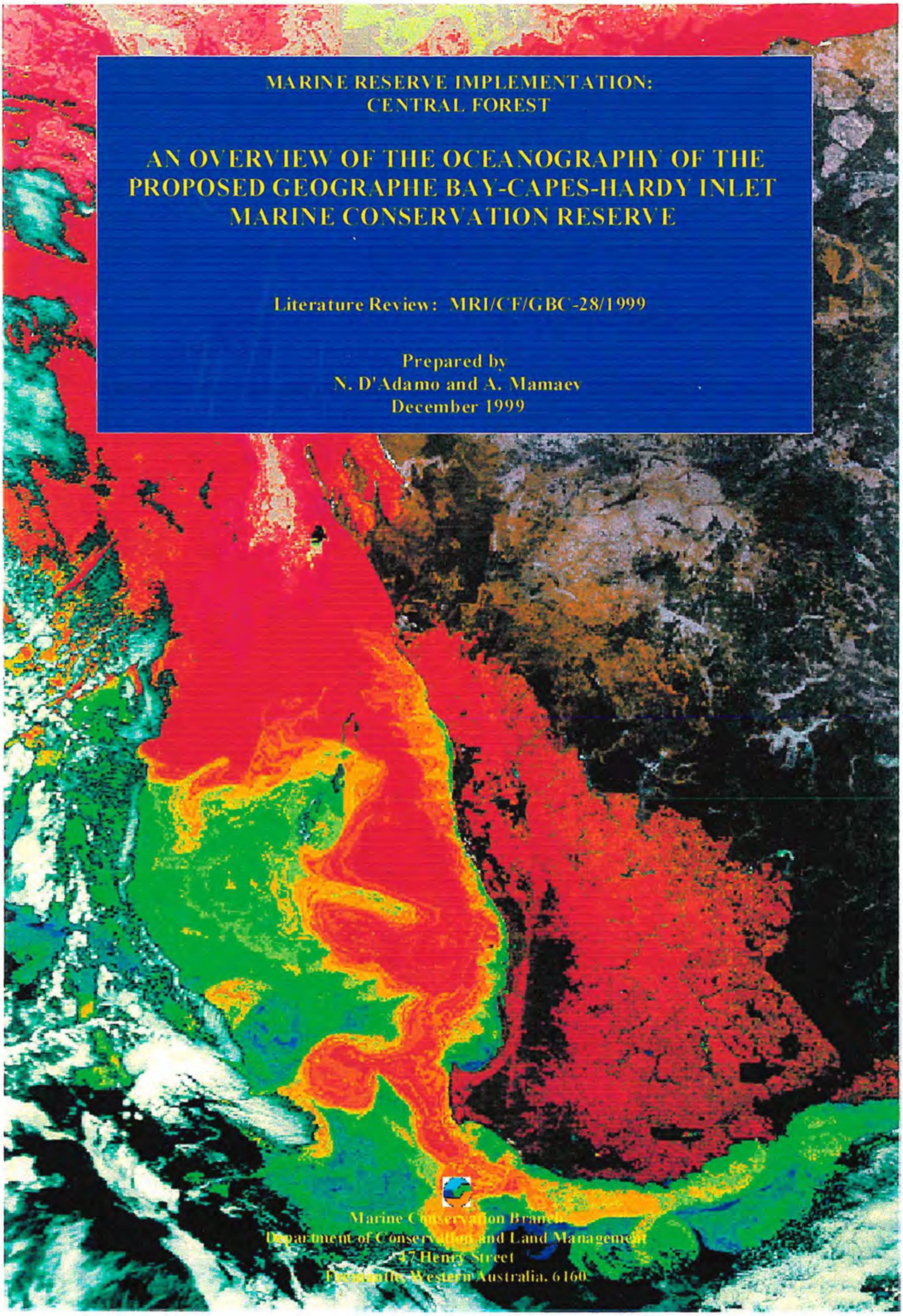


MARINE RESERVE IMPLEMENTATION:
CENTRAL FOREST

AN OVERVIEW OF THE OCEANOGRAPHY OF THE PROPOSED GEOGRAPHE BAY-CAPES-HARDY INLET MARINE CONSERVATION RESERVE

Literature Review: MRI/CF/GBC-28/1999

Prepared by
N. D'Adamo and A. Mamaev
December 1999

Marine Conservation Branch
Department of Conservation and Land Management
47 Henry Street
Fremantle, Western Australia, 6160

MARINE RESERVE IMPLEMENTATION:
CENTRAL FOREST

AN OVERVIEW OF THE OCEANOGRAPHY OF THE PROPOSED GEOGRAPHE BAY-CAPES-HARDY INLET MARINE CONSERVATION RESERVE

Literature Review: MRI/CF/GBC-28/1999

A project partially funded through the Natural Heritage Trust's
Coast and Clean Seas Marine Protected Area Programme
Project No: WA9703

Prepared by
N. D'Adamo and A. Mamaev
Marine Conservation Branch

December 1999

Marine Conservation Branch
Department of Conservation and Land Management
47 Henry St
Fremantle, Western Australia, 6160

blank pages deleted from document

Cover. Satellite image of sea-surface temperature (SST) from NOAA-AVHRR from northwest to southwest Australia showing the Leeuwin Current on 15 August 1991.

This report may be cited as:

D'Adamo N. and Mamaev A. (1999). An overview of the oceanography of the proposed Geographe Bay-Capes-Hardy Inlet marine conservation reserve. Literature Review: MRI/CF/GBC-28/1999. December 1999. Marine Conservation Branch, Department of Conservation and Land Management, Fremantle, Western Australia, 6160.

Copies of this report may be obtained from

Marine Conservation Branch
Department of Conservation and Land Management
47 Henry Street, Fremantle, Western Australia 6160
Ph: 61-8-9432 5102 Fax: 61-8-9430 5408

SUMMARY

This report presents an overview of the climate and oceanography of the proposed Geographe Bay-Capes-Hardy Inlet marine conservation reserve (Figures 1 and 2) of southwest Australia. Partial funding for its preparation has been obtained through the Natural Heritage Trust's Coast and Clean Seas Marine Protected Area Programme, Project No. WA9703. Information is provided on the key circulation and mixing patterns for the region. The report forms a contribution to the Department of Conservation and Land Management's informational requirements for the planning phase of the proposed reserve. The reservation of this area, in the form of a marine conservation reserve, was given a high priority by the State's Marine Parks and Reserves Authority. The formal statutory process involved in developing a marine reserve proposal was initiated by the State Government some two years ago and is being coordinated by CALM.

From an oceanographic context, the region can be viewed as a series of four contiguous areas, namely the southern area of Geographe Bay, the coastal area from Cape Naturaliste to Cape Leeuwin, Flinders Bay and Hardy Inlet.

Hardy Inlet has its hydrodynamics governed by classical estuarine processes, influenced by tide, wind, heat flux, freshwater inputs and density gradients. Typically, during winter and into spring strong freshwater discharge from the Blackwood and Scott rivers leads to the complete expulsion of marine water from the estuary. As discharge rates weaken, marine water enters the system as a salt wedge and the dynamical behaviour of the Blackwood Estuary reflects that typical of salt wedge estuaries. Pooling and trapping of dense saline water at the bottom of the depressions and upstream of bars and sills is a feature of the progressive build-up of salinity within the system.

The overall hydrodynamic behaviours of the other three areas are influenced principally by wind stress and regional currents (the Leeuwin and Capes currents), with tides and stratification playing minor roles within specific nearshore areas. The area south of Cape Naturaliste is relatively exposed, with the nearshore zone subjected to relatively strong swells from the Indian and Southern oceans. In summer/spring the predominance of westward winds along the south coast (Flinders Bay) and northward winds along the west coast (between the capes) leads to the formation and northward advection of the Capes Current. The Capes Current carries relatively low temperature water, derived from upwelling over the shelf and below the thermocline. The upwelled water is relatively rich in nutrients, which feed increases in biomass, measured as chlorophyll "a". The Capes Current travels reasonably close to the coast, however the extent to which it encroaches into the nearshore zone or into Geographe Bay is not fully understood at present. As the winds which generate the Capes Current subside (during autumn and winter) the Leeuwin Current intensifies as a southward flowing boundary current of relatively warm, low salinity water, bringing a mixture of tropical and sub-tropical water nearer to the coast in the region between Cape Naturaliste and Flinders Bay. It appears that the Leeuwin Current is effectively restricted from entering Geographe Bay due to the shallowing nature of the bay, hence bypassing the bay as it rounds the capes. The extent to which the Leeuwin Current or water derived from it, penetrates into the nearshore zone is presently unclear. The presence of tropical and temperate flora and fauna in the area reflects the respective roles of the Leeuwin and Capes currents in introducing seasonal flows of warm tropical and cold temperate waters. Anecdotal evidence from local users of the marine region indicate that the beaches are relatively warm during winter and relatively cold during summer, which points to the need for further investigation to clarify the role of these broad-scale currents on the ecology of the nearshore zone.

The hydrodynamic characteristics of the nearshore embayments and lagoonal areas between Cape Naturaliste and Flinders Bay are yet to be studied in any great detail and this provides another area of research that would be of benefit to the management of the proposed marine conservation reserve area.

TABLE OF CONTENTS

* * *

LIST OF FIGURES

* * *

1 INTRODUCTION

1.1 BACKGROUND

In recognition of the importance of conserving the State's marine biodiversity, the Minister for the Environment established the Marine Parks and Reserves Selection Working Group (MPRSWG) in 1986. The main aim of the MPRSWG was to identify representative and unique areas of Western Australia's marine waters for consideration as part of a statewide system of marine conservation reserves under the *Conservation and Land Management (CALM) Act* 1984. The MPRSWG's report was released in June 1994 and identified over seventy such candidate areas throughout the coastal waters of Western Australia (CALM, 1994) (Figure 3).

The State's vesting body for marine conservation reserves is the Marine Parks and Reserves Authority (MPRA), which was established in 1997. The MPRA has prioritised the candidate areas for implementation as marine conservation reserves. The Geographe Bay-Capes-Hardy Inlet region encompasses two of the MPRSWG recommended areas, namely Geographe Bay-Cape Leeuwin and Hardy Inlet. The MPRA has assigned a high priority for implementation of the combined area as a marine conservation reserve.

Under the State Government's marine and conservation strategy, detailed in *New Horizons - The way ahead in marine conservation and management* released by the Western Australian Government in 1998 (WA Government, undated), there is a requirement for:

> *"Extensive assessment, community consultation and management planning before a new marine conservation reserve is established."*

An essential component of this is that:

> *"A comprehensive assessment of the area's biological and economic resources, and social values is carried out."*

In view of the high standing that the Geographe Bay-Capes-Hardy Inlet region has in the MPRA's priority list for new marine conservation reserves, CALM applied to Environment Australia for funding to perform a biological/oceanographic study of the area. Funding of $72,000 for the project was obtained through Environment Australia's Natural Heritage Trust, via the Coast and Clean Seas Marine Protected Area Programme, Project No. WA9703. This constituted approximately half of the resources required to complete the survey and complemented CALM's contribution to the project, valued at approximately $97,000.

The data acquired through this project is required for the determination of the relative conservation values of the respective major habitats of the proposed Geographe Bay-Capes-Hardy Inlet marine conservation reserve. It also contributes to the information base required for the marine reserve planning process, during which marine reserve boundaries and zones for multiple-use will be considered for the area.

This project has been coordinated by CALM's Marine Conservation Branch (MCB) and conducted in collaboration with the South West Capes District Office of CALM's Central Forest Region.

1.2 STUDY AREA

The study area for this survey comprises the State Territorial waters from Busselton, in Geographe Bay, to White Point on the eastern edge of Flinders Bay (Figures 1 and 2), and also the lower reaches of the Blackwood Estuary. State Territorial waters extend out to 3 nautical miles from the State Territorial Baseline.

The broad-scale features of the offshore bathymetry have been clearly illustrated by Gersbach (1999), through a three-dimensional oblique perspective plot (reproduced here in Figure 2) which encompasses the region from Geographe Bay around to Flinders Bay. As Gersbach (1999) points out, the distinctive feature of the bathymetry is the partitioning of the continental shelf into upper and lower shelves, a terrace-like structure. The upper shelf is bounded by the 50 m isobath and the continental shelf break by the 200 m isobath.

More detailed descriptions of the bathymetry and geomorphology of the various sub-regions of the study area are given throughout the text of this report.

1.3 OBJECTIVE

The objective of this report is to provide an overview of the climate and oceanography of the Geographe Bay-Capes-Hardy Inlet region.

2 CLIMATE, WATER LEVEL, WAVES AND LITTORAL DRIFT

2.1 WINDS

Southwest Australia experiences a typical 'Mediterranean' type climate, characterised by hot, dry summers and mild, cool wet winters. The major controlling influence on the weather is the latitudinal position of the axis of the 'subtropical ridge' (ie the west-east axis of the belt of high pressure systems that encircle and continually move around the globe in an eastward direction) (Figure 4). These high pressure systems have associated counterclockwise wind circulations (counterclockwise because they are in the southern hemisphere). The axis migrates north-south annually, being at its northernmost in winter and southernmost in summer.

Detailed descriptions of the climate of southwest Australia are available in Fahrner and Pattiaratchi (1994), Pearce and Pattiaratchi (1999), Australian Bureau of Statistics (1989) and Commonwealth of Australia (1993). The following precis draws from these publications.

During winter, the ridge axis is located at its northernmost latitude (25-30° S), resulting in a westerly prevailing wind stream acting over the southwest of the State. This enables cold fronts and strong westerly winds from the Roaring Forties to regularly penetrate the southwest at an average of about five times per month. Storms associated with these fronts typically last for about one day or less and generate strong northwest-southwesterly winds with speeds up to about 25-30 knots. The weather is otherwise relatively mild in winter with winds variable and relatively weak.

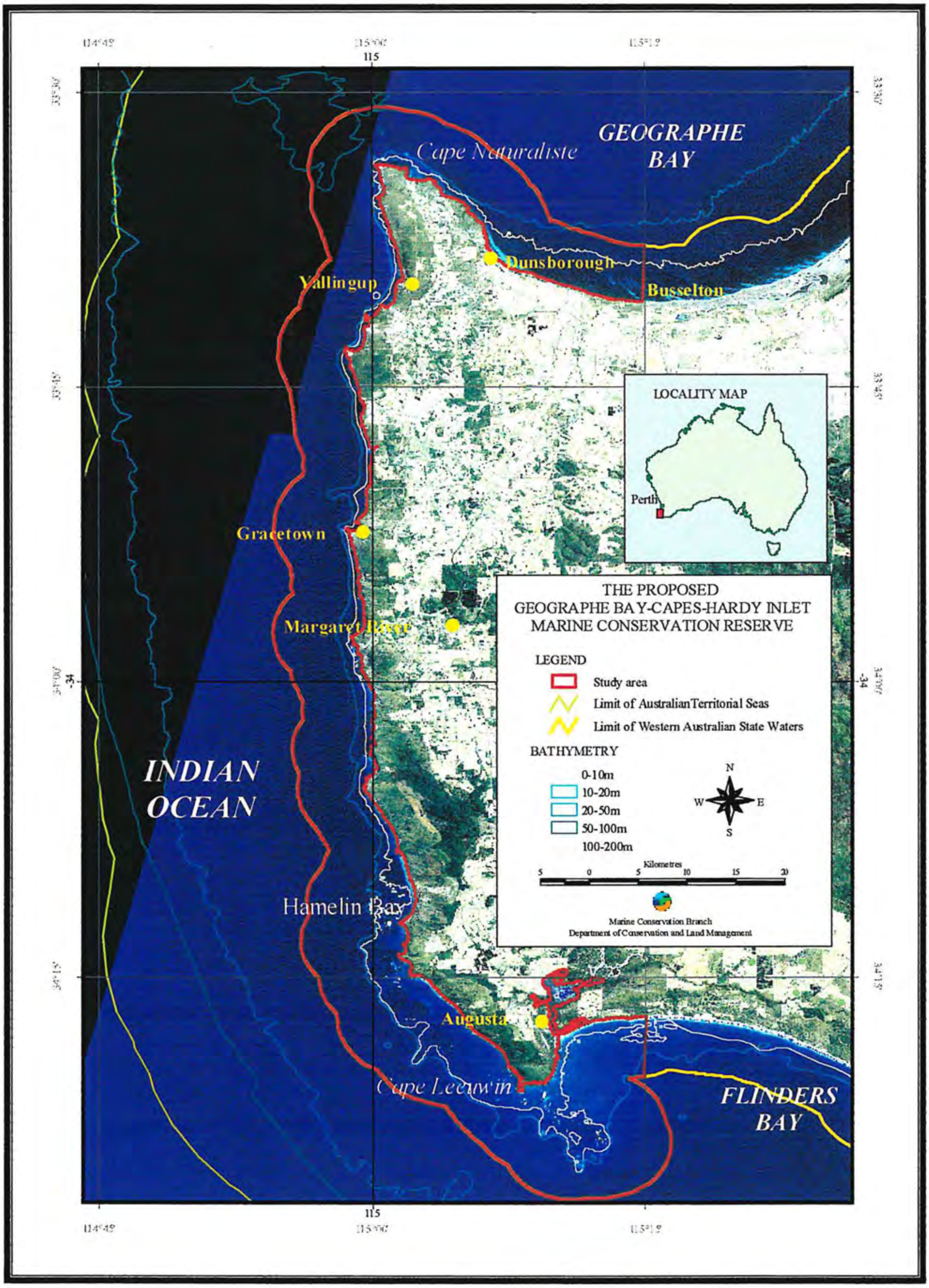


Figure 1. The proposed Geographe Bay-Capes-Hardy inlet marine conservation reserve.

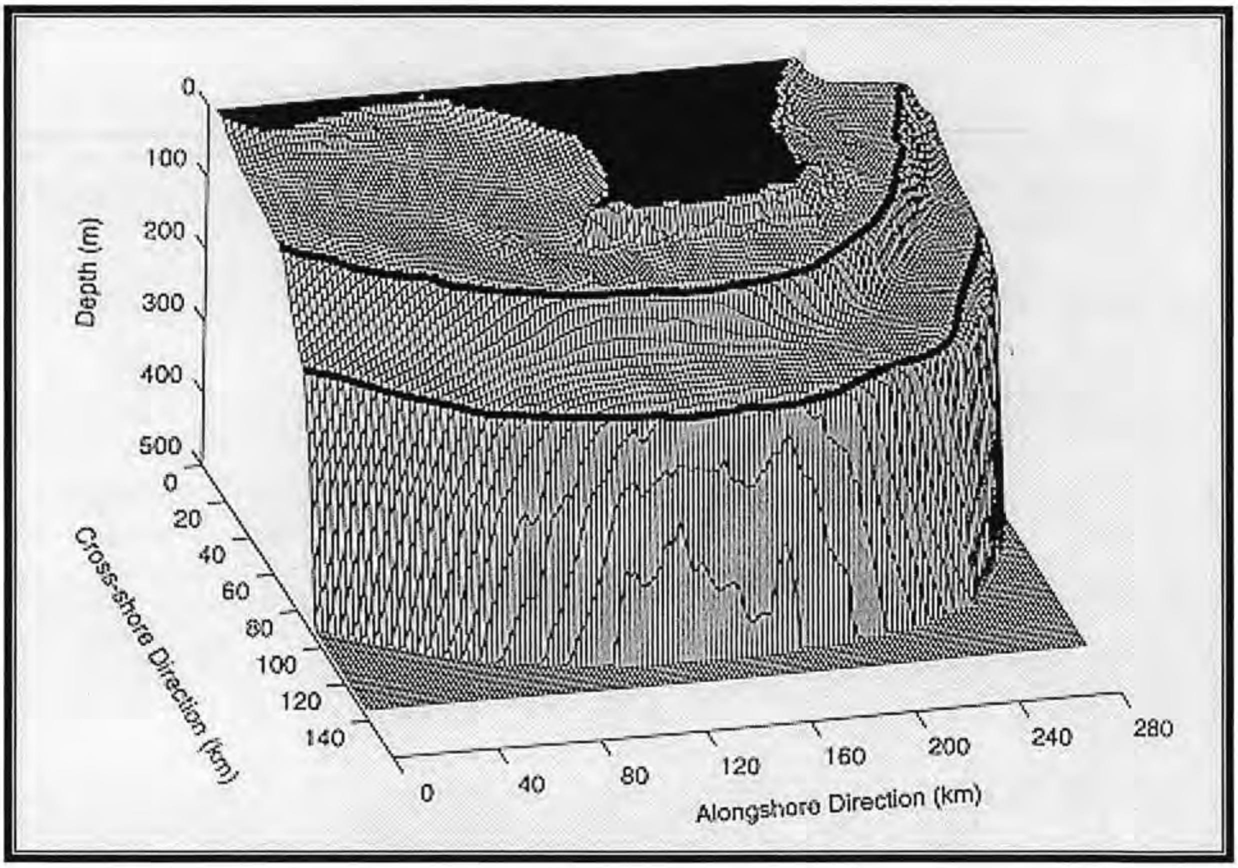


Figure 2. Bathymetry of the Geographe Bay-Capes-Hardy Inlet coastal region.

The bathymetry has been flattened out at 500 m and was digitised from relevant sheets from the Australian National Bathymetric Maps Series. The cross-shore axis is from 115.3° E to 114.3° E along 32.5° S and the along shore axis is from 32.5° S to 35.0° S along 114.3° E. The oblique three-dimensional perspective plot of the shelf was reproduced courtesy of Dr Guy Gersbach and taken from Gersbach (1999).

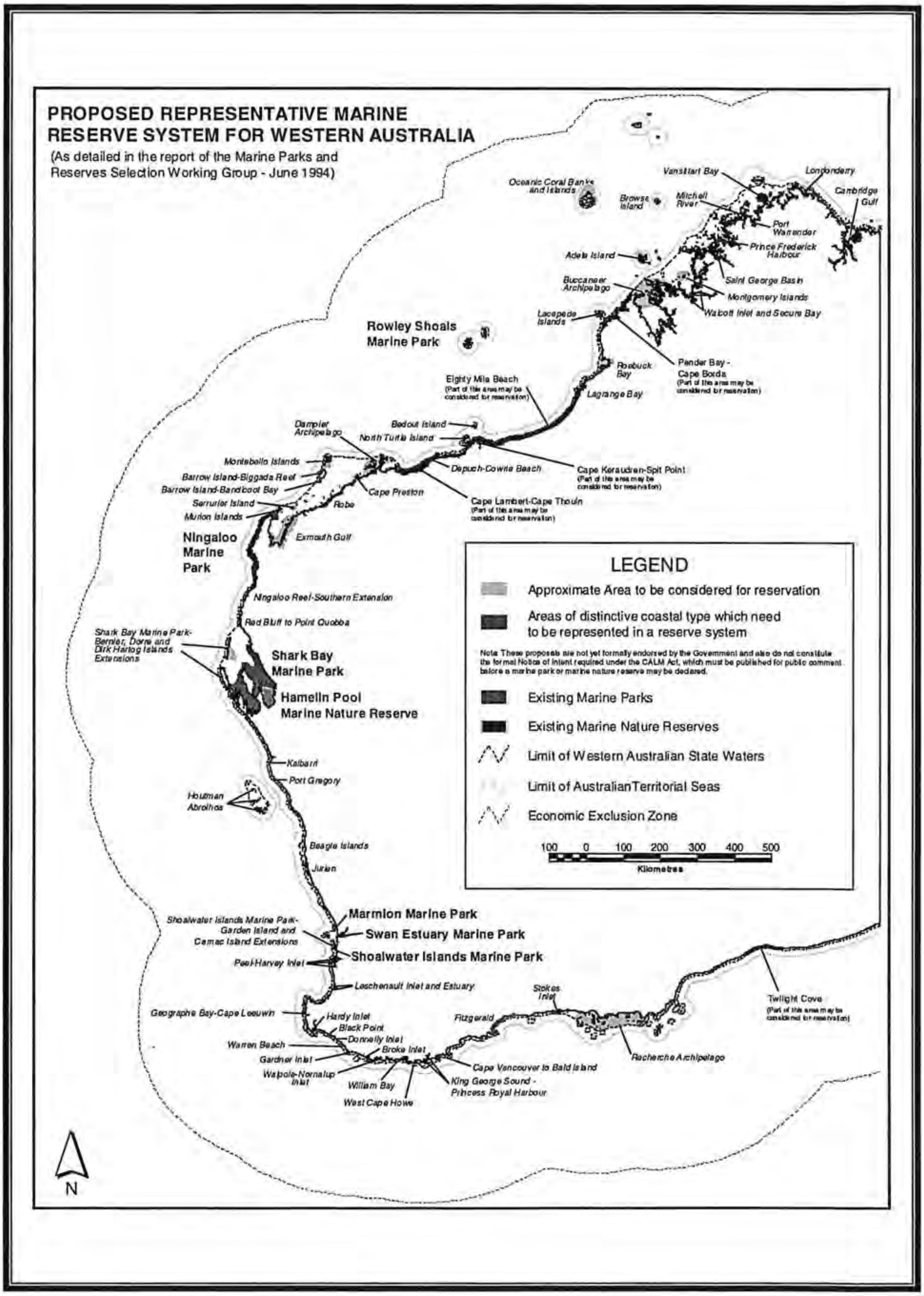


Figure 3. Map showing areas recommended as worthy of marine reservation in the Report of the Marine Parks and Reserves Selection Working Group (CALM, 1994).

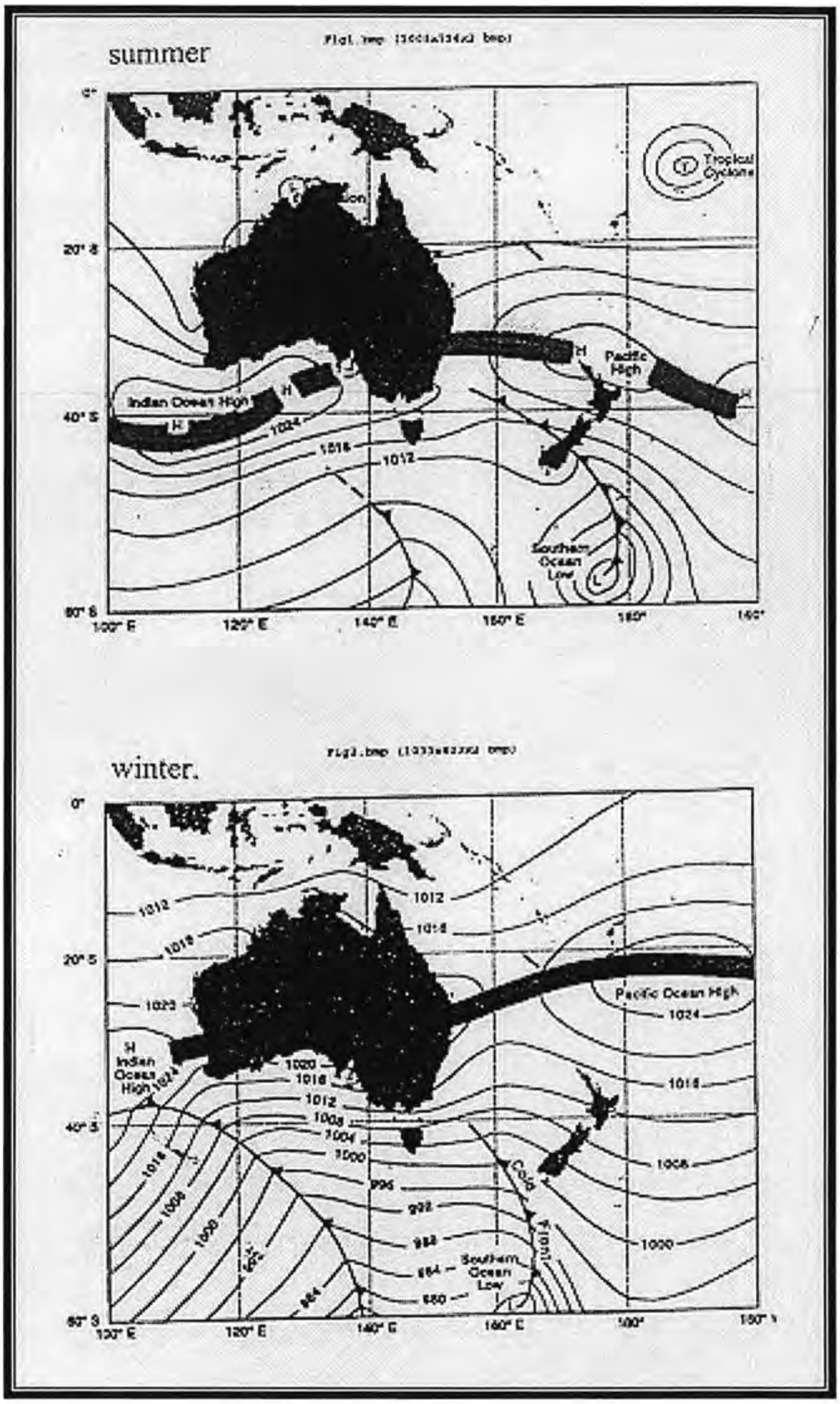


Figure 4. Representative examples of typical summer (top) and winter (bottom) isobaric weather charts over the Australian and western Pacific regions highlighting latitudinal differences in the position of the Sub-tropical Ridge of high pressure (ie. the anti-cyclonic belt) and associated synoptic scale systems.

The dark line indicates the approximate centre-line of the 'ridge' in mid-summer and mid-winter, respectively. The charts were obtained from the Commonwealth Bureau of Meteorology.

With the change of season in summer, the ridge axis moves to its southern extremity (about 40° S) and cold fronts rarely penetrate into the south of the State with any strength. Hot east-southeasterly winds prevail over the southern half of the State in summer. This prevailing pattern is modulated on almost a daily basis from mid-spring to late summer, by strong afternoon south-southwesterly sea-breezes (of order 20 knots) along the west coast and strong southwest-southeasterly seabreezes along the south coast.

The wind fields during the changeover seasons of spring and autumn are characterised by mild variable winds, with relatively few strong storms or sea-breezes.

Appendix 1 presents two typical series of synoptic charts for southwest Australia, one for each of summer and winter, respectively. These contain chronological descriptions of the weather as each series progresses from start to finish (from Commonwealth of Australia, 1993), and highlight the above mentioned coastal wind patterns.

Wind roses and wind speed percentage occurrence histograms from Cape Naturaliste and Bunbury are presented in Appendix 2 (from Fahrner and Pattiaratchi, 1994). Appendix 2 also presents a diagram of monthly mean wind vectors for 1988-92, inclusive, along with 36-year long term means, for Cape Naturaliste and Cape Leeuwin, respectively (from Pearce and Pattiratchi, 1999).

2.2 CYCLONIC DEPRESSIONS

Every year, from November to May an average of about two cyclones cross the northwest coast. These weaken into cyclonic depressions and may occasionally pass down the State and over the southwest (once in every four years, on average), bringing gale force winds and heavy rains with them.

2.3 AIR TEMPERATURE

The hottest month of the year at Bunbury is February, for which the mean of maximum air temperatures is 27.8 °C and mean of minimum air temperatures is 15.1 °C. The coldest month of the year at Bunbury is July, for which the mean of maximum air temperatures is 16.8 °C and mean of minimum air temperatures is 8.4 °C. Detailed statistics on air temperatures for the region are available in Australian Bureau of Statistics (1989).

2.4 RAINFALL AND EVAPORATION

Mean annual rainfall at Bunbury is about 870 mm (Australian Bureau of Statistics, 1989), with about 85 percent of the total annual rainfall occurring during May to September, and with June having the highest monthly average (183 mm). Evaporation isopleths from Australian Bureau of Statistics (1989) show evaporation to be about 1000 mm per year over the southwest corner of the State. Evaporation is highest in summer and lowest in winter. Rainfall and evaporation distributions over Western Australia are presented in Appendix 2.

2.5 WATER LEVEL FLUCTUATIONS

Tides (ie astronomically produced water level changes) along the southwest coast are small, being typically less than 0.5 m, but with a maximum of no more than about 1 m. The tides are mixed (ie diurnal and semi-diurnal), with the diurnal fluctuations dominating (Hodgkin and Di Lollo, 1958). The area is micro-tidal due to the close proximity of an amphidromic point offshore of Cape Naturaliste (Pugh, 1987).

Wind can raise or lower coastal sea levels depending on whether water is being forced towards or away from the shore by onshore or offshore winds, respectively. Furthermore, barometric pressure induces isostatic changes in water level due to the 'inverse barometer effect', under which an increase (or decrease) in barometric pressure of 1 millibar lowers (or raises) water level by approximately 1 cm. Hodgkin and Di Lollo found that combined meteorological effects produced changes in water level comparable to changes caused by tides.

In addition to the above effects, 'bulges' of water can propagate down the Western Australian coastline after their formation over the northwest coastal regions of the State by winds associated with large scale synoptic pressure systems. These are termed Continental Shelf Waves and produce water level changes of up to about 30 cm off Western Australia (Hamon, 1966; Harrison, 1983, Webster, 1983). These large undulations in water level have characteristic dimensions that scale with the pressure systems that produce them (of order 500-1000 km) and may take up to 5-10 days to pass a coastal site. Once formed they travel close to and down the coast, under the influence of the earth's rotation (ie the Coriolis force).

2.6 WAVES

Waves in the region are a combination of 'swell' developed in the Roaring Forties of the Indian and Southern oceans and locally generated wind waves (termed 'sea'). Therefore, along the west, southwest and south coasts prevailing swell arrives mainly from the southwest. Measurements of waves off southwest Australia (see Fahrner and Pattiaratchi, 1994) show that swells have a period of about 12 seconds and heights typically of up 2 m, while sea generated by local wind is short crested with periods of 5-10 seconds. Southwesterly swell refracts around Cape Naturaliste to approach the shoreline of southern Geographe Bay from the west-northwest.

2.7 LITTORAL DRIFT

Under prevailing swell conditions, littoral currents move sediments to the east along the southern coast and to the north along the western coast. The prevailing drift is interrupted by storms, during which the direction of sediment movement can change markedly in response to changing swell and/or sea directions. Department of Conservation and Environment (1980) contains further details on littoral drift patterns for Western Australia.

3 OCEANOGRAPHY

3.1 LEEUWIN CURRENT AND CAPES CURRENT

At the broadest spatial and temporal scales, the most important oceanographic influences in the near-shore coastal region from Geographe to Flinders bays are the warm southward flowing Leeuwin Current and the cold northward flowing Capes Current, respectively. The Leeuwin Current is driven from the northwest to southwest of the State by a poleward sea-level height gradient (which overwhelms the opposing effect of prevailing south-southwesterly winds). The Leeuwin Current is strongest during mid-autumn to mid-spring. The cooler northward flowing Capes Current is driven by south-southwesterly winds during mid-spring to mid-autumn.

The Leeuwin Current transports warm, buoyant, low-salinity, nutrient-poor tropical water down the Western Australian coastline from the northwest waters of Australia (see Figures 5 and 6, showing schematics of the Leeuwin Current, reproduced from Pearce, 1991, and Figure 7, a typical sea-surface temperature satellite image of the Leeuwin Current provided by the Department of Land Adminstration of Western Australia). It is fed by the tropical waters of the Pacific-Indian Throughflow and large-scale eastward-flowing currents which bring tropical and sub-tropical waters in towards the mainland from the Indian Ocean. The Eastern Gyral Current carries tropical water in towards the Pilbara coast and the West Australian Summer Current, a derivative of the West Australian Current (which travels northwards well offshore of the continental slope), carries sub-tropical water in towards the central west coast. See Pearce (1991), Cresswell 1991, Bray *et al* (1997), Myers *et al* (1995) and Wijffels *et al* (1996) for details on these large-scale flow features.

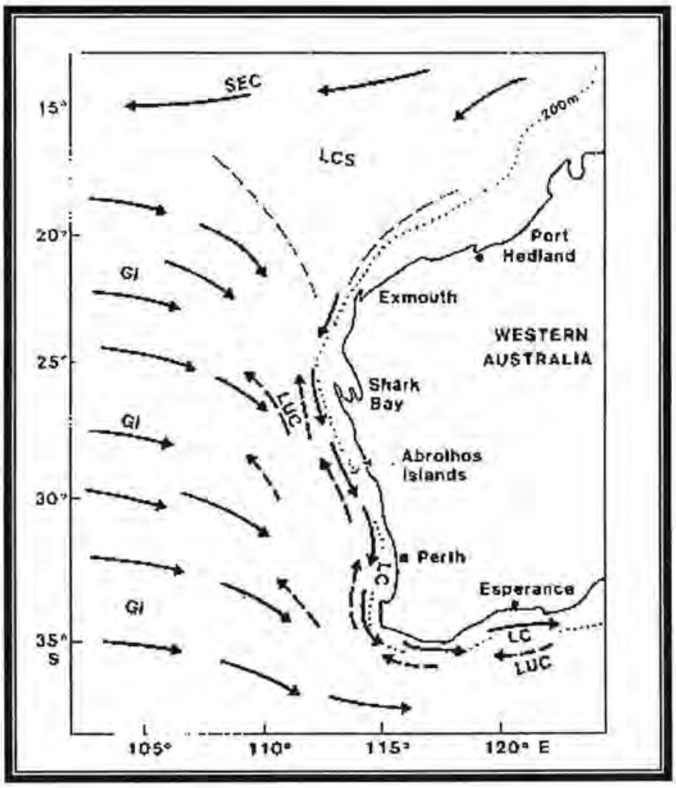


Figure 5. Schematic diagram of the main schematic features of the Leeuwin Current system.
GI = geostophic inflow from the open ocean, LC = Leeuwin Current, LCS = Leeuwin Current source area, LUC = Leeuwin Undercurrent, SEC = South Equatorial Current. Solid arrows are surface currents, dashed are subsurface. The dotted line shows the 200 m contour. Reproduced courtesy of Alan Pearce, taken from Pearce (1991).

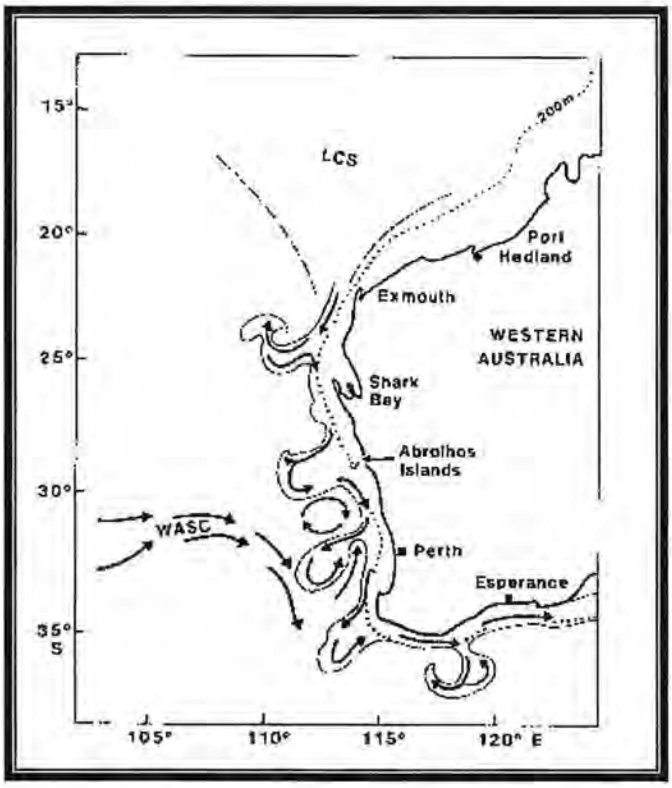


Figure 6. Schematic diagram of mesoscale features of the Leeuwin Current system, derived largely from satellite imagery.

The Leeuwin Current itself is shaded, the solid arrows indicating the flow in the warm surface meanders and jets as well as the currents in the cooler offshore waters. WASC = Western Australian Summer Current (modified from Andrews, 1997). The dotted line shows the 200 m contour. Reproduced courtesy of Alan Pearce, taken from Pearce (1991).

The Leeuwin Current carries tropical flora and fauna southward to the temperate coastal regions of the State. The Leeuwin Current effectively bypasses Geographe Bay on its approach to Cape Naturaliste, but then travels closer to the mainland between the two capes and along the south coast en-route to South Australia (Cresswell and Peterson, 1993). During mid-autumn to mid-spring the absence of sustained opposing equatorward winds, in conjunction with the effect of the earth's rotation, enables the Leeuwin Current to flow fairly consistently over the continental slope and mid-shelf. During this time onshore winds (from the northwest quadrant) associated with frontal systems, which occur a few times per month, occasionally force water derived from the Leeuwin Current to encroach onto the shelf and closer to the shore (Mills *et al*, 1996). The Leeuwin Current is relatively nutrient-poor, warm and buoyant. Its presence over the continental slope and shelf effectively suppresses any tendency for broad-scale upwelling of deeper nutrient-rich waters up onto the shelf, that would otherwise normally be forced by typical upwelling-favorable equatorward winds. Despite its low nutrient status, the Leeuwin Current is of fundamental relevance to many ecological characteristics of the marine ecosystems off Western Australia, acting as a strong vehicle for the transport of eggs, larvae, flora, juvenile and adult fishes and marine mammals. For example, as pointed out in Pearce and Pattiaratchi (1999), not only is it responsible for the presence of tropical marine organisms off the west and south coasts of Western Australia (Maxwell and Cresswell, 1981; Pearce and Walker, 1991; Hutchins and Pearce, 1994), but it also has a major influence on the life histories and fisheries associated with a number of fish species (Lenanton *et al*, 1991), including the southern bluefin tuna (Davis and Lyne, 1994) and western rock lobster (Pearce and Phillips, 1988). The Leeuwin Current also influences the distribution of some sea birds (Wooler *et al*, 1991).

During spring and summer the onset and persistence of strong south-southwesterly winds along the west and southwest coasts of Western Australia results in the Leeuwin Current being driven offshore, to be replaced closer to the mainland by northward flows of relatively cold water. Such countercurrents have been identified off the Ningaloo Reef (Taylor and Pearce, 1998), Abrolhos Islands (Cresswell *et al*, 1989) and southwest corner of the state (ie, the Capes Current, Pearce and Pattiaratchi, 1999 and Gersbach *et al*, 1999). It has recently been established that the Capes Current is fed by nutrient-rich upwelled water from the region between Cape Mentelle and Point D'Entrecasteaux (Gersbach *et al*, 1999 and Pearce and Pattiaratchi, 1999). The upwelling is driven by winds with a westward component off the south coast and northward component between the capes. The upwelled water is believed to be drawn from over the outer shelf and from just beneath the thermocline at depths of about 50 m or more. Hence, an important ecological characteristic of the Capes Current is that it is relatively rich in nutrients derived from deep sub-thermocline waters, thereby promoting the growth of phytoplankton as the upwelled water is driven along the coast and exposed to photosynthetically active radiation in the photic zone. Furthermore, it has been suggested (Gersbach *et al*, 1999) that the Capes Current may have important implications for the salmon fisheries off Western Australia as it may affect the migration of adult salmon around Cape Leeuwin. Figure 8 presents examples of recently processed satellite imagery of sea-surface temperature, ocean colour and chlorophyll-induced radiation, showing the relatively low temperature and high chlorophyll "a" in the Capes Current (courtesy of Associate Professor Mervyn Lynch, Curtin University of Technology, Western Australia).

Appendix 3 presents a copy of the report of Pearce and Cake (1999), containing a chronological series of typical monthly sea-surface temperature satellite images from off the southwest coast of Western Australia. These data show the presence of the Leeuwin Current and Capes Current, including periods of transition between these two current systems (reproduced with the permission of Alan Pearce, CSIRO Division of Marine Research).

3.2 CIRCULATION IN SOUTHERN GEOGRAPHE BAY

Geographe Bay is a relatively protected embayment that faces north and is protected from the direct impact of prevailing southwesterly swells by Cape Naturaliste (Figure 2). The bay's bathymetry is relatively simple, with a gentle offshore gradient deepening the profile gradually to about 50 m at the outer edge of the study region. The nearshore bathymetry of the bay is characterised by a series of submarine sandbars which rise up to 2 m above the surrounding sea floor. Water depth increases to about 4 m within several hundred metres of the shore. Naturaliste Reefs, about 35 km due north of Cape Naturaliste, form a major bathymetric feature in the outer part of the bay.

A recent major oceanographic study of the bay (Fahrner and Pattiaratchi, 1994) has shown that its oceanography is influenced principally by the local meteorology and the force of earth's rotation (called the Coriolis force) which turns currents counterclockwise in the southern hemisphere. Tides are relatively small (<1 m) and wind is the principle forcing which drives circulation and mixing throughout the bay for most of the time. Fahrner and Pattiaratchi (1994) found that the net transport of water through the bay is in a northerly direction reflecting the predominance of northward-directed winds for a large percentage of the time. Water level variations become important for circulation only during intense storms and cyclonic depressions. Fahrner and Pattiaratchi (1994) refer to a number of other hydrodynamic mechanisms that have secondary influences on net circulation when compared to wind-driven circulation. These comprise wave-induced circulation, flows driven by density gradients (generically termed 'baroclinic' circulation), submarine groundwater discharge and other freshwater inputs from drains and rivers.

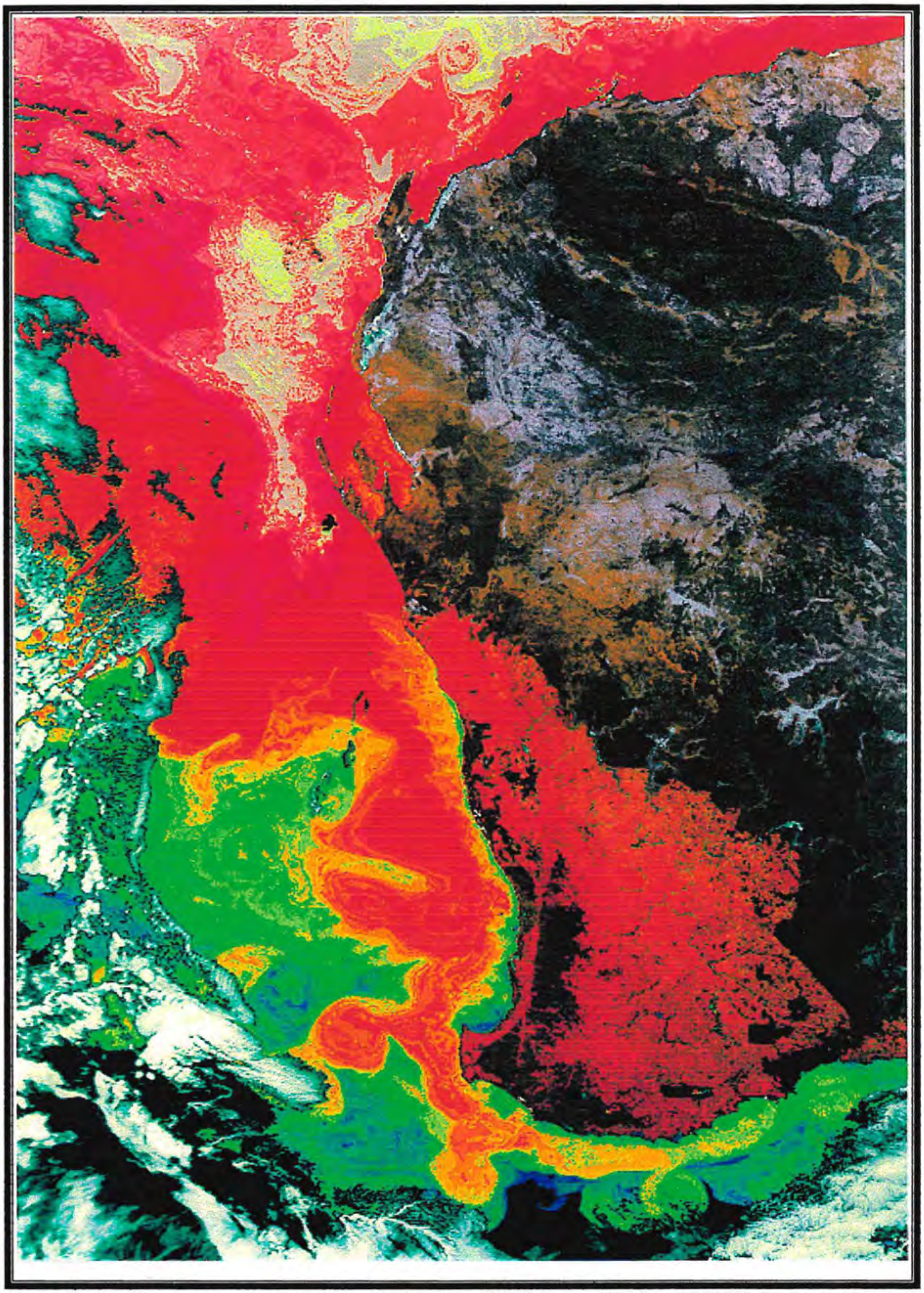
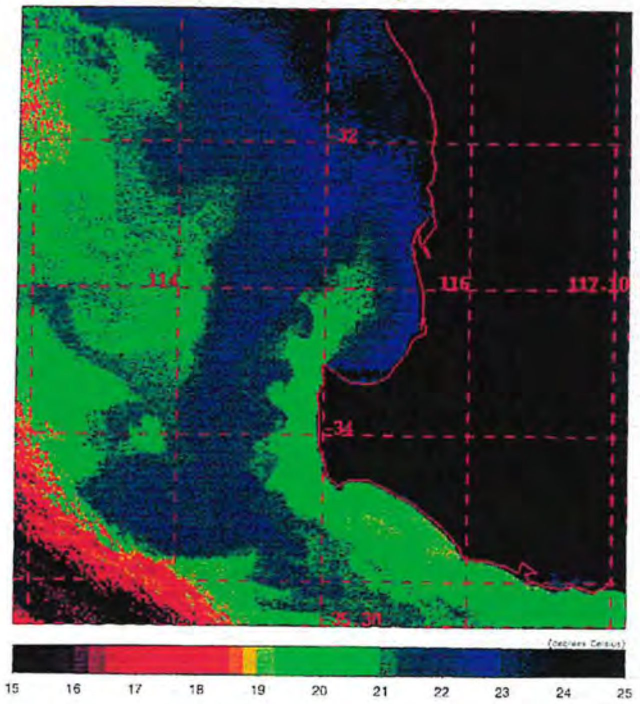


Figure 7. Satellite image of sea-surface temperature (SST) from (NOAA-AVHRR) from northwest to southwest Australia showing the Leeuwin Current on 15 August 1991.

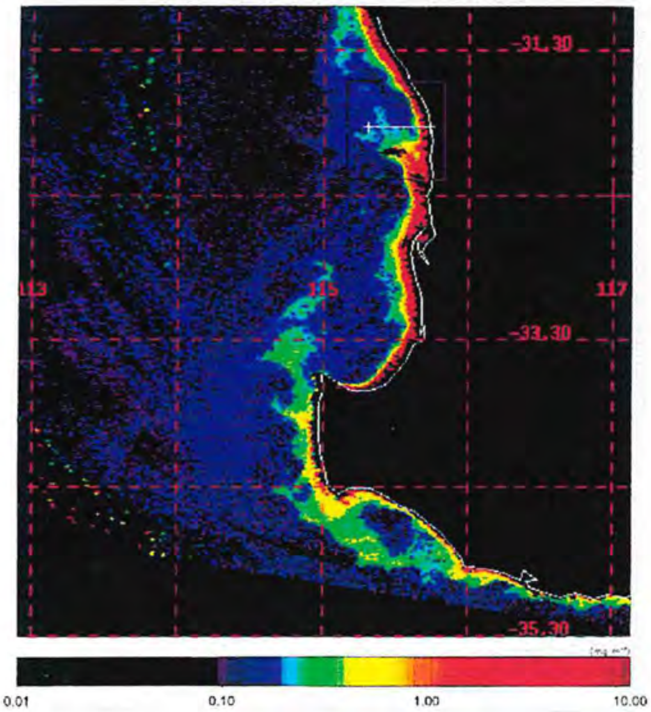
Red indicates the general warm water flow and meanders of the Leeuwin Current. Blue represents oceanic water. Clouds obscure the SST image around the south and southwest sides of the frame. Off Perth the core of the Leeuwin Current was about 3 °C warmer than nearshore water. Data obtained from Department of Land Administration. Image originally processed by Alex Wylie for the Southern Metropolitan Coastal Waters Study (Simpson *et al*, 1996).

NOAA14 SST for March 17, 1998



(Provided by Associate Professor Mervyn Lynch, Remote Sensing and Satellite Research Group of the School of Physical Sciences, Curtin University of Technology).

SeaWiFS chlor_a for March 17, 1998



(Provided by Associate Professor Mervyn Lynch, Remote Sensing and Satellite Research Group of the School of Physical Sciences, Curtin University of Technology).

Figure 8. NOAA-AVHRR sea-surface temperature image (top) and complementary chlorophyll "a" distribution (bottom) in the Capes Current on 17 March 1998.

Images processed by the Satellite Research Group of the School of Physical Sciences, Curtin University of Technology, and provided by Associate Professor Mervyn Lynch.

The extent to which the Leeuwin and Capes currents influence the hydrodynamics and/or water quality of Geographe Bay is as yet not fully understood. However, the available satellite imagery on this issue suggests that the Leeuwin Current generally bypasses the area, due to the restricting nature of the bathymetry, with bottom friction coming into play as a major opposing force on the current as it tries to encroach into the shallowing bay. In contrast, the action of onshore winds during spring and summer appears to enable the Capes Current to spread into Geographe Bay, with field evidence reviewed by Fahrner and Pattiaratchi (1994) suggesting that it has the propensity to reach into Geographe Bay as far as Busselton. Further investigation would be required to clarify the characteristics of intrusion of Capes Current water into Geographe Bay.

The inferred wind-driven circulation patterns for Geographe Bay are summarised below. These results are based on historical field data and on the hydrodynamic model results of Fahrner and Pattiaratchi (1994) (with the model forced by 15 knot winds). These results should be read with reference to the model output in Appendix 4. In the following precis 'strong' currents refer to those with speeds greater than 0.1 m s^{-1} and 'weak' currents to those with speeds less than 0.1 m s^{-1}.

- The current response to winds depends very much on the strength of the wind and also on the local relative alignments of the coast and wind.
- A predominantly northward transport of water is maintained under westerly, southwesterly and southerly winds with relatively strong nearshore currents following the perimeter of the bay in the direction from Cape Naturaliste to Myalup. Southerly winds produce relatively weak variable currents in the nearshore zone between Cape Naturaliste and Busselton.
- Southeasterly winds result in predominantly offshore transport of water with strong northward currents in the nearshore zone north off Koombana Bay, weak variable currents in the nearshore zone between Busselton and Bunbury and moderate to strong westward currents in the nearshore zone between Cape Naturaliste and Busselton.
- Easterly winds also result in an offshore transport of water but in a predominantly southwestward direction, with weak currents in the nearshore zone north of Koombana Bay and strong nearshore currents south of Koombana Bay that follow the perimeter of Geographe Bay towards Cape Naturaliste.
- Northwesterly winds result in a predominantly onshore transport of water with relatively weak and variable currents in the nearshore zone between Busselton and Bunbury, but stronger eastward currents in the nearshore zone west of Busselton.
- Under all the wind directions that were used in the simulations, relatively strong currents (greater than 0.2 m s^{-1}) were predicted for the area over and around Naturaliste Reefs, a result of the complex and relatively shallow bathymetry of that reef area.

Field data, in conjunction with these model results, indicate that mean long-term (ie averaged over periods of weeks or more) current speeds in the nearshore zone of the bay are typically of order 0.05-0.1 m s^{-1} and driven principally by winds. Storm events can increase current speeds to 0.1-0.2 m s^{-1} or more. Tides cause currents with speeds of less than about 0.025 m s^{-1}. Fahrner and Pattiaratchi (1994) estimate that density differences set up by differences (or gradients) in temperature and salinity across and along the bay may be capable of inducing, at best, mean currents of about 0.01 m s^{-1}. Fahrner and Pattiaratchi (1994) discussed the limitations of their model results and pointed out that the bottom-resistance factors used may have been low and that the incorporation of greater bottom resistance to flows by seagrass meadows, sandbars and complex nearshore bathymetry would reduce the predicted speeds.

Flushing times were also calculated by Fahrner and Pattiaratchi (1994) for a control volume (Figure 9) in the nearshore zone off Busselton for common wind directions at constant speeds of about 10 knots. Flushing times are defined here as the time it takes for most (about 70 percent) of the original water in the specified control volume to exit the control volume. Flushing times of between three and five days are predicted for easterly, southerly and south-westerly winds, while flushing times of the order of 14 days are predicted for south-westerly and westerly winds. Fahrner and Pattiaratchi (1994) pointed out that these results need to be considered within the limitations of the control volume approach and also that, in reality, flushing times for north-westerly winds are likely to be smaller than the value quoted because higher wind speeds usually accompany frontal systems that bring winds from the northwest quadrant. In addition, Fahrner and Pattiaratchi (1994) also point out that the effect of cold water intrusion into Geographe Bay, associated with the Capes Current, is unknown, but that the effect could be significant during the summer period. These uncertainties point to the need for further work in this area of the hydrodynamics of the study area.

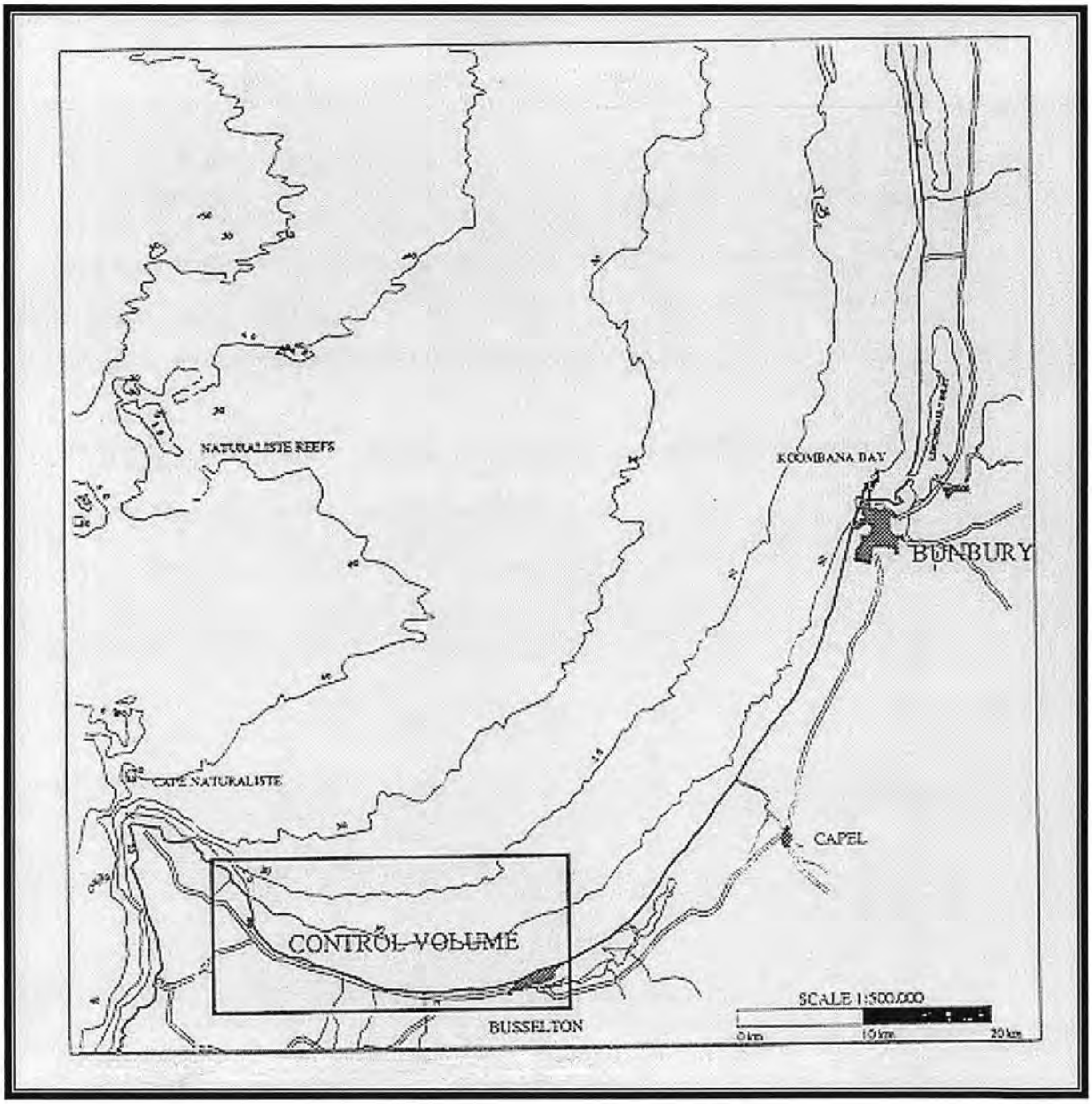


Figure 9. Control volume used by Fahrner and Pattiaratchi (1994) for which flushing times were calculated using a numerical hydrodynamic model.

3.3 CIRCULATION IN THE NEARSHORE EMBAYMENTS BETWEEN CAPE NATURALISTE AND CAPE LEEUWIN

The coastal region between Cape Naturaliste and Cape Leeuwin has a high profile, rocky shoreline subjected to highly energetic seas. Waves arrive from the open ocean and impinge along many parts of the coastline unimpeded. CALM (1994) describe the coastal formations and general features of the associated biota of the coastal zone of the Leeuwin Complex between the two capes as follows:

> *"The granites and gneisses of the Leeuwin Complex are eroded by the sea to form sloping rock faces on exposed headlands and rounded boulder fields in more sheltered situations. There are coarse sand beaches between the headlands. At several locations along the western side of the Leeuwin Block (eg Yallingup, Hamelin Bay), Quaternary aeolianite limestones have been deposited over the granites and gneisses, sometimes with considerable thickness. These tend to form limestone cliffs along the shore, fronted with intertidal limestone rock platforms. Thus the shore of this sector is quite complex with a range of very different habitats. There is one small estuary on the Leeuwin-Naturaliste coast at the mouth of Margaret River. It is of the barred riverine type (Hesp, 1984). Elsewhere there are many freshwater springs along the shore, especially where the aeolianite-granite junction occurs near shore level. Caves are common in that situation."*
>
> *"The rock slopes and limestone rock platforms are usually covered with an algal turf. Kelp and lesser macroalgae dominate the sublittoral zone."*
>
> *"Although the communities of plants and animals on these rocky shores are predominantly of temperate affinities, a notable feature is the presence of a number of tropical species. Whether these populations of tropical species are reproductive and self-sustaining or rely on recruitment from the north via the Leeuwin Current is unknown."*
>
> *"The mixture of temperate and tropical species is typical of the fauna of this section of coast, reflecting the geographic location at the margins of the Southern Australian and Indo-West Pacific Regions and the influence of the Leeuwin Current."*
>
> *"The large swells and excellent breaks at many localities along the Leeuwin-Naturaliste coast, eg Yallingup and Margaret River, provide some of the world's best surfing...The leeward sides of Cape Leeuwin (Flinders Bay) and Cape Naturaliste (Bunker Bay, Eagle Bay, Meelup and Dunsborough), on the other hand, are sheltered shores with high quality beaches and very clear water...".*

There is little information available on the oceanography of the nearshore embayments and inner reef and lagoonal areas along this stretch of coast. To what extent the Leeuwin Current flows into the nearshore zone close to the coast is unknown and the same can be said for the Capes Current. Anectodal reports by residents and visitors who regularly swim and surf in the area indicate that the coastal waters are particularly warm in winter and particularly cold in summer, this perhaps suggesting that the Leeuwin and Capes currents, respectively, are driven very close to shore during these respective periods. Field measurements would be required to further investigate these aspects of the coastal oceanography.

It can be presumed however that wind forcing will be as equally dominant along this coastline as along the Geographe Bay and southern coasts. However, in nearshore semi-enclosed micro-tidal embayments and lagoonal systems it is known that wave-induced circulation, density currents, and internal recirculation patterns can be important influences on the hydrodynamics. Tides are small on this coast and likely to produce only relatively weak currents. There appear to have been no definitive studies on these finer scale processes for the protected inner waters of the Leeuwin-Naturaliste coast.

An indication of the importance of wind-driven flows along the coast is however available in the model results presented in Appendix 4, showing relatively strong nearshore currents south of Cape Naturaliste under typical wind conditions.

The environmental impact assessment of contaminant loadings into semi-enclosed embayments must take account of the possibility of restricted flushing due to the shape of the shoreline and interference to exchange by alongshore reef lines, islands, promontories, headlands and bottom undulations. In addition, the introduction of freshwater via rivers, drains and groundwater into such systems raises the possibility of vertical and horizontal stratification of salinity and therefore density. This type of stratification can influence circulation and mixing by assisting flushing in some cases (due to horizontal density gradients) or restricting vertical mixing due to the formation of a vertically stable water column (ie stratified in density). These research areas are yet to receive detailed attention for this section of coast.

3.4 CIRCULATION IN FLINDERS BAY

This section addresses the area east of Cape Leeuwin encompassing Flinders Bay and the nearby offshore islands of St Alouam and Flinders. The offshore bathymetry is similar to that described above for the coastal zone between the Leeuwin and Naturaliste capes, characterised by the two terrace-like shelves within the 50 m and 200 m isobaths, respectively (Figure 2). It has been described (CALM, 1994) as a high energy coast, subjected to heavy swells generated in the Roaring Forties wind belt in the Southern Ocean. The swell is responsible for a net eastward littoral drift. Between Cape Leeuwin and Israelite Bay the coast is underlain by tough granite rocks, which outcrop as mountains, headlands or islands. At Cape Leeuwin, mean monthly winds are predominantly south-southeasterly during summer to mid autumn, west-southwesterly during winter-spring and weak and variable during mid-late autumn (see Appendix 2).

Along its shores, south-facing headlands and beaches are exposed to strong wave action for much of the time. Although the fine scale oceanography of the area is yet to be studied in any great detail, it is known that the wind plays a dominating influence on broad coastal water circulation along the south coast throughout the year. In addition, the Leeuwin and Capes currents occupy the region during autumn/winter and spring/summer, respectively (refer to the satellite images in Appendix 3).

The Blackwood Estuary discharges significant amounts of freshwater to the coastal zone near Augusta during the winter-spring rainfall/runoff period. Buoyant freshwater inputs to the bay from the estuary will initially spread close to the shore as buoyant plumes, creating a *Region of Freshwater Influence* (ROFI) (Simpson, 1997). The entry of buoyant freshwater plumes into the nearshore coastal zone will set up vertical and horizontal density gradients and frontal zones between the plumes and receiving oceanic water. The dynamics of the ROFI will be significantly influenced by the presence of these gradients. Coastal circulation patterns and vertical mixing eventually disperses buoyant estuarine outflows.

As discussed above (Section 3.1), this area is believed to be within the source zone for the Capes Current, where spring/summer winds with a westward component lead to upwelling of relatively cold, nutrient-rich waters up from depths below about 50 m. This upwelled water is then driven around Cape Leeuwin and northwards as a near-coastal flow. Again, it worth pointing out that recent analyses of satellite imagery at Curtin University of Technology have shown that there are relatively high levels of chlorophyll "a" in the Capes Current (Figure 8). This suggests that the area may play an important role in primary productivity for the coastal waters of Flinders Bay, the Leeuwin-Naturaliste coast, Geographe Bay and beyond to the north. The area is also within the path of the Leeuwin Current during autumn/winter. The extent to which the waters of the Capes and Leeuwin currents penetrate close to shore, and become entrained in exchange currents for the Hardy Inlet for example, is unclear and requires further investigation.

3.5 HYDRODYNAMICS OF THE HARDY INLET

Hardy Inlet is the downstream basin of the Blackwood Estuary (Figure 10) and is classified as a seasonal, permanently open estuary. The inlet opens to the sea via a rather long and narrow entrance channel. This channel breaches a wave-built beach at the mouth of the estuary. Upstream of the mouth, the channel bathymetry undulates between about 2 and 8 m depth en-route to the Hardy Inlet. The inlet has a deep central channel 2-8 m deep, flanked by wide shallow margins less than about 1 m in depth. Two lagoons, The Deadwater and Swan Lake, open into the eastern side of the entrance channel near the mouth.

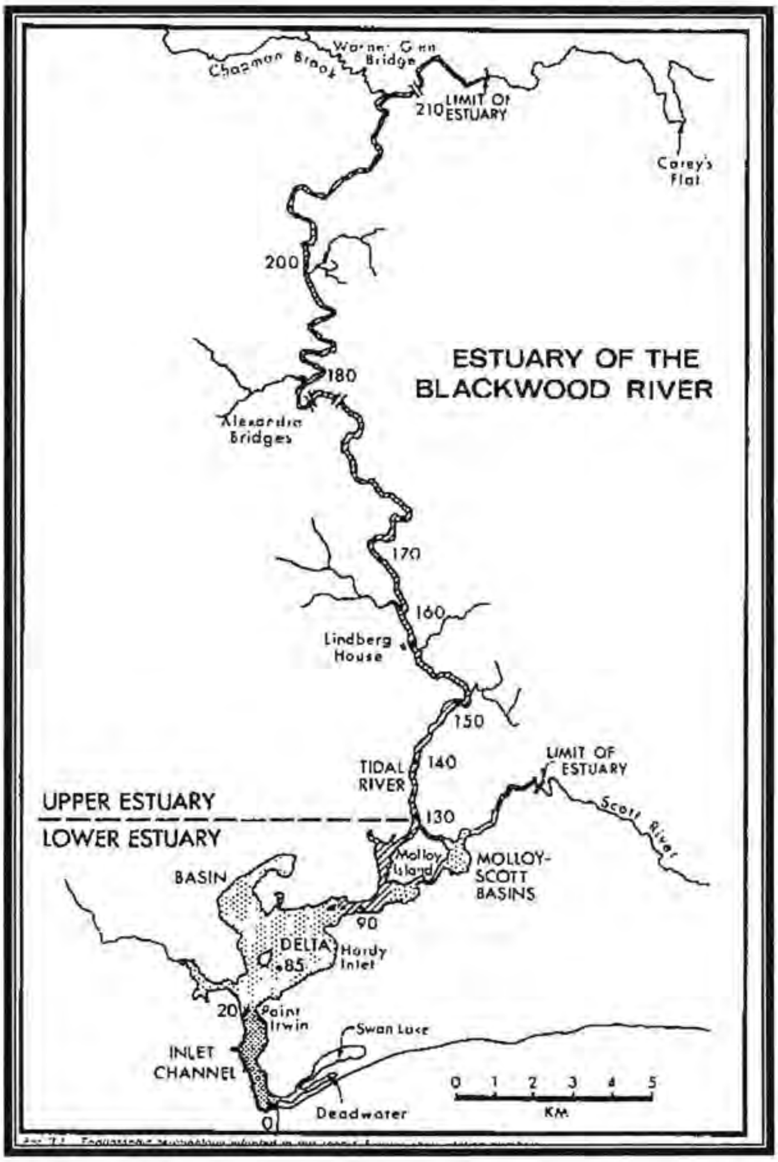


Figure 10. Location map of the Blackwood Estuary, including key topographic place names, showing the layout of the estuary from the mouth to the upper reaches of the Blackwood and Scott rivers.

The stations shown along the length of the estuary are referred to in the salinity section plots of Figure 12. Diagram reproduced from Hodgkin (1976).

There are two shallow bays (< 1 m deep) further upstream, connecting to the western and northwestern sides of the inlet, known as West Bay and North Bay. Molloy Basin is situated immediately upstream of the inlet and is almost completely occupied by Molloy Island. The basin bathymetry around the island is relatively shallow, except for a channel running along its northwest perimeter. The Blackwood and Scott rivers discharge directly into Molloy Basin. The Blackwood Estuary's hydrodynamic characteristics were comprehensively investigated and described by Agnew *et al* (1976) and summarised by Hodgkin (1976). Hodgkin (1976) also gives a comprehensive description of the Blackwood Estuary's climate, geomorphology, hydrogeology, habitats and ecology. The following overview of the hydrodynamics of the Hardy Inlet has been drawn from these two references. The dynamical behaviour of the estuary is influenced by a number of factors, namely riverine freshwater discharge, tidal forcing, wind stress, density gradients, sea water intrusion and vertical mixing by winds, tides and penetrative convection (due to atmospheric cooling).

The estuary has a catchment of 23,000 km^2, within which local rainfall can be as high as about 1200 mm per year (Appendix 2). During winter, total runoff to the estuary typically peaks at about 20 x 10^6 m^3 per day during August. Nearly all of the runoff into the estuary occurs between June and November, inclusive.

Tides are predominantly diurnal and weak in the area, with records collected by Agnew *et al* (1976) returning astronomically induced water level changes of up to 0.7 m. In addition, meteorological effects (eg winds and barometric pressure fluctuations) were found to change water levels by up to 0.6 m over and above predicted tidal water levels.

The following overview of the dynamics of the estuary has been drawn from Agnew *et al* (1976).

The two most important influences on the dynamics of the estuary are freshwater flows from the Blackwood and Scott rivers and tidal pumping of seawater into and out of the estuary via the entrance channel and lower reaches. Until these rivers begin to flow strongly the estuary remains saline, with the dynamics of the lower reaches characterised by the cyclic upstream and downstream movement of seawater as a salt wedge, in response to the diurnal cycle of the tide. Figure 11 shows the salinity condition of the estuary as the flow changes during an annual cycle. Figure 12 presents typical along-estuary vertical profiles of the salinity structure showing the seasonal hydrologic change in the Blackwood. The data in Figure 12 need to be viewed with reference to the accompanying locality diagram (Figure 10). Figure 13 presents the time varying salinity along the surface of the estuary from summer to winter. These data serve to show that the entire system undergoes a dramatic change in its salinity regime from summer to winter, with the Hardy Inlet and Molloy Basin going from essentially marine (greater than 30 ppt) to fresh throughout a typical annual cycle.

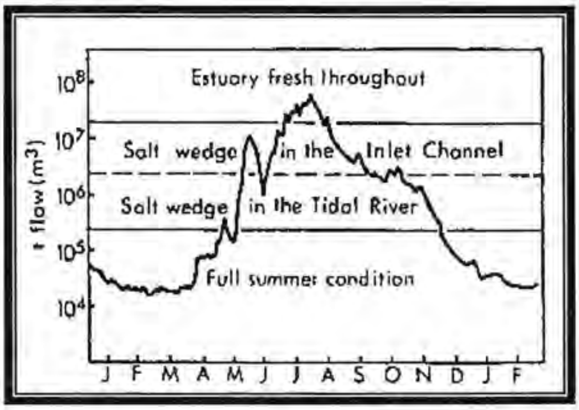


Figure 11. Salinity condition of the Blackwood Estuary as the freshwater discharge into it changed throughout an annual cycle.

Reproduced from Hodgkin (1976). Data originally presented in Agnew *et al* (1976).

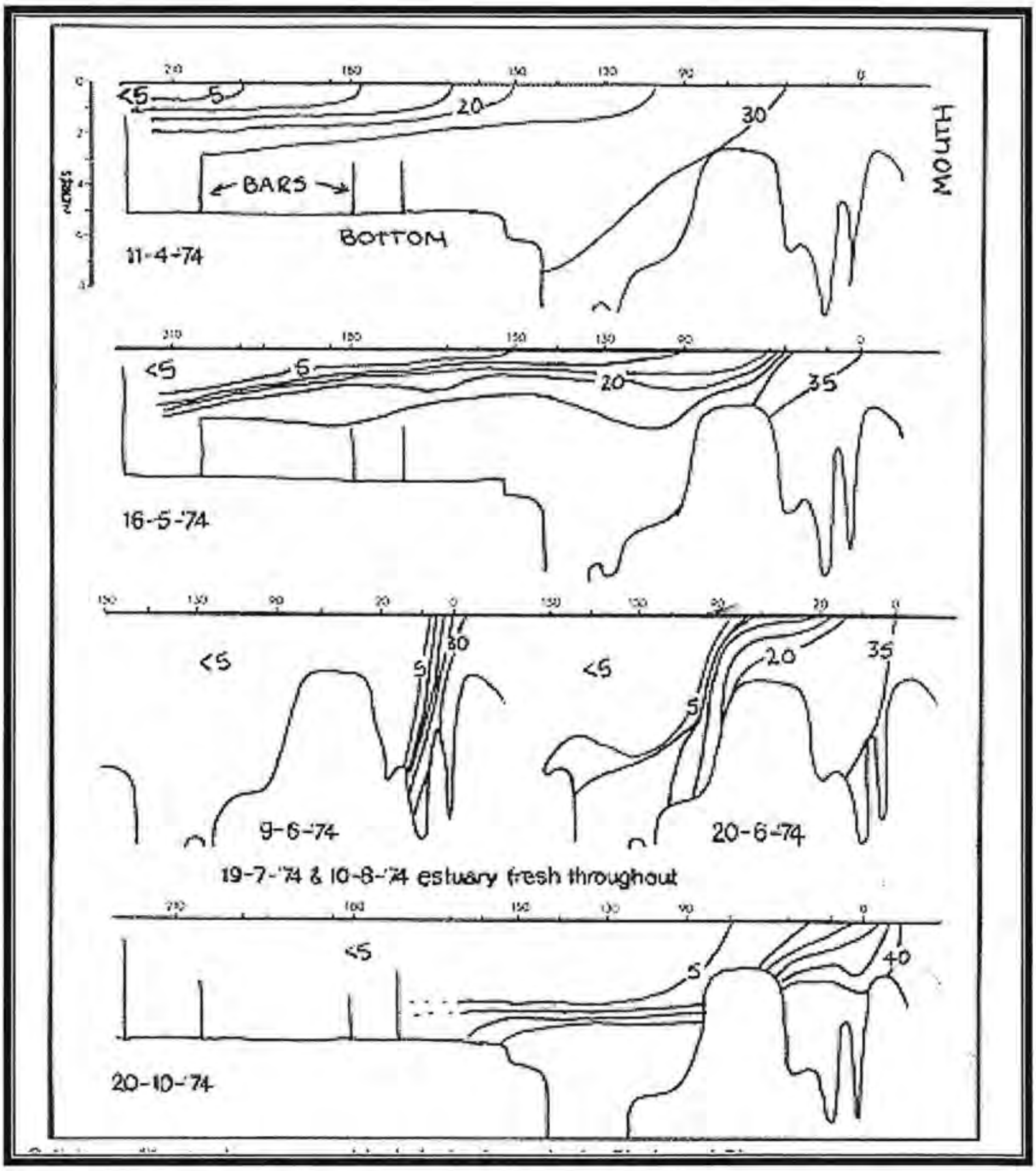


Figure 12. Vertical salinity section plots along the Blackwood Estuary showing typical salinity fields throughout an annual cycle.

Isohaline contours in units of parts per thousand (ppt). Contour interval = 5 ppt. Station number along the profile sections are in reference to the locality map in Figure 10. Data redrawn from Hodgkin (1976). Data originally presented in Agnew *et al* (1976).

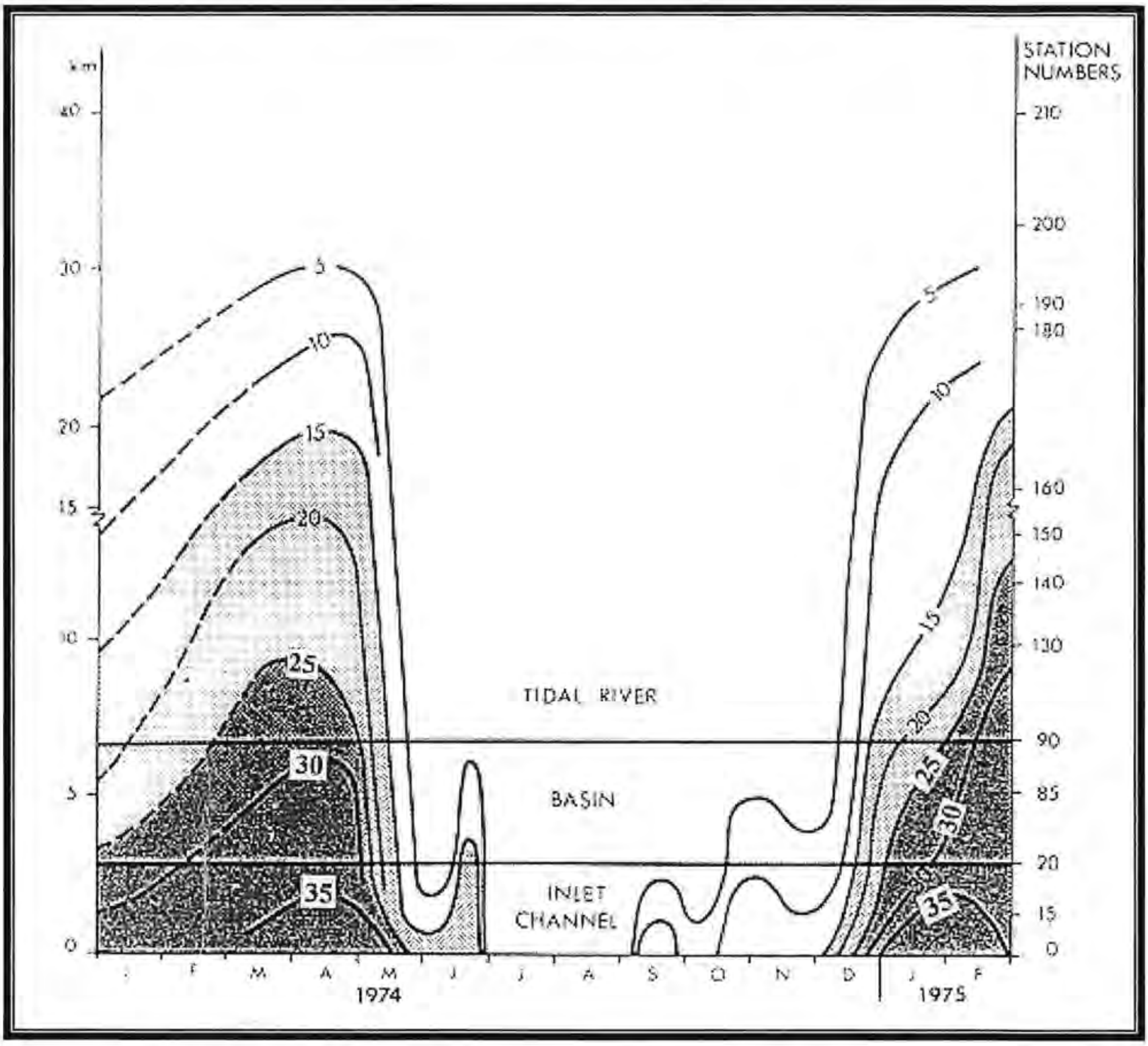


Figure 13. Variation of surface salinity (contours in parts per thousand) along the Blackwood Estuary through an annual cycle.

Reproduced from Hodgkin (1976). Data originally presented in Agnew *et al* (1976).

The presence of sills and depressions along the estuary profile leads to the cyclic trapping and formation of intrusive upstream flows of marine water in the estuary (Figure 14a & 14b). During flood tides the saline water that enters via the mouth flows over the sills and plunges down to the bottom of the deep holes, typical of salt wedge intrusion. Upon the turn of the tide, the presence of a downstream salinity gradient (with surface salinity increasing towards the mouth) leads to a 'shooting' surface flow of relatively low salinity water out towards the ocean. This flow over-rides the denser high salinity water in the holes and upstream of sills. There are two main dynamical consequences of this. First, during ebbs there is intense vertical mixing above the sills and in the shallow basins, forming regions of medium salinity water which, upon the turn of the tide to flood, make their way upstream as intrusive jets, above the bottom-penetrating salt wedge. Agnew *et al* (1976) found these jets to transport water up to 10 km upstream during flood tides. Secondly, because of the presence of relatively dense water upstream of the sills, some of this water remains trapped at the bottom during ebbs as the more buoyant water near the surface heads downstream, out to sea. A strong halocline (zone of intense salinity change) is formed between the outflowing water and more saline water of the salt wedge below. This assists in the retention of sea water within the estuary over successive tidal cycles.

The pooling of dense (high salinity) water in the depressions along the length of estuary promotes deoxygenation below the halocline, with oxygen levels recorded at Alexandra Bridge during 1945-52 showing low oxygen levels at depth, below the halocline (Hodgkin (1976). This is typical in nutrient-enriched estuaries such as the Blackwood. For example, D'Adamo (1985) has shown that the introduction of a salt wedge in the nutrient-enriched Murray River Estuary, Western Australia, leads to the depletion of oxygen near the bottom to concentrations at which fish cannot survive (< 3 mg l^{-1}).

With the arrival of winter rains, runoff and strong river discharges to the estuary, the system is purged again of its saline water. This process begins about May, with flushing complete (all the way to the entrance channel) typically by about mid-winter. Agnew *et al* (1976) indicate that river flow has a negligible effect on the dynamics of the estuary when it falls to below about 0.25×10^6 m^3 per day (during summer and autumn). Vertical stratification is extreme during this period (see Figure 12, 11-4-74).

During summer, in the absence of freshwater discharge, tidal current speeds up to about 0.5 m s^{-1} were typical in the inlet channel, compared to about 0.3 m s^{-1} or less in the inlet and basin (Figure 15). In contrast, freshwater discharge causes outflow speeds up to about 1 m s^{-1} through the basin, inlet and channel as freshwater escapes to the ocean (Figure 16).

4 REFERENCES

Agnew H J, Billings J, Imberger J and Wallace D F (1976). The dynamics of the Blackwood River Estuary. Report No. EFM-1, Environmental Fluid Mechanics Laboratory, University of Western Australia, Nedlands, Western Australia, 6009.

Australian Bureau of Statistics (1989). Western Australian Yearbook: No. 26-1989. Commonwealth of Australia.

Bray N A, Wiffjels S E, Chong J C, Fieux M, Hautala S, Myers G and Morawitz W M L (1997). Characteristics of the Indo-Pacific Throughflow. Geophysical Research Letters, **Vol. 24, No. 21**, pp. 2569-2572, November 1, 1997.

CALM (1994). A Representative Marine Reserve System for Western Australia. Report of the Marine Parks and Reserves Selection Working Group. Department of Conservation and Land Management, Perth, Western Australia.

Commonwealth of Australia (1993). Wind Waves Weather - Perth Waters (Jurien Bay to Bunbury). Bureau of Meteorology Boating Weather Series July 1993. Commonwealth of Australia.

Cresswell (1991). The Leeuwin Current – observations and recent models. In: 'The Leeuwin Current: an influence on the coastal climate and marine life of Western Australia' (eds. A F Pearce and D I Walker). J. Roy. Soc. of WA., **74**:35-45.

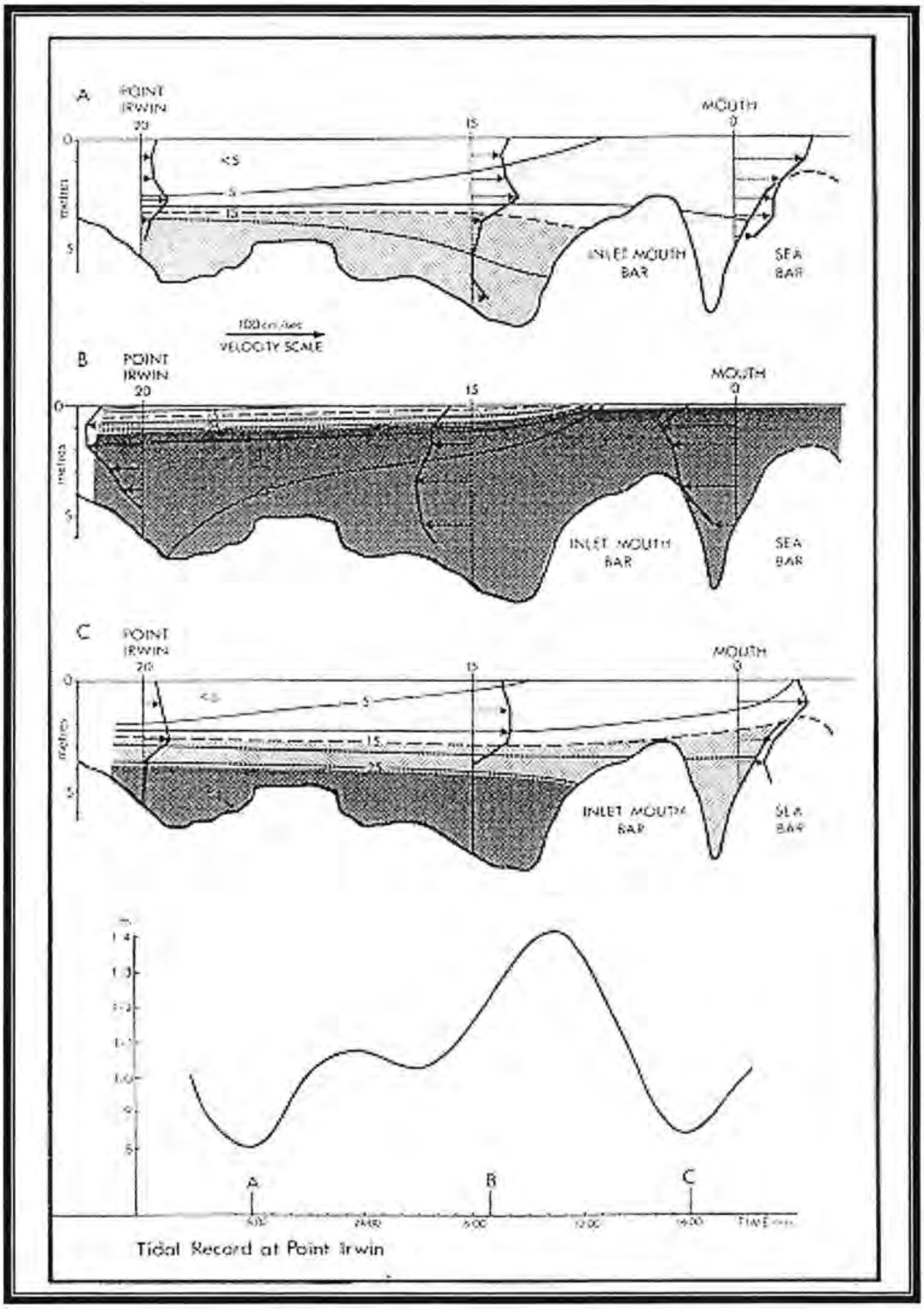


Figure 14a. Entrance channel: Changes in the along-estuary vertical salinity structure of the Blackwood Estuary under flood and ebb tides. Dense saline water that has plunged to the base of undulations ahead of sills during floods is seen to remain trapped in these depressions during succeeding ebb flows:

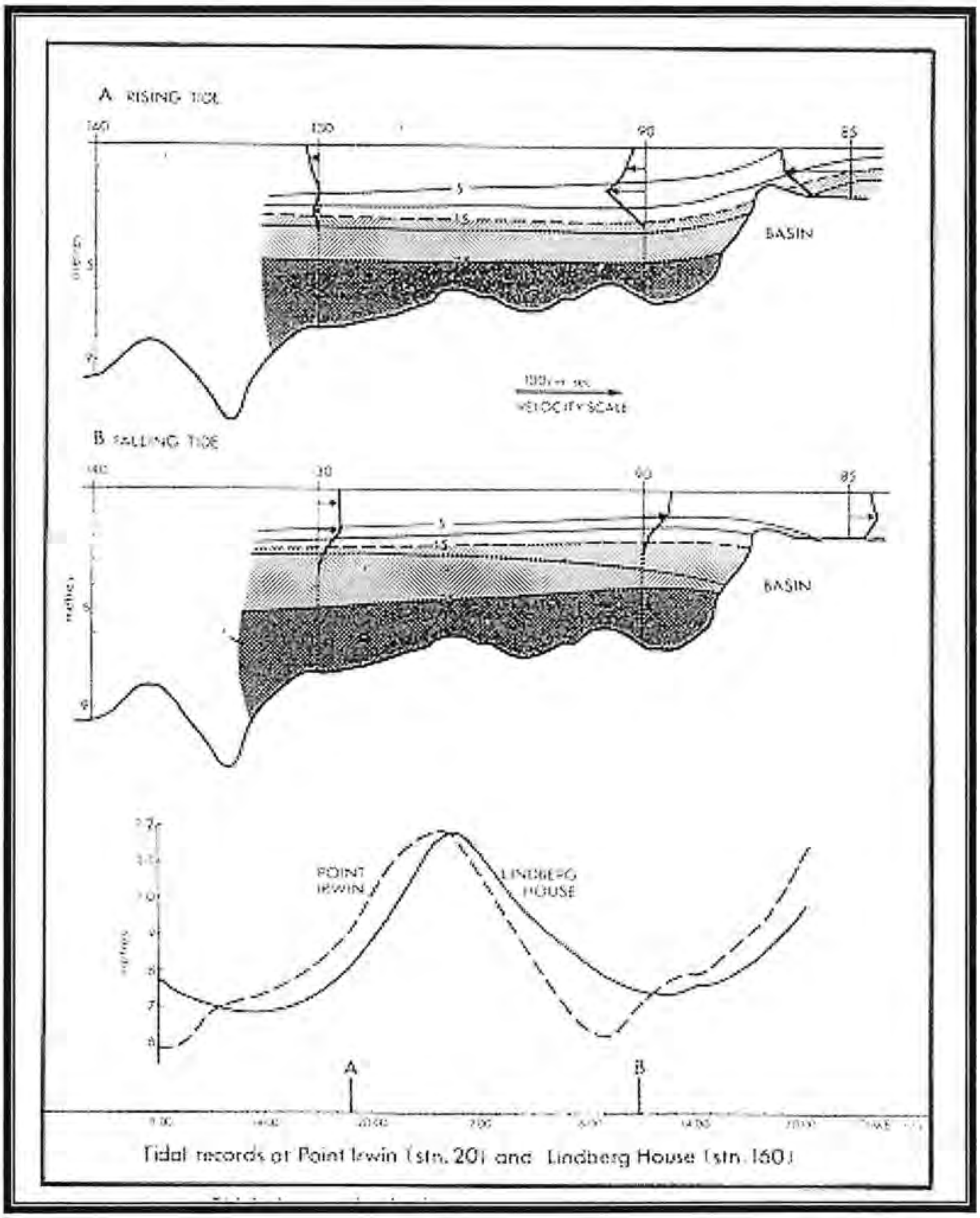


Figure 14b. Hardy Inlet and Molloy-Scott basins: Changes in the along-estuary vertical salinity structure of the Blackwood Estuary under flood and ebb tides. Dense saline water that has plunged to the base of undulations ahead of sills during floods is seen to remain trapped in these depressions during succeeding ebb flows.

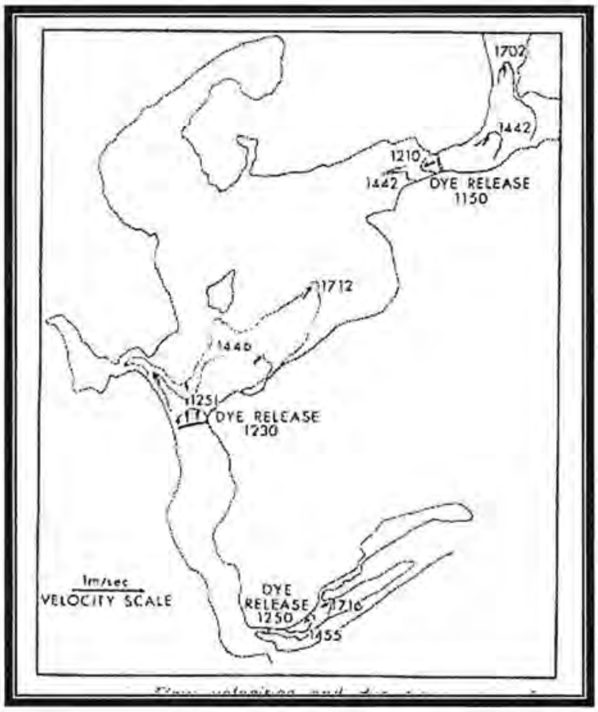


Figure 15. Typical summer flow velocities in the lower reaches of the Blackwood Estuary under low river discharge and tidal forcing.

Reproduced from Hodgkin (1976). Data originally presented in Agnew *et al* (1976).

Figure 16. Typical winter flow velocities in the lower reaches of the Blackwood Estuary during high river discharge.

Reproduced from Hodgkin (1976). Data originally presented in Agnew *et al* (1976).

Cresswell G R, Boland F M, Peterson J L and Wells G S (1989). Continental shelf currents near the Abrolhos Islands, Western Australia. Aust. J. of Mar. Freshwater Res., **40**:113-128.

Cresswell G R and Peterson J L (1993). The Leeuwin Current south of Western Australia. Aust. J. of Mar. Freshwater Res., **44**:285-303.

D'Adamo N (1995). Mixing and transport in the Murray River Estuary, Western Australia. M. Eng Sci. Thesis. University of Western Australia, Nedlands, Western Australia, 6009.

Davis T L O and Lyne V D (1994). Dispersal of the larval stage of the Southern Bluefin Tuna, *Thunnus maccoyii*, in the East Indian Ocean. In: Sammarco P W, Heron M L (eds), The Bio-Physics of Marine Larval Dispersal. American Geophysical Union, Coastal and Estuarine Studies **45**:137-148.

Department of Conservation and Environment (1980). Coastal processes around Western Australia. In: 'Coastal Management in Western Australia'. Bulletin 49, No. 5. Department of Conservation and Environment, Perth, Western Australia, 6000.

Fahrner C K and Pattiaratchi C B (1994). The physical oceanography of Geographe Bay, Western Australia. Reference WP898CF, Centre for Water Research, University of Western Australia, Nedlands, Western Australia, 6009.

Gersbach G H (1999). Coastal upwelling off Western Australia. PhD Thesis. University of Western Australia, Nedlands, Western Australia, 6009.

Gersbach G H, Pattiaratchi C B, Ivey G N and Cresswell G R (1999). Upwelling on the south-west coast of Australia – source of the Capes Current? Continental Shelf Research, **19**:363-400.

Hamon B V (1966). Continental shelf waves and the effects of atmospheric pressure and wind stress on sea level. J. Geophys. Res., **71**:2883-2893.

Harrison G E (1983). Low frequency sea level oscillations along the Western Australian coastline. M. Eng. Sci. (Civil.) Prelim. Centre for Water Research, University of Western Australia, Nedlands, Western Australia, 6009.

Hesp P A (1984). Aspects of the geomorphology of South West Australian estuaries. Department of Conservation and Environment, Bulletin **161**.

Hodgkin E P (1976). An environmental study of the Blackwood River Estuary Western Australia 1974-75. A report to the Estuarine and Marine Advisory Committee of the Environmental Protection Authority. Report No. 1, Department of Conservation and Environment, Perth, Western Australia, 6000.

Hodgkin E P and Di Lollo (1958). The tides of south-western Australia. J. Roy. Soc. WA., **41**:42-54.

Hutchins J B and Pearce A F (1994). Influence of the Leeuwin Current on the recruitment of tropical reef fishes at Rottnest Island, Western Australia. Bulletin of Marine Science, **54**:245-255.

Lenanton R C, Joll L, Penn J, Jones K (1991). The influence of the Leeuwin Current on coastal fisheries in Western Australia. In: 'The Leeuwin Current: an influence on the coastal climate and marine life of Western Australia' (eds. A F Pearce and D I Walker). J. Roy. Soc. of WA., **74**:101-114.

Maxwell J G H and Cresswell G R (1981). Dispersal of tropical marine fauna to the Great Australian Bight by the Leeuwin Current. Aust. J. of Mar. Freshwater Res., **32**:493-500.

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

Myers G, Bailey R J and Worby A P (1995). Geostrophic transport of Indonesian throughflow. Deep-sea Research, I, **Vol. 42, No. 7**, pp. 1163-1174.

Pearce A F (1991). Eastern boundary currents of the southern hemisphere. In: 'The Leeuwin Current: an influence on the coastal climate and marine life of Western Australia' (eds. A F Pearce and D I Walker). J. Roy. Soc. of WA., **74**:35-45.

Pearce A F and Cake J (1999). Preliminary notes on satellite-derived current patterns off Geographe Bay, Western Australia. CSIRO Marine Research Marmion, Western Australia, 6020. (Unpublished).

Pearce A F and Pattiaratchi C B (1999). The Capes Current: a summer countercurrent flowing past Cape Leeuwin and Cape Naturaliste, Western Australia. Continental Shelf Research, **19**:401-420.

Pearce A F and Phillips B F (1988). ENSO events, the Leeuwin Current and larval recruitment of the Western Rock Lobster. Journal du Conseil **45**:13-21.

Pearce A F and Walker D I (eds) (1991). The Leeuwin Current: an influence on the coastal climate and marine lie of Western Australia. Proceedings of a Symposium of the Royal Society of Western Australia and the Western Australian Branch of the Australian Marine Science Association, held at CSIRO Laboratories, Perth Western Australia, 16 March 1991. Journal of the Royal Society of Western Australia. J. Roy. Soc. of WA., **74**

Pugh D T (1987). Tides, surges and mean sea-level. John Wiley and Sons.

Simpson C J, Burt J S, Cary J L, D'Adamo N, Masini R J and Mills D A (1996). Southern Metropolitan Coastal Waters Study (1991-1994) – Final Report. Department of Environmental Protection, Perth, Western Australia, 6000.

Simpson J H (1997). Physical processes in the ROFI regime. Journal of Marine Systems, **12**:3-15.

Taylor J G and Pearce A F (1998). Ningaloo Reef currents: implications for coral spawn dispersal, zooplankton and whale shark abundance. J. Roy. Soc of WA., **82**:57-65.

WA Government (undated). New Horizons, the way ahead in marine conservation and management. Prepared for the Western Australian Government by the Department of Conservation and Land Management, Perth, Western Australia.

Webster I T (1983). Wind-driven circulation on the North West Shelf of Australia. Environmental Dynamics Report ED-83-065. Centre for Water Research, University of Western Australia, Nedlands, Western Australia, 6009.

Wijffels S E, Bray N, Hautala S, Myers G and Morowitz W M L (1996). The WOCE Indonesian Throughflow repeat hydrography sections: I10 and IR6. International WOCE Newsletter, **24**:25-28.

Wooler R D, Dunlop J N, Klomp N I, Meathrel C E and Wienecke B C (1991). Seabird abundance, distribution and breeding patterns in relation to the Leeuwin Current. In: 'The Leeuwin Current: an influence on the coastal climate and marine life of Western Australia' (eds. A F Pearce and D I Walker). J. Roy. Soc. of WA., **74**:129-132.

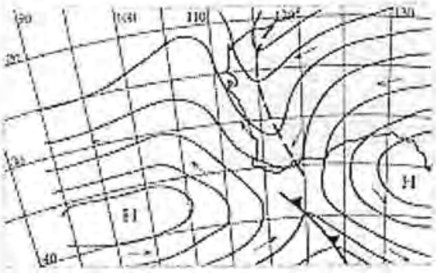
ACKNOWLEDGEMENTS

We are grateful to Alan Pearce, Commonwealth Scientific and Industrial Research Organisation, Dr Charitha Pattiaratchi, University of Western Australia, and Dr Guy Gersbach, Snowy Mountains Engineering Corporation, who kindly gave their permission for the direct reproduction of Figures from various of their publications on this subject. Alan Pearce permitted us to include Pearce and Cake (1999) as Appendix 3 of this report. The Department of Land Administration kindly provided satellite imagery of the Leeuwin Current. We are also grateful to Associate Professor Mervyn Lynch, Curtin University of Technology, for the provision of unpublished satellite imagery of the Capes Current. Thanks also to Kevin Bancroft for assisting in the production of the report.

APPENDICES

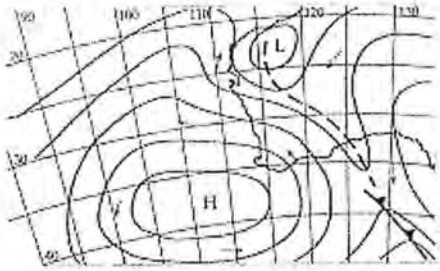
APPENDIX 1. TYPICAL SERIES OF SYNOPTIC CHARTS FOR SOUTHWEST AUSTRALIA, FOR SUMMER AND WINTER, RESPECTIVELY (REPRODUCED FROM BUREAU OF METEOROLOGY, 1993)

A typical summer sequence

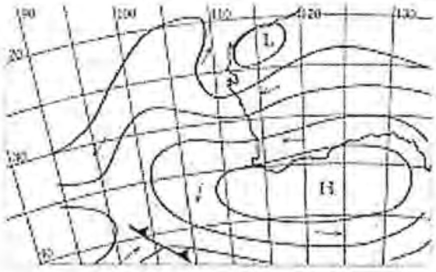


Day 1: A low pressure trough extends in a general north-south direction inland of the west coast. A high pressure system is centred over the Indian Ocean and the ridge axis lies near latitude 37°S. A typical wind profile shows a moderate southeasterly wind of around 10-12 kn in the early morning. It will veer to the southwest by late morning, and freshen to 20 kn and possibly in excess of 25 kn. Overnight the wind will gradually tend southeast again and moderate.

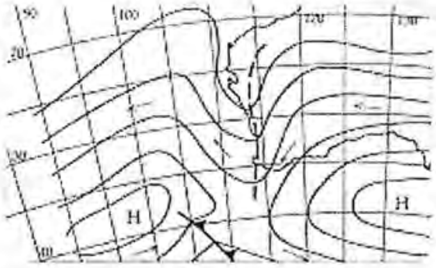
Note: Some of the strongest sea-breezes experienced in the Perth area result from this pattern, particularly if the high to the southwest is intense and rapid rises of pressure are occurring over the far southwest of the State.



Day 2: The low pressure trough is now further east (inland) and the high over the Indian Ocean is closer to WA. The high pressure ridge extends further east to the south of the south coast. The wind pattern is similar to that on day 1, although the sea-breeze may be an hour or so later in arrival and a little weaker. During the night the wind may turn to a gusty easterly.



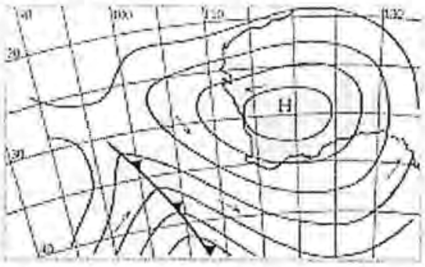
Day 3: The high has moved further east and is now off the south coast and producing a hot easterly airstream over WA. A fresh to strong easterly wind early in the morning will moderate during the day as the temperature increases. A weak sea-breeze of perhaps 15 kn may be experienced from about 3 pm, but the wind is likely to return to the east and freshen during the evening. On some days the mid-afternoon wind will be light and variable (i.e., there will not be a sea-breeze).



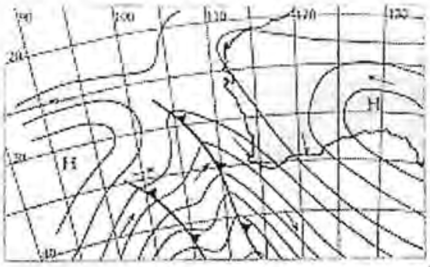
Day 4: The formation of a low pressure trough along the west coast is due to the marked land-sea temperature contrast. Another high is located over the Indian Ocean. A very hot day can be expected along the west coast where atmospheric pressures will fall. Winds may remain from the northeast until well into the afternoon, when a sea-breeze of 10-18 kn is likely to develop.

Day 5: The west coast trough moves inland, bringing a cool change to the west coast with fresh south to southeasterly winds. The synoptic pattern now reverts to that shown in day 1 of this sequence.

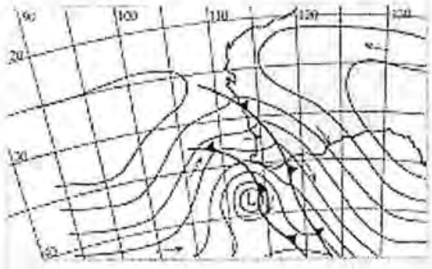
A typical winter sequence



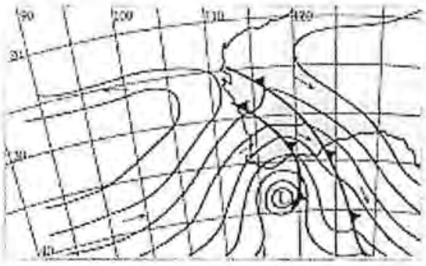
Day 1: A high is centred inland to the northeast of Perth. Light winds and generally clear skies could be expected along the lower west coast. During the night and into daylight hours a light northeasterly wind can be expected. This wind is a local phenomenon associated with the drainage of cold night-time air. However, by the afternoon, a north to northwesterly wind of 5-10 kn can be expected.



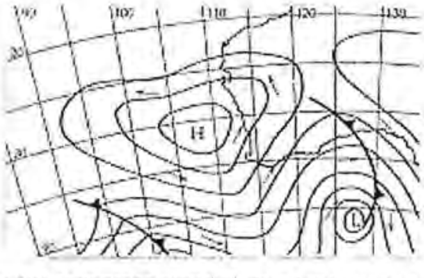
Day 2: The high has moved east into South Australia and a cold front is approaching the west coast. The pressures are falling steadily. A northerly wind of around 10 kn early in the morning backs to the northwest before noon and strengthens to around 20 kn by the late afternoon. Passing showers may be associated with stronger gusts and possible squalls. Caution should be taken if you are intending to sail or fish. The front may accelerate or intensify or both, and the wind will strengthen quickly.



Day 3: The cold front has crossed the lower west coast in the early morning hours. Northwesterly winds 20-30 kn have shifted rapidly southwest with the frontal passage. The mean wind speed decreases slightly after the change. However, the wind soon tends westerly and strengthens again, ahead of the night-time passage of a second front, associated with a low that has developed rapidly in the cold air behind the first front.



Day 4: The second front has caused gales overnight. Pressures rise during the day as the low moves east to the south of the State. Squally west to southwesterly winds gradually decrease in strength, averaging about 20 kn by sundown. Like day 3, this is not a good day to be out on the water.



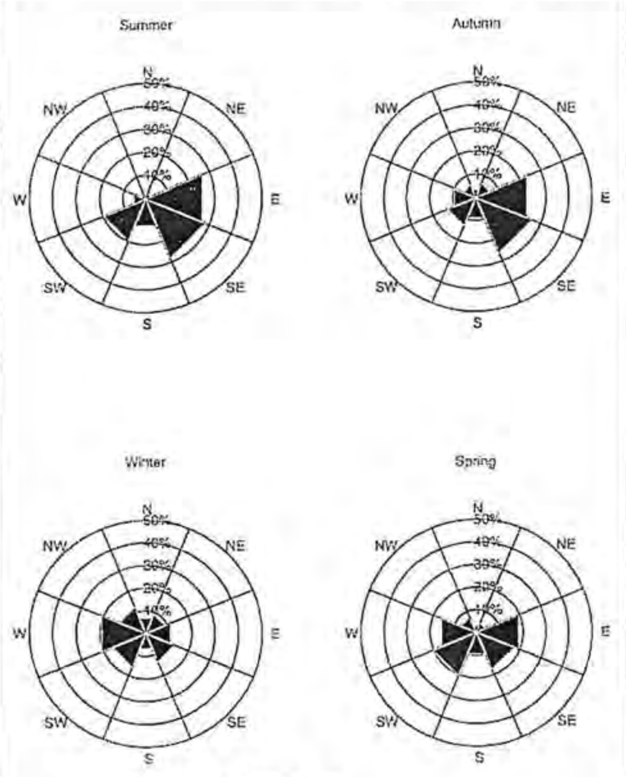
Day 5: The front is now moving across the Bight and another high is approaching the west coast. Conditions have moderated and a 10-15 kn southwesterly wind persists for most of the day, moderating slowly by the evening. Partly cloudy skies are experienced after some early clearing showers. Boating conditions are improving.

Day 5: This is a return to day 1 of the sequence and boating conditions should be quite pleasant.

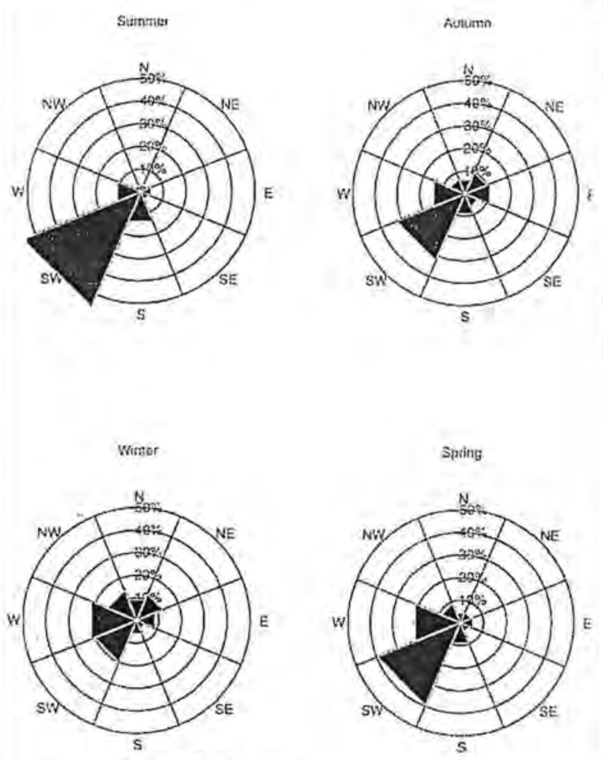
APPENDIX 2. CLIMATIC DATA FOR THE SOUTHWEST OF WESTERN AUSTRALIA (FROM FAHRNER AND PATTIARATCHI, 1994, PEARCE AND PATTIARATCHI, 1999, AUSTRALIAN BUREAU OF STATISTICS, 1989 AND BUREAU OF METEOROLOGY, 1993)

Data sources:

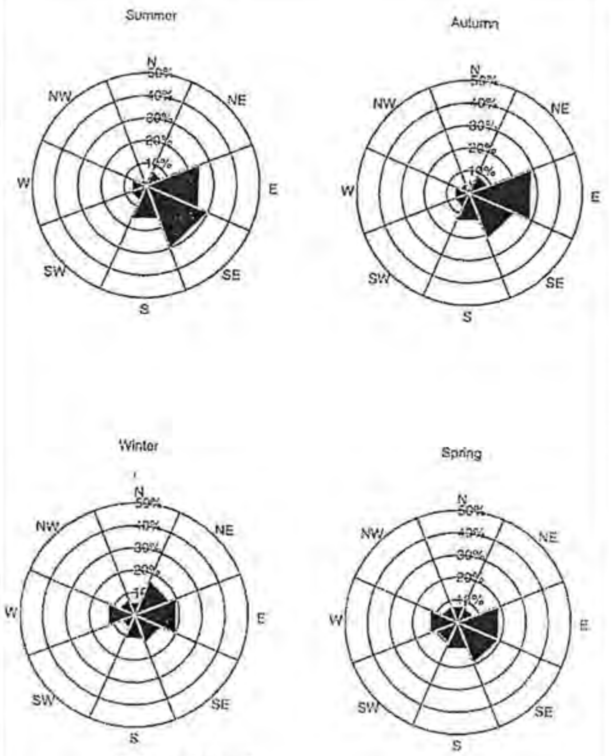
- Wind roses and histograms reproduced from Fahrner and Pattiaratchi (1994).
- Monthly mean wind vectors reproduced from Pearce and Pattiaratchi (1999). Original data from Bureau of Meteorology (1993).
- Mean annual rainfall and evaporation contours reproduced from Australian Bureau of Statistics (1989).



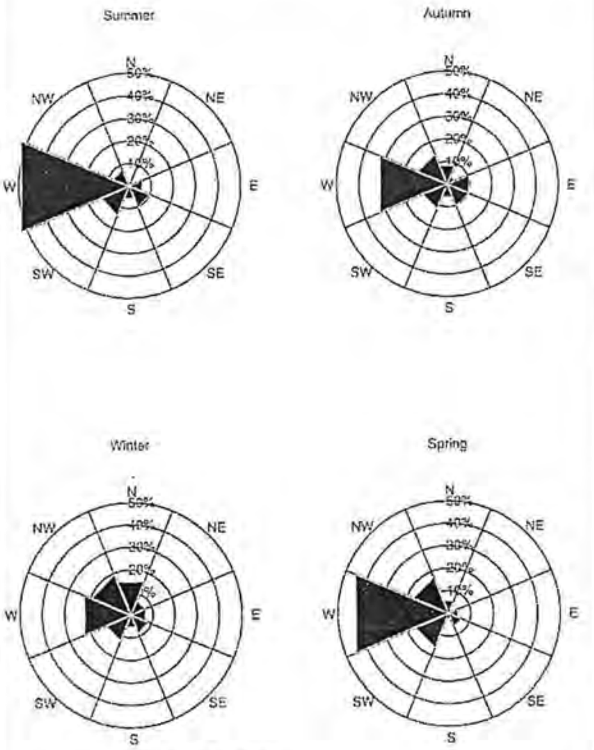
Wind roses - Cape Naturaliste, 9 am



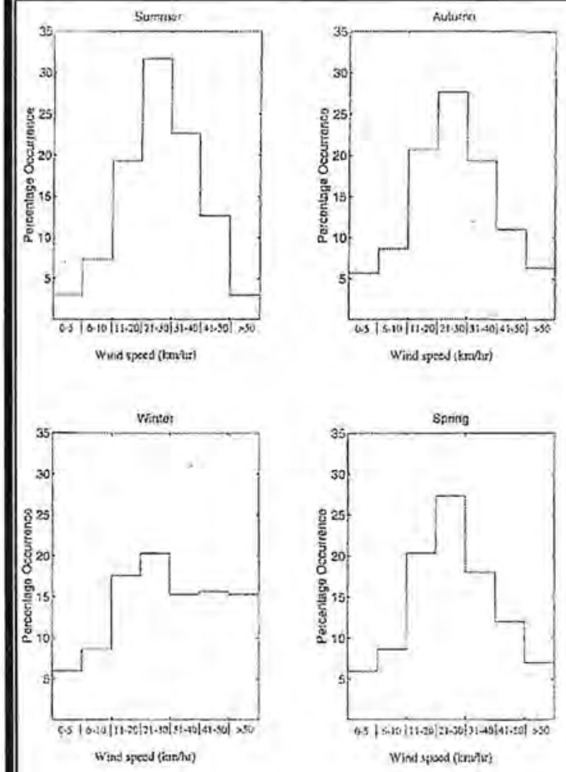
Wind roses - Cape Naturaliste, 3 pm



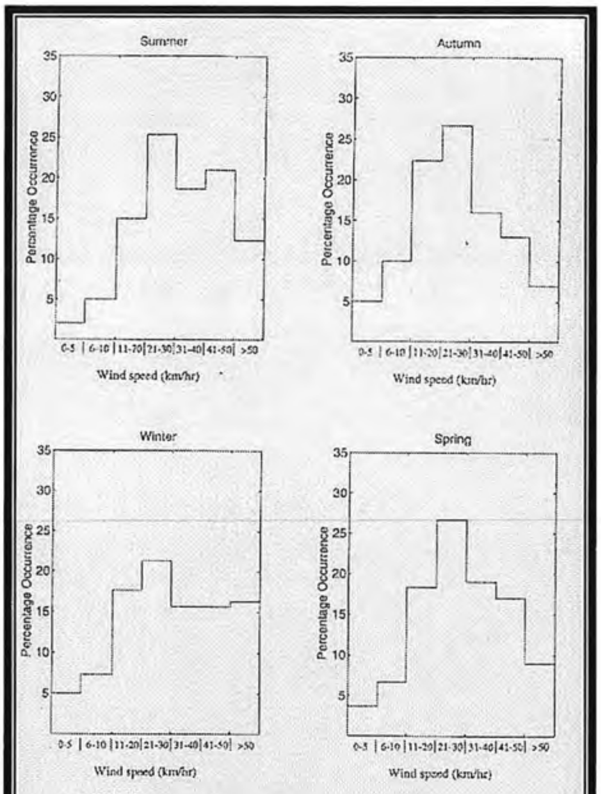
Wind roses - Bunbury, 9 am



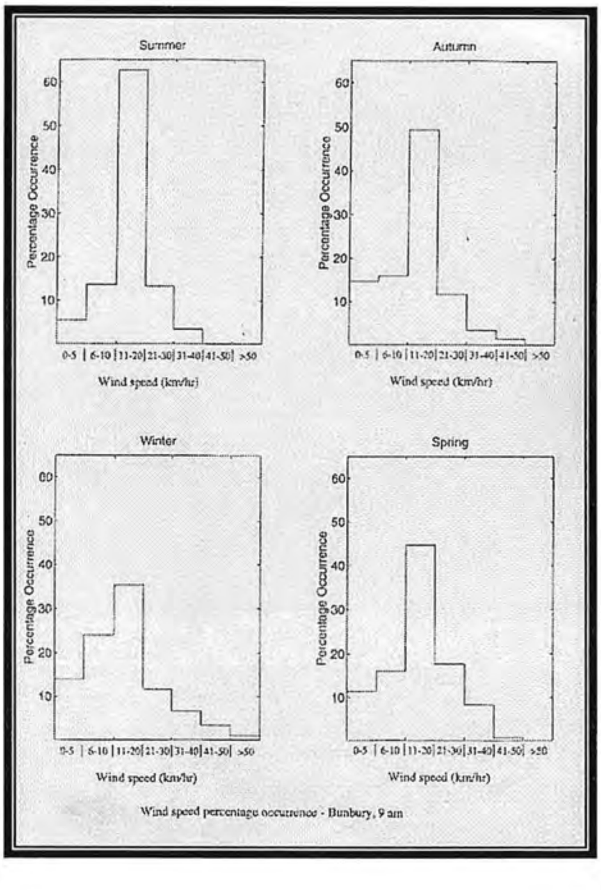
Wind roses - Bunbury, 3 pm



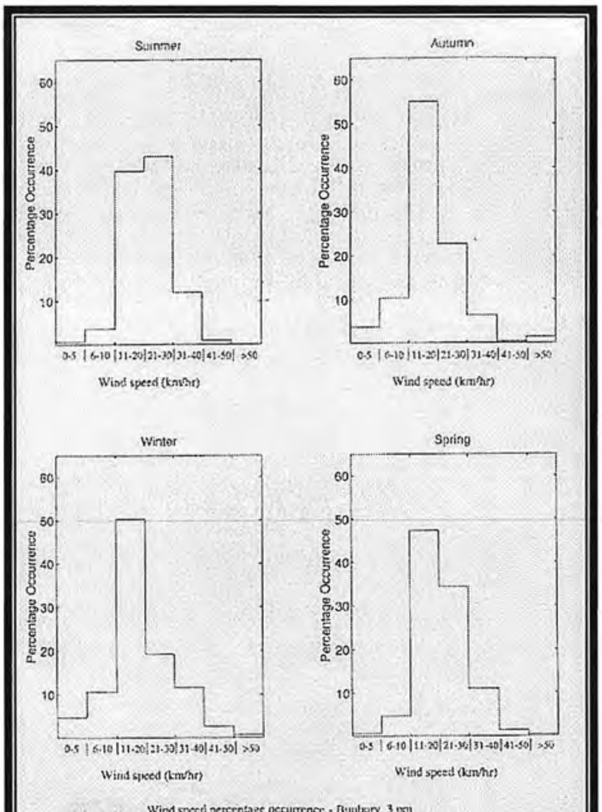
Wind speed percentage occurrence - Cape Naturaliste, 9 am



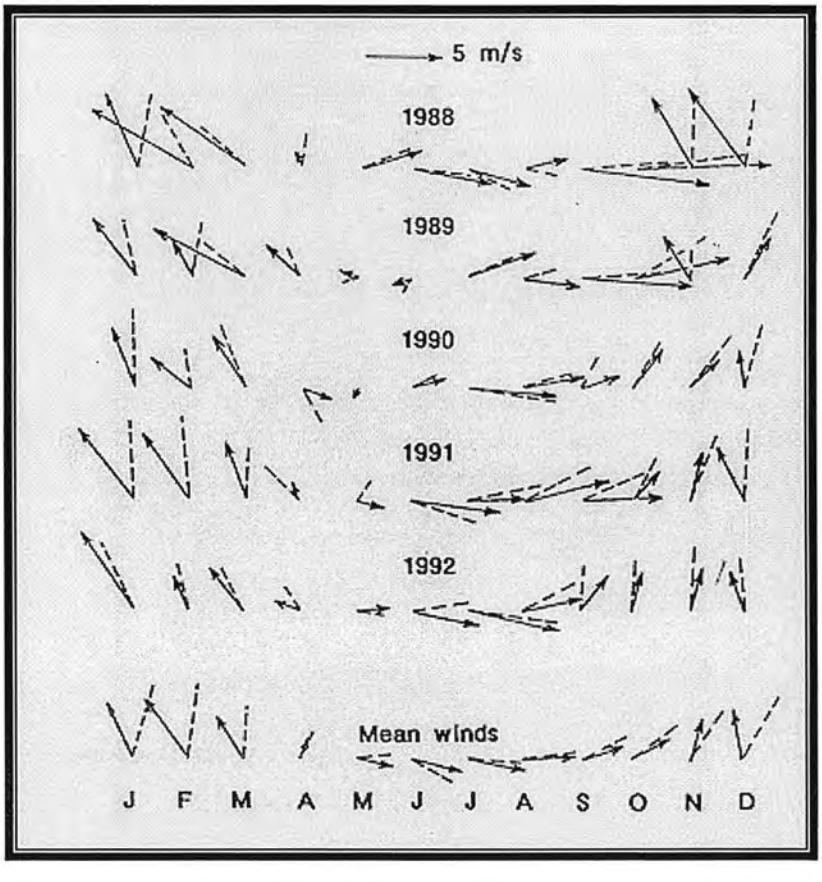
Wind speed percentage occurrence - Cape Naturaliste, 3 pm

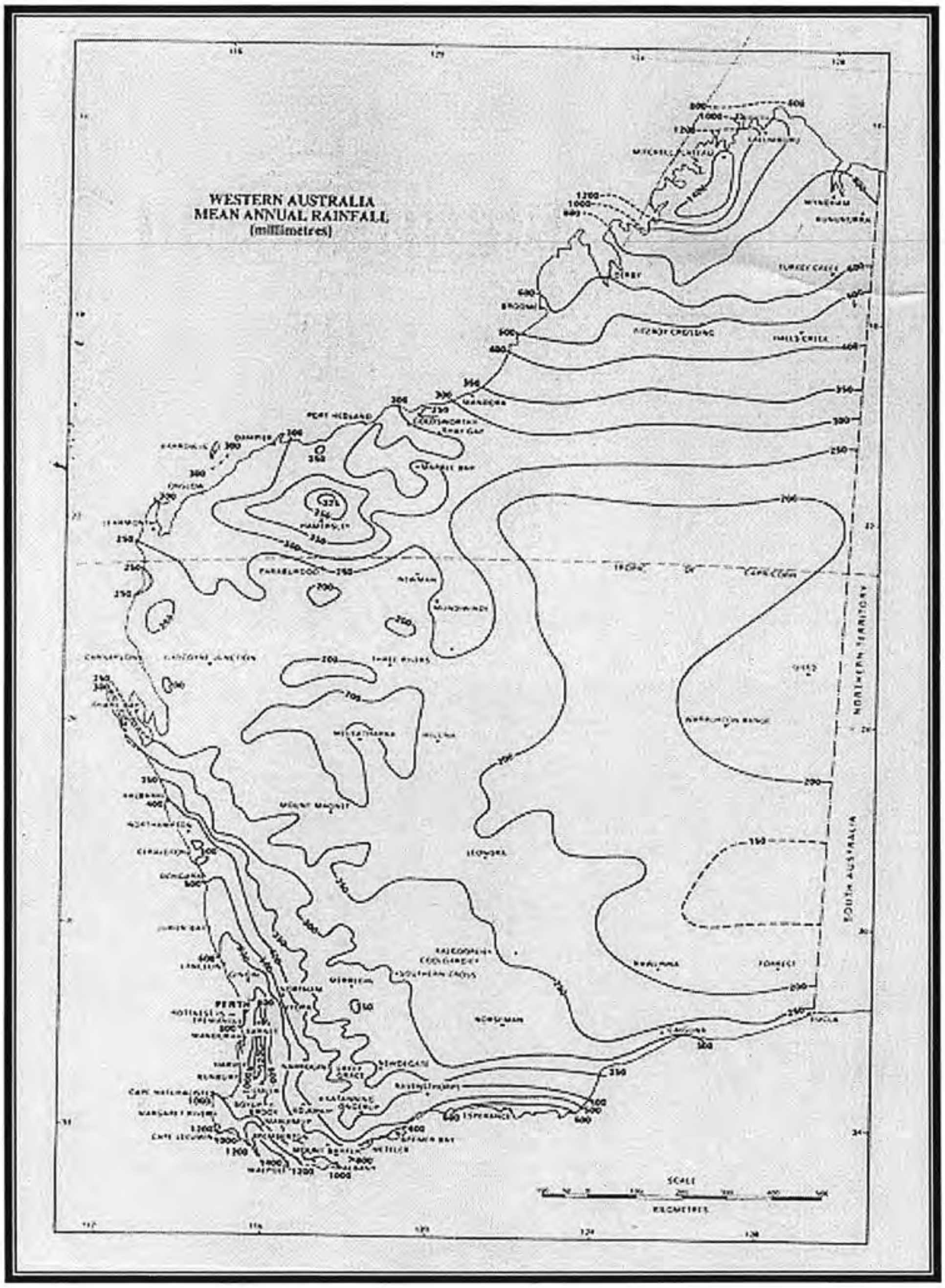


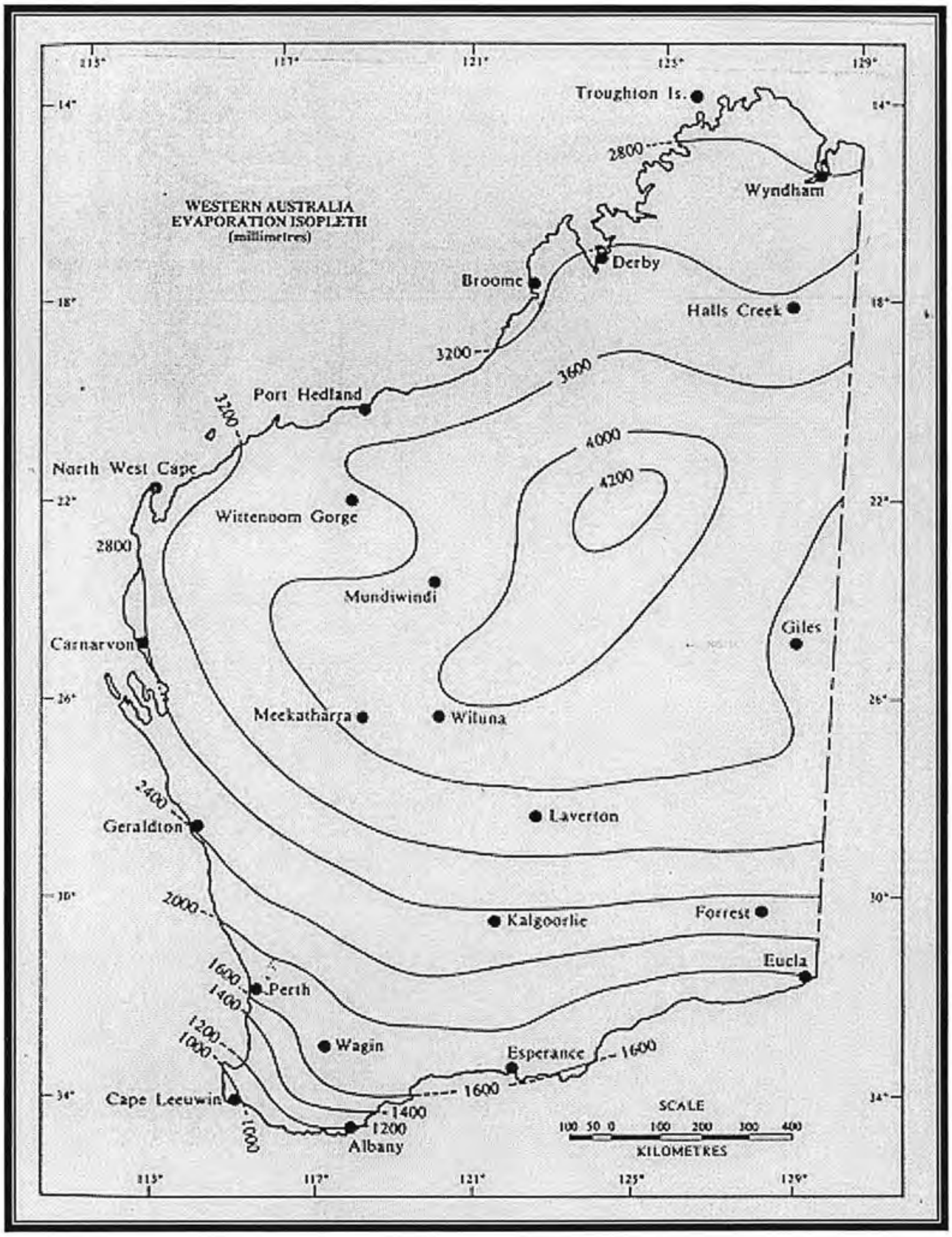
Wind speed percentage occurrence - Bunbury, 9 am



Wind speed percentage occurrence - Bunbury, 3 pm




WESTERN AUSTRALIA
MEAN ANNUAL RAINFALL
(millimetres)
PERTH
NORTHERN TERRITORY
SOUTH AUSTRALIA
SCALE
KILOMETRES


WESTERN AUSTRALIA
EVAPORATION ISOPLETH
(millimetres)
113°
117°
121°
125°
129°
14°
18°
22°
26°
30°
34°
Troughton Is.
Wyndham
Derby
Broome
Halls Creek
Port Hedland
North West Cape
Wittenoom Gorge
Mundiwindi
Giles
Carnarvon
Meekatharra
Wiluna
Laverton
Geraldton
Kalgoorlie
Forrest
Eucla
Perth
Wagin
Esperance
Cape Leeuwin
Albany
2800
3200
3600
4000
4200
2400
2000
1600
1400
1200
1000
SCALE
100 50 0 100 200 300 400
KILOMETRES

APPENDIX 3. SEA-SURFACE TEMPERATURE FIELDS FROM NOAA-AVHRR SATELLITE IMAGERY SHOWING THE LEEUWIN CURRENT AND CAPES CURRENT OFF SOUTHWEST AUSTRALIA (REPRODUCED FROM PEARCE AND CAKE, 1999)

Preliminary notes on satellite-derived current patterns off Geographe Bay, Western Australia

Alan Pearce, CSIRO Marine Research, Marmion, Western Australia

Jodi Cake, CALM Volunteer, Fremantle, Western Australia

11 February 1999

Unpublished manuscript

Introduction

NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite imagery for the southwestern coast of Western Australia has been processed for each month of 1998 to show some of the oceanographic processes in the vicinity of Geographe Bay.

List of images processed

Date	Orbit	Date	Orbit
17 Jan 1998	N14/15714	19 Feb 1998	N14/16180
16 Mar 1998	N14/16533	24 Apr 1998	N14/17083
23 May 1998	N14/17492	23 Jun 1998	N14/17930
15 Jul 1998	N14/18240	9 Aug 1998	N14/18593
8 Sep 1998	N14/19016	19 Oct 1998	N14/19595
15 Nov 1998	N14/19976	12 Dec 1998	N14/20357

The images show ocean temperatures for southwestern Australia in 1998, as well as enlarged images of the coastal region between Mandurah and Cape Mentelle (Figure 1).

Interpretation

January: The (weak) Leeuwin Current (shown by the solid arrow) was bringing warm water southwards, and the cool Capes Current (dashed arrow) was flowing northwards along the inner continental shelf. It seems that the Leeuwin Current may not have penetrated much south of Cape Naturaliste at this time, although with the cloud to the south this is unclear. The shallow water along the coast (and also in the Peel/Harvey system) was warm because of heat input from the sun and atmosphere.

February: A similar situation to January; the Capes Current was now more clearly identifiable.

March: The Leeuwin Current appears to have strengthened and now flowed around Cape Leeuwin towards the south coast. There was still warm coastal water along the shore of Geographe Bay and in Peel Inlet.

April: A dramatic change had taken place inshore, where the coastal water had lost heat to the atmosphere and so was much cooler than the open-shelf water; note particularly the cool region in Geographe Bay itself. Both the Leeuwin and Capes Currents were still flowing.

May: There was still relatively cool water between Cape Naturaliste and Cape Leeuwin, suggesting that the Capes Current may still have been operating (later than usual). A tongue of Leeuwin Current water was penetrating across the shelf towards the coast between Bunbury and the Peel-Harvey system

June: The Leeuwin Current was flowing strongly and had flooded across the shelf into the coastal region between the Capes. Geographe Bay was still cold.

July: Despite cloud over the Leeuwin Current, it appears that the Current was still flowing strongly. The coastal water and the Peel-Harvey were still relatively cold, but some warmer water from the Current was again pushing towards the coast near Bunbury.

August: Although the strongest "core" of the Leeuwin Current lay along the shelf-break, warm water was distributed right up to the coast. There was some hint of warming in the shallowest water along parts of the coastline.

September: Much the same picture as in August; there was a large offshore eddy peeling north-westwards from the Leeuwin Current.

October: Similar to August, but the Peel Inlet was beginning to warm.

November: The Leeuwin Current was weaker, meandering offshore northwest of Geographe Bay, and the Capes Current had commenced flowing. Spring warming was occurring in the shallow coastal water.

December: The Leeuwin Current was again weak and had moved offshore; the Capes Current was flowing. Coastal waters had warmed further.

In summary:

During the summer months, the warm Leeuwin Current is relatively weak because of the strong northwards (opposing) wind stress, and the Current tends to move offshore. The cooler Capes Current flows northwards along the inner continental shelf past Cape Leeuwin and Cape Naturaliste, usually continuing beyond Rottnest Island.

With autumn, the net northward wind stress eases, the Capes Current dies away, and the Leeuwin Current begins to strengthen and move closer inshore again. Large meanders and eddies associated with the Leeuwin Current can carry the warm tropical water over 100 km offshore. The Current continues to flow strongly until late spring when it weakens, tends to move offshore, and the Capes Current re-commences.

Tongues of Leeuwin Current water are often seen penetrating across the continental shelf towards the coast, representing an active exchange of inshore and Leeuwin Current water. This clearly has implications for marine larvae which can be transported either towards or away from the coast by these cross-shelf mixing processes.

The seasonal change in net heat flux into the ocean (in summer) and net heat loss from the ocean (winter) results in a seasonally-reversing cross-shelf temperature gradient. In summer, the shallow coastal water warms, so the temperature falls with increasing distance from the coast into the cool Capes Current, then rises again in the Leeuwin Current. In winter, by contrast, the coastal water in Geographe Bay cools dramatically and there is a strong temperature rise into the Leeuwin Current.

Annual cycles:

To illustrate the annual temperature cycle and its link with some of the processes described above, numerical sea-surface temperatures have been extracted from the monthly images for 3 sites:

(A) just west of Cape Naturaliste (representing the shelf water, influenced by the Capes Current in summer);
(B) further west in the warmest part of the Leeuwin Current;
(C) in the shallow water at the southernmost limit of Geographe Bay.

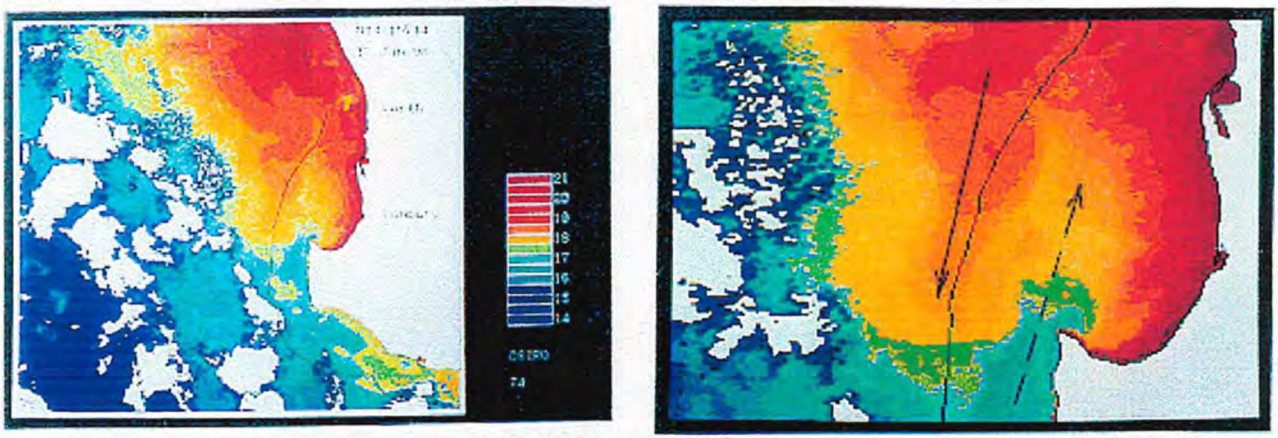
Along the outer shelf, the surface temperature peaked at about 23.5°C in April/May as warm tropical waters spread southwards in the Leeuwin Current, and lowest temperatures of about 19.5°C were found in October. Close inshore off Cape Naturaliste, the temperature cycle was very similar but the temperatures were about 2°C cooler than in the Leeuwin Current, so ranged from 17.3° to 21.3°C.

In the shallow waters of Geographe Bay, the peak temperature was over 23°C in January and March (February was an anomaly), while in August the temperature fell to 15.6°C -- these are more in phase with the annual air temperature cycle, reflecting the important role played by air--sea heat fluxes. Clearly, west of Cape Naturaliste, advective processes (currents) are dominant, while in the less-flushed waters of the Bay, atmospheric effects are important.

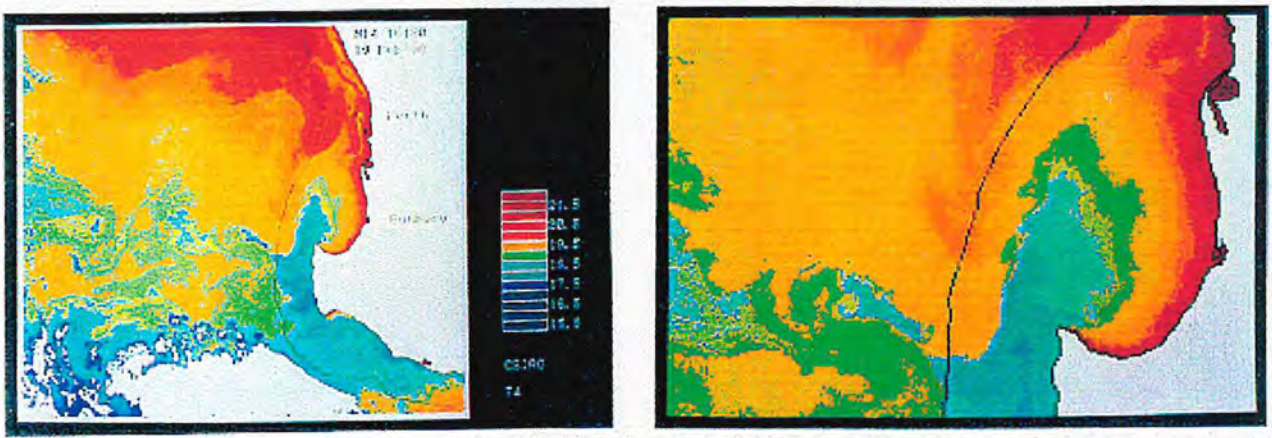
It must be emphasised that these values are merely spot samples (representing 1 km pixels) from a single image in each month, and therefore do not necessarily represent average or even typical conditions. A more detailed analysis of a large number of images in each month (and preferably over a period of a few years) and using larger areas of say 11 km by 11 km would be required to represent the "true" annual cycle more realistically.

Acknowledgements

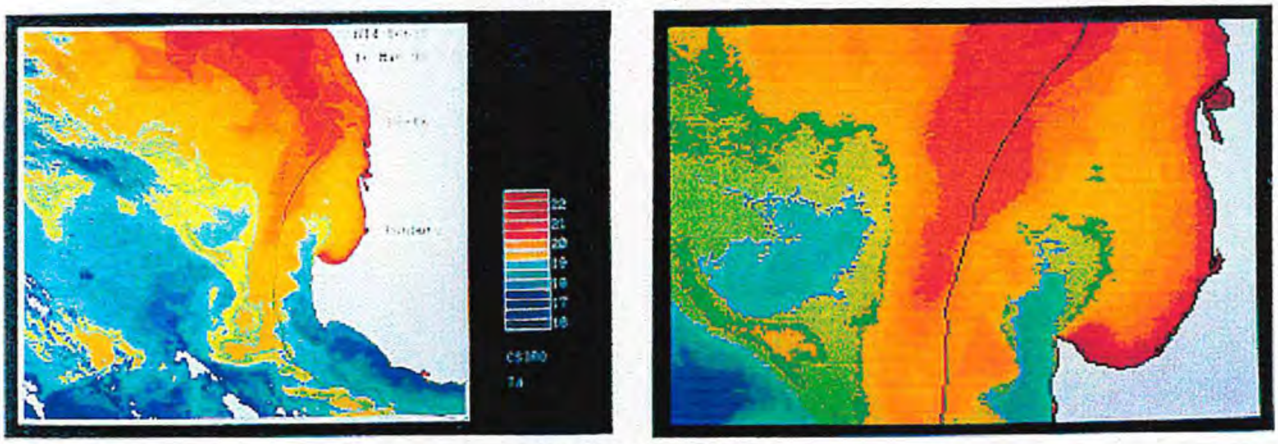
The satellite imagery was acquired from the Western Australian Satellite Technology and Applications Consortium (WASTAC), from funding partly provided by the Fisheries Research and Development Corporation (FRDC). Jeremy Colman (CALM, now Woodside) initiated the project.



17 January 1998



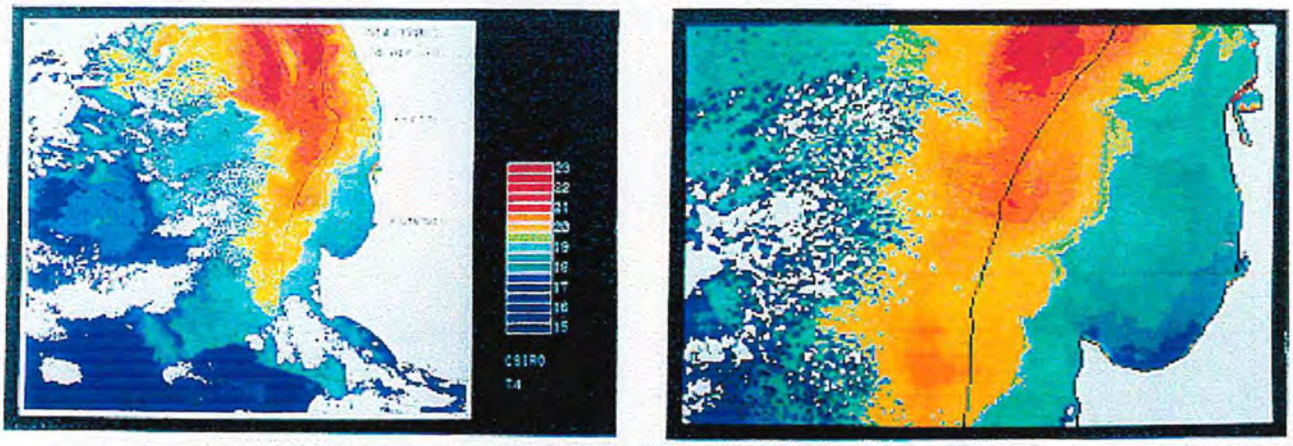
19 February 1998



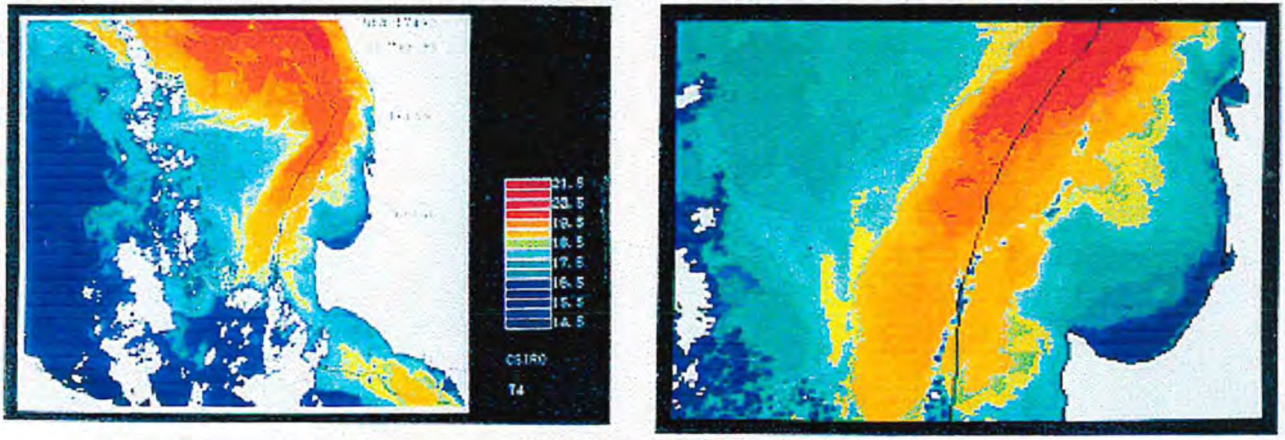
16 March 1998

Figure 1: Monthly satellite sea-surface temperature images for southwestern Australia in 1998, as well as an enlarged image of the coastal region between Mandurah and Cape Mentelle.

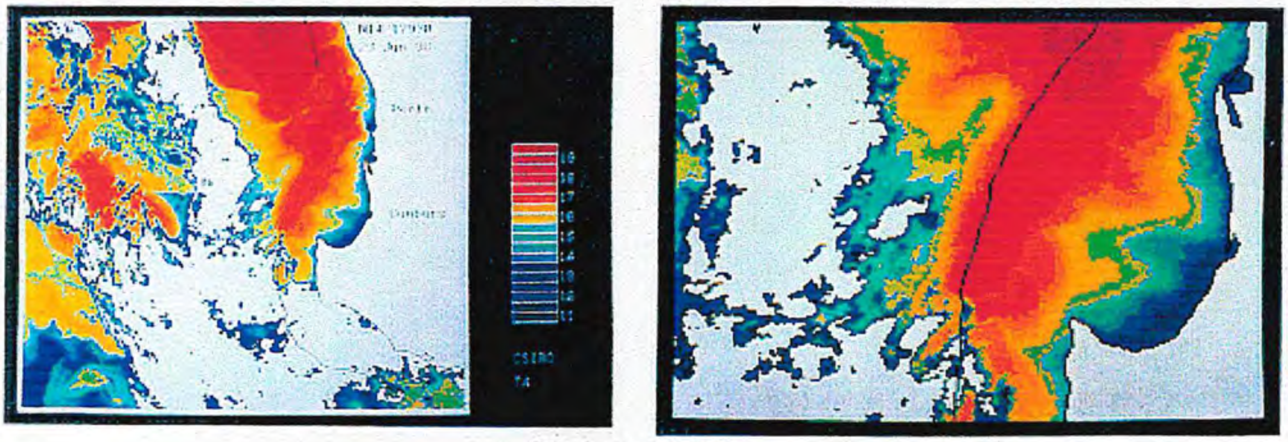
The colour scale shows the brightness temperature in AVHRR Band 4, uncorrected for atmospheric absorption (and so reads one to two degrees low). Warmest water is shown in red, cooling through orange, yellow and green to the coolest water in blue. Clouds are white or mottled blue. The black line marks the 200 m isobath, representing the approximate position of the continental shelf break. Different temperature/colour scales have been used to most clearly display the thermal features in each image, so there is no connection between the scales used.



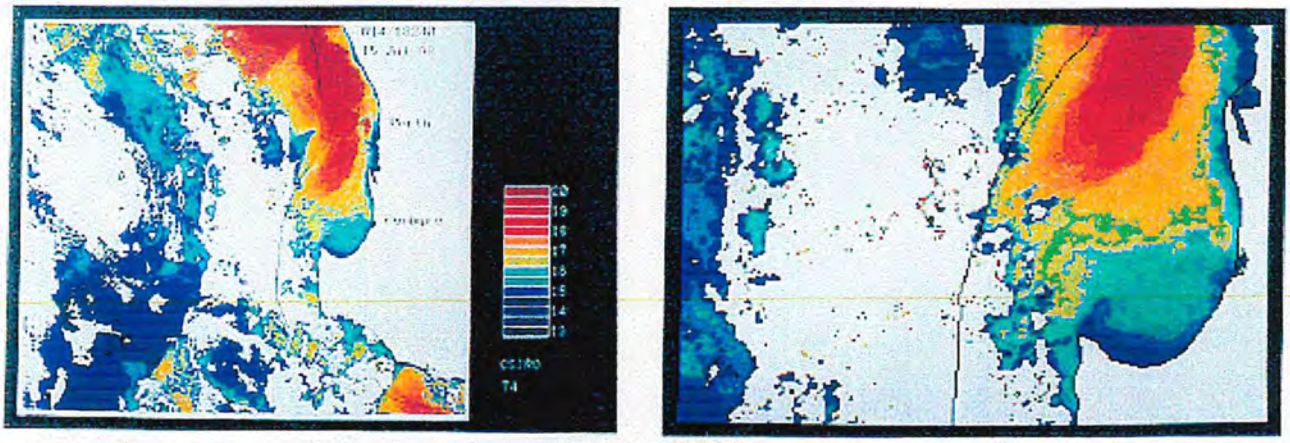
24 April 1998



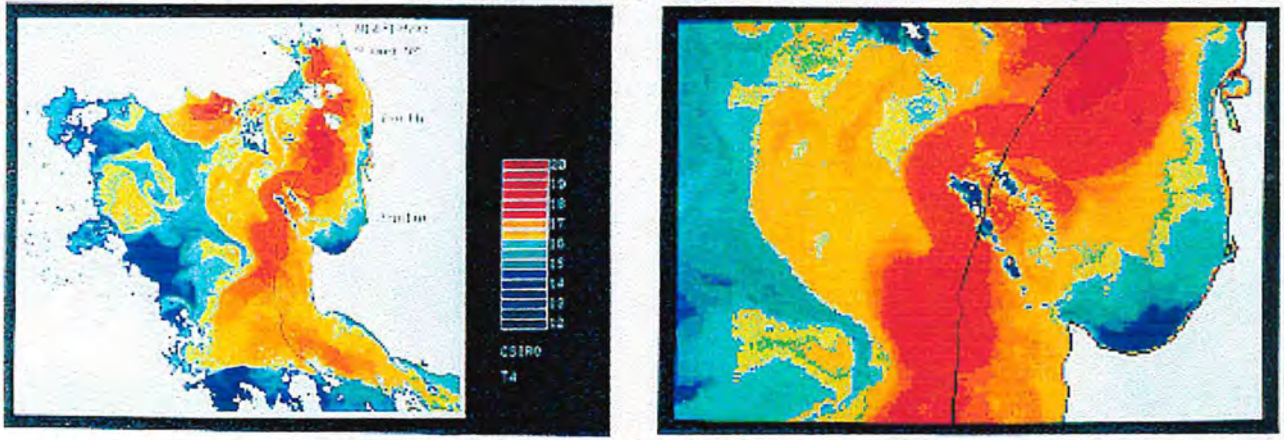
23 May 1998



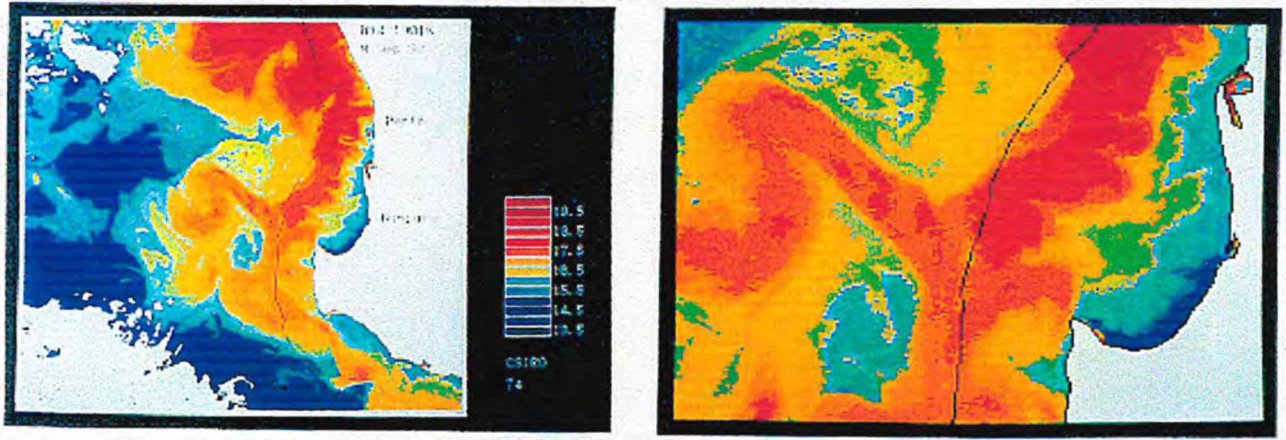
23 June 1998



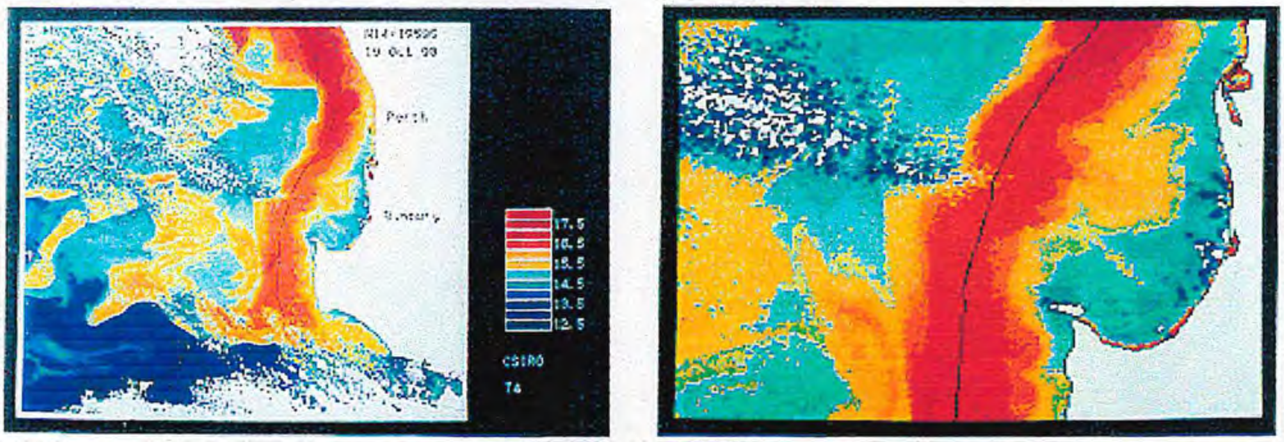
15 July 1998



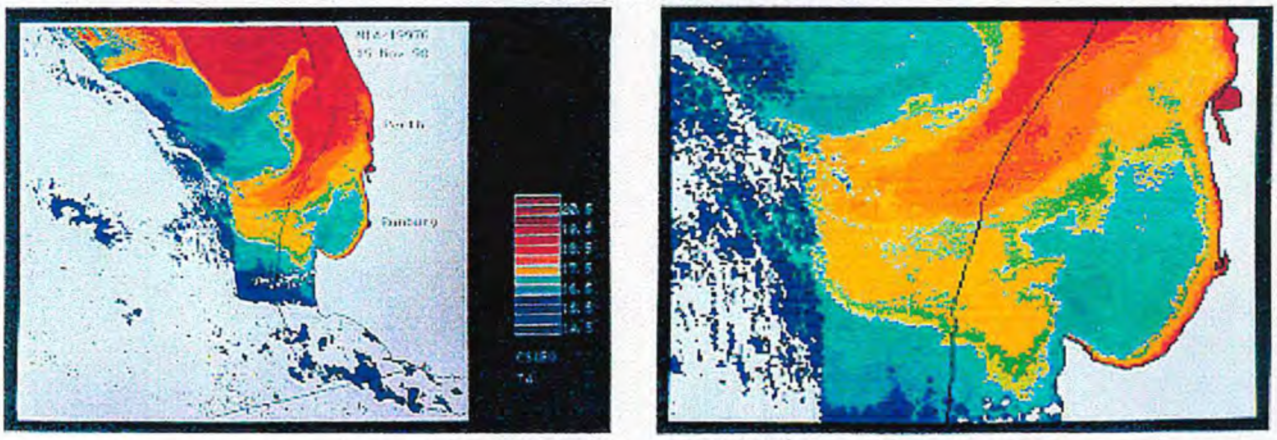
9 August 1998



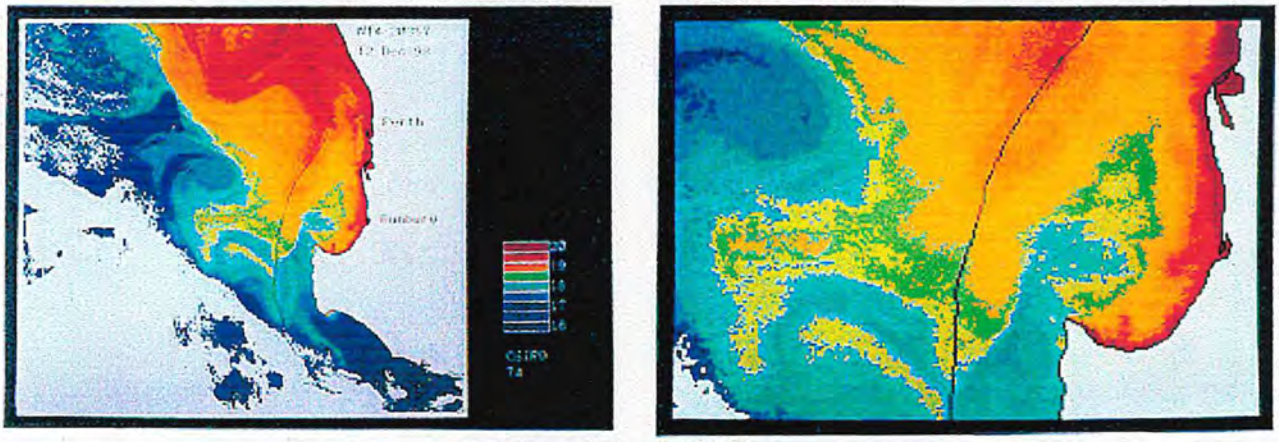
8 September 1998



19 October 1998



15 November 1998



12 December 1998

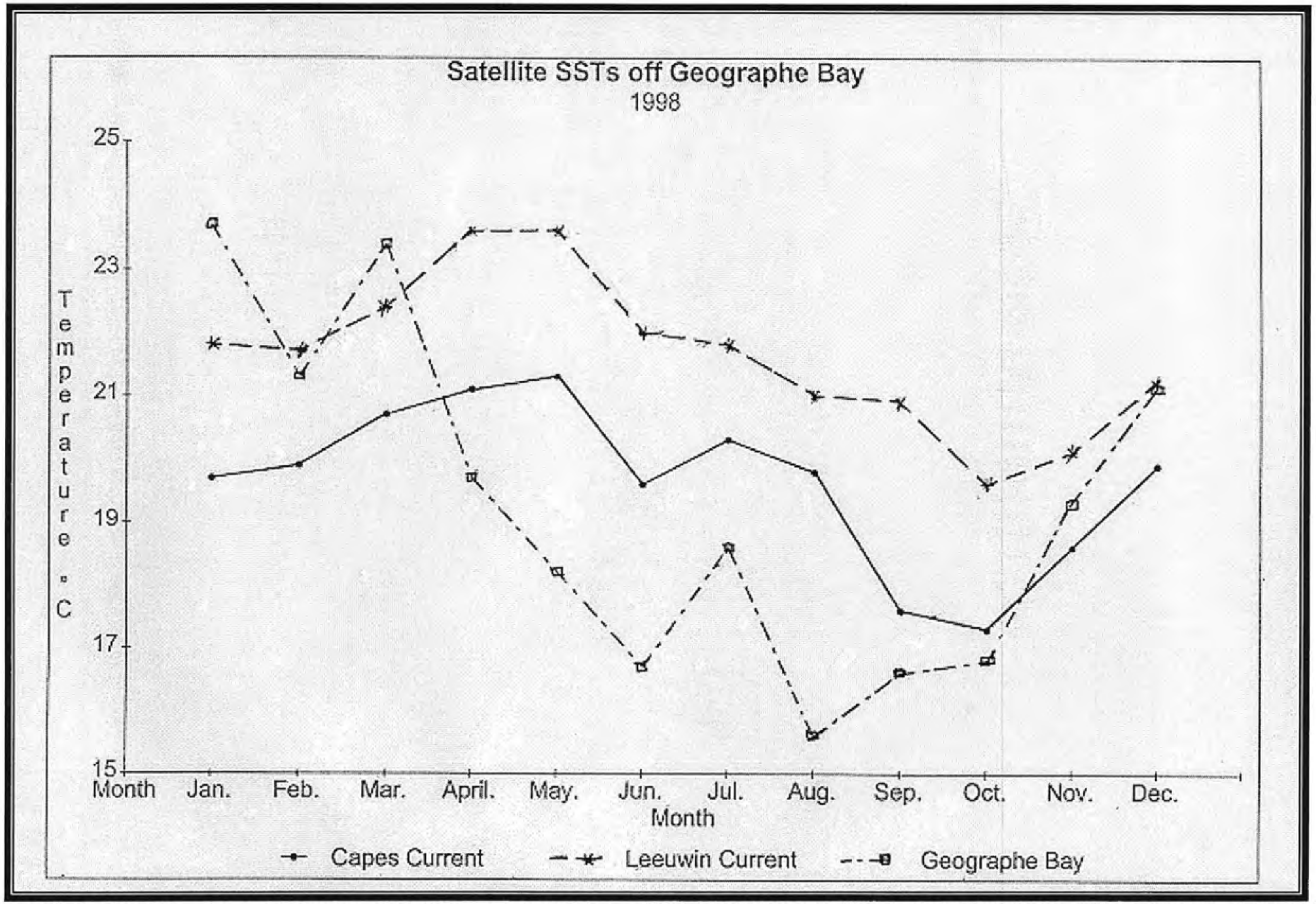
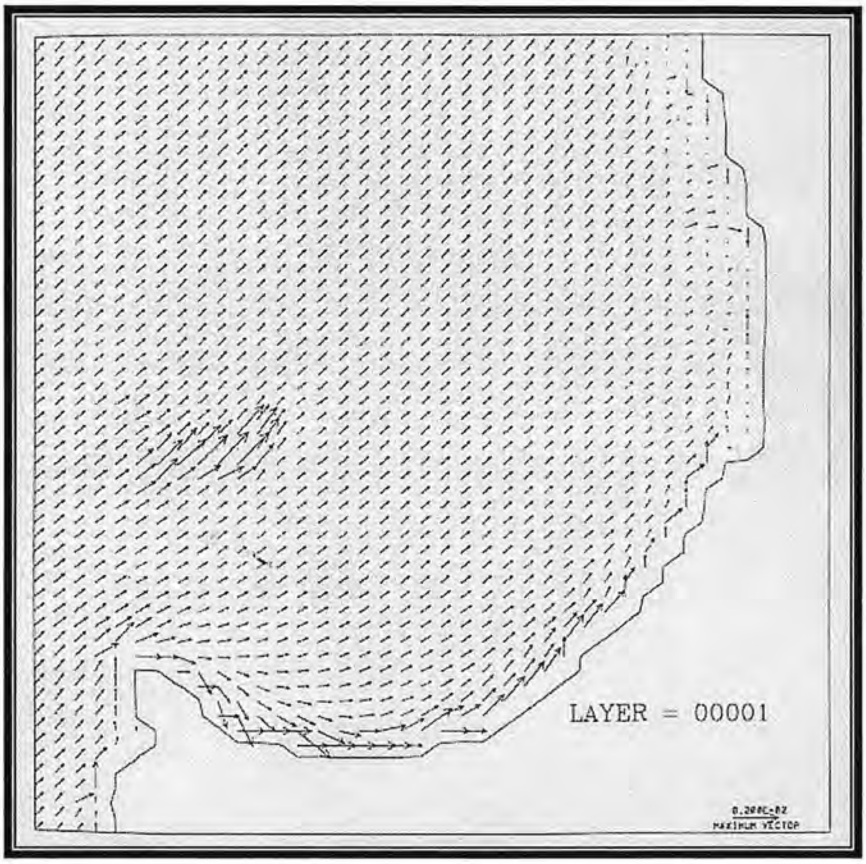
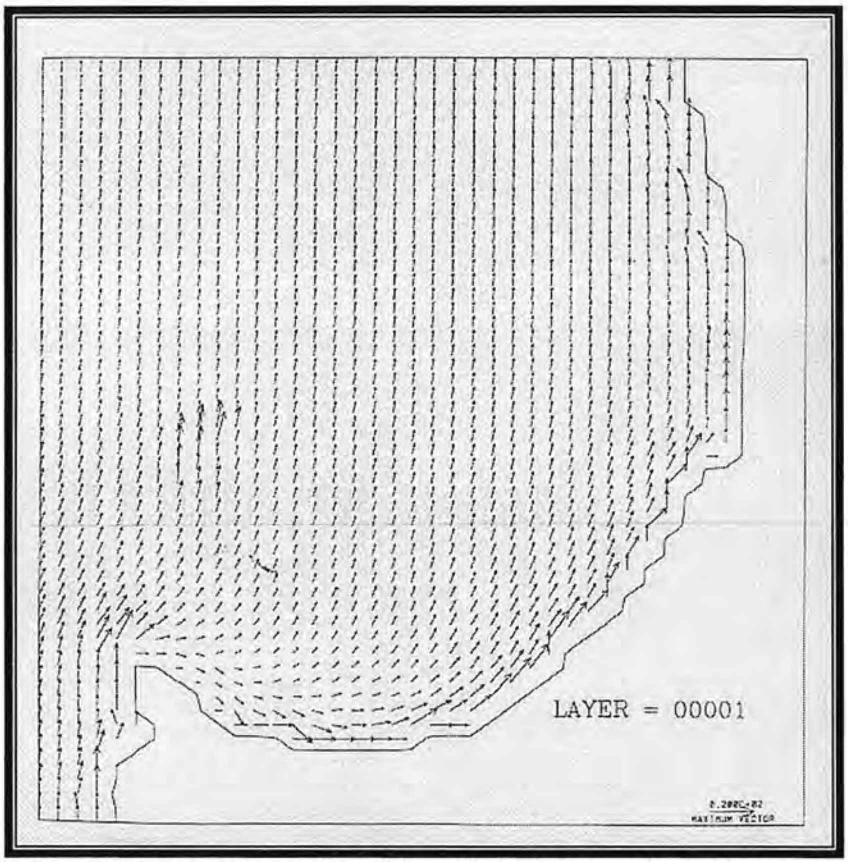


Figure 2: Annual surface temperature cycles at 3 sites extracted from NOAA/AVHRR satellite images for 1998: (A) just west of Cape Naturaliste (Capes Current region), (B) further west in the warmest part of the Leeuwin Current, and (C) In the shallow water at the southernmost limit of Geographe Bay.

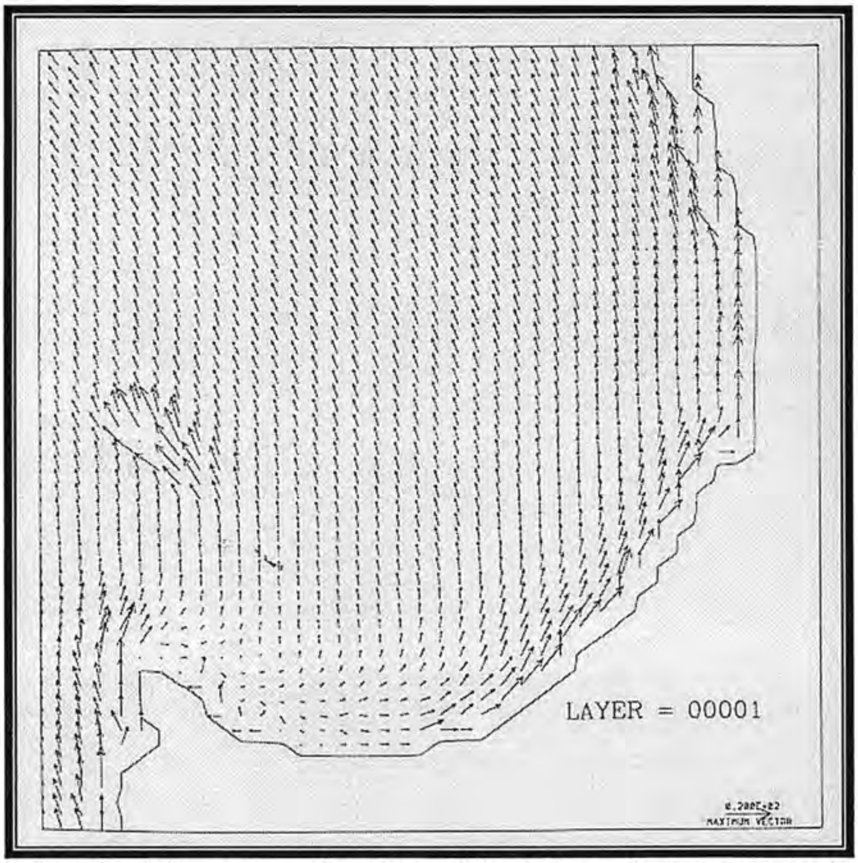
APPENDIX 4. SAMPLE HYDRODYNAMIC MODEL OUTPUTS FOR WIND-DRIVEN FLOWS IN GEOGRAPHE BAY (REPRODUCED FROM FAHRNER AND PATTIARATCHI, 1994)



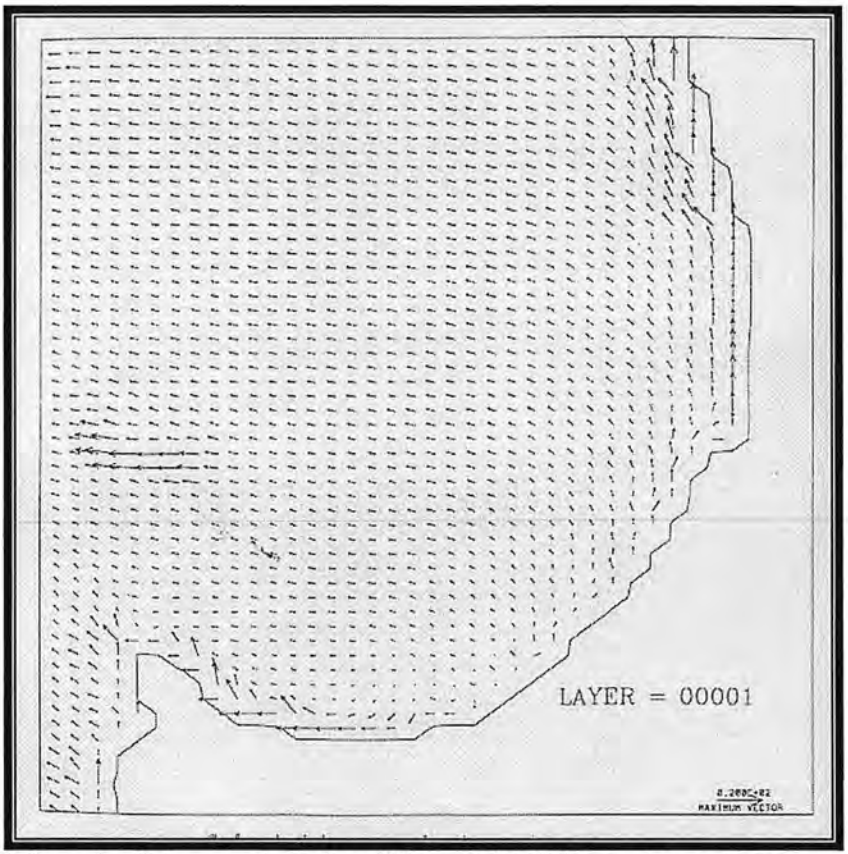
Surface circulation patterns after 48 hrs of simulation under a constant westerly wind of 7.0 m.s^{-1}.



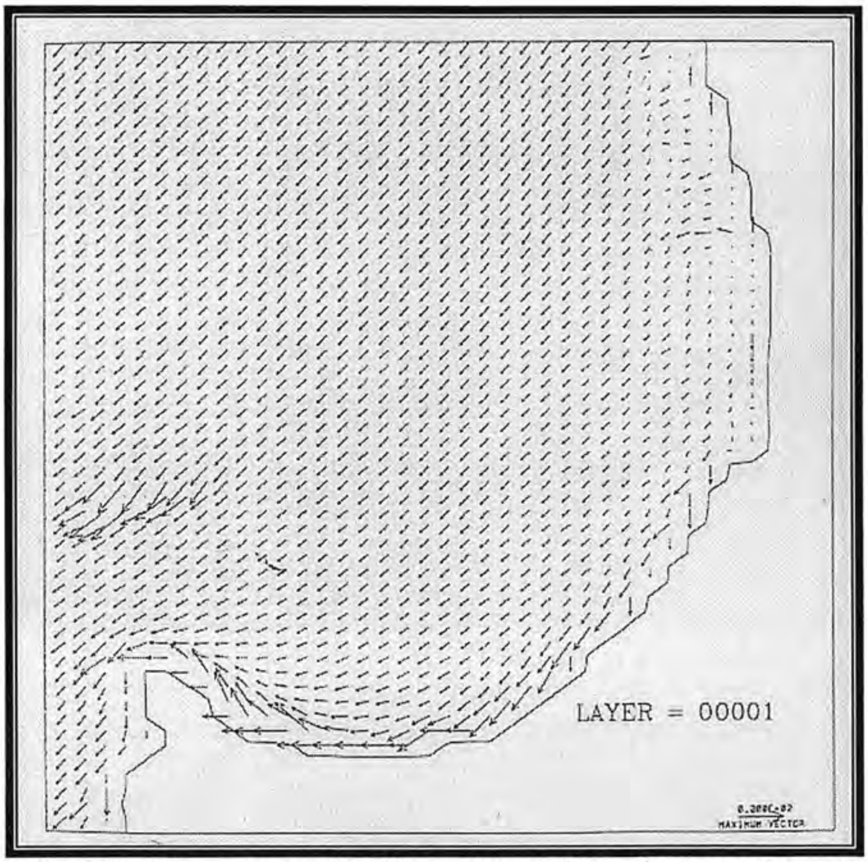
Surface circulation patterns after 48 hrs of simulation under a constant south-westerly wind of 7.0 m.s^{-1}.



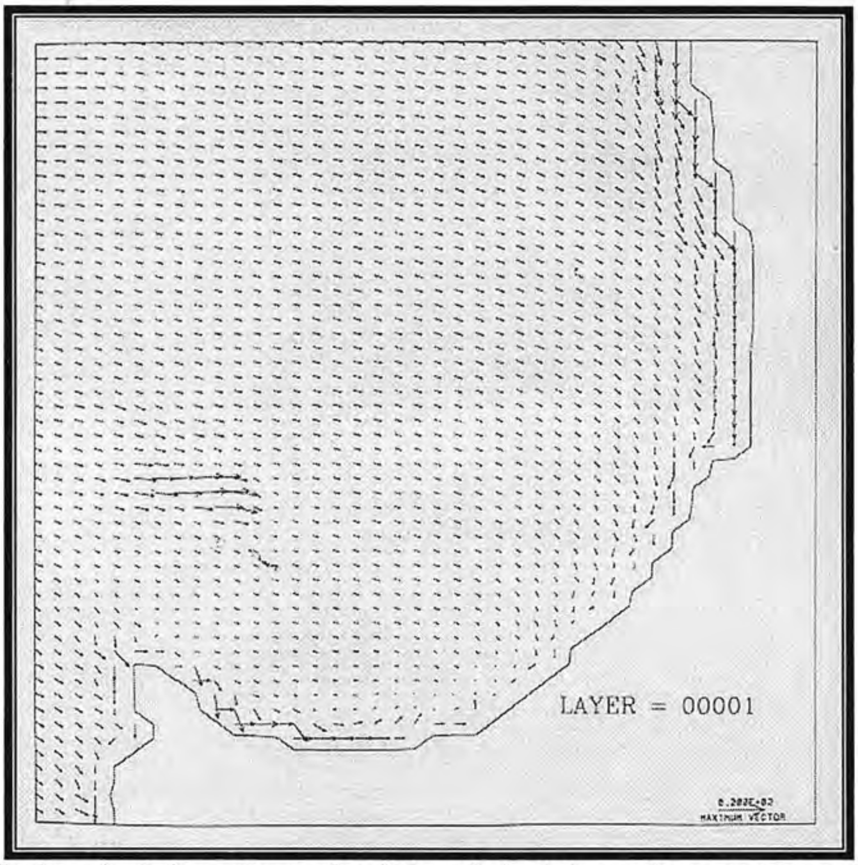
Surface circulation patterns after 48 hrs of simulation under a constant southerly wind of 7.0 m.s^{-1}.



Surface circulation patterns after 48 hrs of simulation under a constant south-easterly wind of 7.0 m.s^{-1}.



Surface circulation patterns after 48 hrs of simulation under a constant easterly wind of 7.0 m.s^{-1}.



Surface circulation patterns after 48 hrs of simulation under a constant north-westerly wind of 7.0 m.s^{-1}.