THE CLIMATE AND PHYSICAL OCEANOGRAPHY OF THE RECHERCHÉ ARCHIPELAGO AND ADJACENT WATERS

JONATHAN VAN HAZEL

This thesis is submitted in partial fulfilment for the degree of Bachelor of Engineering from the Department of Environmental Engineering, at the University of the Western Australia

October 2001
ACKNOWLEDGEMENTS

The completion of this thesis would not have been possible without the contributions and assistance of many individuals. I would like to express my sincere gratitude to the following people:

- Associate Professor Charitha Pattiaratchi for his expertise, guidance, and encouragement
- Greg Ivey for creating a new (but interesting) challenge in the final week before completion
- Nick D’Adamo for his assistance and information, particularly in the early stages of this project
- Mun Woo and Michael Meuleners for their assistance with the data analysis
- Drew Byrne for his work with the bathymetry
- My parents for their boundless support over the years
- The final year group at CWR for providing more than a few laughs throughout the year
EXECUTIVE SUMMARY

The Recherché Archipelago is located on the South Coast of Western Australia surrounding Esperance. It includes the State waters stretching from Margaret Cove, west of Stokes Inlet to Gegelup Point, east of Israelite Bay. The Archipelago contains over 150 islands and stretches well over 200km, with many of the islands lying beyond the 3 nautical mile coastal water boundary that defines the State’s territorial waters limit. The Archipelago attracts a steady flow of tourists to the region, and supports a healthy commercial and recreational fisheries industry.

In June 1994 the Marine Parks and Reserves Selection Working Group released a report identifying over seventy candidate areas around Western Australia worthy of reservation for conservation, scientific, or public recreational purposes. In recognition of the current and projected pressures on the Recherché Archipelago’s rich and diverse ecological and social values, the Marine Parks and Reserves Authority (MPRA) highlighted the Recherché region as one which it considers should receive high priority for investigation as a possible marine conservation reserve.

The State Government’s strategy for marine conservation requires extensive assessment, community consultation and management planning before a new marine conservation reserve is established. Accordingly, this study provides a significant contribution to furthering the understanding of the broad-scale oceanography and, in turn, provides insight into physical factors that may have an influence on the biology.

Meteorological, Water Level, and Sea Surface Temperature data have been analysed and discussed. Images from the SeaWiFS and CZCS satellites as well as ADCP, CTD, hydrology data, collected by a CSIRO voyage has also been used to corroborate the findings. The data has been further supported with the use of a three-dimensional numerical model (HAMSON). This research will provide a platform from which to plan more detailed investigations of the oceanography, as may be relevant to the possible establishment of a marine conservation reserve in the future.
List of Figures vi
List of Tables vii

1 INTRODUCTION 1

1.1 Objective 1

1.2 Study Boundary 3

2 LITERATURE REVIEW 4

2.1 Physical Setting 4
   2.1.1 Bathymetry and Large-scale coastal geomorphology 4
   2.1.2 Climate 4
   2.1.3 Wind Regime 7
   2.1.4 Rainfall 11
   2.1.5 Temperature 11
   2.1.6 Freshwater Inflows 12
   2.1.7 Ocean Currents 13
   2.1.8 Upwelling 13

2.2 Water Level Fluctuations 17
   2.2.1 Surface Gravity Waves 17
   2.2.2 Seiches 23
   2.2.3 Astronomic Tides 23
   2.2.4 Non-tidal Changes 26
   2.2.5 Annual/inter-annual variations 29

3 METHODOLOGY 31

3.1 Numerical Modelling 31
   3.1.1 Governing Equations 31
   3.1.2 The Hamburg Shelf Ocean Model (HANSOM) 32
   3.1.3 Simulations 33
   3.1.4 Island Wakes and Headland Eddies 34
   3.1.5 Bathymetry 35

4 RESULTS 36

4.1 Physical Oceanography 36
   4.1.1 Seasonal changes in Salinity/Temperature 36
   4.1.2 Chlorophyll / Phytoplankton Levels 38
   4.1.3 Circulation patterns 41
   4.1.4 Island Eddies 43

4.2 Franklin Voyage 94/07 44
   4.2.1 ADCP 45
   4.2.2 Temperature, Salinity, and Fluorescence 50
   4.2.3 Nitrate and Phosphorous Levels 55
List of Figures

Figure 1.1 – Proposed Representative Marine Reserve System for Western Australia
Figure 1.2 – Archipelago of the Recherché
Figure 2.1 – Basic Summer Pressure Distribution and Wind Direction
Figure 2.2 – Basic Winter Pressure Distribution and Wind Direction
Figure 2.3 – Percentage Frequency and Wind Strength (1995)
Figure 2.4 – Percentage Frequency and Wind Strength (2000)
Figure 2.5 – Monthly Rainfall Data for Esperance
Figure 2.6 – Monthly Temperature Data for Esperance
Figure 2.7 – Schematic of the upwelling scenario off the southwest coast
Figure 2.8 – Spectral plot of Esperance tidal data
Figure 2.9 – Percentage Occurrence Histogram
Figure 2.10 – Exceedence Curve
Figure 2.11 – Seasonal Percentage Occurrence Histogram
Figure 2.12 – Refraction/Diffraction of Waves approaching from 240°
Figure 2.13 – Predicted Tidal Data for January 1991
Figure 2.14 – Residuals plots for five WA tidal stations
Figure 2.15 – Residual Plots of three tidal stations showing evidence of Continental Shelf Waves
Figure 2.16 – Esperance tidal data showing evidence of Storm Surge
Figure 2.17 – Intra-annual Mean Monthly Sea Level 1991
Figure 2.18 – Inter-annual Mean Monthly Sea Level (1966-1996)
Figure 3.1 – Digitised Bathymetry of the Recherché Archipelago
Figure 4.1 – Intra-annual Sea Surface Temperature variation
Figure 4.2 – Intra-annual Salinity variation
Figure 4.3 – SeaWiFS - Chlorophyll concentration levels and distance offshore
Figure 4.4 – CZCS - Phytoplankton concentration levels and distance offshore
Figure 4.5 – The bathymetry of the Recherché and the major currents of the region (Summer)
Figure 4.6 – The bathymetry of the Recherché and the major currents of the region (Winter)
Figure 4.7 – Franklin Voyage 9407
Figure 4.8 – Surface Currents in the Recherché region
Figure 4.9 – Current Profile for Transect 1 (u-velocity)
Figure 4.10 – Current Profile for Transect 2 (u-velocity)
Figure 4.11 – Current Profile for Transect 3 (u-velocity)
Figure 4.12 – Current Profile for Transect 4 (u-velocity)
Figure 4.13 – Transect 1 – Temperature, Salinity and Fluorescence
Figure 4.14 – Transect 2 – Temperature, Salinity and Fluorescence
Figure 4.15 – CTD Station Locations
Figure 4.16 – TS Plot – Stations 79, 80, 81, 82, 83
Figure 4.17 – TS Plot – Stations 84, 85, 86, 87, 88
Figure 4.18 – TS Plot – Stations 90, 91, 92
Figure 4.19 – TS Plot – Stations 98, 99, 100
Figure 4.20 – Nitrate Levels and the Temperature Profile for Transects 1 & 2
Figure 4.21 – Phosphorous Levels and the Temperature Profile for Transects 1 & 2
Figure 4.22 – Northerly Wind Simulation
Figure 4.23 – Southerly Wind Simulation
Figure 4.24 – Easterly Wind Simulation
Figure 4.25 – Westerly Wind Simulation
Figure 4.26 – Summer Particle Tracking Simulation
Figure 4.27 – Winter Particle Tracking Simulation
Figure 4.28 – Transient Depths for Summer 2000
List of Tables

Table 2.1 – Average Tidal Constituents of the World
Table 2.2 – Tidal Constituent Data for Esperance
Table 3.1 – Characteristics of a wake formed behind an Island, for various values of the Island
  Wake Parameter, P
Table 4.1 – Predicted wake characteristics and the contributing variables of a range of islands in the
  Recherché Archipelago
Table 4.2 – Propagation of Upwelling front with Time
1 INTRODUCTION

In 1986, in recognition of the need to conserve the State’s biodiversity, the Minister for the Environment established the Marine Parks and Reserves Selection Working Group to identify representative and unique areas, worthy of reservation for conservation, scientific, or public recreational purposes. The report was released in June 1994 and identified over seventy candidate areas around Western Australia (CALM, 1994) (Figure 1.1).

Marine conservation reserves are vested in the Marine Parks and Reserves Authority (MPRA). The MPRA has prioritised the various areas that are under consideration to be established as marine conservation reserves. The Recherché Archipelago was identified by the MPRA as one area that should be considered for investigation as a high priority, following the current set of areas currently under formal planning.

The State Government’s strategy for marine conservation, as outlined in New Horizons – The way ahead in marine conservation and management, indicates a requirement for:

“Extensive assessment, community consultation and management planning before a new marine conservation reserve is established”

In view of the priority that has been assigned to this region, an application was made by CALM to Environment Australia to fund biological and oceanographic studies of the region. That application was successful and a component of those funds received have been used to support this review.

1.1 Objective

The objective of this thesis is to provide an overview of the climate and oceanography of the South Coast of Western Australia, focusing on the Recherché Archipelago and neighbouring Stokes Inlet.
1.2 Study Boundary

The study area for this survey includes the WA State waters surrounding Esperance, stretching from Margaret Cove, west of Stokes Inlet to Gegelup Point, east of Israelite Bay (Figure 1.2). The Archipelago contains over 150 islands and stretches well over 200km, with many of the islands lying beyond the 3 nautical mile coastal water boundary that defines the State’s territorial waters limit. However, because the islands are State territory, they each have their own shore lines surrounded by State territorial waters, again defined by the 3 nautical mile offshore limit. In combination, the territorial waters surrounding the Archipelago’s islands effectively extend Western Australia’s territorial waters off the south coast to over 25nm offshore in some areas in the Recherché Archipelago.
2 LITERATURE REVIEW

2.1 Physical Setting

2.1.1 Bathymetry and Large-scale coastal geomorphology
Numerous islands dominate the bathymetry of the region and a relatively narrow (40-80km) continental shelf with depth contours generally parallel to the coastline. The depth of the sea floor within the archipelago averages about 50m. Most of the islands are within the 50m bathymetric contour although some of the outer islands rise from depths of 70m or more. Beyond the continental shelf the depths increase rapidly to 4000m.

The continental shelf along this section of the coast is relatively narrow. In some places it is only 35km from the shore. The islands off the headlands represent the high points of the Albany-Frazer Oregon, now flooded by the ocean

In form and character the islands resemble the granitic headlands of the mainland coast. The rocky shores fall steeply in to the ocean till they reach the sandy floor where the substrate changes abruptly (CALM, 1994).

2.1.2 Climate
The climate of southwest Australia is typically Mediterranean with hot dry summers and cool wet winters. The major controlling factor of these seasons is the north-south migration of the 'subtropical baric ridge' that is formed by high-pressure cells moving west to east across Australia. During summer the ridge at it's southernmost, bringing hot dry weather to the south. During winter the belt lies at its northernmost allowing rain-bearing depressions to move eastwards across the south of the state (Figure 2.1). The counter-clockwise direction of the winds around the high pressure systems means that Esperance witnesses a reversal in wind direction from summer to winter as the baric ridge moves north (Figure 2.2).
Figure 2.1(a): Typical Summer pressure distribution over Australia. Note the presence of the high in the Great Australian Bight.

Figure 2.1(b): Typical Summer wind pattern over Australia. The prevailing winds are easterly over the Recherché.
Figure 2.2(a): Typical Winter pressure distribution over Australia. Note the baric ridge has moved north.

Figure 2.2(b): Typical Winter wind pattern over Australia. The prevailing winds are now more westerly over the Recherché.
2.1.3 Wind Regime

Two years (1995 and 2000) of wind speed and direction data collected by the Bureau of Meteorology at hourly (1995) and half-hourly (2000) intervals was analysed as part of this study. For both years, the annual wind roses (Figure 2.3 and 2.4) indicate that the majority of winds come from the northwest and southeast quadrants. In 1995 the highest occurrences of winds are easterly and the strongest winds are from the north and west (Figure 2.3). In 2000, the winds were strongest and most frequent from the northwest (Figure 2.4). However, the data for the year 2000 is missing the majority of December, creating a skewed frequency in favour of the northeast (winter) winds. For both years, the highest recorded wind speed (averaged over 1 hour) was 17.5 ms$^{-1}$.

The seasonality in the wind direction is shown by the seasonal wind roses (Figure 2.3 and 2.4). Comparing the winter and summer wind regime illustrates the effect of the previously mentioned sub-tropical baric ridge. During summer the baric ridge is at its southern most. The counterclockwise circulation of the winds around the high creates winds from the east and southeast for the majority of summer. When the baric ridge move north in winter, it passes over Esperance, reversing the wind direction. Therefore, the winter winds are predominantly from the northwest quadrant of the compass.

In an effort to understand whether a typical sea-breeze set-up occurred around Esperance each season was broken down into 2-hour intervals to analyse the daily wind regime. The wind roses for each interval are shown in Appendix A and the daily patterns for each season are outlined below.

During summer (December-February) the winds are predominantly from the east and southeast direction. These winds are relatively strong for the year, rivalling the strength of the winter winds. The figures in Appendix A indicate the strongest winds are in the evening from the east (17ms$^{-1}$). They tend to weaken overnight, before swinging southeast in the morning. During the day the southeasterly winds strengthen before turning east again in the evening.

The autumn winds (March-May) maintain the east and southeast component but an increase in the north and northwest winds can be identified. This change in direction is likely due to the movement of the baric ridge as it passes over Esperance. They are generally weak except for some evidence of strong northerly winds in 2000. Appendix A shows evidence that a typical sea breeze system is in place. During the morning the winds are predominantly land breezes from the north. As the land heats during the day the winds shift to the southeast, before a quiet period as the land cools overnight.
Winter winds (June-August) dominate the northwest quadrant and are the strongest of the year. Throughout winter the winds seem equally likely from all directions in the northwest quadrant. The 2hr intervals in Appendix A show the winds are strongest in the morning before weakening into the afternoon. Perhaps this is due to less solar heating of the land than during autumn, preventing the typical sea breeze set-up. The weakening of the north and east winds may be result of a sea breeze trying to establish itself but not having the strength to overcome the winds from the north.

During spring (September-November) the winds are generally weaker and there appears to be no dominant direction. A similar sea breeze / land breeze system to the autumn system is seen but it is less sharply defined. Like autumn north and northeast winds are seen in the morning and the southeast winds in the afternoon.
Figure: 2.3: Percentage frequency of wind occurrence and wind strength (1995)

Annual 1995

Summer 1995

Autumn 1995

Winter 1995

Spring 1995
Figure: 2.4: Percentage frequency of wind occurrence and wind strength (2000)
2.1.4 Rainfall
The rainfall in the Recherché region is that of a typical temperate climate. The relatively dry summers experience an average monthly rainfall of around 20mm and have approximately 5 raindays per month. At the peak of winter in July, the average monthly rainfall almost exceeds 100mm and the number of raindays is around 17 for the month (Figure 2.5).

![Figure 2.5: Monthly Rainfall Data for Esperance](image)

2.1.5 Temperature
The temperature variation in the Recherché is shown in Figure 2.6. The graph indicates that the average summer range is from 27°C to 15°C and the winter ranges from around 17°C to 8°C. The graph also shows the maximum and minimum temperatures recorded and it is interesting to note the range that has been experienced. At some stage Esperance has recorded a blistering 47°C day and has been as low as 2°C.
2.1.6 Freshwater Inflows

Stokes Inlet, which is situated 100 km to the west of the easternmost island of the Recherché Archipelago, is the only significant source of freshwater inflows to the archipelago region. However, the sand bar at the mouth is closed most of the time rendering the inlet fairly ineffectual as an inflow source. Hodgkin and Clark (1989) have researched the ecology of Stokes Inlet in more detail, and found that the inlet had only been reported open six times between 1968 and 1989.

When the Inlet does open, the resulting outflow into the ocean is generally hyper-saline. The salinity of the Inlet is rarely less than 35ppt during the year. Little stratification is present in the Inlet as a result of wind mixing.

The temperature range is slightly greater than the ocean, reaching a high of approximately 25°C in summer and a low of about 12°C in winter.
2.1.7 Ocean Currents

The major current that has been shown to be present in the Recherché Archipelago region is the Leeuwin Current. The Leeuwin Current is driven by an alongshore steric height gradient, which overwhelms the opposing equatorward wind stress. Leeuwin Current water is sourced from the Indian Ocean in the west and Pacific Ocean above the Northwest continental shelf. The South East Trade Winds, in the Pacific Ocean, drive the South Equatorial Current westwards advecting warm surface water towards Indonesian (Pattiaratchi & Buchan, 1991). This results in the flow of warm, low salinity water from the Indonesian Archipelago into the tropical regions of the Indian Ocean. Combined with the geostrophic inflow of water from the Indian Ocean this results in an increase in the sea level in the tropics of some 55cm compared with that along the southern coast of Western Australia (Pattiaratchi & Buchan, 1991). The Leeuwin Current is present year round but is stronger during the winter months. This is discussed further in relation to the Recherché region in section 2.2.5 Annual / Inter-Annual Variations.

A second current of interest, the Capes Current, which exists off the west coast of Western Australia is of particular interest to this thesis because it will be proposed that a similar current could be set up in the Recherché region. The Capes Current originates between Cape Leeuwin and Cape Naturaliste and is driven by persistent southerly winds in the region. It travels north along the continental shelf, transporting cold water from the Southern Sea. The Capes Current runs closer to the coast than the Leeuwin Current and the two interact as they flow past each other in opposite directions (Wearne, 2000). The important component of the Capes Current with respect to the Recherché region is the persistent alongshore winds that drive the Capes Current. This will be discussed further at a later stage.

2.1.8 Upwelling

The possible establishment of the nearshore counter-current raises the question of upwelling in the Recherché region. In a similar manner to the Capes Current once formed, the nearshore counter-current could induce surface waters to move offshore under the influence of the Coriolis Force. This would allow colder water to upwell onto the continental shelf and force the Leeuwin Current to migrate offshore (Gersbach, 2000). The figure below illustrates the upwelling scenario for the south-western coast, which experiences similar forcing to the Recherché region.
Upwelling has particular importance to the biology in the region as the colder waters imported are higher in nutrient value and can act as catalysts for increased production. The existing Abalone, Rock Lobster, Pilchard and Abalone fisheries undoubtedly have an interest in furthering understanding of the processes that support the food chain.

Two numerical methods to determine the likelihood of upwelling occurring are outlined below. The first calculates the transition depth $H^*$, which is the depth at which surface driven currents cease to be able to overcome the steric gradient in the opposite direction. In shallow water, the depth integrated geopotential gradient is small compared to the magnitudes of the wind and bottom stress, so the depth averaged flow is in the direction of the wind (Gersbach, 2000). As depth increases, the geopotential gradient becomes increasingly important until it balances the opposing windstress, resulting in zero depth averaged velocity. The equation to calculate $H^*$ is shown below.

$$H^* = \frac{u^*}{\frac{f_P}{f} \sqrt{\frac{\rho}{\gamma}}}$$  \hspace{1cm} (2.1)

If $H^*$ is greater than the mixed layer depth the upwelling will occur. Conversely, if the mixed layer depth is unknown, the larger $H^*$ is, the more likely it is greater than the mixed layer depth.
The second method calculates the Upwelling Index, which is a unit volume flux of the water transported offshore for a given wind speed. This method scales with the wind speed in the same manner as the transition depth calculation shown above, but can be useful if quantification of the volume transported is required.

\[
q = \frac{\Gamma}{\rho f} \tag{2.2}
\]

A further numerical method to quantify the effect of upwelling involves calculating the movement of the upwelling ‘front’. In reality, no sharply defined front actually exists, so measuring the propagation of ‘fronts’ is an inexact process. Winters, Coates, Ivey, and Sturman (2001) have used laboratory and numerical methods to refine a set of equations that can be used to predict the progress of an upwelling front given a few physical parameters. The models have been tested against the conditions experienced in some well-researched upwelling regions and the results have corroborated the models. Two equations are defined for predicting the frontal position, one for wind stirring alone and another for penetrative convection alone. For wind stirring the front is defined as

\[
l = c_1 \frac{u_*^3}{N^2 \alpha} \sqrt{\frac{t}{\tau}} \tag{2.3}
\]

Where \( u_* \) is the friction velocity, \( N \) is the buoyancy frequency, \( \alpha \) is the bottom slope and \( c_1 \) is a constant (for this case assumed to be 0.75). The prediction for frontal position due to penetrative convection alone is defined as

\[
l = c_2 \frac{u_*^2}{f \alpha} \sqrt{\frac{t}{\tau}} \tag{2.4}
\]

Where \( f \) is the Coriolis Force and \( c_2 \) is a second constant (assumed for this case to be 0.80). These two equations provide independent estimates of the frontal position, \( l \), for a given time \( t \). The point at which the two equations meet is denoted by \( t_t \).

\[
t_t = \frac{c_1^6}{c_2^3} \frac{f^3}{N^4 \alpha^3} \sqrt{\frac{\tau}{t}} \tag{2.5}
\]
For times \( t < t_1 \), wind stirring will dominate and the frontal width will be given by (2.2). For \( t > t_1 \), convection will dominate and the frontal position is given by (2.3).
2.2 Water Level Fluctuations

Water level fluctuations are a combination of several factors, some random, others more deterministic. A spectral plot of the water level data is shown in Figure 2.7. This data was collected from the Esperance Harbour in 1991. Some of the various contributing components are noted on the figure and are discussed in more detail below. The relative importance of each of the components can also be seen on the spectral plot. Clearly the diurnal astronomic tide component is the most important, but the semi-diurnal astronomic tide component and the long period component seem to be of relatively similar strength. Interestingly, a seiche seems to be present at a frequency of about 7 cycles per day (period of 3.4 hours).

2.2.1 Surface Gravity Waves

Surface gravity waves are a combination of swell developed in the Southern Oceans and locally generated wind waves. Raw data collected between 13/12/82 and 20/12/83 was analysed using spectral methods by WNI Science and Engineering. The resulting time series was then analysed by Pattiaratchi (1998).

Maximum significant wave heights of up to 4.5m were associated with storm events. Storms occurred most frequently from autumn (mid April) and continued into spring. Storm frequency is about 8-10 day$^{-1}$ reducing to about 5 day$^{-1}$ during winter. Relatively high waves are experienced for about 1-2 days during a storm event (Pattiaratchi, 1998).

Time series show the mean swell wave period to be around 8sec with a maximum mean period of around 10sec. The sea wave component has a mean of about 4sec and a maximum period of about 5sec.

A percentage occurrence histogram of Significant Wave Height at Magistrate Rock shows 1m waves have the highest occurrence (Figure 2.8). The exceedence curve shows that 50% of waves are larger than 1.45m and 20% are larger than 2m (Figure 2.9). Seasonal percentage occurrence histograms show that the highest waves occur in autumn and spring but the mean height is largest during winter (Figure 2.10).

The refraction/diffraction patterns for waves approaching the Bay from an angle of 240° are shown in Figure 2.11. This is the most dominant direction of wave approach.
Significant Wave heights of 0.65 m and peak periods of 3.3 s were found for typical winter storm events with locally generated winds for duration of 48hrs and mean wind speeds of 10 ms$^{-1}$ from the north-northeast in a mean water depth of 35m (Pattiaratchi, 1998).

**Figure 2.8: Spectral plot of Esperance tidal data**

Spectral plot of Esperance tidal data 1991

- **Diurnal**
- **Semi-Diurnal**
- **Seiche**
- **Long Period**

Cycles per day

Cycles per day
Figure 2.9 and 2.10: Percentage Occurrence Histogram and Exceedence Curve (1982-1983)

Magistrate Rock: Observed Data
Figure 2.11: Seasonal Percentage Occurrence Histogram (1982-1983)

Magistrate Rock: Observed Data
Figure 2.12: Refraction/Diffraction pattern of waves approaching from direction 240° C
(Note: the figure needs to be rotated 60° in a clockwise direction)
2.2.2 Seiches
Enclosed or semi-enclosed bodies of water can be prompted into resonant motions, or seiches, at a set of natural periods of oscillation. The period of these motions is dependent on the depth and horizontal dimensions of the water body. Once established the seiche may last for several hours. For semi-enclosed water bodies, the seiche can be considered as a standing wave with no vertical motion at the open end (node) and maximum vertical motion at the other end (anti-node). The Bay of Esperance where this data is collected from is an example of such a semi-enclosed water body.

The spectral plot in Figure 2.7 confirms the existence of a seiche. Instead of tapering away after the diurnal and semi-diurnal peaks like a normal series of harmonics, the spectrum shows a power peak at seven cycles per day. This peak suggests that the seiche has a period around 3.4 hrs. Given the limitation of the data currently available it is not possible to fully understand the motion of this seiche.

2.2.3 Astronomic Tides
Tides forced by the combined gravitational and centrifugal forces of the earth-moon and earth-sun systems are termed astronomic tides. These tides are highly predictable because of the deterministic nature of the force exerted by the sun and the moon. The observed tide is the sum of a number of partial tides, each whose period corresponds with the period of the astronomical motion responsible for the forcing. Although over 100 of these tidal constituents exist, there are several that dominate. These are shown in Table 2.1. The predicted tidal data for Esperance is shown in Figure 2.12.

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Name</th>
<th>Period (hours)</th>
<th>Relative Magnitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semidiurnal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>M₂</td>
<td>Principal lunar</td>
<td>12.42</td>
<td>100</td>
</tr>
<tr>
<td>S₂</td>
<td>Principal solar</td>
<td>12.00</td>
<td>47</td>
</tr>
<tr>
<td>N₂</td>
<td>Lunar elliptic</td>
<td>12.66</td>
<td>19</td>
</tr>
<tr>
<td>K₂</td>
<td>Luni-solar semidiurnal</td>
<td>11.97</td>
<td>13</td>
</tr>
<tr>
<td>Diurnal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>K₁</td>
<td>Soli-lunar</td>
<td>23.93</td>
<td>58</td>
</tr>
<tr>
<td>O₁</td>
<td>Principal lunar</td>
<td>25.82</td>
<td>42</td>
</tr>
<tr>
<td>P₁</td>
<td>Principal solar</td>
<td>24.07</td>
<td>19</td>
</tr>
<tr>
<td>Q₁</td>
<td>Lunar elliptic</td>
<td>26.87</td>
<td>8</td>
</tr>
<tr>
<td>Long Period</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mₗ</td>
<td>Lunar fortnightly</td>
<td>327.8</td>
<td>17</td>
</tr>
<tr>
<td>Mₘ</td>
<td>Lunar monthly</td>
<td>661.3</td>
<td>9</td>
</tr>
<tr>
<td>Sₙₐ</td>
<td>Solar semiannual</td>
<td>4383.3</td>
<td>8</td>
</tr>
</tbody>
</table>
Tidal oscillations consist of a line spectrum of numerous semidiurnal, diurnal and long period constituents (Wright, 1995). The most pronounced is the semidiurnal moon constituent, $M_2$. The relative importance, to $M_2$, of the various tidal constituents is shown in Table 2.2. To determine the relative importance of the diurnal and semidiurnal constituents the form factor, $F$, is used:

$$F = \frac{H_{K_1} + H_{O_1}}{H_{M_2} + H_{S_2}}$$

(2.6)

Where $H_n$ is defined as the amplitude of the tidal constituent $n$.

<table>
<thead>
<tr>
<th>Name</th>
<th>H (amplitude, cm)</th>
<th>G(phase)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Semidiurnal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$M_2$ Principle Lunar</td>
<td>0.103</td>
<td>320.1</td>
</tr>
<tr>
<td>$S_2$ Principle Solar</td>
<td>0.133</td>
<td>335.6</td>
</tr>
<tr>
<td><strong>Diurnal</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$K_1$ Luni-solar diurnal</td>
<td>0.179</td>
<td>336.4</td>
</tr>
<tr>
<td>$O_1$ Principle lunar diurnal</td>
<td>0.133</td>
<td>314.2</td>
</tr>
</tbody>
</table>

$F = 1.322$

The form factor is interpreted as:

- $F = 0.25$ to $1.5$ Mixed, mainly semi-diurnal tides.
- $F = 1.5$ to $3.0$ Mixed, mainly diurnal tides.

According to the form factor, the tidal character of Esperance is mixed but mainly semi-diurnal. This is inconsistent with the initial findings of the report. The reason for this inconsistency lies in the arbitrary definition of the form factor’s transition from semi-diurnal to diurnal. The form factor boundary between diurnal and semi-diurnal is shown above to be 1.5. This value is not definitive. Because the Esperance tides have a form factor close to 1.5 only indicates that the tidal characteristics are highly mixed.

Figure 2.12 shows the typical tidal characteristics for the region. It is clear from this plot that the diurnal tides dominate. While the semi-diurnal peaks are clear (the smaller local peaks), they are of smaller magnitude than the diurnal peaks.
Figure 2.13: Predicted Tidal Data for January 1991

Water level height above datum
2.2.4 Non-tidal Changes

*Continental Shelf Waves*

The existence of long period waves with a period of about ten days is seen on the spectral plot (Figure 2.7). These most likely correspond to continental shelf waves that are formed by barotropic pressure changes at the air/sea interface far from the Esperance coast (Provis and Radok, 1979). Tropical cyclones generated along the north-west continental shelf off Western Australia are an example of such a pressure change. These cyclones can produce winds of up to 40ms\(^{-1}\) and generate long period waves that propagate due to the Coriolis Force. By looking at the residuals of five different tidal stations along the Western Australian coast, the propagation of continental shelf waves can be examined. Data for stations from Geraldton to Esperance shown in Figure 2.13 indicate that variations of up to 0.5m are possible. Travel times from Dampier to Fremantle are of the order of 5-6 days (Fahrner & Pattiaratchi, 1994). Figure 2.14 shows a month of data for three tidal stations, indicating the propagation of continental waves down the coast. Three peaks are highlighted in Figure 2.14, A, B, and C. Peak A is clearly in the middle of the 31\(^{st}\) of January, peak B is in between the 31\(^{st}\) of January and the 1\(^{st}\) of February, and peak C is in the middle of the 1\(^{st}\) of February. Clearly the sea-level anomaly is propagating around the coast.
Figure 2.14: Residual plots for five WA tidal stations 1991
Storm Surge

A storm surge is a meteorological tide with an abnormal rise of seawater and is mainly induced by strong winds (wind set-up) and abrupt atmospheric change (inverse barometric effect) (Horikawa, 1978). Changes in sea level generated by extreme meteorological events, such as winter storms and cyclones, may be positive or negative depending on whether the sea level is higher or lower than predicted. The effect of storm surge is most severe when these extreme meteorological events occur in conjunction with high tide. Figure 2.15 from the Transport Department of WA shows how storm surge can affect the water level in Esperance. From residual plots it has been shown that storm surge levels are regularly of the order of 50cm.
2.2.5 Annual/inter-annual variations

Annual Variations
The variation in the monthly mean sea level at Esperance has amplitude of up to 30 cm during the year of 1991 (Figure 2.16). It reaches a maximum during July, the middle of winter, and a minimum during the two summers (90/91 and 91/92) that are present in the data. This variation is consistent with the strong seasonality of the Leeuwin Current. The Leeuwin flows all year but is significantly stronger in the winter months and weaker during summer. Hence the sea level reaches a maximum over May-June and a minimum during December-January (Pattiaratchi and Buchan, 1991).

Inter-annual Variations
The variations in the average monthly sea level at Esperance from 1966 to 1996 are shown in Figure 2.17. The first six or seven years of sampling were corrupted by a datum shift and have been disregarded. Between 1974 and 1996, the average sea level fluctuates about 130mm. These fluctuations have a period of approximately 5 years. The cause of the inter-annual fluctuations is due mainly to the varying strength of the Leeuwin Current. The strength of the Leeuwin is in turn driven by more global forcing effects such as the El Nino/La Nina phenomenon.
Figure 2.17: Intra-annual Mean Monthly Sea Level 1991

Figure 2.18: Inter-annual Mean Monthly Sea Level
3 METHODOLOGY

The following section outlines the methodology used in this study. The theory behind the modelling and methods of analysis are briefly described.

3.1 Numerical Modelling

Three-dimensional numerical models are a useful tool for predicting hydrodynamic influences on coastal regions. They can incorporate water level gradients, wind regimes, bathymetry data and other measured parameters to accurately predict currents and circulation that can then be linked to biological, chemical and morphological processes that occur in marine systems. One such model is the Hamburg Shelf Ocean Model (HAMSOM). This model is based around a set of physical equations briefly described in section 3.1.1.

3.1.1 Governing Equations

Three-dimensional hydrodynamic modelling revolves around the equations governing conservation of mass, conservation of momentum, and conservation of the scalar variables, salinity and temperature.

Conservation of Mass

Assuming an incompressible fluid, the conservation of mass can be given by the continuity equation;

$$\frac{fu}{fx} + \frac{fv}{fy} + \frac{fw}{fz} = 0 \quad (3.1)$$

where u, v, and w are the velocity components in the x, y, and z directions respectively.

Conservation of Momentum

The Conservation of momentum can be applied in the x, y and z directions and is generally given by the Navier-Stokes equations,

In the x direction:

$$\frac{fu}{ft} + u \frac{fu}{fx} + v \frac{fu}{fy} + w \frac{fu}{fz} = -\frac{1}{\rho} \frac{fp}{fx} + \frac{f}{fx \parallel} f + \frac{fu}{fx} \nabla \nabla - A_{uu} \frac{fu}{fx} \nabla - A_{uy} \frac{fu}{fy} \nabla - A_{uz} \frac{fu}{fz} \nabla$$

$$\quad (3.2)$$
In the y direction:

\[
\frac{f_v u}{f} + \frac{f_v v}{f_y} + \frac{f_v w}{f_z} = -\frac{f P}{\rho} - \frac{f u}{f_y} - \frac{f v}{f_x} - \frac{f w}{f_y} + \frac{A_h}{f_x} \frac{f v}{f_y} + \frac{A_v}{f_y} \frac{f v}{f_z} + \frac{A_v}{f_y} \frac{f v}{f_z} \tag{3.3}
\]

where \(u(x,y,z,t), v(x,y,z,t), w(x,y,z,t), P(x,y,z,t)\) are the velocity components and the pressure fluctuations. \(A_h\) and \(A_v\) are the horizontal and vertical kinematic eddy viscosities that are applied at the upper boundary of the depth-range (layer). Under varying wind and stratification conditions it is assumed that \(A_v\) is a space and time dependent parameter (Backhaus, 1985).

The conservation of moment equation in the z direction reduces to the hydrostatic approximation by assuming that vertical inertia is small with respect to the gravitational force,

\[
\frac{f P}{f_z} = -\rho g \tag{3.4}
\]

### 3.1.2 The Hamburg Shelf Ocean Model (HANSOM)

The Hamburg Shelf Ocean Model (HAMSOM) is a three dimensional numerical model developed by Backhaus (1985). Non-linear, primitive, three-dimensional equations based on a semi-implicit numerical scheme described by Backhaus (1985) and Stronach et al (1993) provide the foundations for the model. Depth integration of the equations of motion is achieved by using fixed, permeable interfaces between individual layers. The model assumes incompressibility and hydrostatic equilibrium incorporating the Bousinesq approximation. At open boundaries, velocity, temperature, and salinity must be prescribed, and a zero flux condition is used at closed lateral boundaries. Kinematic boundary conditions are applied at the sea surface and non-linear quadratic stress terms are applied at the bottom.

The model domain is defined according to a grid of cells, having a longitudinal, a latitudinal and a Cartesian vertical co-ordinate. Each cell contains salinity, pressure and temperature at the centre, and the velocity components at the centre of the face, and thus vertical homogeneity within each model is assumed. The relevant equations for each layer are then depth averaged.

Tidal effects, wind stress, atmospheric forcings and external flows can be applied. Tidal forcing is applied through the specification of the amplitude and phase of up to 5 tidal constituents, namely the \(K_1, O_1, M_2, S_2,\) and \(N_2\). Wind forcing is defined by the calculation of the induced surface shear stress. The expression takes the quadratic form of the following.
\[
A_y \frac{f u}{f z} = \tau_{w, surface} \frac{\rho_{air}}{\rho_{water}} C_p U_{\text{wind}} \sqrt{U^2_{\text{wind}} + V^2_{\text{wind}}} \tag{3.5}
\]

Time stepping is achieved through the use of a centred Crank-Nicolson scheme, in order to avoid numerical damping. The time step in the model is calculated using the Courant Friedrichs Lewy (CFL) condition (3.6) and is often small as a consequence. The CFL condition governs the distance travelled by a surface gravity wave, impelling it to be less than the grid size used.

\[
\Delta t \leq \frac{L}{\sqrt{2gh_{\text{max}}}} \tag{3.6}
\]

Where, \( L = \) grid size
\( h_{\text{max}} = \) maximum depth

3.1.3 Simulations

Four different simulations were run initially to investigate the major currents that would be established under the different wind regimes. The northerly and easterly simulations were representative of winter conditions and the westerly and southerly simulations describe the summer regime.

A further two simulations were run using Lagrangian water particle tracking. The particle tracking model plots the path followed by differently positioned particles. HAMSOM contains such a particle plotting program and the outputs for the Recherché model are shown in section 4.3.
3.1.4 Island Wakes and Headland Eddies

The interaction between currents and surface and subsurface topographic features such as reef systems, islands and headlands generate complex three-dimensional secondary flows which significantly influence the distribution of biological material (Pattiaratchi, 1994). Laboratory experiments by Batchelor (1967), Gerrard (1978) and van Dyke (1982) have shown that two-dimensional flow past a plate may be parameterised by the Reynolds number, the ratio between the inertial to the frictional terms in the Navier-Stokes equation

\[ Re = \frac{UL}{n} \]  

(3.7)

Where \( U \) is the horizontal velocity, \( L \) is the cross-sectional length and \( n \) is the kinematic viscosity. Using field data collected from Rattray Island (NE Australia), Pattiaratchi, 1994, has shown that the wake structures observed in shallow coastal waters may be described using an island wake parameter, \( P \), where:

\[ P = \frac{UH^2}{K_zL} \]  

(3.8)

where \( U \) is the horizontal velocity of the current, \( H \) is the water depth, \( K_z \) is the vertical eddy viscosity coefficient and \( L \) is taken as the diameter of the island. Characteristic wake parameters and the predicted wake patterns are summarised in Table 3.1:

<table>
<thead>
<tr>
<th>Island Wake Parameter, ( P )</th>
<th>Wake Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;&lt; 1</td>
<td>Friction dominates; hence quasi-potential flow exists within the wake</td>
</tr>
<tr>
<td>= 0 (1)</td>
<td>Stable wake</td>
</tr>
<tr>
<td>&gt; 1</td>
<td>Instabilities occurs in the wake</td>
</tr>
<tr>
<td>&gt;&gt; 1</td>
<td>Friction is negligible; similar to that formed at high Reynolds numbers (\textit{i.e.} eddy shedding)</td>
</tr>
</tbody>
</table>
3.1.5 Bathymetry
The bathymetry of the region was developed using existing data obtained from the Admiralty Map. Unfortunately, only the bathymetry around the island had been surveyed and did not include any data within the islands. Using a plot of the WA coastline and MATLAB, the islands were overlaid on the existing data and digitised with the help of Drew Byrne from the Geography Department of the University of Western Australia. Using GIS Arc View and GIS Arc/INFO programs developed by Environmental Systems Research Institute Inc. (ESRI), the islands were combined with the existing data. The missing data was assumed to have a uniform depth of 50m although the slope to the shore and the islands was smoothed to obtain greater realism. A 3-D image of the bathymetry used in the modelling is shown in Figure 3.1.

Figure 3.1 Digitised Bathymetry of the Recherché Archipelago
4 RESULTS

4.1 Physical Oceanography

4.1.1 Seasonal changes in Salinity/Temperature
The seasonal variation in mean sea surface temperature (SST) and salinity are shown in Figures 4.1 and 4.2. These were approximated from data presented on the IRI/LDEO Climate Data Library website. The surface temperature reaches a maximum during March of approximately 20.8 °C and a minimum during September of 15.8 °C whilst the salinity range from a maximum of 36.10 psu during the summer to 35.65 psu during the winter.

The observed changes in salinity and temperature may be described as follows: due to increased solar heating, the SST’s increase from October reaching a maximum during March. In general, there is lag in the SST with the solar heating with maximum SST's occurring after the atmospheric temperature maxima. Here, it is also possible that southeasterly winds during the summer results in upwelling which will counter the solar heating. With the easing of the summer winds the sea surface temperatures can continue to climb into early autumn. Salinity is also higher during the summer months due to evaporation. During the winter months, the salinity decreases due to a stronger presence of the Leeuwin Current, advecting lower salinity water into the region. The Leeuwin Current also prevents extreme cooling of the shelf through advection of higher temperature water. Therefore the seasonal variation in temperature may not be as large as it would be without the effect of the Leeuwin. The variation in salinity is probably greater than it would be without the Leeuwin.

Some sea-surface temperature satellite imagery of the Southwest coast is shown in Appendix B, illustrating the effect and extent of the Leeuwin Current in the Recherché region. The data in Figure 4.1 shows that the water temperature varies seasonally so it is difficult to assess the effect that the warmer Leeuwin Current waters.
Figure 4.1: Intra-annual Temperature Variation

Figure 4.2: Intra-annual Salinity Variation
4.1.2 Chlorophyll / Phytoplankton Levels

Using satellite imagery of chlorophyll and phytoplankton levels in the near shore can be very useful in analysing the physical oceanography of a region. Subtle changes in ocean colour signify various types and quantities of marine chlorophyll and phytoplankton. The changes in chlorophyll and phytoplankton can therefore act as a tracer to help determine circulation patterns in the world's oceans.

The Recherché region can be viewed with two satellites, the Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project and the Coastal Zone Colour Scanner (CZCS). Both satellites are capable of achieving a sufficient level of resolution to distinguish the general current patterns but often have their views restricted by cloud cover. A selection of relatively good images for one particular year is displayed in Appendices C (SeaWiFS) and D (CZCS). The CZCS images are of higher quality than the SeaWiFS images but have fewer unobstructed images available.

Both sets of images show a seasonally varying band of higher concentration chlorophyll and phytoplankton close to shore. The concentration levels and the width of this band are shown in Figures 4.3 and 4.4. Due to the availability of more images the SeaWiFS curve is smoother than the CZCS satellite. The SeaWiFS images are ten years older than CZCS images and have a corresponding lower level of resolution. However, they both indicate annual peaks of concentration and bandwidth around April and yearly lows around November. These patterns are similar to those observed off the Western coast of WA and is attributed to the changes in nutrients and light climate. It is highly likely that in these clear oceanic waters a sub-surface chlorophyll maximum is present. Therefore the actual concentrations of chlorophyll through the water column is higher than those measured by the satellites, which only view the surface concentration. This helps to explain the chlorophyll high in April, which may be due to the upwelling favourably conditions created with the predominant easterly and southeasterly winds over summer.
Figure 4.3: Chlorophyll concentration levels and distance offshore

**SeaWiFS - chlorophyll concentration**

- **Concentration (mg/m³):**
  - 0.0
  - 0.2
  - 0.4
  - 0.6
  - 0.8
  - 1.0
  - 1.2

- **Month:**
  - 1
  - 2
  - 3
  - 4
  - 5
  - 6
  - 7
  - 8
  - 9
  - 10
  - 11
  - 12

**SeaWiFS - chlorophyll band width**

- **Distance offshore (km):**
  - 0
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60
  - 70
  - 80
  - 90
  - 100

- **Month:**
  - 1
  - 2
  - 3
  - 4
  - 5
  - 6
  - 7
  - 8
  - 9
  - 10
  - 11
  - 12
Figure 4.4: Phytoplankton concentration levels and distance offshore

CZCS - phytoplankton concentration levels

Concentration (mg/m^3)

Month

CZCS - phytoplankton band width

Distance offshore (km)

Month
4.1.3 Circulation patterns

The satellite imagery of the Recherché (Appendices C and D) indicates that the Leeuwin Current has a large influence on the circulation (and therefore physical characteristics) of the region. As mentioned above, the Leeuwin's seasonally varying strength has an influence on sea levels. It also causes a decrease in salinity during winter. The effect on chlorophyll and phytoplankton has also been mentioned, showing another close relationship with the Current. The effect of the Leeuwin on temperature was difficult to quantify from the data; however, the sea-surface temperature images do show that the Leeuwin imports warmer waters, especially during winter.

While the Leeuwin Current is visible in the satellite images, during the summer months there is some evidence of a counter-current that acts closer to shore. The satellite images are not very clear on this issue so some further examination is required. Whether this current acts in a similar way as the Capes Current (Pearce and Pattiaratchi, 1999) remains to be seen. The Capes Current is set up and is driven by persistent southerly winds (i.e. blowing parallel to the coast). The summer prevailing winds from the east and southeast certainly provides a similar alongshore forcing in the Recherché region, indicating that a similar along-shore current could be set up.

Figure 4.5 shows the possible summer counter-current acting during summer, while the Leeuwin dominates during winter (Figure 4.6). It is predicted the counter current would act in the same manner as the Capes Current
Figure 4.5: The bathymetry of the Recherché and the major summer currents of the region

Possible summer counter-current

Leeuwin Current

Summer

Figure 4.6: The bathymetry of the Recherché and the major winter currents of the region

Leeuwin Current

Winter
4.1.4 Island Eddies

The Island Wake Parameter for five of the islands in the Recherché Archipelago has been calculated in Table 4.1. The islands chosen represent the range of island scales in the archipelago. A range of values of 0.5-1.0 ms\(^{-1}\) has been assumed for the current speed. This is based on a typical speed of the Leeuwin Current that has been shown to move around 0.5-1.0 ms\(^{-1}\) and the ADPC data that indicates wind driven current speeds of around 1 ms\(^{-1}\) are possible. The horizontal length scale has been taken from the north south cross section of the islands. The highest speed currents will be flowing parallel to the shore so this is appropriate.

<table>
<thead>
<tr>
<th>Island</th>
<th>H (m)</th>
<th>L (m)</th>
<th>U (ms(^{-1}))</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Woody Island</td>
<td>30</td>
<td>2240</td>
<td>0.5 - 1.0</td>
<td>2.0 – 4.0</td>
</tr>
<tr>
<td>Middle Island</td>
<td>30</td>
<td>6420</td>
<td>0.5 - 1.0</td>
<td>0.7 – 1.4</td>
</tr>
<tr>
<td>Mondrain Island</td>
<td>30</td>
<td>7020</td>
<td>0.5 - 1.0</td>
<td>0.6 – 1.2</td>
</tr>
<tr>
<td>Button Island</td>
<td>10</td>
<td>299</td>
<td>0.5 - 1.0</td>
<td>1.7 – 3.4</td>
</tr>
<tr>
<td>Figure of Eight Island</td>
<td>50</td>
<td>3880</td>
<td>0.5 - 1.0</td>
<td>3.2 – 6.4</td>
</tr>
</tbody>
</table>

Mondrain and Middle Islands are easily the two largest islands in the Archipelago and as the above table shows, the two least prone to eddy shedding. As island size decreases the wake parameter increases. This indicates that eddy shedding is possible for most of the other islands in the Archipelago given a small increase in the velocity of the passing current. Looking at the lower range of wake parameter values, even in a “normal” strength Leeuwin Current (0.5ms\(^{-1}\)), Woody Island and Figure of Eight Island are predicted to have instabilities and possibly eddy shedding in their wake. Button Island is one of the smallest islands and is situated in a relatively shallow section in Esperance Bay. It also is predicted to have instabilities in the wake. The shallow depth helps to reduce the value of the wake parameter, unlike many of the other small islands, which rise from depths of around 20-30m. Most of these smaller island will continually have eddies forming and pinching off behind them.

Unfortunately, because of the scale of resolution in satellite images of the archipelago, it has not been possible to confirm the existence of such eddies or their interaction with each other.
4.2 Franklin Voyage 94/07

In July 1994, the CSIRO marine research vessel, the Franklin, took measurements in the Recherché region. Using the CSIRO Marine Research website, ADCP, CTD, and hydrology data that was collected on this voyage was downloaded and analysed. The voyage moved from east to west along the south coast of Australia. The transects locations and the station locations that were used in this study are shown below in Figure 4.7.

Unfortunately, none of the transects enter the State territorial water that define the technical extent Archipelago. While this is inconvenient for direct analysis of the Recherché area, this was the only data of its type available at the time. It is also necessary to have an understanding of the waters around the region as well as directly in the Archipelago because ocean currents don’t recognise when they are leaving State defined boundaries.

Figure 4.7: Franklin Voyage 9407
4.2.1 ADCP

Franklin Voyage 9407 collected Acoustic Doppler Current Profile (ADCP) Data in the Recherché region. The voyage was undertaken during the middle of winter and as previously explained the Leeuwin Current is expected to flow strongly around this time of year. To verify the presence of the Leeuwin and investigate if any other major currents are present the data was arranged in two ways using MATLAB, plotting the surface velocities of all transects on the same plot, and plotting the velocity profiles with respect to depth for each transect.

**Surface Currents**

The surface current plot in Figure 4.8 ratifies the winter predictions that were proposed earlier. While the presence of the Leeuwin Current is clearly seen in Transects 3 and 4, it is important to note that the Leeuwin doesn’t seem to have a large influence on the shallower waters in the Archipelago. In fact the strength of the current is greatly reduced close to the islands in both Transects 3 and 4. This further verifies that the current observed is indeed the Leeuwin Current, which is expected to travel along the edge of the continental shelf.

At Transect 1 and 2, the situation changes. In the previous prediction, the Leeuwin is expected to continue around the coastline into the Great Australian Bight following the continental shelf. One interpretation of the data suggests that the Leeuwin Current starts turning northeast to follow the coast but then turns eastwards again. This change in direction appears to be due to the formation of a large eddy at the eastern end of the Recherché Archipelago. As the Leeuwin turns northeast it converges with this eddy and is forced east again. At this point of convergence some sort of downwelling would be normal. This will be discussed later so it is sufficient to mention at this point that the data does not appear to show any significant signs of downwelling.

Due to the lack of data it is difficult to draw solid conclusions as to the formation and direction of these currents. It is possible that the current turning north is not part of the Leeuwin Current but is in fact an eddy as well. It is possible that the Recherché Archipelago causes large scale eddies to be created as the Leeuwin Current flows past.

A summer situation would provide a remarkably different current situation. Because the wind is a far more effective driving force on the shelf, the set up of an alongshore counter-current to the Leeuwin is a distinct possibility. Unfortunately a voyage has not been undertaken in the region during the summer months.
The second analysis of the ADCP data is shown in Figures 4.9 – 4.12. Each transect had its u-velocities plotted with respect to depth and distance along the transect. The u-velocities are plotted because the presence of alongshore currents are what we are interested in finding. As is the case with the surface currents Transects 3 and 4 show the most conclusive evidence of the Leeuwin on the edge of the shelf. This is most likely due to the perpendicular position of these Transects to the Leeuwin and their position further south than Transects 1 and 2. As the surface currents indicated, there are still strong currents flowing past Transects 1 and 2 but they are not shown on the depth profiles. Because Transects 1 and 2 are not quite parallel to the shore and they are in the middle of an eddy, they show small u-velocities.

The point of convergence mentioned in the surface currents system does not appear to be present in the depth profile. At a point of convergence downwelling is expected but the data gives no
indication that downwelling was occurring. This may simply be because the data was not detailed enough to identify such features. The hypothetical point of convergence is between the two transects so it is possible that the data has missed the evidence of the convergence.

All four Transects show some evidence of a weak under-current in the opposite direction to the Leeuwin. This current seems to exist on the bottom of the shelf slope and sticks close to the slope, clearly seen in Transect 3. Such a current is also observed along the west coast of WA.

In all four transects the current velocity on the shelf is close to zero. The reason for this is open to a few different interpretations. During winter the predominant wind direction has been shown to originate from the northwest quadrant of the compass. In shallow water (i.e. on the continental shelf) winds is the primary driving force. If the region had been experiencing a typical winter wind scenario at the time the ADCP data was collected, a southeastward surface current would be expected on the shelf. This is clear not shown in the data. However, it is possible that the region was experiencing a period of wind calm when the sampling took place. For the wind driven currents to have significant velocity they need to be driven by persistent winds. Removing the driving force of the wind temporarily can cause the shelf currents to abate quickly.

**Figure 4.9: Current profile for Transect 1 (u-velocity)**
Figure 4.10: Current profile for Transect 2 (u-velocity)
Figure 4.11: Current profile for Transect 3 (u-velocity)

Figure 4.12: Current profile for Transect 4 (u-velocity)
4.2.2 Temperature, Salinity, and Fluorescence

Franklin Voyage 94/07 also collected conductivity, temperature and density (CTD) data in the same areas as the ADCP data. Using similar methods as for the ADCP data, the temperature, salinity and fluorescence measurements from this voyage were plotted. Figures 4.13 and 4.14 show the three sea water properties for Transects 1 and 2. The temperature and salinity plots for both Transect 1 and Transect 2 show evidence of downwelling close to the coast. Downwelling is the movement of colder, high salinity (i.e. more dense) water away from the coast along the sea bottom. This occurs because the waters close to the shore have higher evaporation rates, increasing the salinity. Because there is less solar heating in winter, the shallow water cools down, becomes denser and moves along the bottom towards the shelf. This is clearly shown in the salinity plot of Transect 2 and to a smaller extent in Transect 1.

The temperature rise towards the deep end of Transect 2 was initially thought to be an arm of the Leeuwin Current again. On further investigation it was noted that there is no corresponding drop in the salinity profile. A fall in salinity levels would be expected because the Leeuwin transports high temperature, low salinity waters. The salinity levels in Transect 2 clearly decrease in a linear fashion with increasing distance from the shore. The disparity between the temperature and salinity plots may be due to the limited nature of the data. Because only five data stations are available, small experimental errors can quickly compound into large errors in the interpretation. This problem can be further magnified when MATLAB interpolates between points. For this reason any conclusions drawn from such limited data should be treated with a degree of scepticism. A good example of the limitations of the data can be drawn from the lack of evidence of the convergence seen in the surface velocity plots. Neither the ADCP data nor the CTD data has given any indication that the convergence is creating downwelling. Perhaps the spacing of the data has contributed to this lack of evidence.

The levels of fluorescence in both Transect 1 and 2 are higher near the sea bottom on the continental shelf but doesn’t extend into deeper waters off the shelf. Generally ocean waters are clear enough for light to penetrate to depths where nutrient levels are significantly higher than at the surface. The data indicates that nutrient and light levels available to phytoplankton are at their optimum in the 20-60m range. As well as more abundant nutrient availability at depth, phytoplankton is more sheltered from the effects of wind forces. These observations are further supported in the next section, which examines the Nitrate and Phosphorous levels.
Figure 4.13: Transect 1 - Temperature, Salinity, and Fluorescence

Figure 4.14: Transect 2 - Temperature, Salinity, and Fluorescence
The temperature and salinity of the region can be further analysed with the use of TS plots. Figure 4.15 shows the location of the stations that the data was collected from. Figures 4.16, 4.17, 4.18, 4.19 then plot the temperature and salinity profile for each of the stations sampled. TS plots can be used to identify waters that have similar temperature and salinity signatures. As the stations approach the shoreline the salinity increases at a similar rates in all four transects. This is due to the increased rate of evaporation on the shelf that has been previously mentioned. The most interesting feature of the TS plots is a downturn in temperature in the last few stations. This is most prominent in Transects 1 and 2. While the temperature is decreasing the salinity is still increasing. This can be attributed to the effect of the Leeuwin and evaporation on the relatively shallow shelf. The Leeuwin is advecting low salinity high temperature waters along the surface, close to the edge of the continental shelf. This mixes with the colder bottom waters creating a linear increase in temperature with rising depth. On the shelf the effect of the Leeuwin Current is limited and so is its effect on the temperature. The temperature on the shelf is more responsive to atmospheric losses. Therefore, while solar heating causes evaporation and creates the salinity increase, during the winter months the heating is not sufficient to raise the nearshore temperature above that of the Leeuwin Current.

Figure 4.15: CTD Station Locations
Figure 4.16: TS Plot – Stations 79, 80, 81, 82, 83

Figure 4.17: TS Plot – Stations 84, 85, 86, 87, 88
Figure 4.18: TS Plot – Stations 90, 91, 92

Figure 4.19: TS Plot – Stations 98, 99, 100
4.2.3 Nitrate and Phosphorous Levels

Nitrate and Phosphorous levels taken by Franklin Voyage 94/07 have been overlaid on the temperature profiles for Transects 1 and 2. Only surface and bottom values were available from the voyage but they do indicate that both nitrates and phosphorous levels increase with increasing depth and decreasing temperature. While it is difficult to interpolate when the nutrient measurements only outline the boundary values for the profiles, they do agree with the measured levels of fluorescence indicating high phytoplankton growth at depth and in the cooler waters.

Figure 4.20: Nitrate Levels and the Temperature Profile for Transects 1 & 2
Figure 4.21: Phosphorous Levels and the Temperature Profile for Transects 1 & 2
4.3 Model outputs

To better understand the currents that exist on the shelf some numerical modelling of the Recherché region was undertaken. The Hamburg Shelf Ocean Model (HANSOM) effectively shows the currents set up for a particular barotropic forcing. The inputs for this model were the digitised bathymetry and the barotropic forcing (wind only) in the region. Four simulations were run with a constant wind blowing from the north, south, east, and west. The outputs for these models are shown in Figures 4.22, 4.23, 4.24, and 4.25.

From analysis of the wind regime it can be assumed that the winter winds will create a combination of the currents modelled in the northerly and westerly simulations and the summer winds will create a combination of the currents modelled in the southerly and easterly simulations. The currents generated by the northerly and westerly winds (i.e. during winter) move predominately from west to east. Conversely the southerly and easterly summer winds drive the currents from east to west. Therefore, HAMSOM modelling corroborates the previous proposal of a summer current in the opposite direction to the Leeuwin.

Other than the direction of the currents, two other features of the model output are noticeable. Firstly, the fastest current speeds are observed in the shallow sections of the bathymetry. Using particle tracking in the next section these shallow currents are shown to contain greater variability that affected the excursion distance of particles.

Secondly the presence diversion of flow around the islands creates a wake even at the coarse scale of resolution used. In all the model runs an absence of current speed is seen in the leeward side of the larger islands. However, because the grid size for this model was 1111m by 1111m it is impossible to comment further on the state of the eddy or interaction with other currents.

Figure 4.22: Northerly Winds Simulation

A northerly wind is likely during the winter months and is generally strongest in the morning. Clearly a current shadow can be seen to the south of the major islands, indicating that an eddy has
formed behind the island. While the general current direction is to the south, the majority of the currents closest to shore have the tendency to move slightly east as well. This will be due to the effect of the Coriolis, which, in the southern hemisphere, turns currents to the left.

**Figure 4.23: Southerly Winds Simulation**

The opposite wind situation shows the flow of current to the north and northeast. The current in the deeper water already move to the northeast because the Coriolis has had time to turn them before any island obstructions arose. Again the shallow currents are fastest an are turned to the left of their direction of flow, (in this case to the west). Generally, winds originating directly from the south are rare, even in summer. Southwest winds are more likely and the effect of the Coriolis would turn the approaching currents parallel to the shoreline.

**Figure 4.24: Easterly Winds Simulation**

The easterly simulation can be considered the most common summer situation. Importantly the currents are almost exclusively in a westerly direction. This is the direction that will allow Ekman transport to push the Leeuwin offshore and upwelling to occur.
The westerly winds are common during the winter in the Recherché Archipelago. As was the case for the previous simulations the currents are turned left from the wind direction due to the effect of the Coriolis Force. The strongest currents are in the shallow section but as particle tracking shows below, this does not increase the excursion of the particles.

To better understand the transport mechanisms that exist in the Archipelago the HAMSOM outputs were extended to include a particle tracking model. Particle tracking can be useful to predict the path of buoyant surface water. Typically, the wind forcing dominates the direction of motion so the existing model is suitable. The Coriolis Force will affect the motion of the particle, as will physical obstacles like islands and headlands.

A 90-hour typical summer and winter wind sequence was chosen for the model from data collected in 2000 by the Bureau of Meteorology. Eleven particles were tracked in a range of positions throughout the archipelago. The resulting plots are shown in Figures 4.26 and 4.27. Starting positions are noted by a red cross and finishing positions by a black asterix. In both the winter and summer plots the nearshore particles are impeded by the presence of the various headlands and bays that prevent smooth motion. This challenges the previous model outputs that indicated the strongest currents were observed closest to shore. While the shallow nearshore currents may be quickly induced to high velocities, they are also constantly stopping as they encounter the physical barrier of the coast. Particle positioned in the open areas in the archipelago show little deviation from the wind driven path. Notable exceptions include leftward deviation due to the Coriolis Force and significant changes in wind direction.
4.4 Summer Upwelling

Using the equations outlined in section 2.1.8, the likelihood of upwelling occurring and the position of the possible upwelling front has been determined. Equation (2.1) was first used to determine the likelihood of upwelling given the physical properties of the Recherché. Using wind data collected over summer 2000, daily values for $u^*$ were calculated. The steric pressure gradient was determined from data analysed by Godfrey and Vaudrey (1985). From this the transition depth $H^*$ was calculated for each day. The resulting time series is plotted in Figure 4.28.
Figure 4.28 indicates the transient depth varies directly in relation to the wind strength. Any values over 100m will be easily induced into an upwelling situation so it is clear from the plot that during the majority of summer the region is prone to upwelling.

Using equation (2.2) the volume flux created during these upwelling probable times was calculated. The Upwelling Index indicates that fluxes of 1-1.5 ms\(^{-1}\) are typical during upwelling events. To better understand how this flux affects the region, the propagation of the upwelling front was calculated for a number of time periods.

From equation (2.5), \(t_i\) was estimated to be approximately 39 hours. Because the time scale that this study is interested in exceeds 39 hours it is assumed that the front is driven by penetrative convection only. Therefore equation (2.3) is discarded and equation (2.4) is used. From (2.4) the following table was developed:

<table>
<thead>
<tr>
<th>Time</th>
<th>Time (s)</th>
<th>(u^*)</th>
<th>(l) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 days</td>
<td>259200</td>
<td>0.013</td>
<td>11.97</td>
</tr>
<tr>
<td>1 week</td>
<td>604800</td>
<td>0.014</td>
<td>18.92</td>
</tr>
<tr>
<td>2 weeks</td>
<td>1209600</td>
<td>0.010</td>
<td>20.14</td>
</tr>
<tr>
<td>1 month</td>
<td>2592000</td>
<td>0.009</td>
<td>25.28</td>
</tr>
<tr>
<td>2 months</td>
<td>5184000</td>
<td>0.008</td>
<td>31.12</td>
</tr>
<tr>
<td>3 months</td>
<td>7776000</td>
<td>0.007</td>
<td>36.50</td>
</tr>
</tbody>
</table>
Several assumptions were made to achieve these results. N is assumed to be 0.01 in line with similar value found on the west coast of Western Australia. $\alpha$ was estimated to be 0.0025 assuming a 200m drop over 80km. The Coriolis Force, $f$ is $8.15 \times 10^{-5}$, using a latitude of $-34^\circ$.

Table 4.1 predicts that at the end of summer a front 36km offshore is expected. The propagation of this front may slow down with increasing time but if the forcing is maintained, the front continues to move. An important assumption that was made before using this equation is that the forcing is continuous. As the calculations of transition depth show, this assumption is incorrect. However, while there is sometimes a reduction in the wind forcing in the region, it rarely changes direction completely to counter-act any upwelling set-up that may have occurred earlier.
5 DISCUSSION

The following section expands on the results presented in section 4 and discusses the practical implications of the findings.

5.1 Oceanographic Features

The Leeuwin Current has been highlighted throughout this thesis, as it is the nearest major current flowing around the region. The effect of its importation of high temperature, low salinity, low nutrient water has been discussed and will not be canvassed again. However, the reverse effect that the Recherché has on the Leeuwin has not been broached in detail. From satellite imagery the Leeuwin can often be seen splitting or dispersing as it passes the Recherché. The use of ADCP data has indicated the formation of an eddy that may or may not be a permanent or semi-permanent feature. The Coriolis will attempt to force the Leeuwin to flow northeast into the Great Australian Bight after it passes the Recherché but perhaps it is not powerful enough to force the entire current and it splinters. The steric gradient observed by Godfrey and Vaudrey (1985) has weakened considerably by the time it passes the Recherché so the dispersion of the Leeuwin may be due to the lack of sufficient pressure gradient. If this is true then it may take a particularly strong El Nino year to establish a high enough pressure gradient so that the Leeuwin may flow further into the Bight.

The interaction of the many eddies formed around the islands within the archipelago may also create a blockage effect for any current flowing through the Recherché. The surface and depth profiles of the ADCP data indicated that the Leeuwin had little influence over the shelf currents so it is unlikely the dispersion of the Leeuwin is due to the islands. The HAMSOM model outputs and particle tracking simulations indicated eddy effects are visible even at coarse resolution, and they can have a significant effect on the excursion of a particle. Little more can be concluded about these eddy effects without further work with more detailed bathymetry data.

The climatic overview of the Recherché region has been used as evidence to argue for the presence of a nearshore counter-current. On the southwest coast of Western Australia the wind regime is likely to swing from east to west on a daily basis. On the south coast the winds predominantly remain from the same direction throughout the day. The strengthening and weakening seen during the day is most likely due to a ‘normal’ land/sea breeze interaction but not enough to overcome the winds as is normal on the west coast. Further off the coast however the similarities between the two systems become more apparent. As the frictional effect of the coast is reduced with increasing distance from shore the equatorward winds that drive the Capes Current become more persistent than they appear from the shore. This offshore dynamic similarities between the typical wind
regime off the south coast of Western Australia and the west coast is probably the most resounding proof that such a current exists.

If the counter current is assumed to exist for the sake of hypothesis, it raises a question about the effect that it has on the biology of the region. Given the weight of evidence presented it can be assumed that upwelling with occur and this will allow the importation of colder water, bringing with it higher levels of nutrient than are present in coastal waters. This poses an interesting solution to the question raised in section 4.1.2, if upwelling occurs most vigorously during summer, why is a phytoplankton peak observed in April, after summer? It is possible that the satellite images fail to detect high levels of phytoplankton because they are too deep to be registered. The presence of high level of fluorescence below 20m supports this theory. Perhaps the higher wind conditions over summer cause the phytoplankton to sink lower where light attenuation is still satisfactory and nutrient levels are also higher. Then why are higher levels seen during autumn? Perhaps the growth of the phytoplankton has meant competition for light has become of limiting factor. This would drive the phytoplankton towards the surface, where they register on the satellite images. During the winter the strong Leeuwin Current lowers the nutrients available by inputting lower nutrient levels. Consequently the satellites register a fall in phytoplankton concentration. The stronger winter winds would exacerbate the fall in phytoplankton levels as they are driven deeper into calmer waters. During the spring there are no significant sources of nutrient input so the phytoplankton levels remain depressed.

5.2 Modelling
The Leeuwin Current was excluded from the HAMSOM modelling because wind forcing primarily drives nearshore currents. This was indicated by the velocity profiles that were collected by Franklin Voyage 94/07 and are included in Figures 4.9, 4.10, 4.11, and 4.12.

Bathymetric assumptions re depth would have an effect on the speed and motion of the currents amongst the islands in the Archipelago. It has already been shown that the shallow sections of the region have produced the fastest currents and the most deviation from the initial forcing. While the depth assumptions are valid at the scale of resolution used in the modelling for this report, at a smaller scale more detailed knowledge of the bathymetry would be necessary.

The islands have been assumed as flat surfaces in the modelling while in reality they have topography that would create a wind shadow larger than the model indicates. If more detailed modelling of the eddies around the islands was to take place it would be recommended that the effect of wind shadow be included.
The quantification of upwelling and the prediction of the upwelling front could be partially verified with the use of the CZCS and other publicly available satellites. The limiting factor with such satellites currently is the availability of images unobstructed by cloud cover. Given time however, it is probable that a sufficient number of images would be taken that showed the regions and the currents operating within it.
6 CONCLUSIONS

This report has used the available data on the Recherché Archipelago to illustrate what is currently known about this region. Given the lack of any detailed research in the region prior to this report, it can now be used to identify the elements in the region that require further study.

The region surrounding the Recherché Archipelago has predominately northwest winds during the winter, and winds from the east and southeast during the summer. It is proposed that these summer winds create upwelling favourable conditions at a time when the Leeuwin Current is at its weakest. The presence of these upwelling favourable summer conditions has been raised as a possible explanation for relatively high levels of chlorophyll (over twice the background) revealed by the satellite images. The summer winds may also contribute to the formation of a nearshore wind-driven counter current similar in nature to the Capes Current. The Leeuwin Current and this proposed counter current also play a role in controlling nutrients levels in the region. The levels of nutrients then dictate the amount of phytoplankton that can survive in the area. Satellite imagery has shown a strong link between the physical oceanography and the biological characteristics of the region. Hopefully further study of the hydrodynamics of the Recherché will show the existence or otherwise of this counter current.

The rainfall and air temperature patterns for the region are typical for a temperate climate, experiencing relatively hot, dry summers and cool, wet winters.

The Archipelago experiences minimal “freshwater” inflow, with the only major source being Stokes Inlet which only opens to the ocean on average once every 3-4 years. However due to high levels of evaporation, the salinity of the Inlet is rarely less than 35ppt during the year.

The wave climate of the Recherché region has been analysed and shows 50% of waves are larger than 1.45m but only 20% are larger than 2m. The highest waves occur during autumn and spring but mean wave height is larger during winter.

Several factors contributing to fluctuations in water level have been identified. Continental shelf waves can cause significant changes in water levels along the Western Australian coast. Variations of up to 50cm have been shown propagating down the coast and around into the Recherché region. The various lunar/solar forces on Esperance have been used to determine the region as having a mixed but mainly diurnal tide with strong semi-diurnal forcing. A seiche with a period of 3.4 hours has been show to exist in the Bay of Esperance. Finally the water level has been shown to fluctuate
annually and inter-annually due to the seasonal strength of the Leeuwin Current and the El Nino/La Nina phenomenon.

The stronger winter Leeuwin Current greatly influences the surface water temperature and salinity in the Recherché. The temperature is elevated more than it would be otherwise be without the Leeuwin in winter, while the salinity decreases due to the importation of the lower salinity waters of the Leeuwin Current. The Leeuwin still operates in summer but it has less of an impact as it is pushed offshore by the proposed nearshore counter current.

The formation of eddies around the islands in the Archipelago is likely and the types of eddies behind a range of islands has been included. Unfortunately because of the lack of current data in the Archipelago and the scale of resolution of satellite images it is impossible to investigate how the eddies interact.

Several data types collected by the Franklin Voyage 9407 were collected and analysed, providing greater insight to the physical oceanography of the region in winter. ADCP data was used to verify the presence of the Leeuwin Current off the continental shelf. Temperature and salinity data was used to show downwelling near the coast. Fluorescence data indicated that the highest concentrations of phytoplankton are recorded at approximately 20-60m below the surface. This was corroborated by nutrient data which found higher levels of nitrates and phosphorous at depth and in cooler water.

The use of the Hamburg Shelf Ocean Model (HAMSOM) to predict the type of currents that would exist under different wind forcing conditions indicated that the summer wind conditions would produce upwelling favourable conditions. Extending this modelling to include particle tracking for a typical summer and winter day further illustrated the contrasting conditions between seasons in the Archipelago.

Finally, with the use of equations developed by Gersbach (2000) and Winters et al (2001), some numerical prediction to test whether upwelling was occurring and quantification of the upwelling front was performed.
7 RECOMMENDATIONS
This investigation has indicated the importance of the link between the physical oceanography and the manner in which the biology of the Recherché Archipelago can respond to different oceanographic conditions. To fully understand the processes that exist in the Archipelago further work needs to be undertaken on both a larger and smaller scale than this study has covered.

On a smaller scale, the creation of eddies around the islands in the Archipelago will have an impact on any current flowing through the region. The interaction of these eddies with each other may drive local upwelling or downwelling that will play an important role in transport of phytoplankton and other microbial organisms. HAMSON would be a useful modelling tool for this process provided that a more detailed bathymetry can be obtained.

On a larger scale the presence of an eddy of similar magnitude to the Archipelago itself has been detected on the eastern end of the island. Whether this is a permanent or temporary feature is yet to be determined and could explain the observed dissipation of the Leeuwin Current past this point. Further analysis of satellite imagery would assist in determining the nature of the eddy but if HAMSOM was to be used as a modelling tool at this scale the Leeuwin current should be incorporated in the model.

Further data collection to validate the existence of the nearshore counter-current is required. The lack of field data in summer has prevented the verification of such a current. Continued monitoring of ocean properties such as temperature, salinity, fluorescence, and nutrient levels, as well as ADCP data in the region will be of assistance in any further work to prove the existence of this current. If this current does exist the question needs to be asked if it is merely an extension of the Capes Current.

Finally, it would be useful to try to further quantify the effect that upwelling has on the biological response in the region. If the productivity of the region’s biology can be correlated to the strength of the upwelling forces in the preceding season then fisheries and other supporting industries may be able to accurately forecast lean seasons and plan accordingly.
8 REFERENCES

Anon. (1997) Great Australian Bight Marine Park Draft Management Plan, Part B-Resource Information, Natural Resources Group, Department of Environmental and Natural Resources


D’Adamo, N (1997) Oceanographic Requirements for the Establishment and Management of Marine Reserves in Western Australia, Marine Conservation Branch, Department of Conservation and Land Management, Report MCB-02/97


Fahner, C. and Pattiaratchi, C. (1994) The physical oceanography of Geographe Bay, Western Australia, Centre for Water Research, University of Western Australia, Reference WP 898 CF

Gersbach, G (2000) Coastal upwelling off Western Australia, PhD Thesis, Centre for Water Research, University of Western Australia


Green, T (1998) Hydrodynamics Study of Van Diemen Gulf, Centre for Water Research, University of Western Australia, Perth, Western Australia

Herzfeld, M (1997) The annual cycle of sea surface temperatures in the Great Australian Bight, Centre for Water Research, University of Western Australia, Perth, Western Australia


Pattiaratchi, C (1994) Physical Oceanographic Aspect of the Dispersal of Coral Spawn Slicks: A Review. Centre for Water Research, University of Western Australia, WA 6009 Australia

Pattiaratchi, C. (1998) Assessment and Modelling of Oceanographic Conditions at Four Potential Sites for Tuna Fattening in Esperence Centre for Water Research, University of Western Australia, Reference WP 1391 CP


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


APPENDIX A – SEASONAL WIND REGIMES

Summer 2000: 2 hourly percentage frequency of wind occurrence and wind strength

---

Summer 1 am

---

Summer 3 am

---

Summer 5 am

---

Summer 7 am

---

Summer 9 am

---

Summer 11 am

---

Summer 1 pm

---

Summer 3 pm

---

Spring 5 pm

---

Summer 7 pm

---

Summer 9 pm

---

Summer 11 pm

---
Autumn 2000: 2 hourly percentage frequency of wind occurrence and wind strength

- Autumn 1 am
- Autumn 3 am
- Autumn 5 am
- Autumn 7 am
- Autumn 9 am
- Autumn 11 am
- Autumn 1 pm
- Autumn 3 pm
- Autumn 5 pm
- Autumn 7 pm
- Autumn 9 pm
- Autumn 11 pm

Wind speed scale in m/s

3 6 9 12 15 18
Winter 2000: 2 hourly percentage frequency of wind occurrence and wind strength
Spring 2000: 2 hourly percentage frequency of wind occurrence and wind strength
APPENDIX B – SEA SURFACE TEMPERATURES

Mean Sea Surface Temperatures for Southwest Australia

February

April

June
APPENDIX C - SEAWIFS SATELLITE IMAGES YEAR 2000

Chlorophyll a Concentration (mg/m³)

January

February

March
APPENDIX D – SATELLITE IMAGES FROM THE COASTAL ZONE COLOUR SCANNER (CZCS)

Figure A: 1/5/80
Mid/End-Autumn

Figure B: 12/9/80
Start Spring

Figure C: 3/10/80
Mid-Spring
Figure D: 20/10/80
Mid-Spring

Figure E: 1/11/80
End-Spring

Figure F: 11/1/81
Mid-Summer
Figure G: 3/3/81
End-Summer/Start-Autumn

Figure H: 13/3/81
Start-Autumn
Figure I: 20/4/81
Mid-Autumn

Figure J: 10/5/81
End-Autumn
Figure K: 4/1/82
Mid-Summer

Figure L: 29/3/82
Start/Mid-Autumn