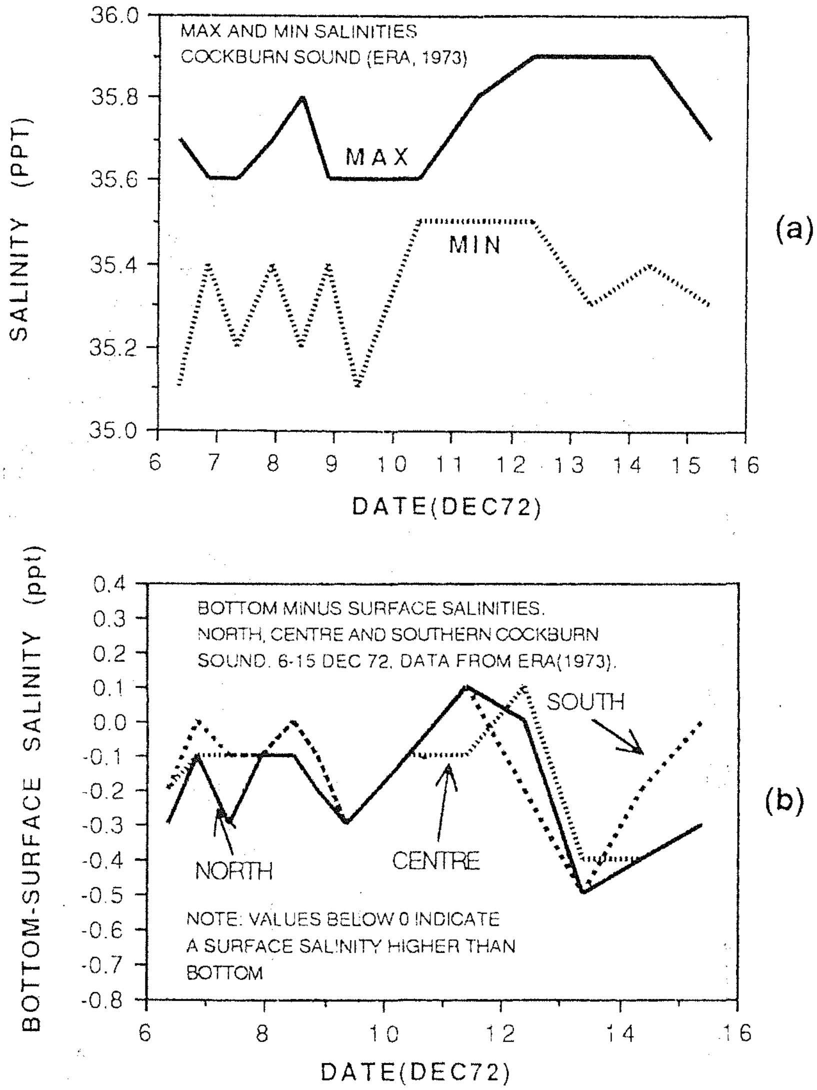


Figure 4.8 Time series of: (a) maximum and minimum salinity and (b) vertical salinity difference in Cockburn Sound during the period 6-15 Dec 1992. Data from ERA (March, 1973).

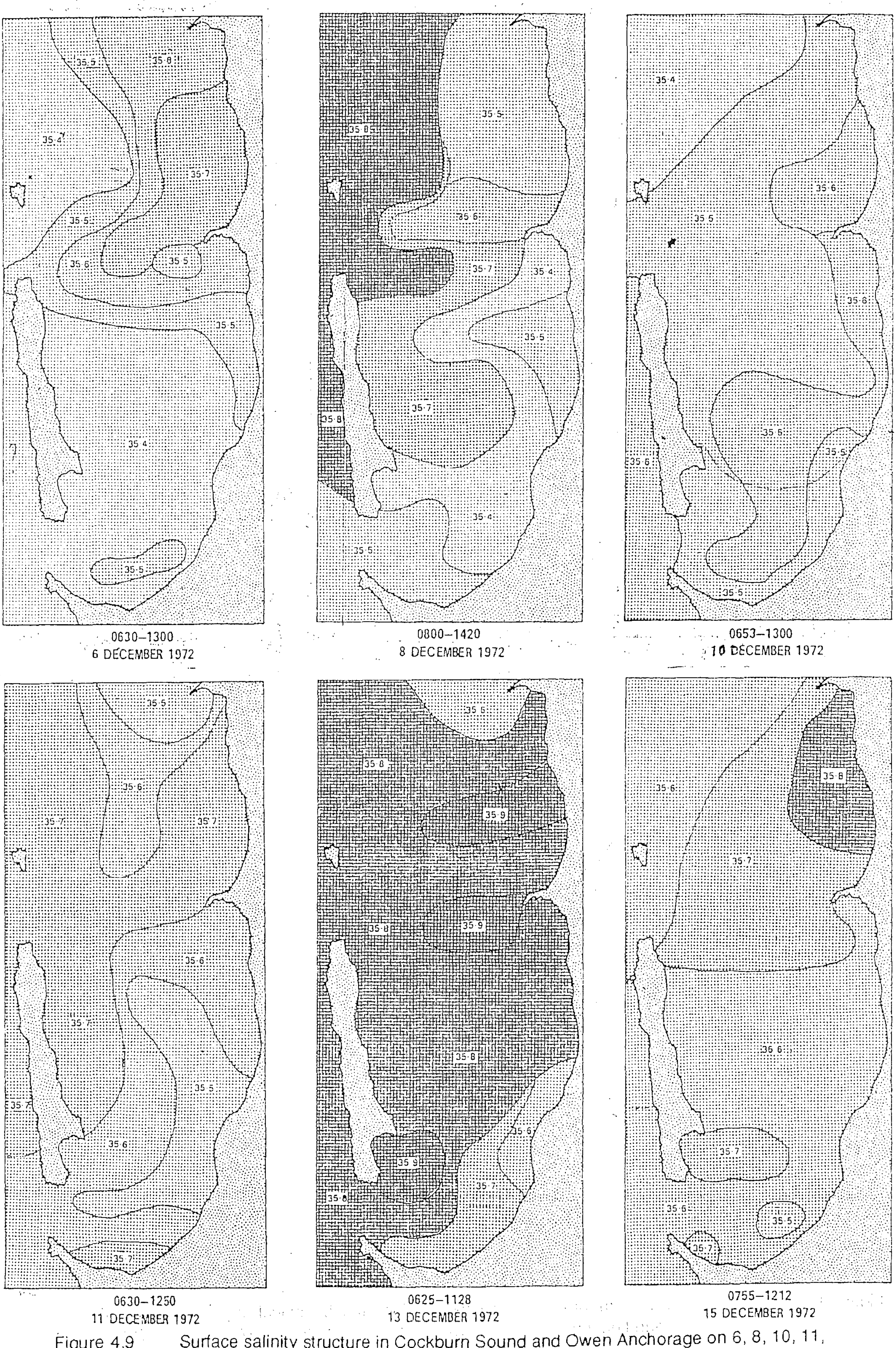


Figure 4.9 Surface salinity structure in Cockburn Sound and Owen Anchorage on 6, 8, 10, 11, 13, 15 Dec 1972. See Figure 4.7 for grid details. Data from ERA (March, 1973).

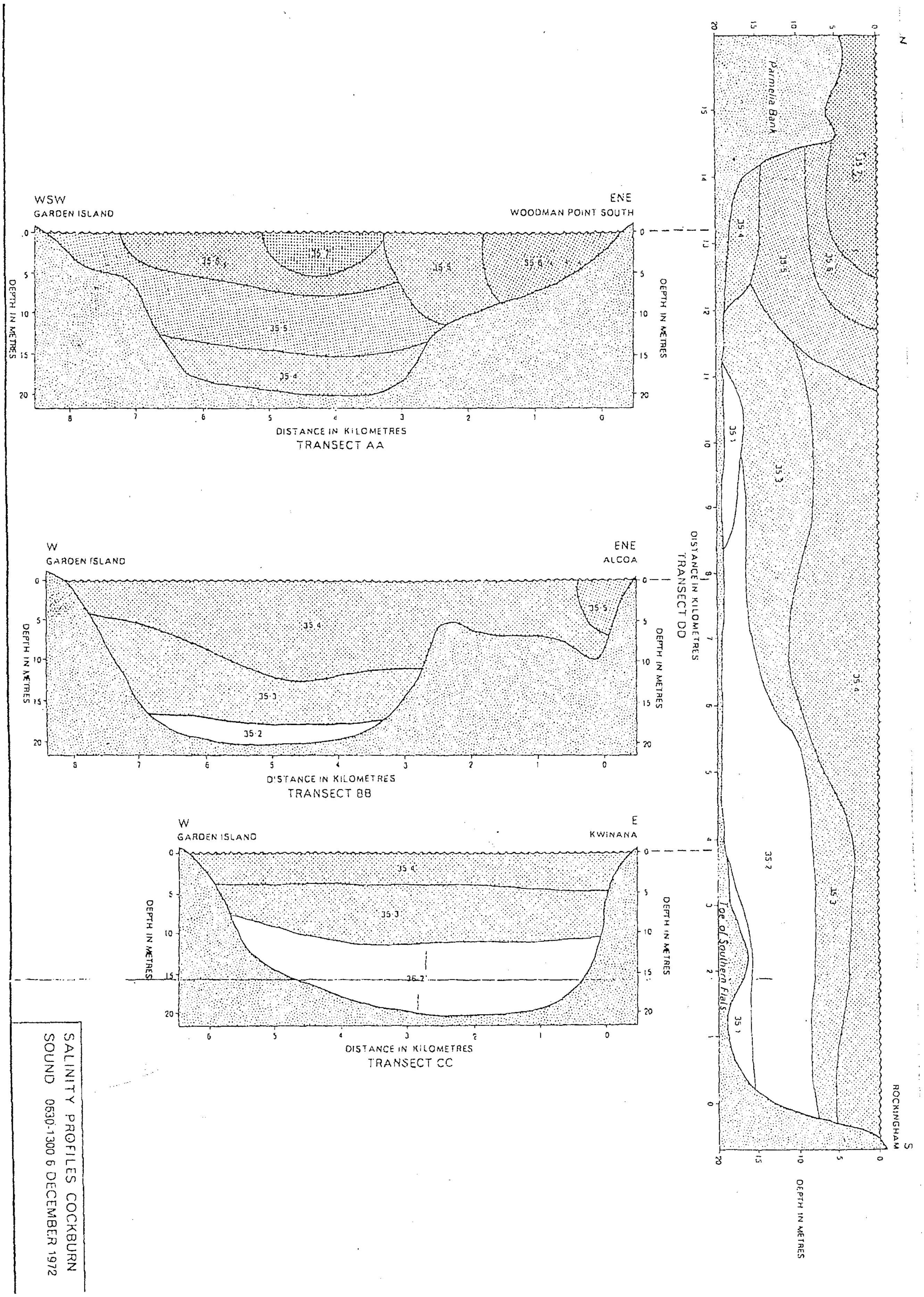


Figure 4.10 Vertical salinity structure of Cockburn Sound: 0630-1300, 6-12-72. See Figure 4.7 for grid details. Data from ERA (March, 1973).

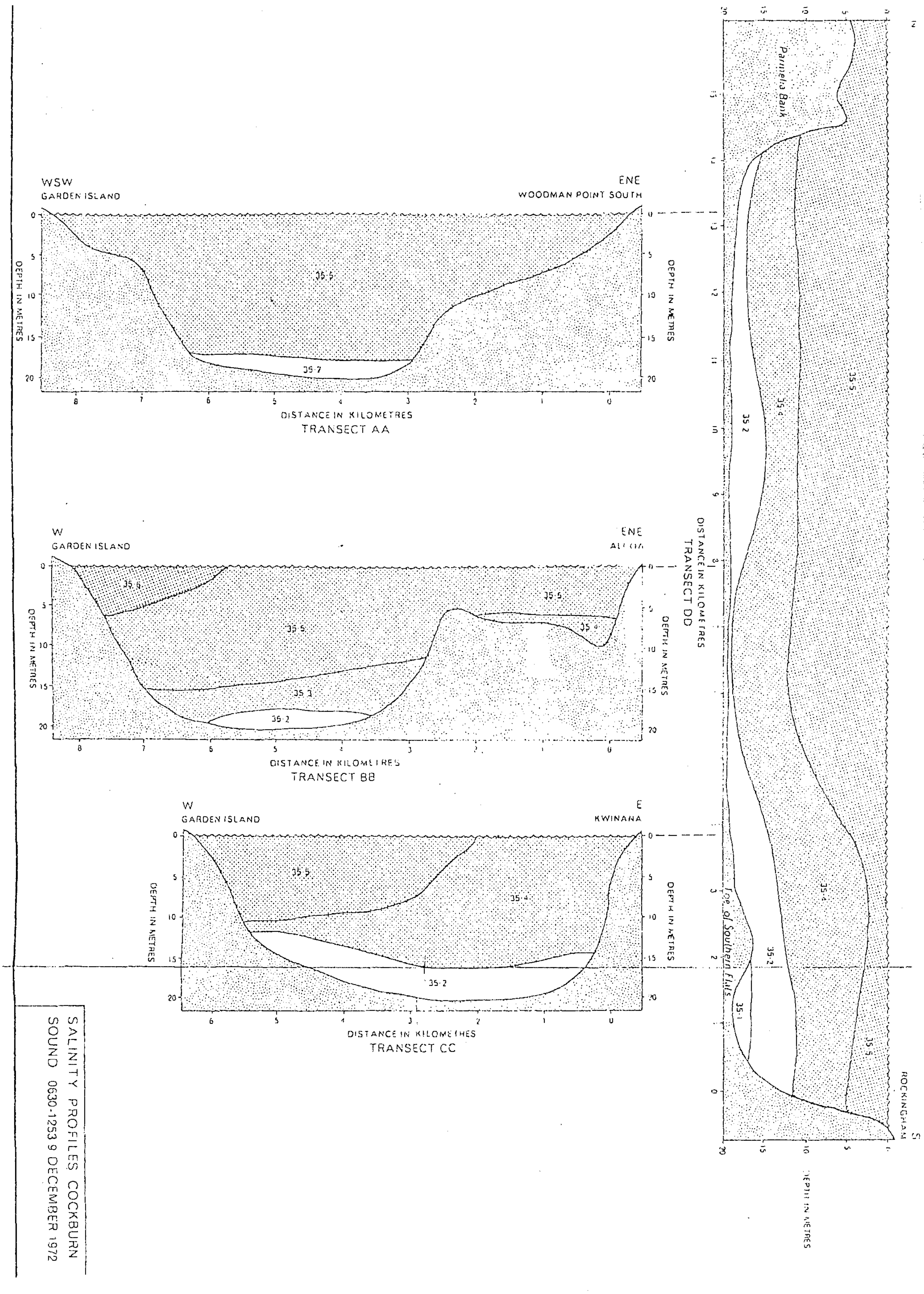


Figure 4.11 Vertical salinity structure of Cockburn Sound: 0630-1253, 9-12-72. See Figure 4.7

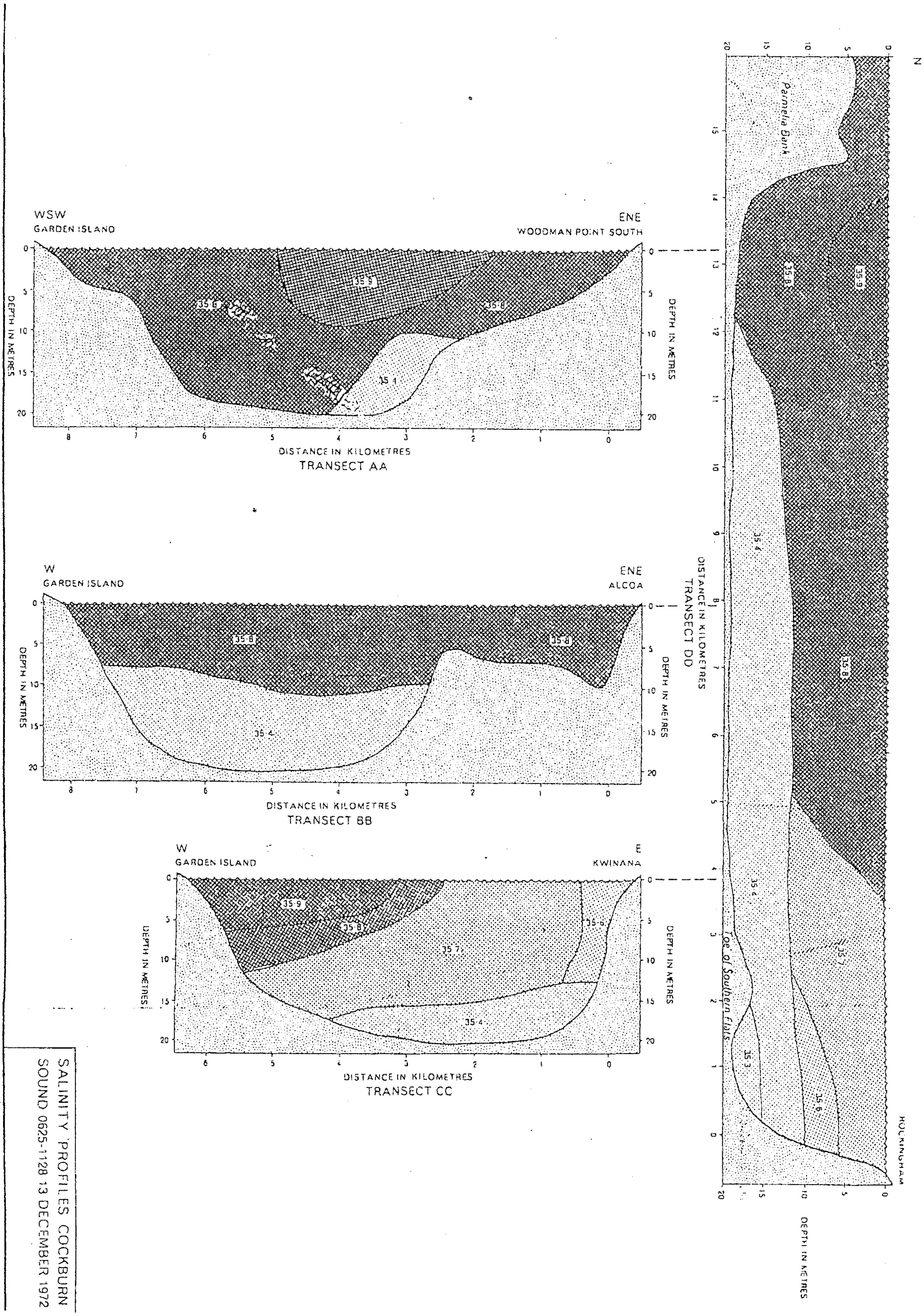


Figure 4.12 Vertical salinity structure of Cockburn Sound: 0625-1128, 13-12-72. See Figure 4.7 for grid details. Data from ERA (March, 1973).

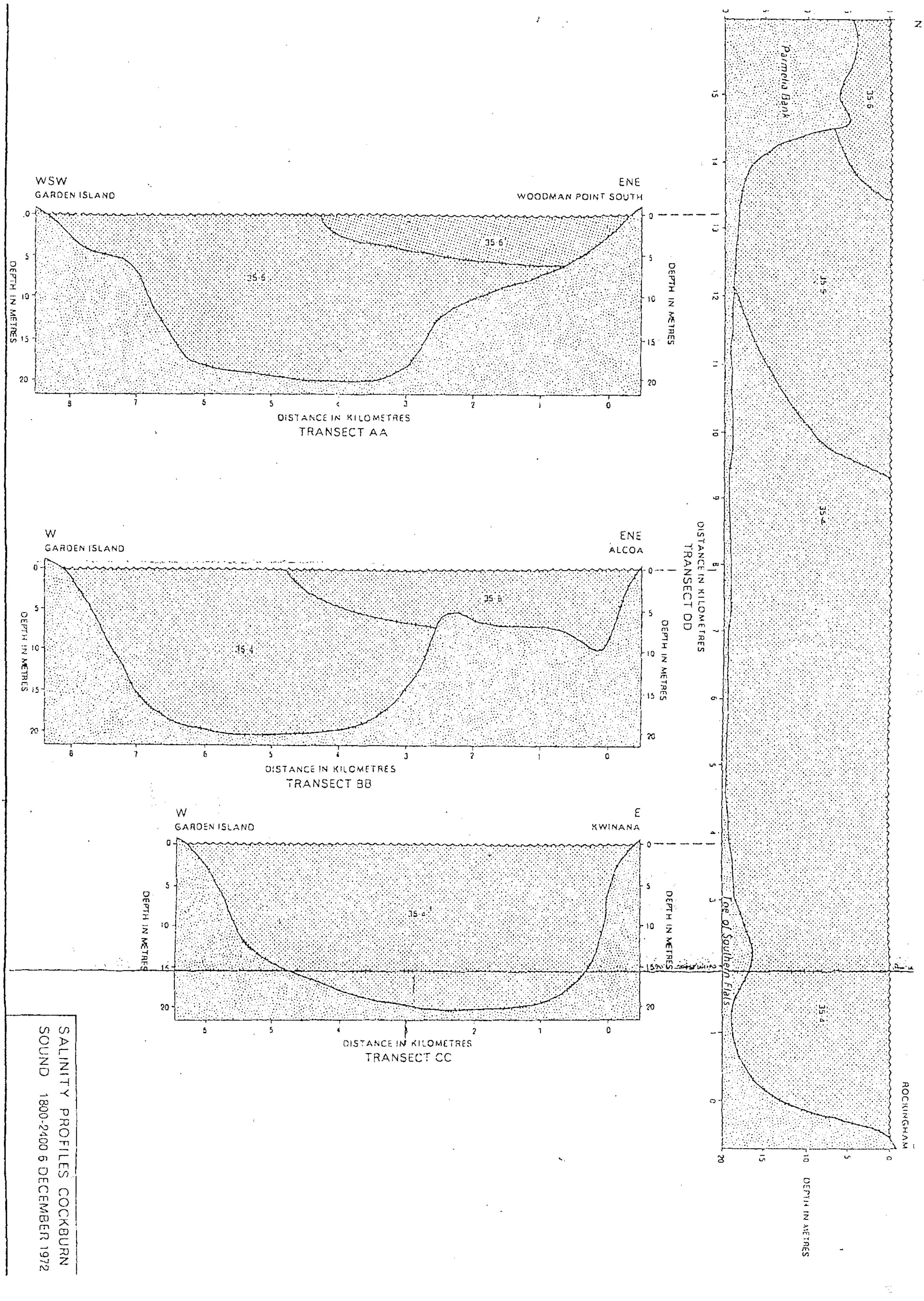


Figure 4.13 Vertical salinity structure of Cockburn Sound: 1800-2400, 6-12-72. See Figure 4.7 for grid details. Data from ERA (March, 1973).

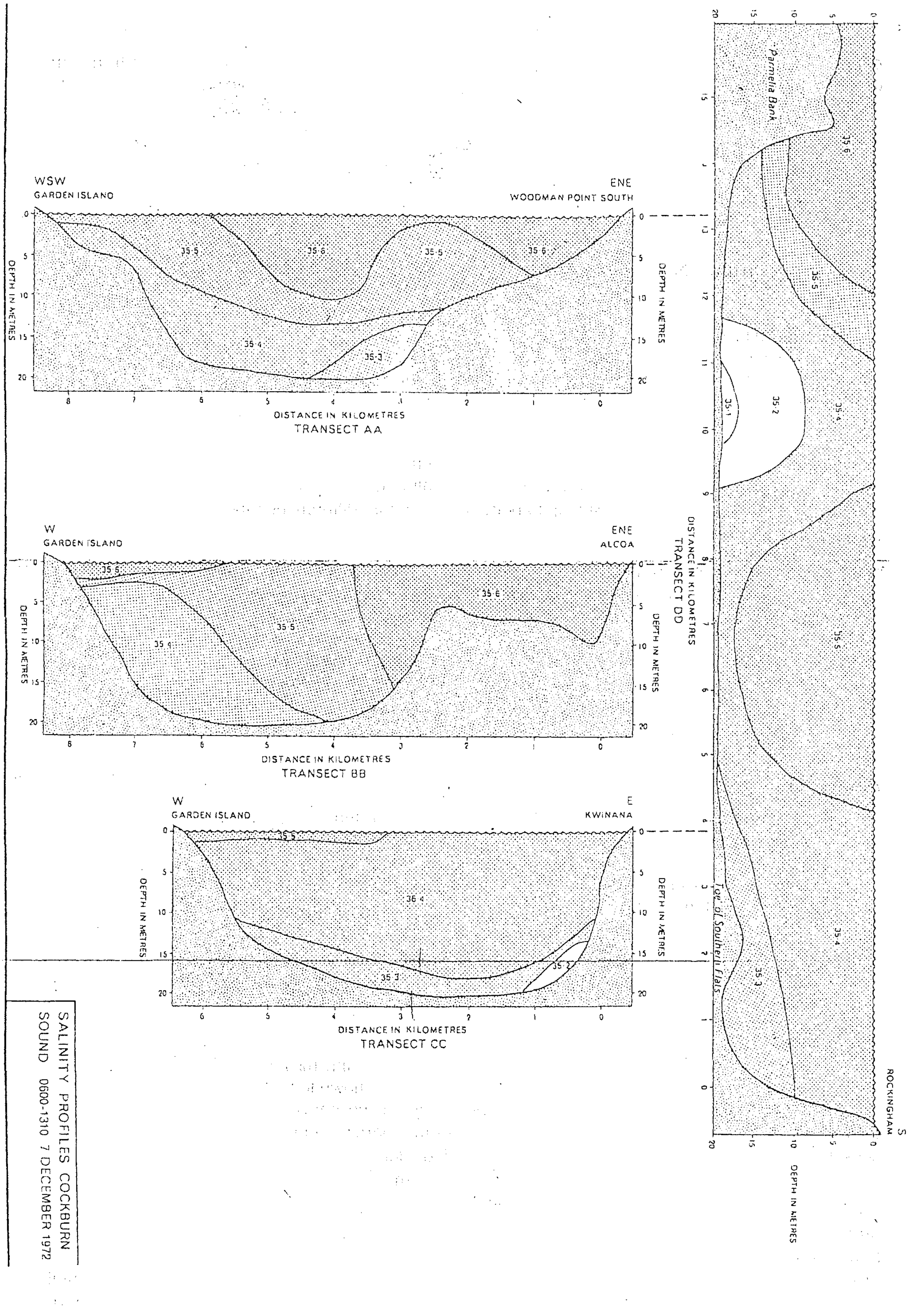


Figure 4.14 Vertical salinity structure of Cockburn Sound: 0600-1310, 7-12-72. See Figure 4.7 for grid details. Data from ERA (March, 1973).

established basin-scale vertical stratification within 24 hours, with the rate of horizontal transport consistent with estimates based on densimetric velocities. Relatively high salinity water appeared to gravitate in via the northern and southern openings.

For a relatively energetic summer period (daily sea-breezes of 5-12 m s^{-1}) the basin was generally vertically isohaline. Vertical stratification was able to re-form during a period of calm (<1 m s^{-1}) by what appeared to be baroclinic relaxation of a previously horizontally stratified structure, in a similar manner to that described above.

4.1.2 Stratification and mixing in the nearshore regions

A more detailed investigation of the temporal characteristics of vertical temperature gradients along the nearshore regions of Mangles Bay was possible by plotting DCE temperature profile data collected at the end of the CBH Jetty 600 m offshore at 20 m depth during 1977 and 1978. Salinity data were not collected.

Weekly data

The temperature contours in Figure 4.15 were derived from weekly data between August 1977 and November 1978. The data suggest that vertical temperature gradients were most prevalent during the spring and early summer periods with top to bottom temperature differences ranging from 0 to 5 ^{o}C.

Daily data

It would appear that vertical temperature stratification was negligible in the summer and autumn of 1978. However, a closer scrutiny of the details of vertical temperature stratification in summer is afforded the considering the time series contours in Figure 4.16, constructed from daily data for January 1978. The water column was strongly stratified in temperature for over two thirds of the days monitored, and vertical isothermality generally occurred only when winds were greater than about 10 m s^{-1} during or shortly prior to the data collection. Vertical temperature differences (top minus bottom) of up to 2 ^{o}C were common. Assuming that vertical temperature structure reflected the vertical density structure then these data suggest that in the nearshore waters vertical density stratification persisted for winds less than about 10 m s^{-1}.

Hourly data

One diurnal stratification event was monitored at Station 214 during 5 and 6 January 1978 and the resulting temporal variation in vertical temperature stratification is shown in Figure 4.17. The stratification intensified throughout the morning of 5 January during which time winds were southerly at about 5-10 m s^{-1}. Winds shifted to SSW and strengthened to about 10-12 m s^{-1} by 1300 and the effect on the vertical temperature stratification was to almost completely eliminate it after about 1700. Winds were sustained at about 10 m s^{-1} until 2400 on 5 January but swung to SE and weakened to about 5 m s^{-1} by 0300 on 6 January. As shown in Figure 4.17 the vertical temperature stratification at 2400 was distinctly different to the day-time case because the coldest water resided at the surface during the night. A possible reason for this temperature inversion was that baroclinic flows of relatively low salinity water entered the nearshore region as a surface flow that had been cooled during the preceding night. An alternative explanation could be the baroclinic advection of warmer, saltier waters into the bottom region during the evening after the day-time wind mixing event that may have left Mangles Bay vertically mixed but horizontally stratified, as was shown to be typical for Cockburn Sound by the contours presented in Section 4.1.1, above. Since no salinity data were collected these explanations are at best postulation. The contours for the morning and afternoon of 6 January again show the diurnal heating pattern of surface waters.. Winds during that morning were about 5 m s^{-1} from the SE and then swung at about 1200 to be SSW and 7-8 m s^{-1}.

Steedman and Craig (1979) performed longitudinal transects of salinity, temperature and currents by profiling the eastern margins of Cockburn Sound at a number of stations along transect lines perpendicular to the shore. They found these parameters to exhibit structure with length scales of order less than 1000 m. Vertical density stratification values of up to 0.2 kg m^{-3} and horizontal gradients of up to 0.2 kg m^{-3} between the eastern flats and adjacent deep basin were measured.

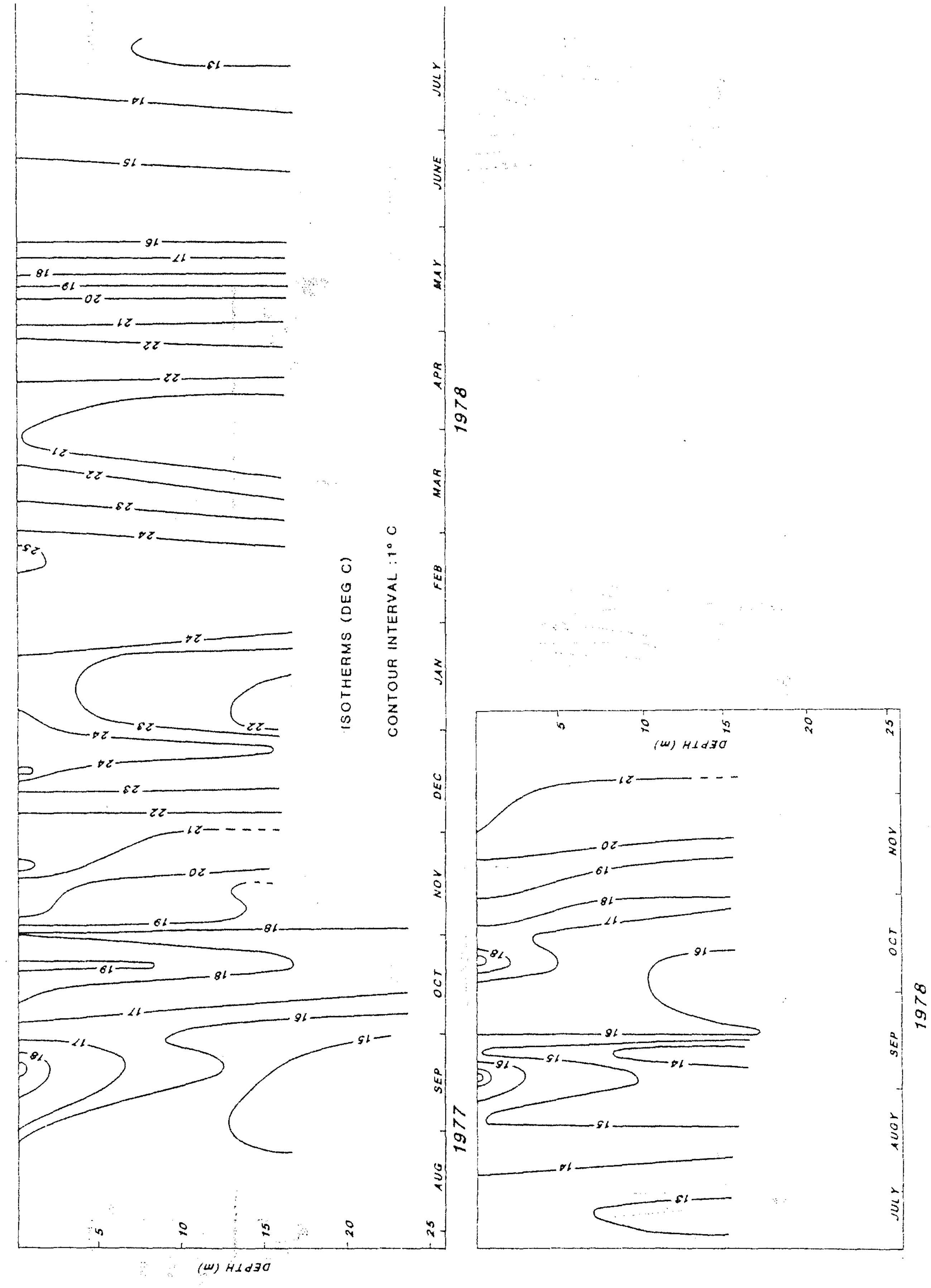


Figure 4.15 Time series contour of vertical temperature structure at station 214 (end of CBH jetty, Mangles Bay, see Figure 4.18) from weekly profiling during Aug 1977 to Nov 1978. Data from DCE.

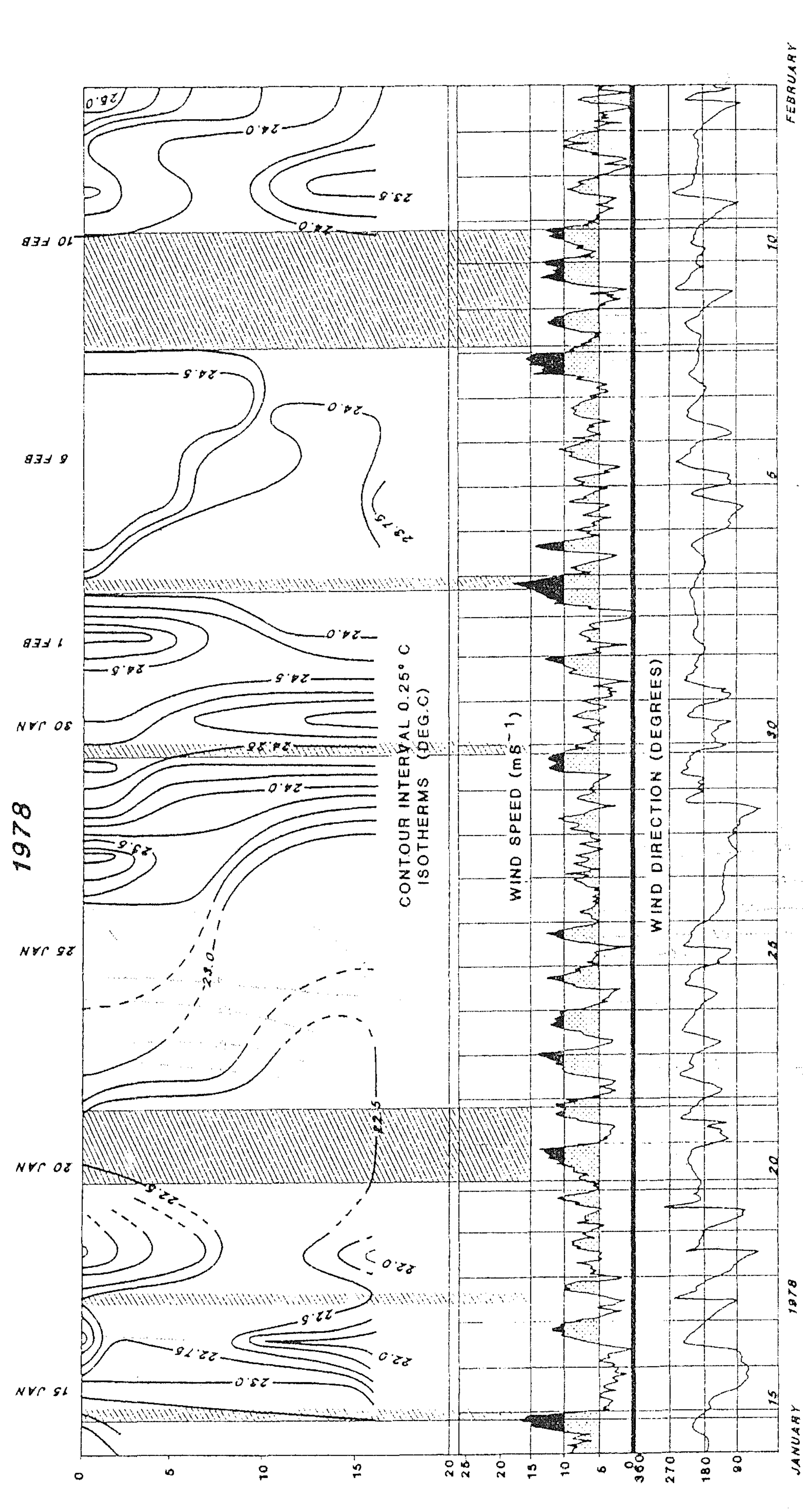


Figure 4.16 Time series contour of vertical temperature structure at station 214 (end of CBH jetty, Mangles Bay, see Figure 4.18) from daily profiling during 14-1 to 13-2-78. Data from DCE.

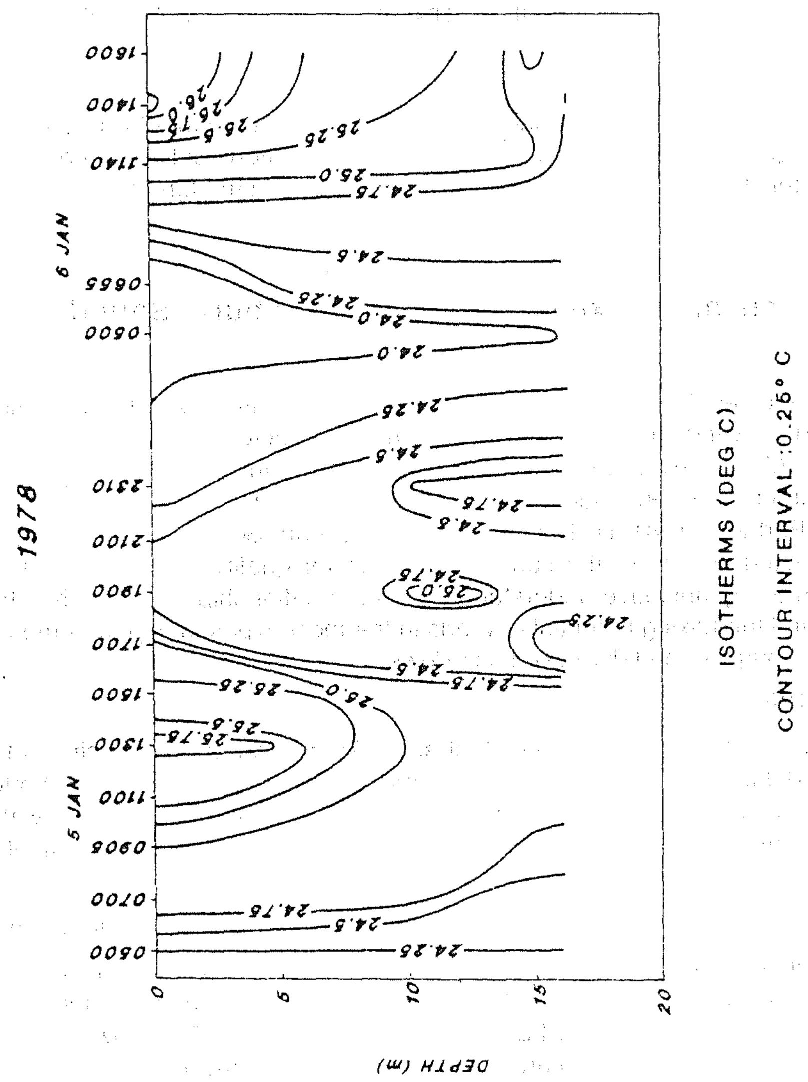


Figure 4.17 Time series contour of vertical temperature structure at station 214 (end of CBH jetty, Mangles Bay, see Figure 4.18) from hourly (approx.) profiling during 0500 5-1-78 to 1600 6-1-78. Data from DCE.

Velocity profiles revealed the occurrence of "coastal jets" along the eastern side of Cockburn Sound with cross-sectional dimensions of order 10 m in the vertical by 500 m in the horizontal and speeds up to approximately 10 cm s^{-1}. These finer scale features were recorded by Steedman and Craig (1979) only between March and May of 1977 but it was believed that they occur throughout the year.

Summary

It would appear therefore, on the basis of daily and hourly vertical temperature time series data in the nearshore regions of Mangles Bay, that thermal stratification undergoes classical diurnal heating patterns due to day-time heating by shortwave radiation. Winds under about 10 m s^{-1} appeared to be unable to break this structure down, however when winds were of the order of 10 m s^{-1} or greater for more than a few hours at a time the vertical structure was effectively destroyed.

The water temperature variation suggests that at night temperatures can be lowered by atmospheric cooling by up to 2 ^{o}C and therefore penetrative convection could be a potentially important vertical mixing agent during nights in summer. This point is discussed further by theoretical analysis in Section 4.1.9, below.

More detailed measurements, ideally utilising CTD instrumentation, would be required over diurnal time scales for a range of wind conditions in order to obtain more definitive conclusions on the hydrodynamic characteristics of heating and cooling and fine scale structure in the nearshore regions of the Sound.

4.1.3 Stratification and mixing in central Cockburn Sound

As discussed in Appendices A3 and A4, the vertical density stratification (due to temperature and salinity gradients) and the wind strength are the most important factors affecting the vertical structure of the water column. Many measurements of vertical structure and corresponding wind velocity in central Cockburn Sound have been made during a number of past investigations (R.K. Steedman and Assoc, in Binnie and Partners, 1981; DCE data from the Cockburn Sound Environmental Study 1976-1979; EPA data collected as part of the summer 89/90 water quality survey of Cockburn Sound). These data afford a more quantitative understanding of the relationship between the strength of the vertical stratification and the mixing potential of winds in the most exposed region of the Sound. They are re-analysed for this purpose and discussed as follows.

DCE data: 1979-1981

Vertical ST profiles were collected monthly in Central Cockburn Sound at DCE site 171 (see Figure 4.18) during the period June 1979 to August 1981. Time series plots of surface and bottom salinities (with associated vertical salinity differences) and surface and bottom temperatures (with associated vertical temperature differences) are presented in Figures 4.19 and 4.20, respectively. Features indicated by these data are as follows.

- The Sound displays a clear seasonal cycle of heating and cooling, and salinity variation.

  Salinity can vary from about 34 ppt in winter to about 37 ppt in summer. The summer salinity maxima are similar to those measured 40 km to the north at the nearshore station of Waterman Bay by CSIRO, as shown in Figure 4.21, taken from ERA (July 1971). However, the minima in Cockburn Sound (as low as 34 ppt) are significantly lower than those at Waterman Bay. The lower salinities in the Sound are due to brackish water flows from the Swan River in winter, as discussed in Section 4.3, below. There are no local river outflows near Waterman Bay. The hypersaline values recorded at both sites in summer (up to about 37 ppt) suggest that evaporative effects are similar at both sites. Pearce and Church (1992) show that in summer salinities at the CSIRO Rottnest site are significantly lower than in the nearshore regions of Waterman Bay and Cockburn Sound, suggesting that evaporation of nearshore waters is an important physical characteristic of Perth's coastal waters.

- Vertical salinity difference between the surface and bottom ranged between 0 and 1.25 ppt in

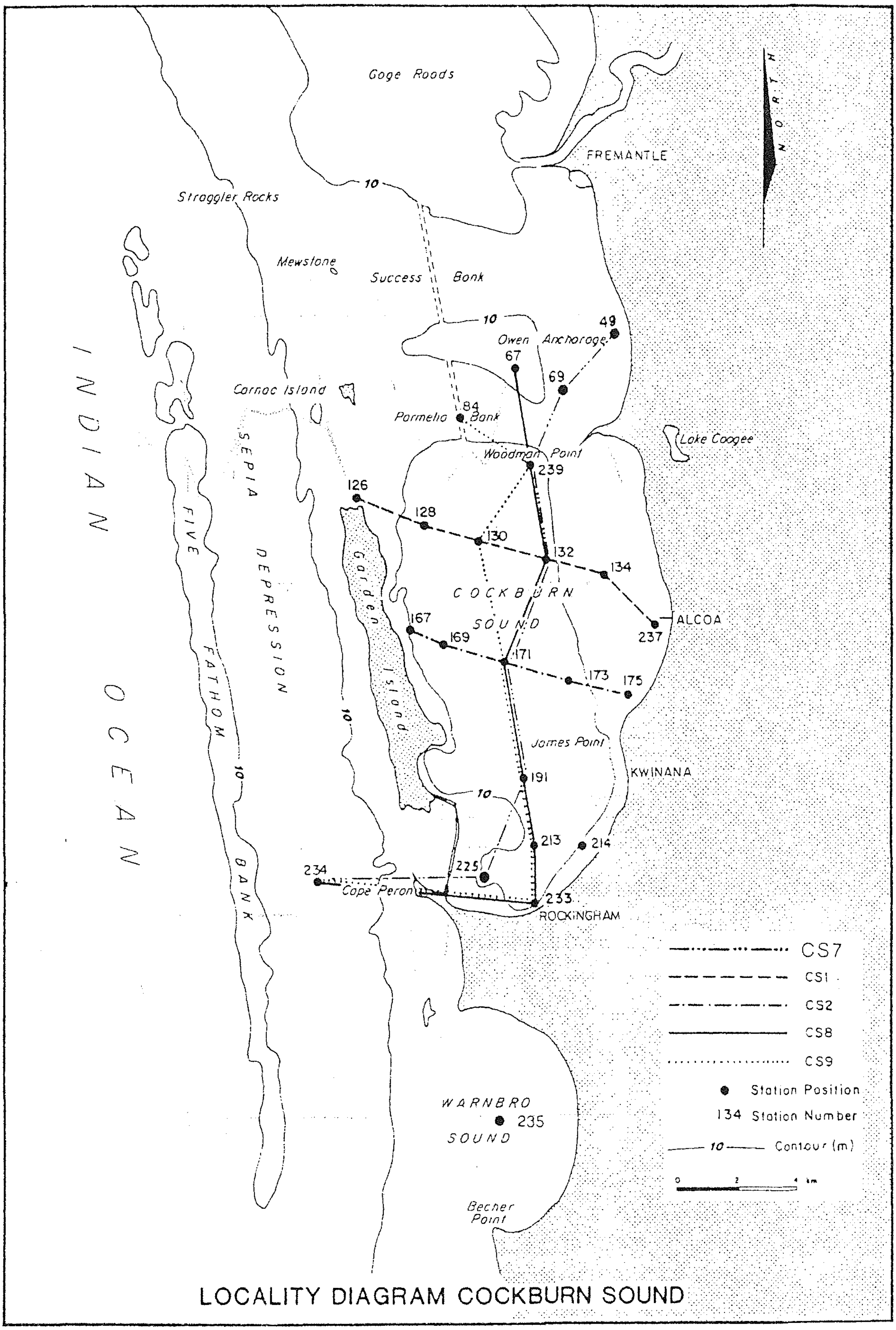
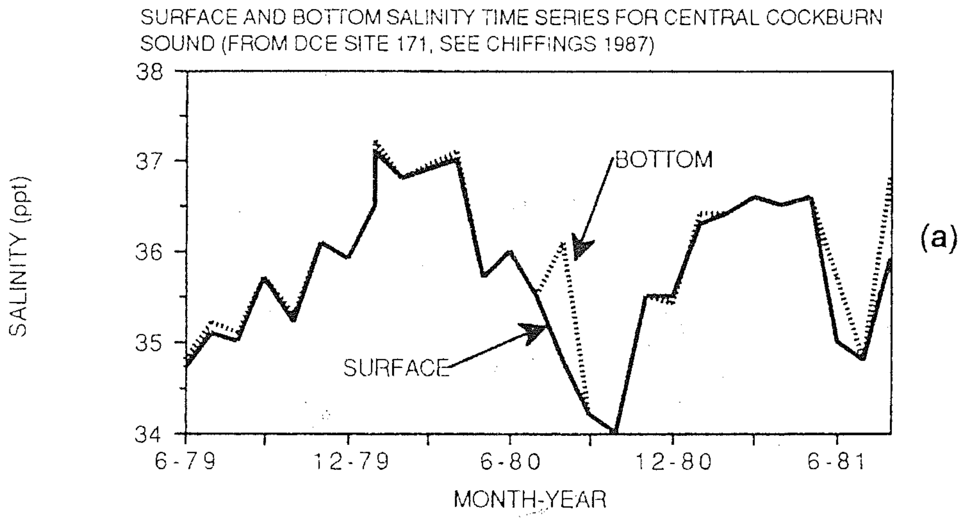


Figure 4.18 Grid of stations visited approximately monthly in Cockburn Sound by DCE during its water quality monitoring programme of 1977-1981 (see Chiffings, 1987). Transects chosen for ST contouring in this report are shown and identified in the legend.



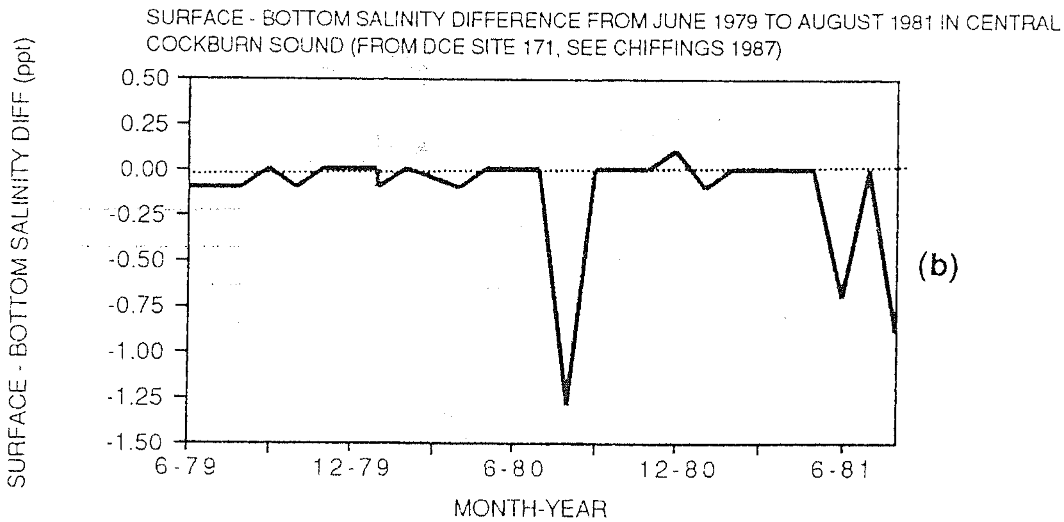
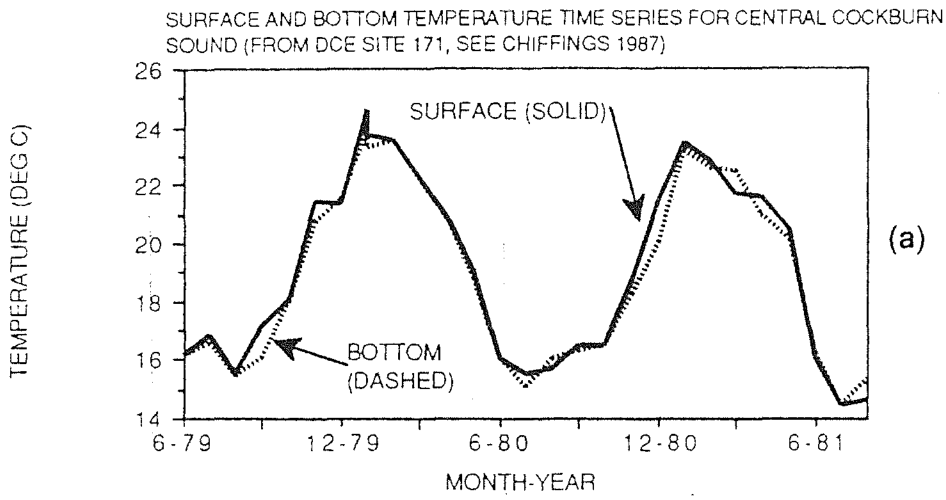


Figure 4.19 Time series of: (a) surface and bottom salinities, and (b) surface minus bottom salinity difference from monthly measurements at DCE site 171 (see Figure 4.18) from June 1979 to July 1981.



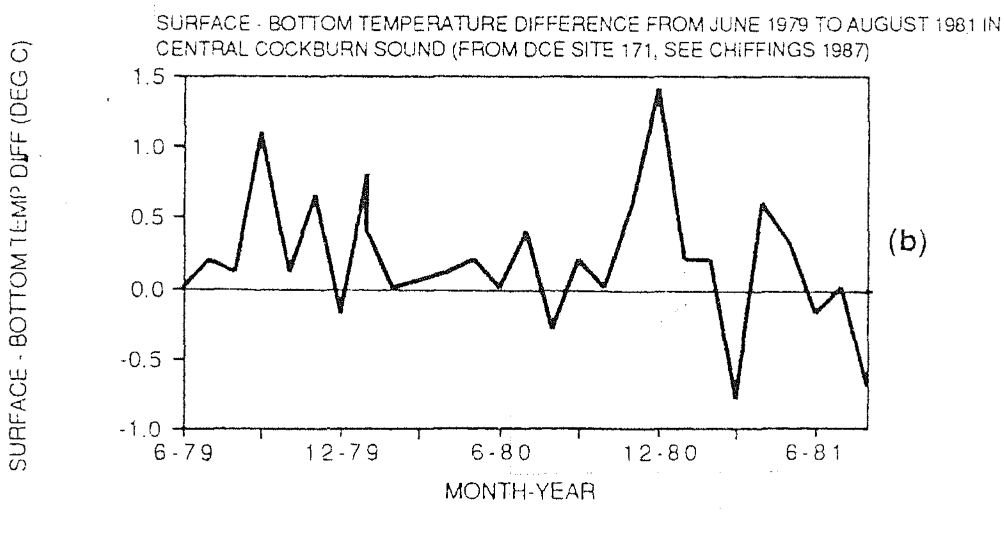


Figure 4.20 Time series of: (a) surface and bottom temperatures, and (b) surface minus bottom temperature difference from monthly measurements at DCE site 171 (see Figure 4.18) from June 1979 to July 1981.

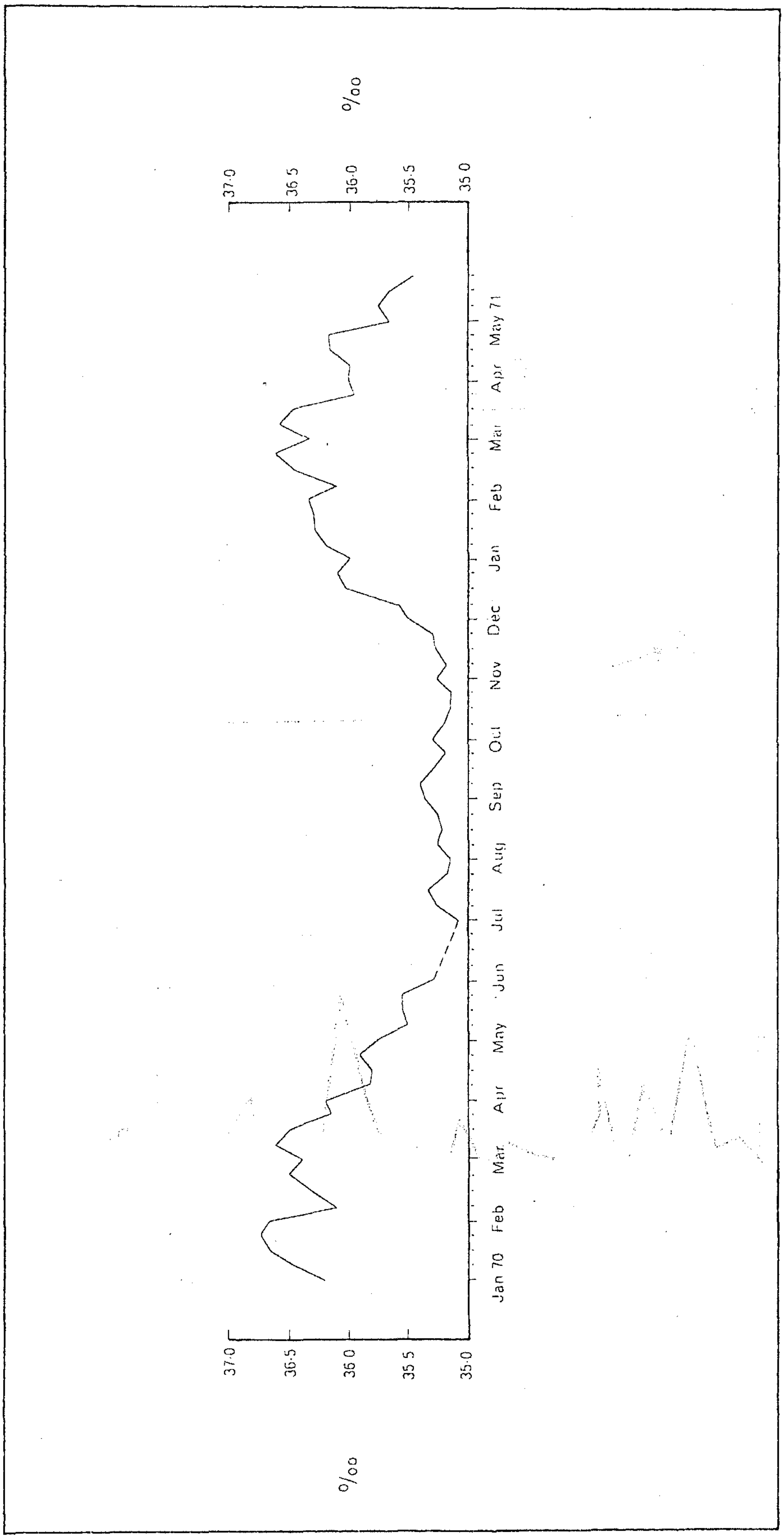


Figure 4.21 Time series of nearshore seawater salinity (parts per thousand) at the Waterman Bay Marine Research Laboratory from Jan 1970 to May 1971, collected weekly by CSIRO (reproduced from ERA (July 1971)).

central Cockburn Sound. Surface salinity was almost always less than or equal to bottom salinities. Greatest differences occurred in winter due to freshwater inputs from Swan River discharges, but during other seasons the differences were generally less than or equal to about 0.1 ppt.

- Temperature varies from about 14 ^{o}C in winter to about 25 ^{o}C in summer in Cockburn Sound and this variation is in response to the seasonal variation in air temperatures (see also Hodgkin and Phillips, 1969). Surface temperatures are generally higher than bottom temperatures, reflecting the effect of thermal stratification by short-wave radiation, (discussed in Appendix A3 and section 4.1.8). Exceptions to this occurred in winter, when buoyant Swan River discharges entered Cockburn Sound as relatively cold, but less saline and therefore buoyant, surface layers (Section 4.3, below). Temperature differences between the surface and bottom occurred on most of the occasions that ST profiling was conducted and differences ranged from about 0.1 to 1.5 ^{o}C.

Winds and vertical structure

Data that indicate the influence of winds upon vertical structure in central Cockburn Sound are now investigated. The DCE monthly ST data profiles were collected at a vertical resolution of 1-2 m. It was therefore possible to determine the upper mixed layer depth. Figure 4.22 presents upper mixed layer depth as a function of time for the DCE data measurement period. The upper mixed layer depth was generally 5-10 m with full depth mixing only occurring 4 times (or about 15 percent of the time).

A more comprehensive vertical density stratification data set for central Cockburn Sound has been synthesized by collating data from the many profiles collected throughout all four seasons during the Cape Peron Outfall Environmental Study (R.K. Steedman and Assoc., in Binnie and Partners, Dec 1981), the Cockburn Sound Environmental Study 1976-1979 (DCE, 1979) and the EPA's summer 1989/90 water quality survey. Wind information has been acquired for the times at which the profiles were made. Scatter diagrams of the relationship between vertical density anomaly (bottom minus top) and wind speed has been constructed from the data set. The wind speed was chosen to represent that which occurred on or immediately prior to the time of profiling. Wind direction was not considered in this analysis but is included in a theoretical prediction of wind mixing in Section 4.1.5.

Figure 4.23a contains the results from the Cape Peron Outfall data set, Figure 4.23b contains results from the Cape Peron Outfall and DCE data sets combined, and finally, Figure 4.23c contains the total data set from all three studies. Figure 4.23d contains an accompanying scatter plot for a station in central Mangles Bay. As shown by Figures 4.23a-d, the central waters of the basin were typically vertically stratified, with only few occurrences of zero vertical density difference. The data suggest that winds of at least 5 m s^{-1} were required for full depth mixing to occur. As would be expected, there is a general trend of decreasing vertical density difference with increasing wind speed. However, the data also suggest that even at wind speeds of 5-10 m s^{-1} appreciable vertical density differences can occur.

This is an important result because winds are less than or equal to 10 m s^{-1} for about 90 percent of the time in summer (see Appendix 1A). From the point of view of the choice of an appropriate numerical model that needed to adequately predict vertical mixing and horizontal transport in Cockburn Sound, this information will be of critical importance. If the system is truly strongly stratified vertically for such a large percentage of the time during the year then a model that adequately incorporates hydrodynamic mechanisms governed by baroclinic effects (due to density differential) will be required.

A more theoretical prediction of the potential of winds to mix the basin is now made.

4.1.4 Critical wind speed analysis to predict the potential for barotropic and baroclinic behaviour

An approach to predict wind-mixing in stratified fluids in small to medium sized basins is described in Appendix A3. Both the Wedderburn number (Imberger and Hamblin, 1982) and the Lake number (Imberger and Patterson, 1990) are presented as analytical tools that can be used to predict the mean

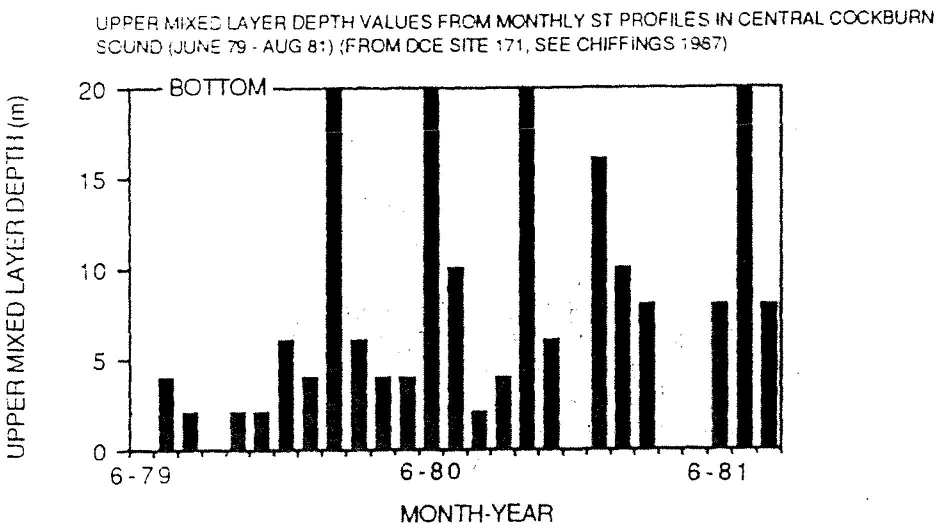


Figure 4.22 Time series of monthly measurements of upper mixed layer depth in central Cockburn Sound at DCE site 171 (see Figure 4.18) from June 1979 to Sep 1981.

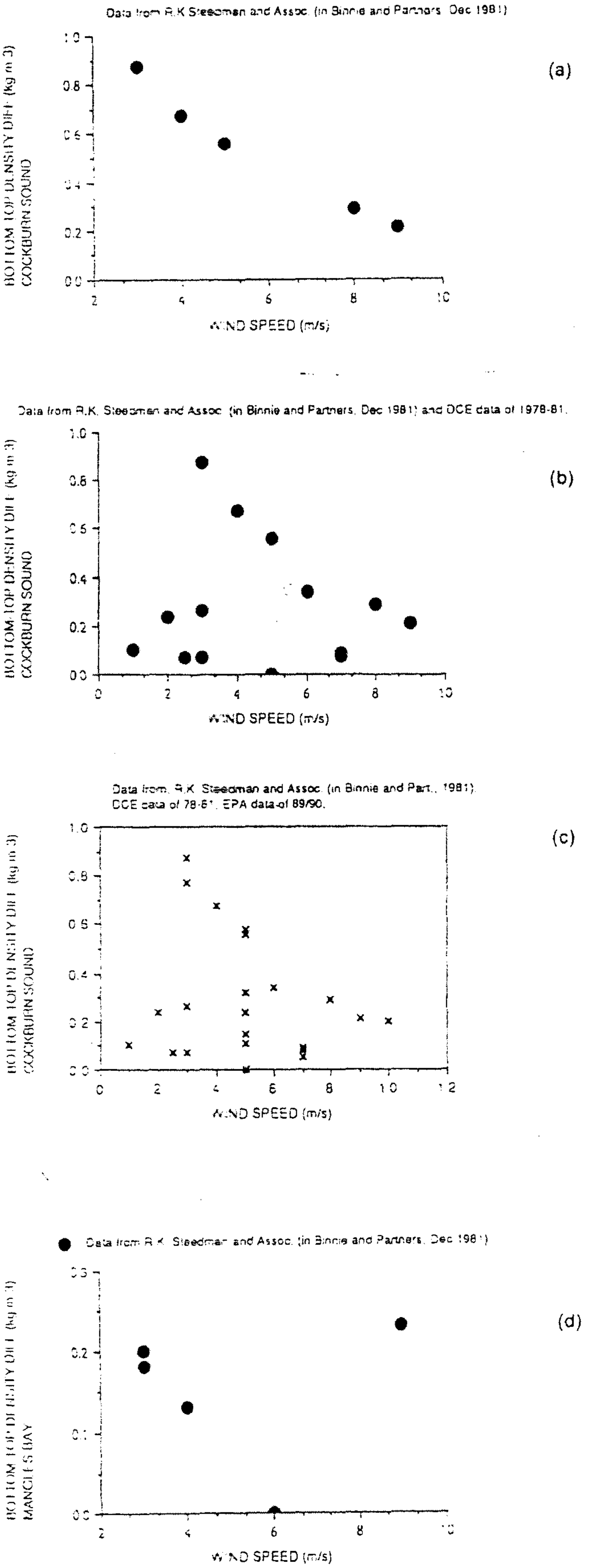


Figure 4.23 Scatter plots of bottom minus surface density difference vs wind speed for central Cockburn Sound and central Mangles Bay. Data from (i) Binnie and Partners (Dec, 1981), (ii) DCE data of 1979-1981, and (iii) EPA data of 1989-1990: (a) plots only data from (i), (b) plots data from (i) and (ii) combined, and (c) plots data from (i), (ii) and (iii) combined, (d) plots only data from (i).

dynamical response of stratified basins to wind stress. These relations essentially consist of a non-dimensional force balance between the stabilising buoyancy force inherent in the stratification and the de-stabilising force due to surface wind stress. The Wedderburn number concerns itself with the upper layer only and the Lake number considers the buoyancy forces inherent in the entire basin volume. The background to their derivation, and the shortcomings in attempting to apply these analytical tools to coastal embayments, rather than to closed small to medium sized basins, is discussed in Appendix A3.

Present theories on the nature of vertical mixing processes in stratified semi-enclosed coastal waters may not be as fully developed as those for lakes, however, many of the dynamical processes that act to stabilise the water column gravitationally, or destroy stratification and cause mass transport will be fundamentally similar. This is because the same forcings, such as atmospheric heating and cooling, evaporation, density currents, internal waves, wind mixing, and wind-drift play important roles in governing the hydrodynamics in both types of systems.

It is acknowledged here that a coastal system is subjected to mechanisms and forcings that lakes are not subjected to such as for example, regional currents, tides, spatially variable barometric pressure fields, and open ends where energy can leak away. Some of the dynamical forcings specific to coastal situations are of a long-term nature. On the other hand, many of the important processes that control the formation of vertical density gradients and the subsequent destruction of these gradients have much shorter and therefore similar characteristic time scales to those that occur in enclosed basins (of the order of 1 day or less) because they respond to forcings of a diurnal nature (eg, heating and cooling, wind). In view of this, the analytical tools developed to classify the nature of wind forced motions in lakes are made use of here in order to conduct a first order analysis of the likely occurrence of baroclinic, as compared to barotropic, behaviour in the semi-enclosed coastal embayments of the southern metropolitan waters.

The formulae presented in appendix A3 are now utilised for a range of summer conditions in Cockburn Sound, with typical initial vertical density stratifications, wind fetch lengths, wind speeds, and upper mixed layer depths drawn from the large data set analysed thus far in this report.

It would appear that in summer the potential for a day-time heating event to cause a vertical temperature stratification of up to 2- 4 ^{o}C over the full depth is possible. In addition, a vertical salinity anomaly of 0.1 ppt was often recorded. Hence, it would not be unreasonable to assume an initial vertical density difference between the surface and bottom of say 0.25 to 1.0 kg m^{-3}. Measurements of upper mixed layers indicate that in summer depths of the order of 2-10 m are typical. Wind directions for the strongest summer breezes are either SW or SE, resulting in a fetch length of about 9000 m. Wind speeds range typically between 0 and 10 m s^{-1}. On the basis of these values a critical wind speed. U_{cr}, where W and L_N both change from being less than to greater than of the order of 1, can be calculated.

<u>Critical wind speed on the basis of the Lake number (Equation A3.15, Appendix A3.5)</u>

The following parameters and information are assumed for the Lake number calculation:

CASE I. Three homogeneous density layers, with the upper two layers being 5 m thick and the bottom layer being 10 m thick. The surface layer density is 1024.0 kg m^{-3}, the middle layer density is 1024.5 kg m^{-3} and the bottom layer density is 1025.0 kg m^{-3}.

This results in $L_N \sim 1$ when wind speed ~ 4.5 m s^{-1}.

CASE II Three homogeneous density layers, with the upper layer being 7.5 m thick and having a density of 1024.0 kg m^{-3}, the middle layer being 2.5 m thick and having a density of 1024.75 kg m^{-3} and the bottom layer being 10 m thick and having a density of 1025.0 kg m^{-3}

This results in $L_N \sim 1$ when wind speed ~ 5 m s^{-1}.

On the basis of the above first order calculation of Lake numbers for a range of simple stratification structures a critical wind speed of the order of 5 m s^{-1} is estimated. This means that for winds less than about 5 m s^{-1} the Lake number is greater than about 1 indicating that winds are unlikely to overturn the entire density structure.

Critical wind speed on the basis of the Wedderburn number (Equation A3.7, Appendix A3.5)

CASE I As above.

This results in W ~ 1 when wind speed ~ 3 m s^{-1}.

CASE II As above.

This results in W ~ 1 when wind speed ~ 5.5 m s^{-1}.

CASE III Two homogeneous layers, each 10 m thick, with the density difference between the two being 1 kg m^{-3}.

This results in W ~ 1 when wind speed ~ 8 m s^{-1}.

CASE IV Two homogeneous layers, each 10 m thick, with the density difference between the two being 0.5 kg m^{-3}.

This results in W ~ 1 when wind speed ~ 6 m s^{-1}.

CASE V Two homogeneous layers, each 10 m thick, with the density difference between the two being 0.25 kg m^{-3}.

This results in W ~ 1 when wind speed ~ 4 m s^{-1}.

On the basis of this first order calculation of Wedderburn numbers for a range of simple stratification structures and vertical density differences a range of critical wind speeds of the order of 3-8 m s^{-1} is estimated. This means for winds less than critical the Wedderburn numbers are greater than order 1 and therefore surface mixing would be characterised by stirring dominated processes, leading to relatively slow upper mixed layer deepening rates. However, for winds greater than critical surface mixing will be most likely attributable to shear dominated processes and the rate of upper mixed layer deepening will be relatively rapid.

By combining the results of the above Lake and Wedderburn number calculations, a range of critical wind speeds of 5-8 m s^{-1} is estimated. This suggests that winds greater than about 5-8 m s^{-1} are required to cause the Sound to be fully mixed vertically for stratification intensities typical of the summer period. Upwelling of bottom waters for such wind situations should be an important mechanism to overall water circulation. It is therefore estimated that Cockburn Sound is likely to retain vertical density structure for winds less than about 5-8 m s^{-1} and hence baroclinic behaviour could be important to vertical and horizontal transport at these times. However, when winds are greater than about 5-8 m s^{-1} it can be expected that the Sound could be vertically well-mixed , with the rate of vertical mixing dependant upon the actual velocity and duration of winds, as evaluated in the following section.

The data presented in Figure 4.23 lend support to this conclusion. It is noted however, that the data from which the points in Figure 4.23 are drawn have not taken into account the duration or direction of the wind, hence the diagram is used as an indicative test of the mixing potential of various wind strengths.

The influence of the duration of the wind upon the eventual depth of surface mixing is now investigated.

4.1.5 Predicting the rate of vertical mixing by winds

As discussed in Appendix A3, the Wedderburn number can be used as an analytical tool to classify the response of the upper layer to wind stress in a stratified basin. For W >> 1 the stirring dominated mixing law (Equations A3.9 and A3.10) can be invoked as a predictive estimator of the rate of upper mixed layer deepening, whereas for W << 1 the shear dominated law (equations A3.11 and A3.12) can be invoked as the predictive estimator. It is to be noted that as the upper mixed layer deepens W becomes larger. Hence, the possibility exists that an initial W << 1 situation can transform to a W >> 1 situation by virtue of an increasing upper mixed layer depth value, and this means that at this point in time the relevant mixing law changes from the shear dominated one to the stirring dominated one, with the rate of deepening declining sharply.

The rate of vertical mixing by winds for typical summer wind speeds and directions and initial stratification conditions is now estimated for various cases.

We begin by stating the assumptions of the calculations, as follows.

- Winds have a fetch of 9000 m from shore to shore, representing SW, SE, or NE winds. It is to be noted that in Mangles Bay the effective fetch for these wind directions will be less than 9000 m, and more like about 5000 m, hence vertical mixing rates will be overestimates for Mangles Bay but more appropriate for central Cockburn Sound.
- The initial upper mixed layer depth is set at 5 m.
- The initial vertical stratification is assumed to consist of two homogeneous layers separated by a discrete density jump.
- The wind starts abruptly after being previously at 0 m s^{-1} and mixing is calculated for a wind duration of up to 24 hours.

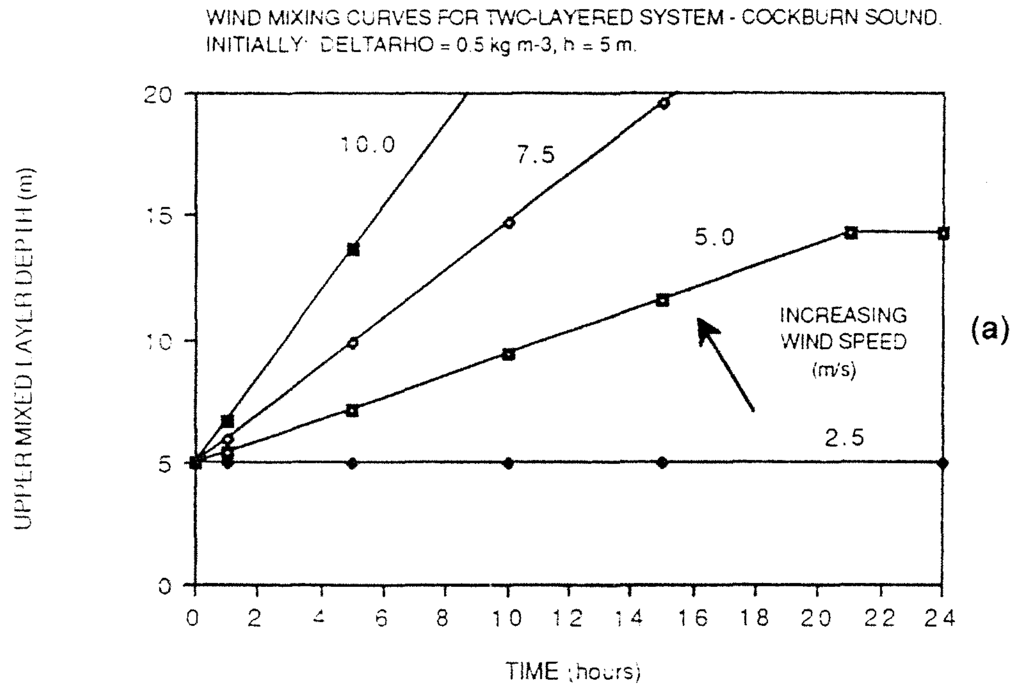
The results of the calculations are summarised in Figures 4.24a and b. Figure 4.24a is for an initial density difference of 0.5 kg m^{-3} and initial upper layer thickness being 5 m. The curves suggest that winds of 5 m or less would not mix the water column down to the bottom. Winds of 7.5 m s^{-1} would mix the water column fully within 15 hours. After blowing for 5 hours the 7.5 m s^{-1} winds are predicted to mix down to only 10 m. Typical durations for strong sea-breeze or offshore breeze events are of the order of 5-10 hours, hence on the basis of the curves in Figure 4.24a mixing could penetrate down to 10-15 m. Figure 4.24b presents a similar set of curves but these are constructed for an initially stronger density difference of 1 kg m^{-3}. As shown, the overall mixing rates are significantly lower than those shown in Figure 4.24a, and this is because of the greater potential energy inherent in the density stratification.

The DCE conducted basin-scale ST profiling in Cockburn Sound between the years 1977 and 1981. The data are presented in many contour plots throughout this report, but a table of the main features in the stratification and corresponding winds has been included in Appendix A5 along with calculated values of corresponding Wedderburn numbers for each period of measurement.

A review of the results in Appendix A5 indicates that in general the basin always displayed horizontal stratification, with vertical stratification being common. Values of W greater than about 0.5 generally accompanied the occurrence of vertical stratification. It is interesting to note that there were instances when significant vertical stratification was recorded yet W values at the time of recordings were between 0.1 and 0.5 (21-9-78, 14-11-78, 18-9-79, 14-10-80 and 14-1-81). Initially this would suggest that the critical W value is closer to 0.1 than 1, however upon closer inspection of the wind data it is apparent that winds immediately prior to the periods of ST measurements were such as to cause W values greater than or equal to about 0.6, and hence the W ~ 1 criteria for vertical structure is recovered.

<u>Summary</u>

As a general conclusion, based on the measurements and first order theoretical predictive calculations presented above it would appear that Cockburn Sound will maintain a vertically stratified nature in summer unless winds are greater than about 5-10 m s^{-1} for periods of the order of 5-10 hours or more. Statistical analyses of long-term wind records for Cockburn Sound show that winds exceed 5-10 m s^{-1} only about 50 percent of the time in summer. Hence, on the basis of the predictive analysis above, it is suggested that vertical stratification, and therefore baroclinic behaviour, could be important to the overall hydrodynamics of the Sound up to 50 percent of the time in summer. More detailed field investigations on the nature of vertical stratification as a function of speed, direction and duration of winds are required as a step to gaining a more quantitative understanding of the vertical dynamics of wind mixing in Cockburn Sound.



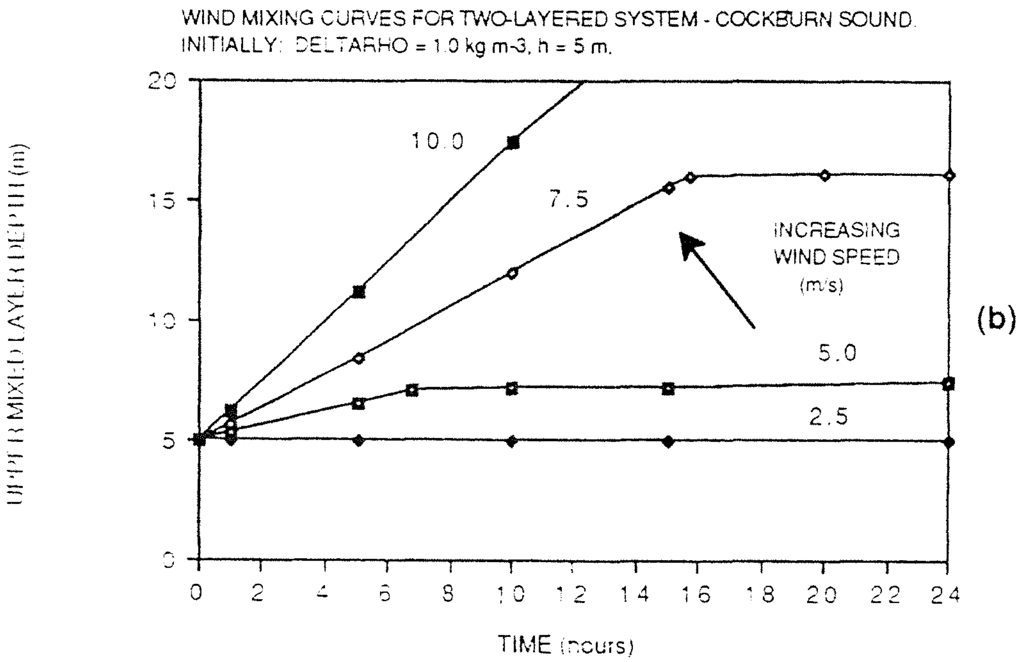


Figure 4.24 Predicted deepening of upper mixed layer depth as a function of wind speed (using formulae from Appendix A3) for a two-layered basin. Two cases of initial vertical density difference are considered (a and b, respectively).

4.1.6 Surface currents inferred from drogue tracking

Environmental Resources of Australia Pty Ltd performed numerous drogue tracking exercises as part of their hydrodynamic field surveys and the general nature and timing of these studies have been described in Chapter 3.

Appendix A6 has attempted to summarise the main results of the drogue tracking surveys by listing together the wind, tide and current patterns that were revealed for each discrete exercise. Appendix A6 begins with a short discussion on the influence of wind drag on the surface buoys of the drogue systems. It is shown by calculating the likely wind drag on the can floats of the drogue systems and comparing this drag to the drag on the submerged cross-vanes due to currents that the two may have been of the same order. Hence, during typical strength winds the drogue tracks are interpreted to suggest surface wind-driven currents only.

<u>Overview of summer drogue tracking results</u>

These data were collected in November-December 1971, when the Causeway was constructed only up to and including the Trestle Bridge.

The exercise aimed to determine pre-Causeway flow patterns through the southern opening. In general, the results indicated that flow was in (towards east) through the opening, in response to strong SW winds (of the order of 5-10 m s^{-1}), with surface currents of 10-20 cm s^{-1} inferred from the data. The tide was rising during all deployments. There was evidence that some of the flow in through the southern opening can be deflected northwards over the Southern Flats, as shown in Figures 4.25a and b, for example. However, in general most drogues placed in the opening moved approximately in a straight line with little deviation during their propagation. Winds tended to alter this simple pattern, and the northward travel of some of the drogues in Figure 4.25b, due to SE winds is indicative of this.

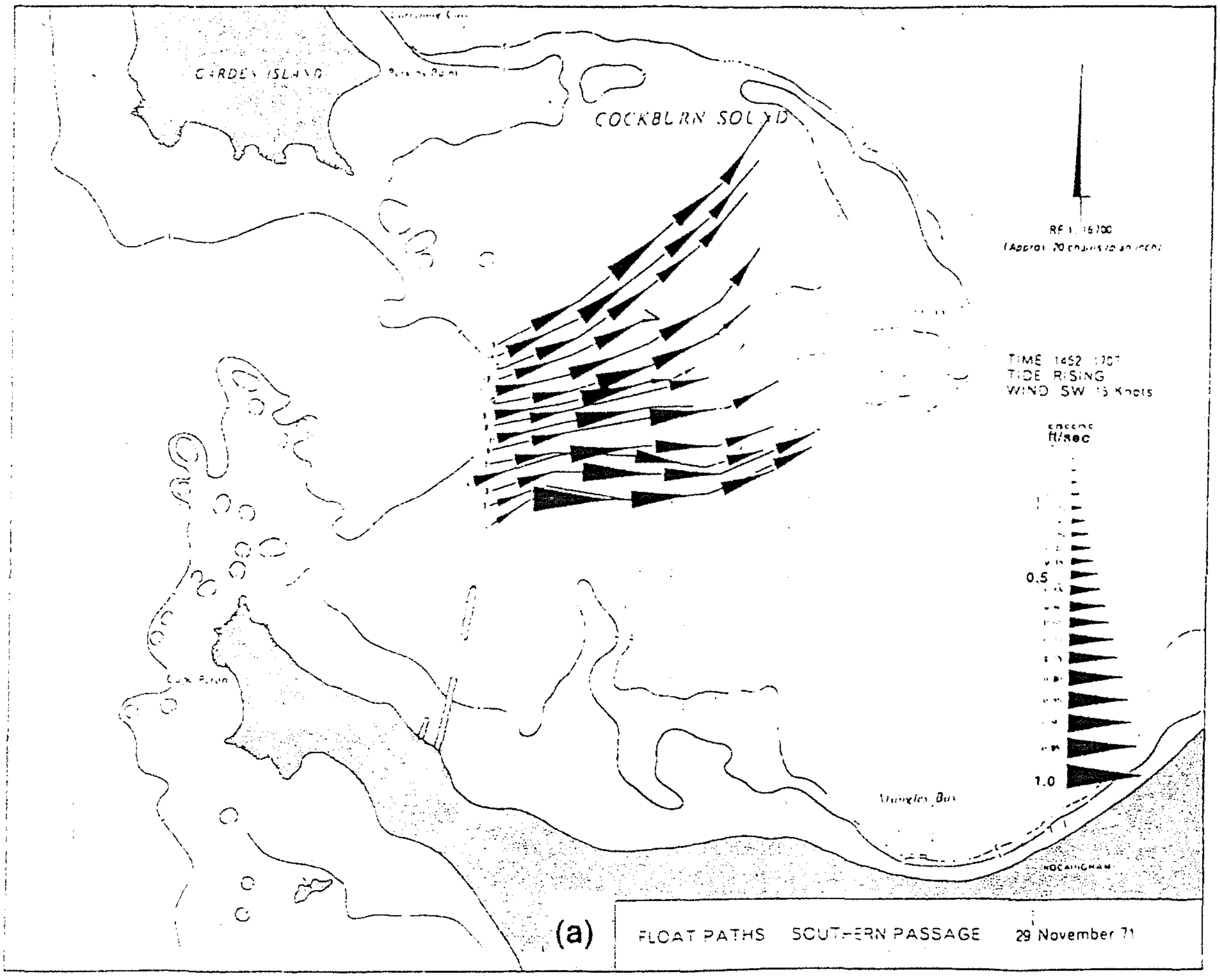
A number of drogue sets were deployed over the Southern Flats and in Mangles Bay, away from the opening. Appendix A6 summarises the results of tracking. In general, drogues moved downwind at 15-30 cm s^{-1}, driven by winds of 7-10 m s^{-1}. For example, one deployment involved the release of 5 and 10 m deep drogues in southern Cockburn Sound, and these were tracked between 8 and 9 December 1971. Winds were SW at 7-10 m s^{-1}. The resulting drogue paths are shown in Figure 4.26 and indicate a predictable downwind movement, reflecting surface wind drift, at 2-3 percent of the wind speed. Therefore, the inferred surface wind drift corresponded well with the "three percent" rule (Appendix A4).

A similarly intensive drogue-tracking campaign was mounted during the following summer throughout the whole of Cockburn Sound, during 6-14 December 1972, when winds were comparably much weaker with respect to December 1971 (see Table 4.2. above, and the data presented in Appendix A6). The main features are highlighted as follows.

During the SSW winds of 6-7 December 1972 surface drift was essentially downwind at 2-3 percent of the wind speed. However, when winds were weak and predominantly offshore or directed towards the south, the surface current patterns around the Sound were more complicated, exhibiting random weak circulatory pattens. This behaviour is highlighted by the drogue tracks in Figures 4.27a and b, for example, where some drogues moved in opposition to the direction of mild winds; see for example, "DROP 6" of 9 December 1972, when the central drogues moved southward while at the same time the drogues over the eastern shelf moved northward and those in between moved eastward. This may indicate basin-scale gyres, with the forcing mechanism not clearly defined.

<u>Summary</u>

In summary, the summer drogue tracking exercises of ERA in the early 1970's suggest that during relatively strong SW winds (5-10 m s^{-1} or more) surface currents are essentially downwind at approximately 3 percent of the wind speed. During weak wind conditions current patterns are more complex, often not reflecting the direction of the wind. It is unclear from the existing drogue data what



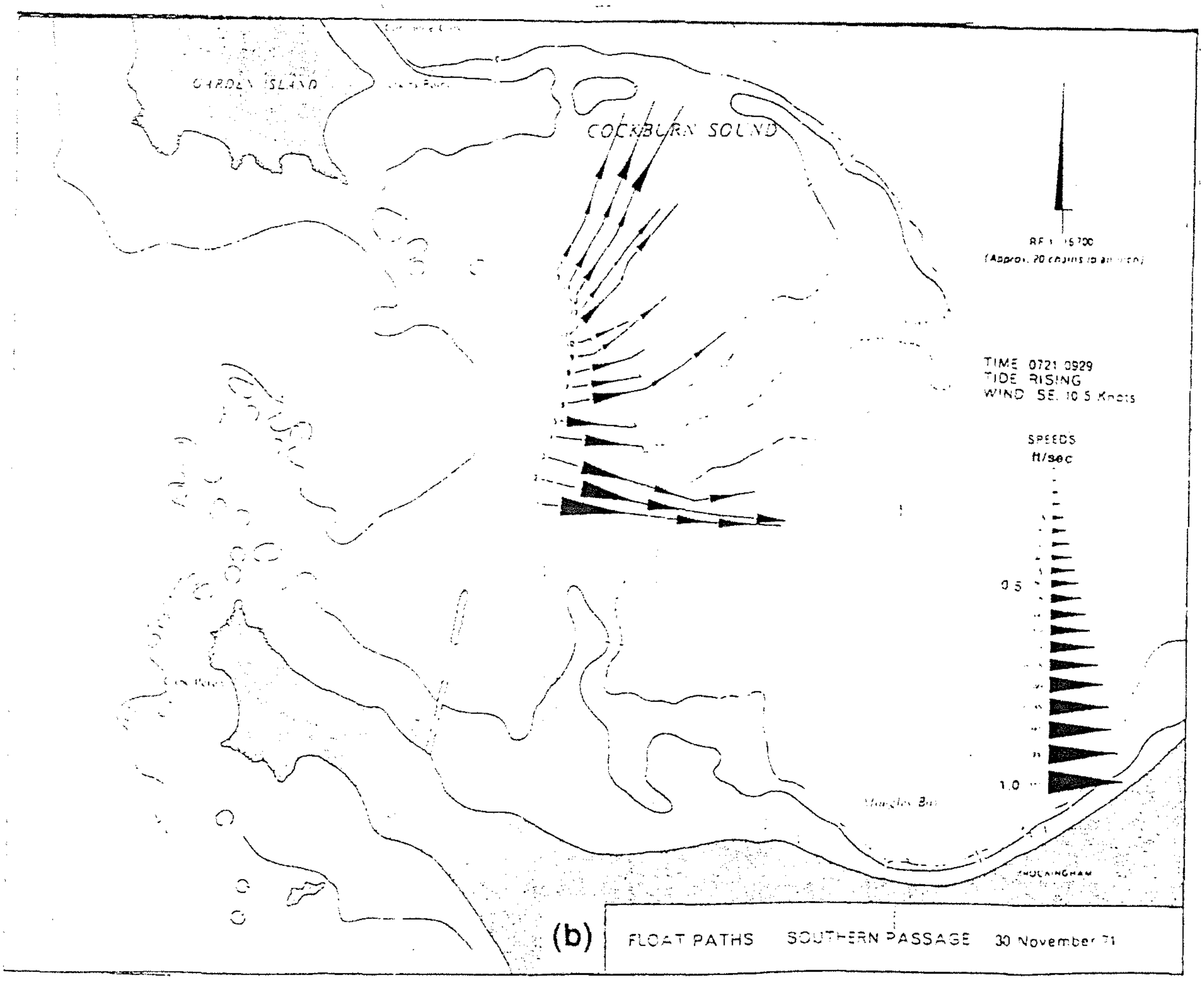


Figure 4.25 Drogue track paths for deployments in the partially constricted southern opening of Cockburn Sound on 29 and 30 Nov 1971. Data from ERA (details in Appendix A6).

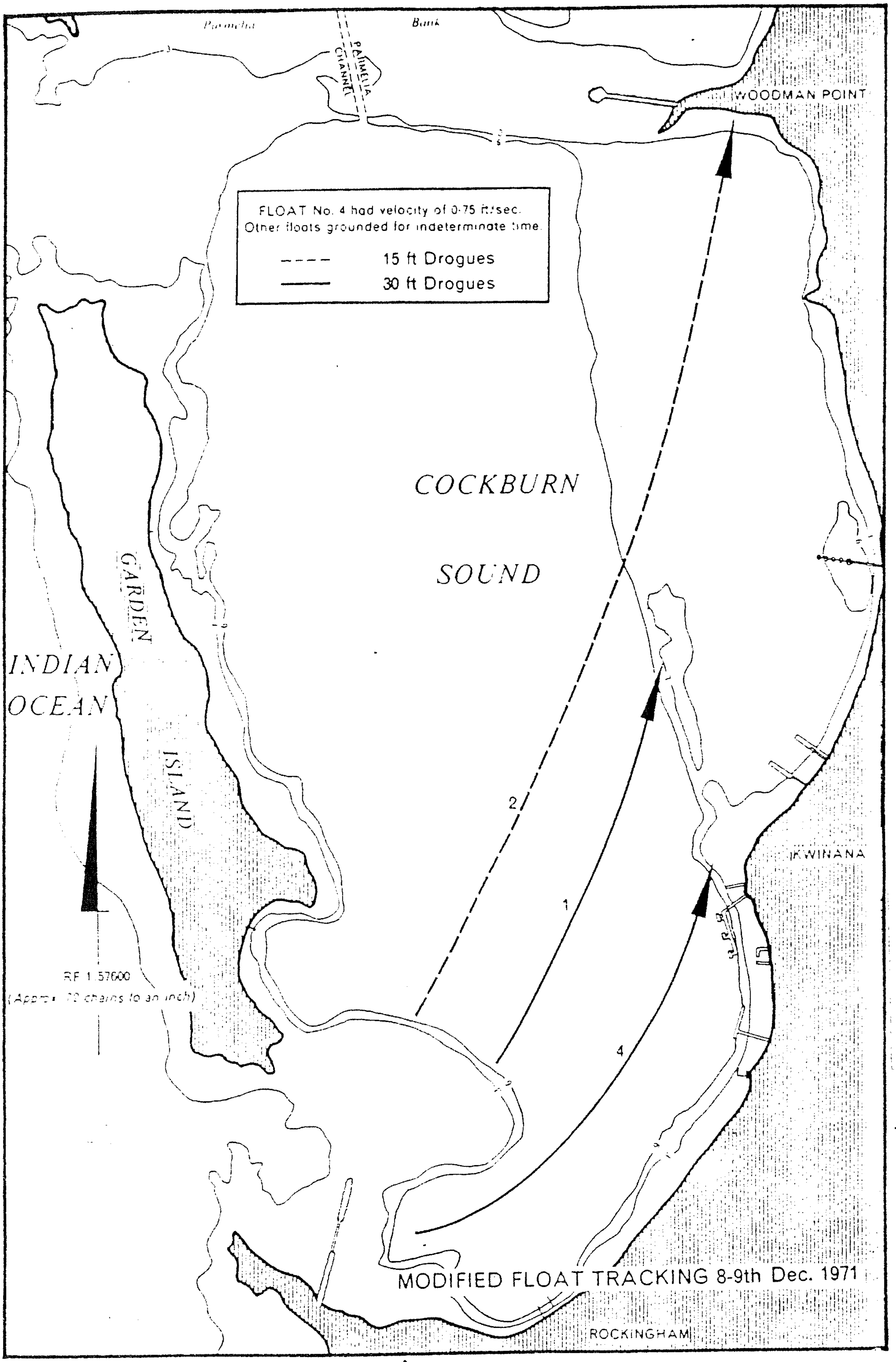


Figure 4.26 Drogue track paths for deployments in Cockburn Sound on 8 and 9 Dec 1971. Data from ERA (details in Appendix A6).

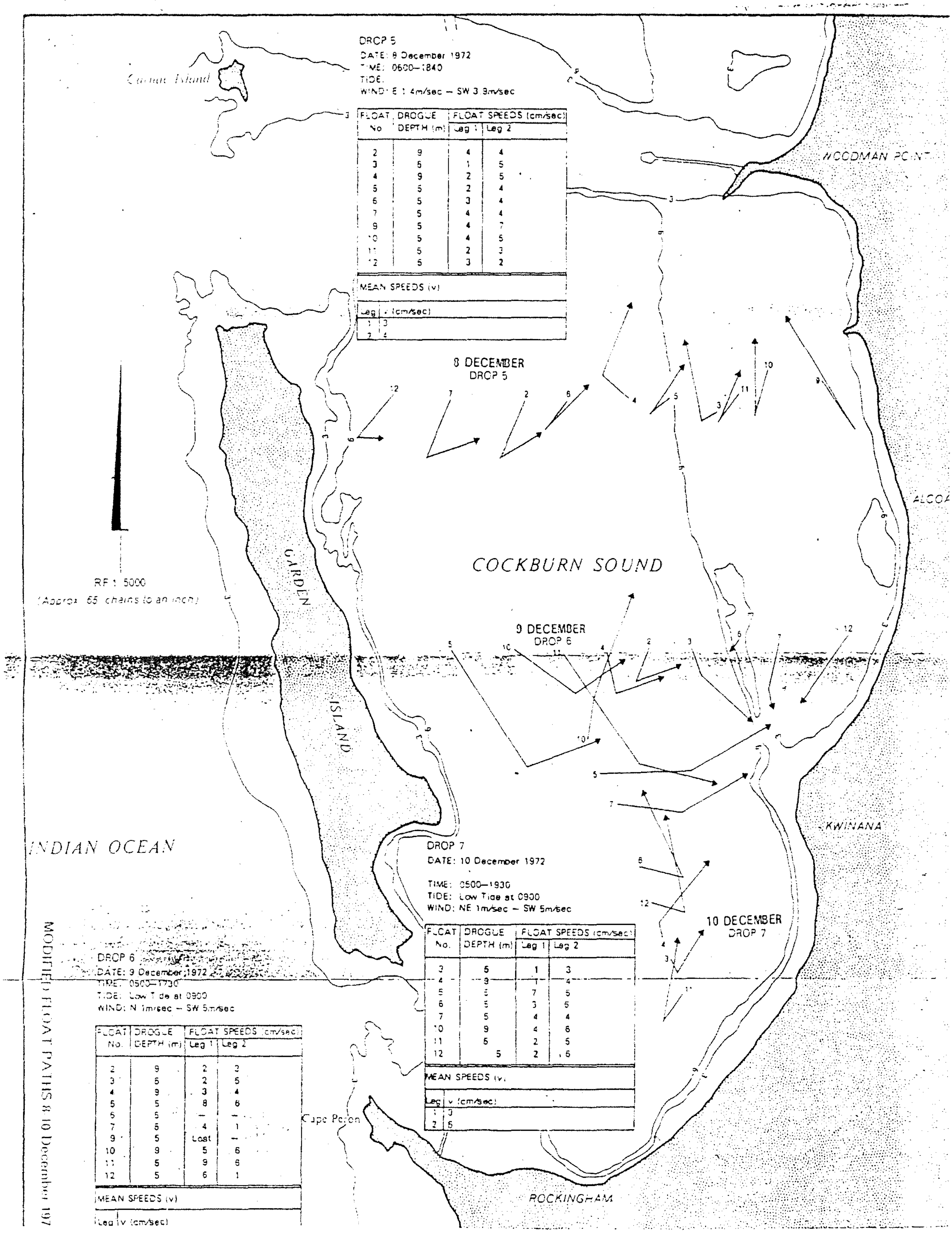
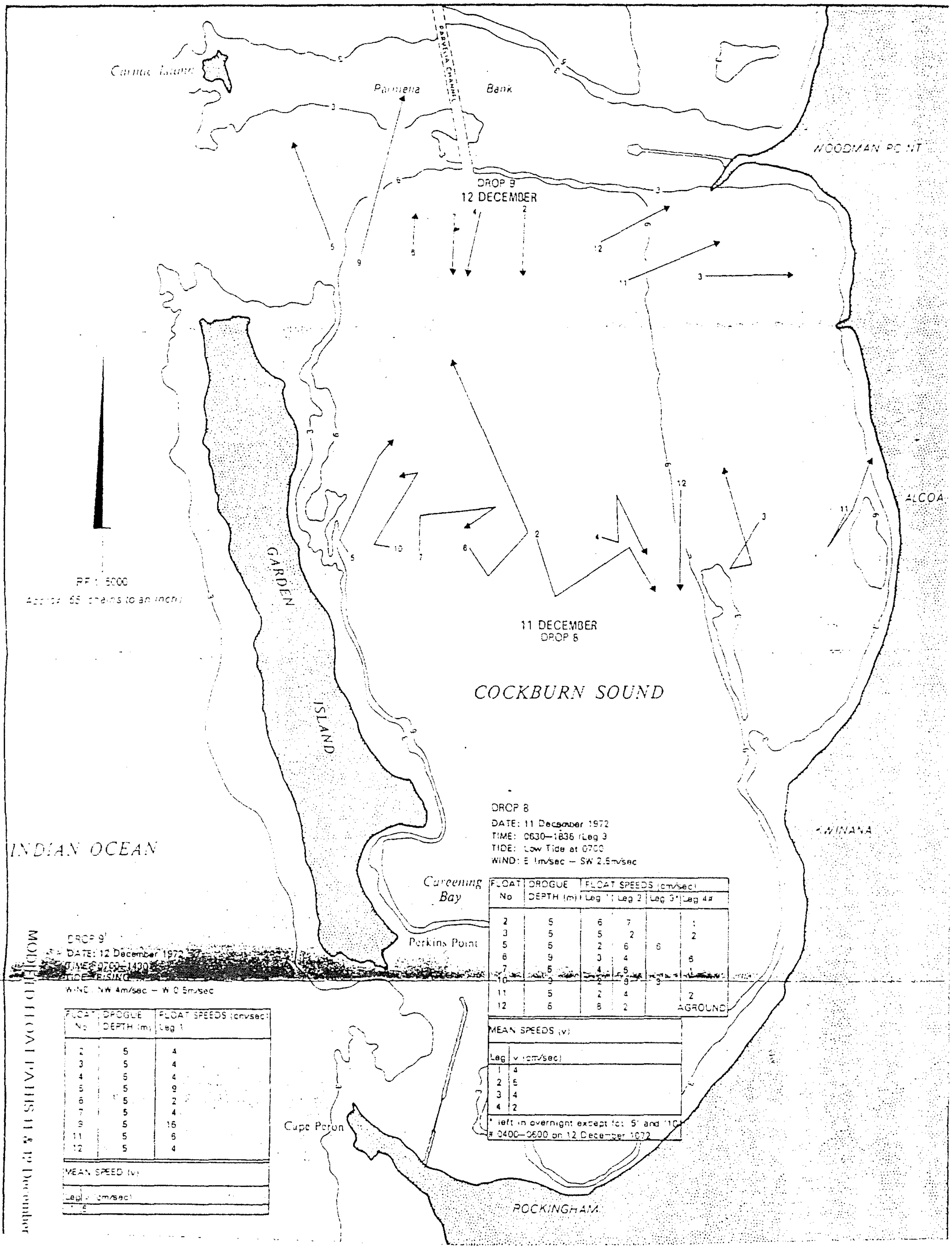


Figure 4.27(a) Drogue track paths for deployments in north, central and southern Cockburn Sound on 8, 9 and 10 Dec 1972. Data from ERA (details in Appendix A6).



FLOAT No	DROGUE DEPTH (m)	FLOAT SPEEDS (cm/sec) Leg 1*	Leg 2	Leg 3*	Leg 4#
2	5	6	7		1
3	5	5	2		2
5	5	2	6	6	
6	9	3	4		6
7	5	4	5		1
10	3	2	8	9	
11	5	2	4		2
12	6	8	2		AGROUND

MEAN SPEEDS (v)

Leg	v (cm/sec)
1	4
2	5
3	4
4	2

* left in overnight except for 5 and 10
\# 0400—0600 on 12 December 1972

FLOAT No	DROGUE DEPTH (m)	FLOAT SPEEDS (cm/sec) Leg 1
2	5	4
3	5	4
4	5	4
5	5	9
6	5	2
7	5	4
9	5	15
11	5	6
12	5	4

MEAN SPEED (v)

Leg	v (cm/sec)
1	6

Figure 4.27(b) Drogue track paths for deployments in north and central Cockburn Sound on 11 and 12 Dec 1972. Data from ERA (details in Appendix A6).

other forcings govern circulation during weak winds but it is postulated that baroclinic forcings and regional currents come strongly into play during such situations. No information on circulation patterns below the surface could be inferred from the existing drogue tracking data because it is likely that wind drag dominated the movement of drogues.

4.1.7 Flow through the causeway

The results of current metering through the southern opening during the early seventies when it was unconstricted and also when it was partially closed by the causeway are presented in Appendix A7, and these are summarised as follows:

- Flux measurements through the southern openings before the causeway was constructed suggest that the replacement times were originally of the order of 5-10 days. Hearn (1991) arrived at similar conclusions on the basis of modelling and field study results.
- Once the causeway was in place summer flows were found to be generally into Cockburn Sound via its openings. Average inward fluxes of the order of 700 m^3 s^{-1} were common, with maximums of the order of 1300 m^3 s^{-1}. This equates to idealised replacement times for the Cockburn Sound volume of 25 and 13 days, respectively.

In view of the identification of the importance of vertical density structure to overall summer circulation in Cockburn Sound the effect of the causeway to flushing may need to be reviewed in a different light. It was previously believed that vertical stratification had only a passive influence on basin-scale flushing. However, the analyses of this report have shown that vertical density structure is common in the Sound during summer, with wind speeds of greater than about 5-10 m s^{-1} blowing for 5 hours or more required to mix the system down to the bottom. Such winds occur less than about 50 percent of the time in summer. If it is therefore accepted that the system is often layered in density, this means that for a significant percentage of the time in summer the relative residence times of waters in Cockburn Sound may vary as a function of depth in the water column. The field and analytical evidence in this report would suggest that surface waters are likely to have shorter residence times in the Sound than deeper waters.

One effect of the causeway may have been to restrict the surface advection of upper layers out of the Sound. The reduction in the width of the surface zone of the southern opening has been significant, changing it from about 4 km to 1 km. Hence, during stratified conditions the flushing of surface waters from southern Cockburn Sound via the southern opening may have been significantly impaired by the blocking of the width of the surface outflow zone due to the presence of the causeway, but further field and modelling verification would be needed to quantify the actual impact of this structure to flushing of the Sound, and in particular southern Cockburn Sound.

4.1.8 Differential heating and cooling

The theoretical background to these mechanisms is presented in Appendix A3. Differential heating and cooling between Cockburn Sound and the adjacent oceanic waters is demonstrated to occur on seasonal time scales by the time series temperature plots in Figures 4.28a, b, and c. These plots are constructed from monthly measurements of vertical temperature stratification conducted by the DCE from June 1978 to August 1981 at sites in central Cockburn Sound and central Sepia Depression (see Figure 4.18). As shown there is a seasonal pattern in the relative temperatures of both surface and bottom waters at these two sites. In late spring to early autumn Cockburn Sound is warmer than Sepia Depression by up to about 2 ^{o}C, whereas in winter the reverse is true with Sepia Depression warmer than the Sound by up to about 3 ^{o}C (see Figure 4.28c). The same seasonal trend was also found to occur between Warnbro Sound and Sepia Depression (Section 3.1.8). The differential heating and cooling is most likely due to the semi-enclosed and shallower nature of the nearshore waters when

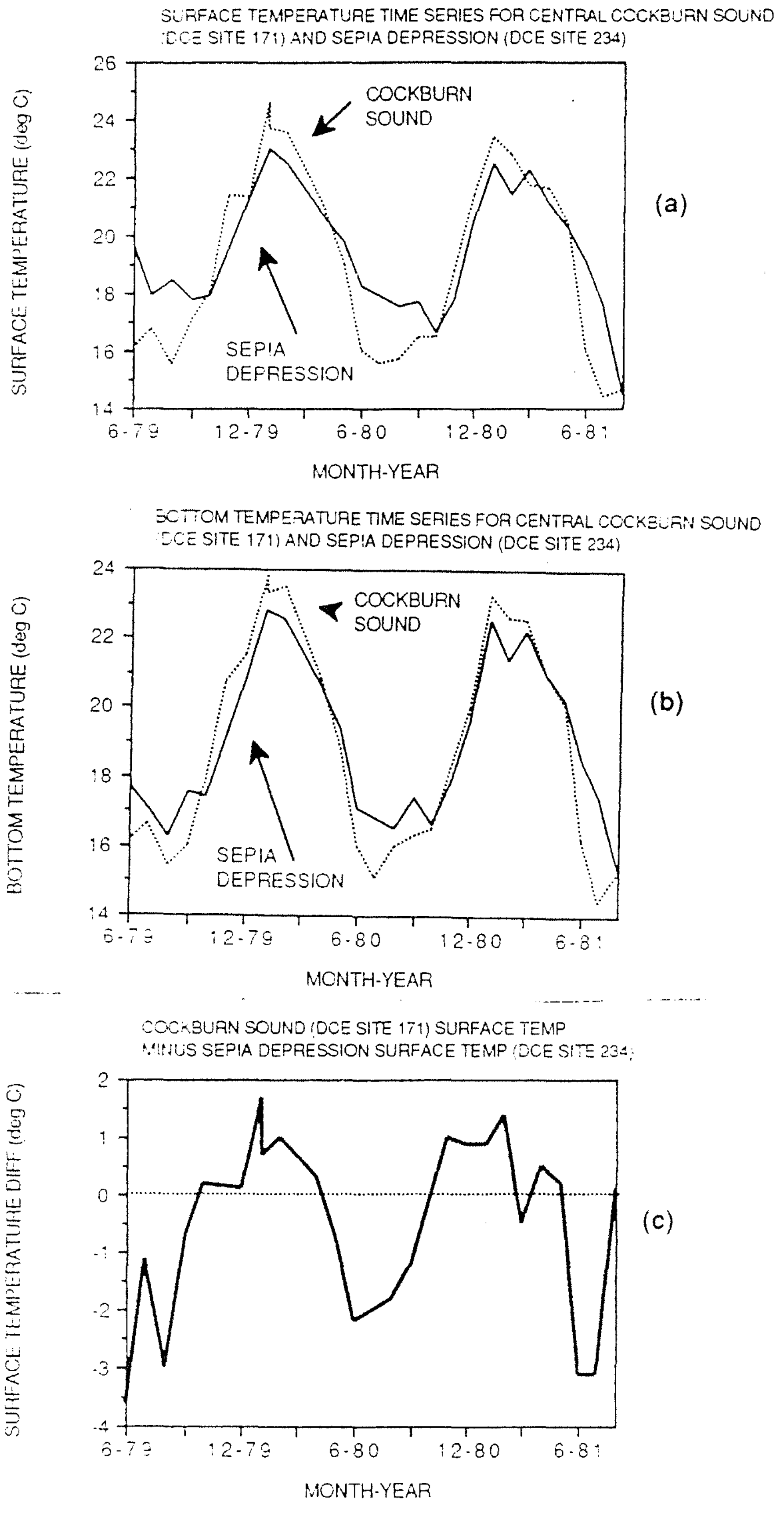


Figure 4.28 Time series plots of (a) surface and (b) bottom temperature in Cockburn Sound (site 171) and Sepia Depression (site 214), and (c) difference in surface temperature of the two sites. See Figure 4.18 for site locations. Data from DCE surveys of June 1979 to July 1981.

compared to the deeper more exposed waters of Sepia Depression. From the point of view of flushing of the basin, temperature differences between the basin and adjacent waters of up to 3 °C have the potential to drive baroclinic currents of the order of 5-10 cm s^{-1} (see Appendix A3, Equation A3.2).

Within Cockburn Sound the potential for differential heating and cooling to occur does exist due to the variability in the bottom depth. The eastern margin of the Sound consists of a 5-10 m shelf, with the central basin having depths of approximately 20 m. In addition, there are the expansive shallow areas over the Southern Flats, Parmelia Bank and shallow shore region around the inner periphery of the Sound. However, no sufficiently resolute data are available from which these mechanisms can be verified. The DCE data set (1979-1981) did include stations in the deeper and shallower regions of the Sound but the times at which individual stations were visited on particular days varied. Further, there were times when the shallow stations were visited before the deeper stations while at other times this sequence was reversed. Hence, there is the possibility that diurnal heating may have increased temperatures in the time between measurement at two individual sites.

It is possible however, to conduct a first order theoretical estimate of the potential for differential heating by applying Beer's law and the conservation of heat equation (Fischer et al, 1979).

The rate of change of temperature for a 1 m thick slab of water is estimated as follows:

$dT/dt = H/(\rho C_p)$,

where T is the temperature, t is the time, H is the net heat exchange over the 1 m slab thickness, and C_p is the specific heat of water.

A scale of the temperature change, ΔT, in a given time, Δt, for a 1 m thick slab subject to an average heat input of H over the slab depth is therefore given by:

$\Delta T \sim (\Delta t.H)/(\rho C_p)$.

H obviously varies widely on both seasonal and diurnal time scales. For the south-west of Western Australia H can be as high as 900 W m^{-2} during a midsummers day (Fischer et al, 1979). This H is comprised almost entirely of short-wave radiation. A value for H of 750 W m^{-2} is assumed for this analysis. Applying the exponential decay and heat conservation laws for deep water (20 m) and shallow water (defined as less than or equal to 4 m) yields the following distribution of H and associated ΔT for discrete slabs through the water column (Table 4.3). An attenuation coefficient of 0.5 is adopted as a first approximation in the absence of data, ΔT = 8 hours, Cp = 4200 J kg^{-1} $^oC^{-1}$, and density = 1025 kg m^{-3}

Table 4.3. A theoretical calculation of vertical temperature rise in the water column for a deep region (20 m) and a reflecting shallow region (4 m) subjected to the same surface input of short-wave radiation (750 W m^{-2}) for a period of 8 hours.

Depth z (m)	$H(z)=750e^{-0.5z}$ Decay from the surface down (W m^{-2})	T(z) (°C)	$H(z)=101e^{-0.5z}$ Reflected and decaying from the bottom up (W m^{-2})	T(z) (°C)	ΔH Average over the 1 m slab. (W m^{-2})	ΔT (°C)
0	750		14			
1	455	4.03	22	4.15	18	0.12
2	276	2.44	37	2.64	30	0.20
3	167	1.48	61	1.81	49	0.33
4	101	0.9	101	1.44	82	0.55

5	61	0.54	--
6	37	0.33	BOTTOM
7	23	0.20	
8	14	0.12	
9	8	0.07	
10	5	0.04	
11-20	<5	<0.02	

As the predictions in Table 4.3 indicate the 4 m shallows could be warmer than adjacent deeper waters by up to 0.4 ^{o}C near the bottom. The vertically averaged temperature difference between the shallows and deep is about 0.3 ^{o}C. This corresponds to a density decrease of the order of 0.1 kg m^{-3}. This could therefore lead to a baroclinic flow of warmer (less dense) water over colder (denser) water with speeds given by Equation A3.2 of the order of 2-5 cm s^{-1}. This estimate is valid for periods less than inertial (of order 1 day), after which time rotational effects could become important.

The calculations also suggest that during a hot clear midsummers day vertical temperature stratification could develop in the basin with surface waters warming by up to 4 ^{o}C during an 8 hour period. Studies conducted in lakes and reservoirs have clearly shown that horizontal pressure gradients set up by differential heating and cooling are important to mass transport (see Imberger and Patterson, 1990). However, the differences in bathymetry between lakes and coastal basins precludes direct comparison. Hence, diurnal measurements of vertical temperature structure in Cockburn Sound and adjacent waters, during a range of climatic conditions, would be needed to quantify the heating potential of short-wave radiation, and the subsequent cooling of waters by heat losses.

4.1.9 Evaporation and penetrative convection

<u>Evaporation</u>

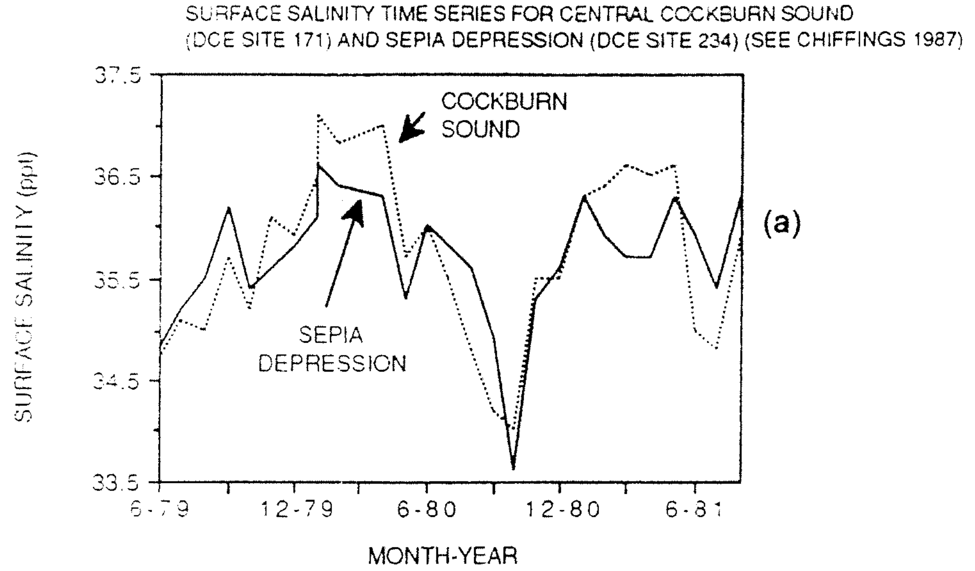
Evaporation in Cockburn Sound, and adjacent basins, could lead to both local salinity increases (hypersalinity) and general increases in the relative salinity of nearshore waters compared to deeper offshore waters. The main hydrodynamic implications of this would be as follows:

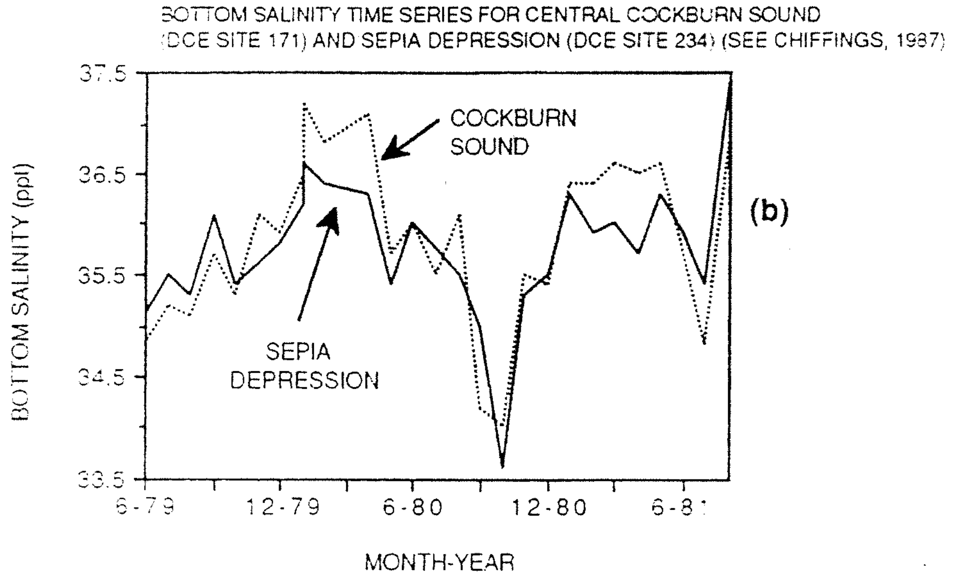
(i) To increase the salinity of bottom waters, hence increasing the strength of vertical salinity, and therefore density stratification, with obvious implications on the rate of vertical mixing.

(ii) To increase the average salinity of nearshore waters, thus possibly promoting the offshore directed advection, as a bottom baroclinic current, of coastal waters. The possibility of this mechanism was discussed by Hearn (1991) and was reviewed in Chapter 3.

The historical data from Cockburn Sound (see Chapter 3) is not comprehensive enough to allow a proper investigation of the possibility of spatially variable evaporation around the Sound due to spatially variable heating. However, long-term time series of surface and bottom salinities (monthly data: 1979-1981, DCE) for Cockburn Sound and Sepia Depression, presented in Figures 4.29a, b and c, show that Cockburn Sound water is hypersaline in summer and generally significantly more saline than the nearby waters of Sepia Depression.

Statistical information from the Bureau of Meteorology indicates that daily evaporation for Perth during hot summer days is on average 8.2 mm but can reach 12 mm. Table 4.4 presents the average daily evaporation for Perth for each month of the year derived from daily pan evaporation data for the period 1967-1990.





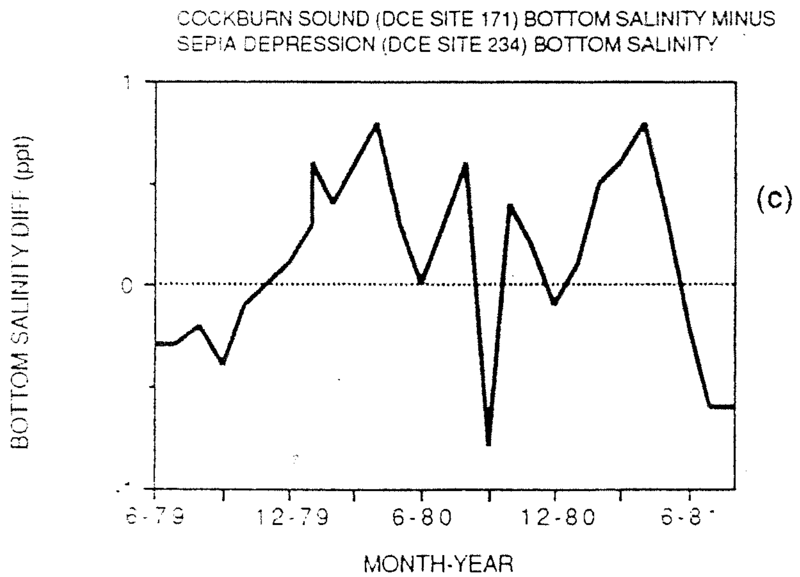


Figure 4.29 Time series plots of (a) surface and (b) bottom salinity in Cockburn Sound (site 171) and Sepia Depression (site 214), and (c) difference in surface salinity of the two sites. See Figure 4.18 for site locations. Data from DCE surveys of June 1979 to July 1981.

Table 4.4. Average daily total evaporation (mm) for Perth. Data from pan evaporation data collected daily from 1967 to 1990 by the Perth office of the Bureau of Meteorology.

MTH	J	F	M	A	M	J	J	A	S	O	N	D
EVAP (mm)	8.2	7.8	6.3	4	2.7	2.1	2.1	2.6	3.6	5	6.4	7.5

If an evaporation of say 8 mm took place during the day over a 20 m water column of water with a density of say 1025 kg m^{-3}, and the 20 mm that was evaporated was replaced by inflowing oceanic water (still at the original salinity) and these two waters masses were then totally mixed, then a new density of the order of 1025.01 kg m^{-3} would result. Hence, if there was minimal flushing of the basin a density of the order of 1025.1 kg m^{-3} would result in 10 days, or 1026 kg m^{-3} in a period of the order of 100 days. Average salinity of the Sound was found to rise by about this rate in the 1979-1981 spring/summer periods (see Figure 4.29). The same rate of salinity increase is also typical of adjacent waters, as discussed in Section 3.1.8.

Hence, it appears that that local evaporation and onshore/offshore salinity differences could be important hydrodynamic mechanisms in summer for Cockburn Sound and adjacent waters.

Penetrative convection

The vertical mixing potential of penetrative convection due surface density increases caused by evaporation and surface cooling is reviewed in Appendix A3.

The potential influence of penetrative convection by surface cooling was discussed in Section 4.1.2, with reference being made to diurnal temperature measurements conducted at the end of the CBH Jetty, Mangles Bay. Temperatures fell by about 2 ^{o}C during the diurnal cycle, and this is a significant drop in temperature considering that the available evidence suggests that diurnal fluctuations in temperatures are of the order of 2-4 ^{o}C. A theoretical analysis of the potential of penetrative convection is now performed by applying Equation A3.3 to predict a turbulent intensity velocity scale and then Equations A3.9 and A3.10 to predict the resulting vertical mixing.

Applying Equation A3.3, with typical values for the parameters of the equation, as given in Appendix A3.3, yields a turbulent intensity velocity scale of the order of 4×10^{-3} m s^{-1}. The rate of surface mixing is now calculated by applying Equations A3.9 and A3.10. Two initial density structure types are assumed: first that there is a homogeneous upper layer above a linearly stratified lower layer, and second that there are two homogeneous layers. The initial depth of the upper layer is set at 5 m.

Linear stratification

The relevant starting conditions and mixing rates are as follows (the initial strength of the stratification is progressively weakened for each successive case).

CASE I $N_o^2 = (g/\rho)(d\rho/dz)_o$, with $(d\rho/dz)_o = 0.1$ kg m^{-3} per m of depth.

Applying Equation A3.9 yields a deepening rate of $0.0459t^{1/3}$, and this equates to an increase in the upper mixed layer of about 1.5 m in 10 hours.

CASE II $(d\rho/dz)_o = 0.05$ kg m^{-3} per m of depth.

Applying Equation A3.9 yields a deepening rate of $0.06t^{1/3}$, and this equates to an increase in the upper mixed layer of about 2 m in 10 hours.

CASE III $(d\rho/dz)_o = 0.01$ kg m^{-3} per m of depth.

Applying Equation A3.9 yields a deepening rate of $0.06t^{1/3}$, and this equates to an increase in the upper mixed layer of about 3 m in 10 hours.

Two-layered structure

The relevant starting conditions and mixing rates are as follows (again, the initial strength of the stratification is progressively weakened for each successive case).

CASE IV Initial density difference = 1 kg m^{-3}.

Applying Equation A3.10 yields a deepening rate of 3.235 x $10^{-7}t$ and this equates to an increase in the upper mixed layer of about 0.01 m in 10 hours.

CASE V Initial density difference = 0.5 kg m^{-3}.

Applying Equation A3.10 yields a deepening rate of 6.47 x $10^{-7}t$ and this equates to an increase in the upper mixed layer of about 0.02 m in 10 hours.

CASE VI Initial density difference = 0.1 kg m^{-3}.

Applying Equation A3.10 yields a deepening rate of 3.235 x $10^{-6}t$ and this equates to an increase in the upper mixed layer of about 0.1 m in 10 hours.

It would appear, therefore, on the basis of the theoretical calculation above, that penetrative convection alone could at best lead to only small amounts of surface mixing (less than 3 m) in Cockburn Sound during typically stratified summer conditions.

The turbulent intensity velocity scale caused by the evaporation of surface waters can be estimated by Equation A3.5. For an evaporation rate of 10 mm per day (an upper limit for summer, see Table 4.4 above) an associated turbulent intensity velocity scale of the order of 1 x 10^{-3} is estimated, and this is significantly less than that calculated for penetrative convection due to surface cooling. Hence, the influence of evaporation on upper mixed layer deepening on short time scales (diurnal or less) is likely to be negligible.

Appropriate field measurements of vertical structure in salinity and temperature using sufficiently resolute CTD instruments can quantify the role of surface cooling to vertical mixing and is recommended for future field studies of Cockburn Sound and adjacent waters.

4.1.10 Submarine groundwater discharge

The introduction of buoyancy flux due to submarine groundwater discharge (SGD) along the coastal margins of the Marmion Marine Park was studied by Johannes and Hearn (1985). They measured the formation of off-shore density stratification due to this mechanism. Freshwater percolates up through the coastal bed and rises to the surface. Nearshore waters are hence slightly less dense than adjacent offshore waters. The horizontal density gradients set up pressure gradients which could drive an offshore directed density flow of buoyant surface water. Hearn (1991) has further postulated that this offshore flow could be deviated into a southward flowing coastal current by Coriolis force (see Chapter 3).

The hydrodynamic significance of this mechanism was also shown for coastal marina flushing by Schwartz and Imberger's (1988) study of the Hillarys Marina, Western Australia. They suggested that this mechanism could be twice as effective as tides in flushing the marina.

Appleyard (1990) has recently reviewed all existing information relating to SGD of the Perth metropolitan coastline and his results were discussed in Section 3.1.8, above. Appleyard's (1990) analysis suggests that an estimate of total SGD into Cockburn Sound is of the order of 30000 m^3 per day. Since the volume of Cockburn Sound is of the order of 1.5 x 10^9 m^3 an injection of 30000 m^3 of freshwater could lower the average salinity of the Sound by no more than of the order of 1 x 10^{-3} ppt.

Hence, as a first order calculation this would suggest that buoyancy flux from SGD would be small compared to the flux from solar heating and the flux which could be inherent in inflows of oceanic waters with a salinity or temperature different to that of the Sound (refer to Figures 4.28 and 4.29, for example). Hence, any hydrodynamic influence of SGD would be, at best, localised near regions of

SGD. ALCOA of Australia Ltd commissioned intensive CTD surveys of the coastal zone adjacent to their operations north of James Point. These surveys were conducted by the Centre for Water Research (University of Western Australia) and the data identified patches of water along the shoreline with salinities slightly less than the ambient seawater of the Sound by about 0.05 ppt. The individual patches had diameters of the order of 100-200 m. This suggests further that SGD could be important to the nearshore hydrodynamics.

Field studies could be employed to check on the importance of SGD to the hydrodynamics of Cockburn Sound and adjacent waters. Further, a theoretical analysis of basin scale gravitational flushing that could be induced by this mechanism, in combination with other sources of buoyancy, should be carried out. One approach that could be followed for this analysis is that of Schwartz and Imberger (1988).

4.1.11 Industrial discharges of buoyant water

The DCE (1979) identified the volumetric discharge rates of all major industrial sources into Cockburn Sound and Owen Anchorage. Most of the effluent is heated seawater and the major freshwater contributor (the Woodman Point Wastewater outfall) is no longer operational.

Owen Anchorage effluent totals approximately 4 ML/day and would therefore make a relatively small impact to the overall stratification. Localised buoyant plumes could however persist around the individual outfalls and their near, intermediate and far-field dilution and spreading characteristics are important to overall water quality.

Within Cockburn Sound most discharges of heated sea water occur around the James Point industrial region. A major input is from the State Electricity Commission's (SEC) power station (3 km north of James Point). This outfall is an open channel flow via a 30 m groin and has a flow of the order of 1000 ML/day. This effluent enters the Sound with a temperature of the order of 40-50 ^{o}C. KNC and CSBP and Farmers combine to discharge about 100 ML/day of heated seawater via a 400 m submerged pipeline with an end diffuser. After initial dilution the effluent reaches the surface less than 0.5 ^{o}C warmer than the ambient seawater.

Fundamentally, the importance to the overall circulation of the introduction of buoyancy from industrial discharges is the same as that from submarine groundwater discharge. The total input of freshwater from industrial discharges is less than 10 percent of that due to submarine groundwater discharge. It is assumed therefore that buoyancy flux into the Sound is not important to the basin-scale circulation patterns of the Sound. However, the localised concentration of polluted buoyant discharge water near the coast poses obvious implications on localised water quality in a water body that is heavily utilised for recreation, fishing and bathing. Hearn (1992) has recently conducted numerical modelling exercises of the spreading and mixing of coastal outfall plumes in Cockburn Sound, and the reader is referred to that work for further details.

4.1.12 Frontal structures

Fronts refer to regions of flow convergence that accompany the meeting of different masses of water with different densities. Slick, foam or debris concentration lines are often visible at the frontal zones due to the convergence of visible matter. Profiling of salinity and temperature along transect paths that cross slick lines in water bodies can often reveal clear intensive salinity or temperature gradient zones that accompany frontal regions (see, for examples, Imberger, 1983 and Luketina, 1987). Aerial photography is a useful technique that is employed to identify frontal regions of river and estuarine plumes that propagate into coastal waters.

Within Cockburn Sound there have been many visual observations (Chiffings, 1987) of fronts especially along the shelf region between the eastern margin and the central basin, and these observations were often supported by complementary field measurements of Chlorophyll "a", salinity and temperature. Chiffings (1987) established that such frontal features do occur in Cockburn Sound and he pointed out that they represent separation zones between relatively high and less eutrophic water masses. The dispersion of a eutrophic or nutrient rich mass of water lying within a spatial region characterised by frontal zones will be strongly governed by the interplay between the strength of the density gradients between the patch of interest and surrounding waters. Data presented throughout this report highlight the common occurrence of salinity, temperature and therefore density fronts in Cockburn Sound. An understanding of the relative frequency of occurrence, strength and dispersion of fronts will be important the overall understanding of the relationships between pollutant inputs and their subsequent spread and impact on the ecology of Cockburn Sound and adjacent waters.

Field measurements of biological and hydrodynamic characteristics of coastal waters should take account of the need to understand the implications of frontal zones on water quality.

The influence of river discharge on the hydrodynamics of Cockburn Sound in summer is likely to be negligible. However, this is probably not the case in winter when the Swan River adds an appreciable flux of buoyancy, in freshwater inputs, to Cockburn Sound. The influence of river discharge on the hydrodynamics of the southern metropolitan waters is discussed in the proceeding sections.

4.2 Autumn

4.2.1 Mean salinity and temperature

Following summer temperatures and salinities fall significantly in the Sound, and this is evidenced by the long-term monthly data presented in Figures 4.19 and 4.20 (above). This is due to lower air temperatures and evaporation rates and is consistent with the seasonal trend recorded further north at Waterman Bay (see Figure 4.21) , as discussed by Pearce and Church (1992). By May daily evaporation is at an average of about 2.77 mm, which compares to about 8.2 mm in mid-summer.

The Cockburn Sound and Sepia Depression time series ST data in Figure 4.29 indicate a reversal of onshore-offshore temperature and salinity gradient direction during the autumn period. Whereas in summer nearshore salinities are relatively high, in autumn the situation reverses. Freshwater inputs from rivers and urban drainage may also begin to contribute a buoyancy flux in autumn. During autumn temperatures of nearshore waters fall below those of offshore waters, as shown in Figure 4.28. Differential cooling, with shallower nearshore waters cooling greater than those of the deeper offshore region, is primarily responsible for the temperature difference.

The occurrence of stratification during autumn is discussed below.

4.2.2 Basin-scale stratification

A general representation of the nature of the basin-scale stratification structure in Cockburn Sound during autumn is given by the results of ST measurements conducted by ERA (July, 1971) and these data are analysed below.

ERA (July, 1971) presented basin-scale contour plots constructed from salinity profiling conducted during autumn 1971 over the grid of stations shown in Figure 4.30. The causeway was only constructed up to and including the Trestle Bridge at the time of the field survey. A selection of those contour plots is used here to summarise the mean autumn dynamics of the Sound. The periods of the data collection were 24-26 March, 1-3 April, 28-30 April and 17-20 May 1971. Table 4.5 presents the mean wind, Swan River flow, and basin-scale stratification details for each of these periods.

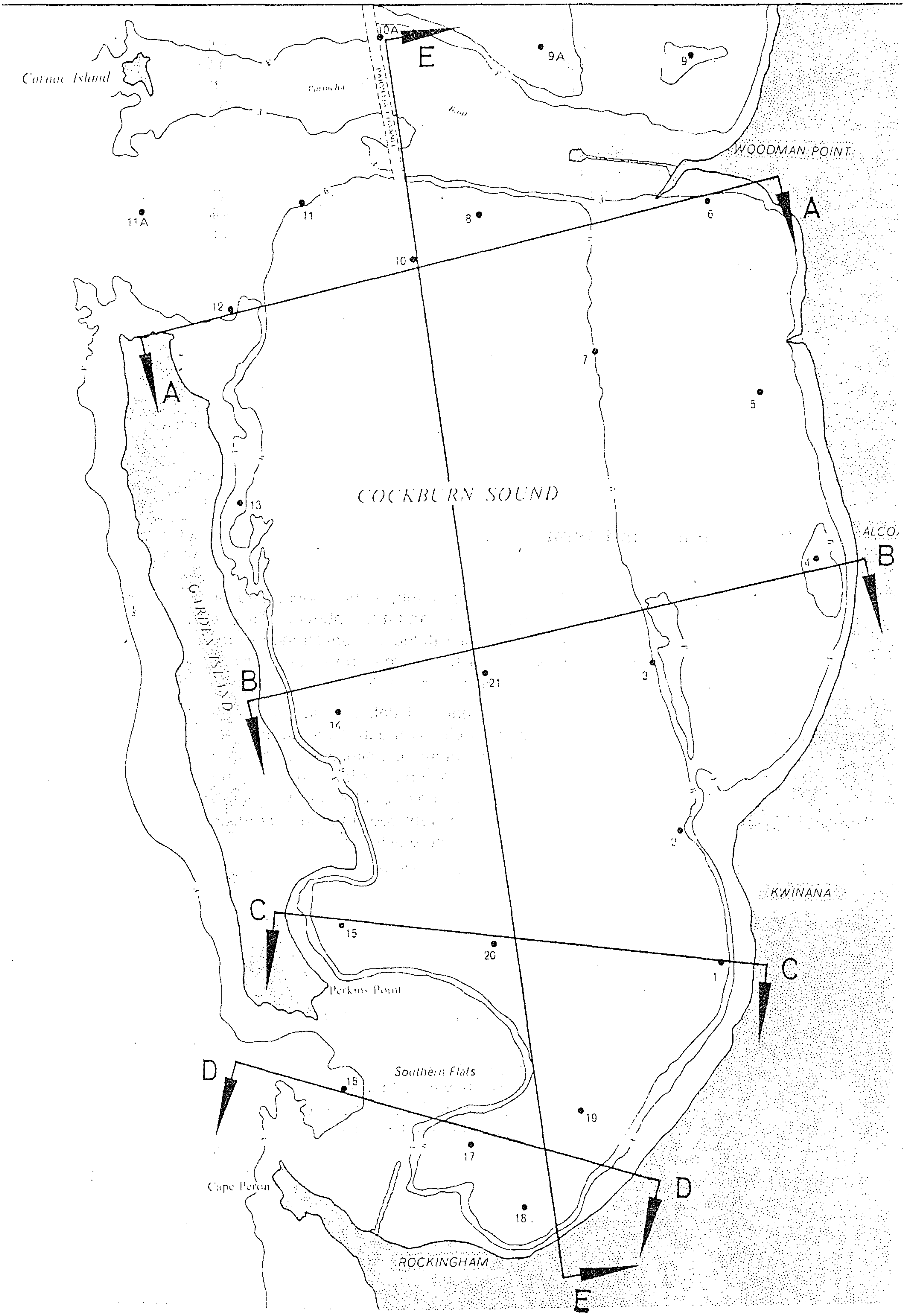


Figure 4.30 Grid layout and station numbers for the ERA salinity-temperature profile surveys conducted in Cockburn Sound during autumn 1971 (ERA, July 1971).

Table 4.5. Wind, Swan River flow and basin-scale mean stratification characteristics of Cockburn Sound during the periods of basin-scale salinity profiling by ERA during autumn 1971 (from ERA, July 1971).

Date	Mean wind		Swan River flow	Characteristic salinity stratification	
(1971)	($m\ s^{-1}$ & DIR)		($m^3\ s^{-1}$)	Vertical	Horizontal
24 Mar	0-10	SSW	Negligible	Isohaline	Patchy
25 Mar	5	SE	Negligible	Isohaline	Patchy
26 mar	5-8	E	Negligible	Isohaline	Patchy
1 April	2-5	NNE	30	Stratified	Patchy
2 April	2-5	NE	10	Stratified	Patchy
3 April	5	ENE	10	Stratified	Patchy
28 April	0		Negligible	Stratified	Patchy
29 April	0-5	SSW	Negligible	Stratified	Patchy
30 April	1-4	SW	Negligible	Isohaline centrally but stratified near north and south openings	Patchy
17 May	3-5	W	2	Isohaline (as per 30 April)	Patchy
18 May	~ 10	WNW	2	Isohaline (except Mangles Bay)	Patchy
19 May	5-7	N	2	Stratified	Patchy
20 May	3-7	SW	2	Isohaline (as per 30 April)	Patchy

ERA (July, 1971) 24-26 March 1971

Between 24 and 26 march 1971 the basin was generally vertically isohaline. The surface plan contours in Figure 4.31 indicate a northward advection of relatively less saline oceanic water in through the southern opening at an average rates of about 2 km per day. The northward winds of 5-10 m s^{-1} winds during the period (Table 4.5) were probably responsible for both the northward advection and vertically isohaline nature.

ERA (July, 1971) 1-3 April 1971

The Swan River was flowing relatively strongly and the general decrease in salinities in the northern half of the Sound (Figure 4.32) was probably due to the southward advection of brackish water from the Swan River by the N-NE winds. Coriolis force probably deflected the buoyant flow towards the coast (as described in Chapter 3). The accompanying vertical contour plots in Figure 4.33 show the buoyant frontal nature of that flow into Cockburn Sound. These data suggest one possible scenario for the way in which the Sound changes its salinity structure in autumn due to freshwater buoyancy inputs from the Swan River. Winds were less than 5 m s^{-1} during the period and were not able to break down the salinity stratification, and this is consistent with the predictive analysis on wind mixing in Section 4.1.5, above.

ERA (July, 1971) 28-30 April 1971

We see by the surface plan contours in Figure 4.34 that the basin is receiving relatively low salinity water from the ocean via both openings during weak winds and low Swan River flow. Hence, this indicates incursions into Cockburn Sound of low salinity regional coastal waters, again suggesting the reversal of salinities from summer highs to winter lows.

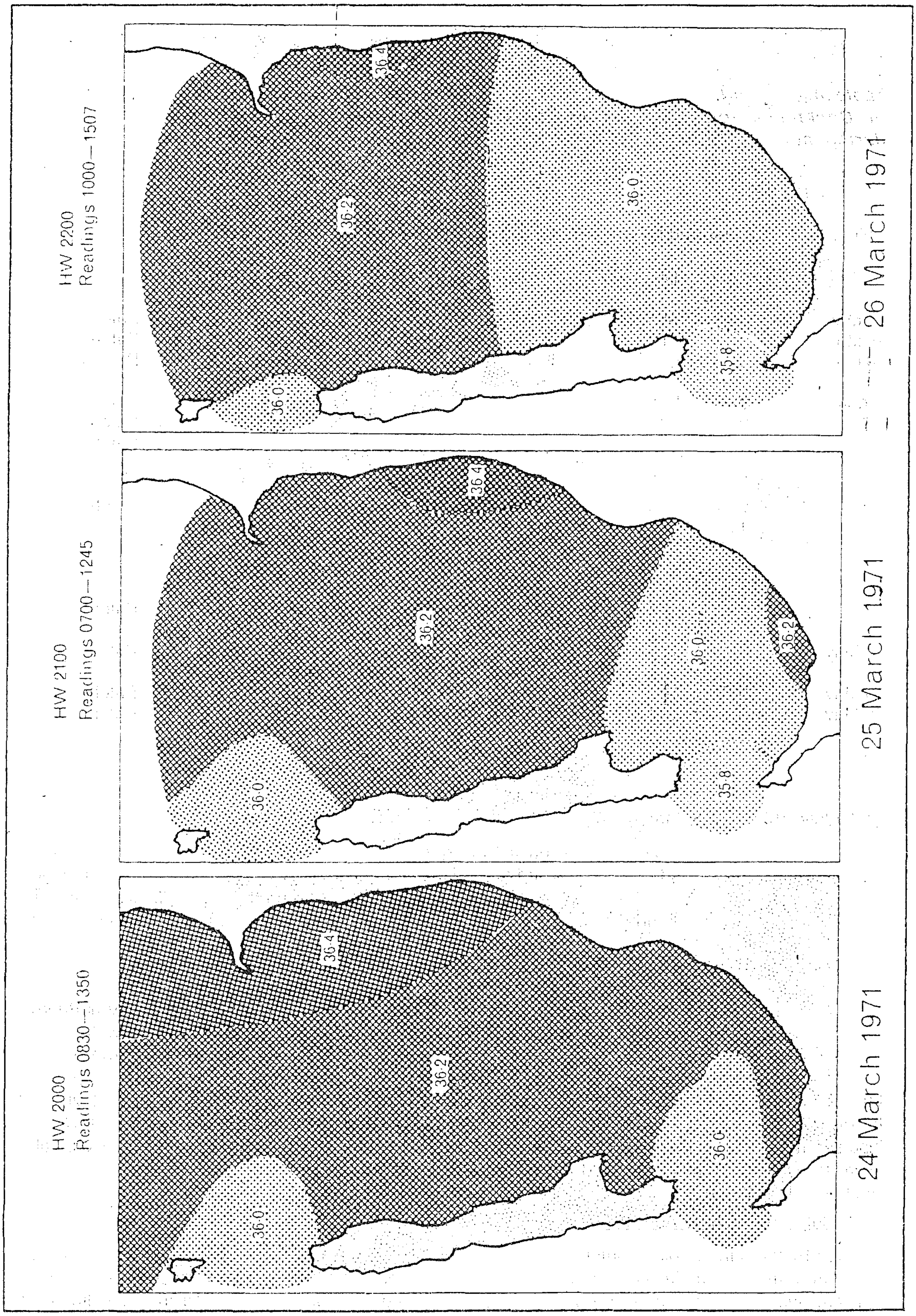


Figure 4.31 Surface salinity structure of Cockburn Sound on 24, 25 and 26 March 1971. See Figure 4.30 for grid details. Data from ERA (July, 1971).

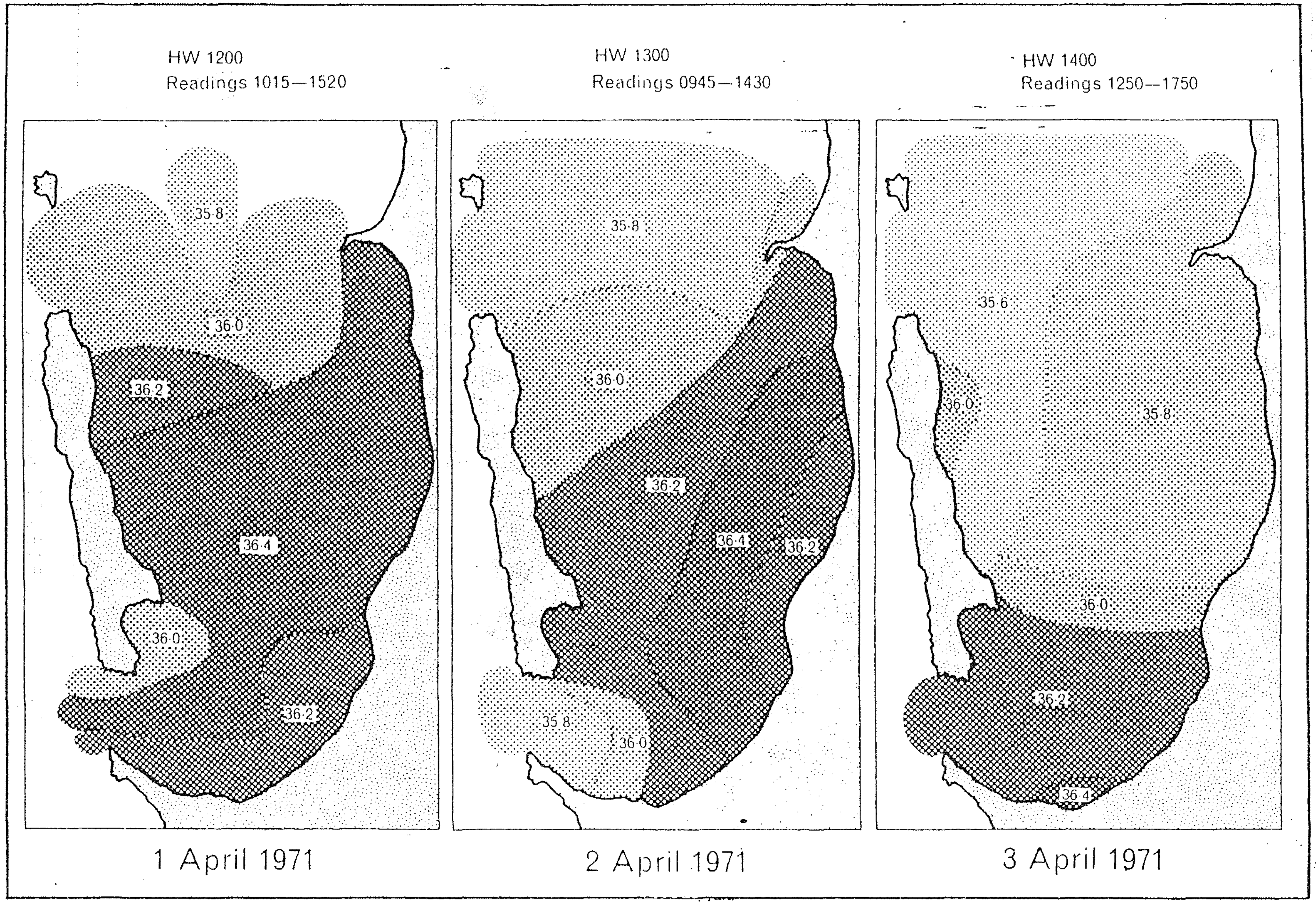


Figure 4.32 Surface salinity structure of Cockburn Sound on 1, 2 and 3 April 1971. See Figure 4.30 for grid details. Data from ERA (July, 1971).

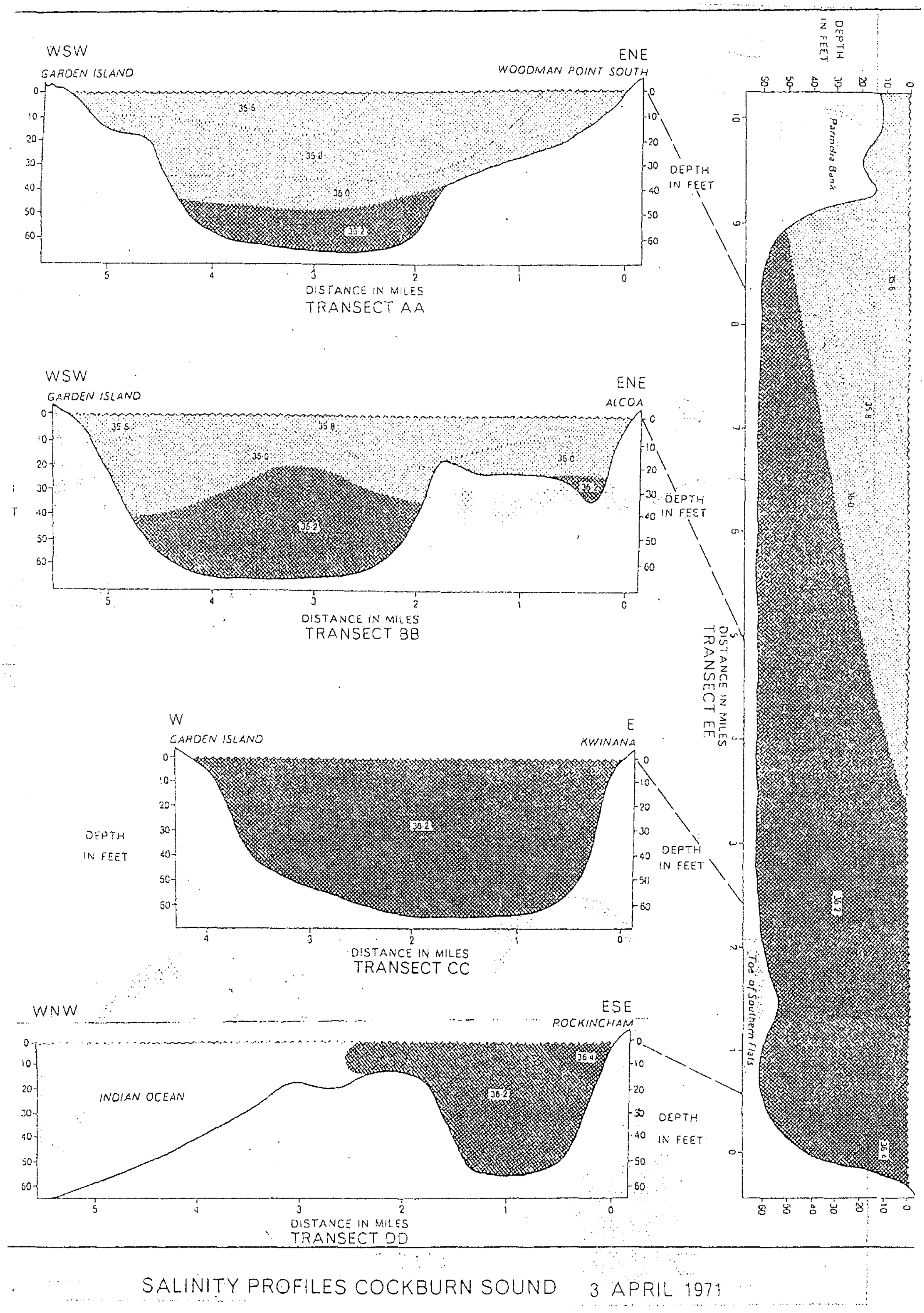


Figure 4.33 Vertical salinity structure of Cockburn Sound: 1250-1750, 3-4-71. See Figure 4.30 for grid details. Data from ERA (July, 1971).

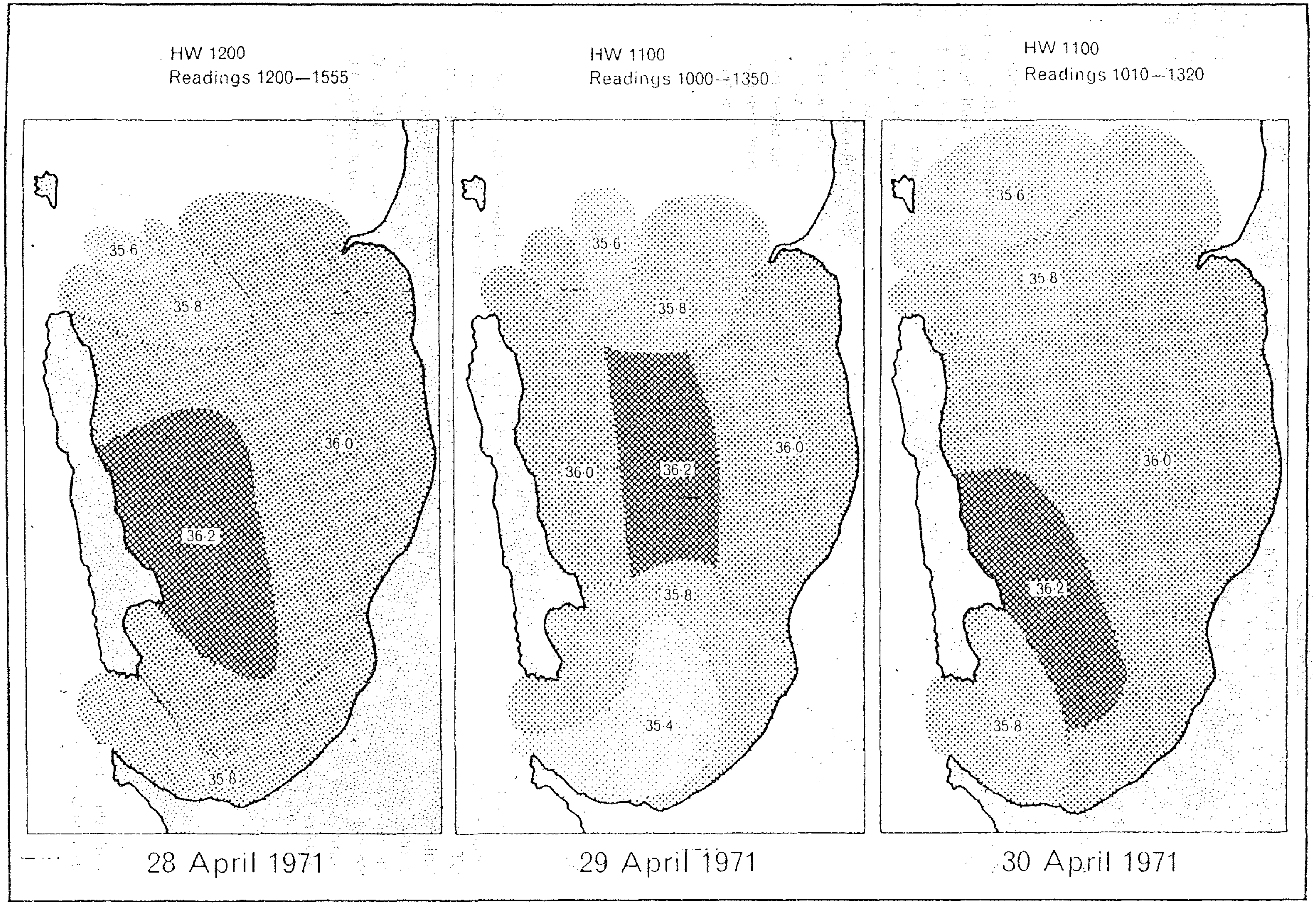


Figure 4.34 Surface salinity structure of Cockburn Sound on 28, 29 and 30 April, 1971. See Figure 4.30 for grid details. Data from ERA (July, 1971).

ERA (July, 1971) 17-20 May 1971

In Figure 4.35 the entrance of relatively low salinity water via the two openings is shown to be continuing during this period. Salinities have declined, now being as low as 35.2 ppt compared to maximum recorded during 24-26 March of 36.4 ppt. Winds during the period May 17-20 ranged from 3-10 m s^{-1} however the rate at which buoyancy was introduced to the Sound must have been sufficient to maintain some vertical stratification in salinity, as suggested by the basin-scale stratification in the vertical contour plots of Figure 4.36 for May 19.

4.2.3 Exchange

The seasonal regional current pattern was discussed in Appendix A7, where it was shown that autumn is the period when summer northward flows reverse in general direction to then flow southward during winter. The results of flow monitoring under the bridges (Appendix A7) suggest that flows were variable in net direction through the southern opening, sometimes flowing out and sometimes flowing in. Average flow rates were of the order of 500 m^3 s^{-1}, which represents a replacement time for the whole of Cockburn Sound's volume of the order of 35 days. Based on maximum flow rates recorded in autumn maximum replacement times of the order of 9 days were calculated. It is to be noted once again, that such replacement times are calculated on the basis that there is continuous basin-scale mixing, which mixes inflows with the whole basin volume. This was not the case in Cockburn Sound in summer, as shown above, and is also not a valid assumption for autumn or winter, as will be clearly shown below. Attention is once again drawn to the results of the upper mixed layer deepening analysis for summer (sections 4.1.4 and 4.1.5, above) and the wind speed versus vertical density difference plots in Figure 4.23 (above) that show that it takes winds of the order of about 5-10 m s^{-1} or more, blowing for more than a few hours, to fully mix the basin.

4.3 Winter

4.3.1 Mean salinity and temperature

The trend to declining salinities and temperatures that occurs in Cockburn Sound during autumn (above) continues into winter, with eventual values reaching seasonal minima. The Cockburn Sound ST time series plots (1979-1981) that were presented in Figures 4.19 and 4.20 exemplify this point. Salinity fell to about 34 ppt and temperature to about 15 ^{o}C during the three respective winters in central Cockburn Sound. This is consistent with the seasonal trend in salinity and temperature along the metropolitan coastline (see Figure 4.21 for Waterman Bay, and Figures 3.5 and 3.6 for Warnbro Sound). The low winter salinities near the coast are due to the low rates of evaporation compared to summer with a large excess of precipitation over evaporation being typical, and also due to freshwater buoyancy inputs of freshwater along the coast by rivers, drains and submarine groundwater discharge. The influence of rivers is discussed below in Section 4.3.3.

The direction of nearshore-offshore salinity and temperature gradients are opposite to those for summer. In winter Cockburn Sound water is up to 3 ^{o}C cooler than Sepia Depression and salinity in Cockburn Sound up to 1 ppt fresher than Sepia Depression. River inputs of freshwater and relatively low air temperatures are responsible for this.

A hydrodynamic implication of the occurrence of such gradients in salinity and temperature between nearshore and offshore waters is that there is the possibility of accompanying density gradients, which could drive baroclinic exchange currents between nearshore and offshore waters, as was elaborated upon in Chapter 3.

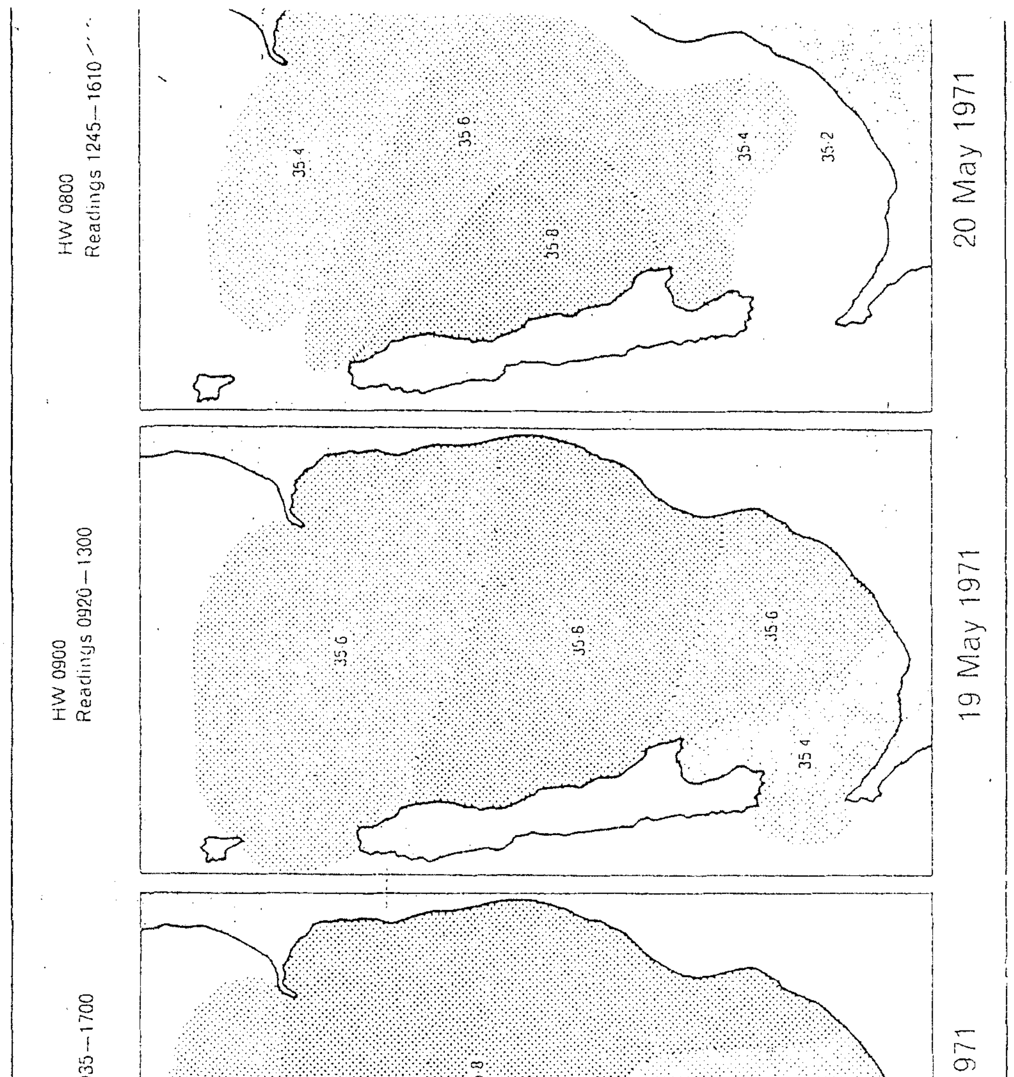
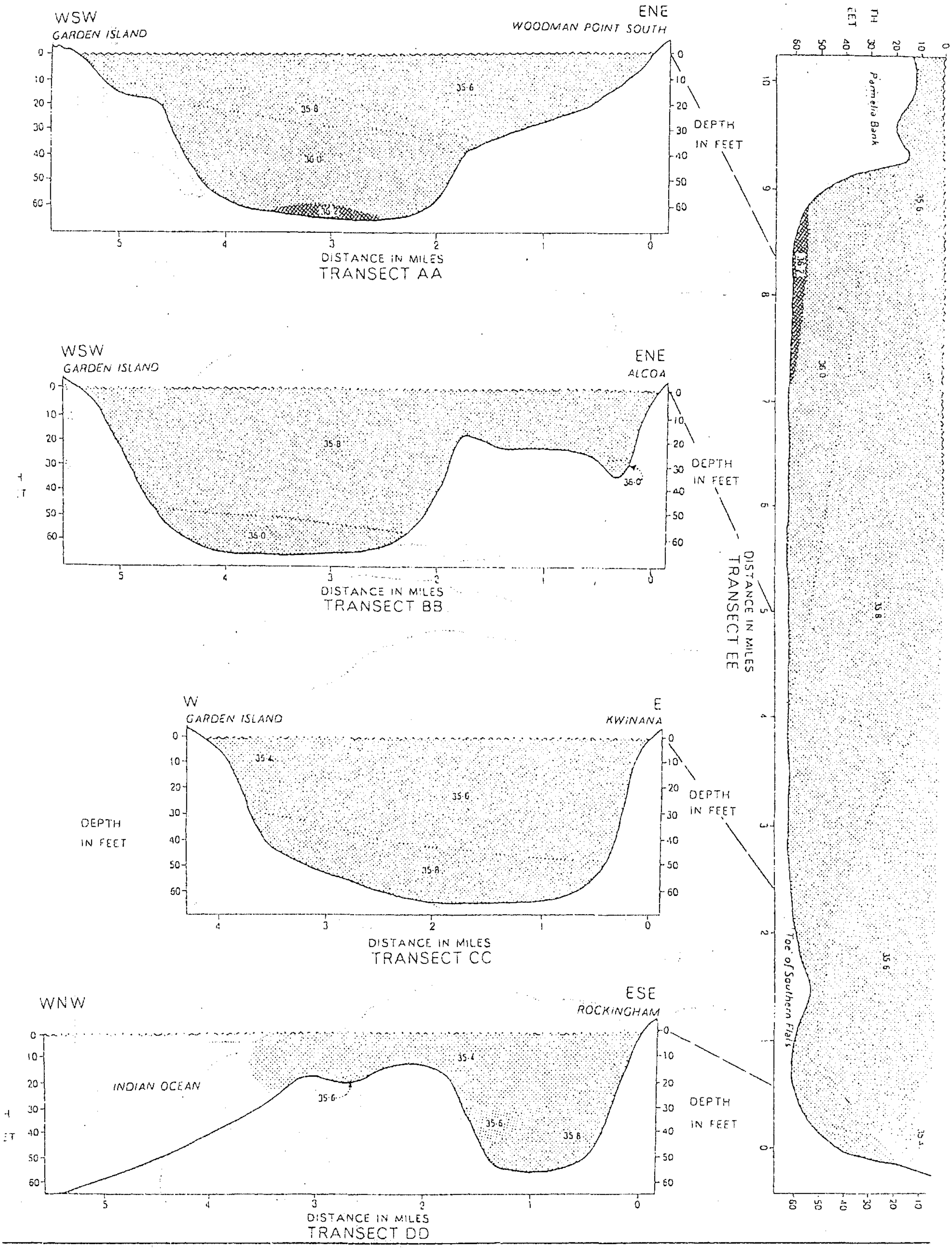


Figure 4.35 Surface salinity structure of Cockburn Sound on 17, 18, 19 and 20 May, 1971. See Figure 4.30 for grid details. Data from ERA (July, 1971).



SALINITY PROFILES COCKBURN SOUND 19 MAY 1971

Figure 4.36 Vertical salinity structure of Cockburn Sound: 0920-1300, 19-5-71. See Figure 4.30 for grid details. Data from ERA (July, 1971).

4.3.2 Mean regional currents and exchange through the southern openings

As discussed in Appendix A7, the net regional flow in the nearshore region (including the nearshore basins such as Cockburn Sound) is southwards during winter, and this drives a net outflow through the southern opening . The current meter data reviewed in Appendix A7 for winter 1975 indicate that the average net flux out through the southern bridge openings was of the order of 570 m^3 s^{-1}, which is equivalent to an idealised replacement time for Cockburn Sound's volume of about 30 days. Under extreme NW storm conditions this replacement time can be as low as 4 days assuming that the storm winds persist throughout the four-day period. Drogue-tracking of flows through the southern opening by ERA before and after the causeway was constructed provided some interesting results (see Appendix A6) and these are summarised below.

During 12-30 July 1971, when only the Trestle Bridge had been completed, up to twenty drogues were repeatedly placed along the alignment of the proposed causeway and then tracked. In general the tide was falling throughout the exercises. Winds were generally N/NW, but on some days SW winds occurred. Most drogue runs revealed that during southward winds the flow in the opening was out (towards west) at speeds of the order of 15-25 cm s^{-1} and that flow tended to converge towards the centre of the opening. This feature of the flow is typified by the tracks of Figure 4.37a and b. The tide was generally falling and hence would have reinforced the outflows caused by the predominantly southward wind stress over the water surface of the Sound.

On some occasions (13 July: 0836-1042 and 1147-1337 for example, see Appendix A6) the tide was rising, the wind was N/NW or W/NW at 5 m s^{-1} and yet the flow was still tracked to be outward and converging towards the centre through the southern opening (see Figures 4.38a and b, for example), suggesting that wind-driven or regional southward drift overcame the tidal influence in the region along the then proposed causeway alignment. However, this mean flow pattern was not always the observed response to these wind and tide conditions. For example, on 27 July (0748-1013) the tide was rising and winds were NE at 7 m s^{-1}. The resulting data is shown in Figure 4.39, and it is clear that initially the drogue tracks displayed converging outflow, but that eventually the drogues exhibited a clockwise gyre behaviour once in the region near the true neck between the Sound and the Sepia Depression.

The above discussion highlights the competing influence, upon flow through the southern opening, of wind forcing (or regional southward drift) and tidal forcing across the southern opening. In addition, it is to be remembered that the drogue systems were probably strongly influenced by surface currents due to the relatively large drag area of the cans used as floats (see the discussion at the beginning of Appendix A6). Hence, a more conclusive summation of flow characteristics through the southern opening in winter is not possible at this stage, given the data available. This aspect of the dynamics at the southern opening, in particular now that the causeway and accompanying bridge openings are fully in place, requires further field investigation.

4.3.3 The Swan River buoyancy flux, stratification and wind mixing

Seasonal ST characteristics

The simplest data set to open this discussion is the seasonal (monthly) ST measurements that were presented in Figures 4.19 and 4.20. They show the surface and bottom salinity and temperature (respectively) variation from June 1979 to August 1981. Vertical salinity differences of the order of 0-0.1 were typical in central Cockburn Sound during the winters, but there were occasions when surface salinities as much as about 1 ppt lower than bottom salinities were recorded. It will be shown that the Swan River plume causes these types of situations in salinity structure on a basin-wide scale. Vertical temperature differences in central Cockburn Sound are also shown to be common in winter, with vertical differences ranging from 0 to about 1 ^{o}C. The occasional recordings of surface temperatures lower than bottom temperatures is brought about by the surface advection of cold low salinity water into Cockburn Sound, originating from the Swan River. These points are discussed in the following.

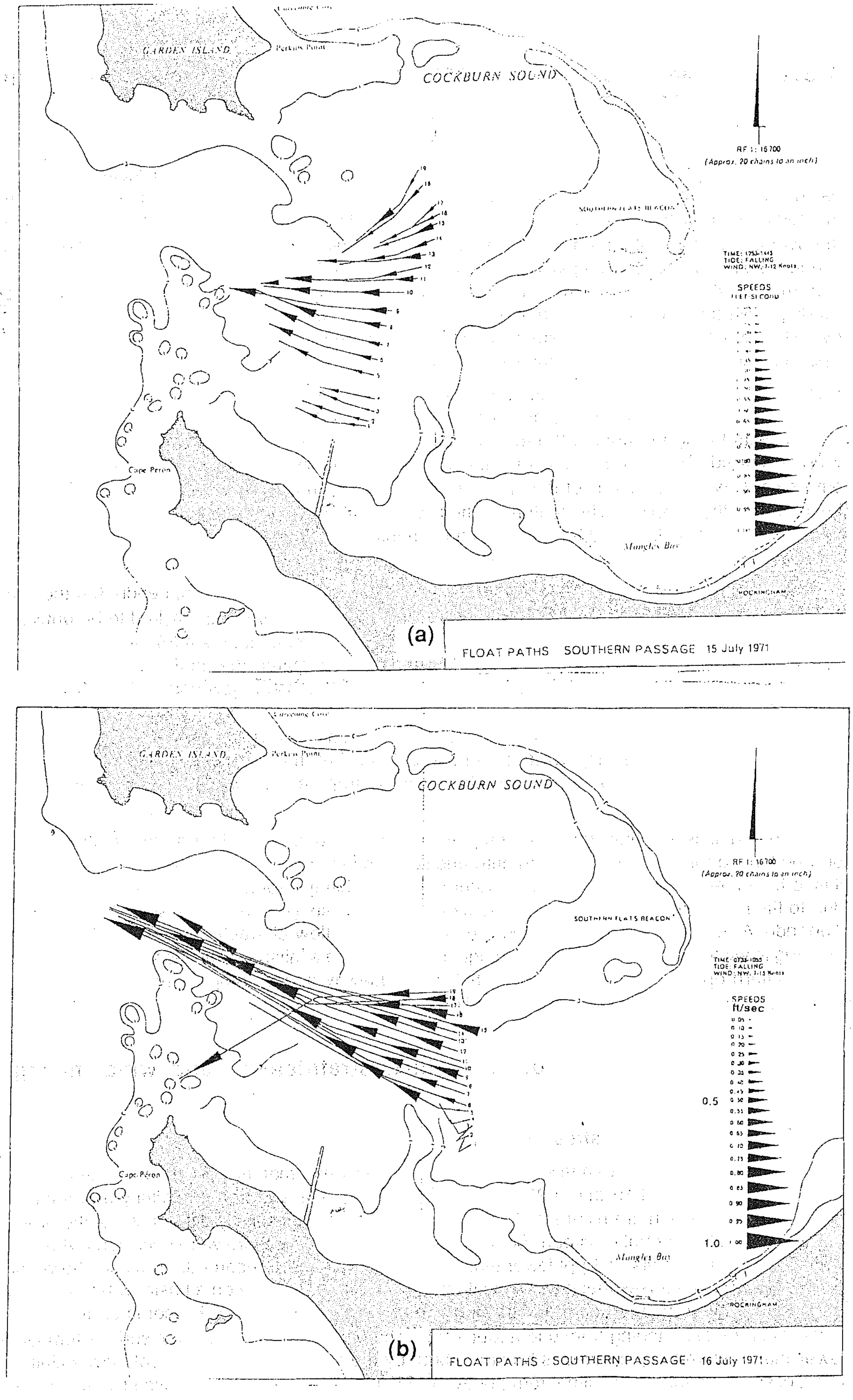


Figure 4.37 Drogue track paths for deployments in the partially constricted southern opening of Cockburn Sound on 15 and 16 July 1971. Data from ERA (details in Appendix A6).

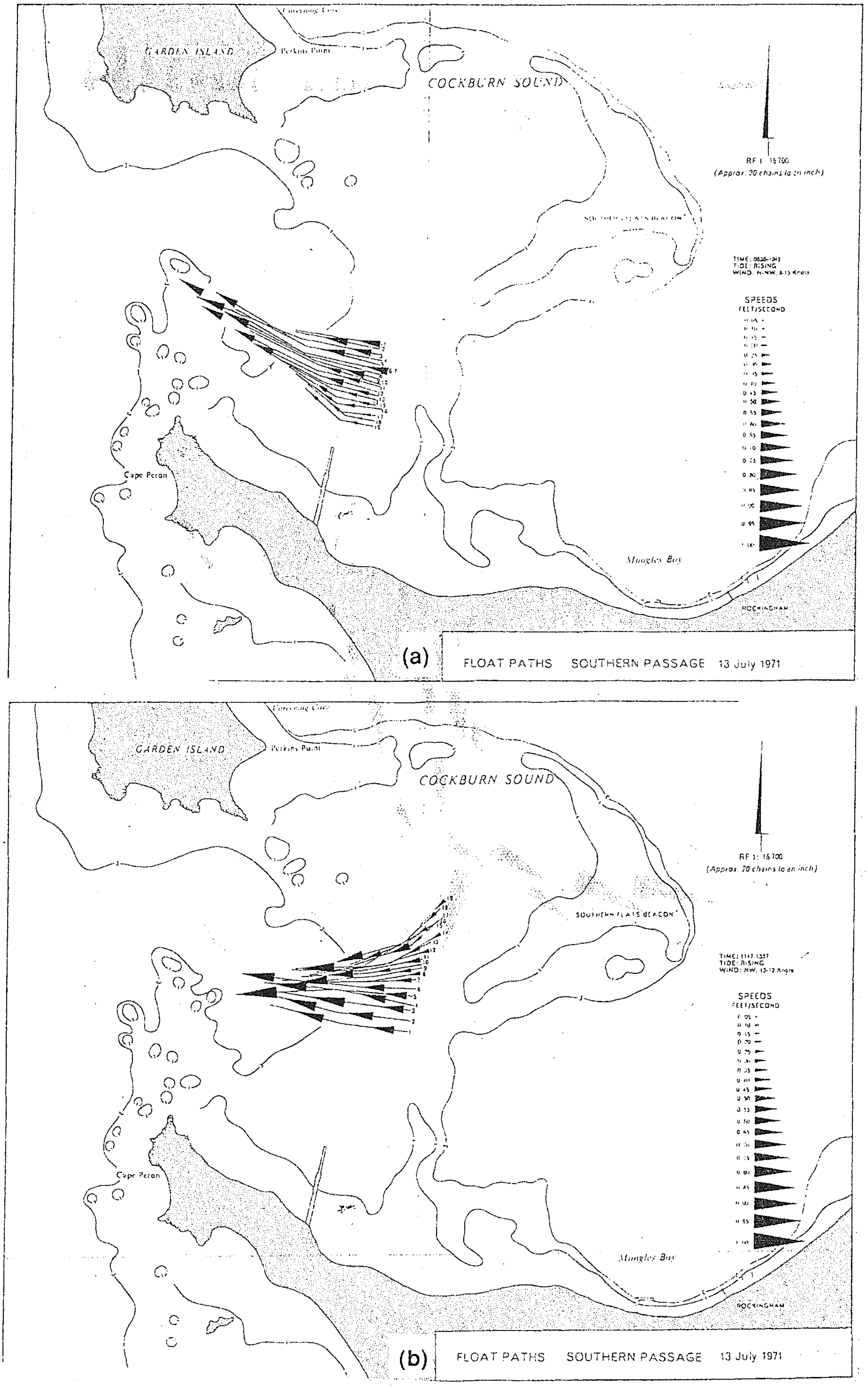


Figure 4.38 Drogue track paths for deployments in the partially constricted southern opening of Cockburn Sound on 13 July 1971. Data from ERA (details in Appendix A6).

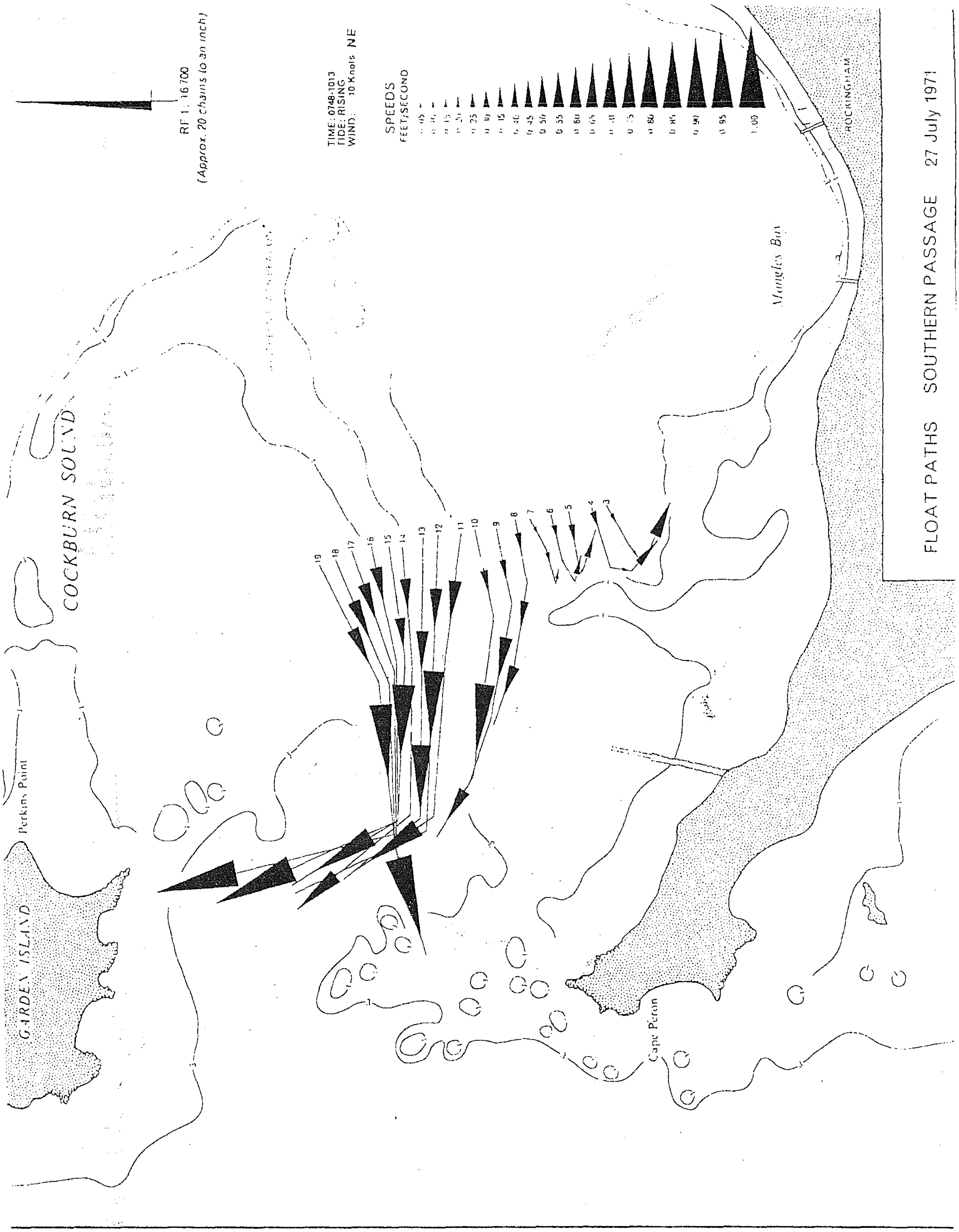


Figure 4.39 Drogue track paths for deployments in the partially constricted southern opening of Cockburn Sound on 27 July 1971. Data from ERA (details in Appendix A6).

Swan River flows

The discharge characteristics of the Swan River, on a seasonal basis, are summarised in Figure 4.40. These data were provided by the Water Authority of Western Australia (WAWA), Surface Water Branch, and take account of the major contributions to total Swan River flow from its most important tributaries (Avon River, Ellen Brook, Jane Brook, Canning River and Helena River). As shown, the net annual discharge is generally of the order of 100-500 x 10^6 m^3, but can be as high as about 1500 x 10^6 m^3.

In terms of buoyancy flux, and the potential to lower mean salinities in Cockburn Sound should the Swan River flow be advected directly into the system, a freshwater volume as small as 10 x 10^6 m^3 could potentially lower the average density of the Sound's entire volume by about 0.2 kg m^{-3}. A review of the WAWA's long-term flow records for the Swan River shows that typical monthly winter discharges range from 25 to 150 x 10^6 m^3, and hence the potential for the Swan River outflow to lower mean basin-scale densities, should a significant proportion of it advect into the Sound, appears to be high. In addition, it has been established by past studies that the Swan River plume advects into the Sound as a buoyant gravitational overflow, hence the average density of the surface plume would be even lower than that calculated above because the assumption that the entire volume of the Sound mixes with the freshwater that enters the Sound is not necessarily valid.

The basin-scale stratification and vertical mixing characteristics during a range of Swan River flow events and accompanying wind intensities is now investigated. The ERA salinity and temperature profile data sets (see Chapter 3) are made use of in this discussion.

ERA winter stratification data

A range of basin-scale salinity data sets were collected during the early seventies by ERA (Nov, 1970; Dec, 1971; Nov, 1972; Aug, 1973). For each of the four individual study periods the Swan River flowed with different intensity. Table 4.6 contains the mean flow characteristics of the Swan River and wind information during those periods. Figures 4.41 to 4.52, following, present a selected series of contour plots and vertical stratification data from these four studies.

Table 4.6. Swan River flow information for the four individual salinity survey periods conducted by ERA during the winters of 1970, 1971, 1972, and 1973. Data from ERA (Nov, 1970; Dec, 1971; Nov, 1972; Aug, 1973).

Survey period	Wind	Swan River flow rate (approx to within 10 percent, in millions of m^3)			
		Daily (millions of m^3 day^{-1})		Monthly (millions of m^3 mth^{-1})	
		Day	Total	Month	Total
	($m\ s^{-1}$)		(millions of m^3)		(millions of m^3)
July 1970		1-6-70	0.5	June-70	70
		20-6-70	2		
		26-6-70	7		
		1-7-70	6.5	July-70	70
		3-7-70	4.5		
	5-7 SW	**6-7-70**	**3**		
		10-7-70	2		
		16-7-70	1		
		22-7-70	0.75		
		23-7-70	2		
	0-5 NNW	**28-7-70**	**3**		

July 1971		1-7-71	0.2	June-71	10
	5 WNW	**9-7-71**	**0.40**		
	5-8 WSW	**20-7-71**	**0.35**		
	3 E	**21-7-71**	**0.35**		
	5 NE	**22-7-71**	**0.35**		
	3 NE	**23-7-71**	**0.3**		
July/Aug 1972		1-7-72	0.5	June-72	10
		5-7-72	1.5	July-72	30
		22-7-72	0.5		
		23-7-72	1.3		
	2 E	**24-7-72**	**1.4**		
		25-7-72	1.1		
	3-5 ESE	**26-7-72**	**1.1**		
	2-5 E-ESE	27-7-72	1.25		
	2-6 ESE	28-7-72	1.4		
	NO DATA	29-7-72	1.5		
DAY	5 E-N-W	30-7-72	1.5		
NIGHT	5-15 S	30-7-72	1.5		
	5-10 ESE- S	**31-7-72**	**1.6**		
	5-15 E-N	1-8-72	1.5		
	10-15 WNW	**2-8-72**	**1.6**		
	5 NE	**3-8-72**	**2.1**		
	5-10 SW	**4-8-72**	**2.6**		
August 1973		28-7-73	9		
		1-8-73	5	August-73	175
	15 NW	**4-8-73**	**4**		
		8-8-73	15		
	10 NW	**9-8-73**	**10**		
	4 NW	**16-8-73**	**6.5**		
	6 NE	**20-8-73**	**5**		
	CALM	**23-8-73**	**4**		
	0-3 SW	**27-8-73**	**2.5**		

As is indicated by Table 4.6, the four ERA winter surveys encompassed a relatively wide range of Swan River winter flow conditions, ranging from the low flows in July 1971 to strong flows in August 1973. The influence of these flows on vertical and horizontal stratification in Owen Anchorage and Cockburn Sound is discussed below.

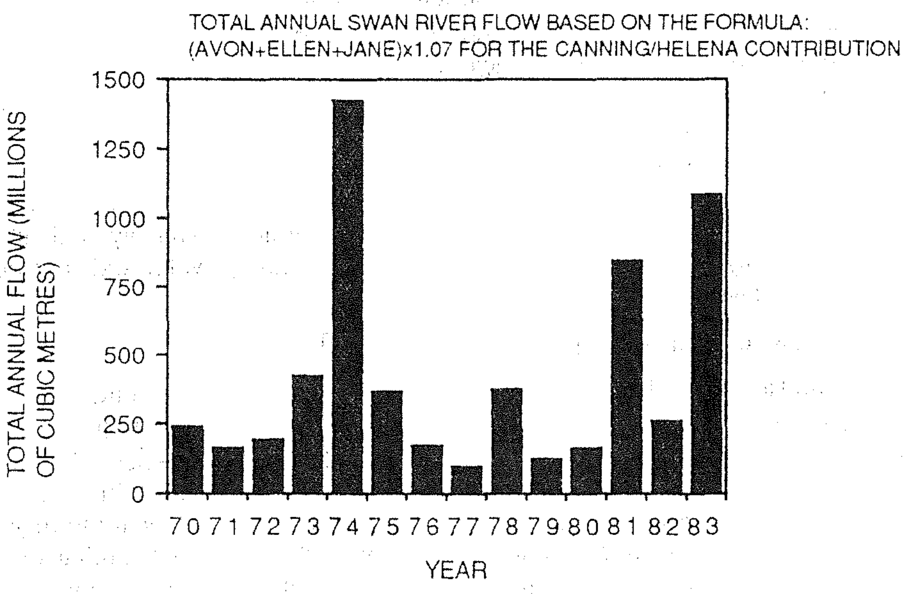


Figure 4.40 Total annual Swan River flow from 1970 to 1983 (data from Water Authority of Western Australia).

Low Swan River flow conditions: 0.3-0.4 x 10^6 m^3 day^{-1}.

The Swan River was in low flow during the July 1971 survey. The basin-scale vertical salinity stratification was relatively weak, as indicated by the surface contours and vertical contours from 21 July 1971 of that data set (Figures 4.41 and 4.42, respectively). Vertical salinity differences (top to bottom) rarely exceeded about 0.2 ppt. There was however, significant horizontal salinity structure, with the least saline water generally occupying the eastern margin of the Sound. The low flows were sufficient to lower the general salinities of the Owen Anchorage region, and this probably provided the source of the less saline water along the eastern Cockburn Sound margin. Winds were WNW on 19 July and would have driven the less saline water into the Sound. However, for the next two days winds were WSW or E, and therefore cannot explain the further occurrence of the 35.1 ppt water in southern Cockburn Sound on 21 July. The dark arrows in the diagrams indicate net water flow direction inferred from drogue tracking (Appendix A6). The flow directions through the southern openings are consistent with the mean daily wind directions. One possible explanation for the lateral stratification is that the low salinity water in Owen Anchorage was swept into the Sound by a net southward drift, with the less saline, and therefore probably less dense, water forced against the coast by the action of the earth's rotation, as described in Chapter 3.

By following some of the isohalines in Figure 4.41, it would appear that water down the eastern margin was advected through the Sound in times of the order of less than 5 days. However, water in the western half of the Sound was generally of constant salinity, and therefore relatively static in general position. ERA (Dec, 1971) analysed the propagation of patches of isohaline water and concluded that throughflows varied from 3-6 days.

Medium Swan River flow conditions: 1-2 x 10^6 m^3 day^{-1}.

During July 1972 the Swan River was flowing relatively strongly, with the total discharge for the month being approximately 30 x 10^6 m^3. Cockburn Sound was stratified in salinity both vertically and horizontally as a result of the buoyancy flux from the river. Vertical salinity differences (top to bottom) of the order of 0.2 to 0.5 ppt were common. The surface and vertical contour plots in Figures 4.43 to 4.46 typify the stratification for that period. Again, the preference for low salinity water to reside along the eastern margin is noticeable. The winds ranged in direction and in speed from relatively calm to strong (up to 10 m s^{-1}). The basin displayed vertical and horizontal stratification throughout all these wind conditions. The lowest salinities were recorded in Owen Anchorage near the source of freshwater at the Swan River mouth .

On the basis of isohaline tracking ERA (Nov, 1972) concluded that throughflows for isohaline patches of water varied from 2-9 days during the winter survey period.

Medium to strong Swan River flow conditions: 3-5 x 10^6 m^3 day^{-1}.

Figures 4.47 and 4.48 present the surface and vertical salinity contours for the region on 6 and 28 July 1970, respectively. These two diagrams display entirely different basin-scale salinity structure, even though the Swan River was flowing with approximately similar flow intensities. On 6 July the system was stratified strongly, both vertically and horizontally, with vertical salinity differences (top to bottom) of up to 1 ppt recorded. The SW winds were not able to flush the buoyant water out of the Sound entirely. In contrast, on 28 July the Sound was less stratified. Winds were relatively calm, and there appeared to be a low salinity front entering the Sound via the southern opening. The forcings responsible for the two individual structures are not readily identifiable from the existing data set.

Strong Swan River flow conditions: 5-10 x 10^6 m^3 day^{-1}.

The total monthly discharge for August 1973 was about 175 x 10^6 m^3. The surface salinity contour data, as well as the longitudinal and lateral vertical salinity contours are presented in Figures 4.49 to 4.51. Figure 4.52 is the longitudinal density contour plot for 16 August 1973, presented here to highlight the similarity that density and salinity structure has during winter, because in comparison to temperature gradients, the salinity gradients dominate in their influence on density.

As shown by the contour data, the basin retained significant vertical and horizontal stratification throughout the survey period, during which time winds reached up to 15 m s^{-1} on some days. Vertical salinity and density differences of up to 2 ppt were recorded. Hence, the buoyancy flux from the Swan River induced significant stratification in Cockburn Sound. The data suggest that winds of 10-15 m s^{-1}

were not able to completely destroy vertical salinity gradients. Further data suggesting the general inability of winds to homogenize the water column during the month of August 1973 are given by the time series plots in Figure 4.53a and b, of top, middle and bottom density for northern, central and southern Cockburn Sound and meteorological data (from ERA, Aug 1973). These data indicate the vertical density stratification as a function of time and wind. As shown, the Sound was rarely found to be vertically mixed.

ERA (Aug, 1973) tracked isohaline patches through Cockburn Sound to conclude that throughflows were of the order of 6 days or more.

Extent of the influence of the Swan River plume.

ERA (November, 1970) reported on the results of a limited set of aerial photographs from which they were able to identify Swan River water by the distinctly brown colour caused by unicellular green algae of the type *Melosira Sp.* Successive flood pulses were tracked in time by photography. ERA summarised the general spatial characteristics of individual plumes and their results are shown in Figure 4.54. As suggested by the data, propagation as far offshore as Sepia Depression and as far south as central Warnbro Sound occurred. The causeway was not yet constructed when these data were collected

The implication of the now existing causeway on this transport mechanism is unknown. However, the results of the aerial tracking raise interesting questions regarding the fate of pollutants originating in Cockburn Sound (nutrients, industrial wastes etc) and Sepia Depression (wastewater). One speculative conclusion that could be drawn is that there exists the potential for these pollutants to be advected southwards in coastal boundary currents, driven counterclockwise towards the coast by Coriolis forcing, and advected over the Shoalwater Bay reef system eventually arriving in inner Warnbro Sound. The ecological implications of this type of transport would require further investigation upon verification of the existence of such flows.

Vertical mixing by winds

The above analysis suggests that in general Cockburn Sound exhibits significant vertical stratification through periods of winds ranging from calm to of the order of 10 m s^{-1}. The wind statistics presented in Appendix A1 indicate that winds are less than about 10 m s^{-1} for over 85 percent of the time in winter. Hence, circulation patterns in the Sound during winter are likely to be influenced by stratification for this same percentage of the time. Further, vertical mixing is not likely to regularly penetrate to the bottom, and this means that ecological questions related to nutrient release from the sediments during re-suspension will have to consider rare event type mixing events when severe storm winds cause the vertical structure to be broken down and turbulence penetrates to the bottom. This now requires further field studies of the temporal characteristics of vertical wind mixing as a function of wind intensity, vertical stratification and duration of the wind.

Summary

Vertical and horizontal stratification was a common characteristic of the Sound's structure throughout winter. The identification of the strong influence of the Swan River freshwater outflow in acting as a source of buoyancy flux to Cockburn Sound and Warnbro Sound indicates that local rivers can have their buoyancy flux transported in coastal boundary currents for long distances away from their respective mouths. The influence of the earth's rotation appears to be to cause outflows to rotate counterclockwise (in the southern hemisphere) thus forcing the buoyant surface flows to maintain a nearshore bias. Since it has been identified that the Swan River outflow can be advected as far south as inner Warnbro Sound it is conceivable that the Moore River and the Peel-Harvey Estuarine System may also play important roles in adding buoyancy flux to the coastal waters adjacent to their respective mouths. Hence, field studies aimed at refining our knowledge of the hydrodynamic characteristics of nearshore metropolitan waters will need to address the influence of buoyancy flux from such sources.

4.4 Spring

4.4.1 Mean salinity and temperature

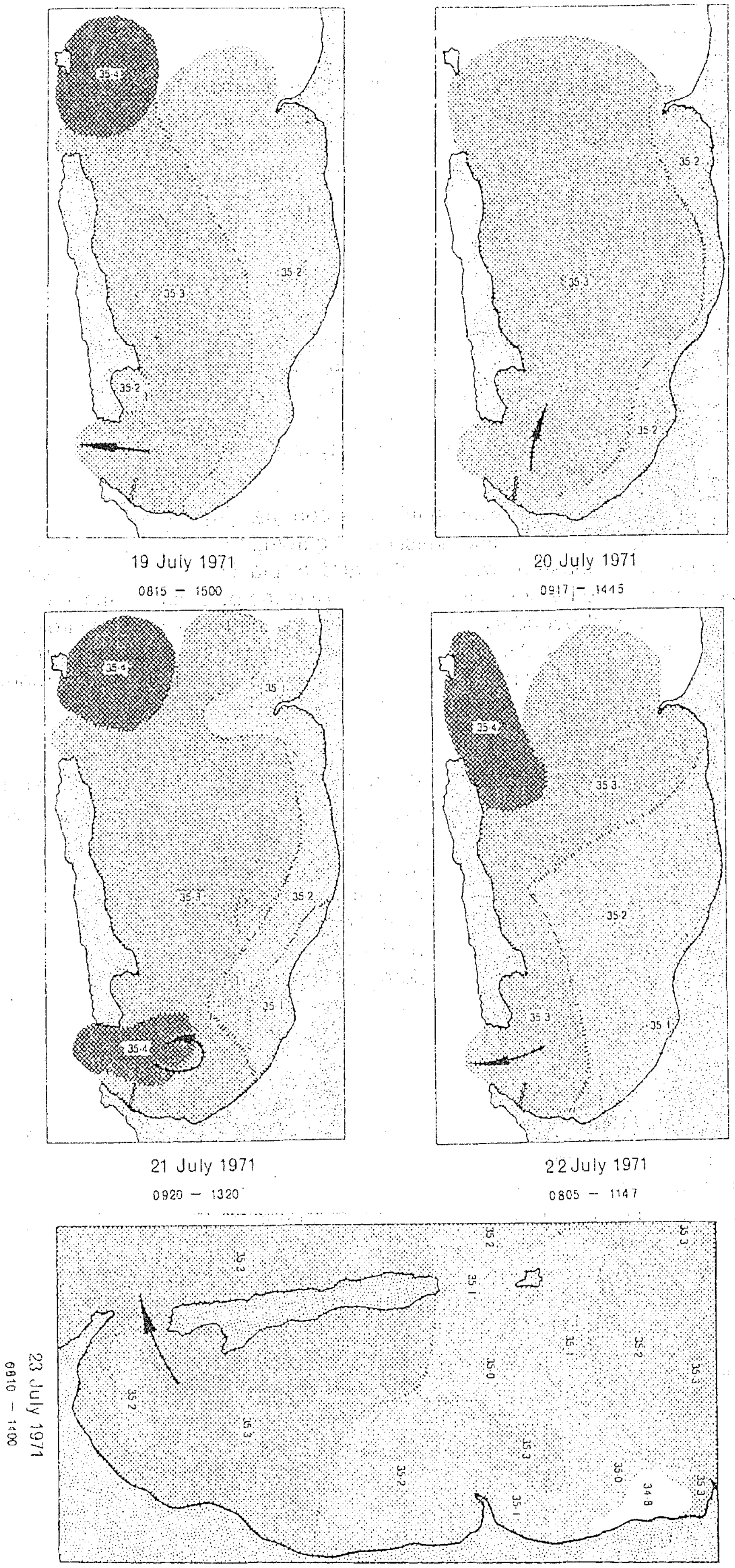


Figure 4.41 Surface salinity structure of Cockburn Sound on 19, 20, 21, 22 and 23 July 1971. Data from ERA (Dec, 1971).

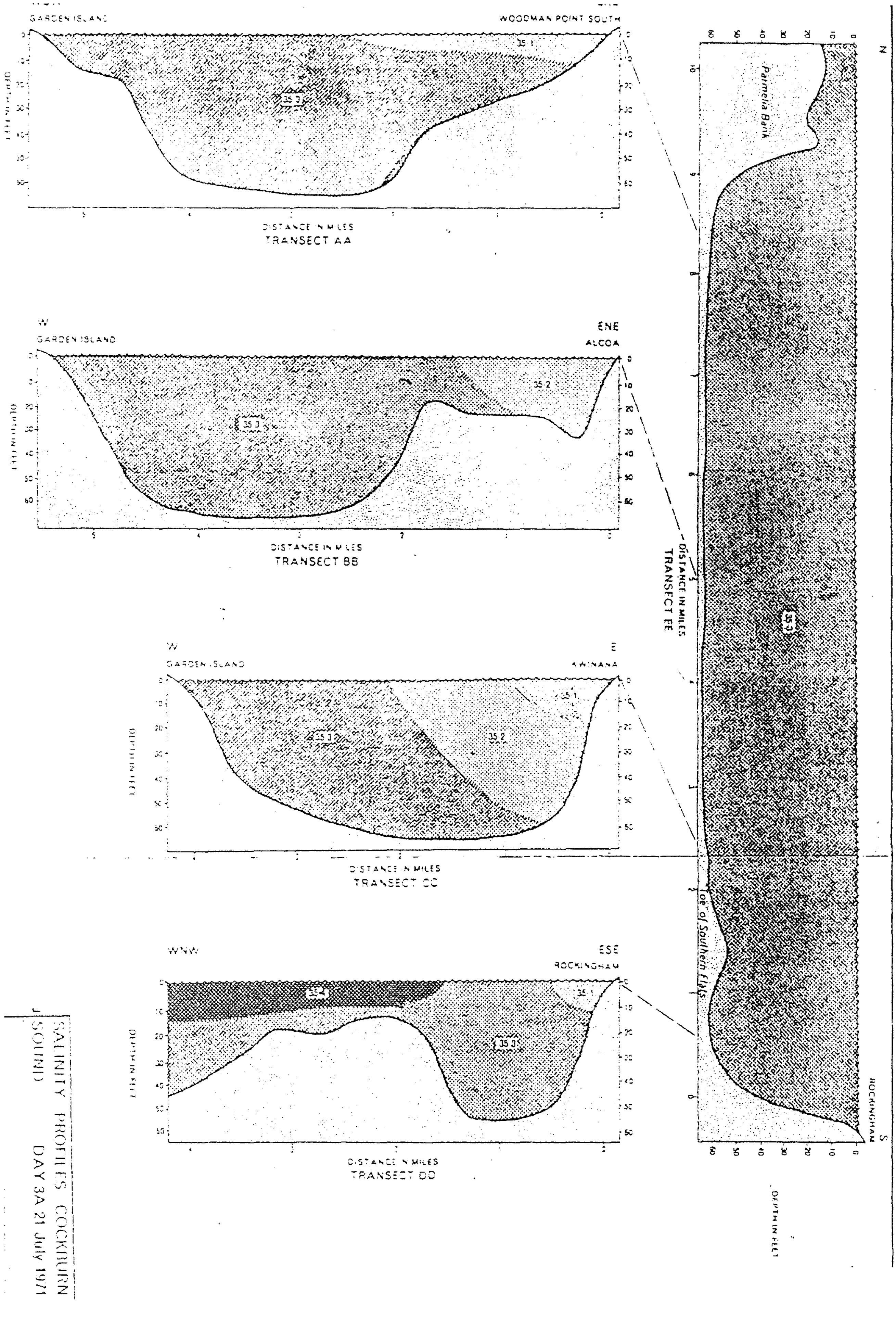


Figure 4.42 Vertical salinity structure of Cockburn Sound: 0920-1320. 21-7-71. Data from ERA (Dec, 1971).

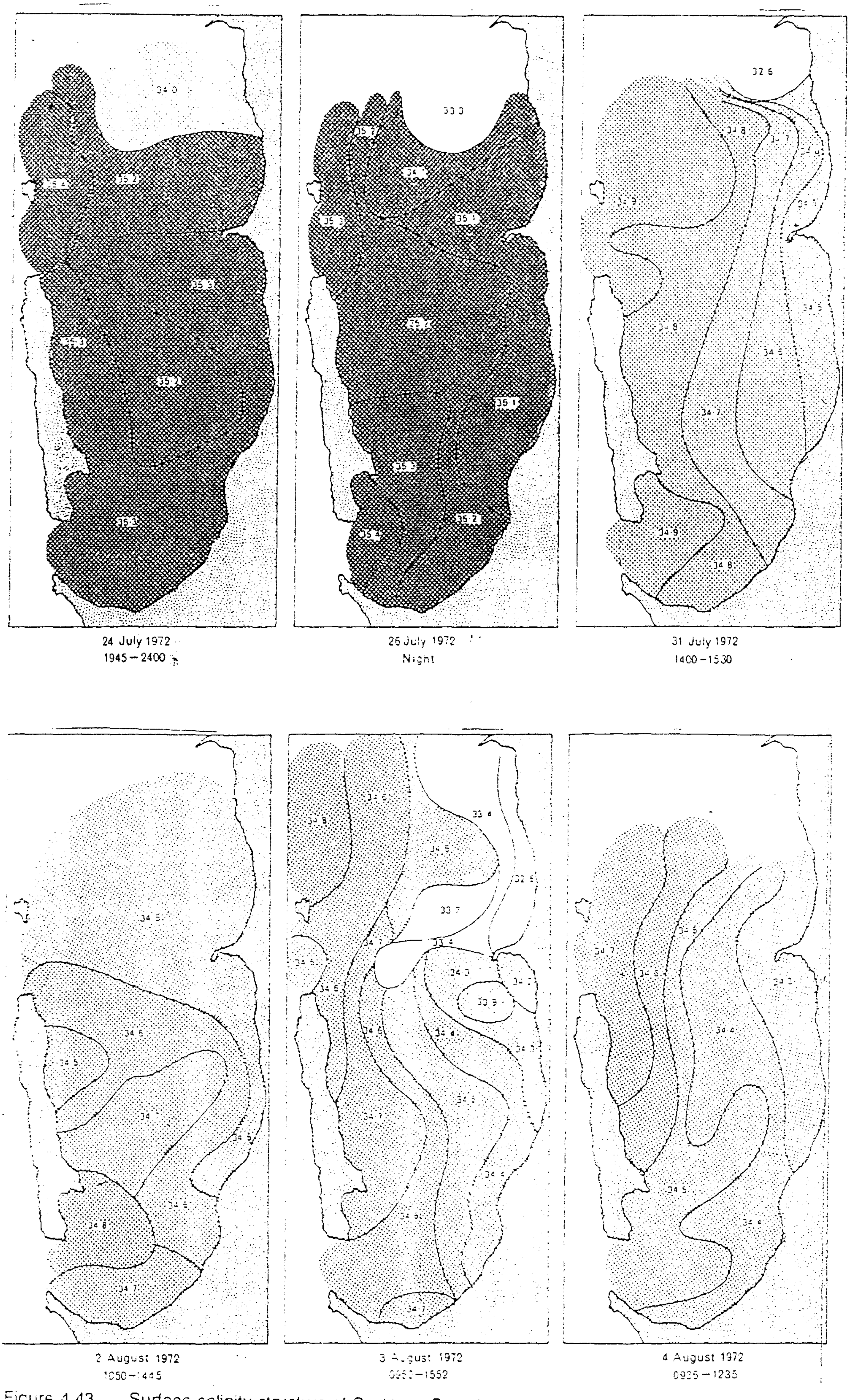


Figure 4.43 Surface salinity structure of Cockburn Sound and Owen Anchorage on 24, 26 and 31 July and 2, 3 and 4 Aug 1972. Data from ERA (Nov, 1972).

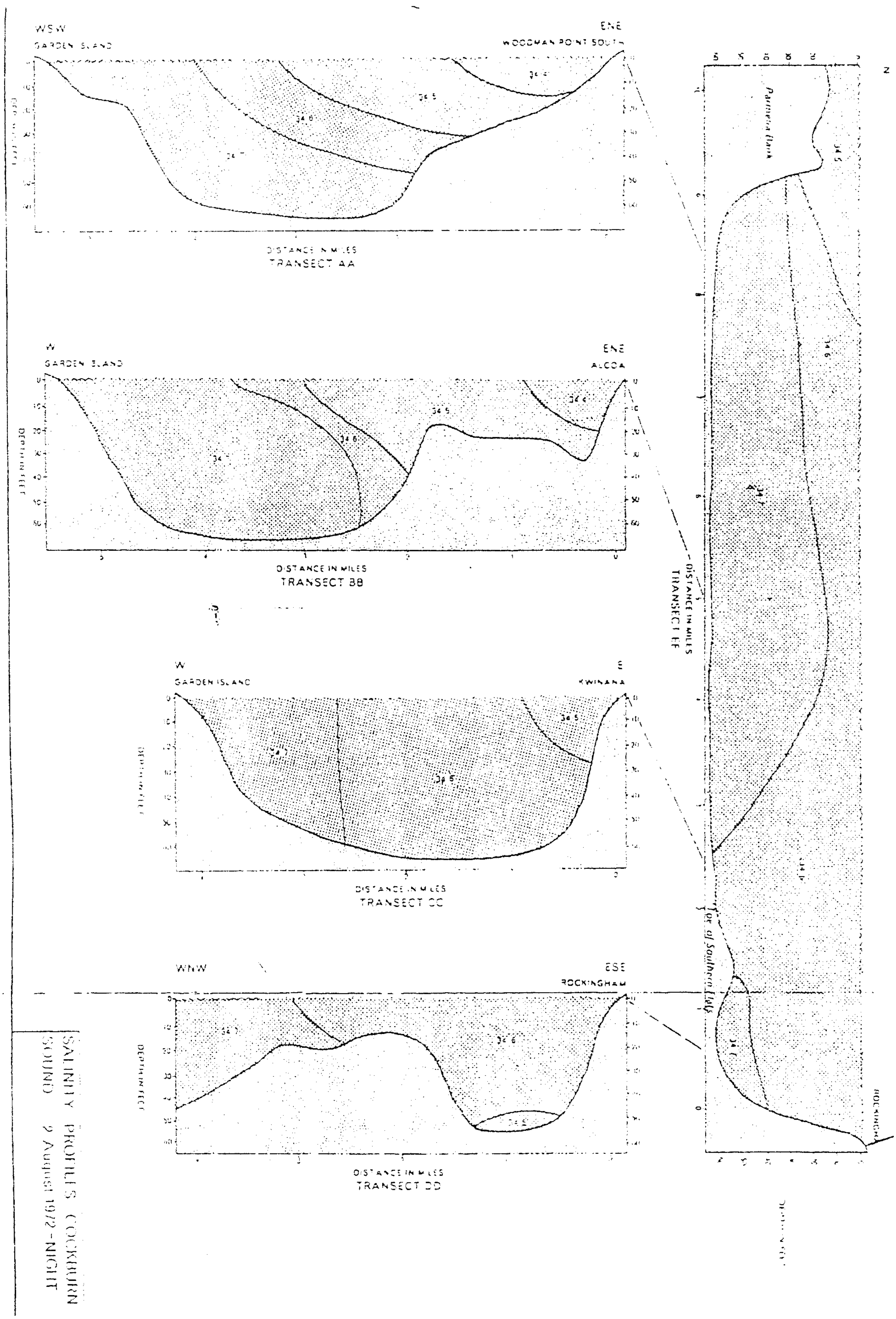


Figure 4.44 Vertical salinity structure of Cockburn Sound: night, 2-8-72. Data from ERA (Nov, 1972).

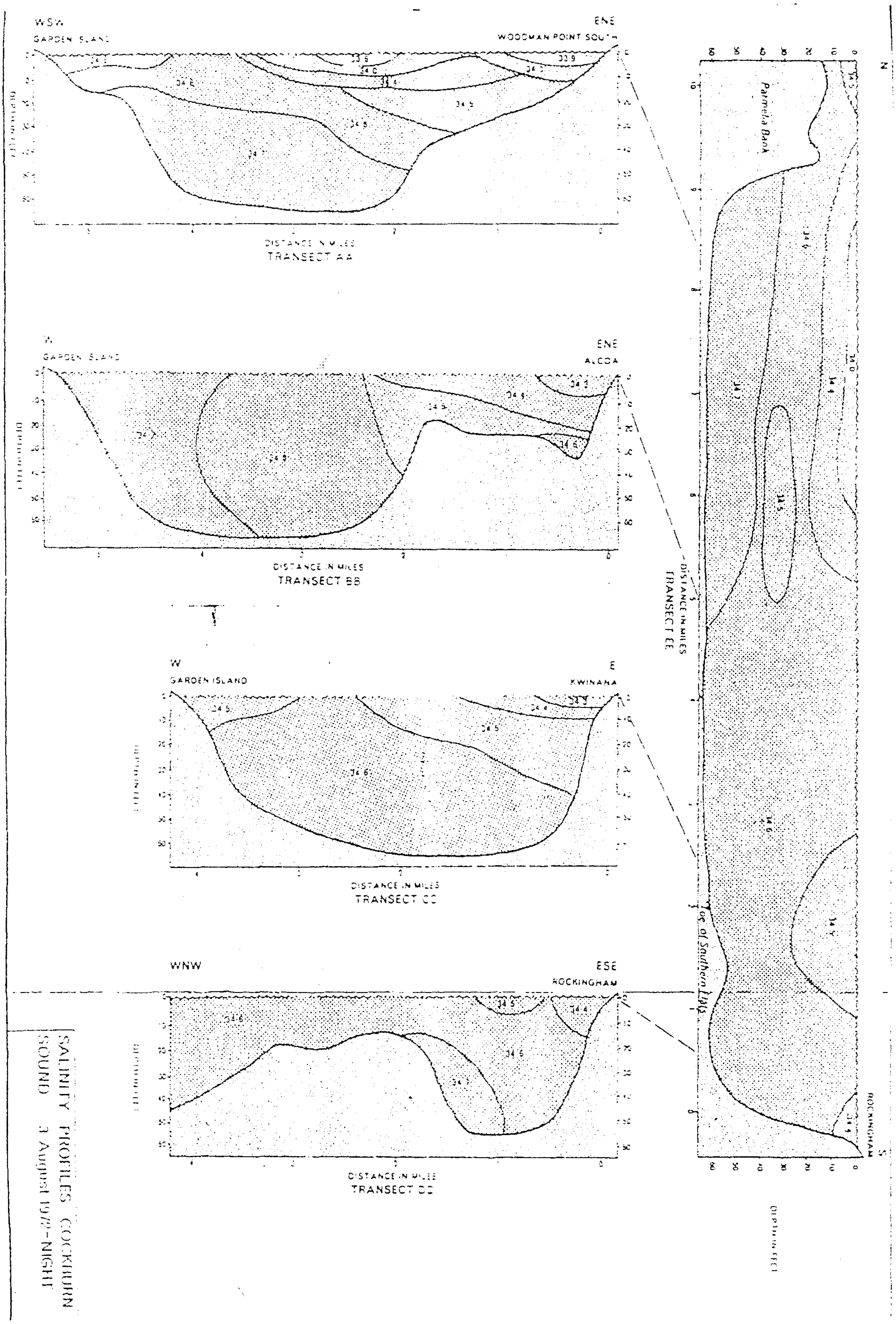


Figure 4.45 Vertical salinity structure of Cockburn Sound: night, 3-8-72. Data from ERA (Nov, 1972).

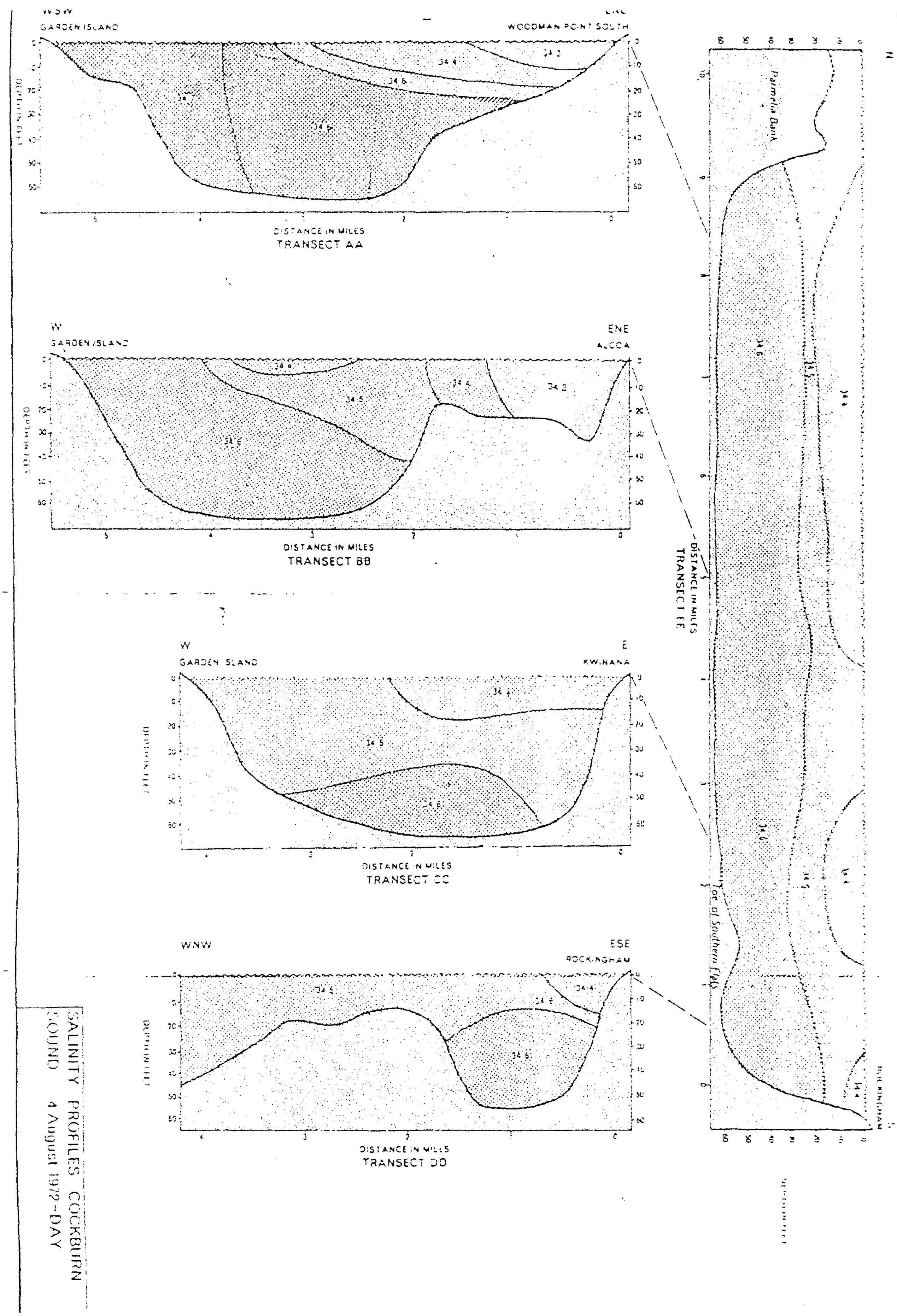
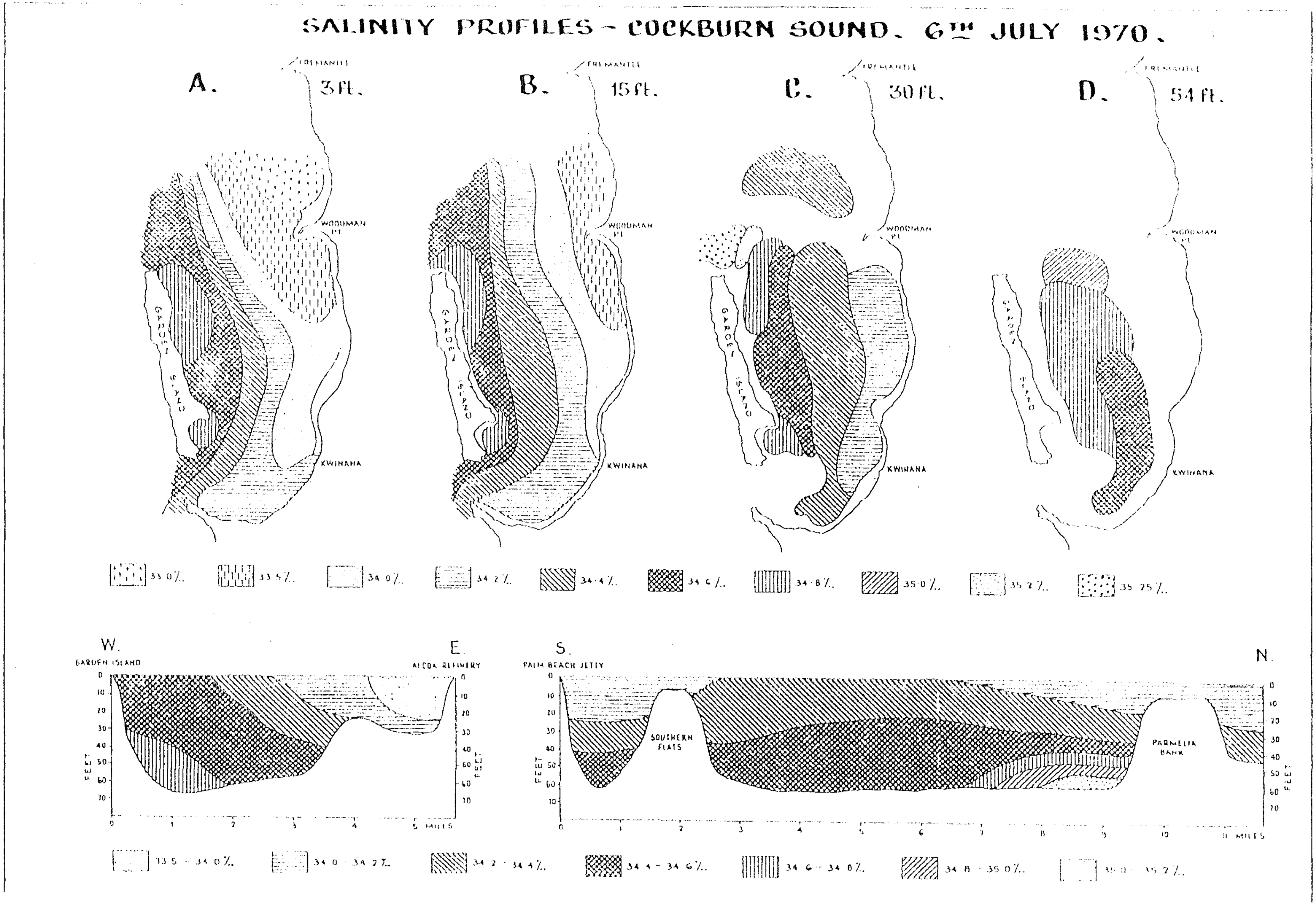


Figure 4.46 Vertical salinity structure of Cockburn Sound: day, 4-8-72. Data from ERA (Nov 1972).

Figure 4.47 Surface salinity structure of Cockburn Sound and Owen Anchorage on 6 July 1970.
Data from ERA (Nov. 1970).



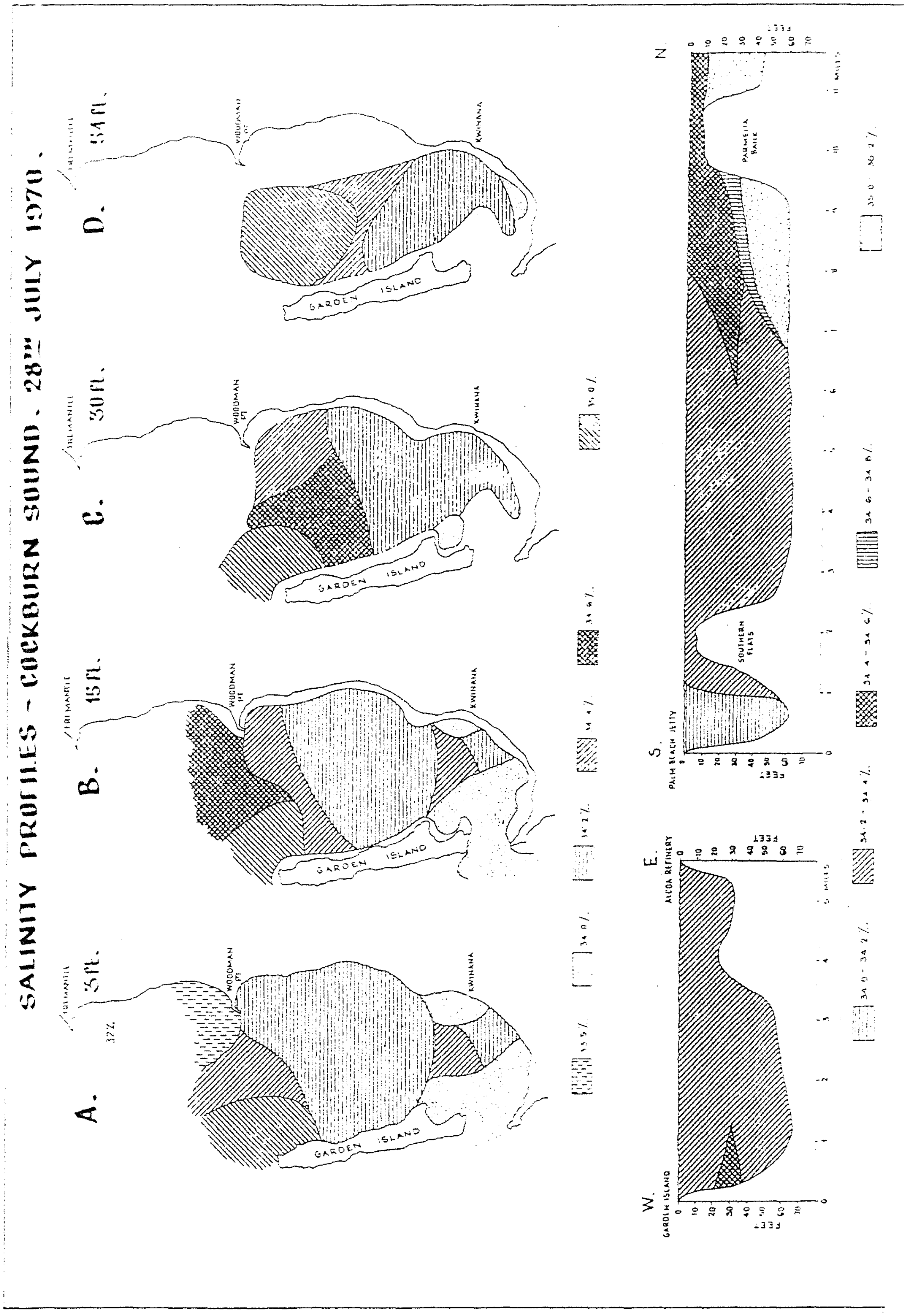


Figure 4.48 Surface salinity structure of Cockburn Sound and Owen Anchorage on 28 July 1970. Data from ERA (Nov, 1970).

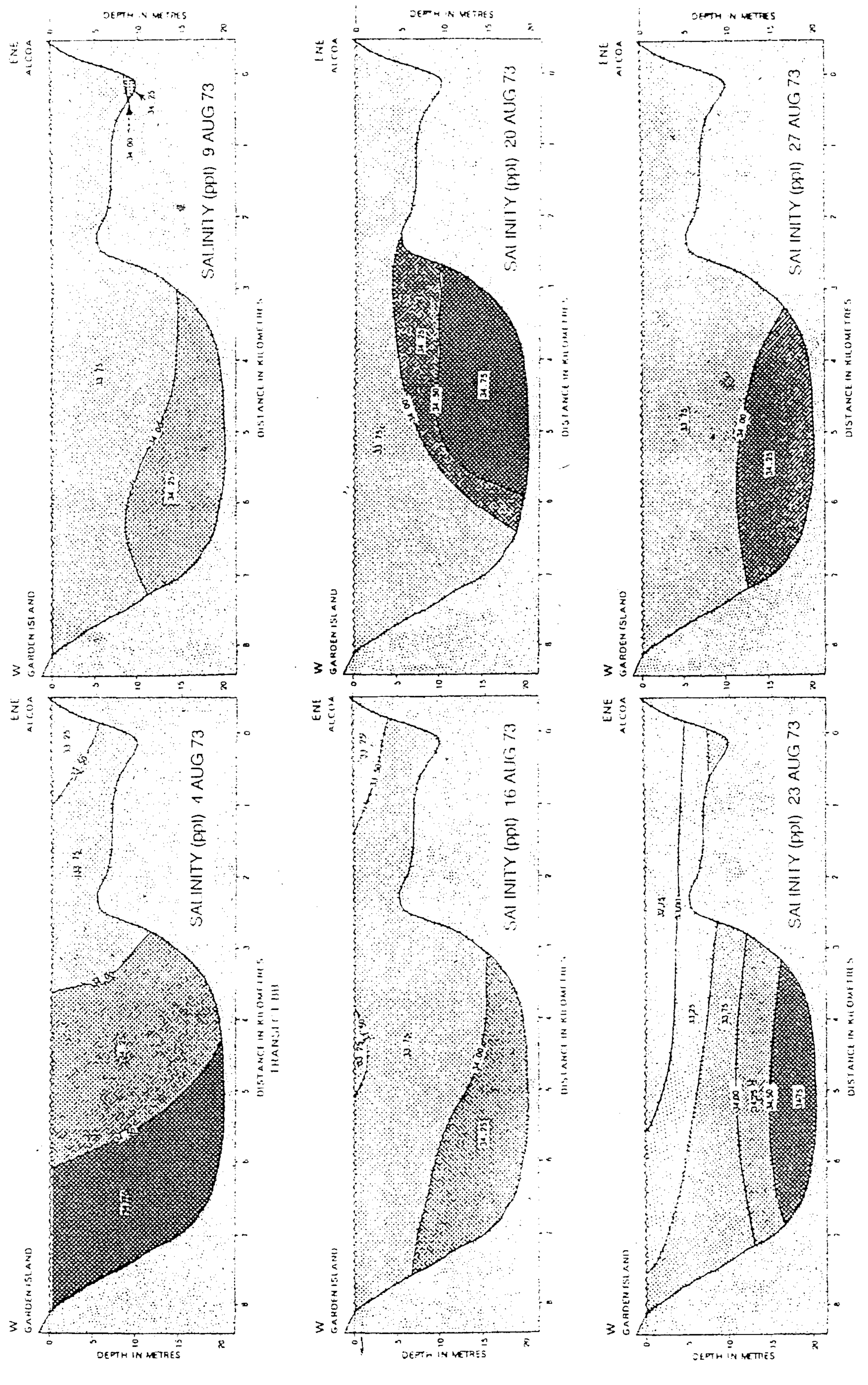


Figure 4.51 Vertical salinity structure in the west-east central alignment of Cockburn Sound on 4, 9, 16, 20, 23 and 27 Aug, 1973. Data from ERA (Aug, 1973).

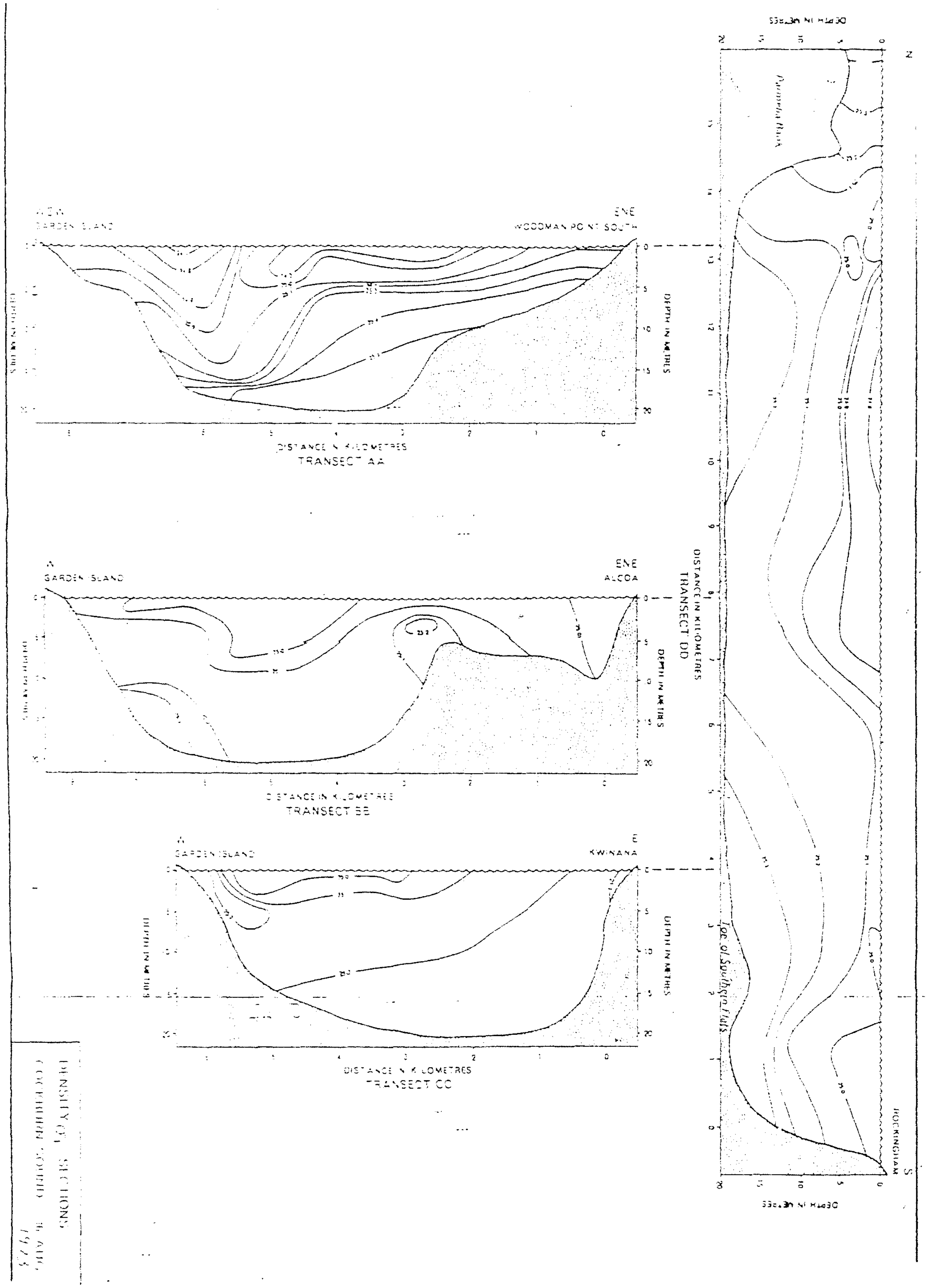


Figure 4.52 Vertical density structure (in sigma-T units: kg m^{-3}) across and along Cockburn Sound on 16 Aug 1973. Data from ERA (Aug, 1973).

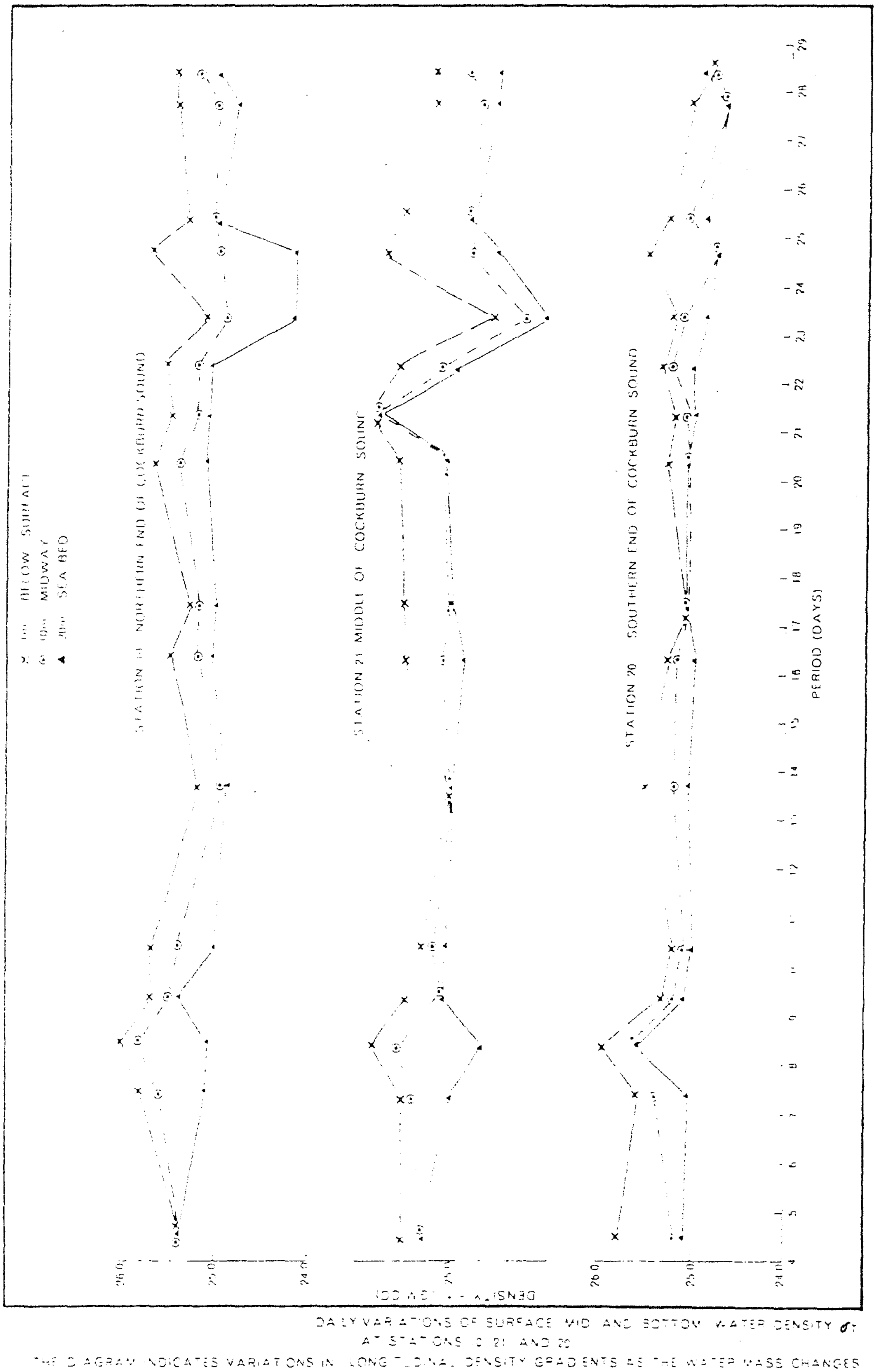


Figure 4.53a Time series of density at the surface, middle and bottom of the water column from sites at the north, centre and south of Cockburn Sound from 4-29 Aug 1973. Data from ERA (Aug, 1973).

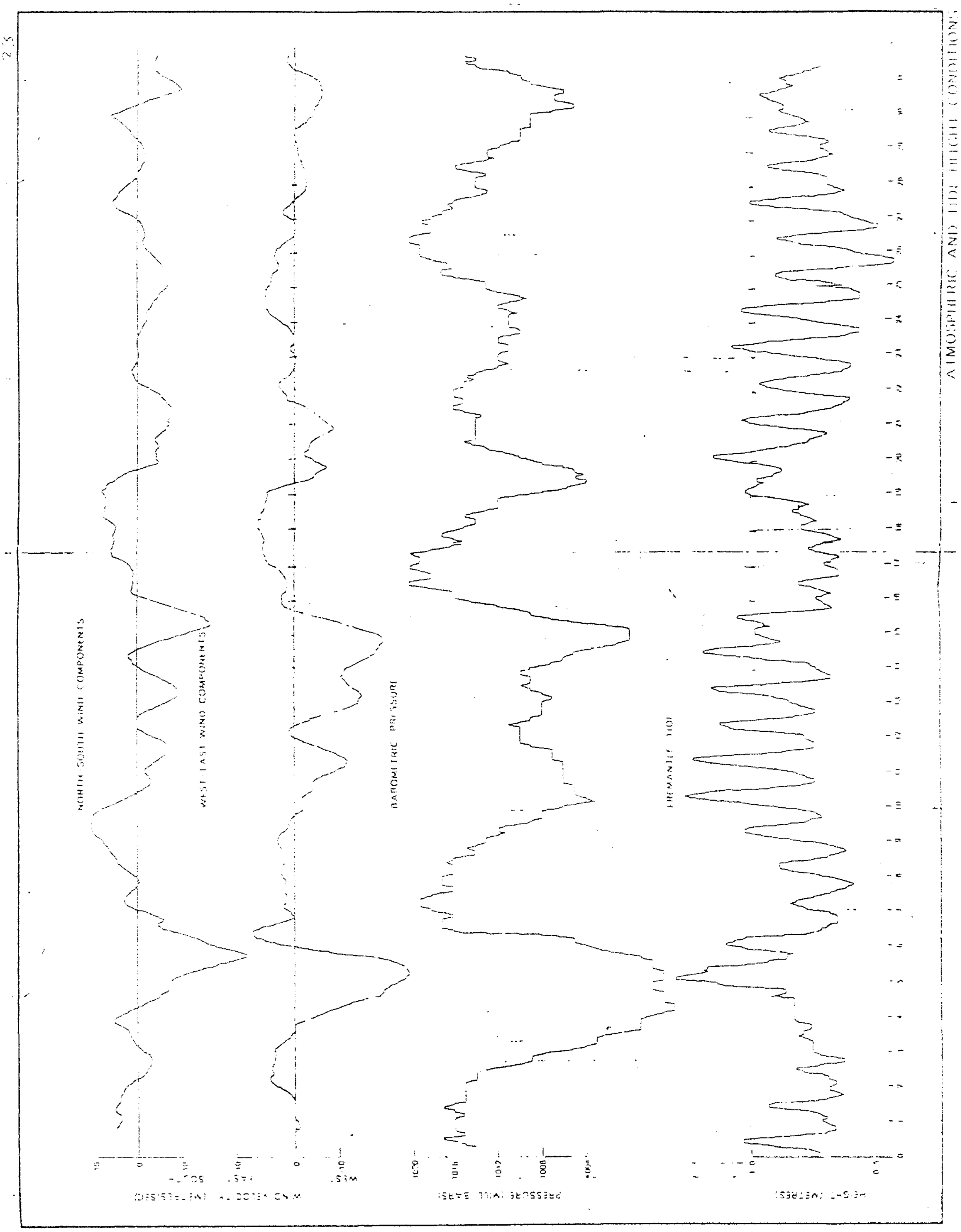


Figure 4.53b Time series of meteorological and tidal data (Fremantle winds, Perth barometric pressure and Fremantle tides) for the period 1-31 Aug 1973, to accompany the density stratification data presented in Figure 4.53. Data from ERA (Aug, 1973).

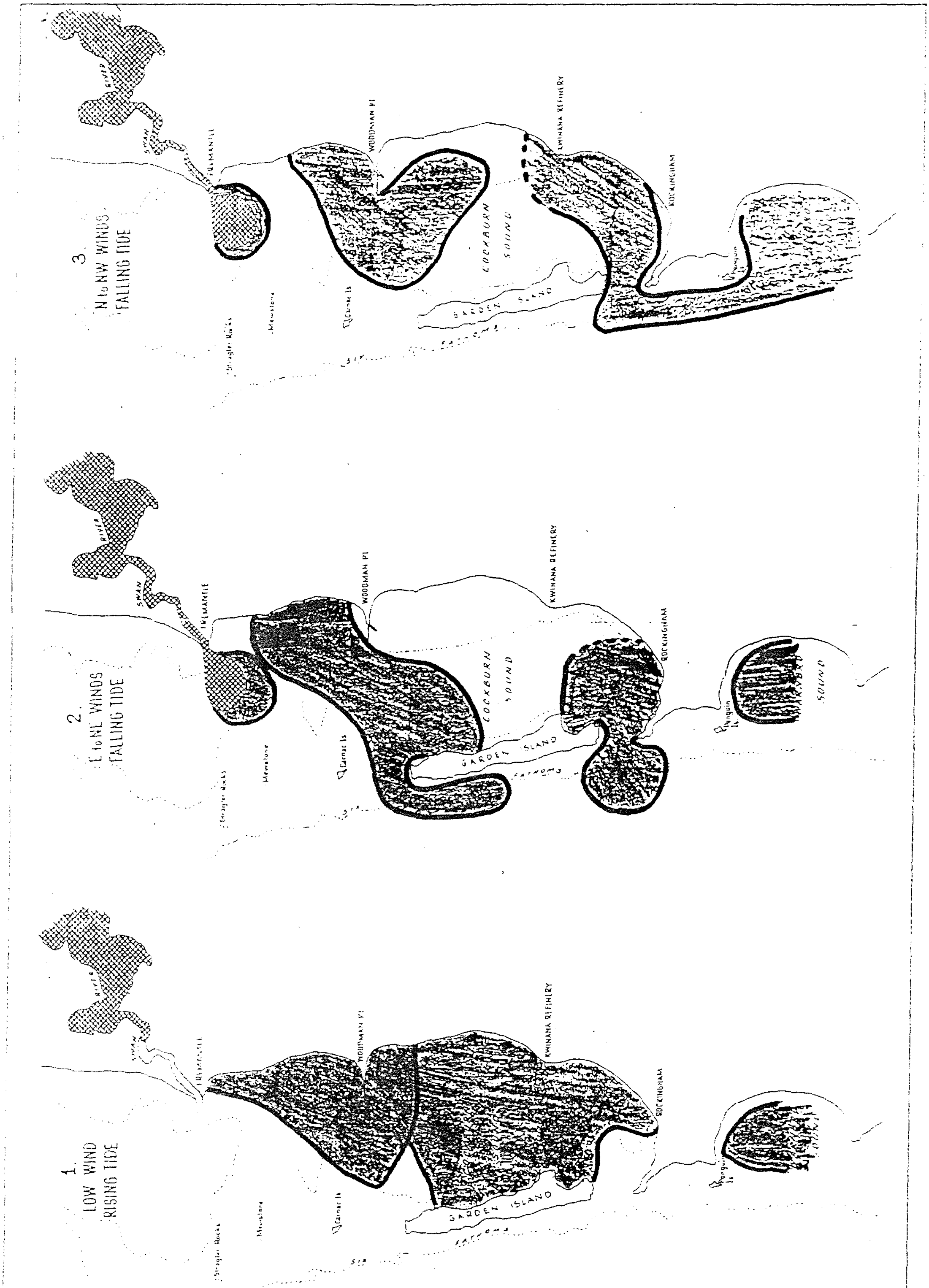


Figure 4.54 Sketched positions of successive Swan River plumes, as observed from aerial surveys during 1970 for various common winter meteorological and Swan River flow conditions. Plumes were tracked by following "brown" ebb pulses of river water stained by the riverine alga *Melosira* (ERA (Nov, 1970).

The mean salinity and temperature characteristics of Cockburn Sound during spring can be inferred from data already presented in Figures 4.15, 4.19, 4.20, 4.28 and 4.29.

Figure 4.15 presents the seasonal variation of vertical temperature structure at the nearshore Mangles Bay station 214 (located Figure 4.18) over an 18 month period (August 1977 to November 1978). It is clearly shown that in early spring the average temperature begins to rise above the seasonal minima of winter. Average temperatures rise from about 15 °C in winter to about 20 °C by late spring (November). In addition spring is shown to be the period when appreciable vertical temperature stratification begins to re-occur, with vertical temperature differences (top minus bottom) reaching values of up to 4 °C.

The centre of Cockburn Sound follows a similar pattern. As shown in the time series plots of Figure 4.19 and 4.20, both salinity and temperature begin to rise after the winter seasonal minima of winter. Winter salinities fall to a minimum of about 34 ppt and temperatures fall to a minimum of about 15 °C. By late spring the salinity and temperature rises to about 35.5 ppt and 20 °C, respectively. As suggested by these data, vertical salinity differences in spring appear to be small, but vertical temperature differences become stronger during spring.

The DCE data set, from which the above data are drawn, also provide an insight into the onshore/offshore salinity and temperature differences during spring. Figures 4.28 and 4.29 present the respective seasonal temperature and salinity variation for these two parameters in central Cockburn Sound and Sepia Depression (west of the Causeway). As shown, during winter the Sound is significantly colder and less saline than Sepia Depression, but throughout the course of spring these differences reverse until eventually by late spring the Sound becomes significantly warmer and saltier than Sepia Depression. The reduced influence of the Swan River outflow (as a nearshore buoyancy source) in combination with higher evaporation rates over the relatively shallow nearshore regions and differential heating are the likely reasons for this seasonal reversal. The potential for baroclinic exchange processes to be set up between the nearshore and offshore waters therefore exists and potential circulation patterns would be as has been already described in Section 3.1.8.

4.4.2 Basin-scale stratification and wind mixing

Summary of the analysis of spring data presented in Appendix A8

On the basis of the vertical stratification data presented by Appendix A8 it appears that during spring significant vertical temperature, and therefore density, stratification will persist in Cockburn Sound unless winds blow at about 8 m s^{-1} or more for at least about 6 hours. Under such strong wind regimes mixing down to the bottom is likely. From the statistical analysis of wind velocity for Cockburn Sound, see Appendix A1, such winds are likely to occur only about 20 percent of the time during spring. Hence, the influence of vertical and horizontal stratification on the general circulation patterns and vertical transport rates in Cockburn Sound are likely to be important at least 80 percent of the time during spring.

4.4.3 Exchange

Reference is made to Appendix A7, which indicates that, on the basis of flow monitoring in the southern opening, mean throughflows in Cockburn Sound during spring are in a transition phase, changing from predominantly southwards in winter to predominantly northwards in summer. On the basis of these data, and similarly collected flow rates during spring periods after the Causeway was constructed, past investigators have deduced that the whole of Cockburn Sound's volume could be replaced in periods of about 35 days on average, or at best 9 days during storm wind conditions. This relies on the validity of the assumption that Cockburn Sound acts as a well-mixed, barotropic, basin.

However, the demonstration in the analysis above, has shown that vertical and horizontal stratification of density is common in spring. Hence, it is unlikely that flow rates through the southern openings alone can be used to infer flushing times of the entire volume of Cockburn Sound. The baroclinic propagation of flows within and through Cockburn Sound must be understood before correlations can be drawn between flow rates at the openings and flushing times of the basin. This matter will require further field and numerical modelling efforts.

5 Mixing and transport in Owen Anchorage

5.1 Seasonal salinity and temperature variation

The mean characteristics of seasonal salinity and temperature in Owen Anchorage are indicated by time series of vertical salinity and temperature stratification produced by the DCE data set from station 67 (located in Figure 4.18) and plotted in Figures 5.1 and 5.2, respectively. The trends are similar to those for Cockburn Sound, discussed in Chapter 4 above.

Summer salinities in Owen Anchorage become hypersaline due to local evaporation and reach up to 37 ppt. Surface salinities are generally lower than bottom salinities. In winter the influence of the Swan River outflow is to cause strong vertical salinity stratification (see Figure 5.1b, for example), with brackish water often layering the surface of Owen Anchorage, as shown by many of the contour plots presented in preceding sections. Surface salinities as low as about 30 ppt have been recorded in Owen Anchorage during periods of strong Swan River discharge (see section 4.3).

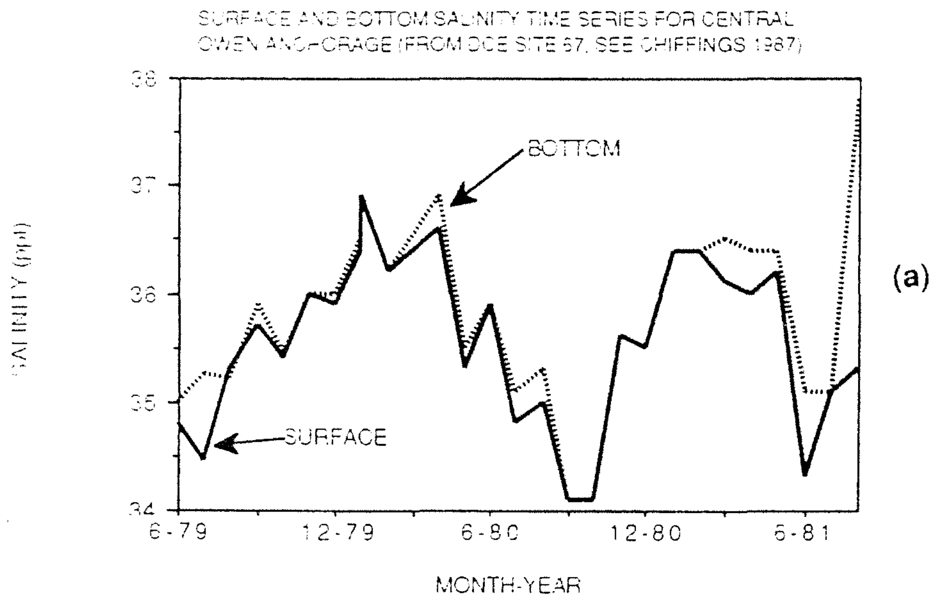
Seasonal temperature variation in Owen Anchorage also reflects that of Cockburn Sound. As shown in Figure 5.2a the seasonal range in temperature is 14 to 24 ^{o}C. Throughout the two years of monthly temperature measurements, vertical temperature differences were almost always found to be non-zero. Surface temperatures were generally higher than bottom temperatures in summer (see Figure 5.2b) due to thermal heating by solar radiation, but in winter relatively cold, low salinity, freshwater from the Swan River was found at the surface as a buoyant layer.

It was found that vertical temperature or salinity stratification occurred in central Owen Anchorage on about 80 percent of the 27 occasions that monitoring was conducted.

Salinity and temperature data, that were complimentary to those in Figures 5.1 and 5.2. were also collected. Figure 5.3 presents the time series of salinity and temperature difference between Owen Anchorage and Sepia Depression over the period June 1979 to August 1981. As shown, there is a seasonal pattern, with Owen Anchorage being more saline and warmer than Sepia Depression in summer and less saline and colder than Sepia Depression in winter. Local evaporation and thermal heating in summer and differential cooling and freshwater flux of colder water from the Swan River in winter are the primary reasons for this seasonal pattern.

Figure 5.4 presents similar time series plots to those in Figure 5.3. but this time using Cockburn Sound in comparison to Owen Anchorage. There is some indication that in winter Owen Anchorage is generally less saline than Cockburn Sound, and this is most likely due to the influence of the Swan River freshwater outflow being closer to Owen Anchorage than central Cockburn Sound. During spring salinities in Owen Anchorage are generally greater than in Cockburn Sound. But as summer progresses this situation reverses, probably reflecting the influence of higher local evaporation rates in Cockburn Sound, or the greater trapping of relatively dense hypersaline water in the central basin regions of the Sound

Owen Anchorage is more exposed to regional currents than is Cockburn Sound and the formation of hypersaline water due to evaporation is likely to be more quickly counteracted by flushing and mixing mechanisms in Owen Anchorage in comparison to Cockburn Sound. These assertions are speculative at this stage and a more detailed field survey of the salinity and temperature structure of these regions is required over time scales compatible with the formation and subsequent mixing or flushing of different salinity or temperature waters.



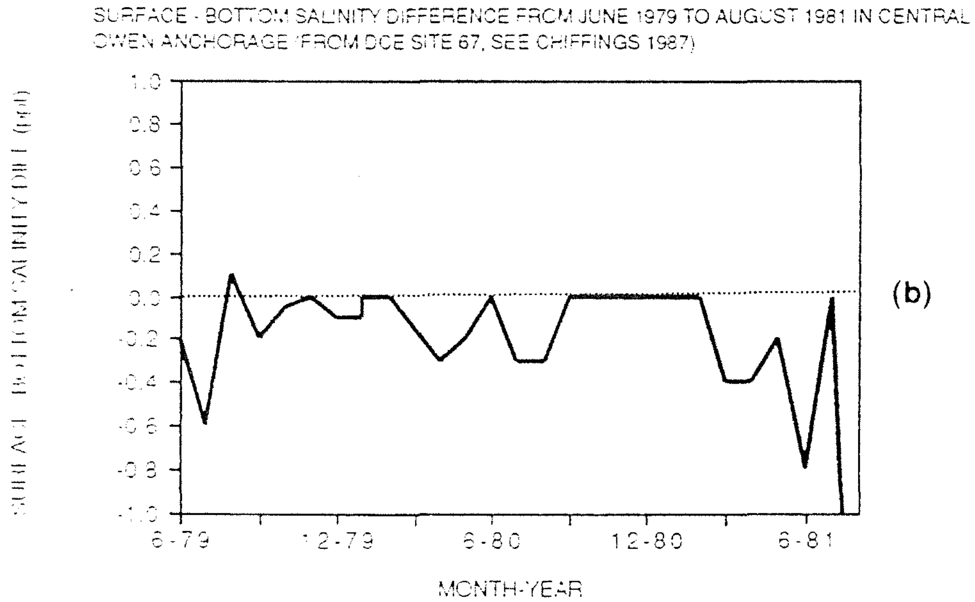
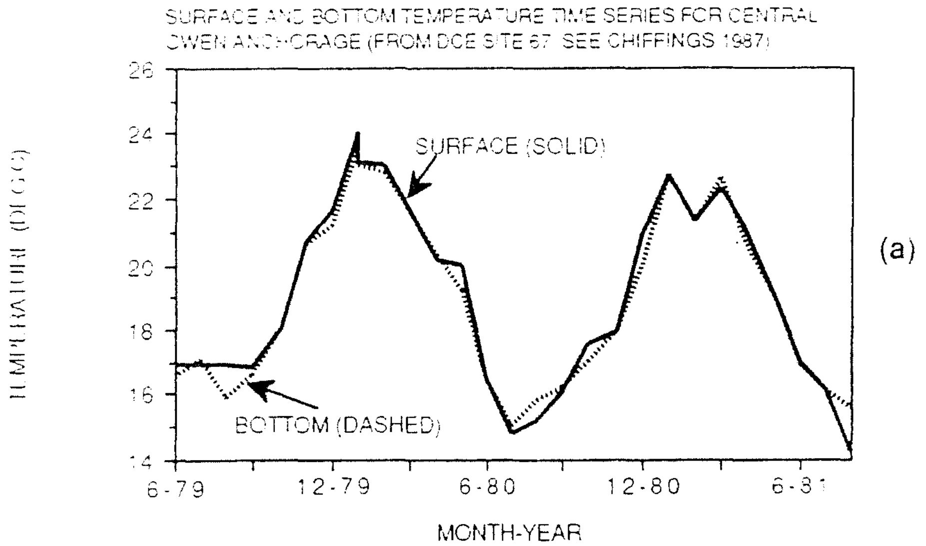


Figure 5.1 Time series of: (a) surface and bottom salinities, and (b) surface minus bottom salinity difference from monthly measurements at DCE site 67, Owen Anchorage. (see Figure 4.18) from June 1979 to July 1981.



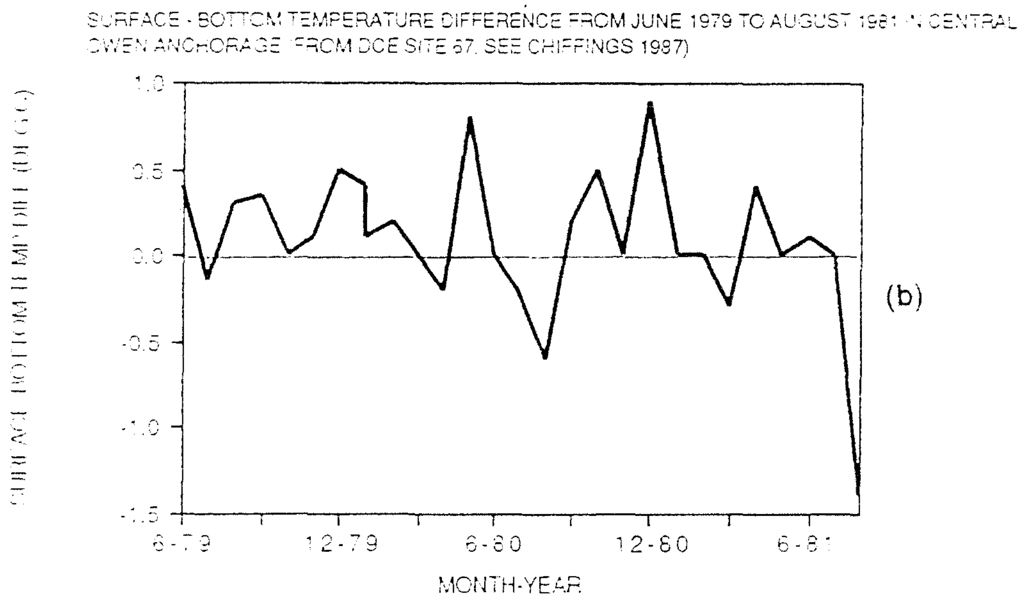
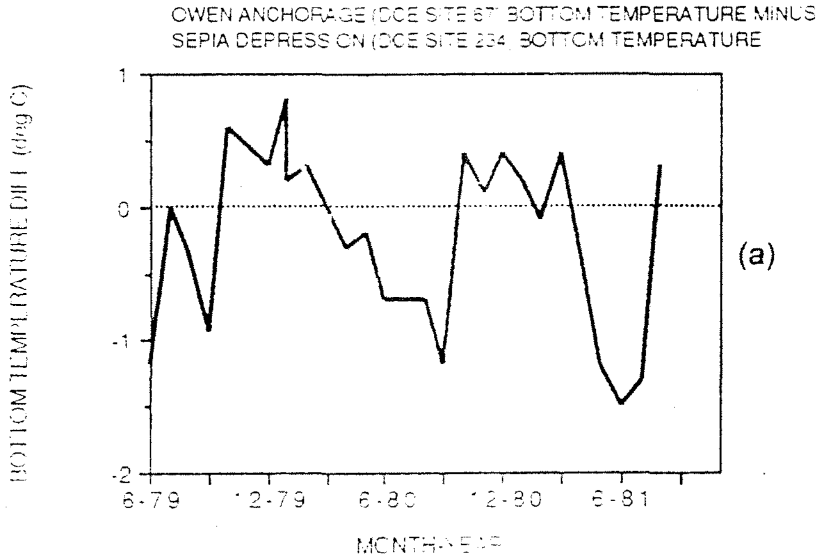


Figure 5.2 Time series of: (a) surface and bottom temperatures, and (b) surface minus bottom temperature difference from monthly measurements at DCE site 67, Owen Anchorage, (see Figure 4.18) from June 1979 to July 1981.



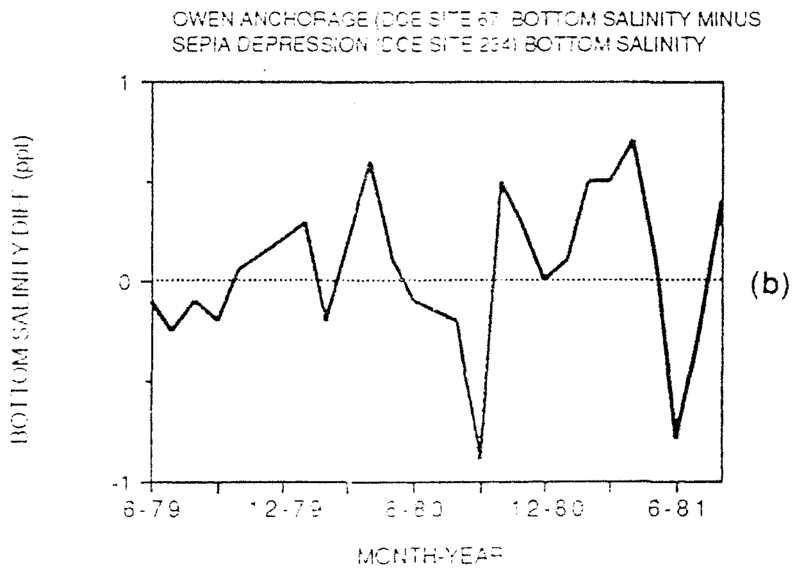


Figure 5.3 Time series of (a) Owen Anchorage (DCE site 67) bottom temperature minus Sepia Depression (DCE site 234) bottom temperature and (b) Owen Anchorage (DCE site 67) bottom salinity minus Sepia Depression (DCE site 234) bottom salinity from monthly ST measurements during June 1979 to July 1981. Station locations in Figure 4.18.

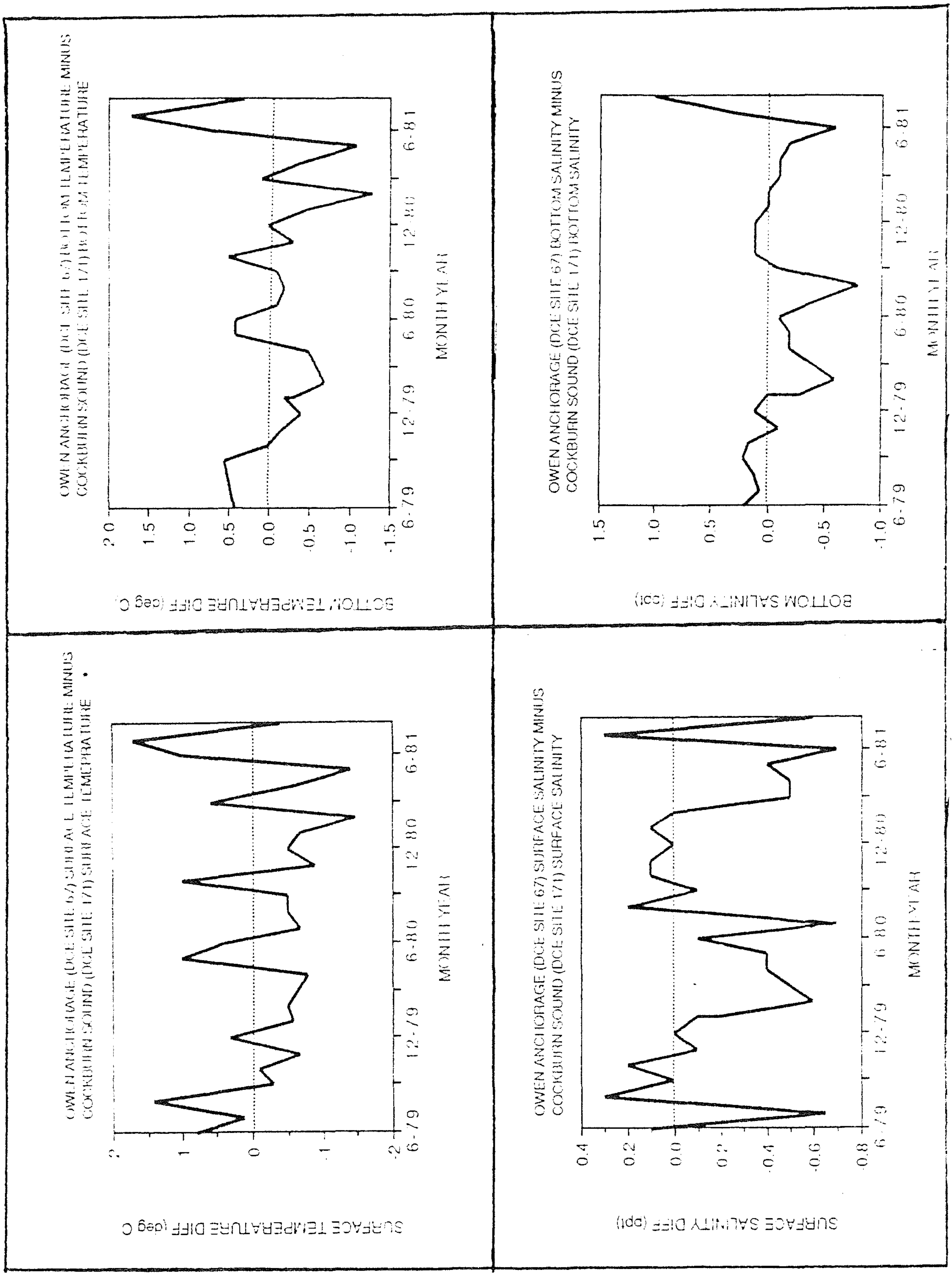


Figure 5.4 Time series plots of differences between Owen Anchorage (DCE site 67) and Cockburn Sound (DCE site 171) surface and bottom temperatures and salinities from monthly ST measurements during June 1979 to July 1981. Station locations in Figure 4.18.

5.2 Basin-scale stratification and wind mixing

The historical data set on basin-scale stratification and wind mixing is not as comprehensive for Owen Anchorage as it is for Cockburn Sound. However, a number of surveys have been conducted in the past and the data allow a simple analysis of the seasonal characteristics of basin-scale stratification and the potential of winds to mix the basin.

The ERA measurements of basin-scale stratification conducted during the period 1969-1973 generally included the Owen Anchorage region. Many of the resulting surface salinity contour plots have already been presented in this report. It is evident that Owen Anchorage is typically horizontally stratified in salinity throughout the year, with individual patches of isohaline water having horizontal dimensions of the order of 1-5 km.

For details of stratification in Owen Anchorage the reader is referred to the discussions and contour plots contained in the preceding sections on the summer, autumn, winter and spring hydrodynamics as the majority of contour plots presented encompass either the entire region or a significant area of Owen Anchorage. Vertical and horizontal stratification appears to be as common in Owen Anchorage as it is in Cockburn Sound. This generally reflects the fact that the same buoyancy sources act to stratify both basins, namely solar heating and the Swan River freshwater outflow (see Chapter 4 for typical data sets highlighting this point).

Wind mixing in Owen Anchorage can result in spatially variable deepening, with the deep basin often remaining vertically stratified while being surrounded by fully mixed shallower regions over the Success and Parmelia Banks. Vertical ST profiles collected along the two transects shown in Figure 5.5 through Owen Anchorage and the adjacent northern region of Cockburn Sound exemplify this point. Figures 5.6 and 5.7 present the resulting salinity and temperature contours from the two field surveys (on 15 March and 5 April 1991, respectively). On 15 March 1991 (Figure 5.6) the areas over the Banks are seen to be vertically mixed, whereas the central Owen Anchorage and northern Cockburn Sound basin areas remained vertically stratified below about 8-10 m. The winds were about 5 m s^{-1} and from the NE/NW. On 5 April 1991 (Figure 5.7) the winds were slightly weaker (3-5 m s^{-1}, SW) than on 15 March, and this is reflected in the fact that there is vertical stratification both over the basins and the shallower regions (Success and Parmelia Banks).

The relationship between wind strength and vertical stratification is indicated by plotting these two parameters for a range of wind speeds and corresponding vertical density differences (bottom minus top) drawn from a data set provided by R. K. Steedman and Associates' measurements (in Binnie and Partners, Dec 1981) from the central Owen Anchorage basin throughout the year of 1981. These data are plotted in Figure 5.8, and as shown appreciable vertical density differences occurred for winds that ranged from 2 to 9 m s^{-1}. These data suggest that Owen Anchorage is generally vertically stratified during winds less than about 8-10 m s^{-1}.

5.3 Exchange between Owen Anchorage and Cockburn Sound

The data discussed thus far show that the northern exchange region of Cockburn Sound is typically vertically stratified. This suggests that exchange via the northern opening could be strongly influenced by vertical density gradients. The data presented in Figures 5.6 and 5.7 highlight this point. We see quite clearly the existence of appreciable stratification in the northwest gap, with the zone of most intense salinity or temperature gradients occurring at about the depth of the gap (5-10 m). The structure of 15 March 1991 (Figure 5.6) could represent a surface buoyant flow into Cockburn Sound of less saline, but colder water in from the ocean. On 5 April 1991 (Figure 5.7) the structure could be indicative of a bottom density current flowing in through the northwest gap of relatively cold, and more saline water. It is plausible therefore that baroclinic exchange patterns could be important as a complimentary feature to barotropic exchange at the northern opening.

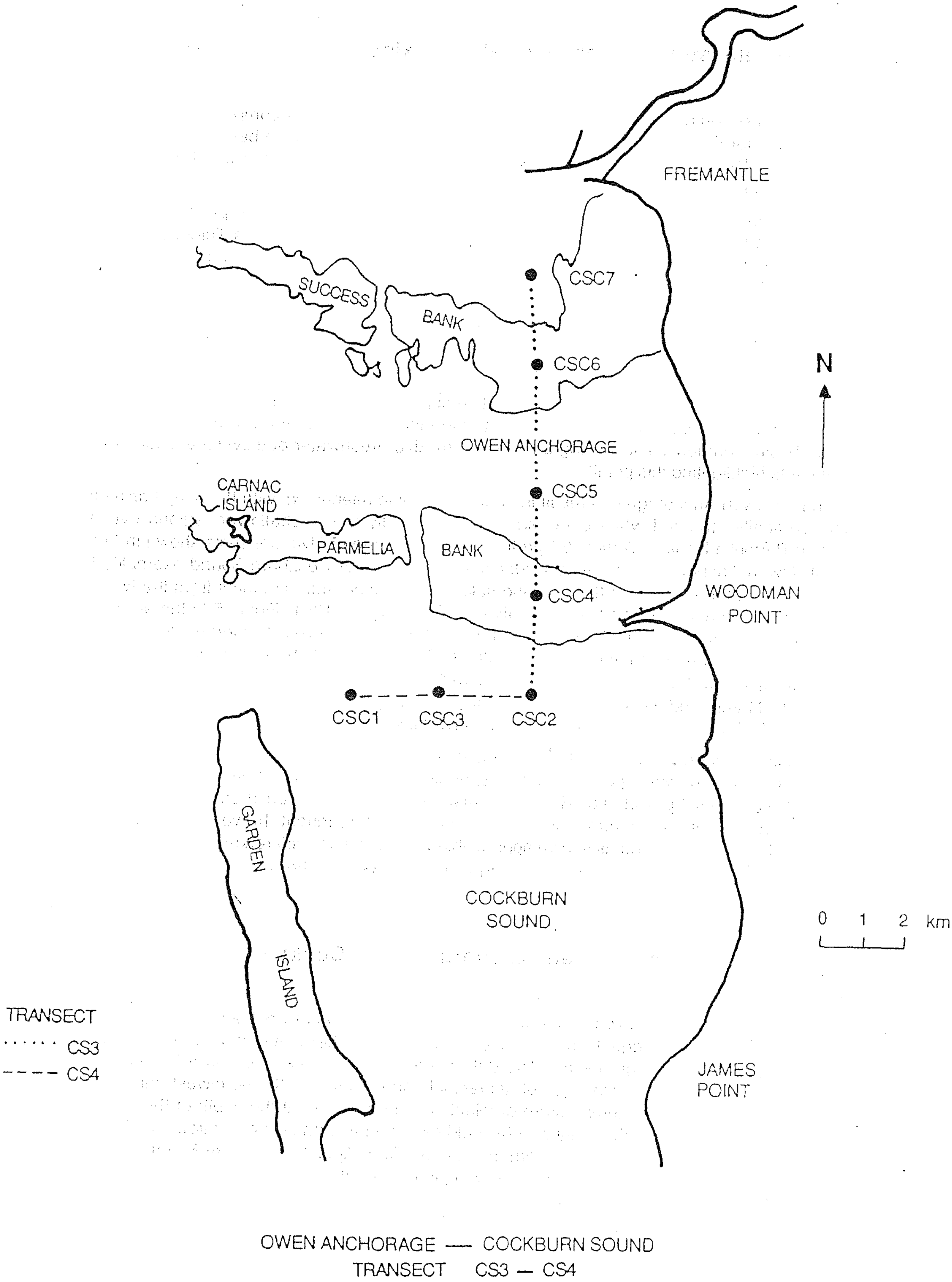


Figure 5.5 Station locations and transect paths from ST profiling conducted in Owen Anchorage and northern Cockburn Sound during EPA surveys in 1991.

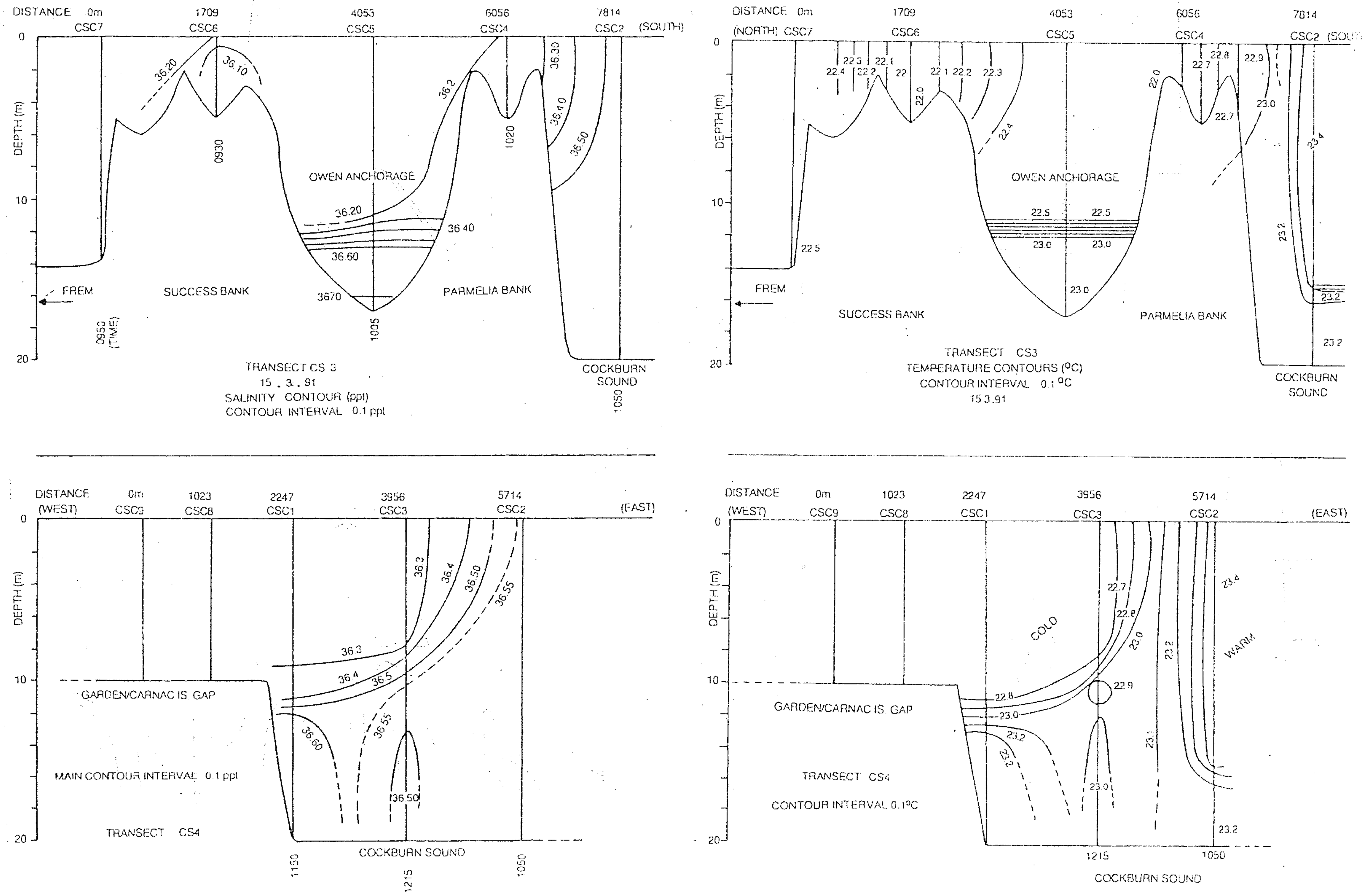


Figure 5.6 Vertical salinity and temperature contour plots from ST data collected by the EPA along transects shown in Figure 5.5 in Owen Anchorage and Cockburn Sound on 15-3-91.

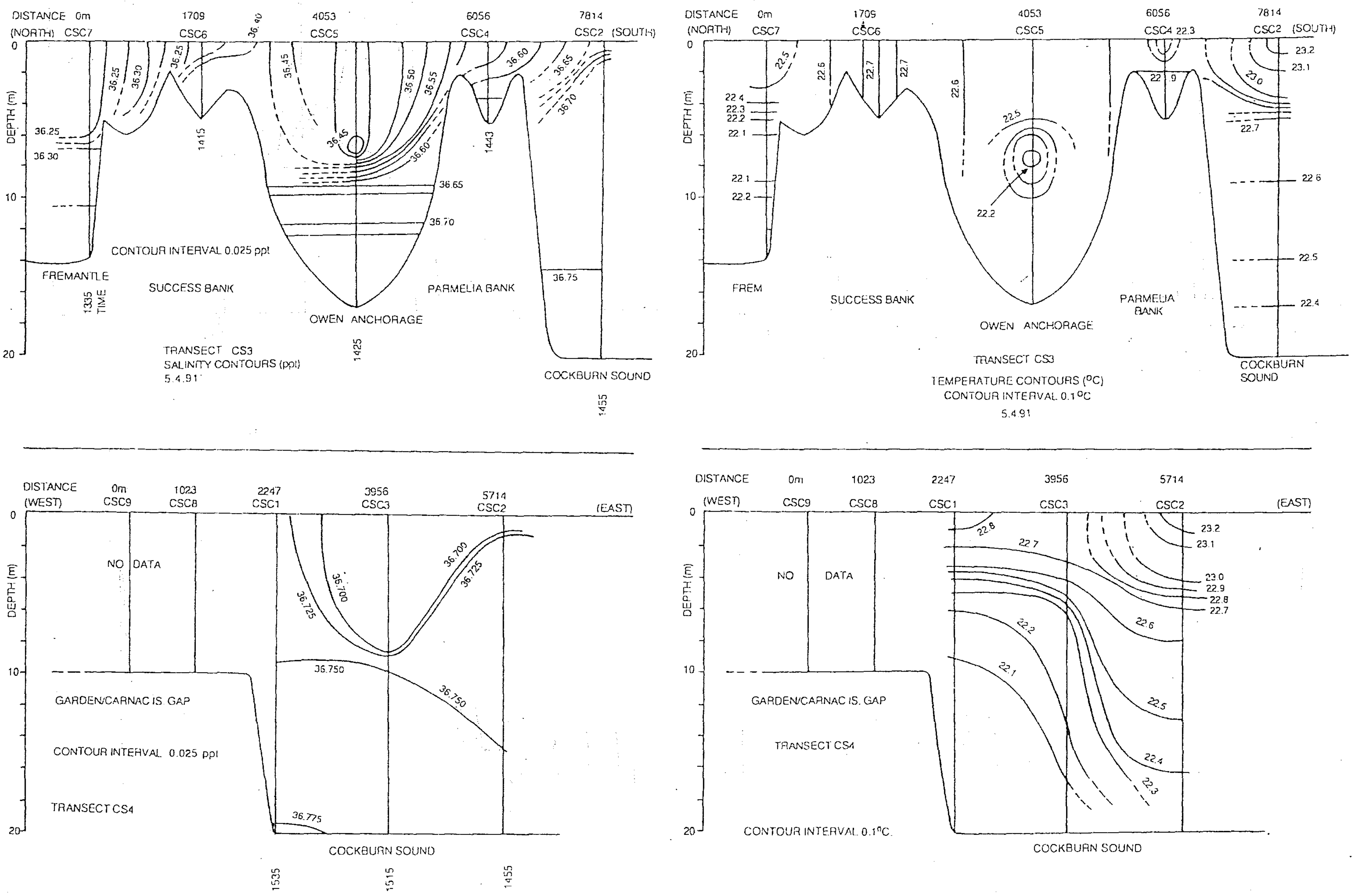


Figure 5.7 Vertical salinity and temperature contour plots from ST data collected by the EPA along transects shown in Figure 5.5 in Owen Anchorage and Cockburn Sound on 5-4-91.

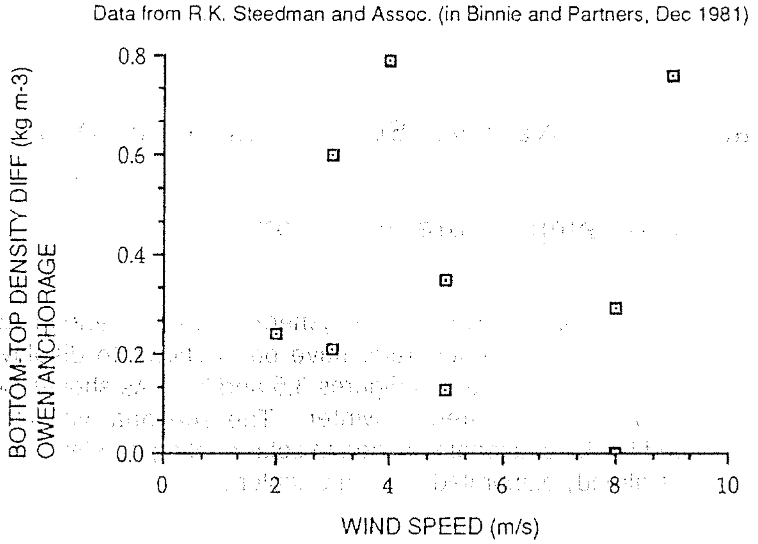


Figure 5.8 Scatter diagram of bottom minus surface density difference versus wind speed in central Owen Anchorage from a number of ST profiles collected by R K Steedman and Associates (in Binnie and partners, Dec, 1981).

5.4 Influence of stratification on mixing and flushing

If external waters enter the Sound as surface, intermediate or bottom density currents, it is possible that the efficiency of mixing processes in diluting polluted resident waters of the Sound with relatively unpolluted external waters will could be impeded. The prediction of flushing times of the Sound's volume as a whole is therefore complicated without an adequate understanding of the baroclinic circulation patterns within the Sound and between the Sound and outside waters. The data presented thus far show that vertical and horizontal salinity, temperature and/or density gradients are common, and are likely to be a characteristic of the water structure for over 50 percent of the time on average, when winds are less than about 5-10 m s^{-1}. The importance of baroclinic mechanisms will have to be verified by further field surveys of the basin-scale stratification over diurnal time scales. The prediction of interior mixing, circulation and flushing in these basins by numerical mathematical models will have to address this issue.

6 Mixing and transport in Warnbro Sound and Sepia Depression

6.1 Seasonal salinity and temperature variation

Both Warnbro Sound and Sepia Depression exhibit the same general seasonal trend in salinities and temperatures that Cockburn Sound and Owen Anchorage have been shown to display, and data highlighting these trends has already been presented in Figures 3.5 and 3.6. As shown, both regions are more saline and warmer in summer compared to winter. The seasonal variation in water temperatures and salinities is forced by the seasonal variation in solar heating, freshwater inputs from the Swan River and evaporation, as already elaborated upon in Chapter 3.

6.2 Basin-scale stratification and exchange between Warnbro Sound and Sepia Depression

In addition to the general seasonal trend in the individual time series of salinity and temperature for the two regions, there is also an important difference in the relative salinities and temperatures between Warnbro Sound and Owen Anchorage. As shown in Figures 3.5 and 3.6, during summer Warnbro Sound is consistently more saline and warmer than Sepia Depression, whereas during winter the Sound is generally less saline and colder than Sepia Depression. During spring and autumn the relative directions of these onshore-offshore ST gradients undergo their seasonal reversals.

These results are important from a hydrodynamic point of view, in terms of their implication on onshore-offshore exchange mechanisms. It is possible that the occurrence of such salinity or temperature gradients may lead to baroclinically enhanced or controlled exchange mechanisms at hydraulic communication gaps in the reef structure that separates Warnbro Sound from Owen Anchorage.

The EPA has been monitoring ST structure in the Warnbro Sound - Sepia Depression region, and the stations that comprise the survey grid are shown in Figure 6.1. A portable Yeo-Kal Model 602 salinity-temperature meter was used. Two data sets are discussed, one for 19 March 1991 (representing summer conditions) and one for 5 June 1991 (representing winter conditions).

The summer data (19 March 1991) along the east-west transect, WS10, are shown in the contour plot of Figure 6.2. The wind during that day was light, blowing from the SE at 5-7 m s^{-1} during the morning and then weakening to 2-5 m s^{-1} at about midday. As shown, there were significant horizontal gradients in both salinity and temperature across the transect. The individual basins were relatively isohaline vertically and horizontally, but a significant horizontal salinity difference existed between

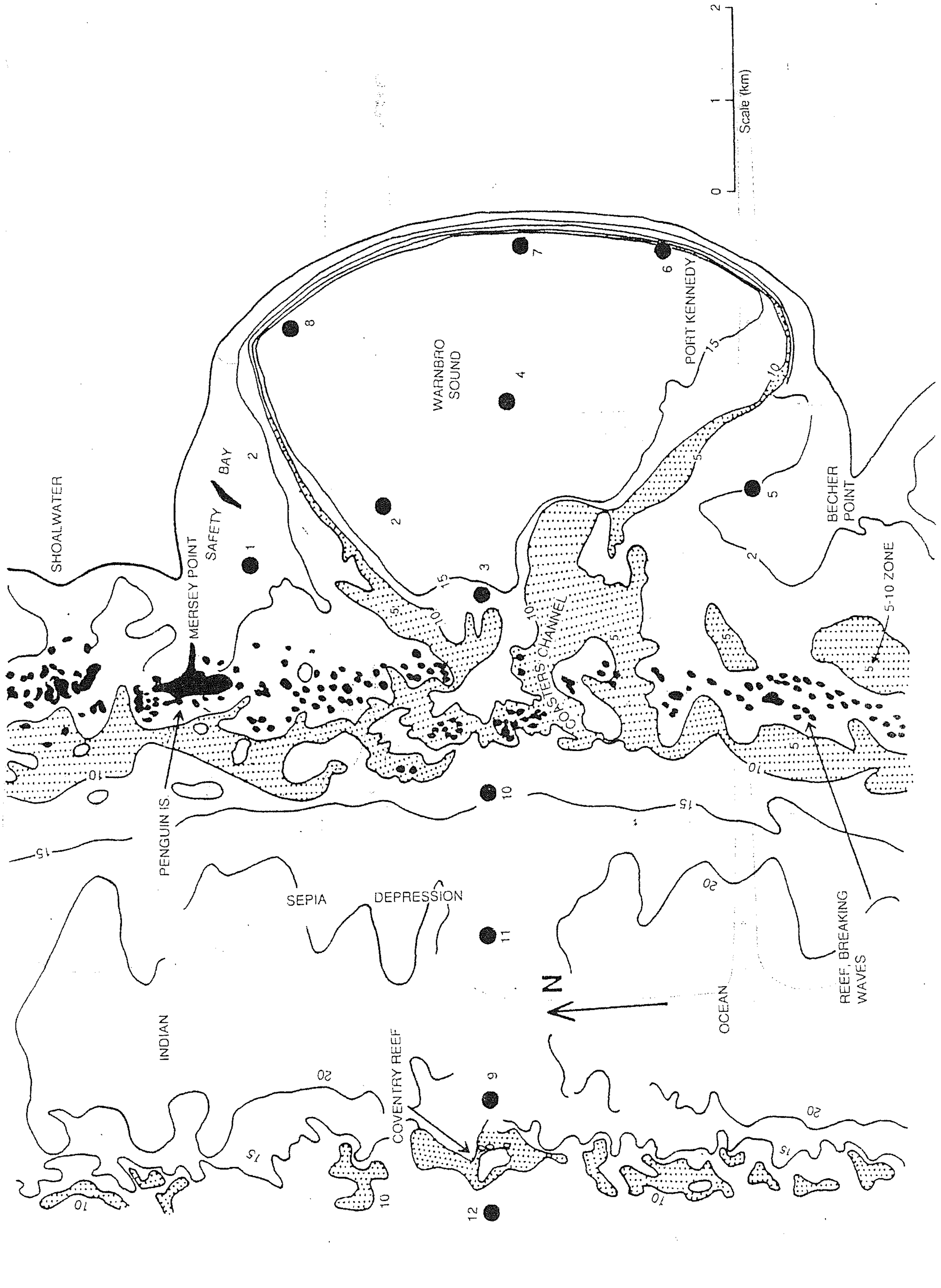
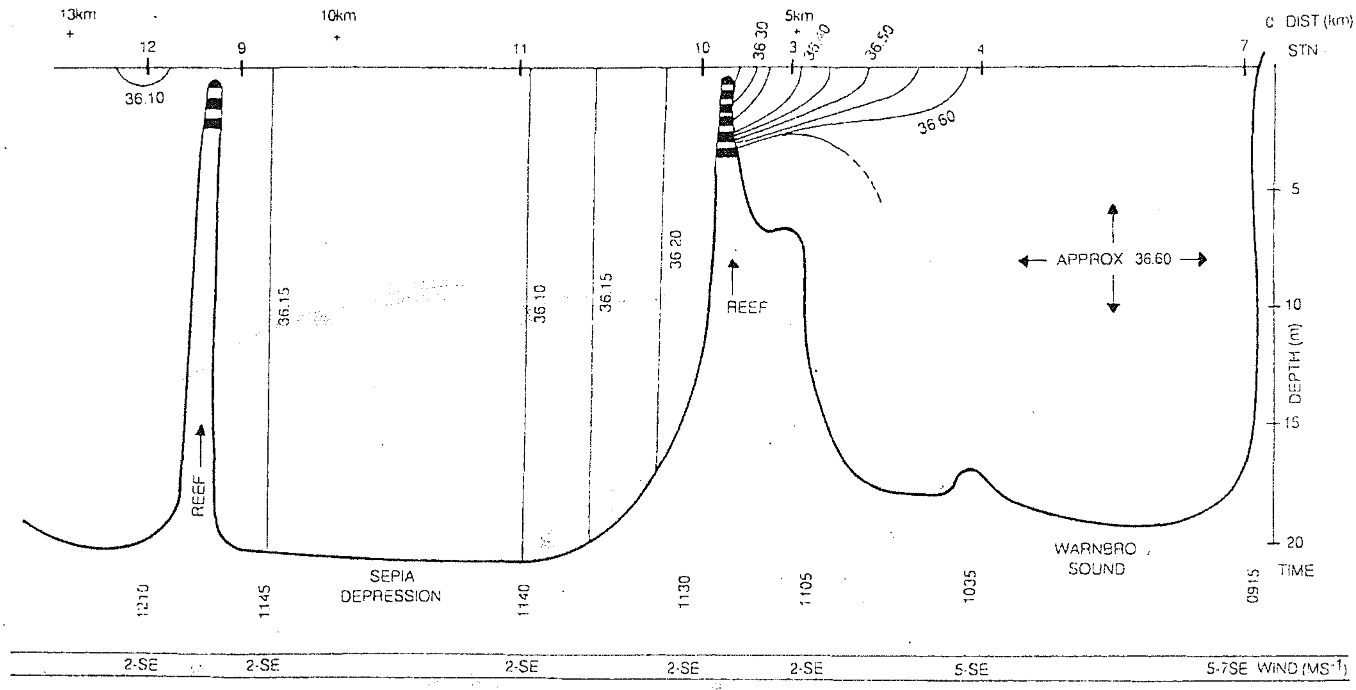
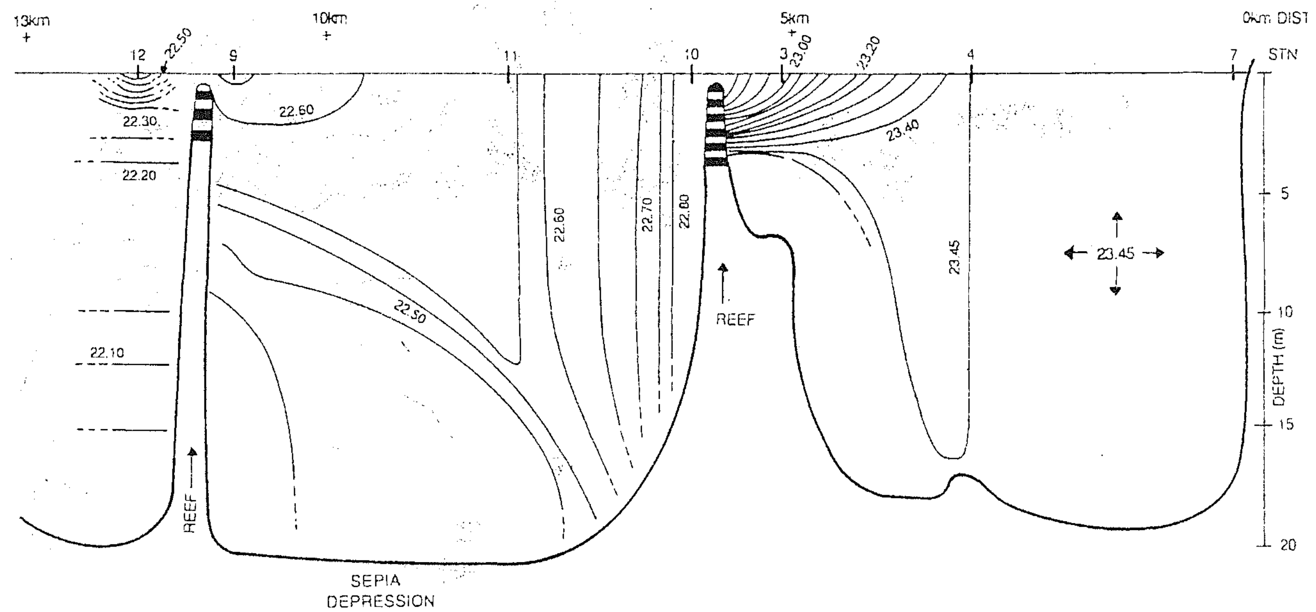


Figure 6.1 Grid of stations (1 to 11) from the 1990/1991 EPA surveys of water quality and ST structure of Warnbro Sound and adjacent Sepia Depression.



ISOHALINES (ppt)
19.3.91

13km SALINITY TRANSECT - WARNBRO SOUND/SEPIA DEPRESSION EPA DATA
TRANSECT WS10



ISOTHERMS (°C)
19.3.91

13km TEMPERATURE TRANSECT - WARNBRO SOUND/SEPIA DEPRESSION EPA DATA
TRANSECT WS10

Figure 6.2 Vertical salinity and temperature structure along the west-east transect from Coventry Reef to the Warnbro Sound coast, at stations shown in Figure 6.1, on 19-3-91.

them across the Coasters Channel gap in the reef line. This salinity difference was accompanied by a similarly striking temperature difference. The stratification suggests a possible surface front of relatively less saline but slightly colder water entering Warnbro Sound from Sepia Depression as a baroclinically enhanced gravitational overflow. The vertically homogeneous nature of Warnbro Sound, in contrast to the vertically stratified nature of Sepia Depression, probably reflects the mixing influence of the strong morning winds (during which the Warnbro Sound measurements were taken) and the subsequent mild wind conditions of the afternoon (during which the Sepia Depression measurements were made and the thermal stratification was re-established).

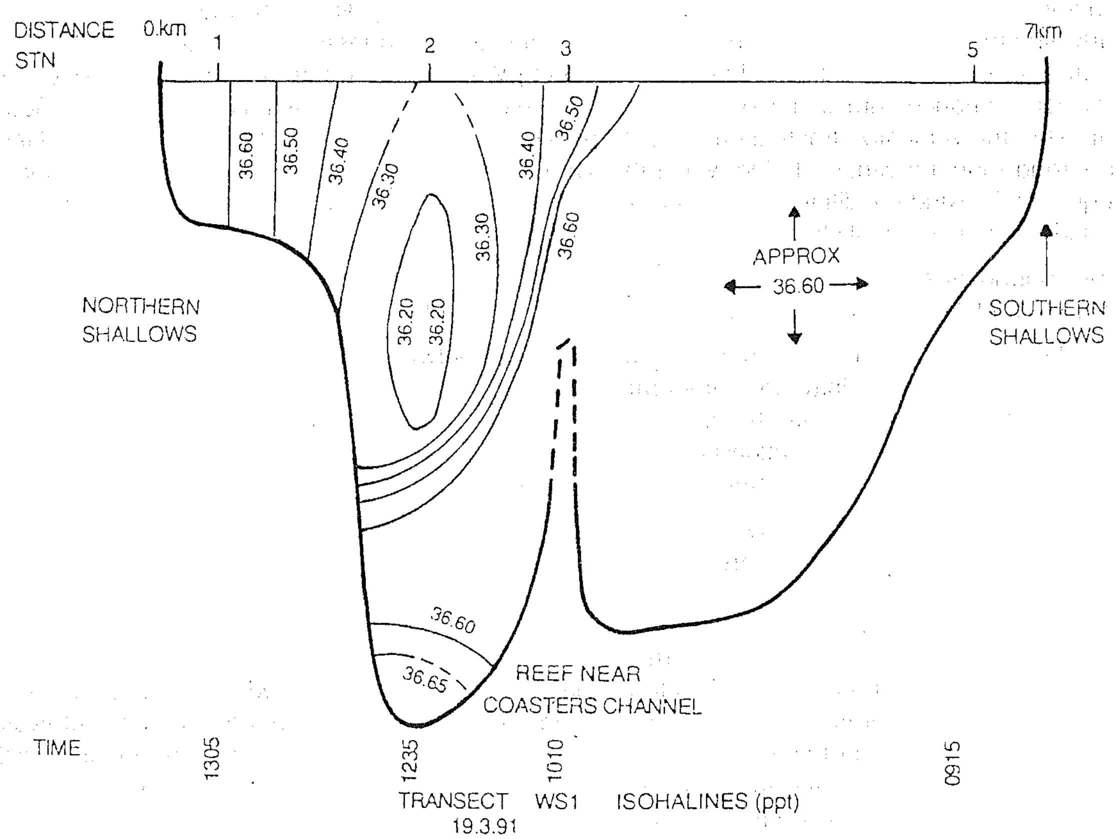
Warnbro Sound was significantly more saline and warmer in comparison to Sepia Depression on 15 march 1991 and this is consistent with the seasonal trends evident in Figure 3.5 and 3.6.

A more detailed view of the horizontal ST gradient region between these two water bodies is offered by the contour plots of salinity and temperature along the north-south transect, WS1, presented in Figure 6.3. The contours reveal that the stratification in the Sound was three dimensional. It would appear from Figure 6.3 that the inflowing water was intrusive in nature with an intermediate depth core of relatively cold and less saline water flowing into the northern half of Warnbro Sound.

The winter data (5 June 1991) have also been presented as salinity and temperature contour plots along transect WS10, and these are shown in Figure 6.4. The difference in the direction of the onshore-offshore salinity and temperature gradients in comparison to the summer data (Figure 6.2) is evident. As shown, Warnbro Sound is both less saline and colder than the adjacent Sepia Depression (this feature is consistent with the long-term seasonal trends that were displayed in Figures 3.5 and 3.6). As for the summer stratification contours along Transect WS10, the winter contours reveal an intense horizontal temperature gradient zone through the Coasters Channel gap in the reef system that separates the Sound from the Depression. Salinities either side of that gap were equal (to within the instrument's resolution) and therefore a salinity front did not accompany the temperature front. The winds on that day were relatively light, blowing from the NE at 2-5 m s^{-1}. The basin-scale temperature stratification data suggests that winds less than about 5 m s^{-1} were unable to cause appreciable surface mixing in either Warnbro Sound or Sepia Depression.

The seasonal horizontal salinity and temperature differences between the two regions appear to have typical values of up to 0.5 ppt and 2 ^{o}C, respectively. Hence, typical density differences of the order of 0.5 kg m^{-3} could result. By using Equation A3.2, and assuming a baroclinic density exchange with a characteristic thickness of half the depth of the channel (the Coasters Channel and adjacent gaps are of the order of 6 m deep), a densimetric velocity of the order of 5-10 cm s^{-1} is calculated. By assuming a combined length for all of the gaps combined equal to about 2000 m yields a flux by baroclinic exchange of the order of 300-600 m ^{3} s^{-1}. Warnbro Sound has a volume of the order of 10^8 m^3, and assuming a fully homogeneous basin, an exchange flux of 300-600 m^3 s^{-1} equates to a replacement time for the Sound's volume of 2-4 days. Warnbro Sound can however be vertically and horizontally stratified for a large percentage of the time throughout the year, as will be shown in the analysis following in Section 6.3, and this invalidates the assumption of continuous homogeneity. Hence, any estimates of exchange rates can only be indicative at this stage, and without further information on the temporal characteristics of horizontal stratification and exchange through the openings between the two water bodies, more quantitative calculations are not possible. This again points to the need for further field surveys to refine the understanding of such processes.

In summary, the summer and winter stratification data (along transects WS10 and WS1) suggest that baroclinic exchange at the openings between the Sound and Depression could be and important transport mechanism. The relative strength of baroclinic and barotropic exchange mechanisms is not identifiable from the existing data sets, and this should be addressed in future field studies aimed at quantifying both the internal circulation and mixing characteristics and exchange processes of Warnbro Sound and Sepia Depression.



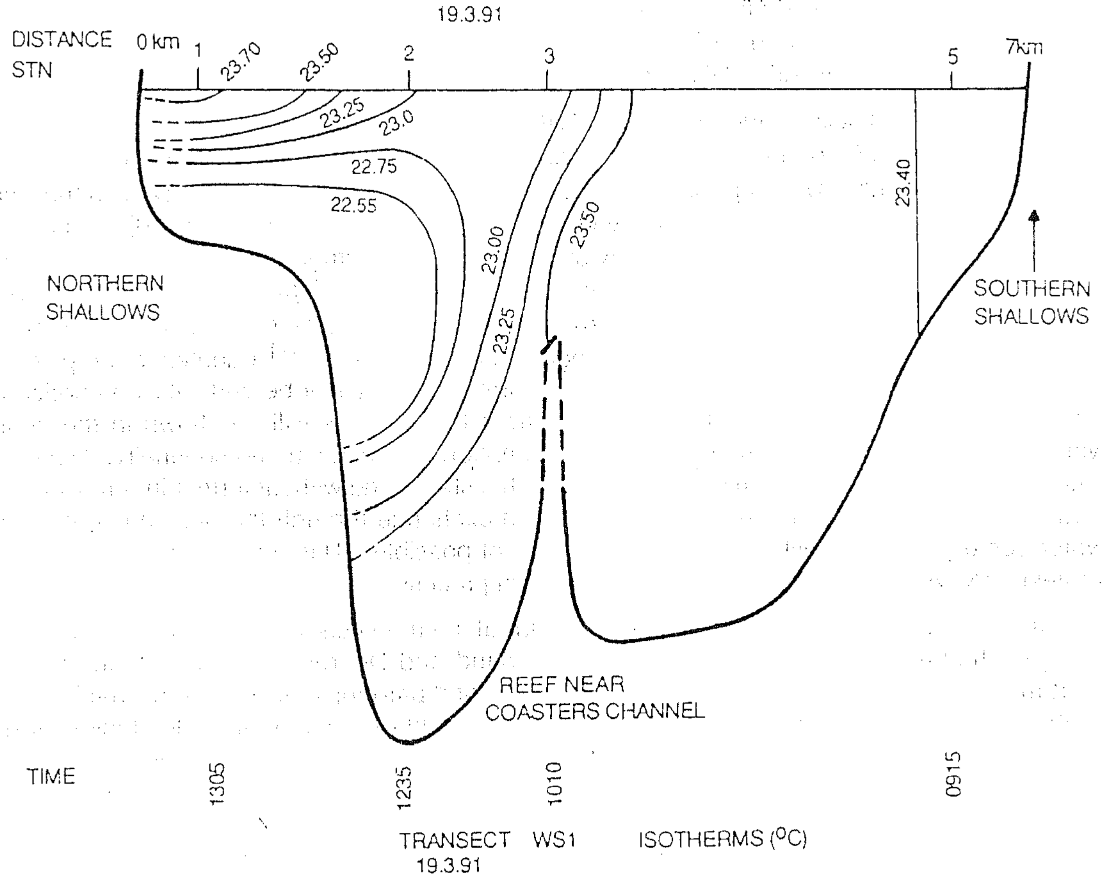
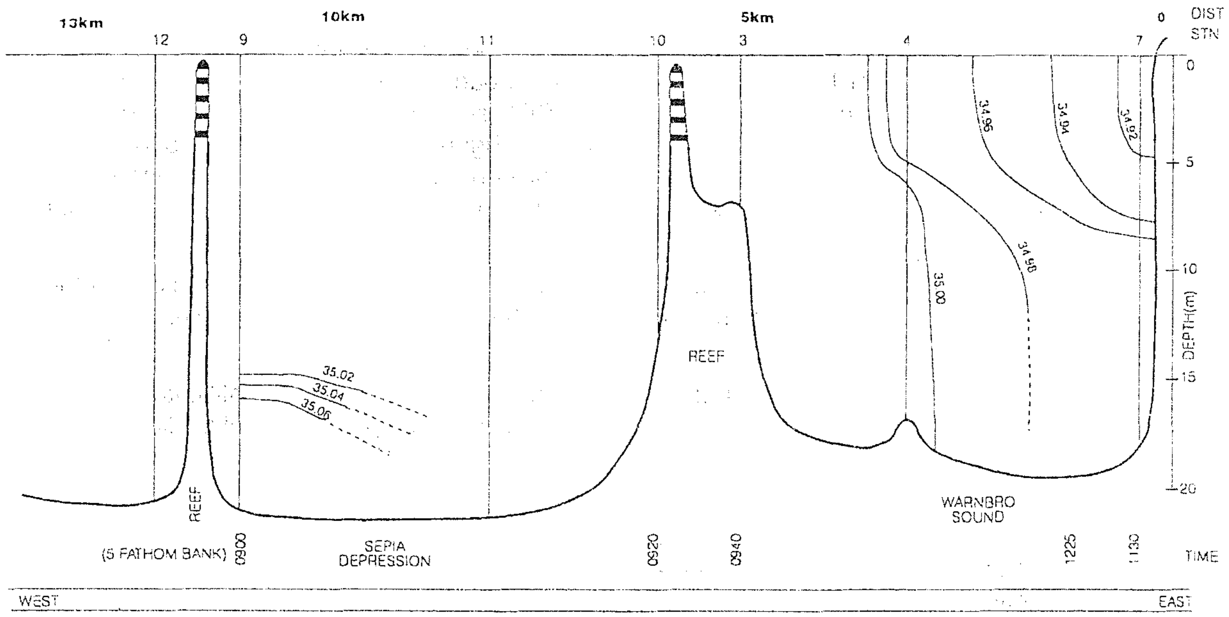
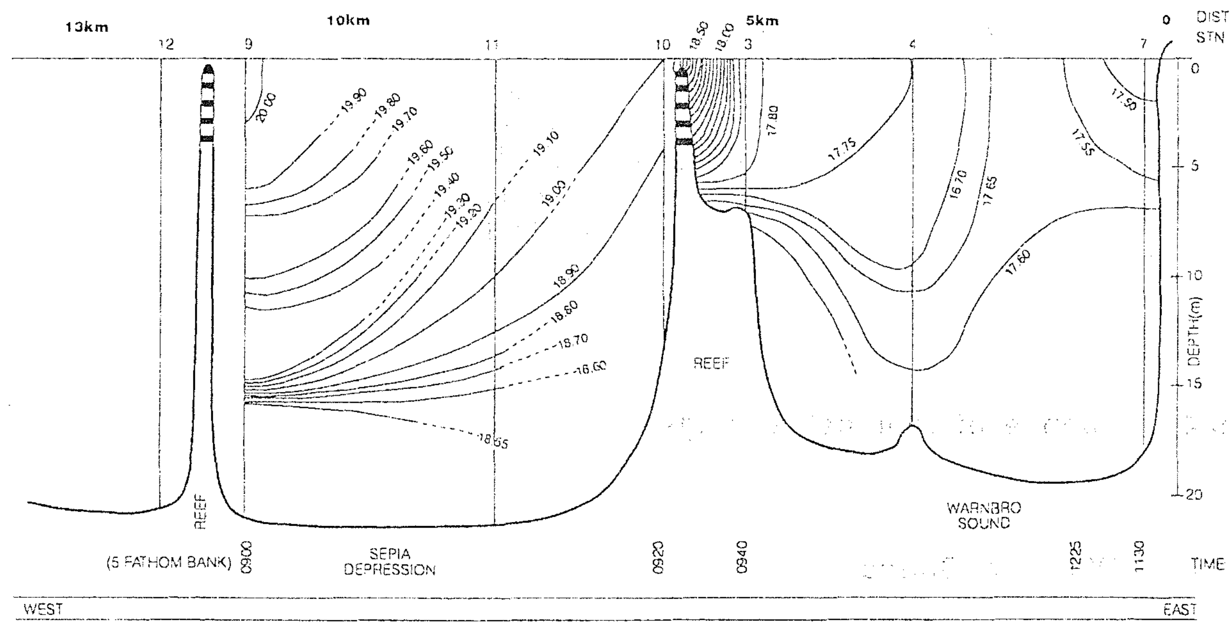


Figure 6.3 Vertical salinity and temperature structure along the north-south transect from in Warnbro Sound, at stations shown in Figure 6.1, on 19-3-91.



CONTOUR PLOT OF SALINITY (ppt)
DATE:5-6-91
CONTOUR INTERVAL: 0.02 ppt
COMMENTS: LIGHT BREEZE 2-5ms⁻¹ NE



CONTOUR PLOT OF TEMPERATURE (°C)
DATE:5 6-91
CONTOUR INTERVAL: 0.05°C and 0.10°C
COMMENTS: LIGHT BREEZE 2-5ms⁻¹ NE

Figure 6.4 Vertical salinity and temperature structure along the west-east transect from Coventry Reef to the Warnbro Sound coast, at stations shown in Figure 6.1, on 5-6-91.

6.3 Vertical mixing

The seasonal ST data set collected by the DCE (discussed above in Section 6.1) also indicates the occurrence of vertical salinity or temperature stratification throughout the year. For this purpose all vertical ST profiles collected in central Warnbro Sound (DCE site 235, see Figure 4.18) and central Sepia Depression (west of the Causeway, DCE site 234, see Figure 4.18) have been used to produce monthly records of vertical salinity and temperature differences between the surface and bottom of the water column. These data have been presented as time series plots in Figure 6.5a (salinity) and Figure 6.5b (temperature).

At both sites, for periods when there was either vertical salinity or temperature stratification, surface salinities were generally lower than bottom salinities and the surface temperatures were generally higher than those at the bottom.

In summary, central Warnbro Sound exhibited less occurrences of vertical salinity stratification than did Sepia Depression, but about the same relative occurrence of vertical temperature stratification. Taking both salinity and temperature stratification into account indicates that Warnbro Sound was vertically stratified over half the time, and Sepia Depression over 70 percent of the time.

The above result leads to the question of the relative occurrence of stratification in these regions as a function of wind strength. R. K. Steedman and Associates (Binnie and Partners, Dec 1981) collected vertical density profiles in central Sepia Depression (west of the causeway) on nine separate occasions during 1981, at various times of the year, during a range of wind conditions. The resulting vertical density difference (bottom minus surface) from these data have been plotted in relation to wind speed at the time of measurement, (Figure 6.6). As shown vertical density differences of more than 0.2 kg m^{-3} occurred on most occasions and winds ranged from about 2 to 9 m s^{-1}. Only on one occasion, when the wind was 8 m s^{-1}, was the water column fully mixed.

The EPA collected vertical ST profiles at eight sites around the basin from 23 January to 26 March, at approximately weekly intervals. Only on one occasion was the water column at site 3 (see Figure 6.1) vertically fully mixed, and this was on 8 March 1991, when winds were SW at 5-7 m s^{-1}. On all of the other days the water column at site 3 was stratified and winds were generally less than 7 m s^{-1}. It would appear that in Warnbro Sound winds of less than about 5 m s^{-1} are unable to break through the vertical stratification. However, further measurements of the spatial and temporal variability of basin-scale stratification as a function of time and wind speed at a temporal resolution of at least 1-2 hours, throughout 1-2 diurnal cycles are now required to establish the potential of winds to homogenise the water in Warnbro Sound.

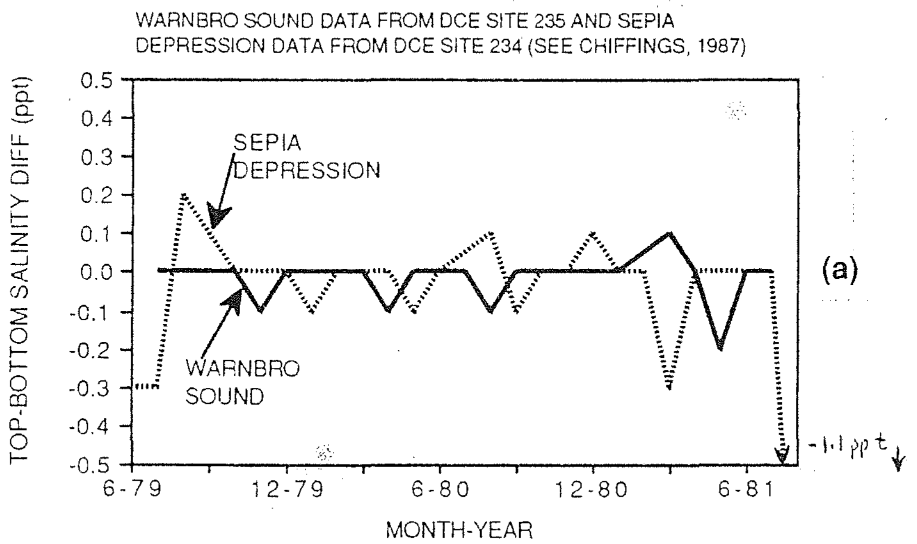
6.4 Influence of regional forcings

6.4.1 Warnbro Sound

No data exists regarding the influence of regional currents on the circulation within Warnbro Sound. There appear to be no available current meter, drogue-tracking or dye dispersion data sets available.

The influence of wind in driving surface drift currents, basin-scale topographic gyres or baroclinic motions during stratified conditions has not been measured in the field to date.

Some evidence of an hydraulic connectedness between Warnbro Sound, Sepia Depression and Cockburn Sound was presented in Figure 4.54 (Chapter 4), showing the southward propagation of a plume of brown-coloured water that emanated from the Swan River mouth as a tidal outflow and then propagated through either Cockburn Sound or Sepia Depression, eventually entering Warnbro Sound. However, no adequate data set exists from which to draw firm conclusions regarding true



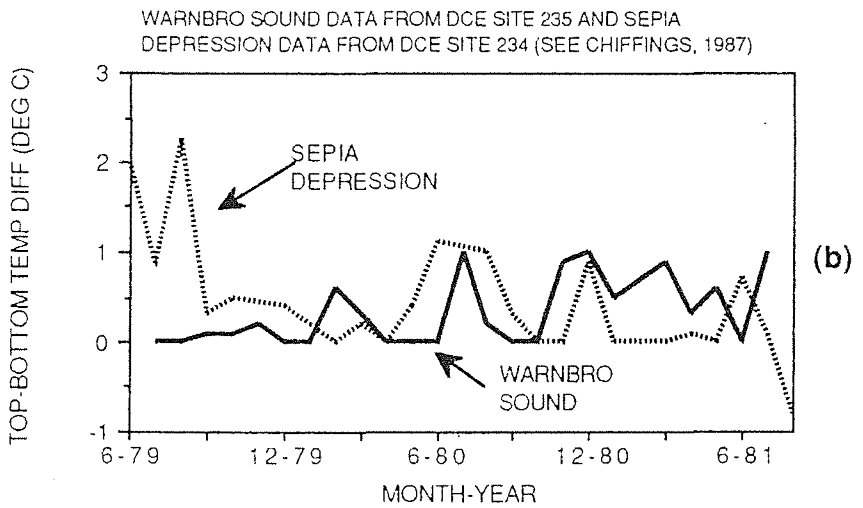


Figure 6.5 Time series plots of surface minus bottom salinity and temperature at individual sites in Warnbro Sound (DCE site 235) and Sepia Depression (DCE site 234) from monthly ST measurements during June 1979 to July 1981. Station locations in Figure 4.18.

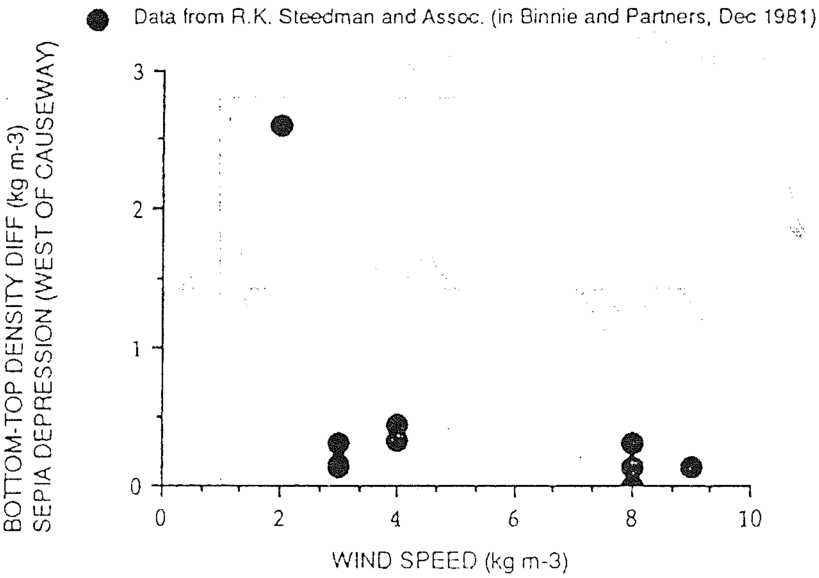


Figure 6.6 Scatter diagram of bottom minus surface density difference versus wind speed in central Sepia Depression (west of the causeway) from a number of ST profiles collected by R K Steedman and Associates (in Binnie and partners, Dec, 1981).

flushing rates of Warnbro Sound due to regional forcings. The importance of regional currents to the exchange patterns of Warnbro Sound would rely either on a theoretical appraisal, numerical modelling effort, further field measurements or mechanisms inferred from the results of analyses of this issue for Cockburn Sound or Owen Anchorage, above. Such an analysis is not within the scope of this report and is recommended as a future exercise in any studies aimed at quantifying the exchange characteristics of Warnbro Sound with adjacent oceanic waters. The data set for Sepia Depression is somewhat more comprehensive due to the studies conducted by R.K. Steedman and Associates (in Binnie and Partners, Dec 1981) relating to the Cape Peron Outfall Environmental studies and those of ERA motivated by the environmental studies of the early 1970's related to the Causeway construction. The nature of these studies was described in Chapter 3, and the results were discussed in preceding sections of this report, and in Appendix A2.

7 General features of stratification, mixing and circulation of the region

7.1 Stratification

Salinity and temperature structure data for the southern metropolitan waters were collected in 1981 by R.K. Steedman and Associates (in Binnie and Partners, Dec 1981). The transect path usually began near Fremantle, ran directly offshore to the 40 m contour, then south to directly offshore of either Warnbro Sound or the Causeway, and then directly towards either of these regions (Figure 7.1). A selection of the resulting contour plots, spanning the four seasons, are reproduced in Figure 7.2, and these typify the seasonal characteristics that were measured during 1981.

The typical seasonal salinity and temperature pattern for the nearshore and offshore waters is evident in the data contours of Figure 7.2. During summer (15 January 1981) there are distinctive offshore gradients, with nearshore salinities and temperatures higher in Cockburn Sound than at that the 40 m contour. Evaporation is generally considered to be the cause of the hypersaline water in summer. (see Pearce and Church, 1992). The summer contours also typify the temperature stratification usually found, that is nearshore waters being warmer (due to differential heating), than offshore waters. The winter contours (21 August 1981) display salinity and temperature gradients opposite to those described above for summer. The autumn and spring contours represent the close similarity that generally occurs between nearshore and offshore salinities and temperatures. It is during these periods that the direction of onshore-offshore regional scale salinity and temperature gradients changes from summer to winter and vice-versa.

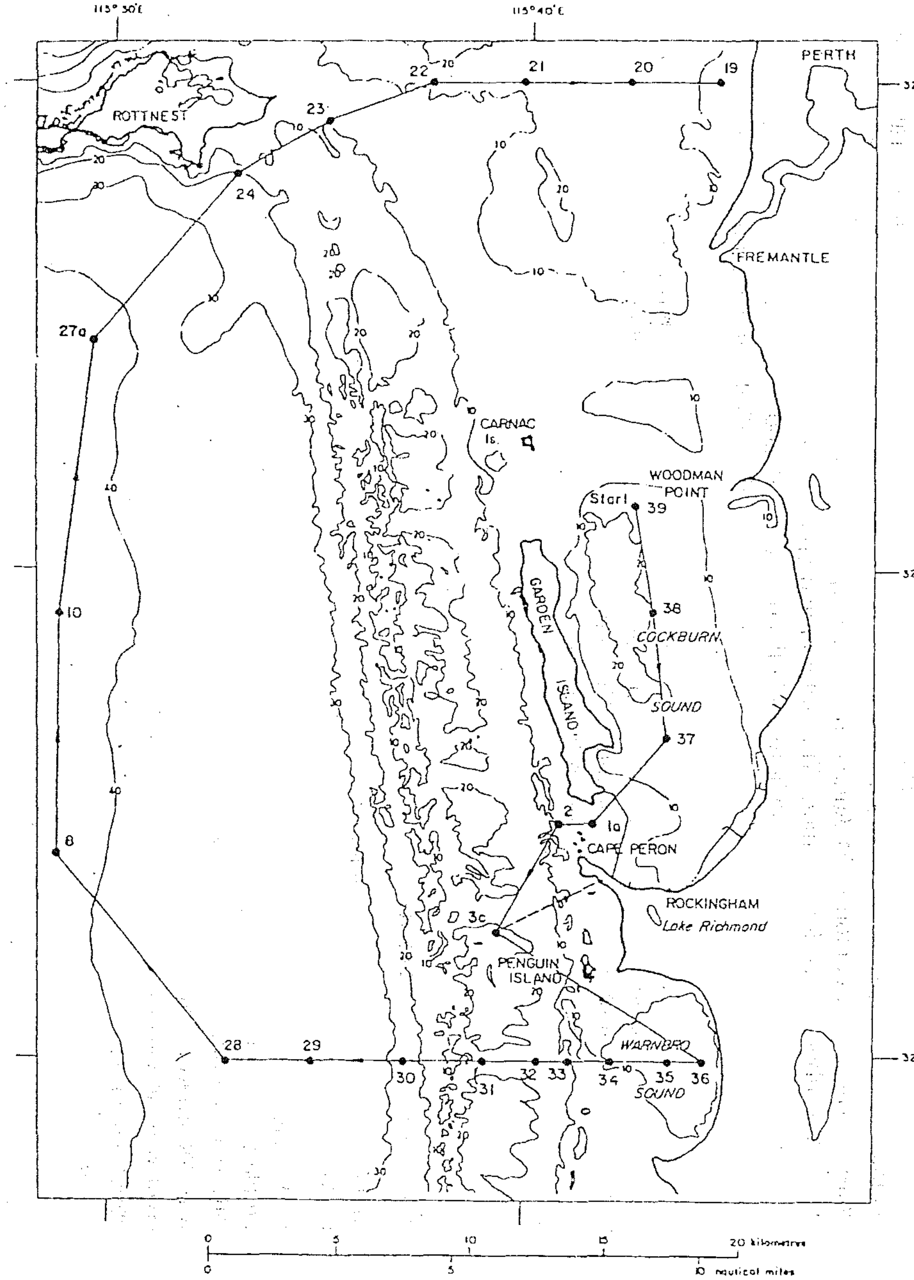
The contours in Figure 7.2 also highlight another interesting feature of the regional stratification structure throughout the year, and this is the regular occurrence of frontal structures, both at the surface and bottom of the water column. These data suggest that baroclinic transport mechanisms may be of importance to circulation in the waters of the wider region of the southern metropolitan waters.

7.2 Vertical Mixing

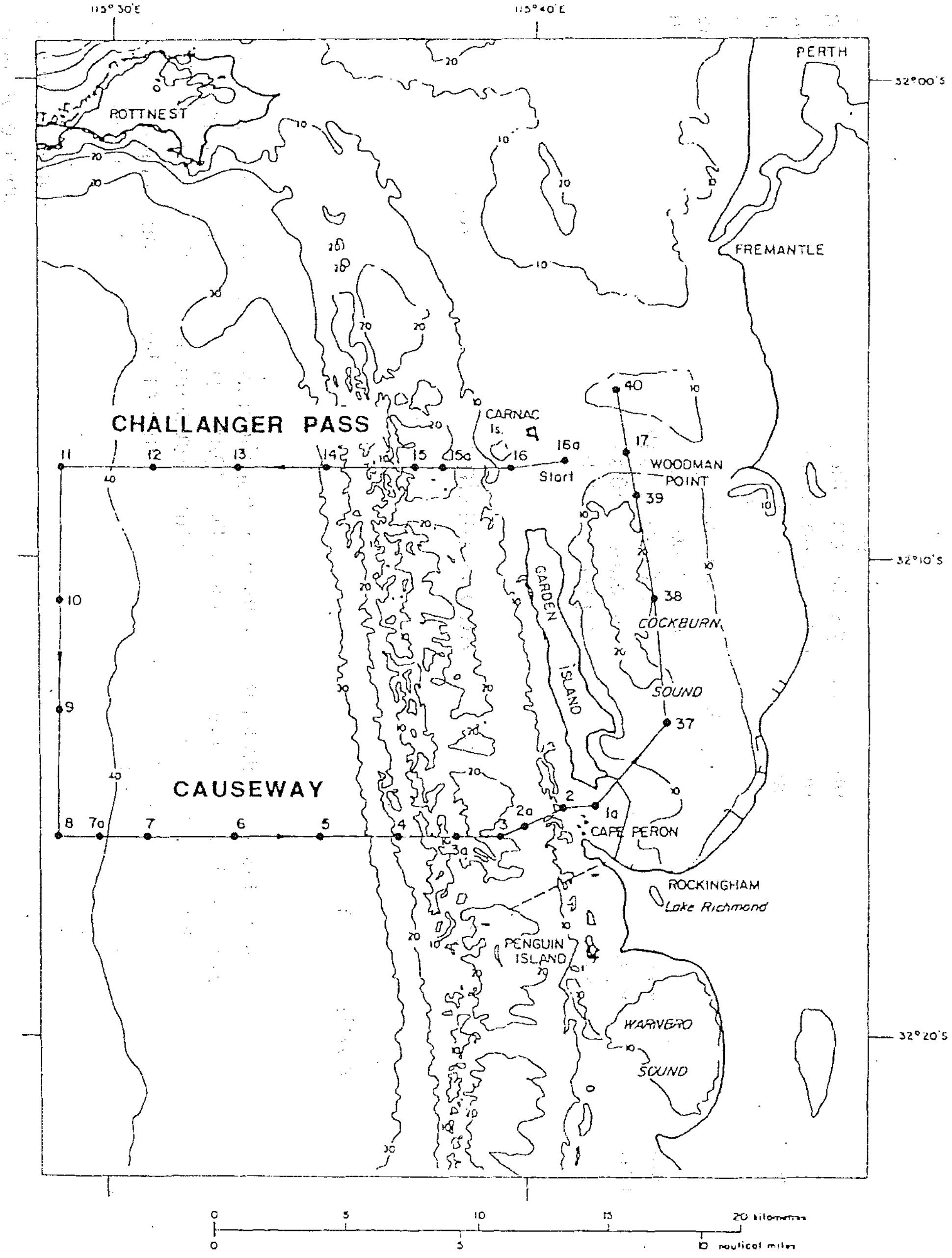
In this section the mixing potential of winds over the entire southern metropolitan coastal waters region is evaluated.

R. K. Steedman and Associates' measurements (see Figure 7.1) throughout 1981 included ST profiling at the 40 m contour (west of Garden Island) and Figure 7.3 is a scatter plot of vertical density differences (bottom minus surface) and associated wind speed values. As shown, vertical stratification was recorded on all occasions, even though winds reached up to about 9 m s^{-1}. The upper mixed layer was however found to vary in thickness from zero to about 20 m, with the occurrences of 20 m upper mixed layers sometimes coinciding with winds greater than 5 m s^{-1} and sometimes with winds of the order of 3 m s^{-1}, hence the introduction into the area of thick surface layers of homogeneous

Figure 7.1 Transect paths followed by R K Steedman and Associates (in Binnie and Partners, Dec 1981) for monthly ST surveys between the mainland and the 40 m contour, west of Garden Island in 1981.



Cruise path and station locations for STD survey, 18th August, 1981.



Cruise path and station locations for STD survey, 21st August, 1981.

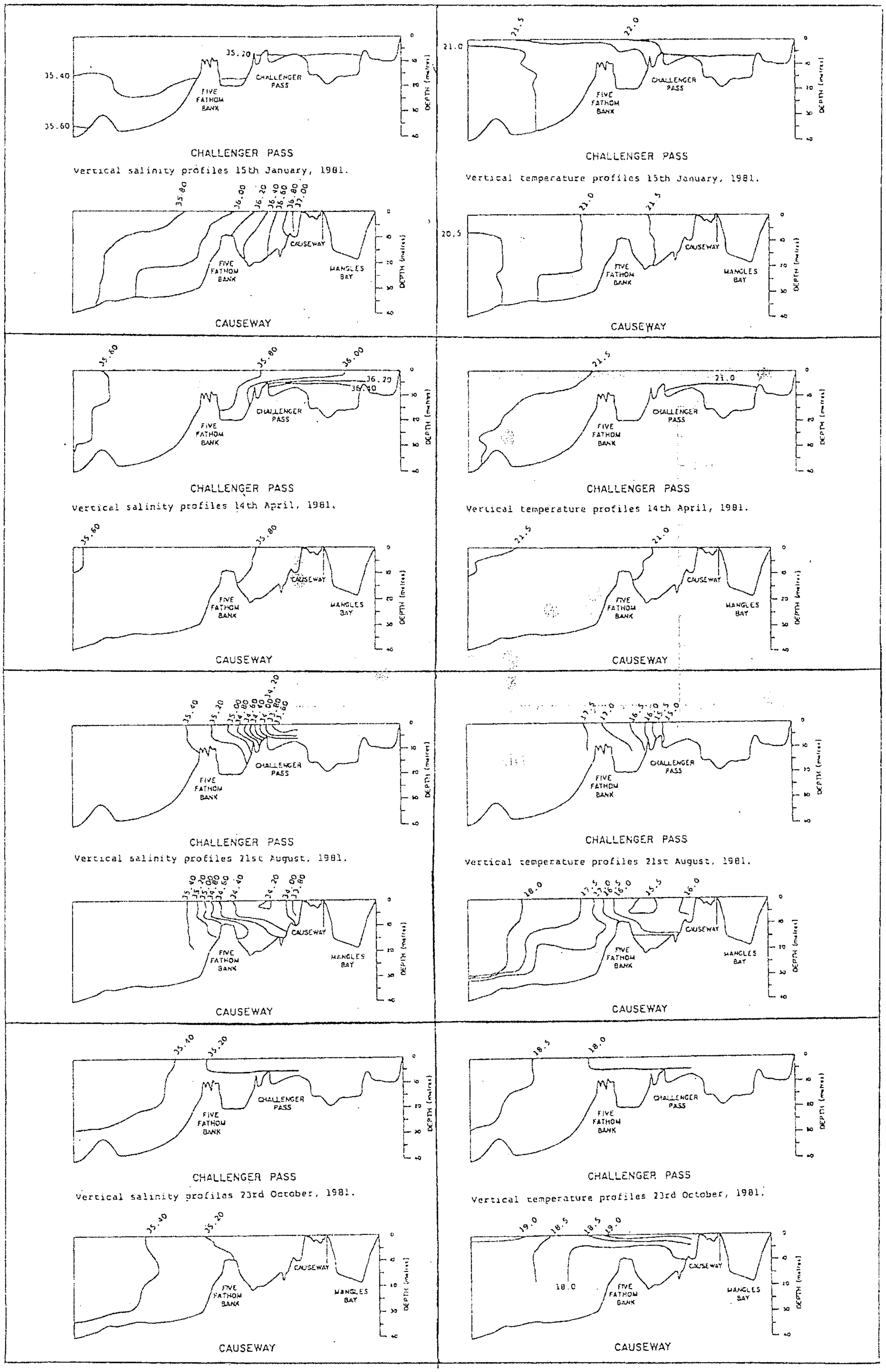


Figure 7.2 A selection of vertical salinity and temperature contours from transects followed during the R K Steedman and Associates ST surveys(in Binnie and partners, Dec, 1981) from summer, autumn, winter and spring 1981. Transect paths in Figure 7.1.

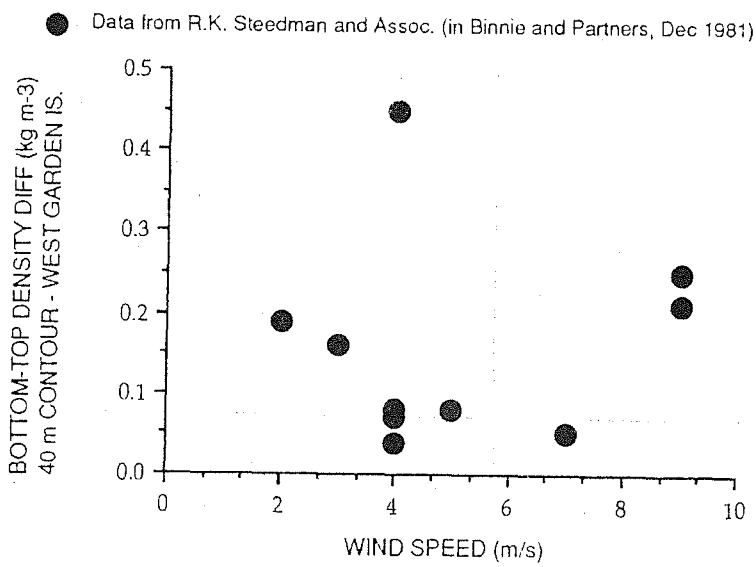


Figure 7.3 Scatter diagram of bottom minus surface density difference versus wind speed at the 40 m contour station, west of northern Garden Island, from a number of ST profiles collected by R K Steedman and Associates (in Binnie and partners, Dec, 1981).

character may have occurred as a result of regional flow patterns, but this remains an aspect of the local hydrodynamics that still requires further field studies before a more quantitative understanding can be obtained.

A more comprehensive scatter plot of vertical density difference versus wind speed has been constructed from data gathered at sites throughout the whole of the metropolitan waters region over a number of seasons. The sites from which the stratification data were collected are: central Gage Roads, central Owen Anchorage, central Cockburn Sound, central Mangles Bay, central Sepia Depression west of both the causeway and Carnac Island, and finally at the 40 m contour west of north Garden Island. The resulting scatter plot is shown in Figure 7.4. The scatter plot indicates that in general vertical density differences become smaller as the wind speed increases, but that on most of the occasions monitored, throughout which time winds ranged from 1-10 m s^{-1} in speed, vertical stratification occurred.

Winds are less than 10 m s^{-1} about 90 percent of the time on average throughout the year. Hence, the general indication from the data in Figure 7.4 is that the southern metropolitan waters are probably vertically stratified for about 90 percent of the time, on average, during the year. In turn, this suggests that baroclinic hydrodynamic transport mechanisms (vertical and horizontal) could play important roles in the hydrodynamic behaviour of these waters for a significant percentage of the time throughout the year.

Summary

The above results highlight the following points with respect to understanding the dominant hydrodynamic characteristics of mixing and transport in the general region of the southern metropolitan waters between Fremantle, Becher Point and the 40 m contour:

- Baroclinic mechanisms are likely to be important to overall mass transport for a significant proportion of the time throughout the year.
- It appears that rare event type storm conditions (winds greater than about 10 m s^{-1}) are required to completely vertically mix the region vertically and hence these events are likely to be critical to seasonal characteristics of nutrient release by turbulent benthic re-suspension of sediments.
- Appropriate numerical models for the prediction of mass transport both vertically and horizontally in the region will probably have to consider baroclinic mechanisms as important agents of overall mass transport.

7.3 Circulation

The general character of regional circulation in the waters well offshore of the nearshore basins has been investigated by Hearn (1991) in his review of the hydrodynamics of the wider region of the Perth metropolitan coastal waters. The reader is referred to that report, which also reviews past numerical modelling efforts. The influence of the Leeuwin Current at this regional scale cannot be discounted as a potentially important hydrodynamic forcing, and regional wind patterns are likely to also be important.

Current meter data from the deep region of the study area (40 m contour) was discussed in Chapter 3 (see also Appendix A2), and as stated the available data lend support to the generally accepted conclusion that regional drift is predominantly southward in winter and northward in summer, with current patterns being more random during the changeover periods in autumn and spring. Typical drift rates from the data set referred to in Chapter 3 were of the order of 5-10 cm s^{-1}, within a range of about 0-25 cm s^{-1}.

The above analysis has also shown that vertical density gradients are likely to be a common feature of the water structure throughout the year. The horizontal stratification that has been identified to occur on a seasonal basis between onshore and offshore waters may well be important in setting up regional scale baroclinic circulation patterns. The potential nature of baroclinic flows that might occur has been discussed in Chapter 3, above, and this matter received detailed attention in Hearn (1991).

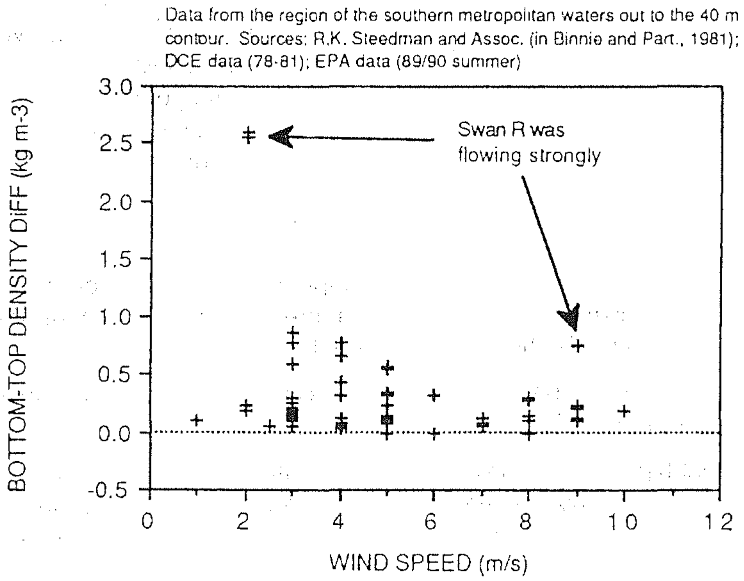


Figure 7.4 Scatter diagram of bottom minus surface density difference versus wind speed from many ST profiles collected by R K Steedman and Associates (in Binnie and partners, Dec, 1981). The sites from which the stratification data were collected are: central Gage Roads, central Owen Anchorage, central Cockburn Sound, central Mangles Bay, central Sepia Depression west of both the causeway and Carnac Island, and at the 40 m contour west of north Garden Island.

In order to better understand the regional circulation and mixing characteristics of Perth's southern metropolitan waters, an appropriate series of measurements of currents, and density structure over relevant temporal and spatial scales will be required. These scales will be governed by the temporal and spatial characteristics of the environmental forcings and also by the regional-scale bathymetric characteristics. In addition, the influence of density stratification in leading to baroclinic flows (either as surface, intermediate or bottom density currents) will also govern the appropriate vertical resolution of required field measurements.

A further analysis of the regional scale hydrodynamics is not within the scope of this report, but would certainly be warranted in any future circulation or mixing studies of this region.

8 Conclusions

The main objective of this report was to synthesize and analyse the large amount of historical data on the hydrodynamics of Cockburn Sound and adjacent waters for the purpose of helping to plan the oceanographic program of the Environmental Protection Authority's southern metropolitan coastal waters study (1991-1994). Data were drawn from reports and archives dating back to 1969.

A specific aim was to quantify the spatial and temporal characteristics of density stratification in the region, and then in turn evaluate the influence of the stratification on vertical mixing and the importance of baroclinic process to the overall hydrodynamics of Cockburn Sound and adjacent waters. This information is necessary so that an understanding of the relative importance of baroclinic and barotropic processes to mixing and transport could be determined, with a view to then assisting in the appropriate choice and development of numerical models required as predictive tools of the hydrodynamics of the system.

The most important conclusion of the study is that in this coastal region both baroclinic and barotropic processes are likely to strongly influence mixing and transport. The relative dominance of either class of processes will depend on the relative contributions of a wide range of individual mechanisms to the hydrodynamics of the region (eg, wind-drift, wind mixing, river discharges, solar heating, evaporation, penetrative convection, coastal boundary currents, tides, Coriolis force, low frequency oscillations, wave pumping, density currents). The more protected regions (eg Cockburn Sound) are subjected to the greatest degree of stratification and baroclinic processes are likely to be at their strongest in these regions.

Barotropic processes are likely to dominate during periods of weak vertical density stratification, which generally accompany prolonged (>5-10 hours) winds of strength greater than about 5-10 m s^{-1}. Whilst vertical stratification was found to be eliminated or significantly weakened as a result of vertical mixing during such wind events, horizontal stratification was found to persist as a common feature of the horizontal structure. On average, winds are greater than 5 m s^{-1} about 50 percent of the time during the year. Whenever winds were less than this intensity vertical stratification was found to be a common characteristic of the water structure, and this suggests that baroclinic processes are likely to be important to the overall hydrodynamics for about 50 percent of the time or more on average throughout the year.

A simple comparison of vertical stratification with wind speeds and other forcings, drawn from the many available data sets, indicates the following more detailed conclusions for the nearshore basins:

- Wind-driven flow appears to be the major mechanism causing horizontal transport of mass .
- Baroclinic density-driven flow due to horizontal density gradients is also an important horizontal transport mechanism, but it remains unclear as to how density currents compare to wind-driven flows from the point of view of basin-scale transport and flushing with adjacent oceanic waters. It appears however, that they have the potential to lead to significant exchange. Further work to clarify their role is needed.
- Vertical density stratification is a common trait of the region , with strongest gradients occurring in the Cockburn Sound and Owen Anchorage regions during winter and early spring, when local freshwater inputs, primarily from the Swan River, cause relatively strong salinity stratification. At other times, temperature appears to be dominant relative to salinity in its effect on the density of the water.
- Solar heating is an important stratifying agent, and this mechanism assumes its greatest importance to the formation of stratification during periods of low Swan River flow, when salinity gradients in the region are weakest.
- The stratification is intermittently broken down by wind mixing. To eliminate typical vertical density differences of the order of 0.1 kg m^{-3} (summer) to 0.5 kg m^{-3} (winter) requires winds of strength 5-10 m s^{-1} or greater, blowing for about 5-10 hours or longer. The most regular occurrence of strong vertical mixing appears to be in summer when the vertical stratification is weakest. In winter the Swan Discharge leads to stronger vertical gradients, and storm winds required for strong vertical mixing occur less frequently than summer sea-breezes. Hence,

sea-breezes and strong northerlies associated with low pressure fronts are particularly important as mixing agents.

- Analysis of data and analytical calculations suggest that the nearshore basins are probably vertically stratified in density for over 50 percent of time, on average, throughout the year.
- Wind-mixing generally leaves the Sound with a horizontally stratified structure.
- The Swan River discharge of freshwater in winter introduces a buoyancy flux that leads to the strongest vertical gradients in Cockburn Sound and Owen Anchorage. Southward wind is the primary forcing agent that drives the freshwater into the Sound. The earth's rotation probably facilitates a nearshore bias to such southward flows by inducing counterclockwise rotation, but its role is not yet quantified.
- Horizontal density stratification is a common characteristic of the nearshore basins throughout the year. For example, in Cockburn Sound and Owen Anchorage it is strongest during winter due to horizontal salinity gradients set up by coastal discharges of Swan River water. Typically these basins display a horizontally patchy density structure, with individual patches generally having scales of 1-5 km.
- Typical density differences across Cockburn Sound and Owen Anchorage range from 0.1-0.3 ppt in summer and up to 2-3 ppt in winter. Such density differences have the potential to drive baroclinic currents with densimetric velocities of the order of 5 to 20 cm s^{-1}, respectively. The effect of rotation on these flows is expected to be important but is yet to be sufficiently quantified in the field.
- The available data did not allow a detailed analysis of the potential mixing due to penetrative convection. It was calculated analytically that penetrative convection is unlikely to be strong enough to erode typical strength pycnoclines in Cockburn Sound. Hence, the effect of penetrative convection could be confined to levels above main pycnoclines, and in summer when salinity gradients are at their weakest penetrative convection might be important in preventing the persistence of daytime thermal stratification in the upper levels of the water column through the night. Diurnal measurements of vertical structure are required to investigate this further.
- Swan River discharge pulses have been tracked to propagate as far south as Warnbro Sound. Hence, the longshore spatial extent of these and other coastal discharges (eg the Peel-Harvey outflow), and by inference contained pollutants, could be of order 30 km or more.
- Salinity undergoes a seasonal cycle, with maxima of up to 37 ppt in summer due to evaporation of nearshore waters. The stratifying potential of evaporation is likely to be important in summer, but little quantitative information exists on this mechanism.
- Throughout the year nearshore-offshore salinity, temperature and consequently density differences are common between the semi-enclosed nearshore regions and the adjacent oceanic waters over the shelf. Coastal discharges of freshwater from rivers, differential heating, evaporation, and differential cooling appear to be the primary agents leading to this trait. In winter nearshore waters are generally cooler and fresher than offshore. By contrast, in summer nearshore waters are generally warmer and saltier than offshore. Reversals in these trends occur in spring and autumn. The role of these gradients in influencing baroclinic exchange between the nearshore basins and adjacent waters could be important and requires field investigation.Typical cross-shelf density differences appear to range between 0.1-0.5 kg m^{-3} throughout the year. It is therefore probable that cross-shelf baroclinic flows, influenced by the earth's rotation (typical Rossby radii of order 1-5 km), could result from such gradients but this mechanism still requires field, theoretical or model verification. Resulting flows for such density differences could have speeds of up to about 10 cm s^{-1}.
- Tides are likely to be relatively unimportant to mixing and flushing, except perhaps in bathymetric constrictions such as channels and openings.
- The role of other forcings in mixing and transport is unclear. Additional mechanisms to be investigated are: the earth's rotation (Coriolis force), the Leeuwin Current, low frequency oscillations, penetrative convection, evaporation, internal waves and wave pumping. These

mechanisms have the potential to significantly influence the hydrodynamics of the nearshore basins, but further field work to investigate their spatial and temporal characteristics is required.

- Exchange estimates from past studies for Cockburn Sound (with the causeway in place) have been based on the assumption that the system is continuously well mixed throughout thereby having its hydrodynamics controlled by barotropic processes. On that basis estimates of replacement times of the order of 30 days or less were calculated (and this compares with estimates of the order of 10 days or less for the pre-causeway case). But the review of past data in this report indicates that the system is stratified both vertically and horizontally for a significant percentage of the time throughout the year. Hence, this invalidates the assumption that the basin is typically well mixed. Throughflows through the openings are therefore likely to be strongly influenced in their vertical position, horizontal pathways, and mixing with resident Cockburn Sound water by the density gradients. In other words, baroclinic processes are likely to be of greater relative importance to the overall hydrodynamics of Cockburn Sound than originally assumed in earlier studies. Hence, the replacement times of individual regions within Cockburn Sound or of the whole of Cockburn Sound's volume becomes more difficult to predict. It is unclear at this stage however, as to the quantitative changes that need to be made to exchange estimates of Cockburn Sound. This requires further field and modelling work, which takes into account the influence of vertical and horizontal density stratification, and forms a major recommendation of this report.
- Numerical modelling of mixing and transport in Cockburn Sound and adjacent waters should incorporate the influence of stratification to correctly simulate the hydrodynamics for periods when the stratification is present, and this appears to be over 50 percent of the time on average throughout the year.

A review of shelf-scale mechanisms was also performed and a summary of their potential relative influence to mixing and transport is given in the following listing. In addition, a similar listing is giving to summarise the potential influence of basin-scale mechanisms to the mixing and transport of the nearshore basins.

PROCESSES INFLUENCING THE HYDRODYNAMICS OF THE SHELF-REGION

Process	Potential influence on transport and mixing	Temporal characteristics	Spatial characteristics	Comments
Coriolis force	Important	Frequent (inertial period of order 1 day).	Entire region	Will influence all flows with time scales > approx. 1 day. Field work needed.
Wind-driven flow	Strong: (horiz. transport up to 20 km d^{-1})	Frequent. Periodic, 1-10 day periods. All year.	Entire region	Important mechanism. Occurs in events of order 5-10 hours duration, within longer term variations with periods of order 1-10 days. Field work needed (esp. to characterise vertical shear in presence of stratification).
Vertical density stratification	Strong	Frequent. All year.	Entire region	Most important in basins. Also important elsewhere. Field work needed to assess influence on vertical mixing, benthic re-suspension, and horizontal transport.

Wind-mixing	Strong	Intermittent. All year.	Entire region	Speeds > approx 5-10 ms^{-1} (occur 50 % of time, on average) needed to break down typical vertical density stratification. Appears to be most effective in summer, when vertical density stratification seems to be at its weakest.
Horizontal stratification and density-driven flow	Medium: (up to 10 km d^{-1})	Unknown (probably frequent, all year).	Unknown (probably extensive)	Important. Field work needed to quantify and detail interaction with rotation.
Low frequency oscillations	Strong: (5-40 km d^{-1})	Unknown (probably intermittent, cyclic with 10 day periods).	Unknown (probably entire region)	Could be important. Theoretical and field investigation needed. Net transport could be small due to cyclic nature in direction of flow.
Leeuwin Current	Strong: (up to 30 km d^{-1})	Probably autumn to spring.	Probably shelf-scale	Likely to be important. Influence on nearshore basins unknown. Field work needed.
Wave pumping	Weak: (up to 5 km d^{-1})	Probably all year.	Unknown (probably primarily basin-scale)	Could be important, particularly in constricted regions (eg lagoons). Field work needed.
Tidal flows	Weak: (up to 2 km d^{-1})	All year.	Entire region	Probably most important through gaps and openings. Field work needed.

PROCESSES INFLUENCING THE HYDRODYNAMICS OF THE NEARSHORE BASINS

Process	Influence on transport and mixing	Temporal characteristics	Spatial characteristics	Comments
Coriolis force	Likely to be important	Frequent (Inertial period of order 1 day).	Basin-scale	Will influence all flows with time scales > approx. 1 day. Field work needed.
Wind-driven flow	Strong: (up to 20 km d^{-1})	Frequent. Periodic, 1-10 day periods. All year.	Basin-scale, depends on fetch, and bathymetry influences the nature of topographic gyres.	Important mechanism. Occurs in events of order 5-10 hours duration, within longer term variations with periods of order 1-10 days. Field work needed (esp. to characterise vertical shear in presence of stratification.

Vertical density stratification	Strong	Frequent. All year.	Basin-scale	Present throughout the year but strongest in winter. Both salinity and temperature. Field work needed to assess influence on vertical mixing, benthic re-suspension, and horizontal transport by other mechanisms.
Wind-mixing	Strong	Intermittent. All year.	Entire region	Speeds > approx 7 ms^{-1} (occur 30 % of time, on average) needed to break down typical vertical density stratification in winter when vertical salinity differences are up to 2-3 ppt. It appears that in summer weaker winds (> approx 5 ms^{-1}) can mix to the bottom because typical vertical density stratification is weaker.
Horizontal stratification and density-driven flow	Strong: (up to 10 km d^{-1})	Important (probably frequent, all year).	Basin-scale	Important. Field work needed to: -quantify importance and interaction with rotation, -detail vertical structure of density current flows, -quantify relaxation of density structure after wind-mixing, -quantify flushing potential of baroclinic exchange
Low frequency oscillations	Unknown	Unknown (probably intermittent, cyclic with 10 day periods).	Unknown (probably basin-scale)	Could be important. Theoretical and field investigation needed. Net transport could be small due to cyclic nature in direction of flow.
Internal waves	Unknown	Unknown (probably intermittent, and all year).	Unknown (probably basin-scale)	Probably important. Theoretical and field investigation needed.
Leeuwin Current	Unknown	Unknown (probably intermittent autumn to spring).	Unknown	Could be important. Influence on nearshore basins unknown. Field work needed to establish effect.
Wave pumping	Weak: (up to 5 km d^{-1})	Probably all year.	Basin-scale	Could be important, particularly in constricted regions (eg lagoons) and gaps. Field work needed.

Tidal flows	Weak: (up to 2 km d^{-1})	All year.	Basin-scale	Probably most important through gaps and openings. Field work needed.

9 Recommendations

This report has concluded that both barotropic and baroclinic processes are likely to strongly influence mixing and transport in the southern metropolitan coastal waters. An associated conclusion is that numerical models of these waters should incorporate baroclinic processes in order appropriately simulate the hydrodynamics. The choice and development of such models will require field data for calibration and verification. Therefore, a major recommendation from this review and analysis of data collected up to 1990 is that further field studies are required to quantify more accurately the spatial and temporal characteristics of the major hydrodynamic mechanisms. Past field studies were limited by the accuracy of instrumentation available at the time. More modern instruments make it possible to detail mixing and transport at more resolute spatial and temporal scales.

Locally available conductivity-temperature-depth (CTD) meters can measure at vertical spatial scales ranging from 1-10 mm in free fall mode, resolving salinity and temperature to 10^{-3} ppt and degrees Celsius, respectively. They can be used to detail the characteristics of vertical and horizontal stratification and interfacial mixing. Manually operated salinity-temperature meters with lower accuracy can collect vertical ST data at a vertical resolution of 0.1-0.5 m and they can be used to complement more accurate instruments to obtain wider spatial coverage in relatively short time periods during measurement campaigns. Drogues, fixed-point current meters and tow-mode acoustic doppler current meters can be used to measure flows. Satellite imagery is available for two-dimensional monitoring of sea-surface temperature and colour. Other parameters such as water level, wave, meteorological, and river flow data can be acquired with standard instruments.

In the following assessment of future field work, regard has been given to the cost and local availability of field instruments.

It is recommended that field measurements be conducted to detail the three-dimensional ST structure and circulation patterns of the region, with the greatest effort in terms of spatial and temporal resolution directed at the nearshore basins (Cockburn Sound, Owen Anchorage, Sepia Depression and Warnbro Sound). The identification of the importance of baroclinic processes means that vertical structure will need to be measured at cm and preferable mm scale in order to detail the formation and erosion of density gradients.

Temporally, measurements will have to capture the time scales of the relevant forcings as follows.

- diurnal heating and cooling, wind mixing, wind-driven flow, wave pumping and tides at hourly to diurnal scales,
- density currents at hourly, diurnal and weekly scales,
- river discharge events at 1-10 day scales,
- rotational influences at time scales greater than about 1 day,
- regional current influences, such as the Leeuwin Current and low frequency oscillations, at 1-100 day scales,
- current metering, meteorology, seasonal salinity, temperature and density variation at monthly to yearly scales.

Spatially, the following scales would suffice for the resolution of measurements:

- Vertical structure and turbulence in the basins at 0.001 - 0.01 m resolution
- Vertical structure in the surrounding shelf regions at 0.1 m vertical resolution
- Currents at least near surface, middle and bottom, with vertical shear detailed at 0.1 m vertical resolution if possible, and horizontally at 5-10 sites per basin. Cost and availability of meters will constrain this requirement.
- Satellite imagery (NOAA and Landsat) at shelf scales.
- Horizontal density structure and ST tracking at 1-2 km resolution in basins and of the order of 5-10 km resolution in surrounding shelf waters. The spatial resolution of field station grids

should be chosen to capture flow patterns governed by the Coriolis force, with the Rossby radius of deformation ranging from order 1-5 km around the study region.

In addition, it is recommended that spectral analyses of available current meter time series data from the Cape Peron Outfall studies, in conjunction with associated meteorological, oceanographic and hydrological data, be conducted.

Since the initial drafts of this report in Dec 1988 and June 1991 a series of intensive field campaigns of the hydrodynamics of Cockburn Sound and surrounding waters have been conducted, with some measurements still in progress. The above recommendations (and those of Hearn (1991)) provided input in the setting of spatial and temporal scales for the field work. Recommendations regarding modelling strategies for the southern metropolitan coastal waters are found in Hearn (1991) and Mills (in prep.).

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Figures

Appendices

Appendix A1

Winds over Perth's coastal waters.

The wind patterns for Cockburn Sound were studied by Steedman and Craig (1979). They performed comprehensive statistical and spectral analyses on 7 years of continuous chart recordings for winds from the Fremantle Port Authority anemometer (at an elevation of 60 m) and assigned the results of that analysis to the wind patterns for Cockburn Sound. They defined 7 major wind patterns, as reproduced in Table A1.1.

Table A1.1: Summary of Cockburn Sound wind patterns (from Steedman and Craig, 1979)

Wind pattern	Wind speeds ($m\ s^{-1}$)	Month	Estimated annual occurrence (%)
Sea breeze	up to 15	October-May	35
Winter high pressure system	~ 5	April-October	18
Low pressure system (storms)	5 - 20	All	28
Summer high-low pressure system	~ 5	October-May	5
Dissipating tropical cyclone]	10 - 30	December-April	<<1
Calms	0-1.5	All	4
Other (unidentified)	2 - 15	All	10

Steedman and Associates (in Binnie and Partners, Dec 1981) described the prevailing wind regime of the southern metropolitan coastal waters, using Cape Peron data as a guide. The wind patterns over the southern metropolitan coastal waters are dominated by the seasonal migration between latitudes of the subtropical high pressure belt. This meteorological structure contains discrete anticyclonic pressure systems (with scales of the order of 1000 km) which encircle the hemisphere in the subtropical latitudes. These anticyclones propagate from west to east.

In summer their centres lie below the Perth metropolitan latitude, and as such a predominantly easterly air flow is directed over the region. This brings the typical hot, dry summer conditions that are well-known for Perth. Prevailing summer winds during the day are often from the south-southwest typically ranging from 2 - 10 $m\ s^{-1}$. Day-time sea breezes can reach 15 $m\ s^{-1}$, and during the evening winds often swing to being easterly and calms can occur.

In winter the centres of the anticyclones lie to the north of the Perth metropolitan region and as such a predominantly westerly air flow is directed over the region. Cold fronts from the west-northwest often pass the coast and bring strong wind conditions. Prevailing winter winds occur from the north-northeasterly directions typically having speeds up to 14 $m\ s^{-1}$. High pressure systems can pass over the southwest coast in winter and bring weak offshore breezes, of the order of 5 $m\ s^{-1}$.

During spring and autumn the pressure systems migrate between their summer and winter latitudes and consequently the climate is in a transition phase. The particular latitude of the anticyclones will determine whether the air stream is predominantly easterly or westerly. Winds are slightly calmer during these transitional phases compared to summer and winter.

Throughout the year, and in particular during summer, sea-breezes can form over the southwest coast. In summer these breezes are at their strongest, often reaching speeds of the order of 10 $m\ s^{-1}$.

In summer and autumn tropical cyclones can form to the north of the State, and sometimes these dissipate into rain-bearing low pressure depressions which propagate southwards over the south-west of the State, bringing with them intense winds with speeds up to 30 m s^{-1}.

Figures A1.1 and A1.2 present the wind data diagrammatically and show the percentage occurrence of winds of particular speeds from particular directions. In summary, the results show that on a seasonal basis, winds were less than 2.5 m s^{-1} about 25 percent of the time, less than 5 m s^{-1} about 50 percent of the time, less than 7.5 m s^{-1} about 75 percent of the time, and less than 10 m s^{-1} about 90 percent of the time. These results agree with Hearn's (1991) recent review of wind patterns over the Perth metropolitan coastal waters.

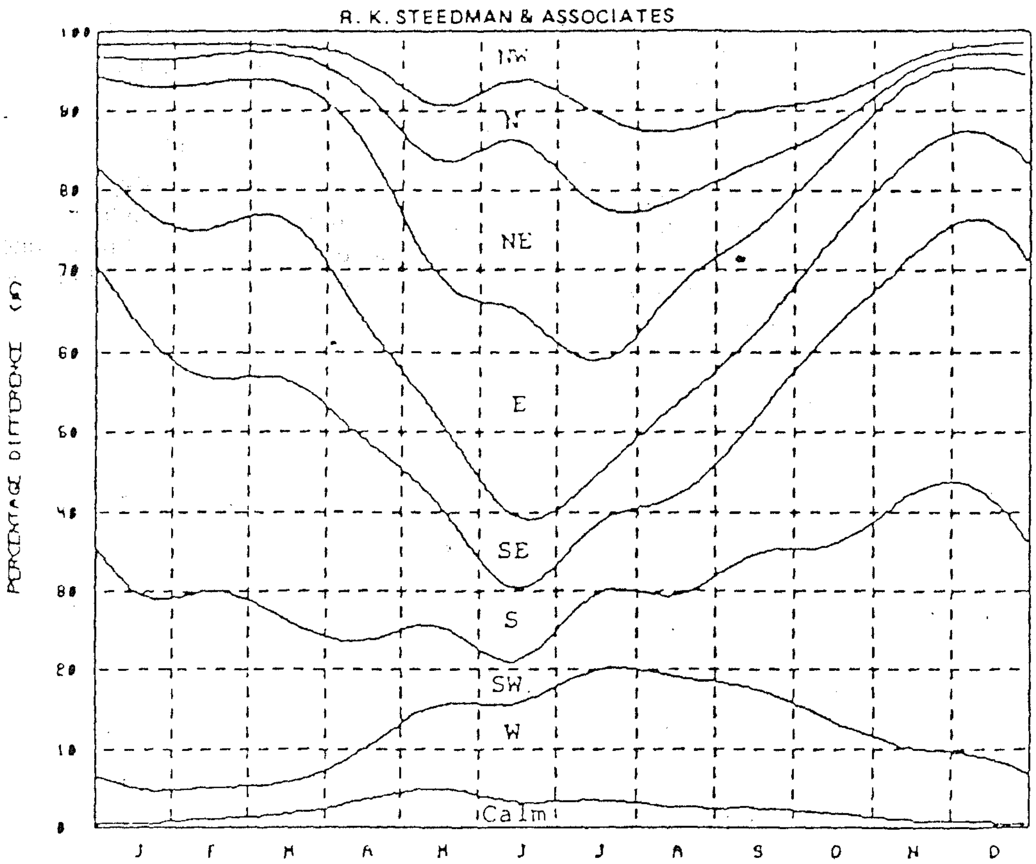


Figure A1.1 Combined monthly one hourly averaged wind direction percentage occurrence diagram - January 1971 to December 1977, Fremantle (32° 03' S, 115° 44' E). Reproduced from Steedman and Associates (1979).

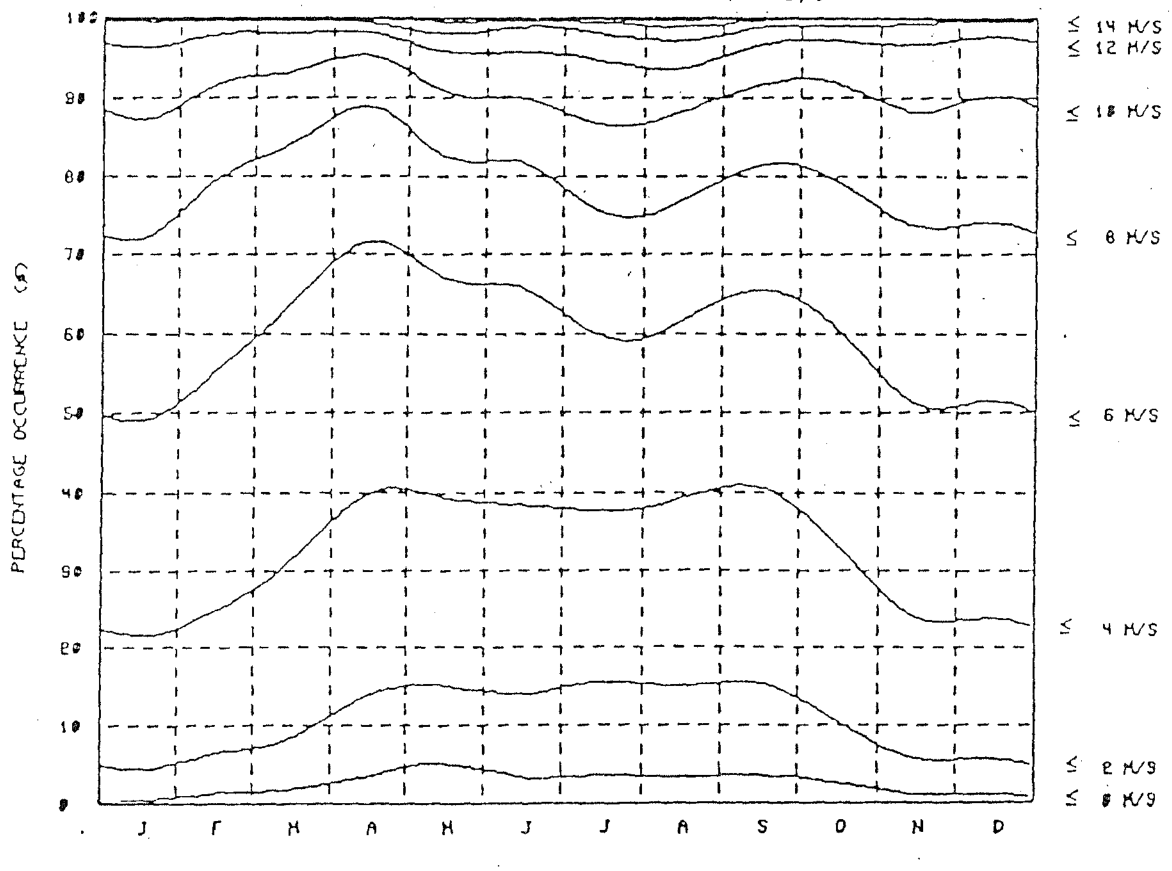


Figure A1.2 Combined monthly one hourly averaged wind speed percentage occurrence diagram - January 1971 to December 1977, Fremantle (32° 03' S, 115° 44' E). Reproduced from Steedman and Associates (1979).

Appendix A2

1981 Cape Peron Ocean Outlet current metering in Sepia Depression and offshore (40 m contour)

As part of the Cape Peron Ocean Outlet environmental studies R.K. Steedman and Associates conducted comprehensive investigations of current regimes and corresponding environmental forcings in the Sepia Depression west of Garden Island and directly offshore in the deeper waters of the 40 m contour (about 25 km west of Garden Island). Meteorological data were recorded throughout 1981. Current metering was conducted almost continuously in Sepia Depression throughout 1981 and from May to December 1981 at the 40 m site. The data and corresponding oceanographic analyses conducted by R.K. Steedman and Associates were presented in Binnie and Partners (Dec, 1981). A summary of R.K. Steedman and Associates' (in Binnie and Partners, Dec 1981) results is as follows:

The seasonal distribution of mid-depth current direction in Sepia Depression was bi-modal, being predominantly northwards in summer and southwards in winter.

Mean speeds in Sepia Depression during summer were of the order of 10 cm s^{-1}. Wind was established to be the dominant driving force for the summer currents. Figure A2.1, taken from Binnie and Partners (Dec, 1981) is a time series plot of wind and currents in Sepia Depression for a typical summer wind pattern, and shows their relatedness. Currents up to about 20 cm s^{-1} are forced by typical sea breezes but strongest events can lead to currents up to 35 cm s^{-1} The data also revealed that the mean northward flow could be reversed to southward for brief periods of one to two days by strong northerly or northeasterly winds.

Mean speeds in Sepia Depression during winter were similarly of the order of 10 cm s^{-1}. Again, wind was found to be the dominant driving force for the winter currents. Figure A2.2, from Binnie and Partners (Dec, 1981) is a time series plot of wind and currents in Sepia Depression for typical winter winds and shows the relatedness of currents to typical wind events. Currents of up to 40 cm s^{-1} can be forced by strong winter storms associated with cold fronts (having a predominant southward wind vector). Occasional temporary current reversals were found to occur due to strong southerly or southwesterly winds.

Mean currents were weakest during autumn and spring, with seasonal reversals of the mean current direction occurring during these periods.

R.K. Steedman and Associates also investigated vertical variation of current velocity. It was found that in summer mid-depth currents were almost twice as strong as currents 3 m above the bottom. The same was true for winter, except that the incidence of oppositely directed current shear was increased, and this was reasoned to be due to an interplay between the forcings of mean seasonal southward drifts (speculated to be due to the Leeuwin Current) and temporary south-southwesterly wind events. Determination of the cause of oppositely directed shear remains as a task for field and numerical model investigations.

The same study also analysed data which strongly indicated that even under calm conditions a residual seasonal circulation pattern exists, with speeds of the order of 5 cm s^{-1} occurring and directed northward in summer and southward in winter. Figures A2.3 and A2.4 (taken from Binnie and Partners, Dec 1981) are scatter diagrams of cross-plots of wind stress and currents in Sepia Depression for January (summer) and July (winter), respectively, and the data generally support the above result. Statistical analysis of long time series of wind records established that calms occur most often in spring and autumn.

Currents in Sepia Depression are obviously strongly influenced by the channeling effect of this bathymetric feature. In order to gain an understanding of mean regional flow patterns away from local features such as this a current meter was placed approximately 25 km offshore of Garden Island at the 40 m contour at a height of 18 m above the sea bed between May and December 1981. The seasonal bi-modal characteristic of currents in Sepia Depression was not as obvious in the current records from the 40 m station (presented in Binnie and Partners (Dec, 1981) as continuous vector plots). The currents at the 40 m station were generally alongshore but occasional periods of westward or eastward

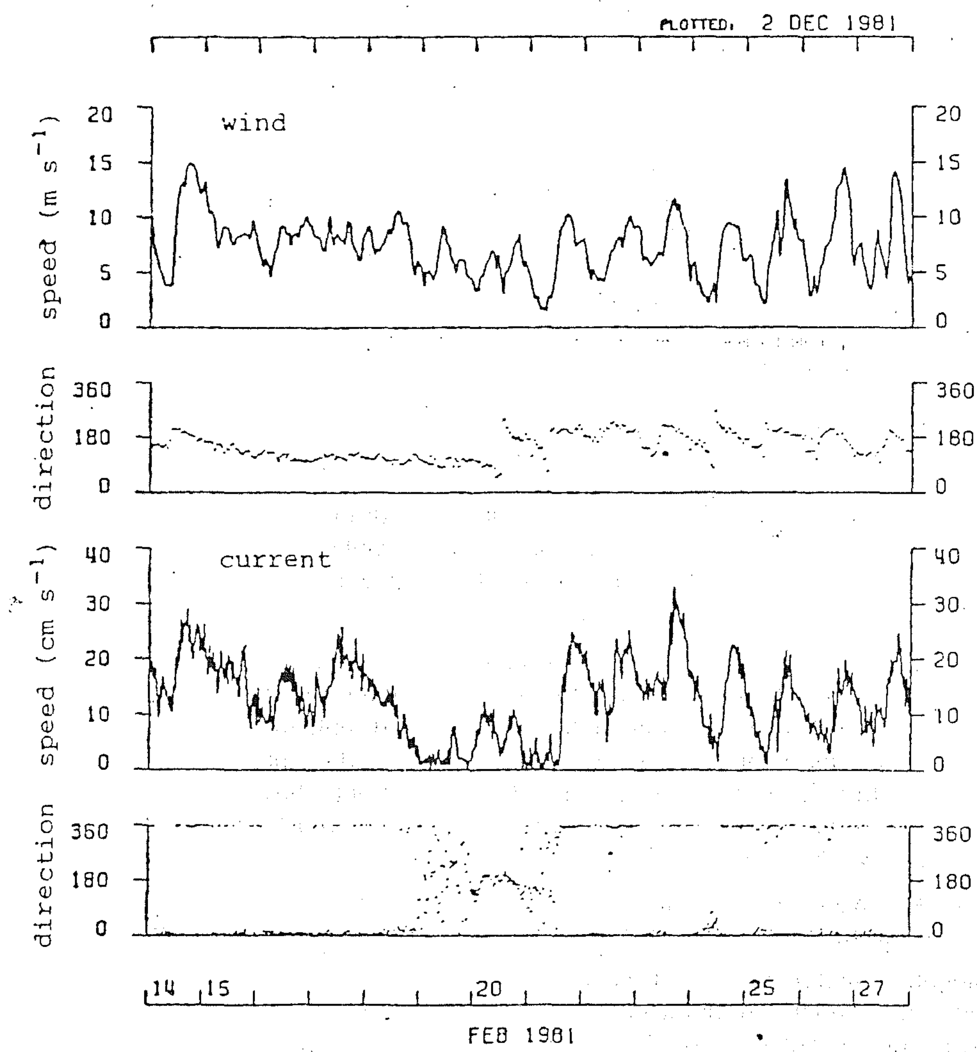


Figure A2.1 Time series plot of wind speed and direction, and current speed and direction from mid-depth central Sepia Depression, showing the response of the waters to typical summer winds (reproduced from R K Steedman and Associates (in Binnie and Partners, Dec 1981).

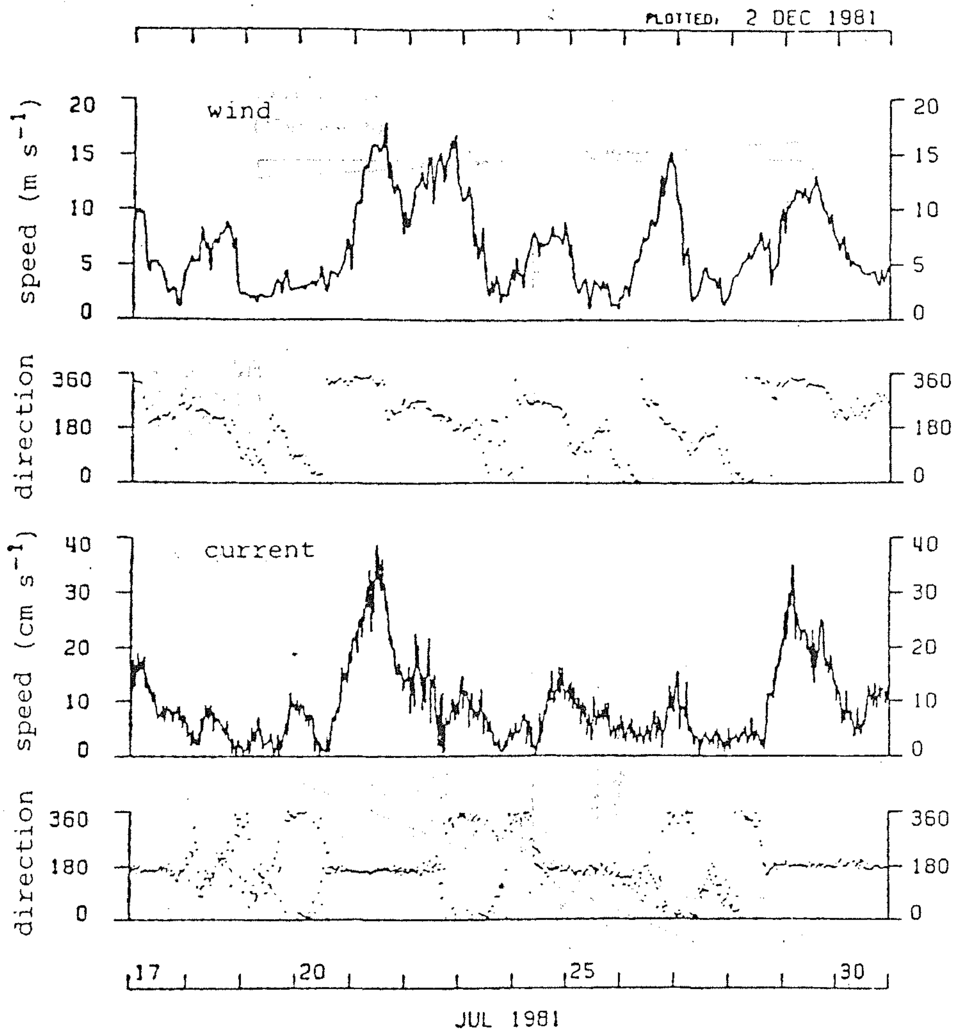
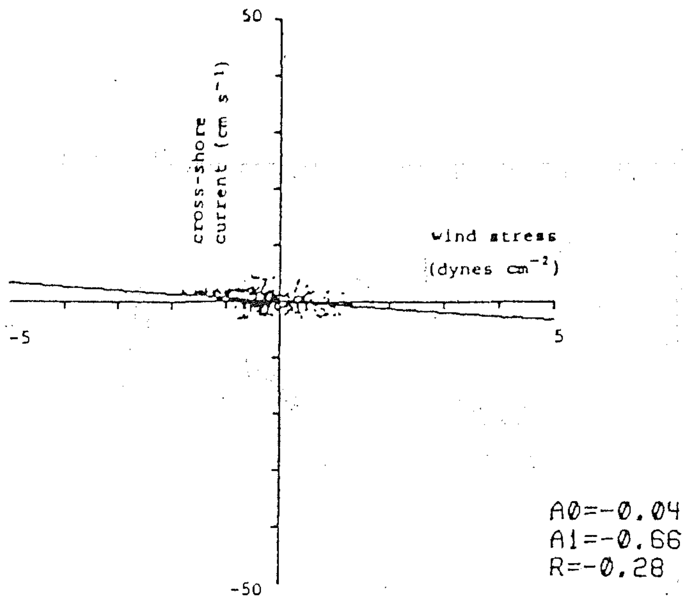


Figure A2.2 Time series plot of wind speed and direction, and current speed and direction from mid-depth central Sepia Depression, showing the response of the waters to typical winter winds (reproduced from R K Steedman and Associates (in Binnie and Partners, Dec 1981).

E-W WIND STRESS VS CURRENT JANUARY 81



N-S WIND STRESS VS CURRENT JANUARY 81

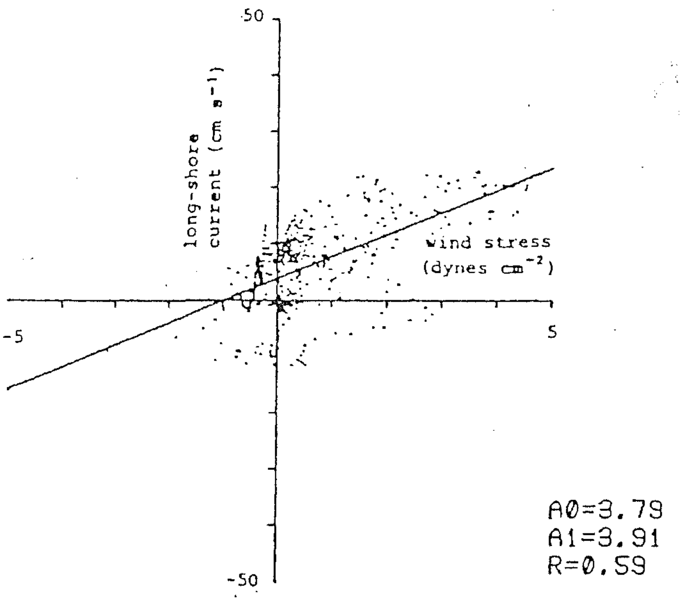
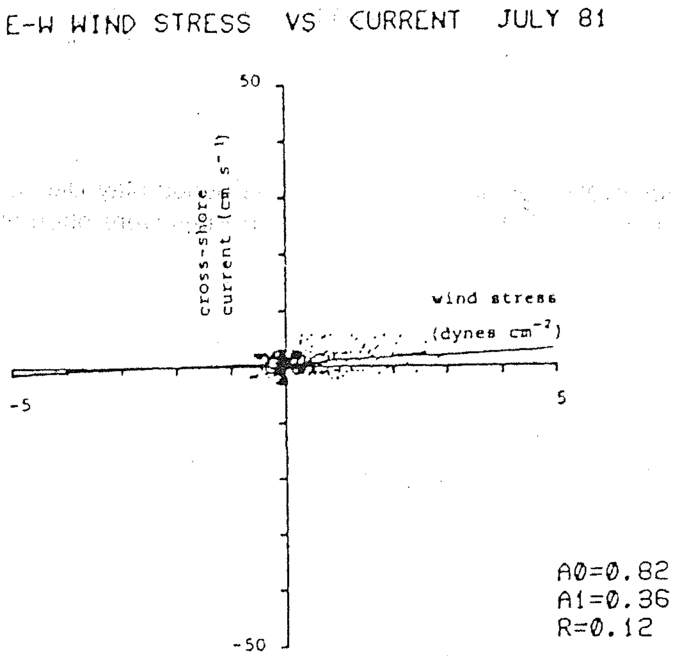


Figure A2.3 Cross plots of wind stress and currents in the Sepia Depression, in the cross-shore (E-W) and longshore (N-S) directions for the month of January 1981 (reproduced from R K Steedman and Associates, in Binnie and Partners, Dec 1981). The currents have been filtered to remove short period fluctuations (amplitude reduction of 50% at 24 hours and 10% at 48 hours).



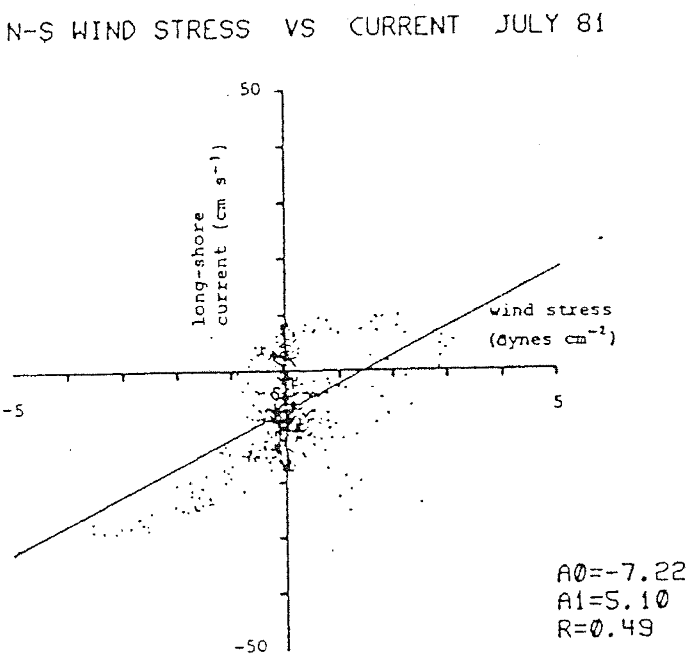


Figure A2.4 Cross plots of wind stress and currents in the Sepia Depression, in the cross-shore (E-W) and longshore (N-S) directions for the month of July 1981 (reproduced from R K Steedman and Associates, in Binnie and Partners, Dec 1981). The currents have been filtered to remove short period fluctuations (amplitude reduction of 50% at 24 hours and 10% at 48 hours).

directed flows were evident, and this is typified by the continuous current vector plot for July 1981, presented in Figure A2.5. In a general sense, the current patterns were more random in direction at the 40 m site than in Sepia Depression. The December record (see Figure A2.6) displayed a definite northward net mean flow direction, but in view of the randomness of the records for other months no definite conclusions regarding seasonal behaviour could be drawn.

Current speeds at the 40 m site, as inferred from the continuous vector plots, lie within a range of the order of 0-25 cm s^{-1}. A visual observation of all vector plots for the period May-December 1981 (in Binnie and Partners, Dec 1981) indicates that mean daily transport rates were often alongshore at speeds of the order of 5-10 cm s^{-1}.

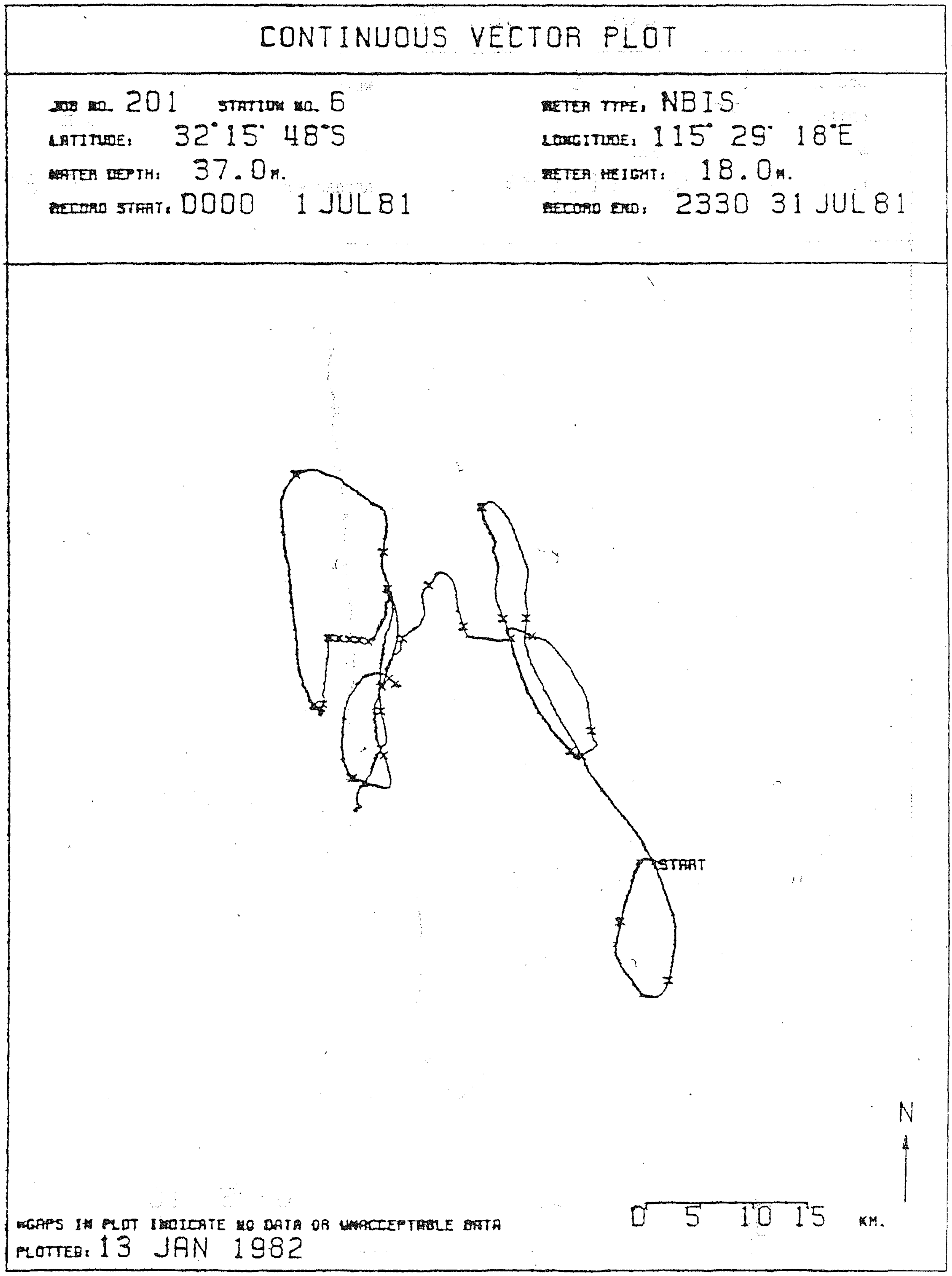


Figure A2.5 Continuous vector plot of a current meter record for the month of July 1981 from a meter at mid-depth at the 40 m contour site (west of northern Garden Island) from the Cape Peron Outfall Study data set (data from R K Steedman and Associates, in Binnie and Partners, Dec 1981).

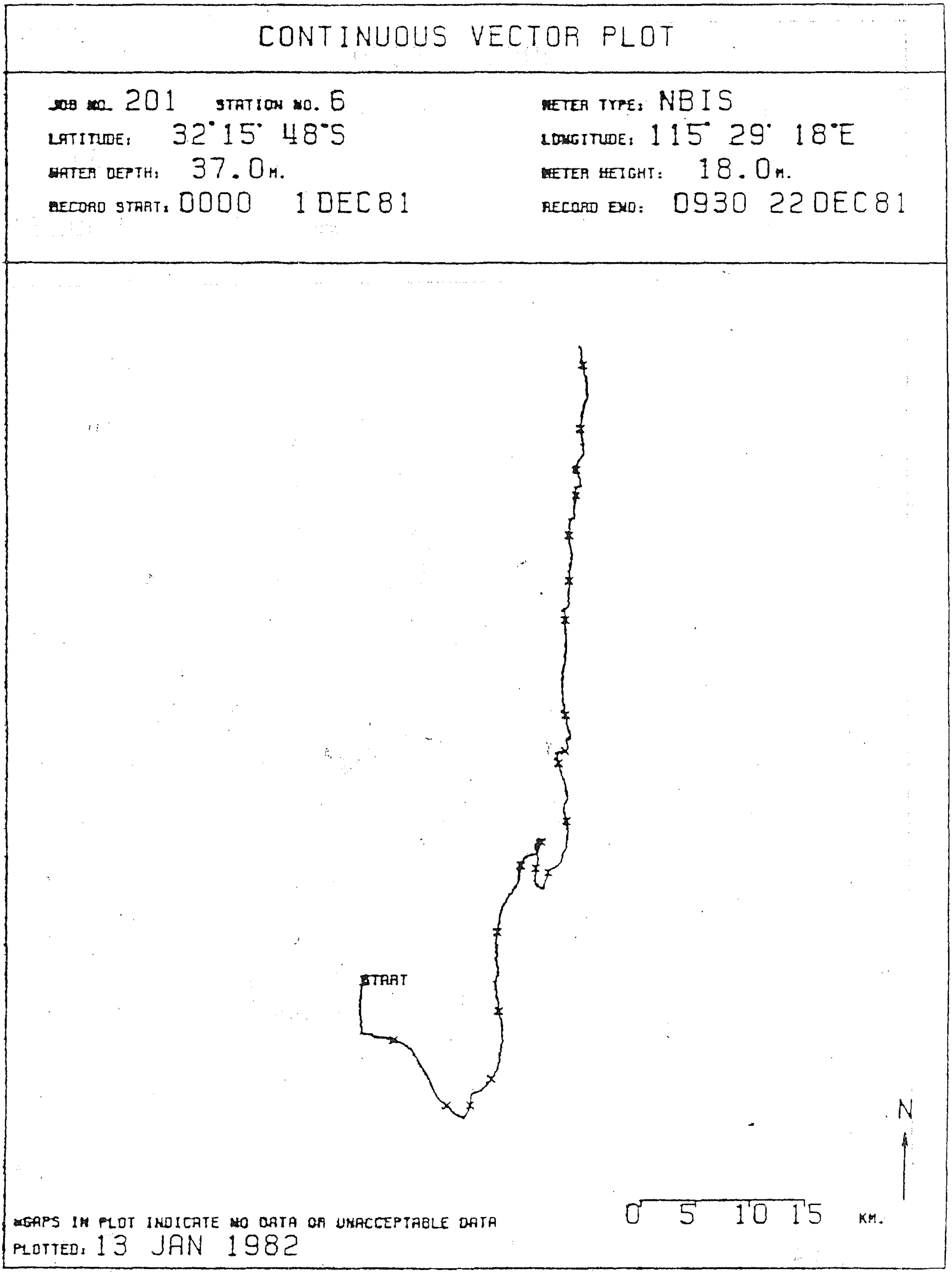


Figure A2.6 Continuous vector plot of a current meter record for the period 1-22 Dec 1981 from a meter at mid-depth at the 40 m contour site (west of northern Garden Island) from the Cape Peron Outfall Study data set (data from R K Steedman and Associates, in Binnie and Partners, Dec 1981).

Appendix A3

Review of processes leading to the formation and erosion of stratification in basins

A3.1 Stratifying agents

The physical horizontal and vertical density structure of a coastal basin will be a consequence of the the competing influences of stratifying agents, such as atmospheric heating and cooling and freshwater inputs and destratifying agents such as wind mixing and penetrative convection.

If we consider an initially well-mixed basin then the following processes could lead to vertical stratification of density (see Imberger and Patterson, 1990).

- Short wave solar radiation, long wave radiation emitted by clouds and atmospheric water vapour heat the water. The heating is strongest near the surface because the intensity of short wave radiation decays exponentially with depth. Hence, the water will take on a vertically stratified temperature structure. Given, that the temperature gradients contribute more to the calculation of density than any vertical salinity gradients that may be present, then buoyancy stabilisation of the water column will result.

- Fresh, or brackish, water inputs that are less dense than the receiving water will enter a basin and reside at the surface. This sets up a vertical salinity, and therefore density, stratification. Buoyancy fluxes due to this mechanism can be introduced via submarine groundwater discharge at the coast, river plumes, industrial freshwater outfalls, municipal stormwater drains, or regional currents of lower salinity waters originating from outside of the basin of interest.

- Relatively saline inputs that are denser than the receiving waters will enter as bottom flows, with their rate of entry governed by the density difference with respect to the receiving water. Such flows could originate from shallow regions where strong day-time evaporation leads to the formation of hypersaline water, which then gravitates into regions of less dense water as baroclinic currents.

- When the receiving waters are already stratified, fluxes of differing salinity or temperature, and therefore differing density, waters could enter a basin at an intermediate depth, with this depth dependent upon the incoming waters' level of neutral buoyancy with respect to the density stratification of the receiving water column.

- In a basin of variable depth cooling may occur more rapidly in shallower areas. The formation of differentially cooled waters may lead to the gravitational slumping of colder, and therefore denser, waters in towards deeper regions that are warmer and possibly less dense (depending on salinity gradients). This mechanism will influence the resultant vertical stratification of a water body.

- In a similar fashion differential heating, for example where shallower waters are heated more than adjacent deeper waters by solar radiation, will lead to baroclinic flows of relatively warm (and therefore less dense) waters from the shallows to the deeper areas as surface convective currents. Other factors may also cause differential heating and these are discussed further in this chapter.

- Differential heating and cooling could just as easily lead to the formation of waters of intermediate density adjacent to a vertically stratified water column, in which case intermediate intrusive density currents would redistribute mass horizontally.

Past studies have suggested that Cockburn Sound changes its dynamical response to environmental forcings from being mainly baroclinic to mainly barotropic when winds exceed about 5 m s^{-1} (Steedman and Craig, 1979). It is shown in this report however that the actual critical wind speed for this transition is more likely to be greater than this.

A3.2 Differential heating and cooling

During the day solar radiation can heat surface waters and set up a vertical temperature stratification. During the night surface waters can lose heat and the day-time stratification can be eroded by the penetrative convection of cooling surface waters.

The heat budget at the surface is comprised of:

Conduction - This is sensible heat transfer and is a forced convection due to the difference in temperature between the air and water and its magnitude is also proportional to wind speed.

Latent Heat - This is evaporative heat transfer and is governed by the surface to air humidity difference and its magnitude is also proportional to wind speed.

Long-wave Radiation - This is an emitted loss from the water surface. The net long-wave radiation loss via the surface must also include incoming long-wave radiation which arrives from clouds.

Short-wave Radiation - This is an input of energy from the sun and is exponentially attenuated with increasing depth in the water column, according to some bulk extinction coefficient, which is in itself governed by water clarity and turbidity.

Indicatively, for the south-west of Western Australia, the net input of thermal energy via these mechanisms has been measured to be up to approximately 900 W m^{-2} for a clear mid-summers day (Fischer et al, 1979).

Short-wave radiation passes through the water column and heats it according to an exponential decay law, known as Beer's law. The characteristic of the exponential law is governed by an extinction coefficient, η, which takes account of varying absorbence of heat in the water column as a function of turbidity and water clarity. Beer's exponential decay law is found to generally fit measured data on the variation of short-wave radiation in water columns as a function of depth, and is given as follows:

$$H_Z = H_{SW} e^{-\eta z} \qquad \text{A3.1}$$

where,

H_{SW} = the incoming short-wave radiation, incident at the water surface, in W m^{-2},

H_Z = the short-wave radiation remaining at depth z,

η = the extinction coefficient which ranges from a value of about 0.2 m^{-1} for clear water to about 4 m^{-1} for very turbid or eutrophic water (Fischer et al, 1979).

If a water body is sufficiently shallow some of the incident short-wave radiation may reflect back upwards towards the surface, with the amount that is reflected of course depending on the reflectance of the bottom. En-route to the surface the reflected radiation will further heat the water column, again being decayed exponentially as thermal energy is transferred to the water. So it can be seen that the shallower the water column the greater the total amount of heating. Hence, for the same incident short-wave radiation and physical conditions of the water (clarity, turbidity and bottom reflectance) a shallow water column will become warmer than an adjacent deeper water column. This is one process that could produce a differentially heated water body in a basin of variable bathymetry. At night this mechanism could be reversed as conductive, evaporative, and long-wave radiation losses cool the water, in reverse manner to differential heating, with the shallower water experiencing a greater cooling effect (Imberger and Patterson, 1990).

Differential heating and cooling are mechanisms that can often be of importance to overall mass transport in water bodies that have a bathymetry characterised by spatially variable depth (Imberger and Patterson, 1990). The shallower regions in a water body will exhibit much greater diurnal fluctuations in temperature due to the heating and cooling influences of the above four mechanisms (conduction, latent heat, long-wave and short-wave radiation) than deeper regions. Under such conditions the role of differential heating and cooling in setting up horizontal temperature, and hence density, gradients may assume importance to overall mass transport in embayments with variable bathymetry by driving convective transports (Imberger and Patterson, 1990). Differential heating can result when the following conditions are present; when there is a significant difference in bottom depth (the shallows heating during the day and cooling during the night at a greater rate than deeper waters); when there is a significant difference in turbidity between adjacent regions of water (the more turbid water absorbing the greatest amount of heat); when there is variable shading (the shaded regions remaining cooler); when there is a variable wind stress (evaporative and conductive cooling of the water surface increases with increasing wind stress); and, when there is spatially variable flux of either warmer or colder water from direct inputs such as tidal fronts, regional currents or streamflows.

Horizontal differences in temperature produced by differential heating in south-west Australian lakes can be typically of the order 1 to 5 ^oC (Imberger and Patterson, 1990). The velocity scale of currents driven by the density differences set up by such temperature gradients can be estimated by the following relation (as reviewed by Simpson, 1982),

$$u \sim (g'h)^{1/2} \qquad A3.2$$

where h is the vertical thickness of the density current.

Proportionality constants for this relation will be of order 0.5 for most situations (Simpson, 1982).

For a range of temperature differences of 1 to 5 ^oC corresponding density differences of order 0.2 to 1 kg m^{-3} are calculated. According to Equation A3.2, if a h = 1 m is used, this would drive horizontal density currents with speeds of the order of 2 to 5 cm s^{-1}, which is equivalent to 70 to 180 m per hour. Such speeds for gravity currents driven by horizontal density gradients have been measured in south-west Australian water bodies (D'Adamo, 1985; Parker and Imberger, 1986), typically, having thicknesses of the order of less than 1 m. Monismith and Imberger (1988) also report on measurements of convective flows driven by differential heating in the Wellington Reservoir, Western Australia; these flows had speeds up to approximately 10 cm s^{-1} and thicknesses of the order of 1 m.

Imberger and Patterson (1990) reviewed the class of convective flows driven by differential heating and cooling and point out that they have a three-dimensional and unsteady behaviour, with the inertia of the water introducing a large phase lag between the thermal forcing and the resulting motions and, also that their importance should not be underestimated in large lakes, for example, where rotation due to Coriolis force is important, because boundary thermal inputs can lead to basin-scale gyres which can, in turn, greatly enhance horizontal transport.

For the southern metropolitan coast differential heating and cooling between the shallower nearshore regions and deeper offshore regions may set up a residual density gradient between onshore and offshore waters, the direction of this gradient depending on the direction of the temperature gradient. Pertinent data on this mechanism are reviewed in Chapter 3 and it is shown that the potential importance of this transport mechanism in driving exchange between nearshore and offshore waters may not be trivial.

A3.3 Convective overturn

Penetrative convection

Penetrative convection involves upper mixed layer deepening due to cooling of surface waters which become denser and fall to their neutrally buoyant density level. As a result the surface layer is mixed by a stirring dominated mixing process, with the deepening rate estimated by the relations given in Section A3.5, below.

A shear velocity scale for convective overturn is given by (Sherman et al, 1978):

$$u_f = [(\alpha g h H_N)/(\rho C_p)]^{1/3}, \text{ where} \qquad A3.3$$

α = the thermal compressibility of water, equal to $1.5 \times 10^{-4}\ ^oC^{-1}$

g = the acceleration due to gravity

h = approximately 1 m, as a first approximation

H_N = the net heat exchange with the atmosphere, which would have an upper limit for the coastal latitudes near Perth of about 200 $W\,m^{-2}$

ρ = the average vertical density of the water, in $kg\,m^{-3}$

C_p = the specific heat of water, equal to 4200 $J\,kg^{-1}\,{}^oC^{-1}$

This mechanism could be important as a vertical mixing agent, especially during conditions when the vertical stratification is initially weak at the onset of a cooling period and this is investigated in Chapter 4.

Convective overturn due to evaporative salinity increases

During periods when the surface of a saline water body evaporates the surface water becomes saltier and thus has a local increase in salinity and therefore density. Turbulent kinetic energy could be produced by convective overturning due to the salinity increases. If the increased salinity raises the density of the surface water such that it is heavier than water immediately below (thermal energy inputs could offset this density increase by heating the surface and thereby decreasing the local density at the surface) then turbulent billowing will transport fluid from the surface down and the associated turbulence will erode the base of the mixed layer by mixing processes dominated by stirring. This can combine with penetrative convection due to surface cooling to cause mixing of the surface water. Imberger and Patterson (1981) introduced the turbulent velocity scale that incorporates the combined effects of surface cooling and evaporation, and called it w_*.

The turbulent velocity scale, q_*, given by the following relation, is a net turbulent velocity scale due to wind shear velocity (u_*) and the turbulent velocity scales due to the combined actions of penetrative convection and evaporation combined (w_*). The scale q_* is given by:

$q_*^3 = w_*^3 + \eta^3 u_*^3$, with A3.4

$w_*^3 = [(\alpha g h H_N)/(\rho C_p)] + \beta g h W_V S_S$, where A3.5

$[(\alpha g h H_N)/(\rho C_p)] = u_f^{\,3}$, and

$\beta g h W_V S_S$ = the velocity scale associated with stirring due to surface salinity increases caused by evaporation. The parameters are defined as follows:

β = the coefficient of saline expansion and is about 40 x $10^{-6}\,ppt^{-1}$,

S_S = the surface salinity in ppt,

W_V is the rate of volume loss of water in $m\,s^{-1}$, and is calculated for example from an evaporation for Perth in mid-summer of 8 mm per day (equating to 9.259 x $10^{-8}\,m\,s^{-1}$) and in mid-winter of 2 mm per day (equating to 2.31 x $10^{-8}\,m\,s^{-1}$). These estimates are typical values drawn from daily pan evaporation data collected by the Bureau of Meteorology in Perth between 1967 and 1990. The Bureau's data set indicate that the maximum likely evaporation throughout the year would be about 12 mm in February and the minimum likely evaporation throughout the year would be about 1.5 mm in July. The effect of evaporation in gradually raising the overall salinity of a coastal basin will be counteracted by the influence of freshwater inputs from submarine groundwater discharges, river discharges, industrial discharges, and relatively less saline waters that may advect into the basin in regional currents. This mechanism is discussed in Chapter 4.

A3.4 Stratification by gravitational overflows

Fresh to brackish discharges emanate out of river mouths during ebb tides as gravitational overflows, with their dynamical behaviour being either jet or plume-like, depending on the balance between inertial, viscous and buoyancy forces (Luketina, 1987 and Imberger 1983). At first these outflows are usually jet-like because of a relatively large momentum flux, with inertia being the driving force. As the jet moves out viscous retarding forces between the overflow and the ambient fluid below begins to dominate over the inertial force and the frontal region of the overflow becomes dominated by buoyancy, with spreading determined by density difference, as well as other environmental factors, such as tide, wind and mean currents. A radially spreading surface plume will have its virtual origin a distance $M^{3/4}B^{-1/2}$ (Luketina and Imberger, 1987) from the source, being the river mouth for the case of Swan River outflow. The influence of the earth's rotation could also be important in deviating the outflow counterclockwise in the southern hemisphere.

A3.5 An approach to predict wind-mixing in stratified basins

If wind velocities are sufficient to lead to turbulence that completely overcomes ambient buoyancy, then mean circulation in Cockburn Sound will be predominantly wind driven and topographic gyres (Csanady, 1975) will form and dominate over secondary transport mechanisms such as density current flows.

Wind stress will work on the water surface of a stratified basin and produce dynamical motions different to those described above for well-mixed basins. The ability of wind to mix through a vertical density stratification will depend fundamentally on whether the kinetic energy introduced by the surface wind stresses are sufficient to overcome the potential energy inherent in the stratification.

Wind stresses will mix the water column vertically at some rate governed by the difference in magnitude between wind stress and the potential energy locked up in the stratification. In the presence of strong vertical density stratification surface buoyant waters will be advected downwind. In the event that a downwind wall is encountered then this advected water will pile up at the downwind end and the density structure will "downwell ".

Given the correct combination of wind strength, fetch length, upper mixed layer thickness, and vertical density difference, the bottom water may be actually be forced to the surface and "upwell" at the upwind end. Under certain conditions the upwelling will be so pronounced that effective horizontal mixing takes place with the upwelling region progressing downwind.

At the end of a wind mixing event the basin may be left in a differentially mixed state, with strong mixing around upwelling regions and shallower mixed layers in the downwind areas. In the post-mixing period the resultant horizontally stratified density structure will relax towards gravitational equilibrium by redistributing adjacent patches of different density water as gravitational currents, driven by density gradients, either at the surface, bottom or intermediate depths. These mechanisms are baroclinically dominated and could ensue within a mean barotropic flow field, say from throughflows through the basin due to regional currents or tidal forces.

Thompson and Imberger (1980), Imberger and Hamblin (1982), Monismith (1986), Imberger (1985), Mortimer (1974), and Csanady (1975) detail a range of more complex dynamical motions that winds induce in stratified basins.

It would be useful to define the critical wind speed at which a basin changes its response from being dominantly barotropic (no density effects) to dominantly baroclinic (flows driven by density differences). In the following section the potential of winds to drive various types of dynamical motions and mix a stratified water column is investigated.

The upper mixed layer (UML) of a stratified water body affected by wind is assumed to consist of three distinct zones (Sherman et al, 1978; Niiler and Kraus, 1977), as follows.

- A thin surface drift zone, which is the site where turbulent kinetic energy (TKE) is produced and then transported to the fluid below.
- A well mixed central layer. Here part of the energy exported from the surface layer is used to mix the fluid by a stirring action.
- Finally, a bottom entrainment zone, which is a thin front separating the turbulent mixed layer from the relatively quiescent fluid below. In this zone the remainder of the TKE generated at the surface (less that which is locally dissipated less that which is radiated downwards by internal waves plus that which is generated locally by "shear") is used to entrain quiescent fluid into the central layer above.

Implied in the above representation of the upper mixed layer are the two main mechanisms that are now recognised as energising entrainment at the base of a surface layer (Imberger and Patterson, 1990), and these are ***stirring*** and ***shear***, described as follows.

The first is termed ***stirring*** (Kraus and Turner, 1967) and uses the turbulent kinetic energy generated at or near the surface by external energy inputs originating from the wind. Stirring is the deepening caused by surface processes such as breaking waves, surface shear stress, Langmuir circulations or convective mixing. Analogous to stirring is the action of a vertically oscillating grid at the surface.

The second process is ***shear*** induced mixing (Pollard *et al.*, 1973) and describes the entrainment arising from the locally produced kinetic energy contained in the shear across the interface between the surface and lower density layers. Shear is used to define the mixing that occurs due to the velocity jump between the upper and lower layers. Shear mixing can be conceptualised as the interfacial instability that will occur when the upper layer is advected as a bulk slab horizontally over the bottom quiescent water. One important mechanism that forms at an interfacial shear zone is Kelvin-Helmholtz billowing (Thorpe, 1987), which are breaking waves that are generated at the interface and mix the two fluids.

After a shear event that results in billowing at the base of a sharp interface, that region becomes a 'smeared' shear layer of thickness

$$\delta \sim (\Delta U)^2/g' \qquad \text{A3.6}$$

where, ΔU is the shear (velocity difference between the upper and lower layers) and g' the reduced acceleration due to gravity (given by $g' = \Delta\rho.g/\rho$, where $\Delta\rho$ is the density difference across the layers) for a two layer fluid (Sherman et al, 1978). The proportionality constant for the above relation varies from between 0.075 and 0.3, depending on initial conditions for density and velocity differences, but Sherman et al (1978) adopt the value of 0.3.

Often these two sources of mixing combine; the stirring motion from the surface sharpens the interface sufficiently to allow shear instabilities to mix the two fluids.

An indication of whether the stirring or shear mechanisms dominate the mixing process is given by the magnitude of a non-dimensional parameter called the Wedderburn number, W, defined as (Imberger and Hamblin 1982)

$$W = (g'h/u_*^2).(h/L) \qquad \text{A3.7}$$

where, g' is the reduced acceleration due to gravity of the density jump at the base of the surface layer which has a depth h, and L is the fetch length . The parameter u_* is the wind shear velocity at the surface, given by (Fischer *et al*, 1979):

$$u_* = (\rho_A C_d/\rho)^{1/2}\, U_{10} \qquad \text{A3.8}$$

where, ρ_A is the density of air, approximately equal to 1.2 kg m^{-3}, ρ is the density of the water, C_d is a drag coefficient that depends on atmospheric conditions and sea-surface roughness but can be approximated as 0.0013 (Fischer *et al*, 1979), and U_{10} is the wind speed at 10 m height.

The Wedderburn number was developed for the idealised case of a two-layer fluid in a uniform fully enclosed rectangular basin. When the wind acts, the surface water is advected downwind where it piles up and forces the bottom fluid to advect in the reverse direction, resulting in a tilted interface. W is essentially a balance between the pressure force arising from the longitudinal density gradient (formed by the tilted interface) and the pressure force due to the free surface slope that is set up by the applied wind stress. The interface will oscillate, but given the correct combination of wind stress, fetch length, upper mixed layer thickness, and vertical stratification this interface could surface as an upwelling region at the upwind end. This type of dynamical behaviour in lakes has been studied numerically (Thompson and Imberger, 1980), analytically (Imberger and Hamblin, 1982), experimentally (Monismith, 1986), and in the field (Imberger, 1985; D'Adamo, 1985; Csanady, 1975; Mortimer, 1974).

Based on laboratory and field experimental verification in lakes, as reviewed by Imberger and Patterson (1990), the overall dynamics of a surface layer in a multi-layered system is determined by the magnitude of the surface Wedderburn number.

A value of W >> 1 implies that the stratification will be only slightly perturbed by gentle wind forces. Tilting of the isopycnals due to the applied wind stress will be small and horizontal variations are negligible. The density structure remains strongly stratified in the vertical with deepening of the surface layer being slow and dominated by turbulence introduced at the surface reaching the base of the mixed layer and eroding the interface. This is the case when surface mixing is dominated by stirring processes.

For W << 1 deepening is dominated by shear processes at the base of the mixed layer. Shear is produced internally and occurs on a time scale much shorter than horizontal convection in the surface layer. The resulting density structure is characterised by a relatively sharp interface downwind and a broad upwelling region at the upwind end.

The Wedderburn number can be used to predict which of the stirring or shear mechanisms dominate in the mixing process. Wedderburn numbers of order less than 1 indicate shear dominant mixing. Wedderburn numbers of order greater than 1 indicate stirring dominant mixing. This classification is useful because two separate methods to calculate the rate of UML deepening have been formulated; by Kraus and Turner (1967) for stirring dominated mixing and by Pollard et al., (1973) for shear dominated mixing.

As an initially large value of W approaches and becomes of the order of 1, the surface stratification will become progressively more severely perturbed by downwind surface advection, with upwelling of bottom waters at the upwind end and strong horizontal and vertical mixing characterising the dynamics.

Many numerical (Thompson and Imberger, 1980), laboratory (Monismith, 1986) and field experiments (Imberger, 1985) have confirmed the applicability of W to stratified lakes. That W can also be of applicability for semi-enclosed water bodies has been suggested for sites such as Koombana Bay (Imberger, 1983) and the Murray River Estuary and Canals (D'Adamo and Lukatelich, 1985). Two factors which must exist for W to be representative of the mean dynamical response of a water body to winds is the presence of a downwind barrier to advected flows and stratification of density.

Hence, stirring will dominate the mixing whenever the wind stress is too weak, the duration too brief, or the fetch too short to allow appreciable shear to build up across the interface. Sherman *et al*., (1978) integrated the turbulent kinetic energy equation vertically over the mixed layer and Spigel and Imberger (1980) isolated the individual contributions from stirring and shear mixing to arrive at the following deepening formulas. A review of the basic theory for the formulation of the following deepening relations is given in Imberger and Patterson (1990).

For deepening dominated by stirring (W >> 1) the entrainment law, as originally introduced by Kraus and Turner (1967), for a two-layer fluid with a homogeneous upper layer and a linearly stratified lower layer, is:

$$h(t) = \eta u_*(6C_k/N_o^2)^{1/3}\, t^{1/3} \qquad \text{A3.9}$$

where $N_o^2 = (g/\rho).(d\rho/dz)_o$ is the buoyancy frequency squared at the initial background density distribution $((d\rho/dz)_o)$, the initial density gradient is assumed to be linear, z is the vertical coordinate (positive downwards), $C_k = 0.13$ and $\eta = 1.23$ are constants that determine the efficiency of energy conversion (Imberger and Patterson, 1990). For the case of stirring in a two-layer fluid where the upper and lower layers are homogeneous but of differing densities, the following deepening law, based on Equation A3.9 applies:

$$h(t) = (C_k\eta^3 u_*^3 t)/(g_o' h_i), \qquad \text{A3.10}$$

where g_o' is the initial reduced acceleration due to gravity based on the initial density jump across the interface, and h_i is the initial upper mixed layer depth.

For deepening dominated by shear (W << 1), the deepening law, as originally introduced by Pollard *et al.*, (1973), for a two-layer fluid with a homogeneous upper layer and a linearly stratified lower layer, is:

$h(t) = (2C_S/N_0^2)^{1/4} u_* t^{1/2}$ A3.11

where C_S = 0.24 is a constant that determines the efficiency of energy conversion (Imberger and Patterson, 1990). For the case of shear in a two-layer fluid where the upper and lower layers are homogeneous but of differing densities, the following deepening law, based on Equ. A3.11 applies:

$h(t) = [C_S/(g_0'h_i]^{1/2} u_*^2 t$ A3.12

The above deepening laws, for shear dominated vertical mixing, were developed for situations where the time since the onset of the wind is less than one quarter of the internal wave period for the propagation of the surface layer sieche in a two-layer basin (Imberger, 1985). The velocity of the surface layer was calculated for the period up until the point that the surface layer sieche reaches the middle of the basin. The period of the surface layer sieche is given by (Imberger, 1985):

$T_i = (2L)/[(\Delta\rho g h_1 h_2)/(\rho H)]^{1/2}$, where A3.13

L = the length of the basin,

$\Delta\rho$ = the density difference between the upper and lower layers, of thicknesses h_1 and h_2, respectively,

ρ = the density of the lower layer, and

H = the basin depth.

For the example of Cockburn Sound, assuming a density difference of 1 kg m^{-3}, a lower layer density of 1024 kg m^{-3}, a basin depth of 20 m, and an upper layer thickness of 5 m a T_i of the order of one day is calculated as a first order estimate. For a smaller density difference, say of 0.5 kg m^{-3}, a T_i of the order of 40 hours is calculated. This means that the quarter period time is of the order of 6-10 hours, which corresponds approximately to the duration of a typical afternoon sea breeze event during the warmer months of the year, or storms at other times of the year.

Using the above formulae, calculations can be performed to make a first order prediction of the potential of winds of varying strength and direction to mix the surface layer. For the southern metropolitan waters this requires information on initial stratification conditions and on the characteristics of winds. Such calculations are performed in Chapter 3.

The Wedderburn number has been shown to be most applicable for the case of a two-layered rectangular basin, and as Imberger and Patterson (1990) point out, the theory by Spigel and Imberger (1980), which provided the background for the Wedderburn number concept, relied completely on the two-layer model. Imberger and Patterson (1990) noted, however, that this type of model does not completely explain the results of some laboratory work which showed clearly that upwelling can occur at Wedderburn numbers considerably larger than one in basins that have a stratification characterised buy more than two discrete layers, such as those of Monismith's (1986) tank experiments where the stratification consisted of a linearly stratified middle layer in between two homogeneous layers (surface and bottom). This led to the development of a new stability criterion for the dynamical behaviour of fluid below an upper layer, based on the so-called Lake number, L_N, attributable to Imberger and Patterson (1990).

The Lake number was developed to describe the gravitational stability of the total mass of stratified water in a basin, thereby complementing the Wedderburn number which is itself a tool for the prediction of surface layer stability. In essence, the Lake number represents a non-dimensional force balance, based on a ratio of the force imposed by a wind stress over the water's surface and the restoring gravitational force of the Lake's total mass about the centre of volume of that mass. In fact, the Lake number is defined as the ratio of moments (about the centre of volume of the lake) of the force of the wind stress and the restoring gravitational force of the displaced mass of the lake acting through its centre of gravity. The lower the centre of gravity lies towards the bottom, the greater the force due to wind stress that would be required to overturn the density structure.

For the case of constant wind stress over the lake surface, and a stratification consisting of an epilimnion, metalimnion and hypolimnion, Imberger and Patterson (1990) define the Lake number as follows:

$L_N = [gS_t(1-z_t/z_m)]/[\rho_o u_*^2 A_o^{3/2}(1-z_g/z_m)]$ A3.14

where S_t is the stability of the lake's mass, given by the integral over the basin depth of the expression $(z-z_g)A(z)\ \rho(z)dz$. The terms in these equations are defined below.

g = the acceleration due to gravity.

z_t = the height to the centre of the metalimnion.

z_m = the depth of the basin.

z_g = the height to the centre of volume of the lake.

ρ_o = is the hypolimnion (bottom layer) density.

$\rho(z)$ = the density at depth z.

A(z) = the horizontal plane area at depth z.

A_o = the surface area of the lake.

Stevens and Imberger (1990) has further simplified the definition of the Lake number for the idealised case of a rectangular basin with three discrete layers, each having a different but constant density, as follows:

$L_N = [g(h_1 + h_2)(h_1h_2\varepsilon_{13} + 2h_2h_3\varepsilon_{23} - h_1h_2\varepsilon_{12})]/(Lz_m u_*^2)$ where A3.15

$h_{1,2,3}$ = the thicknesses of the epilimnion, metalimnion and hypolimnion, respectively, and

$\varepsilon_{ij} = (\rho_j - \rho_i)/\rho_j$.

The Wedderburn number is embedded in the formula for the Lake number, and so in a a sense, the Lake number is a modification of the value of W, based on the strength of the potential energy locked up in the stratification throughout the entire depth.

For large Lake numbers ($L_N >> 1$) the stratification will be severe and dominate the forces introduced by the wind stress; the stratification will tend to remain horizontal, with little or no sieching and little turbulent mixing in the metalimnion or hypolimnion (Imberger and Patterson, 1990). Imberger and Patterson (1990) reviewed both Monismith's (1986) laboratory experiments and Imberger and Spigel's (1987) field measurements in Lake Rotognaio in New Zealand and pointed out that both data sets indicated that where W is small (less than one), but L_N large, the entrainment process is confined to the upper layer with minimal perturbation or mixing in the lower layers; Imberger and Patterson (1990) describe the process as one of simple re-circulation in the upper layer, where the entrained fluid is swept along the interface into the upwind upwelling region, then is mixed in the surface layer downwind by shear dispersion.

However, for a situation where both the Wedderburn and Lake numbers are small (<< 1), we can expect that the stratification will be broken down by turbulent mixing throughout the whole depth in a severe and relatively rapid manner, with the rate most likely governed by deepening laws that model entrainment dominated by shear between the upper layer and fluid below. Such laws were discussed above. Estimates of both W and L_N for Cockburn Sound are made in Chapter 4, under assumptions which simplify the density structure and wind characteristics accordingly, so that a first order understanding can be made of the dynamical response of the stratified basin to wind stress under typical and extreme environmental conditions.

Cockburn Sound is essentially a deep, semi-enclosed basin with a shallow opening to the north. Winds which blow predominantly to the east, west or south should lead to perturbations of a stratified density structure in the Sound, with consequent dynamical adjustments as described in the preceding discussion. It is much more difficult to predict the dynamical response, in terms of tilting or sieching behaviour, of the density structure for a wind that has a significant component of its force vector directed towards an open end. This may prove to limit the applicability of analytical tools such as those described above for the prediction of a water body's dynamical response to environmental forcings. However, they should provide a useful starting point in such analyses for coastal basins such as those of the southern metropolitan coastal waters. Little work of the nature done for lakes has been performed for semi-enclosed coastal embayments and to a great extent much of the work still needed to arrive at an understanding of circulation in such systems will require a fundamental approach, with predictive methods such as those outlined above perhaps providing useful guidance.

Another complicating factor to the prediction of whether a system perturbed by winds responds baroclinically or barotropically is when there is a continued strong flux of buoyancy to the water column during continued mixing. This may occur during a period of wind mixing when there is very strong short-wave radiation or freshwater inputs from river discharges into Cockburn Sound. Field data would be required as a first measure in resolving this question.

Wedderburn number calculations and descriptions of salinity and temperature structure fof the southern metropolitan waters.

DATE	DATA PERIOD	TRANSECT E-W	TRANSECT N-S	TS STRUCTURE VERTICAL T (°C)	VERTICAL S (ppt)	HORIZONTAL T (°C)	HORIZONTAL S (ppt)	FPA WINDS (m s^{-1})/DIR DURING	PRIOR	W'	NATURE OF STRATIFICATION
240877	1400-1610	CS2		NONE	NDA	1/4km	NDA	10/NW		0.02	Vertically isothermal. Some horiz strat. (note Sepia and Warnbro
									10/NW	0.002	were vertically stratified in Temp)
201077	1240-1530	CS2		2.5	NDA	2/4km	NDA	6/SSW		0.94	Spatially variable vertical T strat. Some horiz strat. Centre
									5/E-S	5.2	isothermal, nearshore regions vertically stratified.
081277	1115-1245	CS2		1-2	NDA	5/2km	NDA	5/WSW		0.84	Generally isothermal, except west shore and centre. Some
									2/SSW	4.27	horiz strat.
230178	0950-1125	CS2		0.5	NDA	0.5/2km	NDA	7/SW		0.06	Vertically isothermal across basin, except east shore.
									5/S	0.07	
260778	1130-1230	CS2		0.5	NDA	0.5/2km	NDA	2.5/SSW		1.75	Generally isothermal, except west shore and centre. Some
									3.5/SSE	1.25	horiz strat.
210978	1015-1235	CS2		0.3-0.6	NONE	0.5/8km	0.5/6km	2.5/SE		1.7	Vertical temp strat across entire transect. Horiz strat in temp
									1/SE	16	and salinity.
	0925-1315	CS1		0.3	0.1-0.2	0.8/2km	1/10km	2.5/SE		1.23	Vertical temp strat across entire transect. Bottom slugs in temp
									1/SE	10.5	and salinity. Some horiz strat in temp and salinity.
	1035-1250		CS8	0.3-0.6	0.1-0.5	0.4/3km	0.5/10km	3/SE		0.64	Vertical temp strat along entire transect. Bottom slug of high S and
									1/E	6.25	high T at northern end. Warm T front into basin via northern opening.
141178	1100-1400	CS2		1	NONE	0.5/2km	0.1/1km	6/SW		0.18	Vertical temp strat across entire transect. Some horiz temp strat.
									3/ENE	1.4	
	1100-1500		CS9	0.5-1	0.1	1/16km	0.1/16km	6/SW		0.18	Vertical temp strat along antiretransect. Some vertical salinity strat.
									3/ENE	1.4	High T (slightly low S) front into basin via northern opening.
060679	0940-1240		CS8	0.4	0.1	1/15km	0.5/5km	1-5/NNE		2.4	Vertically stratified in temp and salinity throughout except at southern
									4-7ENE	0.31	end, where fully mixed. Upper layers relatively deep.
180979	0945-1330		CS8	0.3-1.4	0.4	0.5/5km	0.3/3km	2-5/NE-NW		0.36	Vertically stratified in temp along entire transect. Vertical salinity
									1-4/ENE	0.93	strat at north and south ends. Higher T at surface.
150180	0945-1330		CS8	0.3-0.8	0.1	0.5/5km	0.2/3km	1-3/SW		2.7	Vertically strat. in temp along entire transect. Slight vertical salinity
									8/ENE	0.19	strat. at north end. Warm T front into basin via northern opening.

DATE	DATA PERIOD	TRANSECT E-W	TRANSECT N-S	TS STRUCTURE VERTICAL T (°C)	VERTICAL S (ppt)	HORIZONTAL T (°C)	HORIZONTAL S (ppt)	FPA WINDS ($m s^{-1}$)/DIR DURING	PRIOR	W*	NATURE OF STRATIFICATION
220480	0930-1255		CS8	0.1-2.0	0.1-0.4	2/4km	0.5/4km	1/NW	0.1/NW	17.5 1748	Vertical temp and salinity strat along entire transect. Surface fronts of relatively less saline and colder waters in through north and south ends. Entire basin affected by frontal structures.
160780	1020-1245		CS8	0-0.5	0-0.3	1/4km	0.4/4km	7/W	10/WSW	0.46 0.17	Vertically well-mixed in entire southern half of basin. North-east region vertically strat in S and T below about 6 m. Evidence of a relatively low S, low T surface front into north region via north opening.
141080	1044-1310		CS8	0-0.5	0-0.1	1/10km	1/4km	5/NNW	3-4/N	0.26 0.54	Basin well-mixed vertically in S and T except northern half. Warm surface front into basin via north opening. S and T spatially variable horizontally.
140181	0945-1255		CS8	0-0.2	0-0.1	0.7/15km	small	7/SW	2.5/SE	0.06 0.61	Weakly vertically stratified in T, except for isothermal profile at centre of basin. Bottom slug of colder salty water near south end.
150391	0930-1050		CS3	0-0.5	0-0.5	1/2km	0.3/2km	5/NE-NW		0.87	Owen Anchorage has a bottom layer that is more saline but warmer than the surface. North Cockburn Sound is vertically stratified in T and S.
	1050-1215	CS4		0.4	0.3	0.5/2km	0.2/2km	5/NE-NW		0.3	Cold but less saline surface front into Cockburn Sound via NW gap.
050491	1335-1455		CS3	0.8	0.25	0.5/2km	0.25/3km	3-5/SW		0.53	Vertical temp strat throughout. Horizontal variability in T. S dominated density. Owen Anchorage generally fresher than Cockburn Sound and frontal structure indicates surface front entering the Sound via the North opening.
	1115-1535	CS4		0.8	0.1	0.5/2km	0.1/2km	3-5/SW		0.53	A cold salty bottom front entering the Sound via the NW gap. The surface of the northern Sound water was relatively warm.
190391	0915-1210	WS10		0.5	0.3	0.5/2km	0.3/2km	6/SE (AM) 2/SE (PM)			Vertically isohaline across transect except near Coventry Reef and in the Coasters Channel reef region separating the Sound from Sepia Depression. A surface front of fresher, colder water entering the Sound via this region. Horizontal variation in both S and T across transect.
	1010-1305		WS1	0.5	0.5	0.5/2km	0.5/2km	6SE (AM) 2/SE (PM)			Well mixed in S and T over the southern flats but vertically stratified in S and T in the NW region.

Appendix A4
Response of well-mixed basins to wind stress

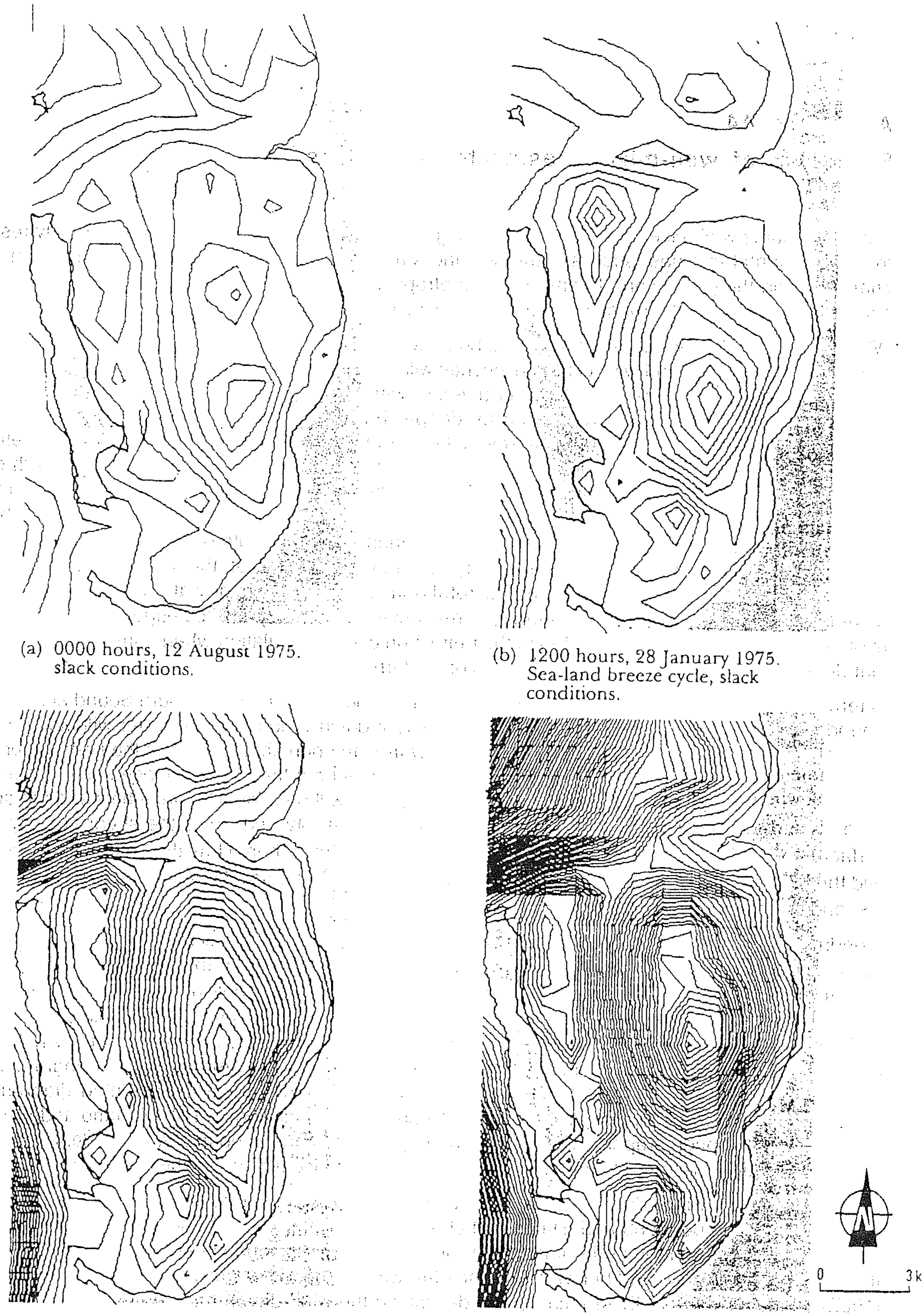
A system that is well-mixed, that is to say homogeneous is density throughout, will generally respond to environmental forcings, such as surface wind stress, in a bulk manner, with barotropic motions characterising the circulation. Examples of barotropic flows are tidally driven circulation, wind driven surface shear flows and throughflows through coastal basins driven by regional currents.

Where wind driven flows encounter a solid boundary, such as a coastal shoreline, a static set-up of water at the downwind end will occur and sieches will be excited. Important, however, is the fact that in most coastal basins the bottom depth is uneven, with peripheral zones characterised by shallow depths and central zones characterised by deeper basin-type bathymetry. Csanady (1975) has reviewed the barotropic circulation patterns that occur in lakes with variable bathymetry and refers to them as topographic gyres. In general, where the water is shallower than the average depth of the basin, vertically averaged transport is with the wind. In the deeper regions vertically averaged transport is against the wind. Numerical models can reproduce this dynamical behaviour for well-mixed basins subjected to wind stress (Csanady, 1973). As Csanady (1975) points out bottom friction limits the maximum current speed of topographic gyres, and the shape of the bottom determines the configuration of the gyres. The Earth's rotational influence can deviate wind-driven currents (counterclockwise in the southern hemisphere) however Csanady (1975) suggests that, as a first approximation, they can be neglected in their effect on overall circulation when compared to the effect that depth variation has on controlling circulation patterns.

In terms of applicability to semi-enclosed coastal embayments, such as Cockburn Sound and Warnbro Sound, the important parameter will be to what extent down-wind set-up of water will occur when a component of the wind stress vector is directed towards an open shore, such as the northern opening of Cockburn Sound. As Imberger and Hamblin (1982) point out the force balance at steady state for barotropic motions due to wind stress, neglecting rotation, will be a local balance between the applied wind stress (of the order of ρu_*^2, where ρ is the water density and u_* is the shear velocity at the surface), the bottom frictional resistance (of the order of ρU_*^2 , where U_* is the bottom shear velocity) and the reverse pressure force (of the order of ρgH, where g is the acceleration due to gravity = 9.81 m s^{-2}, and H is the basin depth scale).

Steedman and Craig (1979) applied a barotropic numerical model to Cockburn Sound driven by wind stress and their predicted circulation pattens are characterised by topographic gyres. A sample output of that model, which Steedman and Craig (1979) suggested was applicable for winds greater than 5 m s^{-1} due to complexities likely to be introduced in the dynamics by baroclinic processes, is presented in Figure A4.1. The circulation patterns in Figure A4.1 were predicted for various wind scenarios, such as calms, sea breezes (weak and strong) and storms, and the topographic gyre patterns predicted by the model are evident. Csanady (1975) has also presented diagrammatic representations of topographic gyres predicted by numerical modelling for Lake Ontario and Fischer et al (1979) present photographic evidence of topographic gyres produced in a variable depth laboratory tank. The reader is referred to these publications for further discussions on this mechanism.

Wind stress is known to drive surface water downwind at speeds up to about 3 percent of the wind speed (see Wu, 1968, 1983 and Hammond et al, 1987, for example). General practice is to assume that wind induces a surface drift of the order of 3 percent of the wind speed, but this is applicable to the surface region only, and below the surface the wind induced current velocity weakens. Csanady (1982) suggests the effective Ekman depth describing the wind-driven layer thickness is of the order of 3D, where D was the Ekman depth defined in Section 3.1.2).



(a) 0000 hours, 12 August 1975.
slack conditions.

(b) 1200 hours, 28 January 1975.
Sea-land breeze cycle, slack conditions.

(c) 0000 hours, 29 August 1975.
Sea-land cycle, peak velocity conditions.

(d) 1200 hours, 20 March 1975.
Peak velocity conditions under cyclone "Vida."

Streamline spacing 200 $m^3 s^{-1}$

Figure A4.1 The model output of streamline patterns predicted by Steedman and Craig's (1979) finite-difference, vertically averaged, 2D model of Cockburn Sound's hydrodynamic response to wind forcing for a number of 'typical' weather conditions, namely slack, weak sea-land breeze, strong sea-land breeze and strong NW storm. Diagram taken from Steedman and Craig (1979).

Few accurate field measurements have been made in the field of the depth variation of wind induced current near the surface. If it is assumed therefore that the upper meter of the water column is driven by a wind at approximately two percent of the wind speed, then this implies a surface transport of 10 cm s^{-1} for a 5 m s^{-1} wind. One important factor that influences wind-driven surface flows is the Earth's rotation which deviates surface currents slightly counterclockwise in the southern hemisphere, and this is discussed in Section 3.1.2.

Appendix A5

Wedderburn Number calculations and descriptions of salinity and temperature structure of the southern metropolitan waters using basin-scale ST profile data collected by DCE during 1978-1981.

Appendix A6

A summary of drogue data collected in Cockburn Sound by Environmental Resources of Australia Pty Ltd between 1971 and 1973.

NOTE: THE DROGUE-FLOAT SYSTEMS WERE GENERALLY OF THE FOLLOWING CONSTRUCTION; A 12" LONG METAL CYLINDRICAL FLOAT OF 6" DIAMETER CONNECTED BY A LINE TO A SUBMERGED CROSS-VANE WITH VANES HAVING RECTANGULAR DIMENSIONS OF 18" X 6" IN 1970 AND 36" X 12" THEREAFTER. THE CAN WAS PARTIALLY FILLED WITH SEAWATER SO THAT IT FLOATED JUST BELOW THE SURFACE IN ORDER TO REDUCE WIND DRAG. HOWEVER, IT CAN BE SHOWN THAT THE DRAG PRODUCED ON THE SURFACE CAN BY WIND DRIFT IS NOT TRIVIAL WHEN COMPARED TO THE DRAG ON THE DROGUE DUE TO TYPICAL SUB-SURFACE CURRENTS. FOR A 5 m s^{-1} WIND AND A 5 cm s^{-1} SUB-SURFACE CURRENT THE DRAG ON THE CAN WILL BE OF THE SAME ORDER AS THE DRAG ON THE DROGUE, HENCE ANY INFERRED SUB-SURFACE CURRENT SPEEDS AND DIRECTIONS BY THE TRACKING OF THE CAN COULD BE IN ERROR BY LARGE AMOUNTS. HENCE, IT IS ACCEPTED THAT THE DROGUE RESULTS PRESENTED IN THE ERA REPORTS FOR WINDS OF ORDER 5 m s^{-1} OR MORE ARE LIKELY TO BE AT BEST, INDICATIVE OF THE DIRECTION AND SPEED OF SURFACE CURRENTS ONLY.

IN 1971 THE DESIGN OF THE DROGUE VANES WAS ALTERED FOR SPECIFIC TRACKING EXPERIMENTS BY USING WHAT WERE DESCRIBED ONLY AS "... LARGE FIBREGLASS QUADRAPLANE DROGUES, SUSPENDED AT 15 AND 30 ft. BELOW PARTIALLY FILLED 12 GALLON DRUMS." IT CAN ONLY BE ASSUMED HERE THAT THE VANES HAD DIMENSIONS OF THE ORDER OF 1 X 1 m^2.

WINTER DROGUE TRACKING EXERCISES

Analysis of July 1971 flow data from drogue tracking in the south passage opening along the alignment of the now existing Causeway. At the time of measurements the Causeway was constructed up to and including the end of the Trestle Bridge (the central wall and High Level bridge were yet to be constructed. Drogue vanes were approximately 1m wide by 0.3 m deep, with their centres about 1.8 m below the water surface. Up to 20 drogues were set in the centre of the opening approximately in a line aligned in the north-south direction and tracked. Data from ERA (1971).

DATE (JULY, 1971)	TIME	WIND (DIR/ M s^{-1})	FLOW IN, OUT OR OTHER (cm s^{-1})	TIDE	STREAMLINES CONVERGED (S, C, N) *	STREAMLINES DIVERGED
12	1453-1639	S 4	CW GYRE 5	F		
13	0836-1042	N/NW 5	OUT 15	R	C	
13	1147-1337	W/NW 5	OUT 20	R	C	
14	0746-1158	NW/SW 2-10	OUT THEN NE 20	F	ALL MAINTAINED DIRECTION	
15	0753-0948	NE/N 3	OUT 15	F	C	
15	1023-1200	N 3	OUT 15	F	C	

15	1253-1445	NW 3	OUT 15	F	C
15	1505-1628	NW 3	OUT - 15	F	ALL MAINTAINED DIRECTION
16	0733-1055	NW 6	OUT 25	F	C
16	1133-1258	NW/W 6		F	
			(Drogues placed in Mangles bay, south of Southern Flats, and displayed random behaviour, speeds being low and less than 3 cm s^{-1})		
16	1351-1610	W 6		F	
			(Drogues placed in Mangles Bay, south of Southern Flats, moved towards E in the centre of the Bay, but initially towards W just south of the southern shelf of the Southern Flats eventually swing CW and moving towards E along that shelf region)		
19	0938-1144	W/NW 5	OUT 10	F	C
19	1258-1446	NW 5	OUT - The central drogues began moving at about 15 cm s^{-1}, but the drogues at the north and south ends of the initial alignment moved slowly OUT at first then changed direction and moved slowly back IN. By the time the central drogues had moved OUT about 500 m they all slowed considerably to about 5 cm s^{-1}. This could be due to the fact that as the drogues were advected further and further westward the direct influence of the NW wind stress at the southern opening took predominance over the outflow that was being caused by the predominantly southward wind stress over the basin as a whole. Tide was FALLING.		
19	1502-1642	W 5	OUT - The drogues were placed along a NW-SE alignment over the southern flats, about 1 km to the southeast of the southern tip of Garden Island. They moved relatively slowly towards the southwest (at 5 cm s^{-1}) and after about 200 m of travel they all slowed to be nearly stationary. The same reason as above (19 July, 1258-1446) is invoked here for this behaviour. Tide was FALLING.		
20	1037-1153	SW 7	IN 12	F	SLIGHT CW GYRE
20	1248-1545	SW 8	IN 12	F	SLIGHT CW GYRE
21	0722-1102	SE 4	IN - Drogues initially placed along a N-S alignment across the centre of the opening. Central drogues moved in at 10 cm s^{-1} then slowed and exhibited CCW gyres, probably in direct response to the SE winds. The northern-most drogues, over the flats, exhibited CCW gyres immediately upon release and then moved towards north, driven directly by wind. Hence, this again suggests that a wind blowing towards the opening over the inner southern channel (within Cockburn Sound proper) did not advect water OUT, but that rather the flow through the channel was IN, opposing the wind, because the shear stress over the Sound's water surface as a whole must have caused a net efflux of water through the northern opening, thereby creating a pressure gradient that drove water IN through the southern opening. Tide was FALLING.		
21	1120-1428	E 4	OUT 8	F	ALL MAINTAINED DIRECTION
21	1507-1639	E/SE 3	Random but generally OUT at very slow speeds of 2-3 cm s^{-1}. Tide was FALLING.		
22	0723-0957	NE 5	OUT 8-12	F	ALL MAINTAINED DIRECTION
22	1133-1326	N/NE 4	OUT 15	F	C

22	1430-1552	N/NW 3	OUT 15 THEN 6	F	C
			Note, again the drogues started moving rapidly then converged and slowed considerably as they approached the opening. Thus, this again suggests that initially the basin-scale flux acts to drive water OUT, but the direct wind shear stress that opposes that outflow predominates locally at the opening. Unfortunately, the drogues were not tracked further to assess whether the flow actually makes it out through to the Sepia Depression. Under such situations, when a wind stress opposes a mean flow direction it can expected that shear could develop, with surface water moving downwind and bottom water moving into the wind, however, this was not investigated by the drogue-tracking exercise.		
23	0806-1003	NE 5	OUT 15	R	ALL MAINTAINED DIRECTION
23	1318-1524	N 5	OUT 15-20	F	C
26	0946-1251	E 4	OUT 8	R	ALL MAINTAINED DIRECTION
26	1340-1529	E 4	IN THEN OUT 10	F	ALL MAINTAINED DIRECTION
			The initial flow IN, opposing the wind, is unexplained. ERA (1971) however, offer two possible reasons: oscillation along an interface or hydraulic barrier due to conflicting water bodies meeting in the gap; or, the synergistic effect of southerly drift and tide within the Sound. It is interesting to note however, that the tide changed the drogue tracking from HW to FALLING, and the behaviour of the drogues may have been indicated a short-term dynamic response to this at the opening.		
26	1538-1631	E 5	OUT 5	F	ALL MAINTAINED DIRECTION
27	0748-1013	NE 7	See below	R	
			Note; the northern-most drogues converged towards the centre of the gap, and moved out rapidly at 30 cm s^{-1}; the central drogues started slowly OUT then converged and increased in speed to about 30 cm s^{-1} by the time they reached the central region of the gap and then headed northward toward the southern end of Garden Island in a CW manner; the southern-most drogues moved at about 5-15 cm s^{-1} in a CCW gyre pattern. Hence, the probable cause of the extreme spatial variability of the flow in the southern opening was competing influence of NE wind stress and rising tide.		
27	1233-1607	NE 7	See below	F	
			The centrally released drogues headed OUT at 20 cm s^{-1}, but the southern-most drogues headed directly downwind towards the southern Mangles Bay shore west of Rockingham and started deviating CCW at 5 cm s^{-1}.		
28	0825-0941	NW 4	OUT 25	HW	CONVERGED SLIGHTLY
28	1108-1245	NW 3-5	OUT 25	F	C
28	1335-1637	NW 5	OUT 25	F	C
29	0849-1249	NW 5-10	OUT 35	F	C
			Note: the southern-most drogues moved southwards towards the southern Mangles Bay shore west of Rockingham driven by the direct influence of the wind.		
30	0900-1245	SW 7-10	IN 10	F	C
			Note: The southern-most drogues moved directly northwards, but		

the northern-most drogues moved towards the NE, being directly downwind.

F = FALLING TIDE

R = RISING TIDE

L = LOW WATER

H = HIGH WATER

S = CONVERGED TOWARDS SOUTHERN REGION OF OPENING

C = CONVERGED TOWARDS CENTRAL REGION OF OPENING (3 M CHANNEL)

N = CONVERGED TOWARDS NORTHERN REGION OF OPENING

FLOWS GIVEN AS TOWARDS A BEARING, EG N = TOWARDS N

FLOW IN = FLOW PREDOMINANTLY TOWARDS EAST, INTO THE SOUND

FLOW OUT = FLOW PREDOMINANTLY TOWARDS WEST, OUT OF THE SOUND

Analysis of July-August 1972 flow data from drogue tracking in southern Cockburn Sound and west of the now existing Causeway in the South Channel. Drogue vanes were approximately 1m wide by 0.3 m deep, with their centres between 2 and 6 m below the water surface. Up to 20 drogues were set at any one time and tracked. Data from ERA (November, 1972). At the time of the exercise the Causeway had been constructed up to the southern edge of the High Level bridge (i.e., the High Level bridge and northern connecting wall was yet to be constructed).

DATE (1972)	WIND (DIR/ M S^{-1})	TIDE	FLOW DETAILS ($cm\ s^{-1}$)
24 July - 4 Aug	Varied		Mangles Bay, flow roughly downwind, influenced by bathymetry, flow approx. 1-2 % of wind speed, and flow at 5 m generally weaker than flow at surface. Central Southern Cockburn Sound (opp. CBH), flow downwind at 1 % of wind speed. Surface speed significantly greater than that at 5 m (by up to 2 X). Mangles Bay shelf margins, flow is deviated with the bathymetry and can flow into the wind. In the deeper central regions of Mangles Bay the flow is generally downwind. Trestle Bridge, flow is IN during a 5 m s^{-1} southerly. This is consistent with the drogue results of 1971.

F = FALLING TIDE

R = RISING TIDE

L = LOW WATER

H = HIGH WATER

C = CONVERGED

FLOWS GIVEN AS TOWARDS A BEARING, EG N = TOWARDS N

FLOW IN = FLOW PREDOMINANTLY TOWARDS EAST, INTO THE SOUND

FLOW OUT = FLOW PREDOMINANTLY TOWARDS WEST, OUT OF THE SOUND

Analysis of August 1973 flow data from drogue tracking in southern Cockburn Sound. Droque vanes were approximately 1m wide by 0.3 m deep, with their centres between 2 and 6 m below the water surface. Up to 20 drogues were set at any one time and tracked. Data from ERA (August, 1973). At the time of the exercise the causeway was fully constructed

DATE (AUG, 1973)	TIME	WIND (DIR/ M S^{-1})	TIDE	FLOW DETAILS (cm s^{-1})
14	1105-1523	W 10	F(SPRING)	DOWNWIND
15	0847-1620	SW 7-10	HW/R(NEAP)	TOWARDS NW
16	0838-1546	NE 4	R/HW/F(NEAP)	Drogues released in central Mangles Bay (deep water) travelled towards SE. Drogues released nearer the shore travelled southwest, alongshore.
17	1338-1553	NE 7	F(NEAP)	Drogues released within 500 m of the Palm Beach jetty, in a line perpendicular to the shore. They all travelled west, alongshore.
18	0827-1114	NE 8	R(NEAP)	Drogues released in northern Careening Bay, and headed downwind, towards the southwest.
20	1000-1639	W/SW 6	F(SPRING)	Drogues released in southern Careening Bay, and headed downwind, towards the northeast.
21	0919-1412	SSW, 5	F(SPRING)	Drogues released just east of the High Level bridge, and headed northward, then rotated CCW into Careening Bay

F = FALLING TIDE

R = RISING TIDE

L = LOW WATER

H = HIGH WATER

C = CONVERGED

FLOWS GIVEN AS TOWARDS A BEARING, EG N = TOWARDS N

FLOW IN = FLOW PREDOMINANTLY TOWARDS EAST, INTO THE SOUND

FLOW OUT = FLOW PREDOMINANTLY TOWARDS WEST, OUT OF THE SOUND

SUMMER DROGUE TRACKING EXERCISES IN COCKBURN SOUND

Feb-Mar 1972.

Many drops were conducted in the nearshore region (from the shore out to the 20 m contour) from Rockingham to the ALCOA Jetty. In general, drogues were released along a perpendicular alignment out from the shallows to about the 20 m contour. Drogue vanes were set at the surface or at a depth of 1.5 m.

Results

Southwest or northeast winds (predominantly alongshore or onshore wind stress): during these conditions drogues moved alongshore, showing little tendency to be advected offshore. Drogues closest to the shore were advected at speeds of the order of 3 percent of the wind speed. Drogues released over the deeper region (deeper than 5 m) travelled at speeds of the order of 1 percent of the wind speed.

Analysis of November-December 1971 flow data from drogue tracking in southern Cockburn Sound. Droque vanes were approximately 1m wide by 0.3 m deep, with their centres between 2 and 6 m below the water surface. Up to 20 drogues were set at any one time in the central region of the now existing Causeway alignment and tracked. Data from ERA (August, 1973). At the time of the exercise only the southern 1 km of the Causeway was constructed (including the Trestle Bridge). Drogues were released approximately in a north-south alignment.

DATE (NOV, DEC, 1971)	TIME	WIND (DIR/ M S^{-1})	FLOW IN, OUT OR OTHER (cm s^{-1})	TIDE	STREAMLINES CONVERGED (S, C, N) *	DIVERGED

29 NOV	1147-1439	SW 7	IN 15	R	N
29 NOV	1452-1707	SW 7	IN 20	R	N
			Note: the salinity tracking in the region confirmed the entrance of oceanic water through the opening. This water came in as a pulse that headed over the Southern Flats, hence exhibiting a CCW deviation once through the opening.		
30 NOV	0721-0929	SSE 5	IN 10-15	R	N
			Note: salinity tracking confirms the entrance of oceanic water in through the opening.		
30 NOV	1003-1524	SSW//SW 3-7	DROGUES RELEASED IN CENTRAL MANGLES BAY		
			DOWNWIND 10	R	
			Note: salinity tracking confirms the entrance of oceanic water in through the opening.		
1 DEC	1610-1712	SW 8	IN 30	R	N
			Note: salinity tracking confirms the entrance of oceanic water in through the opening		
2 DEC	1220-1435	SW 10	DROGUES RELEASED ALONG THE NORTHEAST SHELF EDGE OF THE SOUTHERN FLATS.		
			IN 5-15	R	ALL MAINTAINED DIRECTION (DOWNWIND)
2 DEC	1515-1640	SW 10	DROGUES RELEASED ALONG A NORTH-SOUTH ALIGNMENT IN OVER THE CENTRAL SOUTHERN FLATS.		
			IN 15	R	ALL MAINTAINED DIRECTION (DOWNWIND)
3 DEC	1221-1412	SW 7-10	DROGUES RELEASED ALONG A NORTH-SOUTH ALIGNMENT IN THE WEST END OF THE 20 M BASIN OF MANGLES BAY.		
			CLOCKWISE GYRE AT 10 cm s^{-1}. TIDE RISING.		
3 DEC	1434-1633	SW 8	DROGUES RELEASED ALONG A NORTH-SOUTH ALIGNMENT AT THE EASTERN SHELF OF THE SOUTHERN FLATS.		
			IN 15	R	ALL MAINTAINED DIRECTION (DOWNWIND)
3-4 DEC		SW 5-10	5 AND 10 m DROGUES WERE RELEASED IN CENTRAL MANGLES BAY, JUST EAST OF THE SOUTHERN FLATS AND JUST NORTH OF THE SOUTHERN FLATS. THEY WERE ADVECTED DOWNWIND TOWARDS THE NORTH-NORTHEAST AT SPEEDS OF THE ORDER OF 10 cm s^{-1}, CORRESPONDING TO ABOUT 1-2 PERCENT OF THE WIND SPEED.		
			SALINITY TRACKING SHOWS THE ENTRANCE AND NORTHEASTWARD PROPAGATION OF A FRONT OF OCEANIC WATER IN THROUGH THE SOUTHERN OPENING.		
6-10 DEC			THE SAME CIRCULATION AND SALINITY STRUCTURE FEATURES AS THOSE FOUND BETWEEN 29 NOV AND 4 DEC, ABOVE, WERE OBSERVED TO OCCUR BY SALINITY-MONITORING AND DROGUE TRACKING BETWEEN 6 AND 10 DEC.		

ONE NOTABLE RESULT WAS THE TRACKING OF 5 AND 10 m DROGUES RELEASED IN SOUTHERN COCKBURN SOUND BETWEEN 8 AND 9 DEC. ONE OF THESE DROGUES (THE 5 m ONE) WAS DRIVEN DOWNWIND TOWARDS THE NORTHEASTERN SHORE BY A 7-10 m s^{-1} SW WIND AT AN AVERAGE SPEED OF

ABOUT 20 cm s^{-1}, WHICH CORRESPONDS TO ABOUT 2-3 PERCENT OF THE WIND SPEED. THE OTHER TWO DROGUES WERE AT 10 m DEPTH AND HEADED DOWNWIND EVENTUALLY BEING GROUNDED ALONG THE EASTERN SHELF OF THE 20 m BASIN ADJACENT TO AND JUST NORTH OF JAMES POINT. THESE RESULTS SHOW THAT WINDS FROM THE SOUTHWEST THAT HAVE SPEEDS OF THE ORDER OF 5-10 m s^{-1} OR MORE DRIVE A BAROTROPIC SURFACE FLOW IN APPROXIMATELY A DOWNWIND DIRECTION AT 2-3 PERCENT OF THE WIND SPEED. THE PROPAGATION OF ISOHALINES INFERRED FROM BASIN-SCALE SALINITY PROFILING ARE CONSISTENT WITH THIS FLOW PATTERN.

Analysis of December 1972 flow data from drogue tracking in the whole of Cockburn Sound. Droque vanes were the "modified" type, being larger than those that were normally used, see above, assumed to be approximately 1m wide by 1 m deep, with their centres at 5 or 9 m below the water surface. Up to 10 drogues were set at any one time in and tracked. Data from ERA (August, 1973). At the time of the exercise the Causeway had been constructed up to the southern edge of the High Level bridge (i.e., the High Level bridge and northern connecting wall was yet to be constructed). Drogues were released along various alignments.

DATE (DEC, 1972)	TIME	WIND (DIR, M S^{-1})	TIDE	POSITION	FLOW (cm s^{-1}, $\%U_{wind}$)
6	1200-1900	SW 3-5	R	NORTH-CENTRAL	N 10 2-3 %
7	0500-1400	E-SW 3	LW@0630	SOUTH-CENTRAL	(SEE BELOW)
	NEARSHORE DROGUES ALWAYS DOWNWIND, CENTRAL DROGUES DOWNWIND THEN TOWARDS NW. ALL AT 2 % OF WIND SPEED (APPROX 6 cm s^{-1})..				
7	1245-1900	SW 3	R	SE MANGLES BAY	NE 5 2 %
7	1340-1820	SW 3-5	R	EAST-CENTRAL	NE 10 3 %
8	0500-1840	ENE 2/ WSW 4	LW@0900	E-W LINE, DANCE HEAD TO JERVOISE BAY	(SEE BELOW)
	MOST DROGUES BEGAN BY MOVING TOWARDS THE SW, EXCEPT FOR THOSE NEAREST THE EAST SHORE WHICH MOVED ESSENTIALLY SOUTHWARD. AFTER THE WIND TURNED TO BE SW THE CENTRAL CS DROGUES MOVED NE AND THOSE NEAREST THE EAST SHORE MOVED ESSENTIALLY N-NW. PERHAPS BAROCLINIC MECHANISMS COMPLICATED THE FLOW PATTERNS OVER THE SHALLOWS, AS SUGGESTED BY THE PRESENCE OF OFFSHORE SALINITY GRADIENTS IN THE REGION.				
9	0500-1730	N 1, SW 5	LW@0900	E-W ACROSS CENTRAL COCKBURN SOUND	RANDOM 5
10	0500-1930	NE 1, SW 5	LW@0900	N-S DOWN THE SE CORNER 1.5 km OFFSHORE	RANDOM 4
11	0630-1835	E 1, SW 2.5	LW@0700	E-W ACROSS CENTRAL COCKBURN SOUND	RANDOM 2-5
12	0700-1430	NW 4, W <1	R	E-W FROM THE NW TO NE CORNER	(SEE BELOW)
	THE CENTRAL DROGUES MOVED S, THE DROGUES NEAR THE GI-CI GAP MOVED OUT TOWARDS				

	THE NW, AND THE DROGUES NEAR JERVOISE BAY MOVED ENE INTO JERVOISE BAY. SPEEDS APPROX 5 cm s^{-1}.					
13	0800-1200	SW 2 - 7	R	FAR NE CORNER OVER THE SHELF BREAK	NE 3	0.5-1.5 %
14	0520-1700	SE 2, SW 8	LW@0730	IN A SW-NE LINE AT THE NW CORNER	NW 6, NE 10	1-2 %

NOTE: BETWEEN THE 9 AND 12 DECEMBER THE SURFACE TO MID-DEPTH DROGUE PATTERNS DID NOT REFLECT THE WIND FORCING, AND IN VIEW OF THEIR SOMETIMES RANDOM BEHAVIOUR, SOMETIMES NORTH-SOUTH MOVEMENT, AND MEASURED HORIZONTAL STRATIFICATION A SUPERPOSITION OF WIND CURRENTS, REGIONAL CURRENTS THROUGH THE SOUND AND DENSITY CURRENTS WITHIN THE SOUND MAY HAVE FORCED THE CIRCULATION PATTERNS. IT IS INTERESTING TO NOTE THAT WINDS WERE LESS THAN OR EQUAL TO 5 m s^{-1} THROUGHOUT THAT PERIOD. ON THE OTHER DAYS, WHEN WINDS CLIMBED ABOVE ABOUT 5 m s^{-1}, CIRCULATION PATTERNS DISPLAYED MORE DOWNWIND-TYPE FLOWS.

December 1973

DURING THIS PERIOD WINDS RANGED FROM MODERATE TO VERY STRONG (5-15 m s^{-1}) AND BLEW PREDOMINANTLY FROM THE SOUTHWEST. CONSEQUENTLY, MOST DROGUE TRACKING RUNS REVEALED A STRONG DOWNWIND CIRCULATION PATTERN, THIS PATTERN BEING INFLUENCED BY LOCAL BATHYMETRY IN THE MINOR EMBAYMENTS OF THE SOUND, SUCH AS MANGLES BAY, JERVOISE BAY AND CAREENING BAY. FLOW THROUGH BOTH BRIDGES DURING THE SEA BREEZES WAS INTO THE SOUND.

Appendix A7

Flow measurements through the causeway openings.

During the early seventies many current metering exercises were conducted under the bridges of the causeway. Two types of field techniques were employed; direct fixed point automatic recordings and manual profiling. It was shown that the fixed point records poorly simulated actual flows recorded by two dimensional profiling under the bridges. This was because flow under the bridges was found to vary vertically and horizontally from point to point due to eddying, oppositely directed vertical shear and oppositely directed mean horizontal flow under the bridges. Hence, in the following discussion only the results of two dimensional current meter profiling are discussed.

ERA (July, 1971) conducted a full year monitoring program of direct current metering across the then unconstricted southern opening of Cockburn Sound along the alignment of the causeway. Thirty five current metering exercises were conducted throughout the period 27 May 1969 to 28 May 1970, in which vertical current profiles, at 1.5 m depth intervals, were collected across the widths of both openings at stations spaced about 250 m apart. The individual exercises were spaced in time so as to encompass all four seasons. The vertical current velocity records were used to determine the rate of water flow through the entire opening. The results were presented graphically in ERA (July, 1971) and the diagram from the ERA (July, 1971) report is reproduced here in Figure A7.1.

Figure A7.1 shows the seasonal trend in flow direction and intensity, with the majority of summer flows being into the Sound at rates up to a maximum of about 2000 $m^3 s^{-1}$, and winter flows being out of the Sound at rates up to a maximum of about 3000 $m^3 s^{-1}$. An average flow rate of about 2000 $m^3 s^{-1}$ for summer equates to a replacement time, for the entire Cockburn Sound volume (which is of the order of 1.5×10^9 m^3) of about 9 days, and a flow rate of about 3000 $m^3 s^{-1}$ for winter equates to a replacement time for the Sound's volume of about 6 days. Hence, on the basis of these data collected before the Causeway construction over four seasons it would appear that maximum flows through the southern opening equated to maximum replacement times of approximately 5-10 days for the volume of Cockburn Sound (this is based on the assumption that Cockburn Sound is continuously well-mixed and homogeneous both vertically and horizontally).

One limitation in placing full credence on the above conclusion is that reversals in mean wind direction from north to south or vice-versa would in turn lead to reversals in the mean direction of flow through the southern opening. For example, over a typical meteorological meso-scale cycle (of order 7-10 days) the wind typically shifts through the various quadrants, often changing its predominant vector direction by up to 180 degrees. Hence, the efficiency of throughflows via the southern (or northern) opening would depend on the nature of internal circulation and mixing within Cockburn Sound. For example, one situation which would lead to lower than ideal exchange efficiencies would be the residence of a pulse of recently injected oceanic water in Mangles Bay, and the subsequent expulsion of some of this same water out through the opening during subsequent outflows that may have accompanied a shift in wind direction. It is shown in this report that Cockburn Sound is typically spatially patchy in density structure and that vertical stratification is a common characteristic of the water body for periods when winds are less than of the order of 5-10 $m s^{-1}$. Hence, the Sound does not act like a continuously stirred basin and there is the likelihood that patches of water can remain in the Sound or be advected in the mean flow of the Sound's circulation patterns in a relatively unmixed manner.

Another interesting feature of the results in Figure A7.1 are that in the spring and autumn periods flows are generally weakest, compared to summer and winter, and the direction of these flows is more variable, presumably responding to the more variable wind patterns and other environmental forcings in these seasons.

Direct current metering exercises in the southern openings under the two bridges were conducted in Winter 1975 (R.K. Steedman and Associates, Oct 1975), Spring 1974 (ERA, Jan 1975), Summer 1976 (R.K. Steedman and Associates, May 1976) and Autumn 1975 (R.K. Steedman and Associates, June 1975). The field procedure for these direct current metering exercises were identical to those followed by ERA in the 1969-1970 exercise (ERA, July 1971). The results are summarised below according to season:

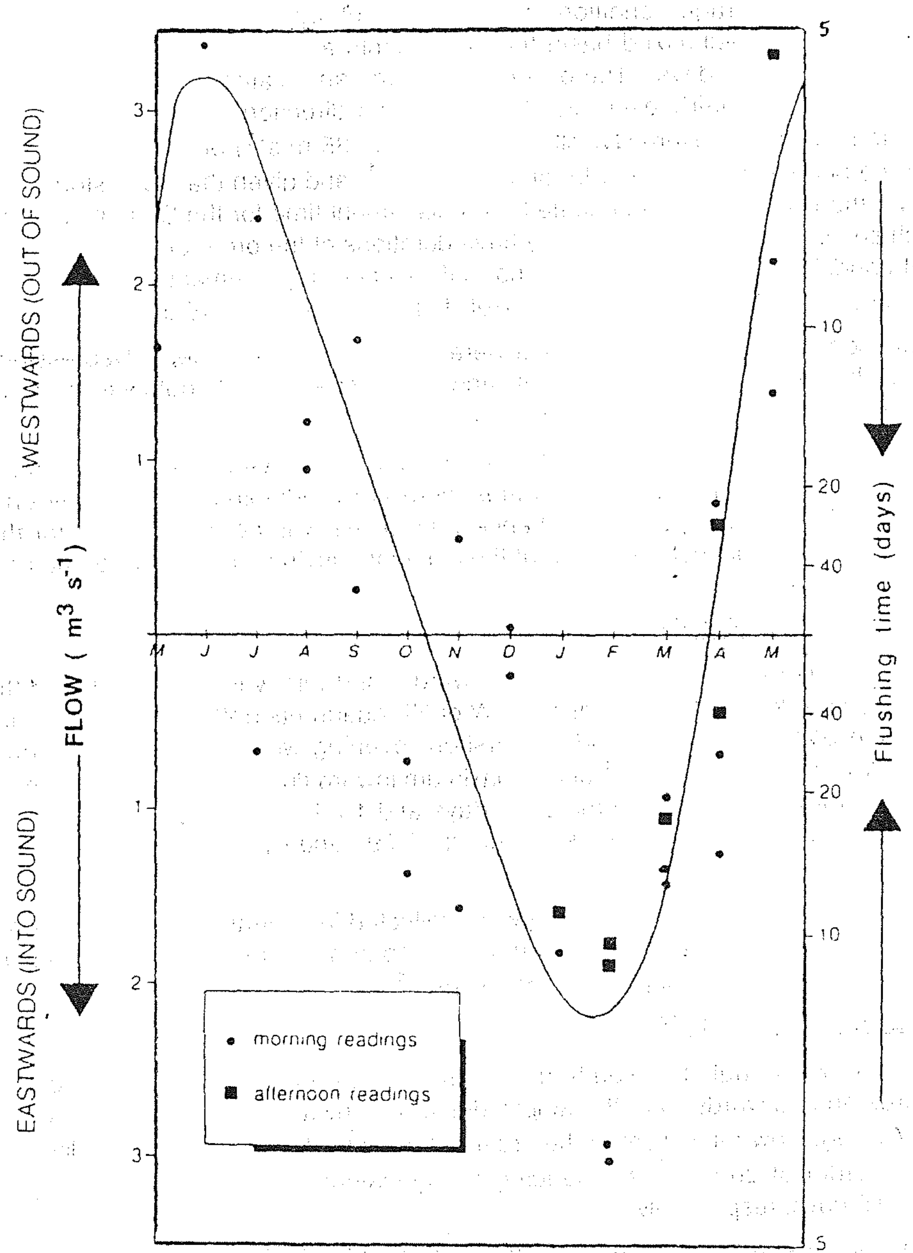


Figure A7.1 Net flow through the original southern opening of Cockburn Sound based on profiling current meter data from a 12 month survey from 27 may 1969 to 28 May 1970 . Data were collected at a vertical resolution of 1-2 m, and at sites approximately 250 m apart across the opening. The diagram is reproduced from Hearn (1991), as re-drawn from ERA (July, 1971)).

Winter 1975 (21 July - 7 Aug 1975)

The predominant net flow direction was out (towards west) through the southern openings. Under what were defined as average conditions the net flux out was of the order of 570 $m^3 s^{-1}$, and assuming a continuously well-mixed basin this represents an equivalent replacement time for the Sound's volume equal to 30 days. The occurrence matrix and statistics for wind directions for the sampling period showed a fairly even distribution of wind direction. Under what were defined as extreme conditions during a severe NW storm (winds up to 35 $m s^{-1}$) on 28 July 1975 maximum net outflow under the bridges was of the order of 4000 $m^3 s^{-1}$, and given that such storm intensities last for a full 4 days, then such flow rates equate to a replacement time for the Sound's volume of 4 days. However, such severe storm events generally have durations of the order of 1 day or less, after which climatological conditions generally return to normal. Hence, replacement times caused by severe storms followed by normal conditions are more likely to be of the order of 10 days or more.

Complementary continuous current meter data were collected in central Sepia Depression 2 m above sea bed west of the causeway between 22 July and 1 August and a net southward flow was returned by the records with average speeds of the order of 15 $cm s^{-1}$.

It would appear therefore, that apart from the severe NW storm event, the net flow in the southern metropolitan waters was southward. The winds were not predominantly from any one particular direction during the monitoring period and hence wind alone was not responsible for this net flow. The data set and analyses did not resolve what the dominant driving forcing was for the net southward flow.

Summer 1976 (17 Jan - 6 Feb 1976)

Under average conditions the net flow was northwards, and this was consistent with the net wind direction which was predominantly towards the NW or NE quadrants (reflecting the influence of typical summer afternoon SW sea breezes and SE offshore evening winds). These conditions led to an average inward flux of order 700 $m^3 s^{-1}$ and a maximum inward flux of 1300 $m^3 s^{-1}$, which equate to replacement times for the Sound's volume of 25 days and 13 days, respectively. Severe NW winds accompanying a passing cyclonic depression during 27-29 January caused outflows of the order of 1500 $m^3 s^{-1}$.

Complimentary continuous current meter data were collected in central Sepia Depression 2 m above sea bed west of the causeway between 17 Jan and 6 Feb and a net northward flow was returned by the records with average speeds of the order of 15 $cm s^{-1}$.

Autumn 1975 (27 Mar - 18 Apr 1975)

The direction of flow through the southern openings showed no clear preferred direction but oscillated inwards and outwards, with the amplitudes of the inwards and outwards oscillations being almost equal. Average flow rates were of the order of 500 $m^3 s^{-1}$, and extreme conditions resulted in flow rates of the order of 2000 $m^3 s^{-1}$, leading to equivalent replacement times for the Sound's volume of 35 and 9 days, respectively.

Average speeds for currents 2 m above the bottom in central Sepia Depression west of the causeway were of the order of 10 $cm s^{-1}$.

Spring 1974 (25 Jul - 19 Sep 1974)

The data from this current metering program for the southern openings returned similar results to those above for Autumn 1975, and the same average and extreme flow rates, and random directional characteristics resulted for flows through the southern openings.

No data were collected in Sepia Depression during spring 1974.

Summary

In summary, it would appear that flows through the causeway are generally northwards during summer and generally southwards during winter. During spring and autumn the mean flow direction undergoes reversal.

Before the causeway was constructed the only comprehensive flow monitoring exercises were conducted by ERA (Dec, 1971) across the then unconstricted southern opening. Those results indicated that flows through that opening were inward in summer and outward in winter, with maximum flow rates between 2000 and 3000 $m^3 s^{-1}$. Assuming the basin was continuously well-mixed vertically and horizontally then these flow rates would be equivalent to a range of replacement times for the Sound's total water volume of about 5-10 days. Flow direction was variable in spring and autumn and flow rates were lower than during summer or winter.

Since the construction of the causeway flow rates through the southern opening have decreased markedly. It would appear that net flow rates through the southern openings for average climatological conditions in summer and winter are now of the order of 550 to 700 $m^3 s^{-1}$, respectively, and of the order of 500 $m^3 s^{-1}$ for spring or autumn. This leads to a range of replacement times for the entire volume of Cockburn Sound water, assuming the basin is continuously well-mixed, of 25-35 days. It has been established by many past studies of the hydrodynamics of Cockburn Sound, and is again demonstrated in this report, that the Sound's water mass is generally stratified vertically and horizontally for average wind conditions, hence the assumption of a continuously well mixed basin is not valid. Therefore, the actual replacement time for the Sound's total volume of water could be different to past estimates. The exact flushing times of Cockburn Sound under various forcing scenarios have yet to be determined.

Hearn (1991) has also reviewed the results of numerical modelling exercises conducted during the 1970's (Steedman and Craig, 1979; Department of Housing and Construction, 1977). As discussed in Section 3.2, above, the models were two dimensional, vertically averaged and barotropic. They were run to predict flushing times for typical meteorological forcing scenarios for the pre and post causeway situation. Hearn (1991) has summarised the predicted flushing times from these exercises and points out that the models suggest that mean flushing times have increases by up to three times since the construction of the causeway. These results are consistent with the flow measurements under the bridges.

Appendix A8

Presentation and discussion of ST data (1978-1981) on the influence of winds to stratification in Cockburn Sound during spring.

A number of basin-scale salinity and temperature stratification data sets have been collated and presented in this Appendix. Winds fell into a number of speed categories, these being 0-5, 5, 5-8 and 10 m s^{-1}. It is instructive to now discuss the individual data sets according to the particular wind regime that occurred.

Wind = approx 0-5 m s^{-1}, NE or SE-SW

Salinity and temperature stratification data collected by DCE on 20 and 21 Sep 1978 along Transects CS8, CS1 and CS2 (see Figure 4.18, Chapter 4) have been plotted and presented in Figures A8.1 a, b and c. As indicated by the contour plots there was basin-scale vertical and horizontal temperature stratification but little vertical salinity stratification. This indicates the dominating influence of thermal stratification on density structure and the negligible influence of buoyancy flux from the Swan River outflow, which had been flowing at a rate of less than about 0.5-1.0 x 10^6 m^3 per day throughout the month. Winds were SSW and up to 7-10 m s^{-1} on 20-9-78 and 2-5 m s^{-1} on 21-9-78. The data present evidence of basin-scale stratification during what were relatively strong winds.

A diurnal measurement of vertical temperature structure was conducted by the DCE at Station 214 (see Figure 4.18) from the end of the CBH jetty (20 m depth) between 0800 September 20 and 1600 September 22, 1977. Individual profiles were generally 2-3 hours apart. Winds ranged from about 4-10 m s^{-1}. The data are produced as a time series contour in Figure A8.2 and, as shown, the water column was generally strongly stratified except during the period 1000-2400 of 21 September, during which time a 5-10 m s^{-1} wind event (SSW) occurred. The diurnal heating pattern is clearly evidenced, with vertical temperature differences (top minus bottom) of up to 4 ^{o}C produced during the day. This is equivalent to about 1 kg m^{-3} difference in density, and on the basis of the predictive analysis of wind mixing conducted in Sections 4.1.4 and 4.1.5, it is not surprising that winds of the order of 10 m s^{-1} were required to mix the water column to the bottom during the diurnal period of Figure A8.2.

Wind = approx 5 m s^{-1}, SSW

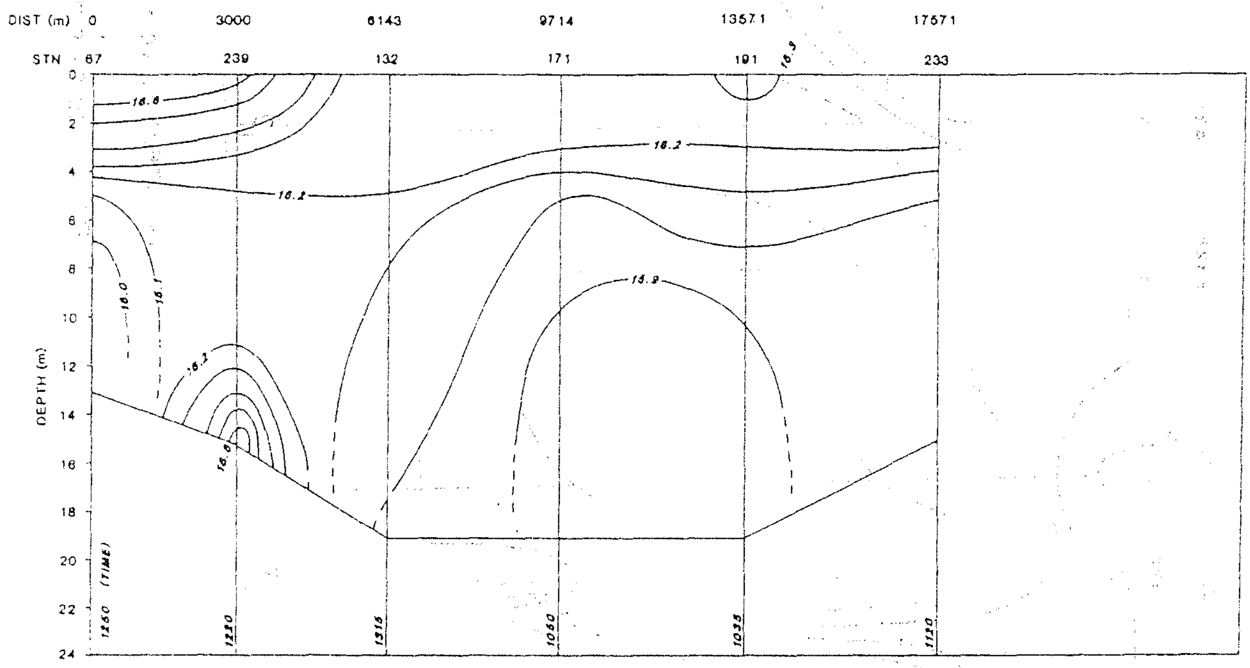
Further evidence of the ability of typical vertical density gradients in spring to resist mixing by winds of the order order of 5 m s^{-1} is given by the temperature-density stratification contour pairs in Figure A8.3, which is from a transect through Owen Anchorage and northern Cockburn Sound visited on 23 October 1981 (Binnie and Partners, Dec 1981). The wind had been blowing at about 5 m s^{-1} for 6 hours from the SSW and the vertical stratification persisted.

Wind = approx 5-8 m s^{-1}, SW

On 14 November 1978 the DCE measured the vertical ST stratification along Transect CS8 (see Figure 4.18) and the resulting contours have been plotted in Figure A8.4. As shown, there was vertical temperature stratification throughout the basin. Vertical temperature differences of up to 1 ^{o}C (top minus bottom) persisted during up to 4 hours of 5-8 m s^{-1} SW winds.

Wind = approx 10 m s^{-1}, S or SW

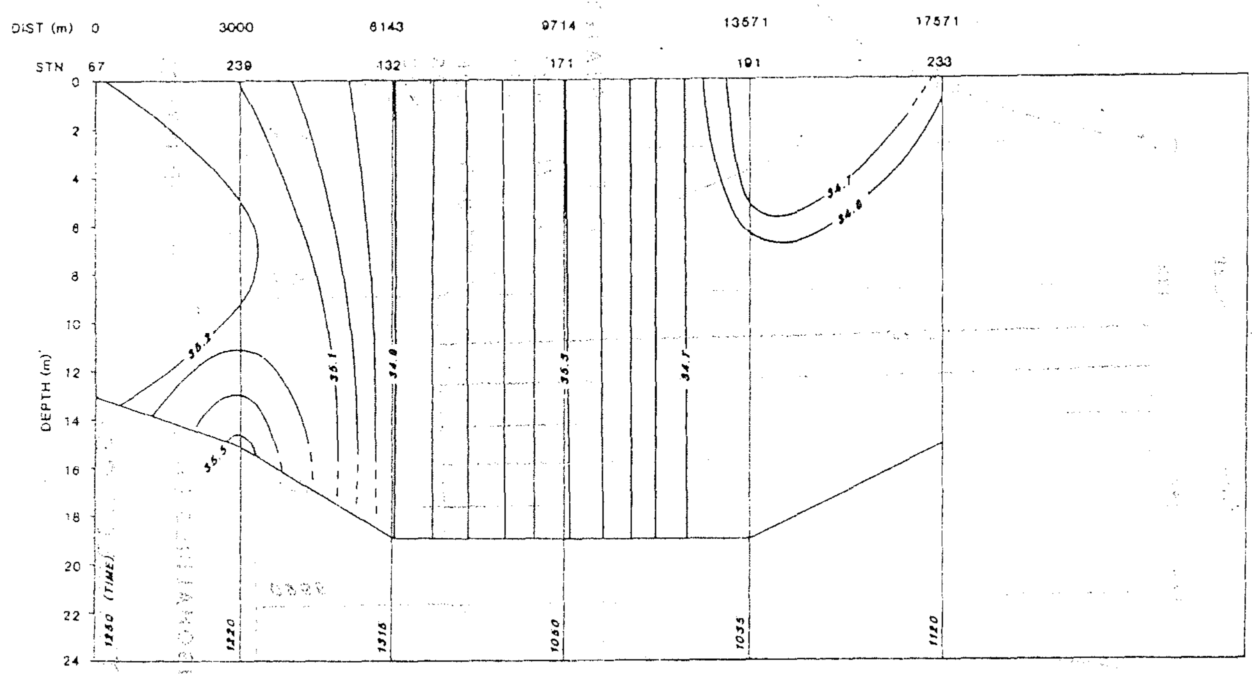
Two instances of 10 m s^{-1} winds are analysed here. First, we have already discussed the vertical homogeneity in density that existed during the 5-10 m s^{-1} southerly wind event of 21 September 1977, as shown in Figure A8.2. Secondly, in Figure A8.5 we present a north-south density contour plot from data collected on 24 Sep 1981 (Binnie and Partners, Dec 1981) when winds had been blowing at approximately 8 m s^{-1} for 6 hours from the SW. As shown, these winds mixed the water column down to at most 15 m.



ISOTHERMS (° C) CONTOUR INTERVAL 0.1° C

TRANSECT CS8 DATE 21-9-78

DATE	STATION
20-9-78	239
	132
	191
	233
21-9-78	67
	171



ISOHALINES (ppt) CONTOUR INTERVAL 0.1 ppt

TRANSECT CS8 **DATE 20-21/9/78**

Figure A8.1a Vertical temperature and salinity contours from a north-south transect (transect CS8, see Figure 4.18) through Owen Anchorage and Cockburn Sound from DCE salinity-temperature data collected on 20 and 21 Sep 1978.

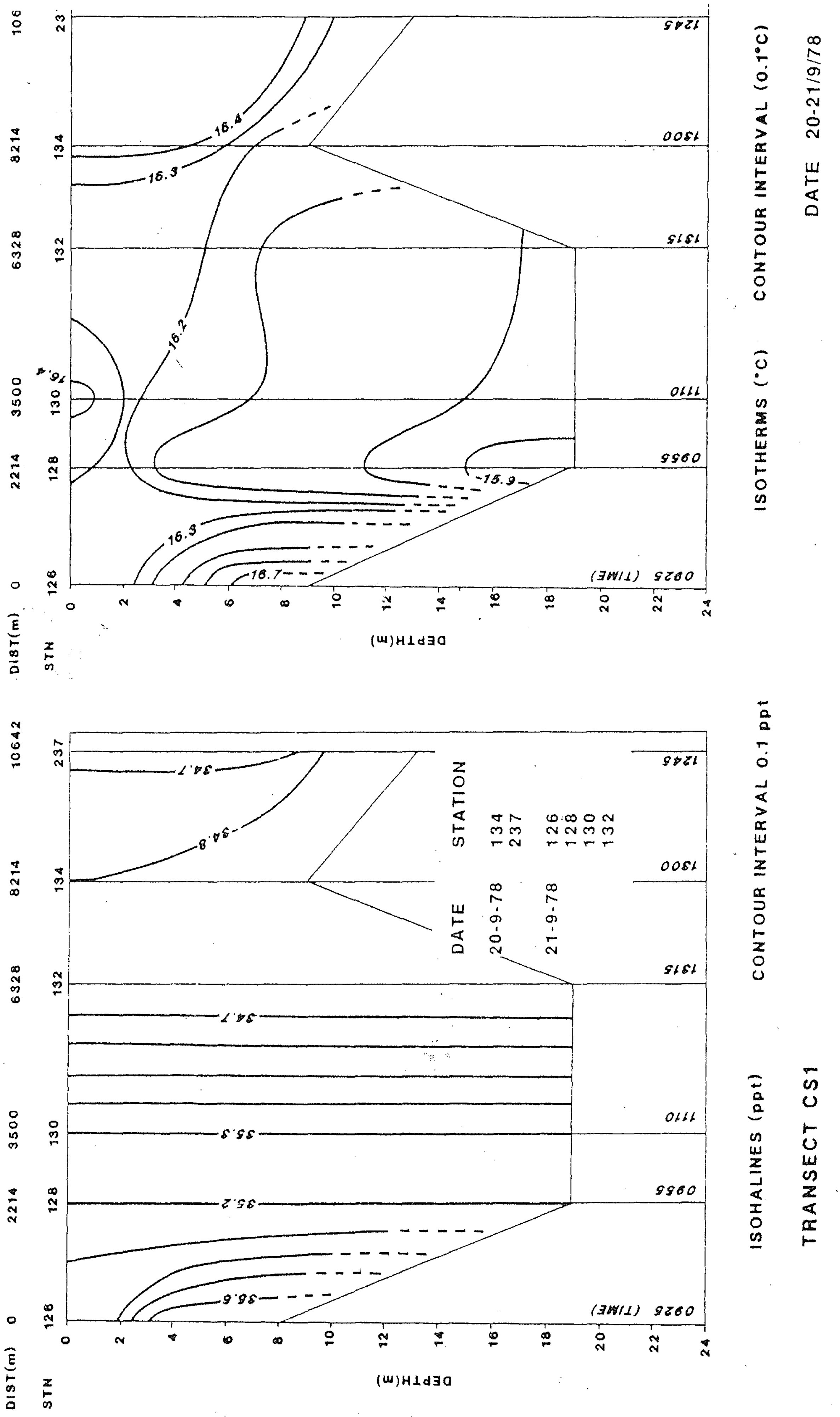


Figure A8.1b Vertical temperature and salinity contours from a west-east transect (transect CS1, see Figure 4.18) in Cockburn Cockburn Sound from DCE salinity-temperature data collected on 20 and 21 Sep 1978.

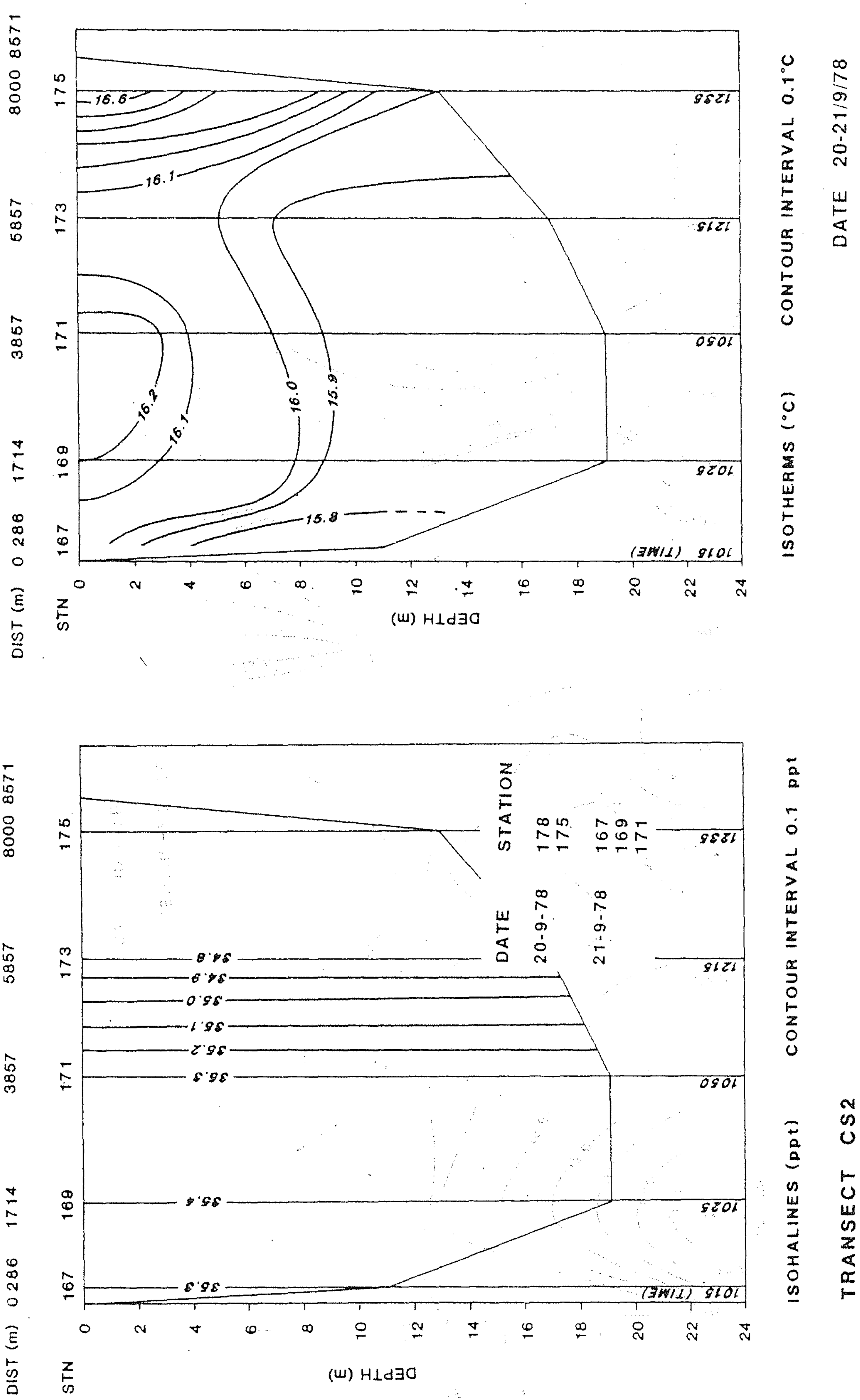


Figure A8.1c Vertical temperature and salinity contours from a west-east transect (transect CS2, see Figure 4.18) in Cockburn Cockburn Sound from DCE salinity-temperature data collected on 20 and 21 Sep 1978.

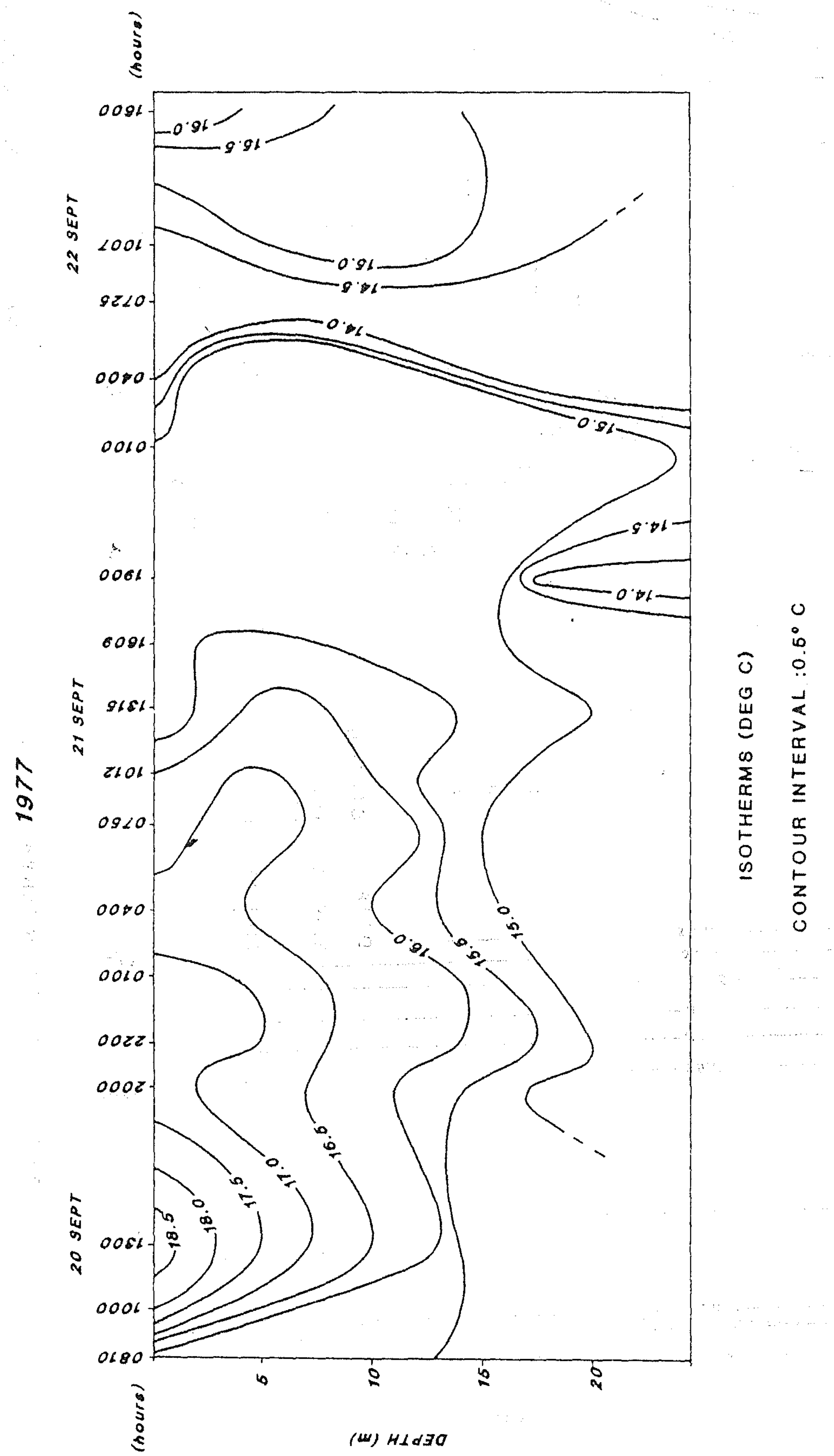


Figure A8.2 Time series contour plot of vertical temperature structure at DCE site 214 (see Figure 4.18) collected at the end of the CBH jetty in 20 m of water at approximately hourly intervals from 0810 20-9-77 to 1600 22-9-77.

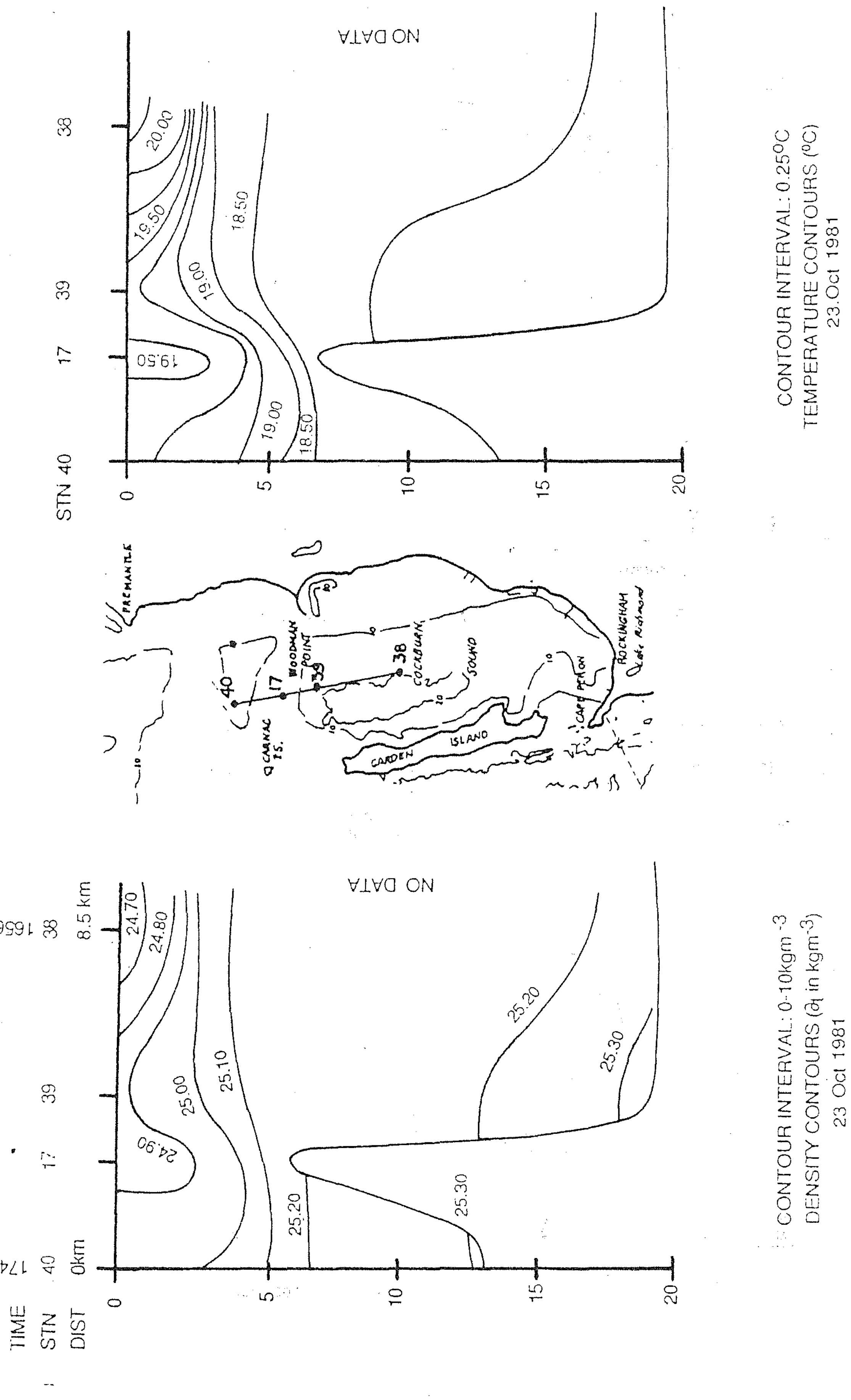
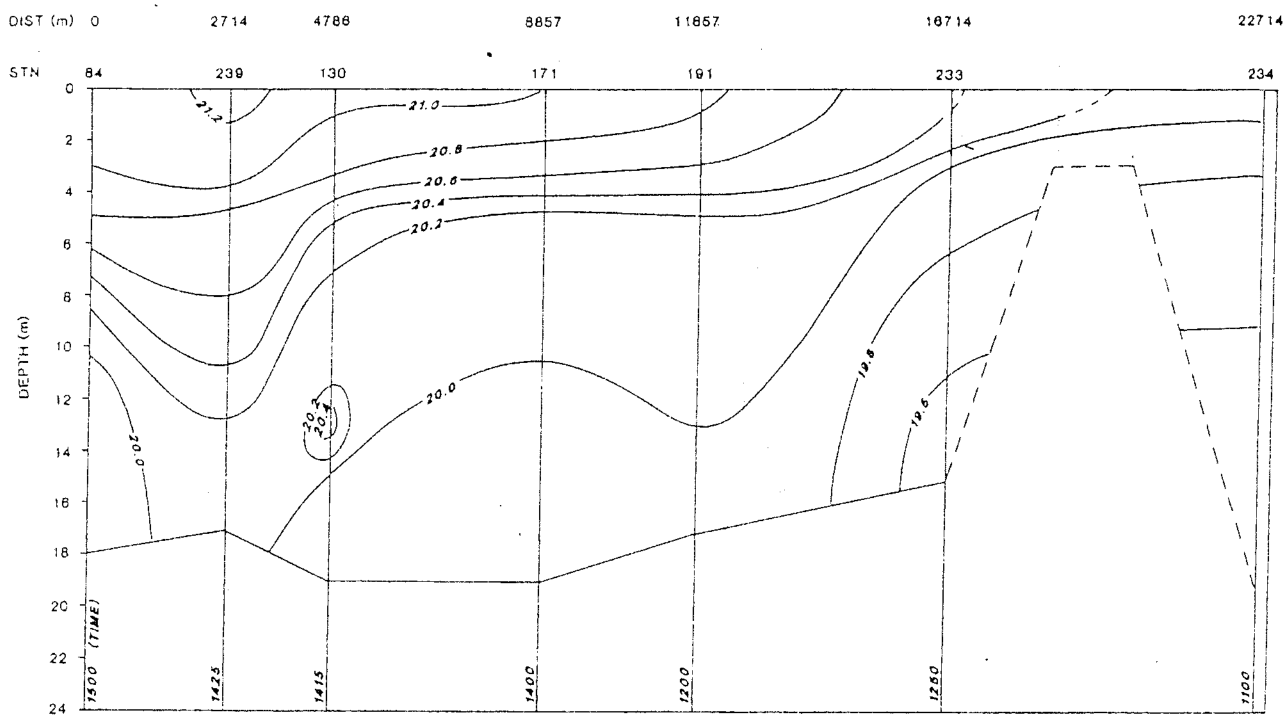
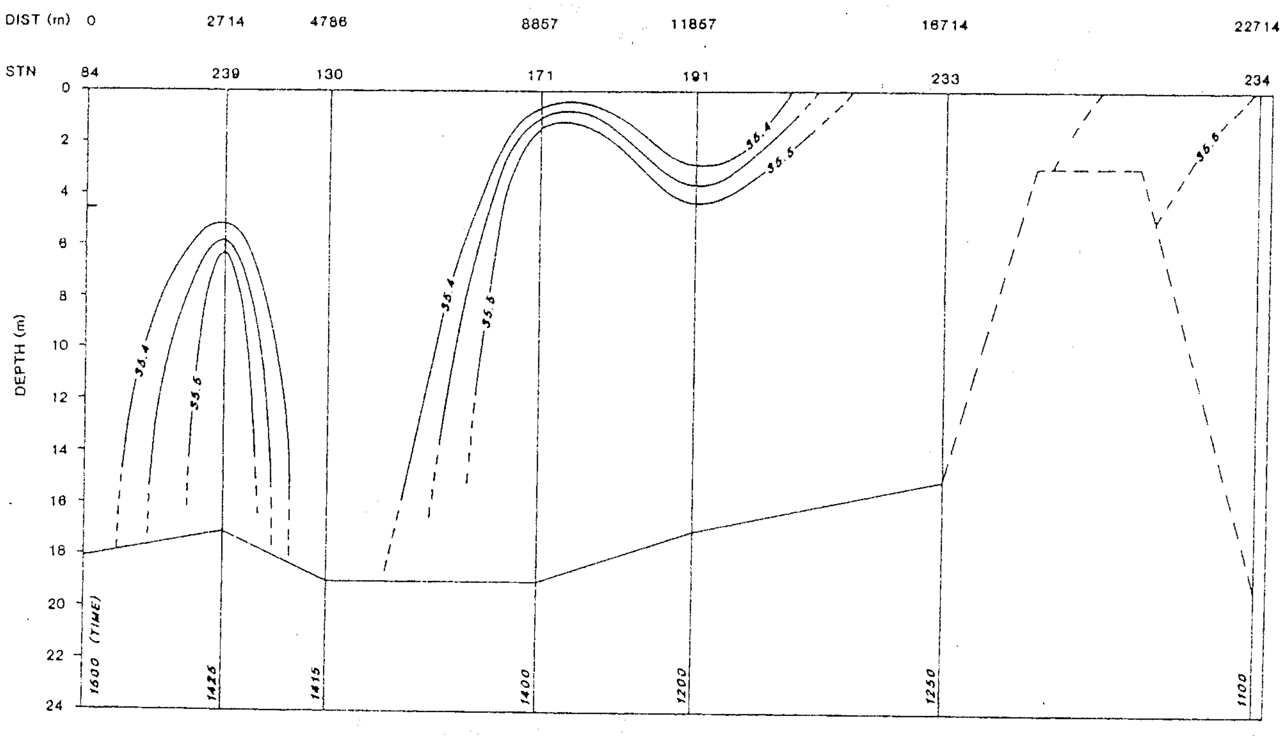


Figure A8.3 Vertical contour plots of density and temperature structure along a north-south transect (see map inset) in Owen Anchorage and northern Cockburn Sound from vertical ST profile data collected by R K Steedman and Associates (in Binnie and Partners, Dec 1981) on 23 Oct 1981.



ISOTHERMS (° C) CONTOUR INTERVAL 0.2° C

TRANSECT CS9 DATE 14-11-78



ISOHALINES (ppt) CONTOUR INTERVAL 0.05 ppt

TRANSECT CS9 DATE 14-11-78

Figure A8.4 Vertical temperature and salinity contours from a north-south transect (transect CS9, see Figure 4.18) through Owen Anchorage and Cockburn Sound from DCE salinity-temperature data collected on 14 Nov 1978.

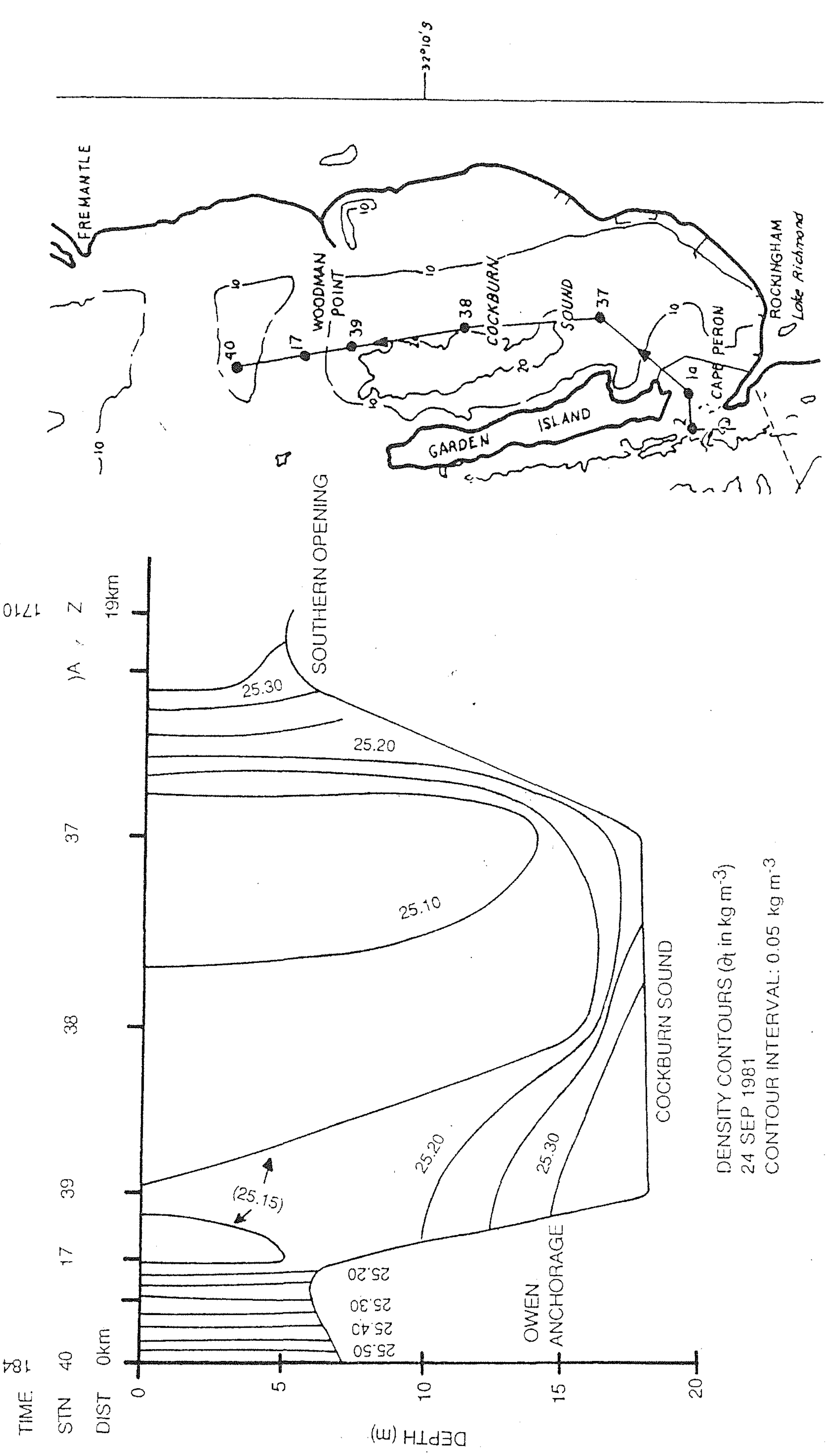


Figure A8.5 Vertical contour plot of density structure along a north-south transect (see map inset) in Owen Anchorage and northern Cockburn Sound from vertical ST profile data collected by R K Steedman and Associates (in Binnie and Partners, Dec 1981) on 24 Sept 1981.