The application of a three dimensional baroclinic model to the hydrodynamics and transport of Cockburn Sound, Western Australia.

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

Department of Environmental Protection
Perth, Western Australia, 6000
Technical Series 76
December 1995

ISBN 0 7309 8066 9
ISSN 1328-7230

The application of a three dimensional baroclinic model to the hydrodynamics and transport of Cockburn Sound, Western Australia.

D. A. Mills and N. D'Adamo

Department of Environmental Protection
Perth, Western Australia, 6000.

Contents

		Page
Acknowledgments		
Abstract		
1.	**Introduction**	**1**
2.	**Description of the study area**	**2**
3.	**Hydrodynamic model**	**6**
	3.1 Model requirements	6
	3.2 Description of the model	7
4.	**Hydrodynamic modelling of Cockburn Sound**	**8**
	4.1 Aims	8
	4.2 Model domain and grid	8
	4.3 Model initialisation, forcing and parameterisation	9
5.	**Model validation**	**11**
6.	**Modelling the seasonal hydrodynamic regimes of Cockburn Sound**	**15**
	6.1 Introduction	15
	6.2 Modelling the 'winter spring' hydrodynamic regime of Cockburn Sound	16
	6.3 Modelling the 'autumn' hydrodynamic regime of Cockburn Sound	22
	6.4 Modelling the 'summer' hydrodynamic regime of Cockburn Sound	29
7.	**Effects of the Garden Island Causeway on the flushing of Cockburn Sound**	**35**
	7.1 Introduction	35
	7.2 Past studies	35
	7.3 Application of a three dimensional baroclinc model	36
	7.4 Effects of the Garden Island Causeway on the 'autumn' regime	36
	7.5 Effects of the Garden Island Causeway on the 'winter-spring' regime	37
8.	**Dispersion of effluent in Cockburn Sound**	**42**
	8.1 Introduction	42
	8.2 Far-field dispersion of effluent in Cockburn Sound	43
9.	**Discussion**	**43**
	9.1 Seasonal hydrodynamic regimes	43
	9.2 Effects of the Garden Island Causeway	46
	9.3 Far-field dispersion of effluent	46
10.	**References**	**47**
11.	**Appendix 1**	**51**

Figures

1. Location map of the study area. 3
2. Bathymetry of the study area. 4
3. Domain for the hydrodynamic model simulations showing locations of current meter sites. 8
4. Wind data input from (a) Naval Base and (b) Rottnest Island for the barotropic model validation. The wind data are presented as speed and direction time series and progressive vector runs. 12
5. Comparison at (a) site 1 and (b) site 2 between measured and modelled currents from the barotropic model validation, driven by winds in Figure 4. 14
6. The annual cycle in the salinity and temperature differences (at 10 m depth) between Cockburn Sound and the mid-shelf, southwest of Rottnest Island. The influence of major forcings on the cross-shelf differences are indicated for each of the six categories (I to VI) within the cycle. The diagonal lines are contours of density difference and data above/below the central contour indicate that Cockburn Sound is less/more dense than mid-shelf water (after D'Adamo and Mills, 1995b). 16
7. Wind data used for the baroclinic model simulation of wind-driven flushing and deep-water renewal in Cockburn Sound under post-storm 'winter' conditions: (a) time series and (b) progressive vector run. 17
8. Starting horizontal salinity field for the baroclinic model simulations of the 'winter' hydrodynamics of Cockburn Sound. 17
9. South-north vertical salinity sections showing deep-water renewal in Cockburn Sound during the post-storm period of 20-23 August 1991 from (a-c) baroclinic model simulations and (d-f) field measurements (wind data as in Figure 7). Measured salinity was projected onto the model transect path (g). 18
10. Baroclinically modelled flushing rates for three depth zones (whole depth, < 5 m and > 15 m) of Cockburn Sound from a 'winter' (18-23 August 1991) simulation under wind conditions shown in Figure 7. 19
11. Schematic of modelled volume fluxes across the openings and an inner west-east section of Cockburn Sound from a 'winter' (18-23 August 1991) baroclinic simulation under winds shown in Figure 7. Volume fluxes are expressed as a percentage of total outflow. 20
12. Baroclinic model simulation of density-induced exchange (with no wind forcing) between buoyant Cockburn Sound water (set at 34.4 pss) and dense shelf water (set at 35.0 pss) after one, three and six days, showing (a) surface salinity, (b) bottom velocity and (c) bottom salinity. 21
13. Starting horizontal salinity field for the baroclinic model simulations of the 'autumn' hydrodynamics of Cockburn Sound. 22
14. Wind data used for the baroclinic model simulation of exchange between Cockburn Sound and shelf waters under 'autumn' conditions: (a) time series and (b) progressive vector run. 23

15. Baroclinically modelled surface salinity fields representing 'autumn' exchange between dense Cockburn Sound water and buoyant shelf water forced by winds (from Figure 14) after (a) 4.5 days (b) 5.5 days and (c) 6 days. 23

16. Baroclinically modelled surface current fields representing the 'autumn' exchange between dense Cockburn Sound water and buoyant shelf water forced by winds (from Figure 14) after (a) 4.5 days (b) 5.5 days and (c) 6 days. 24

17. Baroclinically modelled south-north vertical salinity structure representing the 'autumn' exchange between dense Cockburn Sound water and buoyant shelf water forced by winds (from Figure 14) at (a) 4.5 days (b) 5.5 days and (c) 6 days. 25

18. Vertical density and salinity structure in Cockburn Sound and adjacent waters on 3 May 1994 showing autumn stratification. 26

19. Baroclinically modelled flushing rates for three depth zones (whole depth, < 5 m and > 15 m) of Cockburn Sound from an 'autumn' simulation (wind data as in Figure 14). 27

20. Schematic of modelled volume fluxes across the openings of Cockburn Sound from a baroclinic 'autumn' simulation (wind data as in Figure 14). Volume fluxes are expressed as a percentage of total outflow. 27

21. Baroclinically modelled south-north vertical salinity structure of Cockburn Sound under 'autumn' conditions after 5 days of constant easterly winds at 5 m s^{-1}. 28

22. Baroclinically modelled flushing rates of deep Cockburn Sound water (> 15 m depth) for the entire basin and for the southern part of the basin (between James Point and the causeway) from an 'autumn' simulation. The model was forced with real winds as shown in Figure 14 for 0-2.3 days, and thereafter by a constant easterly 5 m s^{-1} wind. 28

23. Baroclinically modelled surface salinity and velocity fields representing density-induced exchange between dense Cockburn Sound and buoyant shelf waters during calm 'autumn' conditions after (a) 1 day and (b) 4 days. 30

24. Starting horizontal distribution of tracer concentration for the barotropic model simulations of the 'summer' hydrodynamics of Cockburn Sound. Vertical distribution of tracer is uniform. 31

25. Wind data used for the barotropic model simulation of the hydrodynamics of Cockburn Sound under typical 'summer' conditions: (a) time series and (b) progressive vector run. 32

26. Barotropically modelled horizontal velocity fields at (a) 1 m depth (b) 7 m depth and (c) 12 m depth from the 'summer' simulation of Cockburn Sound and shelf waters responding to south-southwesterly winds after 6 days of wind data as in Figure 25. 32

27. Barotropically modelled vertical profile of current speed and direction for Cockburn Sound (eastern margin) from the 'summer' simulation of the sound and shelf waters after 6 days (wind data as in Figure 25). 33

28. Barotropically modelled horizontal velocity fields at (a) 1 m depth (b) 7 m depth and (c) 15 m depth from the 'summer' simulation of Cockburn Sound and shelf waters responding to east-northeasterly winds after 11 days of wind data as in Figure 25. 33

29. Barotropically modelled flushing rates for three depth zones (whole depth, < 5 m and > 15 m) of Cockburn Sound from the 'summer' simulation (wind data as in Figure 25). 34

30. Successive time intervals required for cumulative volume inflows to equal the volume of Cockburn Sound from the 'summer' barotropic simulation (wind data as in Figure 25). 34

31. Baroclinically modelled surface salinity fields from the 'autumn' simulations (a) with the causeway and (b) without the causeway after 3.5 days and (c) with the causeway and (d) without the causeway after 5.5 days. Shading indicates a salinity greater than 35.8 pss. 38

32. Baroclinically modelled south-north vertical salinity structures from the 'autumn' simulations (a) with the causeway and (b) without the causeway after three days and (c) with the causeway and (d) without the causeway after 5.5 days. Shading indicates a salinity greater than 35.8 pss. 39

33. Baroclinically modelled flushing rates for Cockburn Sound comparing 'autumn' simulations with and without the causeway for three depth zones: (a) 0-5 m, (b) > 15 m and (c) total depth. 40

34. Baroclinically modelled south-north vertical salinity structure from the 'winter' simulations (a) with and (b) without the causeway after 3 days (winds as in Figure 7). Shading indicates a salinity greater than 34.1 pss. 40

35. Baroclinically modelled horizontal velocity fields at a depth of 18 m from the 'winter' simulations (a) with and (b) without the causeway after 3 days (wind data as in Figure 7). 41

36. Baroclinically modelled flushing rates for Cockburn Sound comparing 'winter' simulations with and without the causeway for three depth zones, (a) 0-5 m, (b) > 15 m and (c) total depth. 42

37. Far-field dispersion of effluent released from south of James Point: (a) relative concentration of cadmium in surface waters derived from measurements on 28 December, 1978 (adapted from Rosman *et al.* 1980), and (b) relative tracer concentration patterns in surface waters after a 10.5 day barotropic simulation forced by recorded winds for the period 18-28 December 1978. 44

38. Comparison of modelled flushing rates for Cockburn Sound from three simulations using the same wind forcing (as in Figure 14) but with starting salinity distributions for 'autumn', 'summer' and 'winter', respectively, for (a) 0-5 m depth, and (b) > 15 m depth. 45

Tables

1. Levels of the model sigma surfaces and thicknesses of the model sigma layers (expressed as fractions of the local depth of the water column). The sea surface level is denoted as 0.0 and the sea bed as -1.0. 9

2. Boundary condition settings at the open boundaries of the model. 10

3. Mean error and root mean square (Rms) error for the simulated north-south and east-west components of the currents for the three-dimensional barotropic model validation. 13

Acknowledgments

The authors thank the many people who assisted during the course of this investigation. Dr John Hunter suggested the use of the Princeton Ocean Model. Dr Mike Herzfeld and Professor Matt Tomczak (formerly of The Flinders University of South Australia) made available the C-language version of the Princeton Ocean Model and provided invaluable advice on its application. Victor Essers gave programming support for the model data management and post-processing of the model results. The WA Department of Transport (Maritime) provided bathymetric data. Environmental Sciences and Engineering Pty Ltd reformatted and transferred these data. David Griffiths and Dr Peter Rye of DEP provided advice and performed computer systems management. The Air Quality Monitoring Branch of DEP supplied meteorological data. Mike Forde, Mike Lapwood and Tim Daly serviced instruments in the field and Mike Pannell helped to process the field data. Craig Manning edited and formatted the penultimate draft of this paper. Dorothy Chipper undertook the desktop publication of the report. Dr Chris Simpson and Dr Ray Masini offered managerial support and encouragement.

Dr Lance Bode (James Cook University of North Queensland) kindly reviewed a draft of this Technical Series Report and Dr Clifford Hearn (Australian Defence Force Academy, Canberra) reviewed this modelling work as presented in the Southern Metropolitan Coastal Waters Study Final Report.

The State Government of Western Australia supported the Southern Metropolitan Coastal Waters Study within which this work was undertaken.

Abstract

Three-dimensional numerical hydrodynamic modelling investigations of Cockburn Sound were conducted by the Department of Environmental Protection as part of its studies (from 1991-1994) into the marine ecology of Perth's southern coastal zone. The aims of this work were to better understand the exchange fluxes between Cockburn Sound and surrounding waters, the flushing times and internal circulation of the sound and the far-field spread of effluent plumes. The model, a derivative of the Princeton Ocean Model, satisfactorily hindcast currents measured in eastern Cockburn Sound and in Sepia Depression. The model was able to simulate the main characteristics and temporal changes in the measured salinity fields. Baroclinic simulations have shown that underlying seasonal density differences between the sound and external shelf waters significantly affect the wind-driven exchange, circulation and flushing of Cockburn Sound. Three broad 'seasonal' regimes were identified from field data and modelled. In 'winter', estuarine plume water is driven into the sound and then fully vertically mixed by storm winds. Following the storm, buoyant surface water is transported out of the sound and replaced by relatively dense shelf water which subsides and moves across the sea bed of the sound's 20 m deep basin. In 'autumn', relatively buoyant water is driven in across the shallow sills at the entrances of the sound and forms buoyant, stratified surface layers which confine and isolate deep basin water from exchange. Under well-mixed conditions in 'summer' the three-dimensional water flow generally consists of a directly wind-driven surface layer overlying a deeper circulation composed mainly of topographic gyres.

Further modelling has shown that, in the absence of wind, tide and long-shelf pressure gradient forcings, the presence of contrasting embayment-shelf density differences in 'winter-spring' and 'autumn' gives rise to distinct patterns of baroclinic exchange during these 'seasons'. Under these conditions of baroclinic exchange the basin-scale flushing for Cockburn Sound is much more rapid and efficient than if tidal processes acted alone. With the addition of winds of about 5 m s^{-1} or more, the exchange rates are substantially increased beyond those for density-driven relaxation alone. For winds up to 10 m s^{-1}, exchange in the presence of shelf-embayment density differences results in the introduction of vertical stratification to the sound.

In each of the three-dimensional simulations the two-way volume exchange across the northern entrance to Cockburn Sound was greater by a factor ranging from 2 to 3.5 compared to the magnitude of flow through the causeway bridge openings at the southern entrance. Previous two-dimensional model studies had concluded that this factor was close to unity. The total (combined) volume exchange rate via both the northern and southern entrances of Cockburn Sound has been reduced as a result of the causeway construction, though the three-dimensional modelling results suggest that the reduction is about 30 %, rather than the 50 % suggested by previous two-dimensional modelling. The 'autumn', 'winter-spring' and 'summer' circulation and flushing regimes were predicted to occur both in the presence and absence of the causeway, in response to the annual cycle of density differences between shelf and embayment waters. Comparing the results of the baroclinic simulations, with and without the causeway, it was concluded that the most significant differences in the modelled salinity and advection fields in Cockburn Sound occurred near the southern end of the sound.

In modelling the dispersion of water-borne contaminants in Cockburn Sound it was shown that sub-basin scale transport models can not fully account for basin-scale recirculation of contaminant which occurs within the sound, but beyond the model domain. Under barotropic conditions contaminant released just south of James Point has a long residence time in Cockburn Sound. For example, the model predicted that, at the end of an 11 day period in December 1978, 80 % of contaminant emitted during that period was still resident in the sound. Modelling of far-field dispersion from a continuous tracer source in Cockburn Sound therefore requires that sufficient simulation time be allowed for the concentration field to develop. The model was able to reproduce the main spatial features of an actual

contaminant field measured under summer conditions. The far-field modelling of materials dispersion in Cockburn Sound under conditions typical of the 'autumn' and 'winter-spring' hydrodynamic regimes will require that the model include density effects, to realistically simulate advection and transport fields.

1. Introduction

This paper summarises the numerical hydrodynamic modelling investigations of Cockburn Sound that were conducted by the Department of Environmental Protection as part of its studies (from 1991-1994) into the marine ecology of Perth's southern coastal zone. The Southern Metropolitan Coastal Waters Study (SMCWS) aimed to provide a better understanding of the cumulative environmental impacts of contaminants entering these waters (Simpson *et al.* 1993) and a better basis for environmental management.

The hydrodynamic modelling was carried out in conjunction with water quality and oceanographic field studies (Cary *et al.* 1995; D'Adamo and Mills, 1995a, b, c; D'Adamo *et al.* 1995) to investigate water circulation and mixing patterns of the study area in response to a range of meteorological, oceanographical and hydrological conditions. In the context of the SMCWS, the aims of the hydrodynamic modelling were to determine the major hydrodynamic transport pathways of water-borne substances and to determine the flushing characteristics of the marine embayments, in this case, Cockburn Sound.

The use of numerical hydrodynamic modelling in environmental management studies of this nature has increased steadily and in the past few years three-dimensional baroclinic models have been applied to refine the understanding of the hydrodynamics of some systems. Confidence in the ability of a model to provide realistic simulations should be established by obtaining satisfactory agreement between model results and oceanographic field data sets collected under a variety of known forcing conditions in a given area. Once this has been achieved the model simulations are able to complement the understanding derived from field surveys by providing results at a much finer spatial and temporal resolution than would be economically feasible with field survey techniques. The simulations can also be designed to examine alternative scenarios, not encountered in the field surveys, involving changed bathymetry (for example, due to proposed construction works), different contaminant input rates and locations, and other combinations of forcing conditions.

The field and modelling studies reported here have highlighted major hydrodynamic processes which contribute to the circulation, mixing and flushing of Cockburn Sound. These include baroclinic and barotropic (non-baroclinic) processes. *Baroclinic* processes involve horizontal differences in water density which modify the fluid pressure distribution and thereby influence the horizontal momentum balance of the water. In addition, vertical density stratification influences the efficiency of vertical mixing processes. Density gradients arise from heterogeneities in the temperature and salinity of the seawater. The oceanographic field data for the study area indicate that stratification, in the form of horizontal and/or vertical gradients of temperature and salinity, is almost invariably present (D'Adamo, 1992). The potential importance of density effects, including baroclinic processes, to circulation, mixing and flushing in the study area has been acknowledged in previous studies (e.g. Steedman and Craig, 1979, 1983; Hearn, 1991) but not studied in detail. Both the field measurement and modelling components of the SMCWS were designed to provide further understanding of their role and importance.

The bathymetry, meteorological and oceanographical characteristics of Cockburn Sound and its surrounding waters are described in Section 2. The hydrodynamic model used to study this area is described in Section 3 and its specific application to the study area is outlined in Section 4. Experiments designed to validate the model against measured currents are described in Section 5, while the main modelling results, presented in Section 6, focus on the basin-scale hydrodynamics of Cockburn Sound. Section 6 presents the simulation of three distinct seasonal hydrodynamic regimes for Cockburn Sound, the nature of each being determined primarily by the horizontal density differences between the sound and the surrounding shelf waters, and by wind forcing. Section 7 briefly examines the effects of the Garden Island Causeway on the flushing of Cockburn Sound, while Section

8 compares field observations and model results of the basin-scale transport and dispersion of materials released from a point source in Cockburn Sound.

2. Description of the study area

Bathymetry

Cockburn Sound is situated on the southwest coast of Western Australia, near metropolitan Perth, and extends from about 10 km to 26 km south of the Swan-Canning Estuary ocean mouth at Fremantle (Figures 1 and 2). The western side of the sound is bordered by Garden Island. Between Garden Island and the submerged Five Fathom Bank lies the channel-like Sepia Depression, west of which is the open continental shelf.

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

Meteorology

The synoptic-scale weather patterns of the region are controlled by the migration of the anticyclonic belt from about 40 ^{o} S in January to 30 ^{o} S in July. This belt rotates eastward around the globe and results in synoptic variations in the barometric pressure field at periods of about 7-10 days, with synoptic weather patterns broadly reflecting this periodicity.

From about October to March stable anticyclonic pressure cells produce a predominantly easterly airflow over southwest Australia. From June to September the anticyclonic pressure systems and accompanying westerly winds (the roaring forties) are periodically displaced by low pressure cyclonic systems that move rapidly eastwards bringing strong winds (~ 20 m s^{-1}) and rain. Through much of the year local diurnal heating and cooling along the coastline results in a land-sea breeze cycle which is superimposed on the regional pattern, most noticeably in summer. Wind speeds in the Perth region are generally between about 5 and 15 m s^{-1}. Sea-breeze winds from the southwest quadrant occur on over 250 days each year although the strongest sea-breezes (10-15 m s^{-1}) occur mainly during the late-spring to summer period (Hearn, 1991). Apart from during storms (> 10 m s^{-1}), the wind field becomes weaker and more variable throughout autumn and winter.

The annual average rainfall for the Perth region is about 900 mm with over 80 % occurring from May to September. The freshwater discharge pattern from the Swan-Canning and Peel-Harvey estuaries follows that of rainfall, but with a lag of about 1 month. The annual average evaporation is about 1700 mm with maximum and minimum rates of about 9 mm d^{-1} and 2 mm d^{-1} occurring in January and June, respectively.

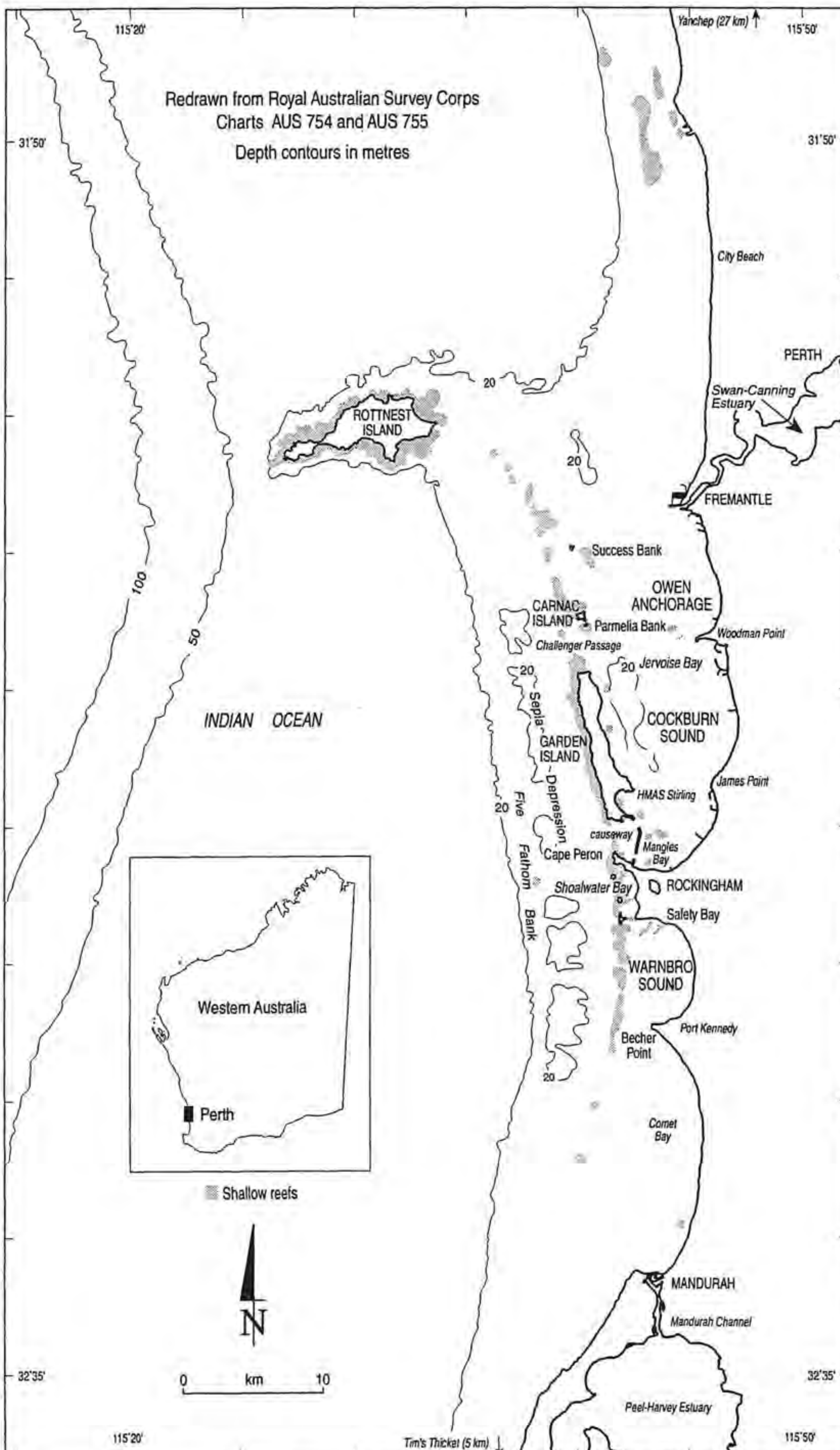

Figure 1. Location map of the study area.

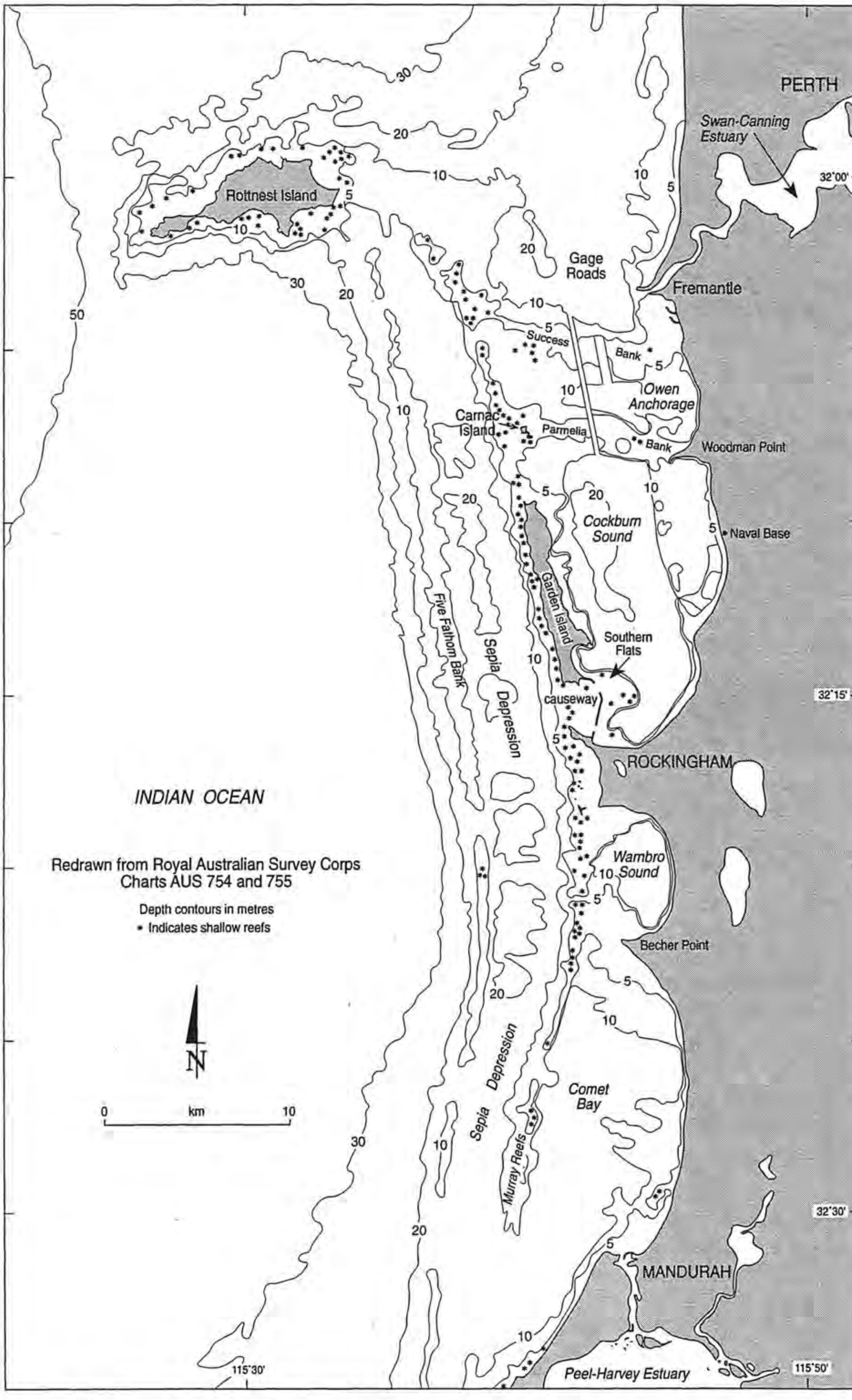

Figure 2. Bathymetry of the study area.

Tides and barometrically forced water level variations

The tides of southwest Australia are relatively small and mainly diurnal. The predicted astronomical tidal range at Fremantle varies from about 0.1 to 0.9 m (Department of Defence, 1994) and the annual mean range is about 0.5 m (Hearn, 1991). Tidal currents for the Perth shelf are typically less than about 0.02 m s^{-1} (Steedman and Craig, 1983; Hearn *et al.* 1985; van Senden, 1991; Pattiaratchi *et al.* 1995).

Variations from predicted astronomical tide heights are mainly due to barometric pressure variations and wind effects. In combination, these meteorological effects can generally alter the water level by up to about 0.3 m during synoptic cycles. It is estimated that low frequency oscillations can cause currents of order 0.01-0.1 m s^{-1} in the shelf zone off Perth (Hearn, 1991; van Senden, 1991).

Local and regional scale circulation and the influence of the Leeuwin Current

The Leeuwin Current typically flows over the outer continental shelf and slope as a warm, low salinity tropical mass, driven by a north to south steric height gradient (Godfrey and Ridgeway, 1985). It is strongest from about March/April to September/October, and is weakened in spring/summer primarily in response to the strength of opposing south-southwesterly winds (Smith *et al.* 1991). The eastern edge of the Leeuwin Current water mass can approach the nearshore zone as a strong temperature/density front and influence the transport of inner shelf waters (Mills *et al.* 1996).

The inner shelf currents have speeds of order 0.1 m s^{-1} (Hearn, 1991; Steedman and Associates, 1981; Pattiaratchi *et al.* 1995). They are primarily wind-driven and bathymetrically controlled, with secondary influences from long-shelf pressure gradients and density effects. In winter, current reversals occur mainly in response to major wind shifts, typically at 3 to 5 day intervals. In summer the currents are driven predominantly northward by prevailing winds from the southerly quadrants. Long-term current meter data (Steedman and Associates, 1981) show that the waters of the inner shelf off Cockburn Sound have a net southward flow in autumn-winter and a net northward flow in summer.

The volume rate of Cockburn Sound throughflow is limited by frictional impedance. Since the cross-sectional area at the southern entrance is several orders of magnitude less than typical cross-sectional areas of the sound, the throughflow has only the potential to generate very weak currents throughout most of the sound.

In sounds and semi-enclosed embayments the wind stress lowers the sea level against the upwind coast and raises the sea level against the downwind coast, resulting in a horizontal pressure gradients which, in conjunction with the wind stress and non-uniform bathymetry, lead to local circulation patterns referred to as topographic gyres (Csanady, 1982). Depth-averaged modelling of Cockburn Sound by Maritime Works Branch (1977a), Steedman and Craig (1979, 1983) and Speedy (1994) indicate the presence of such wind-driven gyres in Cockburn Sound and suggest that these are major contributors to circulation within the sound.

As indicated above, tidal current speeds in the study area are generally very weak, of order 0.01 m s^{-1} in open shelf waters and broad coastal embayments. However they may be stronger near narrow channels or shallow banks and reefs (eg. Speedy, 1994).

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

Density effects

Pearce and Church (submitted) and Hodgkin and Phillips (1969) have demonstrated that the salinity and temperature properties of nearshore and shelf waters differ due to various factors such as differential heating and cooling, differential exposure to the Leeuwin Current, differential salinity increases due to evaporation, and the influence of freshwater runoff. In turn, these salinity and temperature differences determine water density differences. The interaction and response of adjacent water masses with distinct temperature-salinity-density characteristics to forcings such as wind and pressure gradients depends on the density differences between these water masses and the energy available for mixing.

D'Adamo (1992) reviewed past data and concluded that density stratification (horizontal and/or vertical) was almost always present in Perth's nearshore coastal waters. Vertical density stratification influences the way in which the wind-induced momentum is mixed through the water column, and therefore influences the circulation. The presence of horizontal density gradients which influence the pressure field, introduces additional forces driving the motion.

The salinity-temperature-density structure of the southern metropolitan coastal waters was further investigated to determine the annual cycles of shelf and Cockburn Sound water properties (D'Adamo and Mills, 1995b) and to help characterise hydrodynamic processes and regimes, particularly in relation to the mixing and flushing of Cockburn Sound (D'Adamo and Mills, 1995a, 1995c; D'Adamo *et al.* 1995). Routine conductivity-temperature-density (CTD) surveys were undertaken every 1-2 months during 1991-93 to achieve this objective. The key oceanographic processes identified in these surveys were examined in detail during intensive CTD field exercises which captured typical winter (August 1991), summer (March 1992) and autumn (May 1994) conditions, These surveys were supported by current meter, satellite, meteorological and hydrological data acquisition. The findings of these studies provided the basis for the implementation of a three-dimensional baroclinic numerical model to simulate the circulation of these waters.

The dynamical response of a vertically stratified water body has a characteristic length scale due to the earth's rotation, known as the baroclinic radius of deformation (Csanady, 1982). For Perth's coastal waters vertical density stratification is typically in the range of 0.1 to 0.5 kg m^{-3} in 20 m water depth (D'Adamo and Mills, 1995b) and the baroclinic radius of deformation in Perth's coastal embayments, channels and inner-shelf is in the range 1-3 km. The horizontal dimensions of Cockburn Sound (about 15 km long and up to 10 km wide) are larger than this baroclinic radius of deformation so that the response of its density structure should be significantly influenced by the earth's rotation.

Horizontal gradients of density may result from buoyancy fluxes, non-uniform vertical mixing, upwelling of the density structure and other causes. If the wind weakens appreciably, then baroclinic adjustment flows (e.g. Gill, 1982) may occur, as the water body tends toward a state of gravitationally stable equilibrium.

3. Hydrodynamic model

3.1 Model requirements

The hydrodynamic modelling of Cockburn Sound was based on reviews of the local and regional oceanography (Hearn, 1991; D'Adamo, 1992), the findings of the SMCWS oceanography characterisation phase (D'Adamo and Mills, 1995a, b, c; D'Adamo *et al.* 1995) and on a review of available models. The reviews and characterisation confirmed the importance of wind as a primary driving force for the currents and highlighted the fine balance existing in the study region between natural stabilising processes that cause lighter water to move over or form above heavier water (e.g.

freshwater runoff and surface heating) and destabilising processes, such as turbulent mixing by wind stress or penetrative convection due to surface heat loss. The characterisation also suggested the significance of the earth's rotation at basin-scale and shelf-scale, and the essentially three-dimensional nature and time-dependence of the water circulation and mixing regimes.

The hydrodynamic model was therefore required to be three-dimensional, time-dependent, and to be able to simulate responses to a wide range of forcings including imposed (meso-scale or regional) horizontal pressure gradients, tidal forcings, wind stress, horizontal buoyancy fluxes (from estuaries), vertical buoyancy flux (from air/sea transfers of heat and water), local pressure gradients (due to water surface slopes and horizontal density gradients set up within the study area), bottom frictional stresses and the effects of the earth's rotation. The model needed to take account of the relatively complex bathymetry of the study area and to be able to simulate a range of barotropic and baroclinic mechanisms, with realistic vertical and horizontal structure in water movement and water density, and realistic vertical mixing.

Three-dimensional baroclinic modelling techniques are now sufficiently advanced (Spaulding *et al.* 1992) that these models may be used in conjunction with appropriate field measurements to investigate the water circulation and hydrodynamic transport of substances in coastal water bodies under a broad range of meteorological and oceanographical conditions.

3.2 Description of the model

The *Princeton Ocean Model*, also known as the 'Blumberg-Mellor Model' (Blumberg and Mellor, 1980, 1987; Mellor, 1993) was chosen for application to the SMCWS. Over recent years this model has undergone development and successful application to diverse water bodies such as Chesapeake Bay, the Mid-Atlantic Bight, the Gulf of Mexico, the Great Lakes, and the east and south coasts of Australia.

This time-dependent, fully three-dimensional model numerically solves the non-linear primitive equations for the conservation of mass, momentum, salt and heat. The model calculates the density distribution from the modelled seawater temperature, salinity and pressure fields using an equation of state. Horizontal density gradients give rise to baroclinic forcings which feed back into the momentum balance. The vertical density gradients affect the water column stability which modifies vertical mixing in the model, as determined by a turbulence-closure sub-model (Mellor and Yamada, 1982). The model utilises a sigma coordinates system (Phillips, 1957) in which the vertical coordinate is scaled to water depth. In addition to three-dimensional simulations, the model can also be used in two-dimensional (depth-averaged) form.

The version of the Princeton Ocean Model used here is as described in Mellor (1993) but with the computer code modularised and rewritten in the C language by Herzfeld (1995) and with additional model data management and post processing routines developed during the SMCWS (Mills and Essers, 1995). The C language version of the model incorporates a range of open boundary conditions and employs the positive definite advection algorithm of Smolarkiewicz and Clark (1986). The far-field transport of effluent plumes from estuaries and ocean outfalls has been simulated in the model by introducing point sources of volume, heat and salt, following the method of Lazure and Salomon (1991).

4. Hydrodynamic modelling of Cockburn Sound

4.1 Aims

Key issues investigated by this hydrodynamic modelling study were: the nature of exchange between Cockburn Sound and surrounding waters (with and without the presence of horizontal density gradients), the volumetric fluxes associated with exchange, the flushing times and internal circulation of Cockburn Sound, and the far-field dispersion of effluent from sources located within the sound.

4.2 Model domain and grid

The model domain (Figure 3) extends 60 km long-shore, from City Beach in the north to mid Comet Bay in the south, and 23 km offshore, from the mainland coast to Rottnest Island and the vicinity of the 35 m depth contour. The maximum depth in the model domain is 39 m.

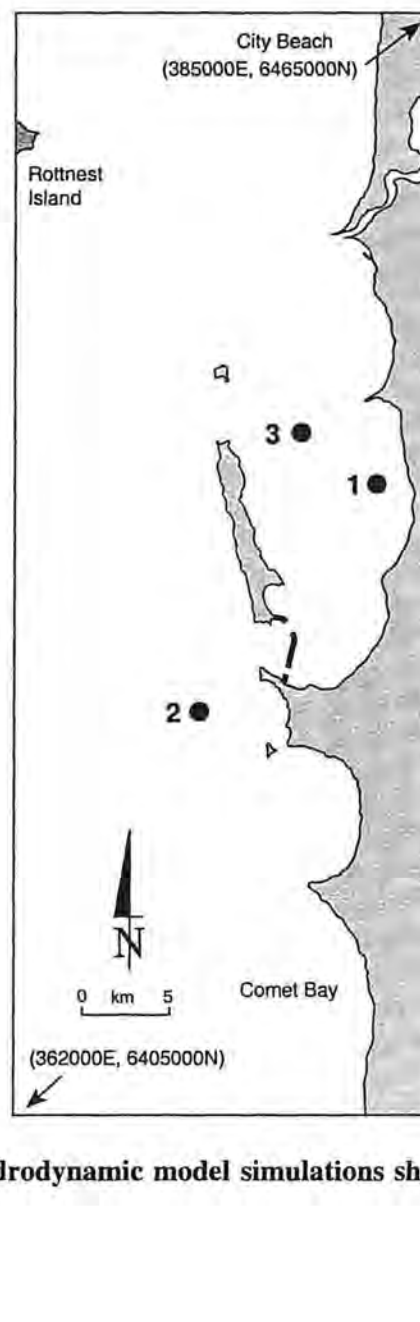

Figure 3. Domain for the hydrodynamic model simulations showing locations of current meter sites.

The model was applied to a grid system which divides the domain area into 500 m square cells. This grid is sufficient to spatially resolve important hydrodynamic boundary features such as upwelling/downwelling zones and coastally-attached buoyant plumes which have widths that scale with the baroclinic radius of deformation (typically about 1-3 km for these waters). The coastline and bathymetry of the area are also satisfactorily represented in the main, with a few exceptions. In particular, it should be noted that the shipping channel through Parmelia and Success banks is not resolved. The cross-sectional flow areas of the two bridge openings in the causeway at the southern entrance to Cockburn Sound have been correctly specified within the grid by slightly adjusting the water depth of these openings. Finer grid resolution would have been desirable, however it would have led to impracticably large computing times for each simulation, given the computing resources that were available for this study. It was deemed equally important for the model to encompass the major bathymetric features in the areas surrounding the coastal embayments, including the islands, reefs and banks, and to remove open boundary effects away from the areas of principal interest. Hence the above balance was struck between spatial resolution and model domain area.

The vertical discretisation used for these simulations consisted of 12 sigma levels, forming 11 layers, four thinner layers (two near the water surface, and two near the sea-bed) and seven thicker layers, as shown in Table 1. Implemented in this way, the model was used to investigate the three-dimensional barotropic and baroclinic response of the study area to a range of external forcings, including surface wind stress, regional sea level gradient, buoyancy inputs from rivers and estuaries, and the mean seasonal density differences between shelf and embayment waters.

Table 1. Levels of the model sigma surfaces and thicknesses of the model sigma layers, expressed as fractions of the local depth of the water column. The sea surface level is denoted as 0.0 and the sea bed level as -1.0.

Sigma surface number	Sigma surface level	Sigma layer number	Sigma layer thickness
1	0.000	1	0.056
2	-0.056	2	0.056
3	-0.111	3	0.111
4	-0.222	4	0.111
5	-0.333	5	0.111
6	-0.444	6	0.111
7	-0.556	7	0.111
8	-0.667	8	0.111
9	-0.778	9	0.111
10	-0.889	10	0.056
11	-0.944	11	0.056
12	-1.000	-	-

The model representation of the bathymetry was obtained from the hydrographic survey data base of the Western Australian Department of Transport. For each 500 m square model grid cell, these data were spatially averaged and then referenced to mean sea level using the difference between chart datum and mean sea level as determined at the permanent tide gauge at Fremantle.

4.3 Model initialisation, forcing and parameterisation

Each model run was started from an initial state of rest with the water surface at mean sea level. For baroclinic simulations, salinity was the variable used to represent the spatial density field, and temperature was maintained constant in time and throughout the model domain. On the basis of routine and intensive field surveys (D'Adamo and Mills, 1995a, b and c; D'Adamo *et al.* 1995) the initial salinity field was set to incorporate the 'climatological' (seasonal) horizontal density difference between Cockburn Sound and shelf waters.

Wind stress was derived from half-hourly time-series data for winds recorded at coastal and offshore locations, using the quadratic formula given in Fischer *et al.* (1979). A long-shelf pressure gradient of order 10^{-7} was applied to allow for the presence of southward residual currents in winter (Steedman and Associates, 1981).

The effects of the earth's rotation was included through the specification of the Coriolis parameter for latitude 32 °S.

For the purposes of far-field dispersion modelling the approach of Lazure and Salomon (1991) has been followed. Buoyant discharge from the Swan-Canning estuary was represented in the model as a flux of both volume and buoyancy introduced through the water surface at specified model grid cells. No additional horizontal momentum was introduced. This approach recognises that the estuarine plume behaviour begins to be dominated by its buoyancy flux (rather than its discharge momentum) at locations very close to the estuary mouth (in this case less than one model grid cell width). This has been confirmed through scaling analysis (Fischer *et al.* 1979), laboratory experiment (Chu and Baddour, 1984) and in the field (Luketina and Imberger, 1987). A similar approach has been used to model the far-field dispersion of effluent from point sources.

The boundary conditions used for these model runs are set out in Table 2. For further details concerning these boundary conditions (in particular the 'user defined' open boundary condition) the reader is referred to Herzfeld (1995).

Table 2. Boundary condition settings at the open boundaries of the model.

Model Parameter	Open Boundary Condition Settings		
	Western Boundary	**Northern Boundary**	**Southern Boundary**
elevation	orlanski radiation	orlanski radiation	orlanski radiation
external velocity (normal)	user defined	user defined	user defined
external velocity (parallel)	orlanski radiation	orlanski radiation	orlanski radiation
internal velocity (normal)	user defined	user defined	user defined
internal velocity (parallel)	orlanski radiation	orlanski radiation	orlanski radiation
temperature	upstream advection	upstream advection	upstream advection
salinity	upstream advection	upstream advection	upstream advection

Tidal forcing, both direct and via the boundary conditions, has not been included in the modelling simulations discussed in this report. This can be justified over most of the model domain, where tidal currents are typically of order 0.01 m s^{-1} and advection length scales over a diurnal period are of order 1 km only. However, in some locally constricted areas, such as in the vicinity of the bridge openings through the causeway at the southern entrance to Cockburn Sound, significantly stronger tidal currents can occur, and water exchange, induced by these oscillatory tidal currents may be locally significant. Notwithstanding these limitations it will be shown that the model results presented in this report are generally consistent with characteristic hydrodynamic responses of Cockburn Sound as measured during the SMCWS.

The model was set to run with an external mode time step of 9 seconds and an internal mode time step of 180 seconds. A detailed list of other model run parameter settings is given in Appendix 1.

5. Model validation

Two approaches have been used to validate the model. For barotropic simulations the model performance has been assessed on the basis of comparisons of model results with time-series of measured currents from meters deployed at locations in Cockburn Sound and in Sepia Depression (Figure 3). While such point-wise comparisons can be readily made and quantified in statistical terms, it is economically feasible to deploy current meters at only a few points throughout the modelled area. For baroclinic simulations it was necessary to calculate the spatial distributions of density-related seawater properties such as salinity, and the changes in these distributions which arise from the movement and mixing of the nearshore coastal waters. The broad characteristics and temporal changes in the measured and simulated spatial salinity fields have been compared in these cases as a means of assessing the simulation ability of the model. Such comparisons have been made wherever possible, and are documented throughout this report.

The three-dimensional barotropic circulation of Cockburn Sound and surrounding waters was modelled for the period 7-29 March, 1992 using real wind data and an estimate of the mean long-shelf pressure gradient, derived from analysis of wind and current meter records.

D'Adamo and Mills (1995a) reported that during much of this simulation period the horizontal density differential between Cockburn Sound waters and adjacent shelf waters was less than 0.1 kg m^{-3} and that the vertical density difference in Cockburn Sound was less than about 0.1 kg m^{-3} (in 20 m) with regular vertical mixing. On the basis of these data they concluded that the application of a three-dimensional barotropic model would provide a reasonable approximation of the hydrodynamic behaviour for this period.

Time-series and progressive vector runs of wind data from the DEP Naval Base station (on the mainland coast of Cockburn Sound) and from the Bureau of Meteorology station on Rottnest Island (approximately 20 km off the mainland coast) are shown in Figure 4 for the simulation period. The time-series data show periods of southerly, easterly and northwesterly winds, and the progressive vector runs highlight the presence of cross-shore differences in the wind field, particularly in the north-south wind component.

Using time-series data of the inshore winds and assuming spatially uniform wind forcing across the model domain, it was found that currents in eastern Cockburn Sound could be satisfactorily simulated, however currents in Sepia Depression were less well simulated. With spatially uniform wind forcing derived from the offshore wind station, the currents in Cockburn Sound were over-estimated by the model. Consequently, the wind stress field used to validate the model was derived from a linear interpolation in the cross-shore direction of the computed hourly wind stresses from these two wind stations.

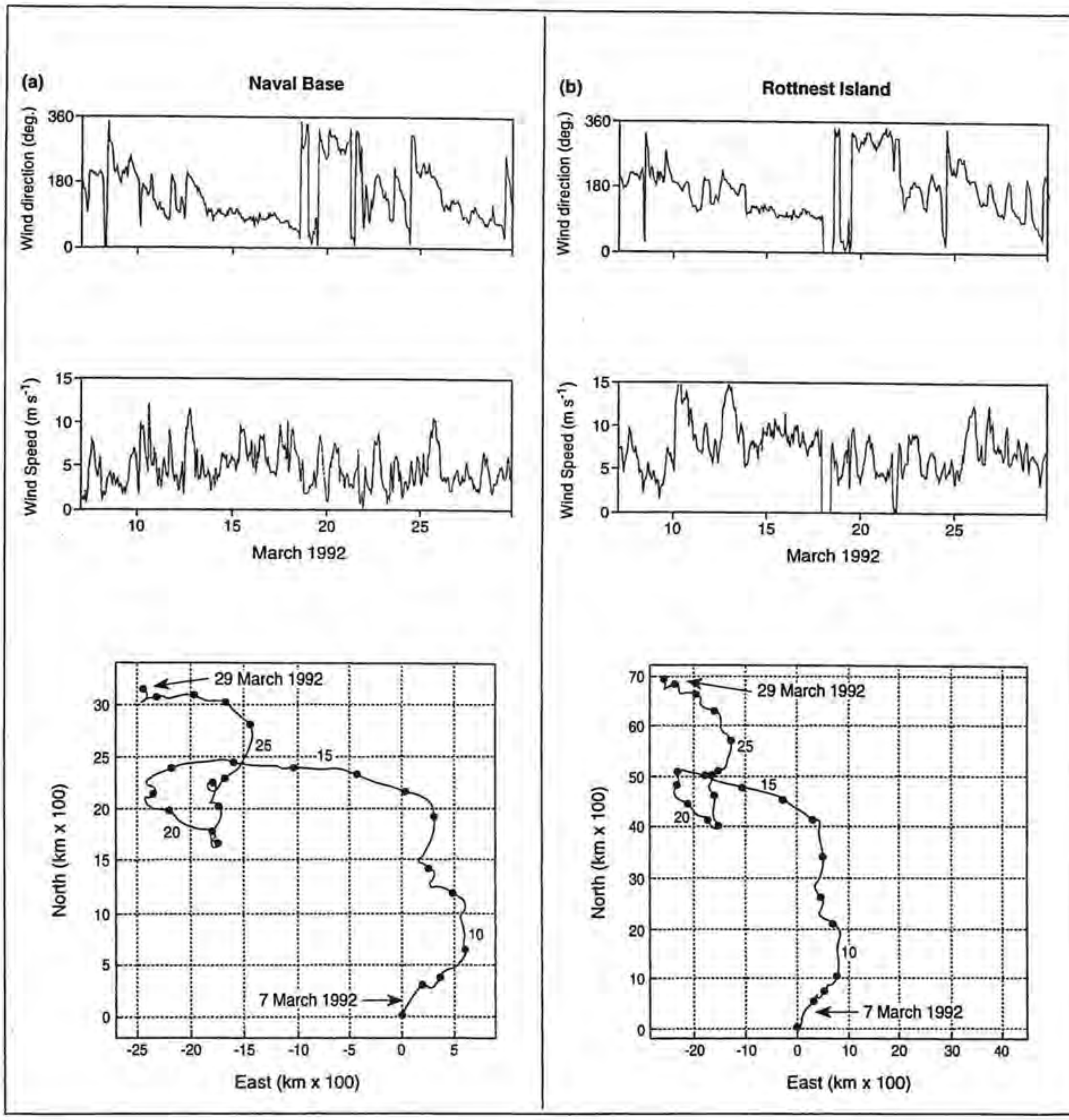

Figure 4. Wind data input from (a) Naval Base and (b) Rottnest Island for the barotropic model validation. The wind data are presented as speed and direction time series and progressive vector runs.

A linear regression analysis was performed between long-shelf wind stress and long-shelf current time-series (collected at site 2 in Sepia Depression, shown in Figure 3) for the period 11 March to 26 April 1992. Following Scott and Csanady (1976) and Steedman and Associates (1981), the results of this analysis were used to infer a long-shelf sea level slope of about -1×10^{-7} for this period and this value was used to guide the specification of an imposed pressure gradient forcing in the validation run of the hydrodynamic model.

Modelled current data from grid cells corresponding to the current meter locations (Figure 3) were extracted to form hourly time-series. The measured and modelled current time-series data for the simulation period are shown in Figure 5 for the sites in eastern Cockburn Sound and Sepia Depression. Table 3 shows the mean error and the root mean square error for the simulated northward and eastward current components, respectively.

Table 3. Mean error and root mean square (Rms) error for the simulated north-south and east-west components of the currents for the three-dimensional barotropic model validation.

Station	North-south component		East-west component	
	Mean error ($m\ s^{-1}$)	Rms error ($m\ s^{-1}$)	Mean error ($m\ s^{-1}$)	Rms error ($m\ s^{-1}$)
1 (4.8/8.6)	0.03	0.04	-0.01	0.02
1 (2.3/8.6)	0.01	0.02	0.00	0.02
2 (15.0/22)	ND	ND	ND	ND
2 (3.0/22)	0.06	0.11	0.04	0.05

(4.8/8.6) - current meter located 4.8 m above sea bed in a total water depth of 8.6 m

ND - Intermittent current meter data only.

The model satisfactorily hindcast the measured currents from the mooring sites in eastern Cockburn Sound and in Sepia Depression. Agreement between model results and current meter measurements for the northern Cockburn Sound current meter site near the Parmelia Bank and the shipping channel was less favourable. This is probably due to the inability of the model grid to resolve the shipping channel, and to the occasional slumping of a northward moving coastal plume of slightly elevated salinity into the northern end of the Cockburn Sound basin (D'Adamo and Mills, 1995a).

As mentioned above, the model was also used in baroclinic mode to simulate the flushing of stratified embayments in winter and autumn and, wherever possible, comparisons are given throughout this report between simulated and observed water salinity and density structures to confirm that the model is reproducing the main basin-scale features of the measured hydrodynamic response of these waters.

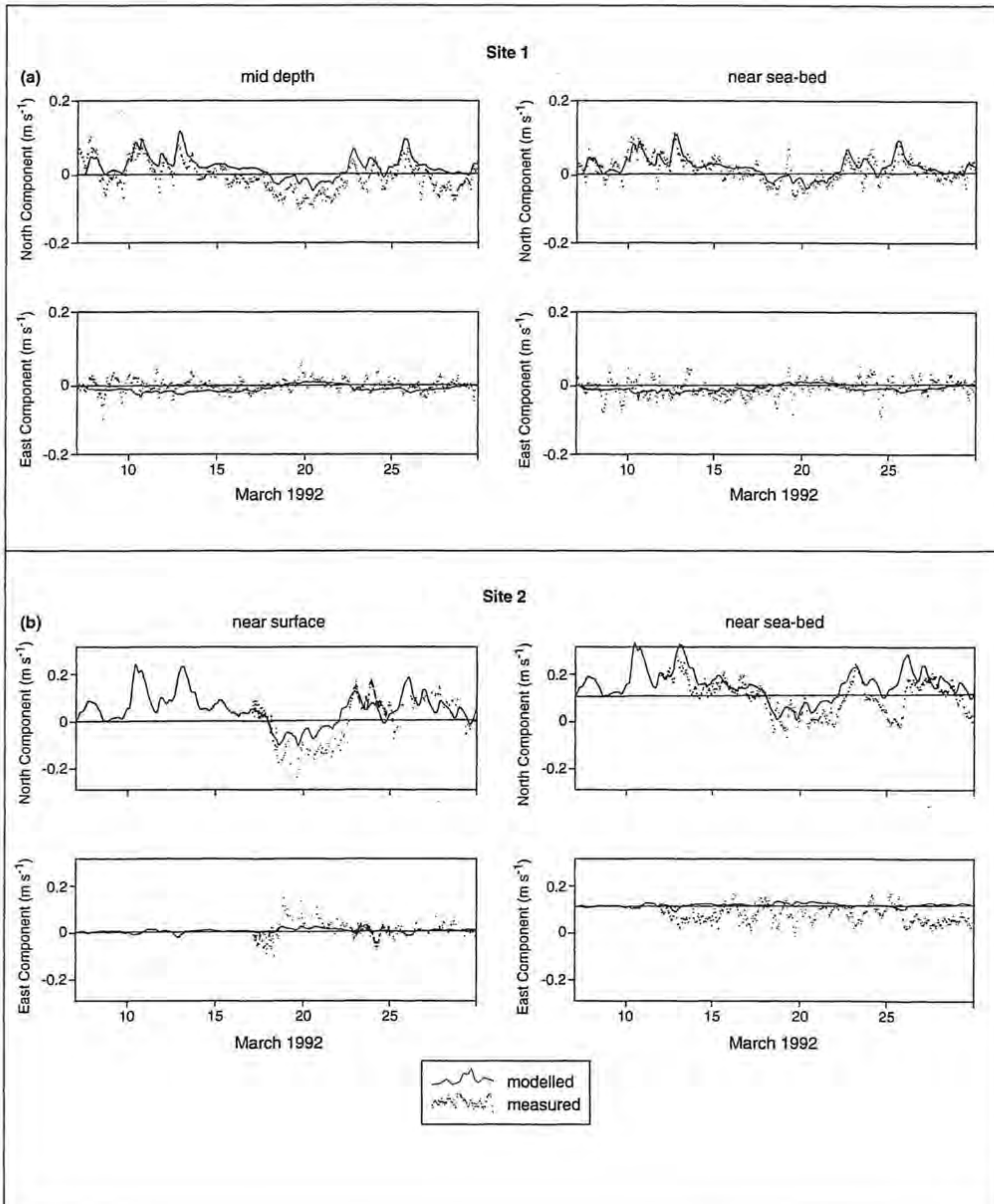

Figure 5. Comparison at (a) site 1 and (b) site 2 between measured and modelled currents from the barotropic model validation, driven by winds in Figure 4.

6. Modelling of the seasonal hydrodynamic regimes of Cockburn Sound

6.1 Introduction

The oceanographic characterisation of the SMCWS area identified distinct annual patterns in the water salinity, temperature and density of Cockburn Sound and of the surrounding shelf waters (D'Adamo and Mills, 1995b). Furthermore, it showed that there is typically a difference in density between these waters, and that this density difference reverses in sign twice as each year progresses (Figure 6). The field observations also suggested that the density difference between Cockburn Sound and shelf waters is a key factor in determining the nature of the circulation and flushing regimes of the sound. Three major hydrodynamic regimes were described: the 'winter-spring' regime, the 'autumn' regime and the 'summer' regime (D'Adamo and Mills, 1995b).

The purpose of this section is to present the results of modelling each of these 'seasonal' hydrodynamic regimes. The model has been able to reproduce major features of the advection field and the temporal development of the density distribution, as characterised by intensive field data sets (D'Adamo and Mills, 1995a, 1995c; D'Adamo *et al.* 1995). It has therefore been used to gain further understanding of the circulation and exchange patterns, and to estimate the flushing rates of the sound. The modelling has also served to determine the relative importance of various forcings (induced by wind, seasonal density differences between the sound and shelf waters, and the earth's rotation) to the essential nature of these regimes. For reasons of computing economy, initial density differences were introduced to the model (via the equation of state) solely through the prescription of an initial salinity distribution, and water temperature was held constant. These simulations concentrate on understanding the influence on embayment flushing of the spatially-variable seasonal climatology of these waters. At present the simulations do not incorporate the diurnal cycle of surface heat and evaporative fluxes, however these should be included in future work, as field data have shown them to influence stratification and vertical mixing of the sound.

The model simulations were initialised with waters of different salinities outside and within Cockburn Sound. *Flushing rates* were calculated from the simulated change of salt content in pre-defined control volumes of the model. Complete (100 %) flushing would have occurred at a time when the salinity of a control volume within the sound became equal to the initial salinity of the external waters. Defined in this way, the flushing generally approaches 100 % in an asymptotic manner.

Water exchange fluxes across the boundaries between Cockburn Sound and the surrounding waters were computed for each of the model simulations. The volume inflows and outflows through the northern and through the southern openings of the sound were each separately calculated for each model time step, taking into account the transverse and vertical variations in the water currents across the openings. These volumes were then cumulated over successive time steps for the duration of the simulation. The *cumulative volume flux time* for Cockburn Sound was defined as the time required for the combined gross inflows through both the northern and southern openings to cumulate to a volume equal to the capacity of Cockburn Sound.

The flushing times for Cockburn Sound (e.g. the times required to reduce the initial salt excess/deficit of the sound by a factor of e^{-1}, equal to 0.37) are generally longer than the cumulative volume flux times, because the change in salt content is a result of net salt flux across the entrances and depends on the details of advection and mixing that take place throughout the water body. However, the cumulative volume flux times are calculated solely on the basis of gross inflows across the boundaries of the water body, and take no account of the nature and characteristic length and time scales of the internal circulation and mixing.

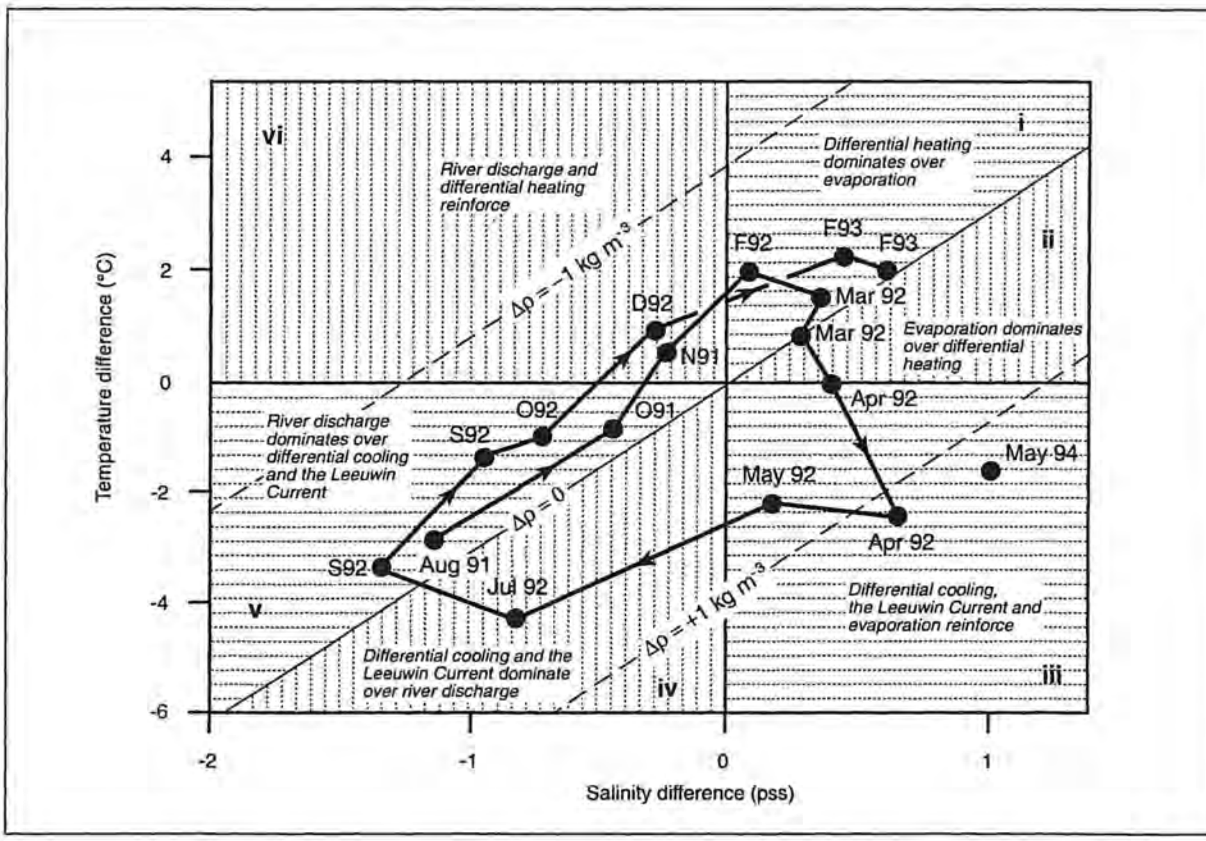

Figure 6. The annual cycle in the salinity and temperature differences (at 10 m depth) between Cockburn Sound and the mid-shelf, southwest of Rottnest Island. The influence of major forcings on the cross-shelf differences are indicated for each of the six categories (I to VI) within the cycle. The diagonal lines are contours of density difference and data above/below the central contour indicate that Cockburn Sound is less/more dense than mid-shelf water (after D'Adamo and Mills, 1995b).

6.2 Modelling the 'winter-spring' hydrodynamic regime of Cockburn Sound

The waters of Cockburn Sound become less dense than shelf waters during winter, due to wind-driven southward incursions of the low salinity Swan-Canning estuary plume into the sound (D'Adamo *et al.* 1995; Mills and D'Adamo, 1995) and warming of the sound waters in spring prolongs this density difference. The period 18-23 August 1991 was chosen for simulation of the 'winter-spring' hydrodynamic regime for two reasons. Firstly, the model results could be compared with an intensive field data set (D'Adamo *et al.* 1995) which had been collected during this period. Secondly, complete vertical mixing of the sound by storm winds on 18-19 August 1991 (Figure 7) and the density difference between the sound and external waters were documented by D'Adamo *et al.* (1995). This justified the use of an initial model salinity distribution which was vertically uniform, with less saline water in the sound and more saline water external to the sound (Figure 8). The resultant initial density difference in the model affected the dynamics of circulation, exchange and vertical mixing throughout the the simulation period. Furthermore, salinity was used in the model to determine the rates of flushing (as defined above in section 6.1) between shelf and sound waters, and to trace the re-establishment of vertical stratification in the sound. The model was initialised accordingly and was forced by local wind data for this period and by a low salinity (buoyant) source at the mouth of the Swan-Canning Estuary. Model results are given in Figure 9.

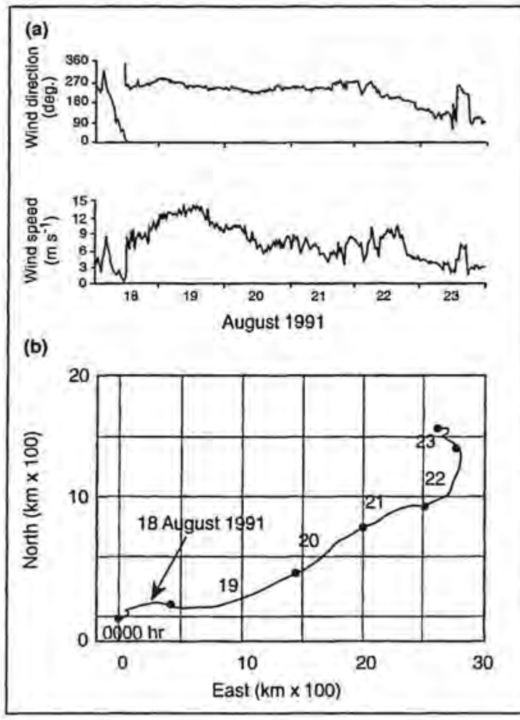

Figure 7. Wind data used for the baroclinic model simulation of wind-driven flushing and deep-water renewal in Cockburn Sound under post-storm 'winter' conditions: (a) time series and (b) progressive vector run.

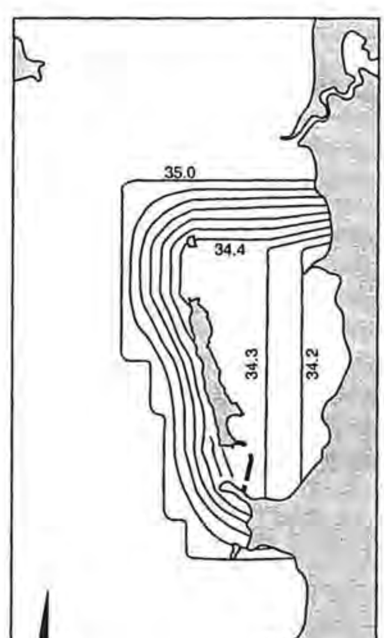

Figure 8. Starting horizontal salinity field for the baroclinic model simulations of the 'winter' hydrodynamics of Cockburn Sound.

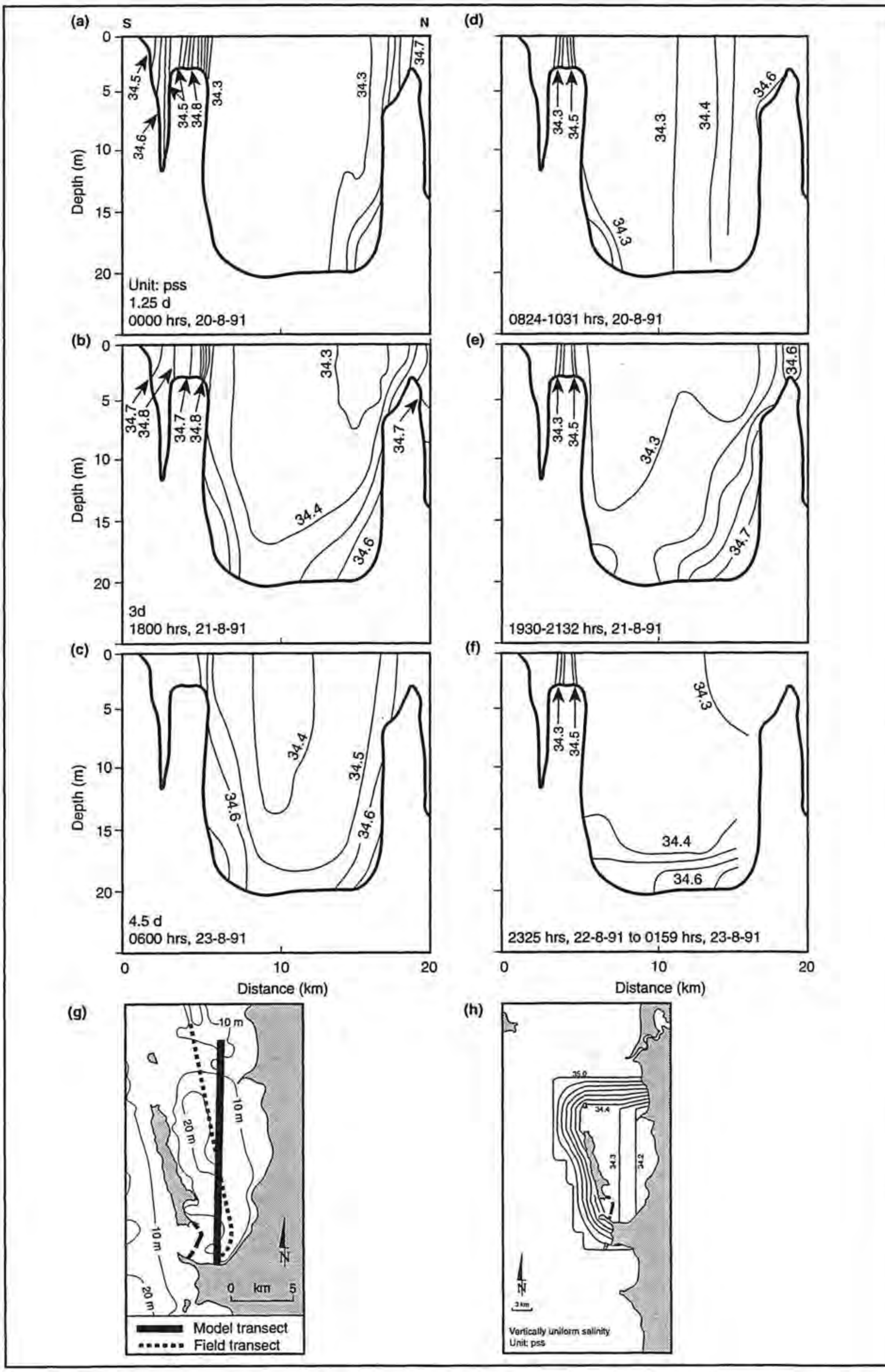

Figure 9. South-north vertical salinity sections showing deep-water renewal in Cockburn Sound during the post-storm period of 20-23 August 1991 from (a-c) baroclinic model simulations and (d-f) field measurements (wind data as in Figure 7). Measured salinity was projected onto the model transect path (g). The initial salinity field for the model was as shown in (h).

As simulated by the model, the sound remained vertically well-mixed during the storm (west-southwesterly winds of 10 m s^{-1} or more) with strong horizontal salinity gradients to the north and south (Figure 9a). Vertical stratification was re-established (Figure 9b) during the following 36 hours of southwesterly winds (5-10 m s^{-1}) by the entry of relatively dense, high salinity water into Cockburn Sound through its northern and southern openings, the subsidence of this water and its horizontal transport across the deep basin. Incoming high salinity water from the north penetrated as a bottom layer to within a few kilometres of the Southern Flats before encountering high salinity inflow from the southern causeway entrances. The high salinity water both uplifted and partially mixed with the sound's lower salinity waters, a portion of which was forced out of the sound as wind-driven surface flows. Under winds (5-11 m s^{-1}) swinging to the south during the following 36 hours, the simulation (Figure 9c) predicted further dense water inflow and the renewal of deep basin water, as indicated by the presence of bottom water with salinity greater than 34.5 pss salinity throughout the length of the basin. Figures 9 d, e and f show vertical salinity sections derived from field data collected along a longitudinal transect in Cockburn Sound during the period simulated by the model. It can be seen that the model is reproducing the major characteristics of the response of the salinity field.

As shown in Figure 10 the deep basin zone (> 15 m below sea surface) of Cockburn Sound was flushed more rapidly than the near-surface zone (0-5 m below sea surface) of the sound due to the subsidence of dense incoming water and its transport across the deep basin. The deep basin zone was 50 % flushed and the near-surface zone was 35 % flushed within six days, under the wind forcing conditions and the initial salinity/density difference conditions that applied to this simulation (Figures 7 and 8, respectively).

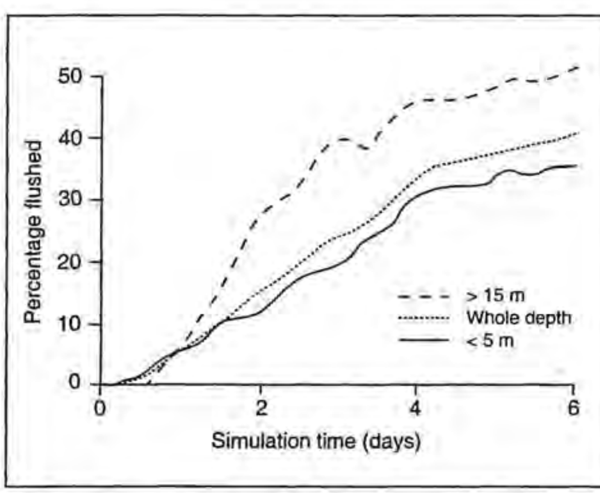

Figure 10. Baroclinically modelled flushing rates for three depth zones (whole depth, <5 m and >15 m) of Cockburn Sound from a 'winter' (18-23 August 1991) simulation under wind conditions shown in Figure 7.

During the period of the simulation (westerly to southerly winds) essentially all of the volume output was across the northern opening and, of the inputs, 66 % was across the northern opening and 34 % across the southern opening. However the southward flux across the east-west section from James Point to Garden Island was less than 40 % of the southward flux across the northern entrance of the sound. A schematic of these volume fluxes is given in Figure 11, which suggests that, in the southern portion of Cockburn Sound, the volume throughflow via the southern opening and the two-way volume exchange across the section west of James Point were of comparable magnitude. In the northern portion of Cockburn Sound the two-way volume exchange across the northern opening was significantly greater than either throughflow due to the flux through the southern opening of the sound, or the two-way volume exchange across the James Point section.

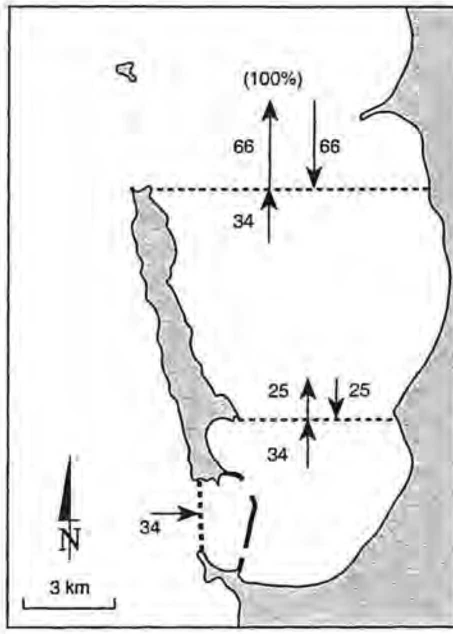

Figure 11. Schematic of modelled volume fluxes across the openings and an inner west-east section of Cockburn Sound from a 'winter' (18-23 August 1991) baroclinic simulation under winds shown in Figure 7. Volume fluxes are expressed as a percentage of total outflow.

The two-way exchange across the northern opening was about twice the magnitude of the throughflow from the southern opening under the conditions of this simulation.

The initial 'winter' density structure is gravitationally unstable, because buoyant basin water is located beside denser shelf water. Modelling has shown that, in the absence of other forcings, this density structure undergoes baroclinic adjustment (influenced by the earth's rotation) which gives rise to exchange, with denser shelf water slumping into the sound and more buoyant water overflowing out of the sound (Figure 12). The buoyant water forms coastally-attached surface plumes which extend southward along the western coasts of Garden Island and Shoalwater Bay, with some buoyant water entering Warnbro Sound (Figure 12a). The denser shelf water first slumps into the northwest corner of Cockburn Sound's deep basin, moves to the east and then spreads southward (Figure 12b and c). It took about six days for the dense inflow to travel the length of the Cockburn Sound basin (Figure 12c). The cumulative volume flux time for Cockburn Sound for this purely baroclinic (with rotation) simulation was about 12 days, which is about 50 % longer than for the corresponding simulation without rotational effects.

The cumulative volume flux time for pure baroclinic adjustment (with rotation) is much smaller than that due to tidal exchange (about 30 days) which was cited by Maritime Works Branch (1977b) as the base level of exchange for the sound. The simulations have shown that the gravitational adjustment process involves the transport of external water throughout the length of the sound in about six days, so that basin-scale mixing is more efficient than for the tidal mechanism, which has a typical advective length scale of about 500 m, much less than the length of the sound.

The cumulative volume flux time for pure baroclinic adjustment (with rotation) in Cockburn Sound was 12 days, about three times longer than for the simulation with wind forcing also included. This suggests that exchange due to baroclinic adjustment alone is significant, but considerably less than exchange due to the combined effects of density and wind forcing for wind speeds in excess of about 5 m s^{-1}. However, as has been shown in Figures 9 and 10, the presence of the density difference between Cockburn Sound and the surrounding waters can strongly influence the nature of the wind-forced circulation of the sound, resulting in differential flushing rates with depth.

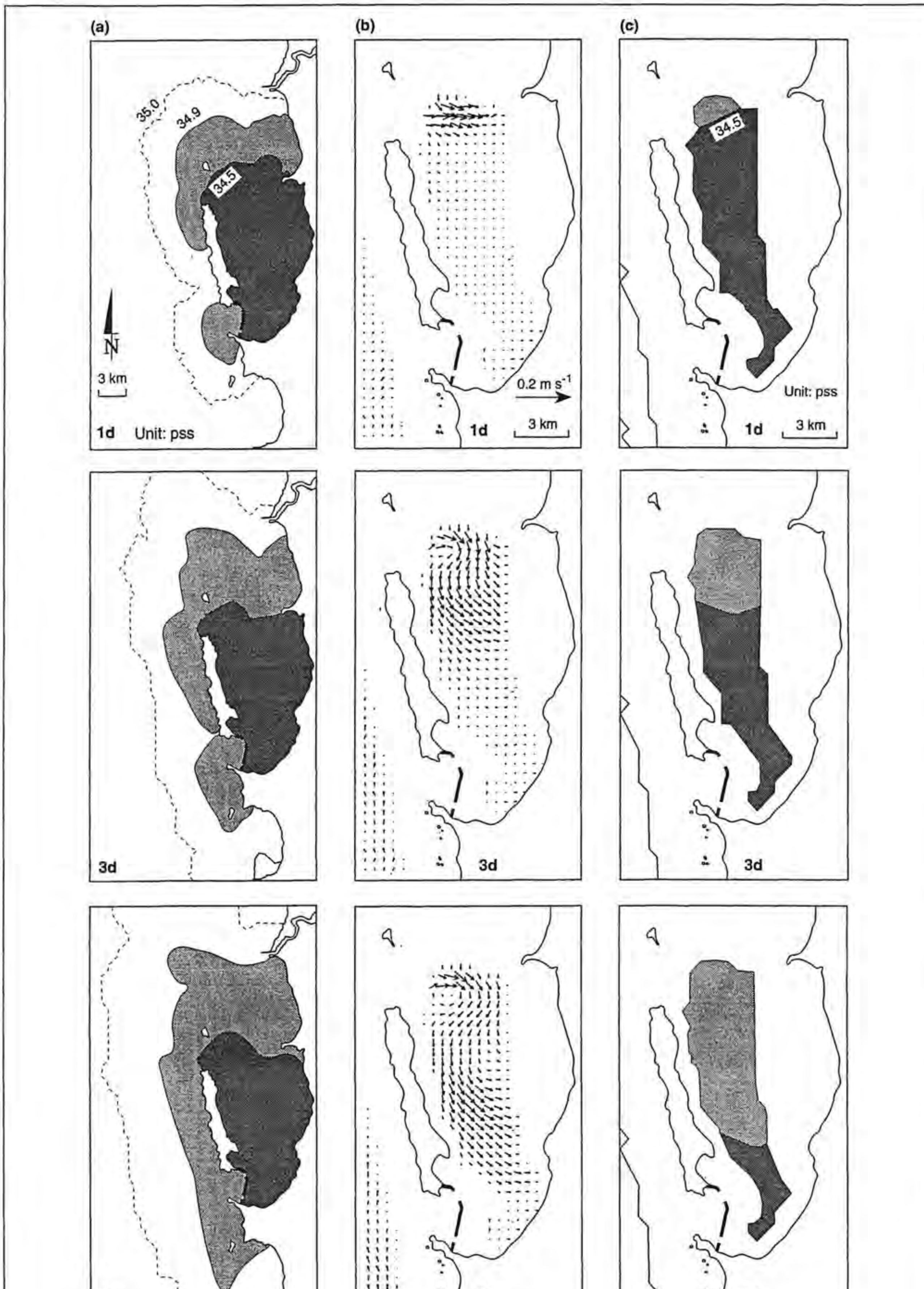

Figure 12. Baroclinic model simulation of density-induced exchange (with no wind forcing) between buoyant Cockburn Sound water (set at 34.4 pss) and dense shelf water (set at 35.0 pss) after one, three and six days, showing (a) surface salinity, (b) bottom velocity and (c) bottom salinity.

6.3 Modelling the 'autumn' hydrodynamic regime of Cockburn Sound

The model was used to investigate exchange processes between Cockburn Sound and surrounding shelf waters during the 'autumn' regime. The period 29 April to 6 May 1994 was simulated in view of the availability of detailed water structure data for 3 May 1994 and to complement the understanding of circulation, mixing and exchange processes drawn from autumn field data (D'Adamo and Mills, 1995c).

The initial salinity field supplied to the model consisted of two vertically uniform water masses, one with 36 pss salinity, occupying Cockburn Sound, and the other with 35 pss, occupying the remainder of the model domain (Figure 13). This gave an initial density difference of about 0.75 kg m^{-3} between the sound and shelf waters. While this is a typical value for the 'autumn' density difference between the sound and the shelf (D'Adamo and Mills, 1995c) there were no field data available during the week preceding 3 May 1994 to provide further guidance in the setting of the initial density field and, in particular, its vertical structure. Hence the model and field results could be compared only in the most general terms. The model was forced by the (evolving) density field and with local wind data (Figure 14) for the period.

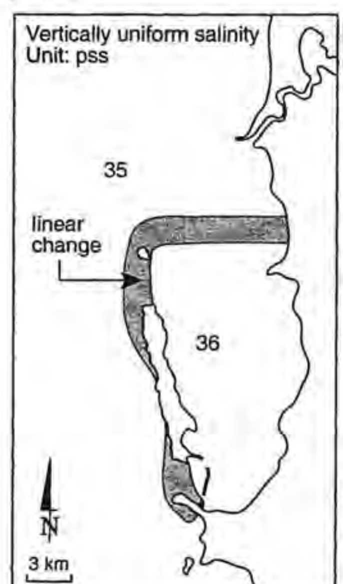

Figure 13. Starting horizontal salinity field for the baroclinic model simulations of the 'autumn' hydrodynamics of Cockburn Sound.

Figures 15a, b and c, and 16a, b and c show near-surface distributions of salinity and currents, respectively, at selected times during the simulation. Figures 17a, b and c present the corresponding vertical salinity structures along a south to north transect line through Cockburn Sound.

The simulation indicates that relatively low salinity shelf waters were introduced into Cockburn Sound and partially mixed, forming buoyant stratified layers (5-10 m thick) which tended to over-ride resident deep basin water (Figure 17), shelter it from wind mixing and isolate it from the major openings of the sound. Wind-driven advection of the buoyant layers was significant (Figure 16) and the model results suggest that it took about 3-4 days for the central surface waters of the basin to be influenced by shelf water (Figure 15). The modelled salinity field varied much more rapidly near the surface than in the deep basin of the sound.

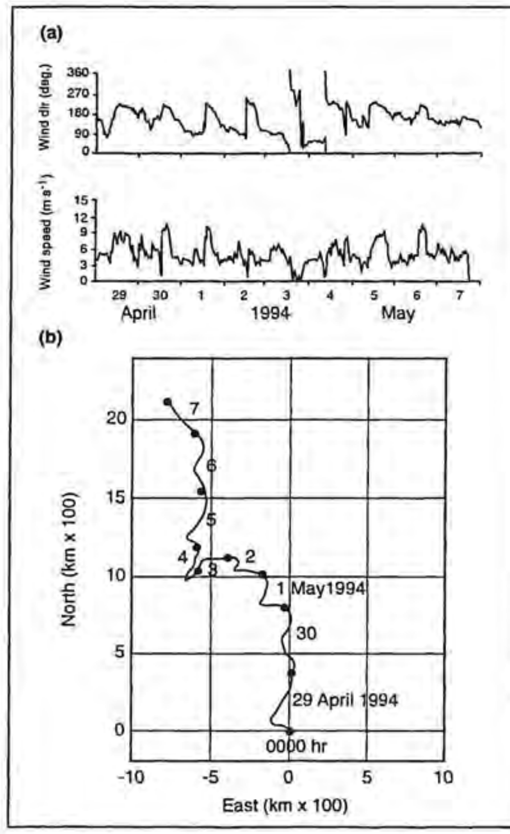

Figure 14. Wind data used for the baroclinic model simulation of exchange between Cockburn Sound and shelf waters under 'autumn' conditions: (a) time series and (b) progressive vector run.

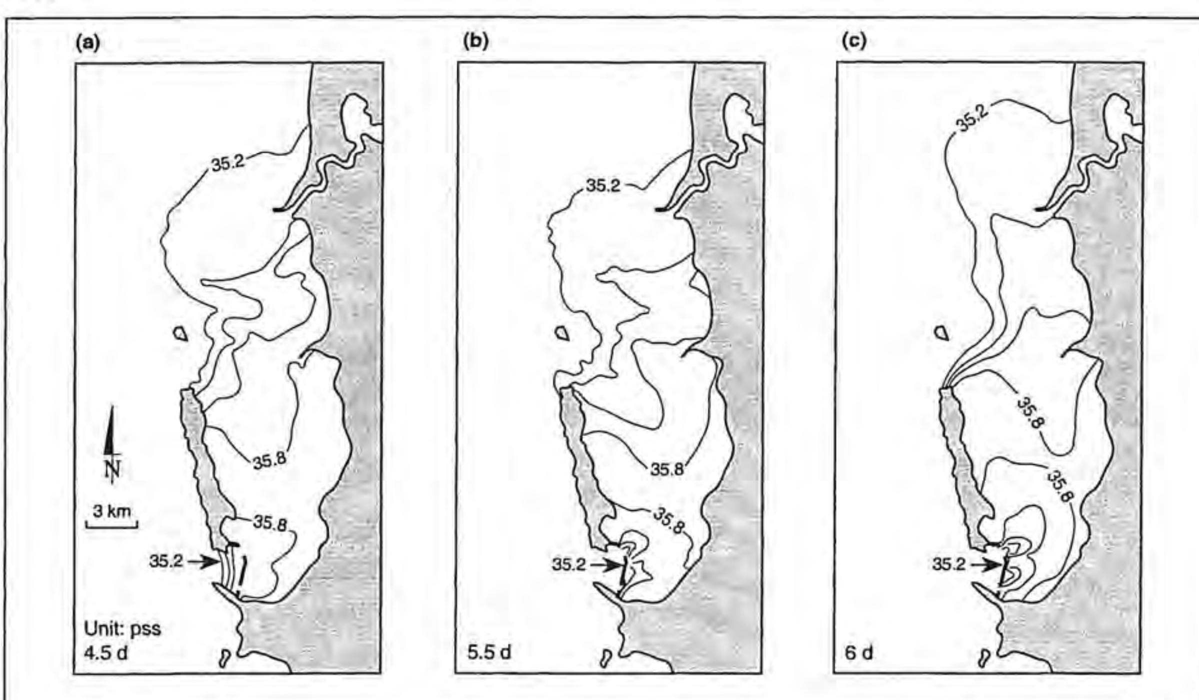

Figure 15. Baroclinically modelled surface salinity fields representing 'autumn' exchange between dense Cockburn Sound water and buoyant shelf water forced by winds (from Figure 14) after (a) 4.5 days (b) 5.5 days and (c) 6 days.

A 30 hour period of predominantly easterly winds preceded the salinity-temperature-density field measurements of 3 May 1994. The model results, 4.5 days into the simulation, indicate that these winds drove surface inflow to the sound via the northern opening and outflow under the causeway bridges (Figure 16a) and that there was also sub-surface outflow through Challenger Passage. Relatively low salinity water was transported southward to central Cockburn Sound (Figure 15a) forming a surface layer which was separated from deep basin waters by a mid-depth zone of vertical stratification (Figure 17a). In contrast, the salinity contours at the southern end of the basin downwelled and the vertical stratification was reduced (Figure 17a). Measurements of vertical salinity structure along a south-north transect of Cockburn Sound were made on 3 May 1994. The measured salinity structure (Figure 18) shows an inclined upper layer of relatively low salinity water in the northern half of the Cockburn Sound basin which does suggest that there had been recent entry of relatively low salinity, buoyant water across the northern opening of the sound under predominantly easterly winds, as predicted by the model.

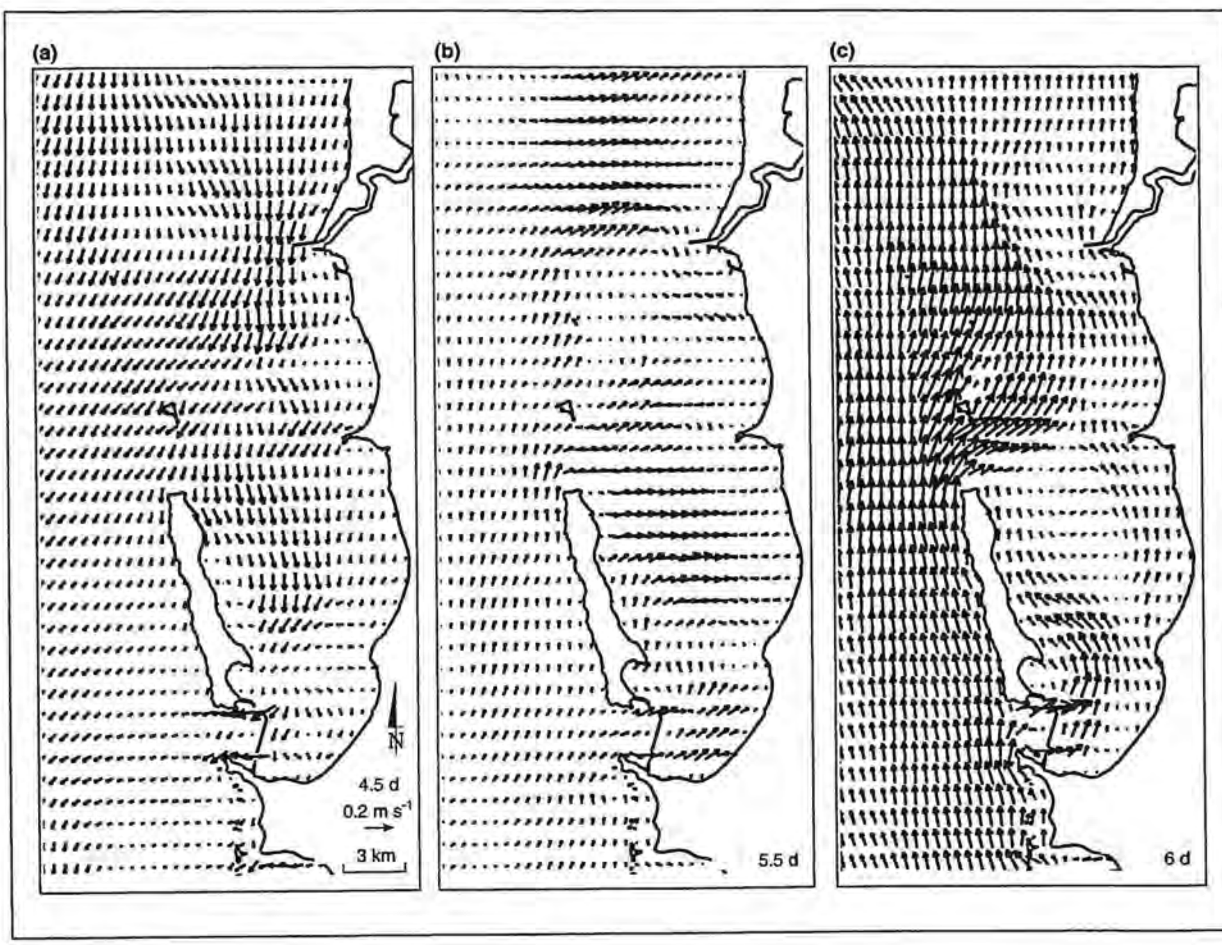

Figure 16. Baroclinically modelled surface current fields representing the 'autumn' exchange between dense Cockburn Sound water and buoyant shelf water forced by winds (from Figure 14) after (a) 4.5 days (b) 5.5 days and (c) 6 days.

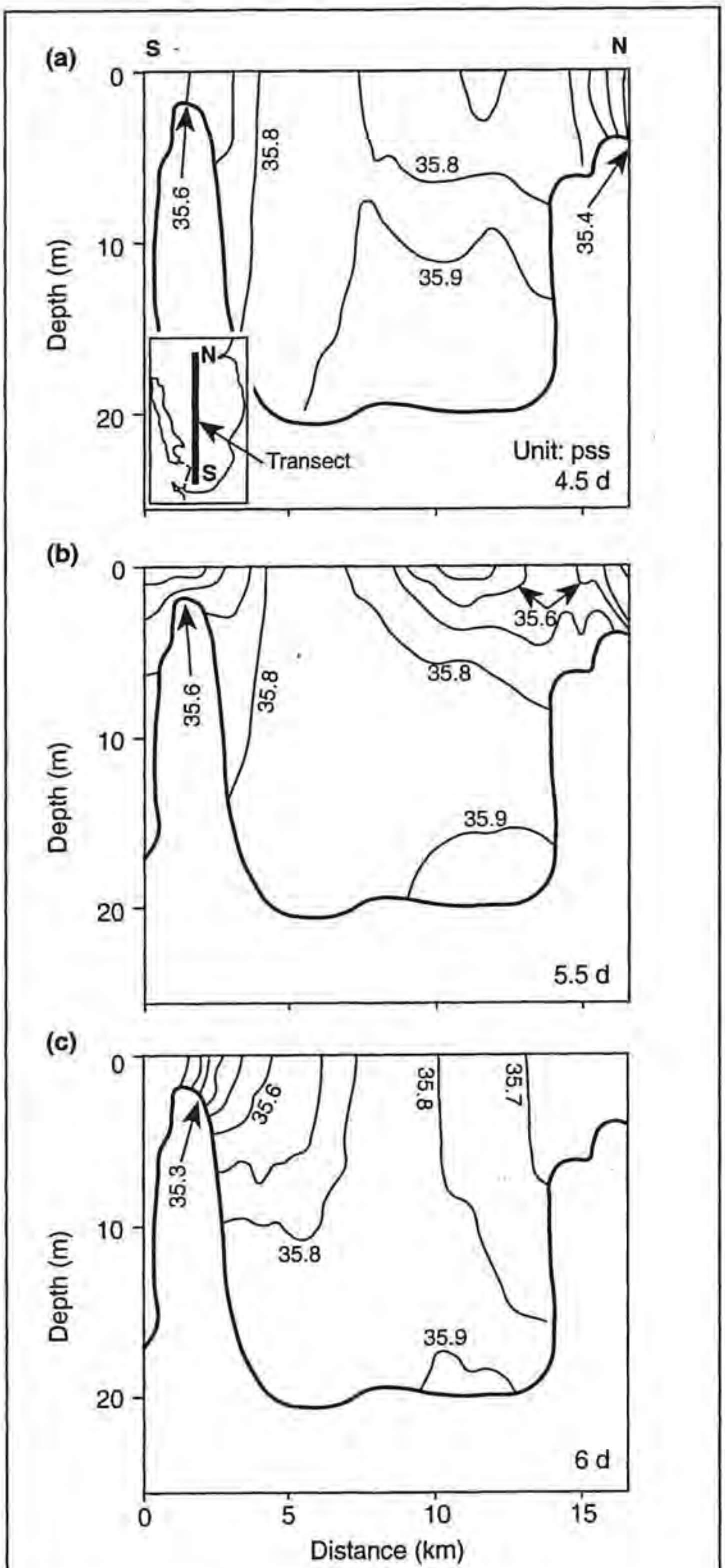

Figure 17. Baroclinically modelled south-north vertical salinity structure representing the 'autumn' exchange between dense Cockburn Sound water and buoyant shelf water forced by winds (from Figure 14) at (a) 4.5 days (b) 5.5 days and (c) 6 days.

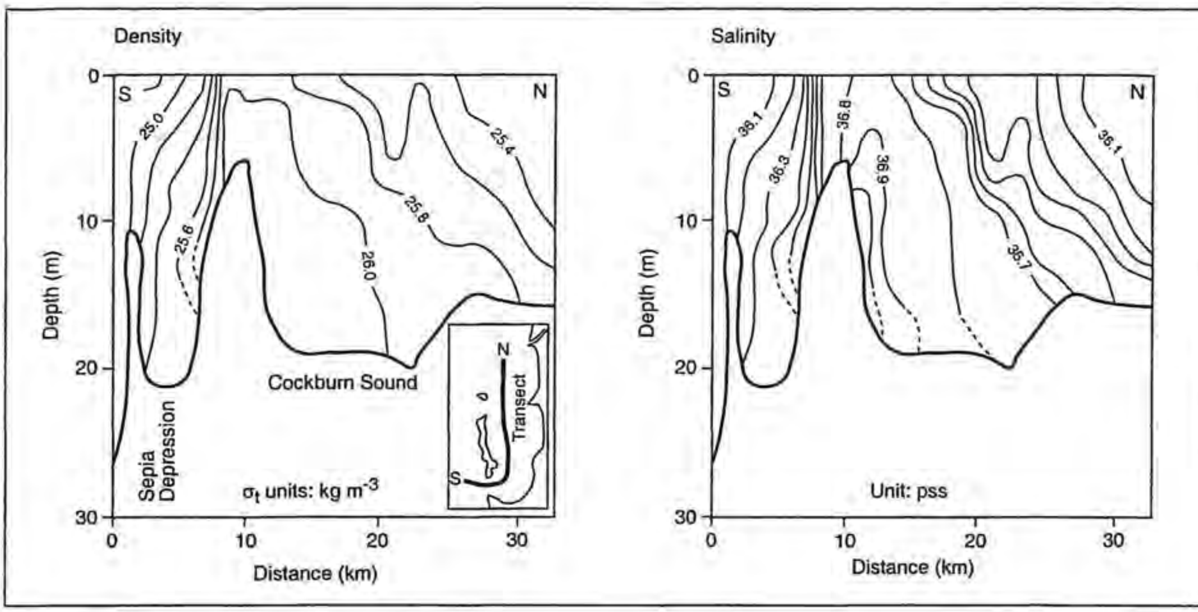

Figure 18. Vertical density and salinity structure in Cockburn Sound and adjacent waters on 3 May 1994 showing autumn stratification.

Further model results are presented from this simulation for midday on 4 May 1994. The winds had remained easterly to northeasterly since the previous day, except for the last hour or two, when winds strengthened from the southwest. The surface currents (Figure 16b) already showed a rapid response to this recent wind shift. However, apart from in the close vicinity of the causeway bridge openings, the salinity distribution reflected the influence of the earlier northeasterly winds and showed the resultant southward migration of considerably lower salinity (e.g. 35.6 pss) surface waters to the centre of the sound (Figure 15b) and the accompanying intensification of the near-surface vertical stratification (Figure 17b).

The model predicts that the ensuing southwesterly sea-breezes of 5 and 6 May 1994 drove low salinity water into the sound through the causeway bridge openings and then transported it northward (Figures 15c and 16c). This led to a strengthening of the near-surface stratification in southern Cockburn Sound to a depth of about 10 m (Figure 17c). Buoyant water which had previously entered via the northern opening was downwelled against central Parmelia Bank (as shown in Figure 17c by the steepness of the salinity contours) reducing the vertical stratification and making this area more susceptible to wind mixing.

As shown by the model results in Figure 19 the near-surface zone (0-5 m below sea surface) of Cockburn Sound was flushed at a greater rate than the deep basin zone (> 15 m below sea surface) of the sound for this 'autumn' simulation. After nine days the near-surface zone was 34 % flushed and the deep basin zone was 25 % flushed. This result is consistent with the introduction of buoyant water into the sound as an upper layer which inhibited the vertical mixing and flushing of denser deep basin waters.

During the period of the simulation (mainly southerly to easterly winds) 97 % of the gross volume output was across the northern opening and, of the inputs, 78 % was across the northern opening and 22 % across the southern opening. A schematic of these volume fluxes is given in Figure 20. The two-way exchange across the northern opening is about 3.5 times the magnitude of the throughflow exchange under the conditions of this simulation.

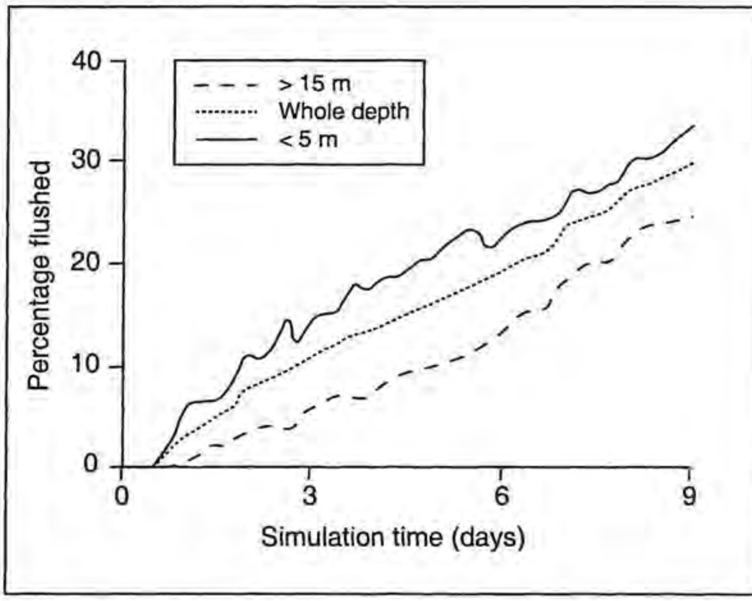

Figure 19. Baroclinically modelled flushing rates for three depth zones (whole depth, <5 m and > 15 m) of Cockburn Sound from an 'autumn' simulation (wind data as in Figure 14).

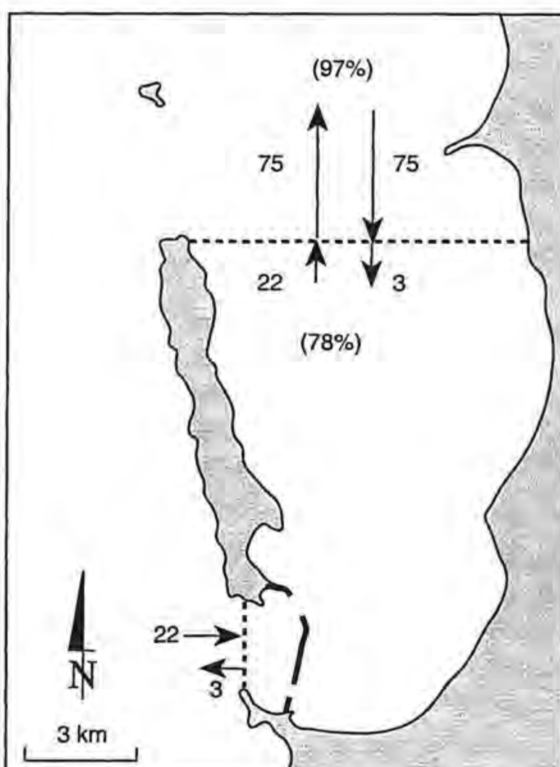

Figure 20. Schematic of modelled volume fluxes across the openings of Cockburn Sound from a baroclinic 'autumn' simulation (wind data as in Figure 14). Volume fluxes are expressed as a percentage of total outflow.

Other simulations (Mills and D'Adamo, 1995) indicate that easterly, northeasterly, northerly and northwesterly winds are favourable to the migration of relatively buoyant, external surface waters across the northern entrance into Cockburn Sound. Southwesterly and southerly winds favour the entry of external waters into Cockburn Sound through the causeway openings.

In autumn, prevailing easterly winds last typically for 2-3 days, but on occasions 5-6 days of easterlies are experienced. Figure 21 presents the modelled vertical salinity structure along a south-north transect after five days of 5 m s^{-1} easterly winds. The vertical stratification extends over the entire length of the main Cockburn Sound basin. Under prevailing easterly winds the deep basin water flushing (salt depletion) rates were lower for the southern section of Cockburn Sound than for the entire sound (Figure 22).

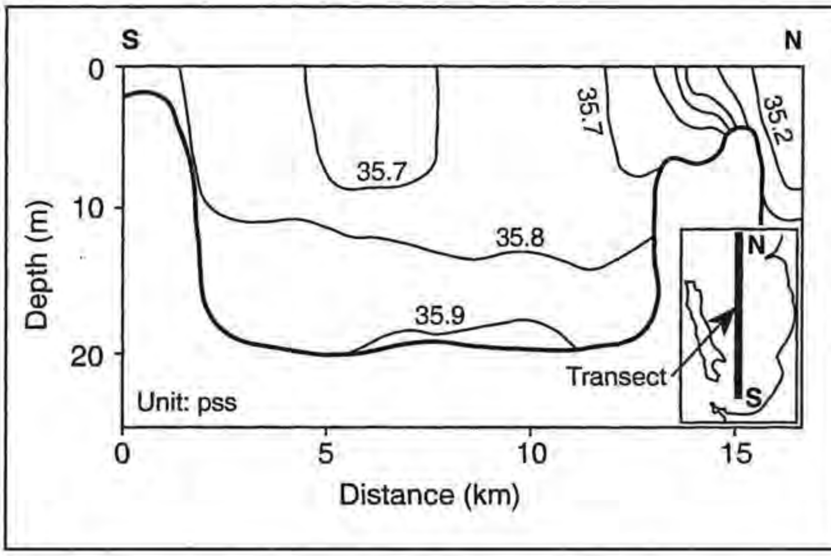

Figure 21. Baroclinically modelled south-north vertical salinity structure of Cockburn Sound under 'autumn' conditions after 5 days of constant easterly winds at 5 m s^{-1}.

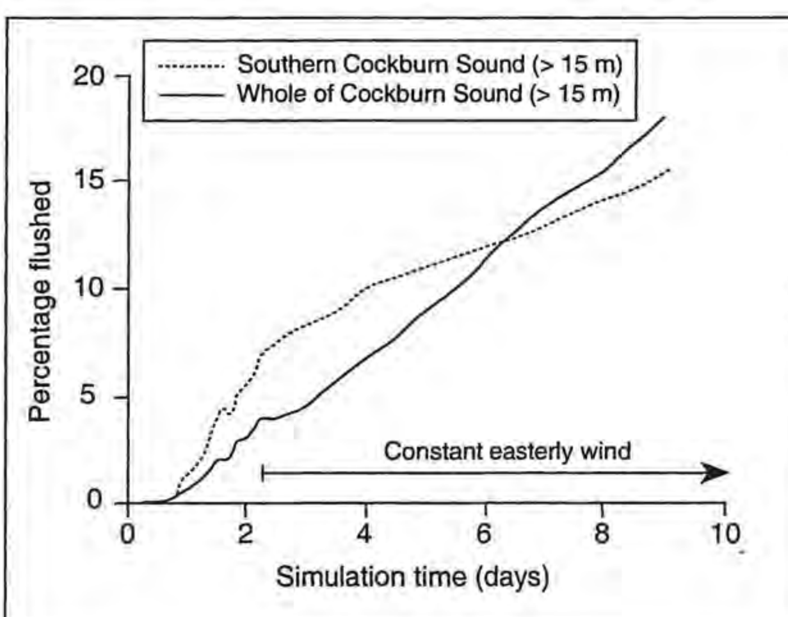

Figure 22. Baroclinically modelled flushing rates of deep Cockburn Sound water (> 15 m depth) for the entire basin and for the southern part of the basin (between James Point and the causeway) from an 'autumn' simulation. The model was forced with real winds as shown in Figure 14 for 0-2.3 days, and thereafter by a constant easterly 5 m s^{-1} wind.

The initial 'autumn' density structure is gravitationally unstable and modelling shows that, in the absence of other forcings, it undergoes baroclinic adjustment subject to rotational effects, resulting in the entry to the sound of buoyant shelf water. Inflow to Cockburn Sound from the north occurs as a buoyant plume attached to the mainland coast, while inflow from the south through the causeway openings propagates northward as a plume attached to the Garden Island coast (Figure 23) reaching the northern end of the island within four days. The widths of these plumes are typically several kilometres, which scales with the baroclinic radius of deformation (1-2 km) for the sound. The cumulative volume flux time for the baroclinic adjustment simulation is about 11 days, which is twice that for the 'autumn' simulation with both wind and density forcing. The combined action of wind and density forcing results in higher exchange rates than for the case of density forcing alone. However, in the presence of wind forcing (varying in the range of speeds up to 10 m s^{-1}) it is the characteristic density difference between the sound and external waters in 'autumn' that enhances circulation and flushing of near-surface Cockburn Sound waters relative to its deep basin waters.

The cumulative volume flux time for pure baroclinic adjustment in 'autumn' (about 11 days) is smaller than that due to tidal exchange (about 30 days) which was cited by Maritime Works Branch (1977b) as the base level of exchange for the sound. This suggests that in fact the underlying mechanism of gravitational relaxation provides the base level of exchange in 'autumn'.

6.4 Modelling the 'summer' hydrodynamic regime of Cockburn Sound

The transition from the 'winter-spring' hydrodynamic regime to the 'autumn' regime is a complex one (D'Adamo and Mills, 1995b). However, on the basis of detailed salinity-temperature-density field data, D'Adamo and Mills (1995a) suggested that it would be reasonable to apply a three-dimensional barotropic model during periods (i.e. the 'summer' regime) when the water densities of the shelf and Cockburn Sound were approximately equal and recurrent full depth mixing due to sea-breeze events was occurring in the sound. During the intensive field exercise of March 1992, for example, the horizontal density differential between Cockburn Sound waters and adjacent shelf waters was less than 0.1 kg m^{-3} and the vertical density stratification in Cockburn Sound was generally less than about 0.1 kg m^{-3} (in 20 m) with regular vertical mixing (D'Adamo and Mills, 1995a).

Previous oceanographic studies of Cockburn Sound (Maritime Works Branch, 1977a; Steedman and Craig, 1979, 1983 and Speedy, 1994) applied depth-averaged barotropic models, forced by wind, long-shelf pressure gradients and/or shelf currents. These modelling studies indicated that the water circulation of the sound is comprised of two components: a direct throughflow, and a system of interacting topographic gyres (Csanady, 1982) mainly controlled by wind and bathymetry. The system of gyres generally dominates the modelled current speeds and directions within the sound. The depth-averaged currents are approximately in the direction of the wind over shallow margins of the sound, with return flows in the deeper central basin. For example, when southwesterly winds predominate, the flow tends northward along the eastern and western shallow margins and southward in the deeper central basin. The depth-averaged topographic gyres were found to be virtually closed circulation features with severely limited volume exchange rates across the wide northern opening of the sound under wind conditions which occur for most of the time. These rates of volume exchange were found to be of similar magnitude to the rates of exchange due to throughflow in the presence of the causeway (Maritime Works Branch, 1977a; Speedy, 1994).

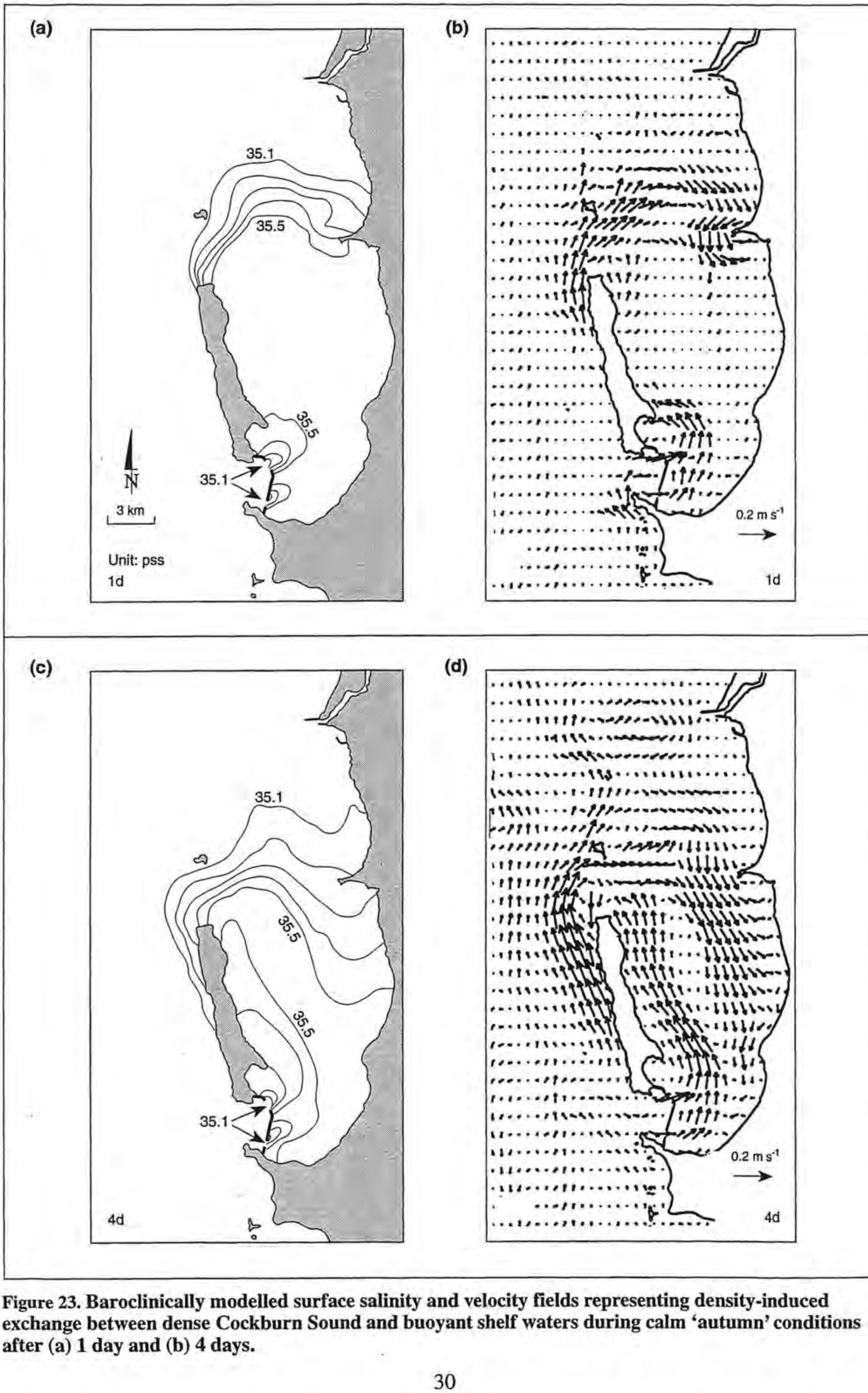

Figure 23. Baroclinically modelled surface salinity and velocity fields representing density-induced exchange between dense Cockburn Sound and buoyant shelf waters during calm 'autumn' conditions after (a) 1 day and (b) 4 days.

The period 7 March to 4 April 1992 was chosen for the three-dimensional barotropic simulation for two reasons: firstly, current meter data were available to enable comparisons between modelled results and field data; secondly, the analyses of intensive salinity-temperature-density field data collected during the period 9-27 March 1992 provided justification for using a barotropic version of the model. The water density variable in the model was set to a constant in space and time (to provide a barotropic simulation) and the variable normally used to represent salinity was this time used to represent a conservative, dynamically-passive tracer. The simulation was initialised with low tracer concentration in Cockburn Sound and high tracer concentration in the rest of the model domain (Figure 24), in order to trace the exchange between internal and external waters. The model was forced with locally recorded wind data for the simulation period (Figure 25).

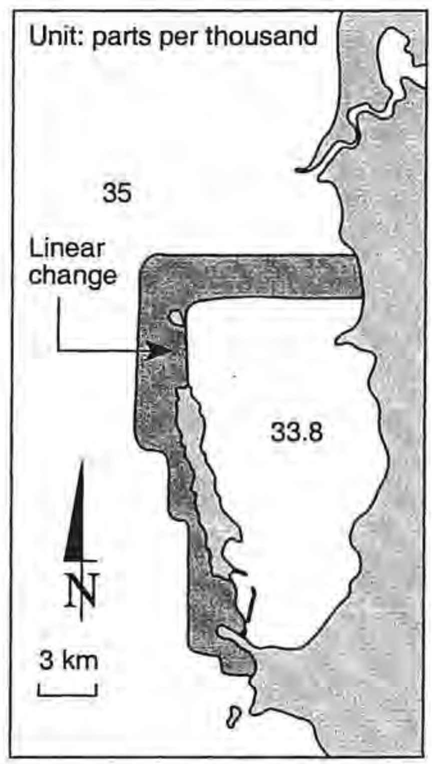

Figure 24. Starting horizontal distribution of tracer concentration for the barotropic model simulations of the 'summer' hydrodynamics of Cockburn Sound. Vertical distribution of tracer is uniform.

The model predicted three-dimensional barotropic circulation patterns generally consistent with the topographic gyres of previous depth-averaged modelling studies (Maritime Works Branch, 1977a; Steedman and Craig, 1983; Speedy, 1994). Figure 26 shows the simulated horizontal current vector fields at three depths (1 m, 7 m and 12 m) below the water surface for south-southwesterly winds. The flow is northward along the shallow eastern and western coastal margins of the sound and southward in the central basin. The surface current field shows the flow of water from the eastern and western shallow margins of Cockburn Sound across Parmelia Bank and out of the sound. The vertical profiles of current speed and direction over the eastern margin of Cockburn Sound (Figure 27) show that flow is approximately downwind throughout the water column and that there is a wind-driven surface boundary layer and a frictionally-impeded boundary layer near the sea bed. The surface current speed is approximately 50 % greater than the depth-averaged current. The non-uniform depth profile of the currents could result in significant differential transport between particles which are positively and negatively buoyant (e.g. phytoplankton).

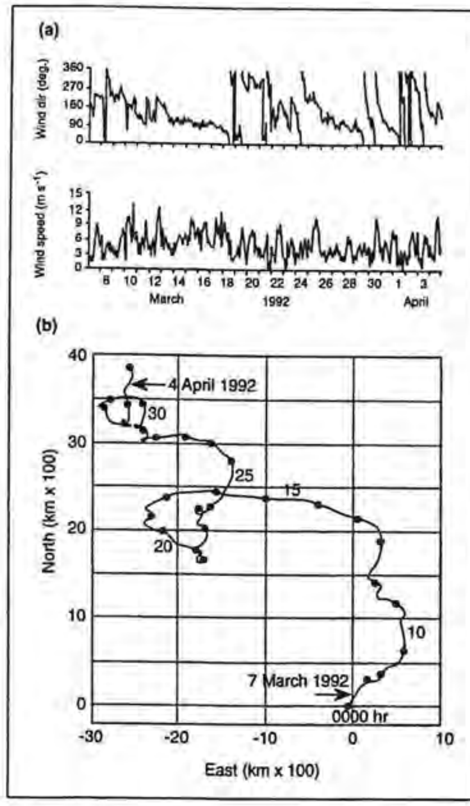

Figure 25. Wind data used for the barotropic model simulation of the hydrodynamics of Cockburn Sound under typical 'summer' conditions: (a) time series and (b) progressive vector run.

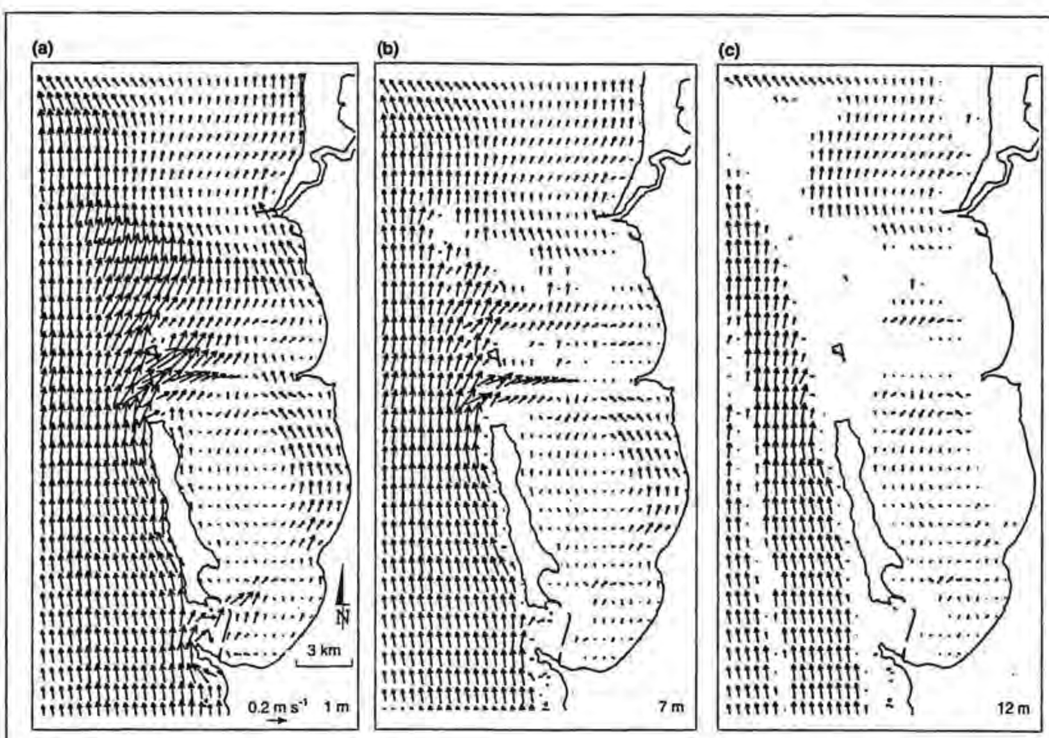

Figure 26. Barotropically modelled horizontal velocity fields at (a) 1 m depth (b) 7 m depth and (c) 12 m depth from the 'summer' simulation of Cockburn Sound and shelf waters responding to south-southwesterly winds after 6 days of wind data as in Figure 25.

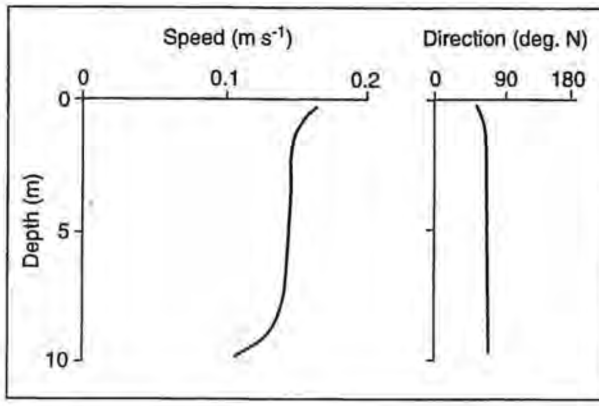

Figure 27. Barotropically modelled vertical profile of current speed and direction for Cockburn Sound (eastern margin) from the 'summer' simulation of the sound and shelf waters after 6 days (wind data as in Figure 25).

For east-northeasterly winds (perpendicular to the principal axis of the sound) the modelled circulation consists of south to southwestward currents outside of the sound with west to southwestward currents over Parmelia Bank and through Challenger Passage. Water movements are much weaker within the sound, except over the Southern Flats and through the causeway bridge openings where strong outflows occur (Figure 28).

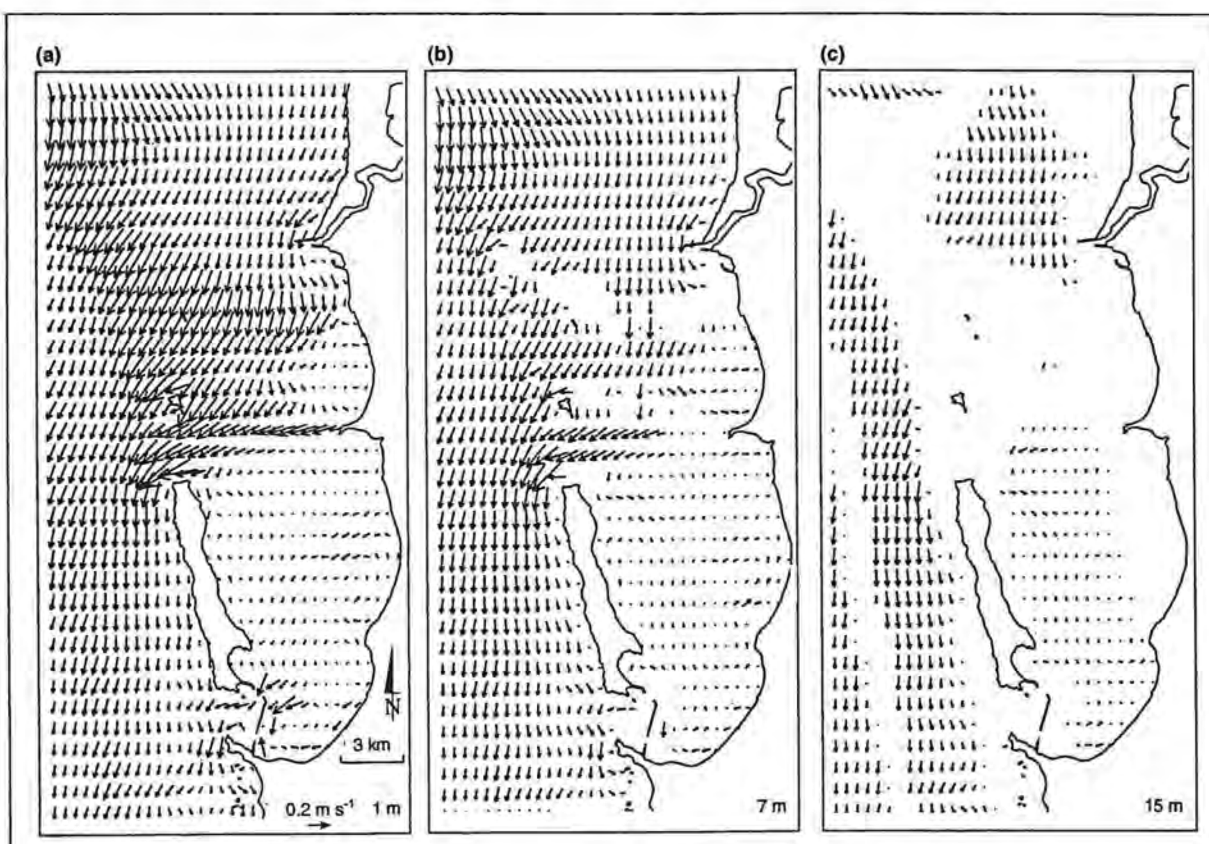

Figure 28. Barotropically modelled horizontal velocity fields at (a) 1 m depth (b) 7 m depth and (c) 15 m depth from the 'summer' simulation of Cockburn Sound and shelf waters responding to east-northeasterly winds after 11 days of wind data as in Figure 25.

In general, the time-scale for vertical mixing to the bottom of the sound is comparable to the advection time (time to advect across one grid cell) and hence the salinity (tracer) is vertically well-mixed throughout the model, although horizontal concentration gradients are still present.

During the 28 day simulation period the flushing of Cockburn Sound progressed in the form of a decay curve (Figure 29). The model predicts that 45 % flushing has been achieved in 28 days. There is minimal difference in the flushing rates of the near-surface (0-5 m below sea surface) zone and the deep basin (> 15 m below sea surface) zone, which is to be expected for a barotropic simulation, since full-depth mixing is not impeded by density stratification and occurs on time-scales much shorter than the characteristic flushing times. Figure 30 shows the successive cumulative volume flux times for Cockburn Sound from the results of the 'summer' regime (barotropic) simulation. These were the successive time intervals required for the gross volume inflows to cumulate to the volume capacity of Cockburn Sound. The cumulative volume flux times were in the range 6.5-10 days for this simulation. This illustrates again that cumulative volume flux times are not necessarily good indicators of contaminant flushing times.

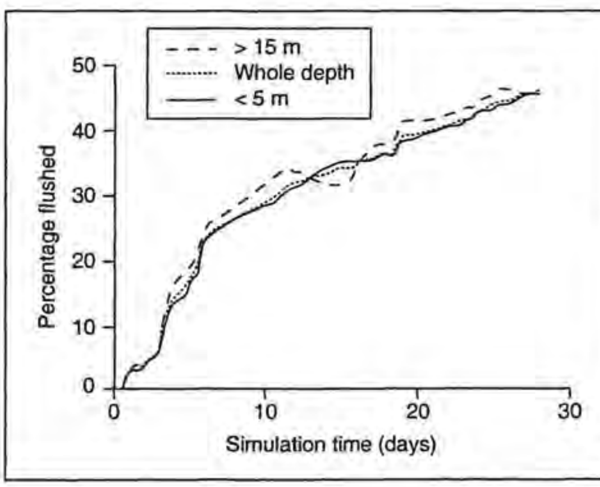

Figure 29. Barotropically modelled flushing rates for three depth zones (whole depth, < 5 m and > 15 m) of Cockburn Sound from the 'summer' simulation (wind data as in Figure 25).

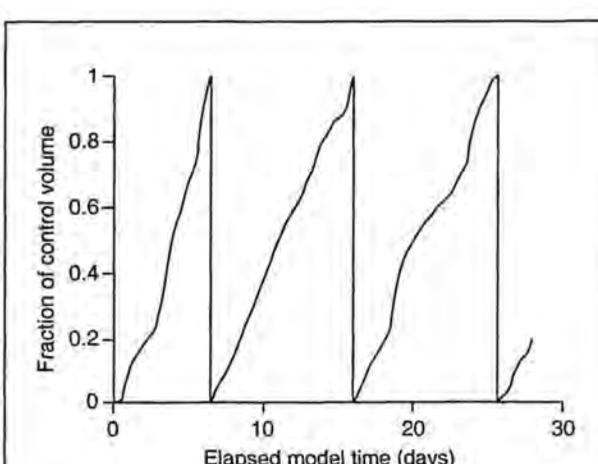

Figure 30. Successive time intervals required for cumulative volume inflows to equal the volume of Cockburn Sound from the 'summer' barotropic simulation (wind data as in Figure 25).

7. Effects of the Garden Island Causeway on the flushing of Cockburn Sound

7.1 Introduction

Construction of a rock-fill causeway between Garden Island and the mainland (west of Rockingham) was completed in June 1974, providing vehicular access to the HMAS Stirling naval facility. The causeway traverses the southern entrance to Cockburn Sound, following the shallowest route between the land masses. Two bridge openings were incorporated into the causeway, with widths of 300 m and 625 m and average water depths of 2.8 m and 4.5 m, respectively. The cross-sectional flow area along the causeway alignment was reduced to approximately one third of its original value, before construction.

7.2 Past studies

Between 1970 and 1976 a series of field surveys was commissioned by the Commonwealth Government of Australia to assess the causes of water flow between Cockburn Sound and the surrounding waters and to report on the changes in flow which occurred as a result of the causeway construction. A complementary numerical hydrodynamic modelling study was initiated, making use of a two-dimensional, depth-averaged, barotropic modelling system with a nested grid facility, developed at the Danish Hydraulics Institute (Abbott *et al.* 1973). Based on these studies, the Maritime Works Branch (1977a and b) concluded that the causeway had (a) reduced volume flow rates through the southern entrance of the sound to about 40 % of their original values, (b) reduced the combined rate of volume exchange across the northern and southern entrances of the sound to about 40-60 % of its original value, (c) significantly changed water current speeds within about 1500 m of the causeway, but had not significantly altered the wind-driven current speeds within the broad interior of Cockburn Sound.

Steedman and Craig (1979, 1983) applied a two-dimensional, depth-averaged, barotropic model to study the wind-driven circulation of Cockburn Sound and to estimate the resultant volume exchange across the northern opening. This study concluded that the two-way exchange flux across the northern opening due to wind-driven topographic gyres was low, and generally of the same order of magnitude as estimates from field data of the net flux through the causeway.

In reviewing these works, Hearn (1991) suggested that the causeway may have led to a significant difference in the overall throughflow (or 'ventilation') of the sound under barotropic conditions, even although the mixing and dispersion of contaminant plumes would not have appreciably changed at a more local scale.

More recently, Speedy (1994) conducted high resolution (100 m cell size) depth-averaged, barotropic modelling of Cockburn Sound and surrounding waters, for the configurations before and after installation of the causeway. The conclusions of this study are broadly consistent with those of the Maritime Works Branch (1977a) model study, which have been listed above. In particular, it was found that the net volume fluxes through the causeway openings are of similar magnitude to the two-way, depth-averaged, barotropic exchange rates across the much larger northern opening due to topographic gyres alone. This study also found that the presence of oscillatory (tidal) flows through the causeway openings had little influence (through frictional damping) on the magnitude of the net throughflows.

These studies all used two-dimensional, depth-averaged, barotropic models which did not account for the effects of density gradients on the dynamics, and were unable to resolve vertical variations in the currents.

7.3 Application of the three-dimensional baroclinic model

The importance of density effects on the hydrodynamics and flushing of the sound has been detailed from field observations (D'Adamo and Mills, 1995b, c; D'Adamo *et al.* 1995) and supporting model results have been presented in this paper. The three-dimensional baroclinic model was therefore used to investigate the influence of the causeway on flushing in the presence of density stratification. An additional advantage of this approach is that model variables such as water salinity can again be used to trace the extent to which external water penetrates into the sound and mixes with resident water, and this provides a further appreciation of the effects of the causeway on flushing of the sound.

The model grid representation of the two causeway bridge openings gives a combined cross-sectional flow area of 3500 m^2, compared to an area of 11 100 m^2 along the same alignment for model simulations without the causeway. This gives a flow area reduction of 67 %, which is close to the reduction of 73 % used by Speedy (1994). However, as previously cautioned, the horizontal grid size of the baroclinic model is too coarse to resolve the exact form and orientation of the bridge openings. Finer model resolution was precluded by the area of the total domain and the computing resources available to this study.

7.4 Effects of the Garden Island Causeway on the 'autumn' regime

The 'autumn' simulation was re-run with the same wind forcing and initial salinity (density) distribution, but without the causeway, to determine how this affected the flushing rates and circulation patterns of the sound.

Under southerly winds the simulated throughflows via the southern opening were stronger in the absence of the causeway, with a more rapid penetration of relatively low salinity, buoyant shelf water into the sound and then northwards, and next to the entire eastern shoreline of Garden Island (Figures 31a and b). Another significant difference in the two simulations is that under southerly wind the absence of the causeway resulted in greater penetration of denser water northward along the mainland coast toward Fremantle.

During a subsequent period of predominantly easterly wind, shelf water penetrated into the sound via the northern opening. A comparison of the simulated surface salinity contours for 1200 h 5 May 1994 shows that, without the causeway, most of the surface waters of the sound (which had an original salinity of 36 pss) had been significantly mixed with inflowing low salinity shelf water (Figure 31d). By contrast, in the simulation with the causeway present (Figure 31c), a large central portion of Cockburn Sound surface water remained close to its original surface salinity.

Vertical sections of salinity along the sound show that greater inflow via the unobstructed southern opening under predominantly southerly winds lowered the salinity in the southern half of the sound over greater horizontal and vertical distances, and reduced the entry of buoyant water across the northern opening (Figures 32a and b). At 0000 hrs 5 May 1994, after predominantly easterly winds, in the absence of the causeway, a mound of high salinity (> 35.8 pss) water was restricted to the central and northern end of the deep basin and overlain by less saline surface water, whereas, with the causeway present, the entire bottom of the sound was covered with this water (Figures 32c and d).

Differences in the rates of flushing of Cockburn Sound during 'autumn' conditions, with and without the causeway, are illustrated in Figures 33a, b and c for the near-surface zone (0-5 m below sea surface), the deep basin zone (> 15 m below sea surface) and the whole water column, respectively. These flushing rates were derived from changes in calculated salt content during simulations where the initial salinity of Cockburn Sound water was greater than that of the surrounding waters (as shown in Figure 13). In each case the flushing rates were greater in the absence of the causeway. Both with and without the causeway the surface zone was most readily flushed and the deep-basin zone was least rapidly flushed.

The baroclinic model predicted that the volumetric flux through the southern opening was reduced to 45 % of its former magnitude by the construction of the causeway. This is in good agreement with previous results (Maritime Works Branch, 1977a and b; Speedy, 1994) considering the spatial resolution of the model.

For the 'autumn' simulations both with and without the causeway, the density excess of Cockburn Sound waters relative to shelf waters in 'autumn' was an important factor in determining the nature of the circulation. In both simulations the deep basin zone of the sound was less readily flushed in 'autumn' than the near-surface zone.

7.5 Effects of the Garden Island Causeway on the 'winter-spring' regime

The 'winter-spring' hydrodynamic regime of Cockburn Sound was simulated with and without the causeway present, using local wind data for the period 9 August 1991 to 18 August 1991. In the absence of the causeway winds from the southwest quadrant forced a greater inflow to Cockburn Sound through its southern opening. The relatively dense inflow subsided and moved northward across the deep basin of the sound. This resulted in more rapid mixing with and displacement of buoyant sound water in the southern half of the basin in the absence of the causeway, as shown by comparing south-north vertical salinity sections for the two simulations (Figure 34). The corresponding near-bottom current vector plots for the two simulations are shown in Figure 35 and show the relative increase in flow speeds in the southern portion and the extended spatial influence of the southern inflow to the sound when the causeway is not present. In summary, the 'winter-spring' mechanism of deep basin water renewal was simulated both with the causeway present and absent, however the rate was quicker in the absence of the causeway.

Flushing rates for the 'winter-spring' regime of Cockburn Sound, with and without the causeway, were calculated from the modelled changes in salt content for various control volumes. These results are presented in Figure 36 a-c and suggest that the presence of the causeway has led to a somewhat decreased flushing rate for the entire sound, including both the near-surface and the deep basin zones.

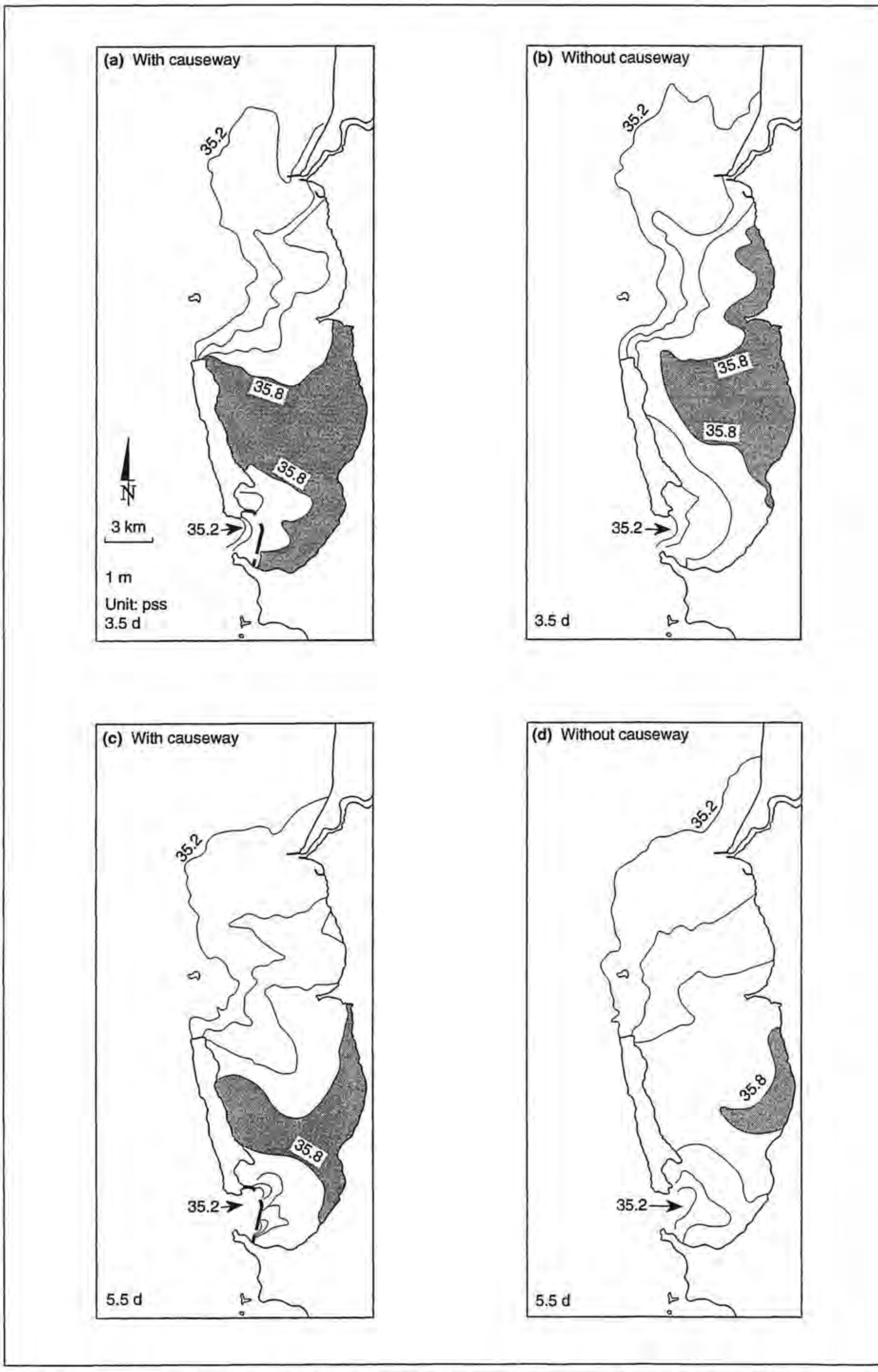

Figure 31. Baroclinically modelled surface salinity fields from the 'autumn' simulations (a) with the causeway and (b) without the causeway after 3.5 days and (c) with the causeway and (d) without the causeway after 5.5 days. Shading indicates a salinity greater than 35.8 pss.

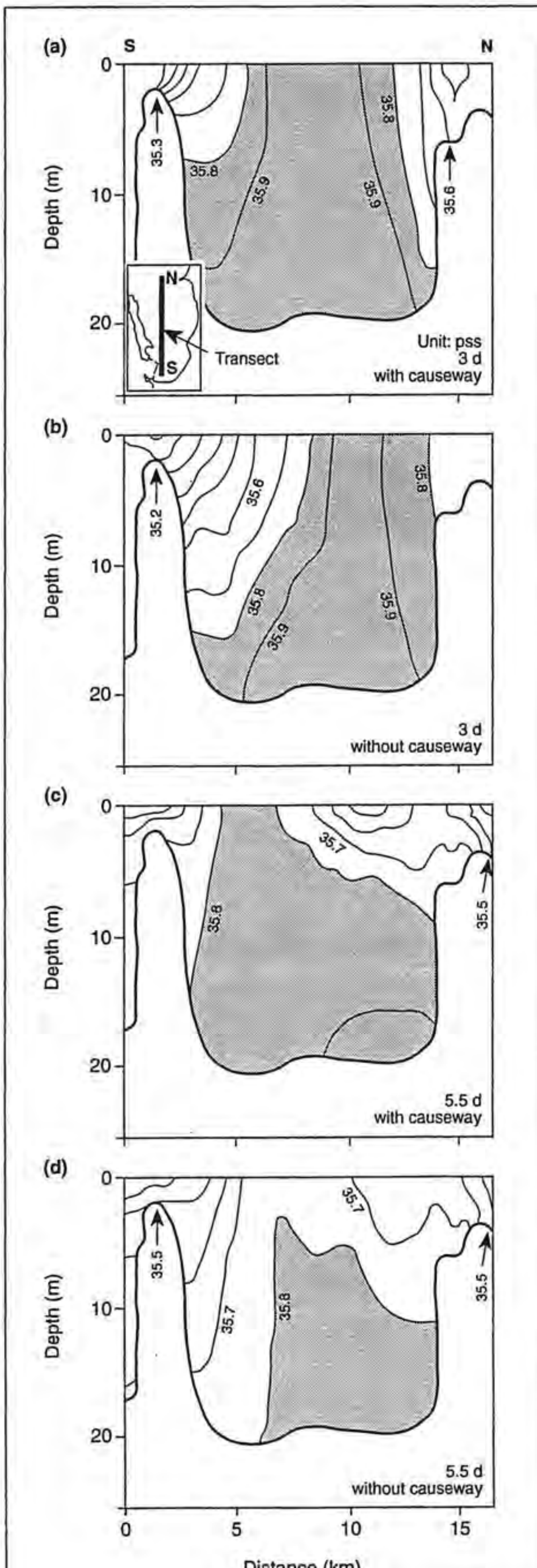

Figure 32. Baroclinically modelled south-north vertical salinity structures from the 'autumn' simulations (a) with the causeway and (b) without the causeway after three days and (c) with the causeway and (d) without the causeway after 5.5 days. Shading indicates a salinity greater than 35.8 pss.

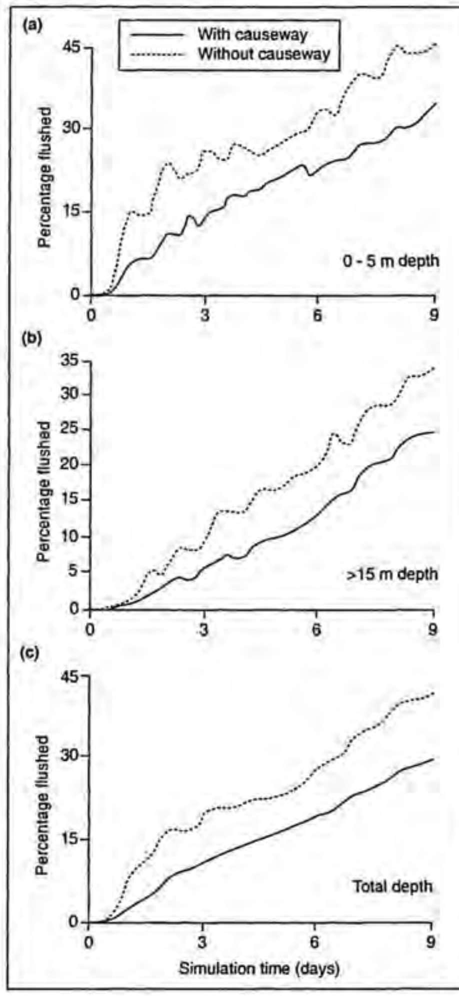

Figure 33. Baroclinically modelled flushing rates for Cockburn Sound comparing 'autumn' simulations with and without the causeway for three depth zones: (a) 0-5 m, (b) > 15 m and (c) total depth.

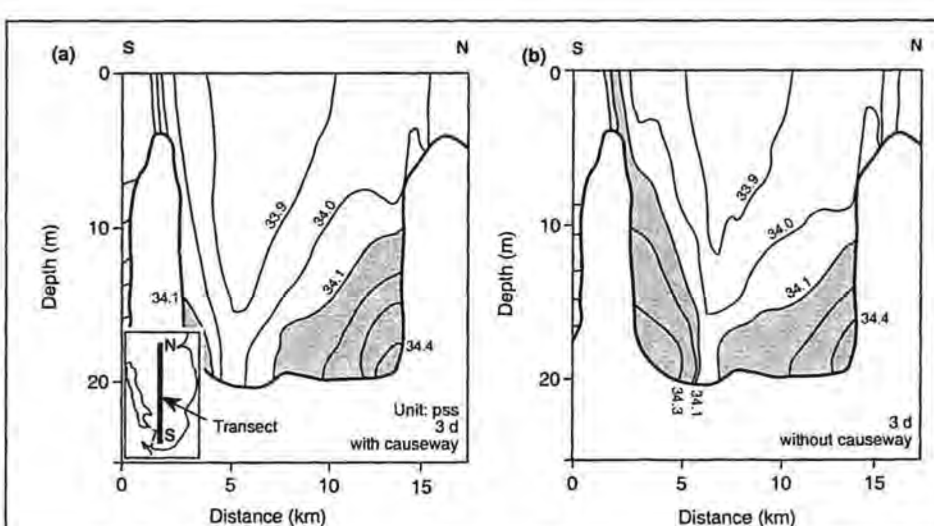

Figure 34. Baroclinically modelled south-north vertical salinity structure from the 'winter' simulations (a) with and (b) without the causeway after 3 days (winds as in Figure 7). Shading indicates a salinity greater than 34.1 pss.

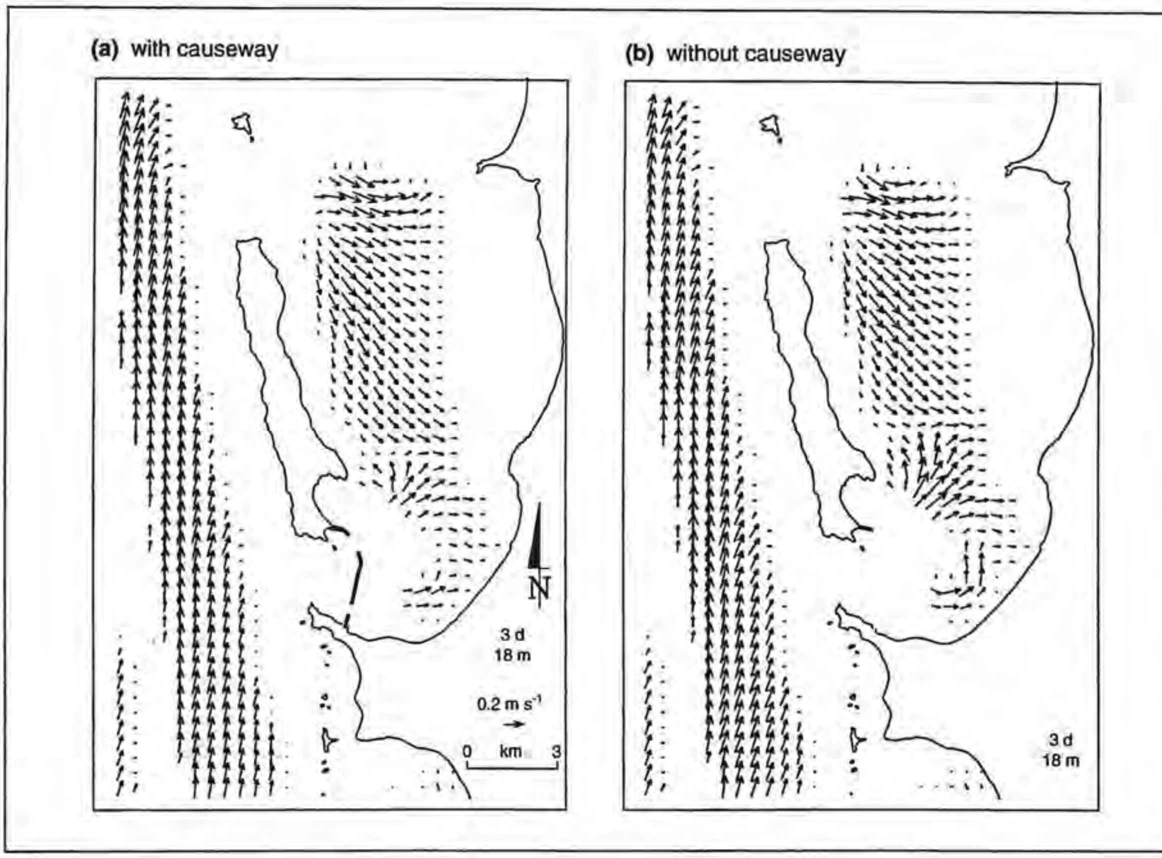

Figure 35. Baroclinically modelled horizontal velocity fields at a depth of 18 m from the 'winter' simulations (a) with and (b) without the causeway after 3 days (wind data as in Figure 7).

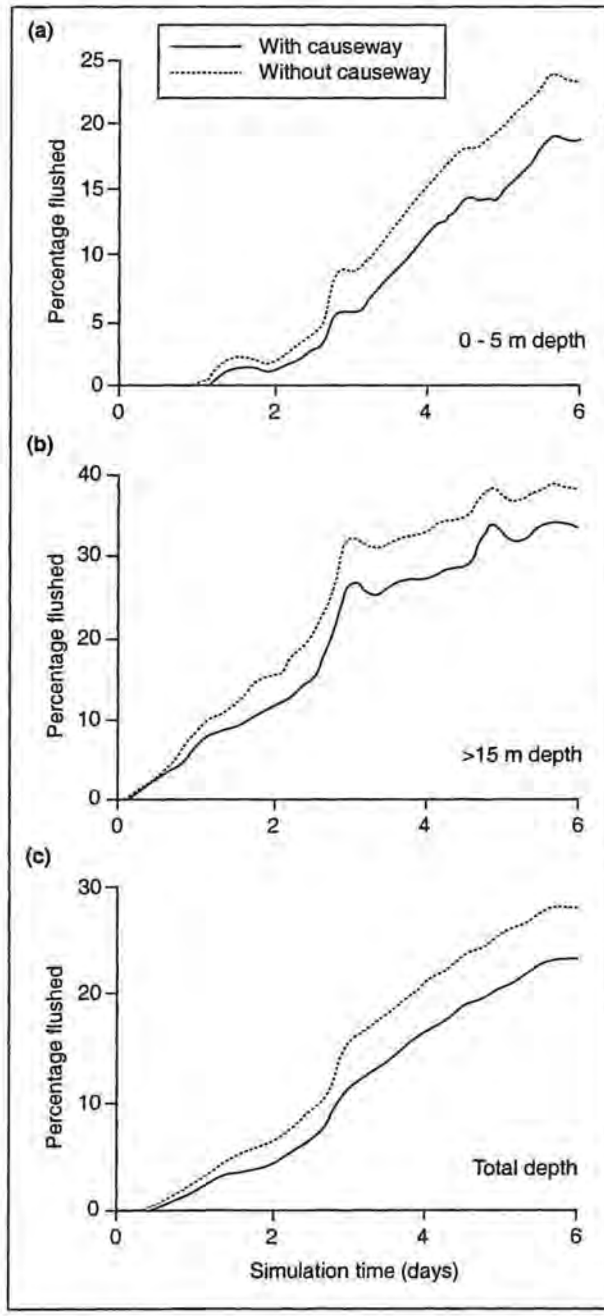

Figure 36. Baroclinically modelled flushing rates for Cockburn Sound comparing 'winter' simulations with and without the causeway for three depth zones, (a) 0-5 m, (b) > 15 m and (c) total depth.

8. Dispersion of effluent in Cockburn Sound

8.1 Introduction

The mixing and dispersion of effluent discharged from a point source outlet can be broadly considered in terms of three zones or regions (Fischer *et al.* 1979). Near the outlet, the mixing is determined mainly by the momentum and buoyancy of the effluent. For a positively buoyant effluent outlet located on the sea floor, for example, this initial mixing occurs as the effluent rises toward the sea surface in the form of a buoyant jet. Far from the outlet, the transport and mixing of the effluent are governed mainly by the ambient water circulation characteristics and turbulence levels of the general area. The effluent plume in the far-field is no longer significantly influenced by the original density of the effluent or the design details of the outlet. Between the near-field and the far-field zones there is a region of transition where effluent dispersion depends both on the discharge characteristics and on the ambient oceanographic conditions. The purpose of this section is not to examine the individual mixing characteristics in the near-field zone of each outfall, which in most cases is confined to horizontal length scales of order 100 m, but rather to use the three-dimensional hydrodynamic model to simulate the far-field transport of released contaminant over length scales of order 10 km, and to compare the simulation results with historical field data.

8.2 Far-field dispersion of effluent in Cockburn Sound

In 1978-79 Cockburn Sound surface seawater samples were taken from a grid of stations with 2 km spacing and analysed for cadmium levels (Rosman *et al.* 1980). The purpose of this study was to map the surface distribution of cadmium throughout Cockburn Sound and to relate it to an industrial discharge of gypsum, located south of James Point, which (at that time) constituted the major cadmium input to the sound (Department of Conservation and Environment, 1979). The measured cadmium concentration field of 28 December 1978 has been used as a basis for comparison with simulated dispersion fields produced by the model. It was estimated that cadmium had been released to the sound at a rate of approximately 4.5 kg d^{-1} for about one month before the time of these measurements (Rosman *et al.* 1980).

The three-dimensional model was set to run barotropically with a constant source of dynamically-passive tracer released at the location of the gypsum discharge. The model was forced with Garden Island wind data from the period 18-28 December 1978. During this period wind speeds were in the range 0-9 m s^{-1} and the wind underwent two anticlockwise cycles, bringing breezes from all directions, before settling between southwesterly to easterly for several days prior to the time of the cadmium field survey. The near-surface dilution contours after 10.5 simulation days, corresponding to the time of the cadmium survey, are shown in Figure 37b. At this time the simulated plume extended mainly to the north of the source, with highest concentrations over the eastern margin of the sound. Near Woodman Point, the simulated plume was divided into two branches. One branch crossed the eastern Parmelia Bank and extended further northward into Owen Anchorage. The other branch was transported southward over the central deep basin of Cockburn Sound in response to typical flow recirculation (see, for example Figure 26) under the prevailing summer wind conditions. Simulated tracer was found to the southwest of the source, and very low concentrations were present external to the sound, within a few kilometres of both the northern and southern entrances. All of these features of the simulated tracer field were also found in the measured cadmium distribution, illustrated in Figure 37a. The model indicated that, after 11 days simulation, 80 % of the contaminant emitted from the source was still resident in Cockburn Sound. This result is generally consistent with the low flushing rates for the sound, derived from the 'summer' barotropic simulation (see section 6.4). Quantitative comparisons between the simulated and measured cadmium plume results will therefore require that the model be run for a longer period, taking into account the duration of continuous discharge from the cadmium source and the contaminant flushing rate from the basin.

9. Discussion

9.1 Seasonal hydrodynamic regimes

Previous studies of the Cockburn Sound hydrodynamics employed two-dimensional, depth-averaged barotropic models which calculated water circulation patterns composed of wind-driven topographic

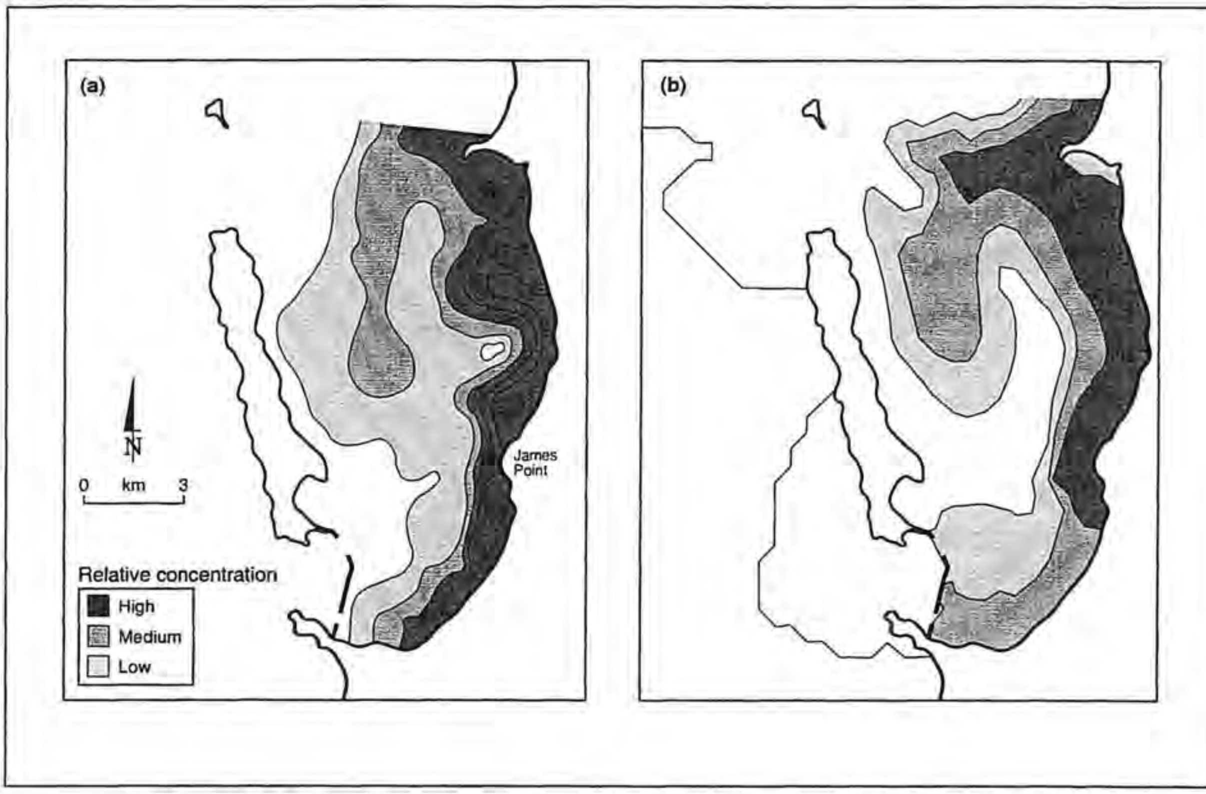

Figure 37. Far-field dispersion of effluent released from south of James Point: (a) relative concentration of cadmium in surface waters derived from measurements on 28 December, 1978 (adapted from Rosman *et al.* 1980), and (b) relative tracer concentration patterns in surface waters after a 10.5 day barotropic simulation forced by recorded winds for the period 18-28 December 1978.

gyres and throughflow. These model studies did not account for the dynamical role of density gradients. However field measurements have shown that vertical and/or horizontal density gradients are almost always present and this has emphasised the need to understand the role of density gradients in mediating the wind-driven circulation of the sound.

The three-dimensional, baroclinic simulations described in this paper have shown that the presence of an underlying density difference between the sound and external shelf waters (and its change from season to season) plays a key role in determining the nature of the wind-driven exchange, circulation and flushing of Cockburn Sound. Field data show that the shelf-sound density difference undergoes an annual cycle, with Cockburn Sound water being relatively dense in autumn/early winter, and relatively buoyant in winter/spring. This annual cycle and its relationship to the seasonal hydrodynamic regimes of the sound is further discussed in D'Adamo and Mills (1995b). Three broad 'seasonal' regimes have been identified from field data and modelled. In 'winter', buoyant estuarine plume water is forced into Cockburn Sound by winds from the northeast and northwest quadrants, and then vertically mixed by storm winds from the northwest and/or southwest quadrants. Under moderating southerly wind conditions, buoyant water is then transported out of the sound and is replaced by relatively dense shelf water which subsides and is transported across the deep basin of the sound, thereby resulting in a vertically stratified basin. In 'autumn', relatively buoyant water is driven in across the shallow sills at the entrances of the sound and forms buoyant, stratified surface layers which confine and isolate deep basin water from exchange. Under well-mixed conditions in 'summer' the three-dimensional circulation characteristics are generally consistent with the wind-driven topographic gyres and throughflow described by previous studies, however they also include a wind-driven surface layer and a frictionally impeded bottom layer.

To further establish the above findings, three parallel simulations were conducted with the same wind forcing in each case, but different initial salinity/density distributions appropriate to the 'autumn', 'winter' and 'summer' regimes. As shown in Figure 38, the flushing of the near-surface zone (0-5 m below sea surface) is advantaged by a salinity/density distribution with a relatively dense Cockburn Sound (typical of 'autumn'), the flushing of the deep basin zone (> 15 m below sea surface) is advantaged by a relatively buoyant Cockburn Sound (typical of 'winter'), and flushing is intermediate for the 'summer' (barotropic) simulation.

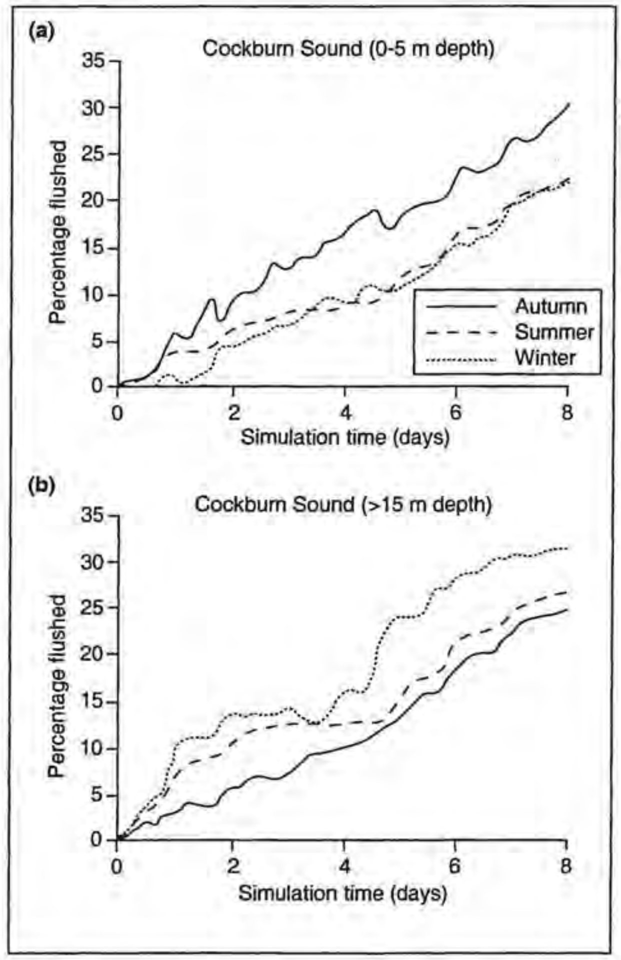

Figure 38. Comparison of modelled flushing rates for Cockburn Sound from three simulations using the same wind forcing (as in Figure 14) but with starting salinity distributions for 'autumn', 'summer' and 'winter', respectively, for (a) 0-5 m depth, and (b) > 15 m depth.

For winds in excess of about 5 m s^{-1}, the addition of the wind forcing increases the exchange rates substantially beyond those for gravitational relaxation alone. Furthermore, for winds with speeds up to 10 m s^{-1}, in the presence of shelf-embayment density differences, exchange can introduce vertical stratification to the basin, enhancing the gravitational stability of the sound. The density stratification changes the way in which momentum (imparted by wind stress at the water surface) is distributed throughout the water column. The wind-driven circulation is also mediated by density effects. The simulations have confirmed that density effects can remain of dynamical significance in association with wind speeds up to 10 m s^{-1}, as concluded by D'Adamo (1992) who reviewed historical density stratification and wind data. The presence of vertical stratification does not necessarily imply a lack of flushing. In 'winter', for example, high vertical stratification in Cockburn Sound results from an efficient flushing process.

In each of the 'autumn', 'summer' and 'winter-spring' wind-driven simulations the two-way volume exchange across the northern opening was greater by a factor ranging from 2 to 3.5 compared to the magnitude of flow through the causeway. This result is at variance with the findings of the two-dimensional model studies, which concluded that this factor was close to unity. Since the three-dimensional model is able to resolve vertical current profiles, it could more accurately calculate exchange across the larger northern opening section.

In the absence of forcings such as wind, tide and long-shelf pressure gradients, an embayment-shelf density difference still leads to underlying exchange and flushing because this distribution of water masses is gravitationally unstable. The model has been used to simulate the gravitationally-driven circulation for 'winter' and 'autumn' conditions. It has been shown that, although the influence of the earth's rotation lowers the intrinsic rate of baroclinic exchange, it is still considerably greater than the estimated rate of tidal exchange during 'autumn' and 'winter'. Furthermore the modelling has shown that the density-induced gravitational exchange involves penetration of shelf water along the entire length of the sound within about 10 days, whereas the length scale of tidal advection is about 500 m, so that basin-scale flushing of Cockburn Sound due to tidal processes alone is likely to occur as a slow diffusive process.

The distinct seasonal hydrodynamic and transport regimes identified in Cockburn Sound should be considered in the design of future programmes to investigate the dispersion of effluent and to monitor environmental quality in the sound.

9.2 Effects of the Garden Island Causeway

The results of past two-dimensional modelling studies, which suggest that, on average, the flux through the southern opening of Cockburn Sound has been reduced by construction of the causeway to about 40 % of its former value, are supported by this study.

The total (combined) volume exchange rate via both the northern and southern entrances of Cockburn Sound has been reduced as a result of the causeway construction, though the three-dimensional modelling results suggest that the overall reduction is about 30 %, which is less than the 50 % suggested by the previously reported two-dimensional modelling studies.

Former studies reported by Maritime Works Branch (1977a and b) invoked tidal currents as a base flushing mechanism under calm conditions (with an exchange time of about 30 days), and concluded that the construction of the causeway would not have significantly altered the tidal exchange rates. This study has pointed out that, in the presence of seasonal density differences between waters of the shelf and Cockburn Sound, the exchange rates due to baroclinic adjustment alone are generally greater than those due to tide. The gravitational adjustment flows penetrate along the length of Cockburn Sound whereas the length scales of tidal advection are generally of the order of 500 m; this is the case both with and without the Causeway,

The onset of distinct circulation regimes ('autumn', 'winter-spring' and 'summer') due to seasonal density differences between shelf and embayment waters was predicted to occur both in the presence and absence of the causeway. Comparing the results of the baroclinic simulations, with and without the causeway, it was concluded that the most significant differences in the modelled salinity and advection fields in Cockburn Sound occurred toward the southern end of the sound, reflecting the proximity of this region to the inflows via the southern opening.

9.3 Far-field dispersion of effluent

The dispersion of water-borne contaminants in Cockburn Sound needs to be modelled at the appropriate spatial scale. Sub-basin scale transport models do not account for recirculation of contaminant which occurs within the sound, but beyond the model domain. Under southerly winds, for example, contaminant mass may be transported northward along the eastern margin of the sound before some proportion of that mass is recirculated southward over the central deep basin, or alternatively proceeds further northward into Owen Anchorage.

Contaminant released just south of James Point has a long residence time in Cockburn Sound, under quasi-barotropic conditions. For example, the model predicted that, at the end of an 11 day period in December 1978, 80 % of contaminant emitted during that period was still resident in the sound. Modelling of far-field dispersion from a continuous tracer source in Cockburn Sound therefore requires that sufficient simulation time be allowed for the concentration field to develop.

The model was able qualitatively to reproduce the main features of the plume under summer conditions.

The far-field modelling of materials dispersion in Cockburn Sound under conditions typical of the 'autumn' and 'winter-spring' hydrodynamic regimes will require that the model include density effects, to realistically simulate advection and transport fields.

10. References

Abbott M B, Damsgaard A and Rodenhus G S (1973). System 21, "Jupiter" (A design system for two-dimensional nearly horizontal flow). *J. Hydraulic Res.* **11(1)**: 1-28.

Blumberg A F and Mellor G (1980). A coastal ocean numerical model. In: 'Mathematical Modelling of Estuarine Physics, Proc. Int. Symp., Hamburg, Aug. 1978' (eds. J Sunderman and K P Holz). Springer-Verlag, Berlin: 203-214.

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

Breckling J (1989). The analysis of directional time series: applications to wind speed and direction. In: 'Lecture Notes in Statistics-61' (eds. J Berger, S Fienberg, J Gani, I Olkin and B Singer). Springer-Verlag.

Cary J L, Masini R J and Simpson C J (1995). The water quality of the southern metropolitan coastal waters of Perth, Western Australia: The influence of regional and local scale forcings. (Department of Environmental Protection, Perth, Western Australia, 6000). Technical Series 64.

Chu V H and Baddour R E (1984). Turbulent gravity-stratified shear flows. *J. Fluid Mech.* **138**: 353-378

Csanady G T (1982). Circulation in the coastal ocean. D Reidel Publishing Company, Dordrecht, Holland.

D'Adamo (1992). Hydrodynamics and recommendations for further studies in Cockburn Sound and adjacent waters. (Environmental Protection Authority, Perth, Western Australia, 6000). Technical Series 41.

D'Adamo N and Mills D A (1995a). Coastal water transport and vertical mixing during summer in the nearshore zone off Perth, Western Australia - the roles of wind-driven mixing and advection, thermal stratification and penetrative convection. (Department of Environmental Protection, Perth, Western Australia, 6000). Technical Series 67.

D'Adamo N and Mills D A (1995b). Seasonal variation in the physical structure of the coastal zone off Perth, Western Australia - implications for exchange between the nearshore embayments and mid-shelf waters. (Department of Environmental Protection, Perth, Western Australia, 6000). Technical Series 69.

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

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

Department of Conservation and Environment (1979). The Cockburn Sound Environmental Study (1976-1979). (Department of Conservation and Environment, Perth, Western Australia, 6000). Report 2.

Department of Defence (1994). Australian national tide tables 1995. (Australian Government Publishing Service, Canberra, ACT, 2600). Australian Hydrographic Publication 11.

Fandry C B, Leslie L M and Steedman R K (1984). Kelvin-type coastal surges produced by tropical cyclones. *J. Phy. Oceanog.* **14**: 582-593.

Fischer H B, List E J, Koh R C Y, Imberger J and Brooks N H (1979). Mixing in inland and coastal waters. Academic Press, New York.

Gill A E (1982). Atmosphere-ocean dynamics. Academic Press, New York.

Godfrey J S and Ridgeway K R (1985). The large-scale environment of the poleward-flowing Leeuwin Current, Western Australia: longshore steric height gradients, wind stress and geostrophic flow. *J. Phys. Oceanogr.* **15**: 481-495.

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

Hearn C J, Hunter J R, Imberger J and van Senden D (1985). Tidally induced jet in Koombana Bay, Western Australia. *Aust. J. Mar. Freshwater Res.* **36**:453-479.

Hodgkin E P and Phillips B F (1969). Sea temperatures on the coast of south Western Australia. *J. Roy. Soc. of W. Aust.* **52**: 59-62.

Herzfeld M (1995). User's guide for the Blumberg-Mellor 3-D numerical ocean model, C version. (Flinders Institute for Atmospheric and Marine Sciences, Flinders University of South Australia, Bedford Park, South Australia, 5042). Computing Report 15.

Lazure P and Salomon J C (1991). Coupled 2-D and 3-D modelling of coastal hydrodynamics. *Oceanologica Acta*, **14(2)**: 173-180.

Luketina D A and Imberger J (1987). Characteristics of a surface buoyant jet. *J. Geophys. Res.* **92(C5)**: 5435-5447.

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

Maritime Works Branch (1977b). The environmental significance of the Garden Island Causeway, Cockburn Sound, Western Australia. (Maritime Works Branch, Australian Department of Construction, Perth, Western Australia, 6000). Report MW80.

Mellor G L (1993). Users guide for a three-dimensional primitive equation numerical ocean model. Unpublished report. Atmospheric and Oceanic Sciences program, Princeton University.

Mellor G L and Yamada T (1982). Development of a turbulence closure model for geophysical fluid problems. *Rev. Geophys. Space Phys.* **20**: 851-875.

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

Mills D A and Essers V R (1995). User manual, file structure and graphics programs for a 3D hydrodynamic model adapted from the Princeton Ocean Model. Unpublished data report. (Department of Environmental Protection, Perth, Western Australia, 6000). Data Report SMCWS HYDRO-14.

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

Pattiaratchi C B, Imberger J, Zakar N and Svenson T (1995). Perth Coastal Waters Study: Physical measurements. Project P2. Unpublished report to the Water Authority of Western Australia. (Water Authority of Western Australia, Leederville, Western Australia, 6007).

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

Phillips N A (1957). A coordinate system having some special advantages for numerical forecasting. *J. Meteorol.* **14**: 184-185.

Rosman K J R, de Laeter J R and Chegwidden A (1980). Distribution of cadmium in Cockburn Sound, Western Australia. *The Science of the Total Environment* **16**:117-130.

Scott J T and Csanady G T (1976). Nearshore currents off Long Island. *J. Geophys. Res.* **81**: 5401-5409.

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

Smith R L, Huyer A, Godfrey J S and Church J A (1991). The Leeuwin Current off Western Australia, 1986-1987. *J. Phys. Oceanogr.* **21**: 323-345.

Smolarkiewicz P K and Clark T L (1986). The multidimensional positive definite advection transport algorithm: further development and applications. *J. Comp. Phys.* **67(2)**: 396-438.

Spaulding M L, Bedford K, Blumberg A, Cheng R and Swanson C (1992). Estuarine and coastal modeling. Proceedings of the 2nd International Conference, Tampa, Florida, November 13-15, 1992 (eds. M L Spaulding, K Bedford, A Blumberg, R Cheng and C Swanson). American Society of Civil Engineers, New York.

Speedy V (1994). A numerical model of the effects of the Garden Island Causeway on the flushing of Cockburn Sound, Western Australia. Unpublished Honours thesis. (Department of Geography and Oceanography, University College, University of New South Wales, Australian Defence Force Academy, ACT, 2600).

Steedman and Associates (1981). Cape Peron wastewater ocean outlet effluent dispersion studies. In: 'Cape Peron ocean outlet. Feasibility study. Volume 3. Supplementary Report - oceanographic working papers' for Binnie and Partners Pty Ltd. Unpublished report, by Binnie & Partners Pty. Ltd. in association with G B Hill & Partners, to the Metropolitan Water Supply Sewerage and Drainage Board. (Metropolitan Water Supply Sewerage and Drainage Board, Perth, Western Australia, 6000).

Steedman R K and Craig P D (1979). Numerical model study of circulation and other oceanographic aspects of Cockburn Sound. A report to the Department of Conservation and Environment, Perth, Western Australia. (R K Steedman and Associates, Perth, Western Australia, 6000). Report 64.

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

van Senden D C (1991). Review of the physical oceanography of Perth metropolitan coastal waters. Unpublished report to the Water Authority of Western Australia. (Water Authority of Western Australia, Leederville, Western Australia, 6007).

11. Appendix 1

The values of the internal model parameter settings used in the simulations described in this paper are set out below. The role of these parameters within the context of the Princeton Ocean Model is fully described in Mellor (1993).

Internal model time step (s) =	180.0
External model time step (s) =	9.0
Number of time steps where external mode advective terms not updated =	5
Horizontal diffusivity Prandtl number =	1.0
Constant in time smoother to prevent solution splitting =	0.1
Constant in Smagorinsky horizontal viscosity =	0.1
Constant in Smagorinsky horizontal diffusivity =	0.1
Initial vertical kinematic viscosity ($m^2 s^{-1}$) =	00.1
Initial vertical diffusivity ($m^2 s^{-1}$) =	0.0001
Initial horizontal kinematic viscosity ($m^2 s^{-1}$) =	10.0
Initial horizontal diffusivity ($m^2 s^{-1}$) =	10.0
Bottom roughness parameter (m) =	0.002
Reference coriolis constant (s^{-1}) =	-7.7×10^{-5}
Beta (($m^{-1} s^{-1}$) =	0.0