MODELLING OF TROPICAL CYCLONES
ON THE NORTH WEST SHELF

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Attention: The Dean

Dear Sir,

It is with great pleasure that I submit this thesis, entitled “Modelling of Tropical Cyclones on the North West Shelf”, as a partial fulfillment of the requirements for the degree of Bachelor or Engineering (Environmental) with Honours.

Yours Sincerely,

Matthew Zed
Abstract

This study examines the hindcast skill of an ocean circulation model at reproducing the oceanographic conditions measured at Woodside’s North Rankin A (NRA) platform during the passage of Tropical Cyclone Monty in the summer of 2004. The performance of several turbulence closure schemes, and their impact on the vertical mixing dynamics, is examined under the extreme forcing induced by the passage of the cyclone. The model employed was the fully three-dimensional Rutgers Regional Oceans Modelling System (ROMS). Boundary and initial conditions for the model were taken from CSIRO’s BLUElink global circulation model, and the cyclone winds were taken from the CycWind model produced by the Australian Maritime College. Each of these forcing files was compared with field observations taken at NRA. Results showed that CycWind slightly overestimated the observed winds by approximately 15% during the cyclone’s peak intensity and BLUElink demonstrated a near linear deviation in temperature through the water column of approximately +0.8°C near the surface to +2°C near the seabed. The ROMS model produced a close correlation with the field observations at NRA, with the most accurate results achieved using the Mellor-Yamada 2.5 turbulence closure scheme. Maximum near-seabed current speeds of approximately 0.68 m s⁻¹ were produced, comparable to the field measurements of approximately 0.8 m s⁻¹. The model underestimated the rate of vertical mixing induced by the cyclone, with the temperature field reacting slower than observations at NRA as a result of the model not resolving the subgrid-scale processes within the flow field. It did, however, accurately predict that the water column almost completely mixed to approximately 26°C, as observed in the field data. Output at other locations (6) demonstrated that the mixing depth induced by the cyclone was directly correlated with the magnitude of the wind stress and the strength of the temperature stratification. An anticlockwise eddy-like structure appeared adjacent to the seabed in the wake of the cyclone, generated by a cyclone-induced density instability throughout the water column. This vorticity response had a significant impact on the current speeds near the seabed, producing a double peak in the near-seabed currents at NRA that was only just discernable in the field observations.
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1.0 Introduction

The North West Shelf (NWS) of Australia is a particular region subject to intense tropical cyclone activity. It receives approximately 10% of the global total of generated cyclones throughout the year, with these occurring predominantly during the summer months. Historical data records from the NWS have shown that cyclones are the most significant natural disturbances affecting the region, along with internal waves and occasional tsunamis (Hearn & Holloway 1990).

The NWS is also home to one of Australia’s largest and thriving oil and gas industries. The natural gas operations, known as the NWS gas project, is Australia's largest ever resource development, based on the huge North Rankin A and Goodwyn A gas fields (Fraser & Bruce 1998). This presents a problem as the intense weather activity, produced by tropical cyclones, has a direct bearing on the operations of these industries and the design criteria for their structures. Whilst the ambient conditions may set the operability criteria for the offshore operations, it is the severe weather conditions experienced during cyclones that determine the survival criteria.

As a result of this, understanding the environmental impact of severe tropical cyclone events has been a key focal point for many stakeholders that exist in cyclone affected areas. The destructive impact that these storm events have on coastal residents and industrial activities clearly indicates the critical need for a better understanding of cyclone dynamics. This provides the rationale for this study, which is aimed at studying the impact that cyclones have on mixing through the water column and their role in the generation of strong subsurface currents near the seabed.
1.1 Objectives of this Study

This study is aimed at gaining a better understanding of the influence that tropical cyclones have on the dynamics through the water column, with specific reference to the generation of subsurface currents near the seabed and temperature stratification. This is achieved through examining the ability of the Rutgers University Regional Oceans Modelling System (ROMS) to reproduce oceanographic conditions during the passage of a real tropical cyclone on the NWS. The cyclone event analysed for this study was Tropical Cyclone Monty of early 2004, which was selected primarily due to the existence of reliable oceanographic and meteorological data at Woodside’s North Rankin A (NRA) platform. ROMS was used since its high order numerical computation scheme enables low levels of energy dissipation within the model, meaning that the transfer of energy through the water column as a result of the cyclone wind stress would be most accurately represented.

The modelling was performed with the use of realistic cyclone winds and boundary forcing throughout the entire water column, distinguishing it from earlier studies where the cyclone radius and maximum winds were kept constant (Hearn & Holloway 1990; Sullivan 2006). Subsurface current generation and the mixing influence of the cyclone were examined with particular reference to NRA, where a comparison with field observations could be made, and at points located directly on the path of the propagating cyclone.

In the past, there has been significant research into the impacts that tropical cyclones have on the surface and subsurface waters in which they operate. Recent improvements in the capabilities of computer models have allowed the nature and forcing behind tropical cyclones to be analysed in far greater detail than in the past. There are, however, many limitations to the modelling process, such as those related to computational efficiency and a lack of understanding of the complex atmospheric, land and ocean systems that affect the cyclone characteristics.

So far, analysing the impact of cyclones at the surface, such as their role in wave generation, has reached a high degree of accuracy in modern cyclone models (Chao, Alves & Tolman...
2005; Wu et al. 2004). The impacts that cyclones have on the subsurface environment, however, is still an area of high ambiguity, with little evidence that modern models are effectively replicating the real environmental conditions through the water column. This includes understanding of the role of cyclones in the generation of subsurface currents and the vertical mixing characteristics that affect salinity and temperature stratification both during and after cyclone events.
2.0 Literature Review

The North West Shelf (hereafter the NWS) has long been an area of particular interest for many stakeholders. Petroleum companies, such as Woodside Offshore Petroleum, Apache Energy, Chevron Australia and BHP Petroleum have existed in the area for decades due to its rich supply of LNG and crude oil resources (Fraser & Bruce 1998). Conservation groups have also given the area much attention due to the rich marine biodiversity that exists in its shallow water ecosystems. This has seen the NWS become a fundamental fishing area for the West Australian Fisheries and also a key location for tourism in the state (CSIRO 2002).

These joint interests have been the driving force behind the numerous studies that have been conducted in relation to the NWS region. This section provides an overview of the physical and dynamic environment that characterises the NWS, paying particular attention to the impact that cyclones have on the area. There is also a review of past studies that directly relate to cyclone modelling on the shelf, and how these provided the background for the current study.

2.1 Physical Characteristics of the NWS

2.1.1 Location

The NWS characterises the ocean and adjacent land mass that extends from the northwestern coast of Western Australia towards the southern most islands of Indonesia. Overall, the shelf covers a distance of 2000 km from The North West Cape in the southwest corner to Melville Island in the northeast (CSIRO 2002). Part of the geographical extent of the NWS, from the North West Cape to Broom, is illustrated in Figure 1.
The NWS is bounded by coastline to the southeast, and its offshore extent is defined by a 200m depth contour, as illustrated in Figure 1. The region expands rapidly North of the North West Cape from approximately 10 km to 200 km width offshore from Barrow Island (Holloway 1983). From here, the width of the shelf is relatively uniform along most of its extent, slightly extending along the northeast border to 300 km wide at Cape Londonderry and the Joseph Bonaparte Gulf (Lim 2003). The shelf encompasses a series of offshore islands and reefs, with some of the more notable being Barrow Island and the Dampier Archipelago in the southwest region and Scott Reef in the northwest.

### 2.1.2 Bathymetry

The bathymetry, or subsurface topography, of the NWS is relatively uniform across most of its extent, as indicated in Figure 1. Beyond the 200 m depth contour that defines the boundary of the NWS, the seabed rapidly deepens to over 1200 m at a region known as the
shelf break (CSIRO 2002). The most considerable drop in seabed elevation occurs to the North of Dampier where the North Australia Basin is located, shown by the 5000 m depth contour in Figure 1. Here, the depth drops from 200 m to below 5 km over a horizontal distance of less than 200 km at its steepest section (Fieux et al. 1993).

*Bathymetry at NRA*

One particular location of interest on the NWS is the North Rankin A platform (NRA). The NRA platform is located approximately 135 km offshore from Karratha at approximately 19.5745°S and 116.1363°E. The platform, commissioned in 1984, is one of the two main oil and gas production facilities operating on the NWS, with the other being the Goodwyn A platform, located 23 km southwest of NRA (Fraser & Bruce 1998). Extensive environmental data that has been recorded from NRA since its establishment makes it an ideal source of atmospheric, as well as oceanographic information.

Water depth at NRA is approximately 124.5 m and the surrounding bathymetry relatively uniform, with an almost constant gradient towards the shore at Karratha (Dolan, Williams & Crabtree 2001). Approximately 40 km offshore from NRA exists a particularly steep section of the shelf break, which is characterised by a steep drop in water depth from 200 m to over 1.2 km over a horizontal distance of less than 200 km. This region is believed to have a significant impact on the hydrodynamics occurring at NRA, with particular reference to the subsurface currents that exist in the region (Van Gastel, Ivey & Antenucci 2007).

**2.2 Oceanographic Features of the NWS**

**2.2.1 Temperature and Salinity**

Temperature and salinity variations on the NWS have a direct bearing on the hydrodynamic process that occur within the water column, as outlined in 2.2.2 below. During the summer months, sea surface temperatures on the NWS can reach 30°C, mainly attributable to the
through-flow from the Indonesian Archipelago that drives the Leeuwin Current, combined with high levels of solar radiation (Holloway 1996). These high temperatures have a significant impact on the atmospheric pressure in the region and are believed to influence the extent of cloud build-up and rainfall across southern Australia. Below the surface, in the outer-shelf region, water temperatures are maintained at around 23°C to depths of approximately 100 m. In winter, the mean surface water temperature cools to approximately 26°C, attributable to the lower levels of solar radiation (Katsumata 2006).

Salinity levels on the NWS are relatively low when compared to other oceanic regions. This is a result of the throughflow from the Indonesian Archipelago, which brings the low salinity warm waters that characterise the Leeuwin Current (Smith et al. 1991). Average salinity over most of the NWS is approximately 34.2 ppt with little variation occurring both through the water column and during the year (Holloway 1996). It should be noted that hyper-saline waters do exist near the extremely shallow inter-tidal mudflats, where evaporation rates are high. Here concentrations of up to 37 ppt have been recorded, however, this has little bearing on deeper water characteristics. Most of the changes in temperature and salinity are only noticeable in the upper 100 to 200 m below sea level (Holloway 1996).

### 2.2.2 Density Distribution

Density, and its relation to the temperature and salinity through the water column, is the main determinant in energy transfer both vertically and horizontally through the water column. In relation to the hydrodynamics occurring on the NWS, the horizontal variability of the density and shear flow stratification is considered particularly important to both surface flows, through wave propagation, and subsurface currents (Holloway 1996). The horizontal variability of density on the NWS can be best described by the presence of the oceanic mixing layer and pycnocline layer.

The oceanic mixing layer (OML) is the surface region of the ocean that directly interacts with the surface atmospheric conditions, shown as the “mixed layer” in Figure 2. Mixing within this layer is driven by a combination of wind stress and convective processes within
the water column that occur predominantly at night. The dynamic mixing properties that exist within this upper layer allow it to maintain an almost linear density by the balancing of temperature and salinity gradients within the water column (Kantha & Clayson 2000).

![Figure 2: Generalised longitudinal profile of the Atlantic ocean from Greenland to Antarctica showing the locations of the mixed layer, pycnocline and deep layer (Schiele 2007).](image)

The pycnocline, located below the OML as illustrated in Figure 2, is characterised by a sharp increase in density due to changes in temperature and/or salinity. This layer acts as a barrier to mediate the exchange of turbulent kinetic energy, momentum and heat exchange into the lower reaches of the ocean. In the circumstance where a decline in temperature is responsible for an increase in density, the pycnocline is known as a thermocline. If, on the other hand, salinity increase results in a density increase at lower depths, the pycnocline is known as a halocline (Kantha & Clayson 2000).

Pycnoclines typically occur at depths greater than 500 m, however, seasonal pycnoclines have been known to develop within the mixing layer (Schiele 2007). Off the NWS pycnoclines have been observed to exist only 40 m below the surface in the deeper waters over 1000 m deep. In shallower regions where water depths are 250 m or less, this layer becomes less distinct and the water column is dominated by the OML (Grimshaw et al. January 2005).
2.2.3 Seasonal Variations to Stratification

During the summer months the oceanic waters of the NWS are strongly stratified (Holloway 1985). Since salinity is relatively constant throughout the water column, as stated in 2.2.1, it is the changing temperature that is responsible for most of the density distribution within the water column. As the winter season approaches, the surface waters cool, making temperature gradients through the water column more uniform and well mixed in the upper 120 m of the NWS (Holloway 1985). This collapse in the stratification typically occurs in autumn and is believed to occur as a result of a combination of factors including wind-driven advection, surface cooling and tidal mixing (Katsumata 2006).

2.3 Environmental Forcing

2.3.1 Winds

Wind direction in northern Australia is dominantly determined by the location of the Subtropical High Pressure Belt and adjacent low pressure systems to the south. The Belt is characterised by a number of anticyclones encircling the southern hemisphere in the subtropical latitudes. The Subtropical Ridge, a line connecting the centres of these High Pressure Systems, is located near the Tropic of Capricorn at approximately 25°S during the winter months and in the summer it drops in latitude to approximately 35 to 40 °S (Pattiaratchi 2007). Typical locations of this high pressure belt are shown below in Figure 3.
The anticlockwise winds of the Subtropical High Pressure Belt to the immediate South of the NWS during winter bring easterly and southeasterly winds to the region. During the summer, as the ridge moves further south, low pressure systems develop over the NWS as a result of land surface heating. The line connecting the centres of these low pressure systems is known as the Inter Tropical Convergence Zone (ITCZ) or “the Doldrums”, also illustrated in Figure 3. This is the location where the trade winds from each of the hemispheres meet (Pattiaratchi 2007). The closer proximity of the ITCZ in summer results in southwest and northwesterly prevailing winds between Port Hedland and Wyndham. In coastal areas, during the summer months, local sea-breezes develop due to atmospheric temperature gradients between the land and sea, which tend to dominate daily wind patterns. It is during this period that the area is particularly subject to tropical cyclone events (CSIRO 2002).

2.3.2 Tides

Oscillations in sea surface height from tides are a direct result of the lunar and solar gravitational pull on the earth. Tides are composed of a number of diurnal and semi-diurnal constituents that, in combination, determine the overall resultant tide in a particular area. The different oscillation periods of these constituents causes variations in the long-term tidal
range. Periods when the tidal range is the highest are known as spring tides whereas periods of low tidal range are known as neap tides (Holloway 1983).

The NWS is characterised by a large semidiurnal tidal range all year round, predominantly determined by the principle lunar and solar tidal constituents $M_2$ and $S_2$ (Hearn & Holloway 1990). It is noted as one of the main tidally affected areas around the Australian coastline with a macrotidal shelf (a location where mean spring tides exceed 4 m) existing between Port Hedland and Darwin (Porter-Smith et al. 2004). In other locations on the shelf tidal ranges of up to 8 m have been recorded, making it a region with one of the strongest tidal dissipations in the world. These strong tides are the dominant cause of vigorous vertical stirring and mixing that occurs on the NWS (Katsumata 2006). The large tidal oscillation on the NWS can be attributable to its distant proximity to an amphidromic point, a location of zero tidal oscillation, and resonance caused by the tidal interaction at the continental shelf (Lim 2003).

**2.3.3 Currents**

There are a number of different mechanisms that drive the ocean currents on the NWS, with some of the more dominant mechanisms described below.

*Wind Driven Currents*

Wind driven surface currents are typically restricted to the top 80 to 100 m of the water column as determined by the depth of the OML, described in section 2.2.2 (Schiele 2007). These currents are changeable and respond to variations in wind, precipitation and heating and cooling effects at the surface. Turbulent mixing within the OML allows the vertical flux of horizontal momentum to be transferred through the water column which produces these surface currents. The rate of this flux is dependent on a number of factors, with the most important being the strength of the acting wind stress, the OML density gradient and the strength of tidal currents in the area (Kantha & Clayson 2000). Wind stresses on the surface
also result in localized gradients in sea surface heights which, in turn, affect the directionality of the flow of surface waters through altering the pressure gradient. This results in the momentum balance in the offshore waters of the NWS being dominantly geostrophic in nature, balanced between these pressure gradients due the changes in sea surface height and the Coriolis forces that become more predominant further south (Webster 1985). In most locations, these wind driven currents on the NWS have proven to become dominant during the neap tidal periods under normal weather conditions (CSIRO 2002).

These same mechanisms drive the currents caused by tropical cyclones, which are the largest currents experienced in the area. Cyclone Ian of March 1992 produced one of the largest cyclone-driven currents recorded at the NRA platform, reading 1.6 ms\(^{-1}\), with the strongest flows occurring along the regional bathymetry (Sullivan 2006).

**Gravity Currents**

A gravity or density current is the flow of one fluid within another caused by the temperature difference between the fluids (Bongolan-Walsh et al. 2007). These currents are driven by what is known as thermohaline forcing, which is the same mechanism that drives the Leeuwin Current off the West Coast of Australia, the most predominant current on the NWS. The Leeuwin Current is an anomaly to most eastern boundary currents, since it flows in a pole-ward direction when nearly all other eastern boundary currents flow towards the equator. The current brings warm, low salinity waters to the western coastal regions of Australia. The narrow current, less than 100 km wide, has a deep thermocline and is recognised as one of the fastest eastern boundary currents in the world, with a flow rate periodically exceeding 1.5 ms\(^{-1}\) (Batteen, Rutherford & Bayler 1992).

It should be noted, however, that the Leeuwin Current is forced by a number of factors and not just thermohaline forcing. Two of these include the seasonal changes in wind stress and the remote forcing caused by seasonal and inter-annual variations in the Indonesian throughflow, the source of the current. This throughflow causes the dominant broader scale
circulation on the NWS, with weak upwelling of cold deep water onto the shelf also occasionally occurring (CSIRO 2002).

Another anomaly relating to the Leeuwin Current is the Leeuwin Undercurrent that flows beneath the Leeuwin Current towards the equator. Most gravity currents flow in the upper 200 m of the water column, however, some boundary currents, such as the Leeuwin Undercurrent, may be strong to depths of up to 400 to 600 m (Smith et al. 1991).

**Barotropic and Baroclinic Tidal Currents**

Barotropic tidal currents are those defined as being independent of vertical density variations. These currents result from either wind or fluctuations in the sea surface height due to astronomical tidal oscillations and are a depth average of the horizontal velocity through the water column. This change in the sea surface height produces a pressure gradient which drives the current motion in the water column (Kantha & Tierney 1997). Since the NWS is subject to a semidiurnal tidal range, there are four current reversals per day, assuming that the pressure gradients produced by the tides are large enough to overcome ambient drift currents such as the Leeuwin Current. Spring barotropic currents average 0.45 ms\(^{-1}\) over most of the shelf, with this decreasing at areas near the steep shelf break region (Holloway 1983). The barotropic tidal currents that act on the NWS are generally orientated perpendicular to the bathymetry, acting in the same orientation to the propagating tides (Katsumata 2006).

Baroclinic tides, also known as internal tides, are as a result of vertical density fluctuations and are defined by the difference between the total current velocity and the mean flow (Kantha & Tierney 1997). Internal tides are characterised by large variations in amplitudes, phases of currents and vertical displacement over small temporal and spatial scales. Early modelling of internal tides on the NWS found that between 1 and 10 % of the total barotropic energy on the shelf was dissipated by baroclinic tides through the mixing process (Holloway 1996). Recorded amplitudes of these internal waves have been as large as 85 m
near the shelf break, with associated currents comparable to the barotropic tide and evidence of significant bottom intensification (Van Gastel, Ivey & Antenucci 2007).

Baroclinic tidal currents are formed by the interaction of the oscillatory barotropic tide with both the vertical density structure and the underlying bathymetry. Studies have shown that the strongest generation of these internal tides occur when the slope of the internal wave characteristics is close to parallel with the local seabed slope. In regions such as the NWS where strong stratification is predominant, particularly in the summer months, baroclinic tides can play an important role in subsurface flows throughout the water column. Internal tides also affect the oil and gas operations on the NWS as they are particularly sensitive to the strong currents associated with them (Davidson & Holloway 2003).

Understanding these types of currents and their interaction both with the air and through the water column is extremely important to climate and weather studies (Yuan, Martinson & Dong 2004).

2.3.4 Cyclones

Physical Features

Cyclones are intense low pressure systems, typically below 1000 hPa, that rotate clockwise in the southern hemisphere and anticlockwise in the northern, with winds exceeding gale force speeds of 63 kmh\(^{-1}\) (or 17.5 ms\(^{-1}\)) (Harper B. A. 2001). The geometric features of a cyclone consist of a uniform central core of typical radius 20 to 30km. Within the core there exists an atmospheric pressure gradient that varies from mean atmospheric pressure at the outer edge to below 950 mb in the central core in some cases. It is this pressure gradient that drives the winds of the cyclone (Hearn & Holloway 1990). Figure 4 shows the typical wind field geometry of a tropical cyclone system.
Figure 4 shows two axes, one representing the centre of the cyclone on the lower left and the other representing the winds at a distance, \( r \), from the centre of the cyclone. The main components of this diagram to note are the forward velocity of the cyclone, \( V_{fm} \), the velocity at a distance \( r \), \( V_m \), and the line to maximum winds that acts at an angle of, \( \theta_{max} \), with respect to the direction of the cyclone (Harper 2001). The line to maximum winds of the cyclone acts approximately perpendicular to the direction of the cyclone movement, however, only to the left side as illustrated by \( \theta_{max} \) in Figure 4. This is a result of the coupling effect of the peripheral cyclone velocity and the forward velocity of the cyclone both acting in approximately the same direction.
In order to identify the severity of a cyclone the Bureau of Meteorology (BOM) categorises cyclones based on their average wind speeds and maximum wind gusts. The table below identifies these categories and gives an indication of the characteristic wind speeds associated with each of them.

### Table 1: Cyclone severity identification categories (BOM 2000).

<table>
<thead>
<tr>
<th>Category</th>
<th>Strongest Gust (km/h)</th>
<th>Average Maximum Wind Speeds (km/h)</th>
<th>Typical Central Pressure (hPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>&lt; 125</td>
<td>63 – 90</td>
<td>&gt; 985</td>
</tr>
<tr>
<td>2</td>
<td>125 – 169</td>
<td>90 – 125</td>
<td>985 – 970</td>
</tr>
<tr>
<td>3</td>
<td>170 – 224</td>
<td>125 – 165</td>
<td>970 – 955</td>
</tr>
<tr>
<td>4</td>
<td>225 – 280</td>
<td>165 – 225</td>
<td>955 – 930</td>
</tr>
<tr>
<td>5</td>
<td>&gt; 280</td>
<td>&gt; 225</td>
<td>&lt; 930</td>
</tr>
</tbody>
</table>

### Relation to Ocean

Past studies have demonstrated that cyclone intensity depends on the storms initial intensity, the atmospheric thermodynamic state through which it moves and the upper-ocean properties along the storm track. Cyclones that are generated over warm tropical waters are subject to large sensible and latent heat fluxes at the sea surface that significantly impact their development and intensification. These surface heat fluxes have a greater influence on its ultimate intensity during the early development stages of the tropical cyclone compared to the later periods of the cyclones life (Brassington et al. 2006). Once developed, however, propagation over warmer waters can result in significant re-intensification of the cyclone. This describes what occurred during the Hurricane Katrina event that occurred off the coast of Florida and the surrounding regions in August 2005. The cyclone, which was initially decreasing in intensity to a Category 3, significantly re-intensified to a Category 5 when it crossed the Gulf of Mexico, where sea-surface temperatures were one to two degrees Celsius above normal (Graumann et al. 2006).
The curl and divergence of wind stress generated by the cyclone depresses the water level beneath it and in its wake. By geostrophy, the balance between the Coriolis force and horizontal pressure gradient, a strong clockwise flow is generated throughout the upper water column. By doing this, the cyclone impacts the stratification within the water column by aiding the transmission of momentum to the ocean and thus enhancing mixing (Davidson & Holloway 2003). The response of these stratified ocean waters to tropical cyclones is baroclinic as a result of the cyclone propagation speeds being similar to the phase speed along the ocean thermocline of typical long internal waves. Near resonance situations at the thermocline are formed as a result of this, causing large internal waves to develop beneath the cyclone (Hearn & Holloway 1990). This illustrates that cyclone impacts are not only an effect on surface waves, but effect the entire wave field through the water column.

A negative feedback mechanism is also known to affect cyclones on the NWS. This mechanism is produced by the ocean-atmosphere interaction as a result of storm-induced surface currents. These currents enhance vertical exchanges within the upper ocean due to momentum and result in sea surface temperature cooling which effectively reduces the cyclone intensity (Brassington et al. 2006).

**Occurrence on the NWS**

The NWS region of Australia receives more cyclones than any other part of the continent, with an average of over ten severe events occurring per decade (Porter-Smith et al. 2004). The majority of the cyclones that enter the NWS occur in the summer months of November to April (Hearn & Holloway 1990). The map shown in Figure 5 illustrates the paths of recorded tropical cyclones traversing the NWS and surrounding waters from late 2000 to early 2005.
Figure 5: Map of tropical cyclones traversing the Northern and North West waters of Australia from November 2000 to April 2005 (BOM 2007a).

Figure 5 shows that the cyclone tracks do not follow a common path, rather they propagate erratically in coast parallel and coast normal directions. What is observed, however, is that cyclones tend to form in the warmer waters of the Arafura and Timor Seas between the Cocos Islands and Darwin (Hearn & Holloway 1990). It is in these warmer waters, as stated earlier, that the cyclone gains most of its intensity. Some of the most significant historical cyclones that have passed through this area are noted in Table 2.
Table 2: Field observations from the most significant tropical cyclones to traverse the NWS. $P_c$ represents the minimum central pressure, $P_e$ the recorded external pressure prior to the cyclone influence and $R_{\text{max}}$ the radius to maximum winds (BOM 2007a).

<table>
<thead>
<tr>
<th>Tropical Cyclone</th>
<th>Month</th>
<th>Year</th>
<th>Lat (deg S)</th>
<th>$P_c$ (hPa)</th>
<th>$P_e$ (hPa)</th>
<th>$R_{\text{max}}$ (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Doreen</td>
<td>January</td>
<td>1968</td>
<td>12.0</td>
<td>970.0</td>
<td>1008.0</td>
<td>28.2</td>
</tr>
<tr>
<td>Ingrid</td>
<td>February</td>
<td>1970</td>
<td>24.9</td>
<td>953.5</td>
<td>1008.0</td>
<td>60.9</td>
</tr>
<tr>
<td>Tracy</td>
<td>December</td>
<td>1974</td>
<td>12.4</td>
<td>945.0</td>
<td>1004.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Joan</td>
<td>December</td>
<td>1975</td>
<td>20.5</td>
<td>907.2</td>
<td>1004.0</td>
<td>29.6</td>
</tr>
<tr>
<td>Trixie</td>
<td>February</td>
<td>1975</td>
<td>19.8</td>
<td>952.0</td>
<td>1005.0</td>
<td>27.8</td>
</tr>
<tr>
<td>Rosa</td>
<td>February</td>
<td>1979</td>
<td>15.2</td>
<td>955.0</td>
<td>1007.0</td>
<td>37.0</td>
</tr>
<tr>
<td>Aivu</td>
<td>April</td>
<td>1979</td>
<td>19.4</td>
<td>957.0</td>
<td>1007.0</td>
<td>22.0</td>
</tr>
<tr>
<td>Orson</td>
<td>April</td>
<td>1989</td>
<td>19.6</td>
<td>905.0</td>
<td>1006.0</td>
<td>29.3</td>
</tr>
<tr>
<td>Ian</td>
<td>March</td>
<td>1992</td>
<td>20.7</td>
<td>968.0</td>
<td>1008.0</td>
<td>33.2</td>
</tr>
<tr>
<td>Olivia</td>
<td>April</td>
<td>1996</td>
<td>21.4</td>
<td>933.0</td>
<td>1003.0</td>
<td>44.7</td>
</tr>
<tr>
<td>Vance</td>
<td>March</td>
<td>1999</td>
<td>22.7</td>
<td>927.5</td>
<td>1004.0</td>
<td>23.5</td>
</tr>
<tr>
<td>Monty</td>
<td>February</td>
<td>2004</td>
<td>20.6</td>
<td>957.0</td>
<td>1005.0</td>
<td>25.3</td>
</tr>
</tbody>
</table>

Some particular cyclones to note are Tropical Cyclone Orson, which recorded a minimum central pressure of 905 hPa, and Tropical Cyclone Tracy, which had a particularly small radius to maximum winds of 7 km. Low central pressures are typical characteristics of high intensity systems, with the radius to maximum winds typically below 30 km for the most severe cyclones (BOM 2000).

### 2.4 Modelling Cyclone Wind Fields

The aerodynamic friction between air and the ocean surface is an important aspect in the momentum balance of developing tropical cyclones (Donelan et al. 2004). The most
commonly adopted numerical model for cyclone wind field generation is the Holland (1980) formulation. A simplified form of this model is provided in Equation 1.1.

\[ v(r) = \left(\frac{r_m}{r}\right)^b (P_n - P_c) \times \exp\left[-\left(\frac{r_m}{r}\right)^6\right] / \rho_a + r^2 f^2 / 4 \right]^{0.5} - r|f| / 2 \]  

(1.1)

Where: \( v(r) \) is the azimuthal wind speed

- \( b = 1.5 + (980 - P_c) / 120 \) - is a form factor,
- \( P_c \) - the cyclone central pressure,
- \( P_n \) - the ambient environmental pressure,
- \( r \) - the distance from the centre of the cyclone,
- \( \rho_a \) - the atmospheric density,
- \( f \) - the Coriolis parameter, and
- \( r_m \) - the radius to maximum wind intensity.

(Davidson & Holloway 2003)

Many models have been developed to generate cyclone wind fields using slight variations of the same baseline formulation as outlined by Holland (1980). Two of these include the TC-Laps system produced at the Bureau of Meteorology (BOM) Research Centre in Melbourne and the CycWind model produced by the Marine Modelling Unit (MMU) at James Cook University in Townsville (Davidson et al. 2005; McConochie, Hardy & Mason 2004).

One important finding in recent years, in regards to the maximum wind velocity produced by cyclones, is that through dimensional reasoning the maximum azimuthal wind velocity can be determined, as shown in Equation 1.2.

\[ v_{\text{MAX}}^2 = \frac{T_S - T_O}{T_O} \frac{C_k}{C_D} (k^* - k) \]  

(1.2)

Here \( T_S \) and \( T_O \) represent the sea surface temperature and mean temperature at the tropopause, the boundary region in the atmosphere between the troposphere and the stratosphere, respectively. The coefficients \( k^* \) and \( k \) are the respective saturation enthalpy of
the sea surface and the actual enthalpy of the boundary layer. \( C_D \) and \( C_k \) are the exchange coefficients for momentum and enthalpy respectively (Bister & Emanuel 1998).

### 2.4.1 Wind Stress and the Drag Coefficient

Often the model input requires the wind velocities to be converted to wind stress. For extreme wind speeds, the drag coefficient used to calculate the wind stress from the wind speed becomes an extremely important factor. Studies have found that if the empirical drag coefficient is extrapolated from previous findings for wind speeds of less than 20 ms\(^{-1}\), and applied to typical cyclone wind speeds of 40 to 50 ms\(^{-1}\), the intense cyclone systems cannot be sustained due to the drag coefficient significantly exceeding credible values (Donelan et al. 2004).

There are a number of methods to determine wind stress from wind speed, with one common approach provided in Equation 1.3:

\[
\tau(r) = \rho_a C_d v(r)^2
\]

Here \( \tau(r) \) is the azimuthal wind stress (Nm\(^{-2}\)), or vertical transport of horizontal momentum, and \( C_d \) the wind speed dependant drag coefficient (Donelan et al. 2004). The drag coefficient can be calculated either through empirical tests, as shown in Figure 6, or through a relationship with the wind stress, shown in Equation 1.4.

\[
C_d = (0.63 + 0.0633 \times v(r)) \times 0.001 \quad \text{if} \quad v(r) < 25 \text{ ms}^{-1}
\]

\[
C_d = (2.28 + 0.033 \times (v(r) - 25)) \times 0.001 \quad \text{if} \quad v(r) > 25 \text{ ms}^{-1}
\]

(Davidson & Holloway 2003)
The wind fields generated by the cyclone are the dominant forcing behind the model making it therefore the most important aspect in maintaining model accuracy. In order to ensure that the wind data is legitimate it is necessary compare this with observed data taken from the area of interest. Published models, including the TC-LAPS and CycWind models mentioned earlier, must undergo an extensive calibration and data assimilation procedure before they can be deemed appropriate for use. It is important, however, to ensure that the current model input accurately represents observed data in the area, even when these calibration checks have already been performed.

2.5 Previous Cyclone Modelling Studies

The interests of the oil and gas industries and other stakeholders that exist on the NWS has motivated numerous studies that focus on the impact of cyclones in the area. In the past, qualitative results from analysing historical data have been used to gain an insight to the environmental response to cyclones. Studies such as Holloway and Nye (1984) are
representative of this. This particular study examined an extensive dataset collected during and after the passage of cyclones on the NWS, consisting of temperature, currents, sea surface heights and meteorological data. The empirical evidence found that cyclones had the most dramatic influence on current generation during the severe weather event, with these impacts largest for slow moving, high intensity cyclones (Holloway & Nye 1984).

Recent advances in computer modelling systems have enabled the oceans response to tropical cyclones to be analysed in far more detail than before, removing the limitations of qualitative approaches by now focusing on the quantitative impacts of cyclones. This section outlines some of the quantitative modeling studies performed in the past that have had a primary focus on the impact of tropical cyclones through the water column.

2.5.1 Barotropic Modelling of Tropical Cyclones

The Hearn and Holloway (1990) study detailed a three-dimensional hydrodynamic barotropic model, described by Hearn and Hunter (1987), driven by wind and pressure fields, that was applied to the NWS and the adjacent slope regions (Hearn & Holloway 1990). The purpose of this report was to help better understand the effects that cyclones had on currents and water level variations, and to determine how accurately a standard barotropic model explained the NWS response to cyclones. This study found that the circular wind stress pattern, combined with the lower pressure within the centre of the cyclone, caused a distortion in the sea surface height in the wake of the cyclone. This wake resulted in strong westward-flowing coastal and inner shelf currents between the eye of the cyclone and the coast, as a result of the setup at the coast amplifying the sea level gradient.

Hearn & Holloway (1990) found that the stability criteria for the model was largely dependant on the relationship between the minimum grid length scale and the maximum timestep used. They also found the vertical current profiles were highly sensitive to the specification of vertical eddy viscosity, parameterised as a function of wind stress (Hearn & Holloway 1990).
2.5.2 Baroclinic Modelling of Tropical Cyclones

Until recently cyclone models have been limited by omitting the baroclinic response of the water column during the storm events, which dominate during the summer months where strong stratification is present. Similar limitations are found in two-dimensional surface models that include the depth-averaged calculations as well as bottom friction estimates that are usually not properly described in two-dimensional models (Hearn & Holloway 1990). In an effort to more accurately replicate the conditions on the NWS, two studies, produced by Zhu and Imberger (1996) and Davidson and Holloway (2003), were aimed at studying the impacts of cyclones and their link to internal wave generation on the shelf region.

The report produced by Davidson and Holloway (2003) on cyclones focused on the generation of semidiurnal internal tides on the NWS as a result of a passing cyclone, Tropical Cyclone Bobby. The model used for this study was a fully three-dimensional, free surface, nonlinear hydrostatic model called the Princeton Ocean Model (POM). The study was motivated by current mooring observations analysed during the passage of Cyclone Bobby that revealed large vertical excursions at near-inertial frequency of the isotherms within the water column both during and after the cyclone had passed. The model was initialized with realistic stratification and forced by representative barotropic tides at the open lateral boundaries and cyclone winds that were derived from the analytical formulation by Holland (1980), as described in 2.4. This study first performed model runs with idealized cyclones, with a representative wind field of Cyclone Bobby later applied to the model.

Results of the model found that the cyclone modified stratification by turbulent mixing, upwelling, downwelling and density advection both up and down the shelf slope. It was these processes that were found to alter the internal tide characteristics and generation over the continental slope. Mixing was enhanced over the shelf due to the shallow topography near the shelf slope region that created a strong density front at the shelf edge. The water column response to the cyclone passage was also more abrupt in the shallow waters, around 125 metres deep, than in deeper water over 300 metres deep (Davidson & Holloway 2003).
The study by Zhu and Imberger (1996) was another to consider the impact that cyclones had on the generations of internal waves on the NWS during the summer months. The study was based on a three-dimensional numerical model, developed by Zhu and Imberger, used to simulate baroclinic responses throughout the water column to cyclones. The study found that the storm track had a large influence on the responses of the shelf waters, with coast parallel tracks inducing much larger currents, nearly double the speed when compared to coast perpendicular cyclones. It was also concluded that baroclinic phenomena, only qualitatively observed in field observations in the past, were now quantitatively explained by the model (Zhu & Imberger 1996).

*Turbulence Closure*

A study was completed in 1998 by Keen and Glenn on the impact that cyclones had on the generation of subsurface currents in shallow water bodies. In this study, the hindcast skill of the POM, the same baroclinic model used by Davidson and Holloway (2003), was assessed against measured data that had been collected from current meters at the time of the cyclone event. The study focused on the impact that alterations in model domain, resolution, definition of drag coefficients, turbulent mixing parameters and the initial temperature and salinity fields had on the accuracy of the POM (Keen & Glenn 1998).

The study found that performance was most dependent on parameters within the turbulent energy closure scheme, which were slight variations of the Mellor-Yamada 2.5 Scheme for this study, and the initial temperature and salinity distributions (Mellor & Yamada 1982). The study found that reducing turbulent dissipation within the models computation, and hence increasing mixing where density gradients existed, resulted in the best model performance (Keen & Glenn 1998).


2.5.3 Hydrodynamic Modelling of Synthetic Cyclones

The Sullivan (2006) study on the impact of tropical cyclones on the North West Shelf was conducted using the three-dimensional hydrodynamic Model for Estuarine and Coastal Ocean systems (MECO), developed by CSIRO. Three linear cyclone tracks, in both coast normal and coast parallel directions and each with three different propagation speeds, were applied to the NWS. The wind fields were generated using the Holland (1980) formulation, outlined in section 2.4, and supplied meteorological data for typical central pressures and radius to maximum winds. Effects of barotropic and baroclinic currents were not considered in the model, with all oceanographic conditions initially set in a state of rest.

The study found that both the track orientation and the propagation speed had a considerable influence on the generation and strength of the currents produced by the cyclone. Surface current speeds of up to 2.65 ms$^{-1}$ were produced by the model, when a coast parallel cyclone traveling at 5 ms$^{-1}$ was applied. Currents of 2.27 ms$^{-1}$ at a depth of 30 m were produced on the shelf break region when slower moving (approximate propagation speeds of 2 ms$^{-1}$) cyclones were applied. The bathymetry of the NWS was also found to play an important role, with peak currents often forming when the currents aligned themselves with the isobaths (Sullivan 2006).

2.6 Summary

The semi-diurnal tide that exists on the NWS dominates the dynamics of the region for most of the year. During the summer months, however, severe weather activity produced by cyclones results in a complete disruption of these dynamics through the entire water column. It is understood that during these periods, the stratification and surface temperatures have a significant impact on the associated strength of the cyclone and the generation of subsurface currents and degree of vertical mixing experienced through the water column. Detailed analysis of these impacts is still yet to be performed, leaving knowledge of the impact that cyclones have on the subsurface environment still an area of ambiguity amongst researchers. This presents a clear view of the motivation for the current project which is aimed at
providing a more detailed understanding of the impact cyclones have through the water column.

The previous studies undertaken on cyclones modelling, outlined in 2.5, provide a good basis of the findings to date and the problems likely to be encountered in this subsequent modelling study. There are a number of models currently used, both for commercial and research purposes, in the modeling of tropical cyclones and their impact through the water column. The models discussed in section 2.5 are just a few of the three-dimensional models that cyclones have been applied to. The model employed for this study was the fully three-dimensional Rutgers Regional Oceans Modelling System (ROMS). ROMS was selected as it has a vertical mixing scheme that enables baroclinic and barotropic processes to be incorporated in the model dynamics, allowing precise analysis of the impacts that high intensity surface wind stresses have through the water column. Until now, no cyclone modelling has been performed using the ROMS model, and it is the aim of this study to assess the effectiveness of applying a real tropical cyclone event to ROMS over the NWS.
3.0 Methodology

Outlined in this section are the methods that were used to reach the objectives for this study, described in section 1.1. As with most modelling studies the methodology behind this project can be classified into three main components. These include an analysis of the model itself, description of the model setup and model forcing, and the methods used to validate the model and analyse its output.

3.1 Model Description

The fully three-dimensional Regional Ocean Modelling System (ROMS) model, produced by the Institute of Marine and Coastal Sciences at Rutgers University, was the model selected for this study. ROMS is a free surface, terrain following, primitive equations hydrostatic model that solves both physical and numerical algorithms for momentum, salinity, temperature and the equation of state. A number of user defined options in the model enables choice between various advection schemes, pressure-gradient algorithms, turbulence closures and specification of the boundary conditions (Warner et al. 2005). ROMS also allows for the incorporation of thermodynamic effects such as radiative heat fluxes and other meteorological features that impact the temperature and salinity distributions near the surface, such as rainfall and evaporation.

In the horizontal direction, equations are evaluated using boundary-fitted, orthogonal curvilinear coordinates on a staggered grid. These general curvilinear coordinates include Cartesian and spherical coordinate systems. ROMS resolves solutions in the horizontal using a centred second-order finite difference approximation on what is known as an Arakawa “C” grid, meaning that velocity is defined along the edges of the grid cells and other variables, such as sea surface height and pressure, are defined in the centroid of the grid cell (Meuleners, Pattiaratchi & Ivey 2005). In the vertical direction, centred second-order finite difference approximation equations are discretised over variable topography using a stretched, terrain following, sigma-coordinate system on a staggered grid (Shchepetkin & McWilliams 2005). This grid allows for
increased resolution in areas of particular interest, such as at the thermocline or bottom layers. Details of the sigma-coordinate system adopted for this model are explained in section 3.2.2 below.

For economy the hydrostatic, primitive Navier-Stokes momentum equations are solved using a split-explicit time-stepping scheme coupled between barotropic (fast) and baroclinic (slow) modes. A finite number of barotropic steps within each baroclinic step are used to solve free surface and vertically integrated momentum equations, with this separated time stepping constrained for volumetric considerations. This split time-step removes the computational speed limitations that would otherwise result from solving the tides and fast moving gravity waves that are included in the free surface boundary layer computations (Kantha & Clayson 2000). To avoid problems with frequencies unresolved by the baroclinic steps, the barotropic fields are time-averaged before they replace those values within the longer baroclinic step (Shchepetkin & McWilliams 2005).

As with all ocean models ROMS is faced with the issue of turbulence closure, which can also be referred to as describing the flux of energy from the large scale down to the small scale. This problem in turbulence analysis relates to the issues that arise when Reynolds averaging is applied to Navier–Stokes equations, which results in more unknowns than equations, explaining why turbulence remains an unsolved problem in physics (Kantha & Clayson 2000). In order best approximate turbulence in the model, ROMS parameterises the turbulence closure problem through the use of four different, user defined, techniques. Two of these methods are the Mellor-Yamada 2.5 scheme, that uses a length scale to close the system, and the Large, McWilliams and Doney (LMD) scheme that closes the system with a non-local closure scheme which depends on boundary conditions (Large, McWilliams & Doney 1994; Mellor & Yamada 1982). Another is the Pacanowski-Philander scheme that calculates the vertical viscosity and diffusion coefficients through use of the Richardson number, a non-dimensional number that represents the variation in density squared over the variation in velocity squared (Pacanowski & Philander 1981). The final is the Generic-Length Scale (GLS) scheme that uses a number of user defined parameters to determine the degree of mixing (Umlauf & Burchard 2003).
3.1.1 Model Stability

In order to ensure that the ROMS computation remains stable the Courant, Friedrich and Lewy (CFL) condition is used as a stability measure, which determines whether the solution will remain bounded computationally. This stability criterion is measured by what it known as the Courant number. For a sigma-coordinate system the Courant number is a function of the barotropic time step, the bottom depth and the grid cell size (Kantha & Clayson 2000). Mathematically this is represented as in Equation 1.5

\[
\text{Courant #} = 2\Delta t \sqrt{gH} \left( \frac{1}{\Delta x^2} + \frac{1}{\Delta y^2} \right) \tag{1.5}
\]

Here, \( \Delta t \) represents the timestep, \( \sqrt{gH} \) the wave propagation speed in deep water and \( \Delta x^2 \) and \( \Delta y^2 \) the grid cell size in the x and y directions respectively. In theory, for the solution to remain stable and convergent the Courant number must be less than one (Kantha & Clayson 2000). In practice, however, Courant numbers of less than 0.5 are considered acceptable, as was the case in this study.

The Courant number is the most restrictive determinant of the maximum timestep in ROMS, as it has been in all models where it is employed. The split-explicit time-stepping scheme helps to reduce this by using a shorter timestep to solve the two-dimensional, fast moving, barotropic waves and a longer time step to solve the three-dimensional momentum equations. This enables a faster computation by more efficiently solving the three-dimensional equations, that are bounded by the CFL conditions, over a longer timestep (Ezer, Arango & Shchepetkin 2002).

3.1.2 Limitations of the Model

Since ROMS is based on hydrostatic computations, non-hydrostatic processes such as the breaking of internal waves cannot be represented by the model. This presents a problem
since previous studies have found that internal wave breaking does occur on the NWS as a result of the kinematic instability of internal waves that propagate onto the shelf from deeper waters (Vlasenko. V. & Hutter. K. 2002). The precision of the high order energy transfer computations also reduces the amount of momentum dissipation within the model. This often results in amplification of kinetic energy at points where significant disturbances in sea surface heights occur, such as at the boundaries of the model where the tidal forcing is applied.

The strong topography sensitivity of the sigma-coordinate system in the vertical may also produce truncation errors associated with steep pressure gradients it can produce (Song & Haidvogel 1994). It is expected that these may produce problems in the steep regions of the shelf break, however, these should be minimised due to the smoothing of the bathymetry, as detailed in section 3.2 below.

3.1.3 Why ROMS?

The fully three-dimensional basis of ROMS enables detailed modelling of both the barotropic and baroclinic dynamics that are occurring. This is particularly applicable to the NWS where strong stratification and shallow waters result in the system being dominantly baroclinic during cyclone events (Hearn & Holloway 1990). The free-surface features of the model also aid in this area, allowing the large tides experienced in the region to be included in the model computation.

In addition, the options of diverse vertical mixing schemes and the high order numerical computations of the model were a key factor in the selection of ROMS. The high order approximations within the model mean that only a low level of energy dissipation occurs, enabling most of the energy produced by the cyclone to transfer through the water column. This made ROMS particularly applicable to the objectives of this study, part of which was to directly examine the mixing characteristics of the water column during cyclones.
Although cyclone modelling has not yet been performed using ROMS, it was anticipated that this highly developed model would be able to accurately replicate the cyclone induced conditions throughout the water column.

3.2 Model Domain and Bathymetry

The selected model domain for this study was rectangular in shape, consisting of three open boundaries and one closed boundary. The open boundaries were situated on the northeast, northwest and southwest borders of the domain, and one closed boundary existed adjacent to the coast on the southeast border. The extents of the domain were selected based on the path of the selected cyclone and to ensure that it would adequately represent the extent of the shelf region. The approximate extents of the model domain, including the location of the field observation station at NRA and path of the selected cyclone, described in section 3.3, are illustrated in Figure 7.

Figure 7: Plot of the model domain and bathymetry. Location of NRA indicated with the path of Tropical Cyclone Monty shown as the red dotted line.
As shown in Figure 7, the four corners of the rotated grid exists at 18.65°S, 123.33°E and 19.05°S, 112.64°E on the East and West edges respectively and 15.56°S, 122.06°E and 22.10°S, 113.92°E for the North and South edges. The deepest section of the domain is 3343 m and exists at approximately -17.42°S and 117.85°E, near the centre of the northwest boundary. Bathymetry data for the model was obtained from the Geosciences Australia database (Geoscience Australia 2006). A rotated square grid, with edge size of approximately 3.5 km, was used over this rectangular domain, which had approximately 280 grid cells along the northwest and southeast border and 110 along the northeast and southwest.

Land boundaries that existed within the model domain were masked to zero elevation and a minimum depth of 20 m was set to reduce computational errors in the shallow regions where the solution was not a particular focus. As Figure 7 illustrates, the extent of the domain significantly overcompensates for the width of the shelf. This was done intentionally so that the strong winds associated with the cyclone did not impede on the boundary at too great a magnitude, as this would likely result in numerical instability. An example of how the domain was initially modified to compensate for this is presented below in section 3.3.1.

3.2.1 Bathymetry Smoothing

In order to avoid problems that were likely to result in computational error in ROMS the bathymetry of the model was “smoothed”. This was done to ensure that extremely steep or vertical slopes in the bathymetry would not result in truncations errors, described in section 3.1.2, as a result of steep pressure gradients. Plots (a) and (b) in Figure 8 illustrate the transitions in the model bathymetry as the smoothing was applied.
Figure 8: Smoothing transition applied to the model bathymetry from (a) pre-smoothing to (b) post-smoothing.

Plot (a) clearly illustrates the steep slopes of the shelf break region, with the particularly steep section of the break near NRA, as discussed in section 2.1.2. These features are also
evident after smoothing was applied, illustrated in plot (b), signifying that only limited information was lost during the smoothing of the shelf and shelf break region. The most extreme smoothing was applied to the deeper regions below 400 m to ensure that the resolution of the bathymetry on the shelf region was not reduced. The gradual slopes on the shelf meant computation errors would not likely eventuate within this region.

### 3.2.2 Sigma-Coordinate System

An example of the sigma-coordinate grid employed by ROMS is shown in the vertical profile below in Figure 9. This was constructed using the smoothed model domain illustrated by plot (b) in Figure 8.

![Sigma Coordinate Grid - SW Border](image)

**Figure 9: Cross-section of sigma coordinate system at the southwest border of the model domain.**

The vertical sigma-coordinate profile shows that at all depths, the number of layers remain constant. The spacing and number of these lines is specified by the user through the use of two parameters $\theta_s$ and $\theta_b$, which either increase or decrease the resolution near the surface and seabed. For this model the vertical discretization of the sigma-coordinate system was initially set to 40 layers, with coefficients of $\theta_s$ and $\theta_b$ equal to 3 and 1 respectively, as
indicated on the figure. This was considered adequate in solving the deeper water dynamics off the shelf break, and small enough to not result in numerical instability in the shallow regions on the shelf, which was the limiting factor in this study.

### 3.3 Cyclone Monty

When selecting the appropriate tropical cyclone to model for this study a number of cyclones were first considered. Some of these included Tropical Cyclone Fiona, Harriet, Alistair, Ingo and Monty. In the end Tropical Cyclone Monty was selected due to the reliability of the observed field data for the cyclone, particularly at NRA as shown in Figure 10, and the existence of the most up-to-date boundary forcing information for the model over the same period as the cyclone event.

![Figure 10: Tropical Cyclone Monty Track, Dates and Cyclone Category (BOM 2007b).](image)

The unique track of Monty was also a prominent factor in selecting this cyclone. Unlike most other cyclones, the track of Monty consists of a near consistent coast parallel segment followed by a coast normal component. This enables the effects of both of these paths to be identified and related to a previous study on the topic, presented in Sullivan (2006). Cyclone
Monty also remained within approximately 150 km of the coast from the time it was generated on the 12th of February 2004, southeast of Broom, until the time it made landfall near Mardie on the 2nd of March at midnight (BOM 2007b). This not only allowed the model domain to be focused in a small area, only on the shelf region, but also enabled the full path of the cyclone to be observed whilst it traversed the ocean.

Meteorological information on Tropical Cyclone Monty, supplied by the BOM, is provided below in Appendix A.1. According to the BOM, maximum wind gusts for Tropical Cyclone Monty reached 69.45 ms\(^{-1}\) (\(~\) 250 kmh\(^{-1}\)) with average maximum wind speeds of approximately 51.44 ms\(^{-1}\) (\(~\) 185 kmh\(^{-1}\)). This occurred when the cyclone was approximately 76 km southwest of the NRA platform, at 19.9\(^{0}\)S and 115.5\(^{0}\)E at 12 am WST. The minimum central pressure reached by the cyclone was approximately 935 hPa, during the same period that the cyclone attained its maximum winds. It was in this area, as shown in Figure 10, that Cyclone Monty developed into a Category 4 cyclone. According to the Australian Bureau of Meteorology (BOM) this is characterized by maximum wind gusts of 225 to 280 kmh\(^{-1}\), average wind speeds of 165 to 225 kmh\(^{-1}\) and a minimum central pressure ranging from 930 to 955 hPa, as indicated in Table 1 (BOM 2006).

### 3.3.1 Model Wind Forcing

The wind forcing for the ROMS model used data supplied by the Marine Modelling Unit (MMU) at the Australian Maritime College. The wind data was produced using a parametric wind field model known as CycWind. The CycWind model is a double vortex tropical cyclone wind and pressure field model based on an extended version of the parametric model presented by Holland (1980) as outlined in 2.4. The model merges synoptic scale wind fields, typical ambient winds generated outside of the cyclone, with the cyclone winds to replicate the interaction between the cyclone vortex and surrounding pressure systems that dominate the area during the summer months. It does this by using a more detailed pressure model than the fundamental Holland (1980) formulation to ensure a more accurate fit with the synoptic data at distances from the cyclone vortex (McConochie, Hardy & Mason 2004).
Methodology

Empirical tests of the model output with field observations have been performed using the graphical user interface tool CyCal, developed using Matlab. CyCal was developed by the MMU for the sole purpose of interactively calibrating the CycWind model with measured data. Observational data used in the models calibration comprised wind speed, direction and pressure data measured at over 100 meteorological measurement stations. Calibration of the model has been dominantly focused on the Coral Sea region, with 64 historical tropical cyclones proven to accurately be represented in the CycWind model. CyCal has also been used to calibrate approximately 15 cyclones on the NWS, including cyclones Olivia, Orson and Vance, with the results demonstrating extremely close correlations between observed data and the model output (McConochie, Hardy & Mason 2004).

Analysis of the Wind Field

The supplied data output from CycWind was given from 6 am on the 25th of February 2004 until 12 am on the morning of the 3rd of March 2004, providing output of average wind speed every ten minutes. The winds are supplied on a 0.025 degree (or 2.68 km) grid, extending over the entire model domain. For the purposes of our model, and due to the large size of the forcing file, these winds were only extracted on a 60 minute timestep using the 0.025 degree grid supplied.

Information extracted from the wind data set showed that the maximum winds obtained by Cyclone Monty were approximately 48.9 m$\text{s}^{-1}$ at 10 am on the 29th of February. This was comparable to the observation of approximately 51.44 m$\text{s}^{-1}$ made by the BOM stated above, especially since CycWind represents an average over the 0.025 degree grid. The model output also provided the cyclones radius to maximum winds during the period outlined above. The smallest radius to maximum winds extracted from CycWind was approximately 21.6 km at 9 am on February 29. Although this was slightly lower it was still comparable to the observation of 25.3 km in Table 2. Mean radius to maximum winds over the supplied period, as extracted from CycWind, was approximately 30.20 km. Details of the radius to maximum winds and centre point location of the cyclone, as determined by CycWind, have been included in Appendix A.2.
In order to ensure that the wind fields were correctly interpolated onto the model domain and that they matched the cyclone path shown in Figure 7, spatial plots of the wind speed and direction were produced through the use of Matlab. Producing these plots allowed the suitability of the model domain to be confirmed and the identification of coastal areas most significantly impacted by the cyclone. The first plots produced by this script showed that over the initially constructed model domain the centre of the cyclone vortex came within close proximity to the northern border. This was particularly evident during the period when the cyclone gained most of its intensity as shown in Figure 11 below.

![Spatial Wind Speed and Direction Plot](image)

**Figure 11:** Spatial wind speed plot of the supplied CycWind data against the initially constructed model domain. Location of NRA identified by the white & red marker and maximum winds the white marker.

As indicated by the date of the plot, this occurred when the winds of the cyclone were almost at their maximum of 48.5 m/s\(^{-1}\). For this reason, the domain and bathymetry files were restructured so that the new domain extended approximately 120 km in a northwesterly direction. The restructured domain, for the same time period shown in Figure 11, is illustrated below in Figure 12.
Figure 12: Spatial wind speed plot of the supplied CycWind data against the revised model domain. Location of NRA identified by the white & red marker and maximum winds the white marker.

As Figure 12 indicates, the maximum winds on the north-western border were reduced from approximately 26 ms$^{-1}$ to 16 ms$^{-1}$. This was believed to significantly reduce the likelihood of having energy dissipation problems at the boundary.

One particular point to note in both Figure 11 and Figure 12 is the close proximity of NRA’s monitoring station to the maximum winds achieved by Cyclone Monty. As stated earlier, this was one of the particularly important aspects in the selection of Cyclone Monty for the study. Other spatial wind field plots produced that were used in this analysis have been provided in Appendix A.3. These plots show that the maximum cyclone winds, at a given radius, are located approximately perpendicular to the direction of cyclone movement, on the side where the wind direction is the same as the propagating cyclone direction. This is consistent with the literature on cyclone wind field geometry described in section 2.3.4.
Converting Velocity to Stress

Wind data for the model was supplied in terms of wind velocity components, u for meridional and v for zonal. In order to use this to force the model these velocity components had to first be converted to wind stress components. This was done by using Equation 1.3, which takes the wind speed and an estimate of the drag coefficient and air density. For our purposes an air density of 1.177 kgm\(^{-3}\) was used, as this was believed to most accurately approximate the mean air density experienced in the area during a cyclone event. Past papers on this topic, such as Davidson and Holloway (2003), used an air density of 1.34 kgm\(^{-3}\). This, however, appeared to be too large since dry air at 20 °C is approximately 1.21 kgm\(^{-3}\) and moist, warm air, such as that during cyclones, is less dense than dry, cool air (Kantha & Clayson 2000).

The specification of the drag coefficient (C\(_d\)) was a complicated task in itself. There are two ways to define the drag coefficient; constant, or varying with wind velocity. There are a number of formulas proposed to calculate the drag coefficient using the varying with wind velocity method, most determined by studies that have focused on intense wind systems such as those produced by cyclones (Davidson & Holloway 2003; Donelan et al. 2004). For this study, the varying with wind velocity calculation of the drag coefficient was used. This was selected since a constant drag coefficient applied over the whole domain was considered inaccurate due to the high variability of wind velocities between the cyclone winds and the surrounding synoptic winds. Specifically, the Davidson & Holloway (2003) formulation was adopted, as illustrated in Equation 1.4, as it was believed that this split computation best reflected the empirical results obtained in the Donelan et al. (2004) study, described in section 2.4.1. Figure 13 below represents the results of an analysis that was made on the variation in the calculated drag coefficient with increasing wind velocity using the Davidson & Holloway (2003) formulation.
As shown in Figure 13, there is a significant, and almost linear, variation in the drag coefficient with changing velocity, which is reflective of the empirical results illustrated in Figure 6. It also produced a drag coefficient of approximately 0.0030 when using the maximum wind speed from the CycWind file of 48.5 ms\(^{-1}\), which was close to the empirical maximum of 0.0025 as illustrated in Figure 6.

The processing of the supplied CycWind data was done through the use of Matlab. This included transferring the winds onto the rotated grid domain and converting the file into a format recognizable by the ROMS model.

### 3.4 Boundary and Initial Conditions

The ROMS model can be configured for various combinations of open or closed boundaries. In our model there are three open boundaries, as described in section 3.2, that ROMS requires a continuous set of information on temperature, salinity and surface elevation to be supplied for. These boundary conditions, as well as an initial condition file containing the same variables in addition to the u and v velocity components, are stored in NetCDF boundary and initial condition forcing files respectively, known as the climatology file.
The boundary and initial conditions used to force the model were taken from the BLUElink operational ocean prediction system developed by the BOM, the Royal Australian Navy and CSIRO. The development of the BLUElink ocean forecast model was initiated in 2003 to deliver operational short-range forecasts for the Asian-Australian region. These forecasts include information of surface and subsurface ocean temperature and salinity, coastal and ocean current, wave forecasts and eddy generation (Brassington et al. 2006).

In order to test the accuracy of BLUElink an analysis has first been made using the model in hindcast mode. This model output has been named the BLUElink Reanalysis (or BRAN) output. At the time of this report only one of these outputs had been made available to the general public, BRAN 1 (Brassington et al. 2006). The output from this run was produced from early 1992 to the start of 2004, just before the Cyclone Monty event. Another edition of this hindcast output BRAN 1.5 was scheduled to be run in early 2007 for the periods over 2004 to late 2006, however, this was not scheduled to be published until May 2007 (Brassington et al. 2006). Fortunately we were able to access the early output from the BRAN1.5 version, midway through this project. This ensured that the boundary and initial forcing conditions for the model consisted of the latest oceanographic information available. The data was supplied over a 10 km square grid scale in the horizontal plane, extending over the entire model domain. In the vertical, data was supplied over 10 meter increments from 5 m to 205 m depth, and then at exponentially increasing increments from 205 m to 4500 m over a total of 47 layers.

This data was initially supplied in ASCII format, so a Matlab script was used to convert the data to the required ROMS input. An important part to note here, was that a linear interpolation was used to match the BLUElink vertical scale with that of the model. This may have been an inaccurate assumption, however, time limitations made a full-scale analysis of the accuracy of this unfeasible.
3.5 Model Run Timeframe and Other Inputs

When determining the run time for the model, it was decided that a three week “ramp-up” would be sufficient to stabilise oceanographic conditions within the model before the cyclone event was applied. The overall run timeframe for the model was from the 6th of February 2006 to the 14th of March 2006. The different timesteps for the barotropic (2D) and baroclinic (3D) were 5 seconds and 120 seconds respectively. Thus there were 24 barotropic steps within each baroclinic step as defined in section 3.1.

During this initialisation period, before the cyclone winds became evident, and after the cyclone event the model had zero wind forcing. A graphical representation of this, for the grid cell nearest NRA, is shown below in Figure 14.

![Plot of wind speed at 116.125 E 19.575 S for the duration of the model run](image)

Figure 14: Plot of winds forcing for the duration of the model run at the approximate NRA location.

Similar winds to this were applied over the entire model domain. This was believed to be more realistic than an initial postulate to apply a constant wind during the “ramp-up” period.
that would have likely lead to computational error due to sea surface height setup near coastal areas.

In addition to the boundary forcing and wind forcing applied to the model, tides and radiative heat fluxes were also included. Radiative heat fluxes were taken from meteorological data obtained at NRA and the tides were applied by the TPXO.6.2 global ocean tide model, produced by the Oregon State University (Egbert & Erofeeva 2002). The fact that these tides dominate the dynamics in the water column during non-cyclonic events was one reason that justified the lack of wind forcing during the initialisation period (Katsumata 2006).

3.6 Observed Data

The main source of observational data for this study was that recorded at Woodside’s NRA platform, courtesy of Woodside Energy, located at approximately 19.5745°S and 116.1363°E. Figure 15 below is a schematic of Woodside’s NRA platform, showing the location of the oceanographic measuring devices.

Figure 15: Schematic of NRA platform with current meter mooring identified (Courtesy of Woodside Petroleum).
As indicated in Figure 15, the current meters are located away from the central jacket system of the platform, which ensures that interference with the subsurface dynamics by the platform is minimized in the current meter measurements. The NRA platform was an ideal source of field observations due to its close proximity to the cyclone at its state of maximum wind intensity, as affirmed in section 3.3. It was also one of the only locations on the NWS where a continuous set of oceanographic data through the water column was recorded.

### 3.6.1 Meteorological Data

The meteorological data, taken from the NRA platform, included information on air temperature, barometric pressure, wind speed and direction, solar radiation and relative humidity. Of these the main parameters used for this project were wind speed and direction, solar radiation and barometric pressure measurements. This data was supplied on an two minute timestep for the entire 2004 period. A few gaps in the data were present, however, these only occurred after the 2\textsuperscript{nd} of March, two days after the cyclone reached its maximum intensity.

The meteorological data provided by the BOM, shown in Appendix A.1, was also used as a preliminary validation of the CycWind data. This data set, however, was not a particular focus of this study, since it represents information recorded by satellite which is generally not regarded to be as reliable as in-situ meteorological measurements (Santer et al. 2003).

### 3.6.2 Oceanographic Data

The oceanographic data set was supplied for the entire modelled period from the NRA station, as illustrated in Figure 15. This dataset consisted of time-series information on temperature, current speed and current direction at a two minute timestep, as with the meteorological data. The measuring devices used on the platform are located at irregular intervals throughout the water column at approximately 5 m, 30 m, 60 m, 75 m and 117 m above the seabed (ASB). Temperature readings from the current meters were given as in-
situ temperature, so to enable a direct comparison with BLUElink and ROMS, this was converted to potential temperature.

There were two measuring devices located at 22 m and 35 m above the seabed that had no information available over the model run period. The shallow depth at NRA of only 124.5 m, however, meant that the information obtained provided a comprehensive set of oceanographic information in which to compare the model output to.

### 3.7 Model Input Evaluation

The most important aspect in maintaining model accuracy is to first confirm that the model forcing is an accurate representation of what is being observed in the physical environment. For this reason a comprehensive analysis was undertaken to study the accuracy of the model inputs when compared to the supplied meteorological and oceanographic field observations.

#### 3.7.1 CycWind Evaluation

In order to validate the accuracy of the wind forcing file, a comparison was made with meteorological data obtained at NRA. Both wind speed and direction were extracted from the input CycWind file at the grid cell closest to NRA, which was considered more accurate than an interpolation to the exact NRA location since the value at each cell was an average over the 2.68 km grid itself. The results of this comparison have been presented below in section 4.1.

#### 3.7.2 BLUElink Evaluation

Apart from the winds used to force the model, the selection of appropriate and accurate boundary conditions is the next most important aspect in maintaining model accuracy. For
this reason a comprehensive analysis was made on the effectiveness of the BLUElink model at replicating observed conditions at the NRA site.

In order to compare the observed conditions at NRA with the BLUElink output, the observed data was filtered to remove variations that were a direct result of tidal information, which BLUElink does not incorporate in its output. The filter basically removes all of the lower frequency variations in temperature, current speed and current direction from the data set that are below a specified period. Initially this filtering was done with a 30 hour filter, as this was deemed appropriate to remove the impacts of both the semidiurnal and, more importantly, diurnal tidal components. Later the filter was adjusted to 24 hours, as a result of the inaccuracies in the past filter not adequately resolving the thermocline and other variability seen in the BLUElink output. This analysis was visualised by creating profile plots over the water depth at NRA to illustrate the variability through the water column of temperature, current speed and current direction.

In addition to the filtered data, daily averages were calculated from the observed data. This was done to assess both the validity of the filter and for comparisons against the BLUElink data. It should be noted, however, that even with the filter and daily averages applied there is still some information reflective of the tides evident in the data. Also, the random and distant spacing of the current meters located at NRA means that there is the possibility of large variations between these record locations. For this reason it is not possible to make a direct comparison between BLUElink and the observed data, rather only general conclusions can be made from the comparison.

To counter this limitation in the analysis, and to provide further validation of the boundary condition accuracy, a regression analysis was also performed. This helped to remove the inaccuracies behind the assumptions of a linear interpolation between data points in both the observed data and the BLUElink output. In order to simplify this regression analysis, the modelled period was split into two separate time periods: the entire modelled period, from the 6th of February to the 3rd of March, and the cyclone impact period from the 27th of February to the 3rd of March. This segregation of time periods allowed the accuracy of BLUElink during different stages of the model to be analysed.
The results of the BLUElink analysis are presented in section 4.2.

### 3.7.3 Mixing Scheme Evaluation

In order to ensure that the most accurate model prediction was being achieved in our analysis, a number of mixing schemes were tested. These included the Mellor-Yamada, LMD and the GLS schemes identified in 3.1. For the GLS scheme three variations were used that included the k-omega, k-epsilon and k-tao.

The accuracy of each of these schemes was determined by examining their ability to most accurately resemble the oceanographic conditions occurring at NRA, with a particular focus on the temperature profile and mixing induced by the cyclone. The results of this analysis and details of the final scheme employed are provided below in section 4.4.1.

### 3.8 Model Output Analysis

The following methodology was used to analyse the data output from the ROMS model, with the main focus of this based on the objectives of the study outlined in section 1.1. This information was visualised with the use of the Matlab toolbox ODVT (Oceanographic Data Visualization Tool), which had been reconstructed to specifically focus on ROMS output.

For the purpose of this particular study, most emphasis was placed on analysing the model output at NRA, where a direct comparison could be made with the observed data, described in section 3.6. Information on baroclinic velocity, the u and v velocity components, temperature and salinity were all output from the model through the water column at the NRA station. This was extracted for the entire duration of the model run, enabling a direct comparison to be made with oceanographic data extracted for the same period.

In addition to the output extracted at NRA, model output was also extracted at locations along the path of the propagating cyclone for the duration of the model run. This was done
Methodology

to assist in analysing the mixing characteristics caused by the cyclone and to enable quantification of the mixing impact that the cyclone had as the magnitude of its winds increased. In order to maintain a consistent methodology, the points along the cyclone path were extracted at regular intervals in time. These intervals were determined by the location of the cyclone centre every 12 hours from 6 pm on the 27\textsuperscript{th} until 6 am on the 1\textsuperscript{st} of March, with an initial point also taken at its location at 6 pm on the 26\textsuperscript{th} of February. The locations of these extracted points are represented graphically below in Figure 16.

Figure 16: Plot of locations along the cyclone path where model output was extracted

As indicated in Figure 16, the locations output were at varying depths within the domain. This enabled the role that bathymetry played in determining the level of mixing induced by the cyclone at certain areas to be analysed. A summary of each of these locations has been provided below in Table 3.
Table 3: Location features of points included in the model output along the path of the cyclone.

<table>
<thead>
<tr>
<th>Location ID</th>
<th>Location Coordinates</th>
<th>Date Monty Passed Location</th>
<th>Max Wind Speeds at Location (ms⁻¹)</th>
<th>Cyclone Category</th>
<th>Approximate Depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loc 1</td>
<td>-18.6, 121.2</td>
<td>26/02 18:00</td>
<td>14.83</td>
<td>0</td>
<td>44</td>
</tr>
<tr>
<td>Loc 2</td>
<td>-19.2, 119.2</td>
<td>27/02 18:00</td>
<td>24.78</td>
<td>1</td>
<td>70</td>
</tr>
<tr>
<td>Loc 3</td>
<td>-19.2, 117.8</td>
<td>28/02 6:00</td>
<td>31.24</td>
<td>2</td>
<td>104</td>
</tr>
<tr>
<td>Loc 4</td>
<td>-19, 116.8</td>
<td>28/02 18:00</td>
<td>34.56</td>
<td>3</td>
<td>312</td>
</tr>
<tr>
<td>Loc 5</td>
<td>-19.5, 115.8</td>
<td>29/02 6:00</td>
<td>44.77</td>
<td>4</td>
<td>239</td>
</tr>
<tr>
<td>Loc 6</td>
<td>-20.1, 115.2</td>
<td>29/02 18:00</td>
<td>44.23</td>
<td>4</td>
<td>172</td>
</tr>
</tbody>
</table>

Extracting the information at these locations enabled good spatial representation of the impact of the cyclone across the model domain. It also allowed a more detailed analysis to be made at locations surrounding NRA, particularly in the regions near the shelf break as illustrated by the close proximity of the additional extraction points in this region in Figure 16.

### 3.8.1 Scale Issues in Comparisons

As with all modelling studies, there is the problem of making comparisons between field and model output with the varying spatial and temporal scales that they represent. This means that making a direct comparison between the model output and that observed at NRA is not possible under normal circumstances. Figure 17 graphically illustrates this problem for the grid resolution used in this model.
As indicated Figure 17, the model grid cell that represents the closest location to NRA is actually an average over the 16 km$^2$ cell area. For this reason when comparing the results from a point source to that of the model output a direct comparison, particularly for high spatially variable features such as subsurface currents, is nearly impossible.

The resolvable scale of the model is another factor associated with scale issues. Field results at NRA are able to pick up features with a horizontal scale of 120 m, given the two minute sampling rate of the current meters and average current speed of 0.5 ms$^{-1}$. The model output, on the other hand, is only able to resolve features within the flow with a minimum horizontal scale 40 km. This is attributable to the 4 km grid resolution and the fact that features only 10 times this resolution, or larger, are able to be resolved by the model. Understanding these issues makes comparisons between the field and model data far more reasonable given the simplicity of the model when compared to the real world scenario.
4.0 Model Results

This section presents the results of the modelling and data evaluation outlined in the methodology. The results are presented with evaluation of the wind and boundary forcing examined first, followed by the results obtained from the ROMS model.

4.1 CycWind Evaluation

The CycWind data was evaluated spatially to verify the consistency of the interpolated wind field onto the model domain, as detailed in section 3.3.1, using the plots produced in Appendix A.3. Following this, a comparison was made between CycWind and the point source wind data obtained from the NRA meteorological station.

Recorded station information on Cyclone Monty, showed maximum winds of 35.4 ms\(^{-1}\), at a bearing of 77 degrees (TN), as recorded at 4:50 am UTM on the 29\(^{th}\) of February 2004. Comparatively, the CycWind dataset showed maximum winds of 41.3 ms\(^{-1}\) were achieved nearest NRA on the 2.68 km grid, at a bearing of 145 degrees (TN) at 5:00 am UTM on the 29\(^{th}\) of February. Both of these values are characteristic to a Category 3 cyclone event, as defined in Table 1. A comparison between the wind speed and direction at the NRA station for the duration of the model run is presented in Figure 18.
Figure 18: Plot of (a) measured wind speed and (b) direction at NRA (in red) against the wind speeds and wind directions produced by CycWind (in blue).

These time-series plots show that the CycWind data, although at a much lower time resolution than the observed data, reproduces the general wind field trend at NRA. Figure 18 (a) of the wind speed, demonstrates that the CycWind data reproduces the variability in
the field data set with correct phasing, but overestimates the peak speed by approximately 15%.
This is indicated by the slightly higher wind magnitude experienced by CycWind when compared to that measured at NRA, during the cyclone event from the 28\textsuperscript{th} of February to the 1\textsuperscript{st} of March. The symmetrical nature of the cyclone winds, as illustrated in Appendix A.3, results in a shift in the wind direction at NRA of approximately 70\degree, as shown in Figure 18 (b). The implications of this on the model performance are discussed in section 5.1.

\subsection{4.2 BLUElink Evaluation}

The results of the BLUElink analysis, through comparisons with observed oceanographic data at NRA, have been presented below. Plots of the temperature, current speed and current direction through the water column were made for each of the days that the BLUElink data was extracted (from 6\textsuperscript{th} February to 3\textsuperscript{rd} March 2004). In addition, a regression analysis was performed with the temperature and current speed data. For the comparisons, observed data was both averaged and filtered, as outlined in section 3.7.2.

\subsubsection{4.2.1 Boundary Conditions}

Figure 19 and Figure 20 show the initial temperature and salinity profiles through the water column on the northwest and southwest boundaries of the domain.
Figure 19: Plot of the temperature profile input by BLUElink on (a) the NW and (b) SW boundaries from the initial conditions.

Figure 19 indicates the strong temperature stratification that is observed over the NWS for the summer periods, as discussed in section 2.2.3. The thermocline is clearly evident in the water depths of between 100 to 300 m, where the temperature drops from approximately $20^\circ$C to $12^\circ$C.
Figure 20: Plot of the salinity profile input by BLUElink on (a) the NW and (b) SW boundaries from the initial conditions

The salinity profiles in Figure 20 show a much lower vertical variation than for temperature, as anticipated. There is, however, evidence of a slightly higher salinity layer between 100 and 400 m below sea level.
4.2.2 Low-pass Filtered Data

As discussed in section 3.7.2, a filter was applied to the oceanographic data to remove tidal frequency information and to enable a better comparison with the BLUElk d link daily averaged dataset. The effect of the 24 hour low-pass filter on the spectra of the observed temperature at NRA is illustrated below in Figure 21.

![Image: Spectral density plot of observed and 24 hour low-pass filtered temperature at 75 m ASB over the entire modelled period.]

This plot was extracted from the current meter located at approximately 75 m ASB, the second deepest current meter located at NRA as identified in section 3.6.2. As indicated in Figure 21, semidiurnal tidal frequency is almost completely removed from the field data, with only a slight variation in the diurnal tidal frequency still present. The two horizontal red lines on each of the plots indicate the 95% confidence interval. This is the minimum height that a spike in the spectral density, at a given frequency, must be in order to conclude that it is both large and real with 95% confidence. The semidiurnal tidal frequency, observable by the spike to the immediate right of the identified “semidiurnal tide frequency” line in Figure 21, clearly exceeds this.
4.2.3 Temperature

Figure 22 below presents the comparisons between the supplied BLUElink daily average temperature data and the low-pass filtered observational data at NRA. The selected periods shown include the 29th of February, when the cyclone was nearest NRA, and two days before and after this date.
Figure 22: Plot of daily average and filtered observed temperature profiles against BLUElink through the water column at NRA from the oceanographic data set. Dates for (a) to (c) are as titled.

Figure 22 shows that there is approximately a 1 to 2°C deviation between the measured data and the output provided by BLUElink, with BLUElink consistently warmer than observed. The rest of the BLUElink comparison plots of the temperature profile through the water
Model Results

column are provided in Appendix B.1. Figure 23 represents the regression plots of the observed daily average in-situ temperature records against BLUElink’s approximation.

(a) Plot of regression between observed temperature data and BlueLink at NRA from 06-Feb-2004 to 05-Mar-2004

The equation of the line of best fit in blue is $y=0.7841x + 6.9989$ with a correlation coefficient of 0.95227.
Model Results

Figure 23: Regression plots of observed daily average in-situ temperature against the BLUElink approximation at the five current meter locations (different coloured markers represent each depth). Plot (a) is the entire modelled period and plot (b) the cyclone impact period, as titled.

The correlation coefficient produced in both of these regression analyses was above 0.93, implying that a reasonably close correlation existed between the observed temperature data and BLUElinks approximation. Although this correlation is better for the entire period data set, it is the regression line produced during the cyclone impact period that produces a regression line closest to the “perfect correlation line” i.e. one that has a slope of one and an intercept of zero between the two axis.

Figure 23 (a) illustrates that the deviation from the perfect correlation line increases from approximately 0.8°C in the warmer surface waters to approximately 2.5°C in the cooler regions near the seabed. Plot (b) shows a similar deviation in the surface waters, however, less deviation near the seabed of below 2°C, consistent with the deviations observed near the seabed in Figure 22.
4.2.4 Currents

Figure 24 below is a sample of the current speed comparison profiles through the water column, for the same dates as provided for temperature above.
Model Results

Figure 24: Plot of daily average and filtered current speed profiles against BLUElink through the water column at NRA from the oceanographic data set. Dates for (a) to (c) are as titled.

For the most part, BLUElink appears to produce lower than measured current speeds through the water column, with the exception being the profile seen for the 29th of February in Figure 24 (b). In this plot, the current produced by BLUElink goes from 0.5 ms\(^{-1}\) below the average measured speed at 30 m below the surface to 0.2 ms\(^{-1}\) above the measured speed at 10 m below the surface. The remainder of the current speed plots have been provided in Appendix B.2.

Figure 25 below represents a regression analysis of the observed currents speeds at NRA against BLUElink’s approximation, for the same two time periods used in Figure 23.
Figure 25: Regression plots of observed daily current speed against the BLUElink approximation at the five current meter locations (different coloured markers represent each depth). Plot (a) is the entire modelled period and plot (b) the cyclone impact period, as titled.
These plots show that the regression line for current speed is closer to the line of perfect correlation than that for temperature, however, the correlation coefficient is significantly lower. This was anticipated due to the high spatial variability of current speed when compared to temperature. From the plots in Figure 25, however, the greatest variation in current speed occurs nearest the surface, as indicated by the deviation from the perfect correlation line of the 7 m and 49 m depth markers when compared to the results nearer the seabed.

No regression analysis was made on current direction as the low correlation in current speed would void any results obtained in the analysis. For completeness, however, comparison plots of the current direction produced by BLUElink and the respective field measurements have been provided in Appendix B.3. These profiles show a relatively close agreement with the observed data at lower depths, however, this is not the case for all of the modelled days. The larger deviation that occurs at the surface, however, is consistent through most of the data set, with the magnitude of this deviation appearing to vary considerably over both the cyclone and non-cyclone periods.

4.3 Restructured Model Domain

The first few runs that were performed showed the volume averaged kinetic energy significantly increase before the solution became unstable and the model stopped. These were believed to be a direct result of the high variability in the bathymetry at the NW and SW borders of the model. Indications that this was likely the case are shown by the steep slopes of the sigma coordinate computational grid layers, as shown in Figure 9 and Figure 26 below, for the southwest and northwest borders respectively.
The locations believed to cause the model instability are indicated in Figure 26. Locations A and B represent those regions where steep gradients in the bathymetry were causing computational errors within the model. Location C represents another problem encountered with sigma-coordinate grid systems, where too many layers in the shallow domain regions result in instabilities due to the close proximity of each of the layers. These were only representative locations, with other parts of the domain that exhibited similar features also causing instability within the model.

Figure 27 below represents the further smoothing that was applied to the model domain in order to reduce the model instabilities outlined.
As with the first stage of smoothing, shown by plot (b) in Figure 8, more extreme smoothing was applied over the deeper regions of the domain, where water depths were below 400 m. The 400 m depth was selected as its contour was far away enough from the cyclone path and therefore not considered to affect the resolved cyclone induced dynamics which were expected to be largely confined to the upper 200 m, as detailed in section 2.5.2. The contour was also far from the particular region of interest at NRA and considered to have little inference on the predicted cyclone induced dynamics in this region.

In addition to this smoothing, a maximum depth over the domain of approximately 1000m was set, as illustrated by the northwest section of the domain in Figure 27. The number of sigma coordinate layers was also reduced from 40 to 25, as this reduced the computational demand within the model and ensured the remaining, relatively steep bathymetry regions would not result in model instability. The spacing coefficients, $\theta_s$ and $\theta_b$, were also adjusted and analysed for their role in the computational stability of the model. The final runs used slightly adjusted coefficients of 3 and 0.1 for $\theta_s$ and $\theta_b$ respectively. Figure 28 shows the restructured sigma coordinate layers for the southwest and northwest model boundaries.
Figure 28 clearly shows that the steep sections of bathymetry have been removed from the domain. It also illustrates the larger spacing between the fewer sigma layers used in the restructured domain.

### 4.4 Revised Model Runs

Although a number of model runs were performed, including tide and no-tide scenarios, only the model runs that included tidal forcing were used in the final analysis. This was done to ensure the most comprehensive and realistic oceanographic conditions were included in the model computation. Figure 29 shows a comparison between the measured and estimated tidal signature at NRA.
Figure 29: Sea surface height at NRA as measured at the site and as estimated from the model at the closest grid location.

As indicated in the plot, the tides used to force the model were a very accurate representation of those occurring at the site, both in tidal elevation and barotropic velocity, with the spring and neap cycle clearly operating over a period of approximately 14 days. During the neap tides occurring around the 25th of February, however, the model appears to underestimate the magnitude of the tides at NRA.

The 2D and 3D timesteps were also slightly modified, from those stated in section 3.5. The final used, that enabled a complete and stable run to be performed, were 2 seconds for the barotropic and 200 seconds for the baroclinic.

4.4.1 Mixing Scheme Evaluation

In order to ensure that the most accurate vertical mixing scheme was being employed, an analysis was made on the results obtained using the four different turbulent closure schemes identified in section 3.1. There were a total of five different schemes tested that included the LMD, Mellor-Yamada 2.5 and three different variations of the GLS scheme. These included the K-tao, K-omega and K-epsilon turbulence closure schemes.
Unfortunately, the LMD scheme continually became unstable when the cyclone winds reached Category 4 status. For the successful runs, their accuracy was analysed in terms of how precisely they were able to replicate the temperature stratification modifications induced by the cyclone as measured at NRA. The results of this analysis, including only the schemes where a complete run was obtained, are presented in Appendix C.4. From this analysis, the mixing scheme that best appeared to represent the turbulence closure within the model was the Mellor-Yamada 2.5. Sections 4.5 and 4.6 below represent an analysis of the model results obtained using the Mellor-Yamada 2.5 mixing scheme. Under this scheme, the model stability, as measured by the Courant number, was well within stable bounds with a maximum barotropic Courant number of 0.079.

### 4.5 Temperature Stratification and Mixing

The observed current meter data was first filtered, using a three hour low-pass filter, to remove the high frequency fluctuations in temperature signal. This enabled a more effective comparison to be made with the model results and reduced some of the problems associated with scale issues identified in section 3.8.1. Figure 30 shows the transition between the original and filtered temperature data measured at NRA.
Figure 30: (a) Observed and (b) filtered temperature as measured at NRA. Note the heights are ASB and represent current meter locations.

As illustrated by the transition from Figure 30 (a) to (b), the filter smoothes the signal by removing oscillations with periods of less than three hours. This has the effect of slightly dampening the vertical excursions of the oscillations. An example of this is indicated Figure 30, by the marginally reduced peaks in the temperature (circled yellow) at the 117 m ASB current meter location for the unfiltered and filtered plots (a) and (b) respectively. This variation, however, was only minor and the filtered temperature contains an accurate reproduction of the response to the cyclone.
4.5.1 Cyclone Influence at NRA

Figure 31 shows the observed temperature profile at NRA and that produced by ROMS. Wind speeds have been included to illustrate the period of cyclone influence at the site, and to show the difference between the wind forcing observed and that applied to the model. The gap in the field data from the 1st to the 9th of March represents a gap in the observed meteorological dataset.

As illustrated in these plots, and those produced below, the examined period was taken from the 20th of February until the end of the run on the 14th of March. This was due to the instability of the model during the initialization period, which was considered to last for the two weeks from the 6th of February, when the model was initialized, to the 20th of February.

Both the model results and field observations, presented in Figure 31, clearly indicate that the water column is vigorously, but not completely, mixed during the cyclone event. It is observed that the cyclone mixes the water column at NRA at a much faster rate than computed by the model and more rapidly reestablishes a well stratified temperature profile.
This is seen by the fact that the measured data shows that the cyclone mixing event occurs over approximately 12 hours, 12 am until 12 pm on the 29th, whereas the model predicts that this occurs over approximately 1.5 days from 12 am on the 29th until 12 pm on the 1st. The model results, however, quite accurately predict that during the cyclone event the water mixes almost uniformly to approximately 26°C.

4.5.2 Cyclone Influence at Other Locations

The temperature fluctuations through the water column at the six other locations, illustrated in Figure 16, are presented in Figure 32 and Appendix C.1. Temperature readings were output at even intervals throughout the water column and based on the depth at each of the respective locations. Loc 5, shown below in Figure 32, was particularly interesting as it showed that during Cyclone Monty’s maximum intensity, the water column was well mixed to approximately 180 m, again to an average temperature of approximately 26°C.
Unlike the ROMS output at the shallower NRA location, Loc 5 appears to more rapidly revert back to the stratification before the cyclone event. It did, however, show large fluctuations in the temperature profile in the six days following the cyclone event, as indicated in Figure 32. These fluctuations were significantly larger than the pre-cyclone period and likely to be a result of inertial oscillations in the wake of the cyclone.

**4.6 Subsurface Current Generation**

As with the observed temperature information, the current speed was filtered to remove high frequency fluctuations in the data. The results of this are illustrated below in Figure 33.

![Figure 33: (a) Observed and (b) filtered current speed as measured at NRA. Heights are ASB and represent current meter locations.](image)

This filter removed only the high frequency fluctuations in the data set, which enabled an easier comparison to be made between the field and model results presented in section 4.6.1. Again the magnitude of some of the current speed peaks were slightly dampened, however, this was only small (less than 5%), even for the larger peaks occurring during the cyclone event.
4.6.1 Cyclone Influence at NRA

The plots in Figure 34 show that the model is reasonably accurate at determining the subsurface currents generated during the cyclone event.

![Figure 34: (a) Measured and (b) modelled current speed at NRA. Heights are ASB with the solid lines representing current meter locations.](image)

When making a direct comparison to the currents experienced during the cyclone event, although the model appears to compute the peak currents experienced fairly accurately, it produces significantly different current speeds for the overall duration of the cyclone. The time these maximum currents are first realised appears to be fairly consistent with the observed data, occurring just before midday on the 29th of February. After this, however, a double peak is experienced in the model output that is not evident in the field data.

The maximum currents achieved by the model at each of the separate location was analysed and an average discrepancy of approximately 22.3% was determined between the model and field results at all the current meter locations. The values and method used to determine this is presented in Appendix C.3. This percentage difference was larger in the mid depths,
particularly at the 30 and 60 m ASB locations, and a difference of 0.12 ms$^{-1}$ (15 %) was observed in the near-seabed currents.

Another interesting feature, illustrated in Figure 34, is the trough between the double peak that occurs at approximately 10 am on the 29th of February, with the currents throughout the entire water column significantly reduced during this period. The reduction for the near-seabed currents, as indicated by the 5 m ASB location in plot (b), reduces to approximately 0 ms$^{-1}$. An explanation for this is provided in section 4.7.

### 4.6.2 Cyclone Influence at Other Locations

For the other locations, current speed was output at specific locations throughout the water column, as with temperature. The deepest output, however, was set at 5 m ASB so that the near-seabed current speed could be observed at each location.

As indicated by the tidal-like variation in the current speed illustrated in Figure 35, the current speed during ambient conditions is determined dominantly by the tidal oscillations and only moderately by winds.
Figure 35: Current Speed at Loc 1 computed by ROMS. Heights are ASB.

Figure 35 indicates that the current speed is influenced by both the daily semi-diurnal tidal oscillations and the variability in the spring and neap cycles, identified in Figure 29. As the wind speeds increase, as shown in Figure 36 below, the cyclone wind stress applied becomes the dominant factor in the subsurface current generation.
Figure 36 shows that at Loc 5, where the water depth is nearly double that at NRA, the near-seabed currents produced are above 1.2 ms$^{-1}$, the maximum recorded throughout the entire water column at NRA. The current speed response to the cyclone at the other locations are provided in Appendix C.2.

### 4.7 Anticlockwise Vorticity Response

The analyses presented above focused on the time series profiles at specific points within the model domain. This section examines the spatial variation in current speed induced by the cyclone. The model response to Cyclone Monty showed a highly elongated eddy-like feature, with near-seabed currents as high as 1.5 ms$^{-1}$, form in the wake of the cyclone near the seabed. The eddy-like vorticity response formed around the same period that the cyclone achieved its maximum intensity, as it passed Loc 5. The generation and dissipation of this structure, as observed from the bottom sigma layer of the model domain, is illustrated in Figure 37.
Model Results

(a) Baroclinic velocity underlaid with magnitude - 29th Feb 12am

(b) Baroclinic velocity underlaid with magnitude - 29th Feb 6am
Figure 37: Near-seabed (bottom sigma layer) generation and dissipation of the anti-clockwise vorticity response in the wake of the cyclone.

In order to determine the characteristics of this eddy-like system, cross-sections were analysed, both in the cross-shore and along-shore directions, through the core. The locations and time period that these profiles were extracted are indicated in Figure 38 below.
Figure 38: Locations of cross-shore (C-S) and along-shore (A-S) vertical sections extracted through the identified eddy-like system.

The profile plots of these cross-sections are illustrated below in Figure 39.

Figure 39: Vertical cross-cross sections of the eddy-like system in both the along-shore and cross-shore directions.

The height of the eddy-like system, as illustrated by the cross sections produced in Figure 39, was constrained to the bottom depths of the domain, near the shelf break region. This is
clearly visible in the u-baroclinic velocity plot, where there exists a distinct transition in the direction of the flow between the seabed currents and the mid depths and surface currents.

Another interesting feature of the vorticity response, as identified in Figure 37, was the higher magnitude on the northern side of the system. To examine the possible reasons for this, the currents surrounding the eddy-like system were examined. Figure 40 shows the presence of an incoming flow, believed to be a geostrophic flow, during the period the vorticity response was generated. As indicated by the blue arrows, this flow is in a shoreward direction, characteristic of a geostrophic flow.

![Figure 40: Near-seabed (bottom sigma layer) current speed showing location and direction of the incoming shoreward flow (blue arrows).](image)

The flow appears to have a coupling effect with the anticlockwise velocity field of the rotating system which forms a convergent, jet-like flow in the vicinity of the seabed on the northern segment of the eddy-like system. In order to prove that this was likely to be a geostrophic flow the system was also examined at the mid depths of the domain over the same time period, as indicated in Figure 41.
Figure 41 illustrates that this flow is also present near the surface, indicating that it is most likely to be the geostrophic inflow driving the high magnitudes of the eddy-like system on its seaward side. The slight spatial variability in the strength and direction of the flow, however, means that it is not exactly representative of “pure” geostrophic flow.

4.8 **Summary of Model Results**

The table below summarises the results obtained at the six stations analysed, including the results obtained at NRA.
Table 4: Summary of mixing depth and maximum near-seabed currents at each model output location.

<table>
<thead>
<tr>
<th>Station</th>
<th>Date Monty Passed Location</th>
<th>Max Wind Speed at Location (ms⁻¹)</th>
<th>Approximate Depth (m)</th>
<th>Approximate Well Mixed Depth (m)</th>
<th>5 m ASB Current Speed (ms⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NRA Model</td>
<td></td>
<td>41.25</td>
<td>124.5</td>
<td>124.5</td>
<td>0.68</td>
</tr>
<tr>
<td>NRA Field</td>
<td></td>
<td>35.5</td>
<td>124.5</td>
<td>124.5</td>
<td>0.80</td>
</tr>
<tr>
<td>Loc 1</td>
<td>26/02 18:00</td>
<td>14.83</td>
<td>44</td>
<td>44</td>
<td>0.4</td>
</tr>
<tr>
<td>Loc 2</td>
<td>27/02 18:00</td>
<td>24.78</td>
<td>70</td>
<td>70</td>
<td>0.5</td>
</tr>
<tr>
<td>Loc 3</td>
<td>28/02 6:00</td>
<td>31.24</td>
<td>104</td>
<td>64</td>
<td>0.4</td>
</tr>
<tr>
<td>Loc 4</td>
<td>28/02 18:00</td>
<td>34.56</td>
<td>312</td>
<td>102</td>
<td>0.5</td>
</tr>
<tr>
<td>Loc 5</td>
<td>29/02 6:00</td>
<td>44.77</td>
<td>239</td>
<td>180</td>
<td>1.3</td>
</tr>
<tr>
<td>Loc 6</td>
<td>26/02 18:00</td>
<td>44.23</td>
<td>172</td>
<td>112</td>
<td>0.8</td>
</tr>
</tbody>
</table>

As indicated in the table, Loc 5, showed the largest near-seabed currents and the deepest mixing depth. This was anticipated since Loc 5 was where the most extreme winds were experienced. The current speed of 1.3 ms⁻¹ was much larger than expected, however, given that it was nearly double that measured at NRA. The reasons for this are discussed in section 5.4.3.
5.0 Discussion

The discussion for this study has been focused on examining the resultant impact that Tropical Cyclone Monty was found to have on the temperature stratification through the water column and its role in the generation of subsurface currents. Particular reference has been made to the NRA location, where the model response was able to be compared directly with field observations of current speed and temperature through the water column.

5.1 CycWind

The results of the data evaluation of CycWind, illustrated in section 4.1, shows that although there is a close correlation between the wind forcing file and observations at NRA, CycWind does exhibit larger wind speeds resulting from the cyclone than those observed in the field. The $5.9 \text{ ms}^{-1}$ deviation that occurs in the peak wind speed, and slight deviation during the cyclone event, can be attributed to the resolution of the CycWind grid, as detailed in section 3.8.1. The location that the meteorological data represents is located directly on NRA at approximately $19.5745^\circ S$ and $116.1363^\circ E$. Alternatively, the CycWind data refers to an average over the $2.68 \text{ km}$ grid supplied, with the centroid of this closest grid cell located at $19.575^\circ S$ and $116.125^\circ E$. The large impact are of the cyclone, however, means that resolution issues only play a minor role, with a slight inaccuracy in the dataset likely to be the main reason for the discrepancy.

If the equations used to convert wind velocity to wind stress are examined, illustrated in Equation 1.3 and 1.4, it can be seen that the wind velocity term, $v(r)$, goes to the cube when determining the wind stress (considering also the $v(r)$ term in the drag coefficient calculation). This means that the deviation in wind velocity of $5.9 \text{ ms}^{-1}$ can have a significant impact on the magnitude of the wind stress used to force the model. If this deviation is typical over the entire NWS region, not only NRA, it would likely present a problem since the winds are the dominant model forcing during the cyclone event. To
investigate this, comparisons would need to be made at other meteorological measurement stations on the NWS.

5.2 **BLUElink**

5.2.1 **Salinity and Temperature Profiles at the Boundaries**

The temperature profile at the boundary, presented in Figure 19, illustrates the presence of the thermocline within the water column at the shallower depths, consistent with field observations in that region (Holloway 1985). Analysis of the low and high salinity regions within the water column, as illustrated in Figure 20, indicates that there is possibly a high salinity flow coming across the southwestern boundaries and the western portion of the northwest boundary. The salinity signature suggests that it has similar characteristics to the Leeuwin Undercurrent, however, due to the limited scale of the BLUElink dataset extracted, this was not able to be confirmed.

5.2.2 **Comparison Plots at NRA**

The shift between the observed temperature profile and that approximated by the BLUElink solution, although small, is consistent throughout the model computation. Since BLUElink represents the only information on temperature and salinity being read into the model, the deviation would need to be accounted for when comparing the model output with the observed data at NRA.

Two important points to note when analysing the BLUElink comparisons are the spatial and temporal scale issues, outlined in section 3.8.1, and that the circulation dynamics at NRA are strongly influenced by the tides that have been omitted from the BLUElink solution. Due to the 10 km grid employed by BLUElink, the centroid of the closest approximate grid coordinate to NRA is at 19.55°S and 116.15°E. This limitation is also reinforced by the fact
that BLUElink is averaged over the 10 km grid, whereas the observational data is just a single point source of information. This limitation is particularly applicable when analysing the current speed and direction comparisons. It can be seen in Figure 24, which represents the period when the cyclone is nearest NRA, that the observed currents in the area increase in speed as expected, however, BLUElink appears to significantly overestimate this increase near the surface and underestimate it near the seabed. This was evident in the regression plots in Figure 25, which showed a much lower correlation existed between the two data sets when compared to the regression analysis made on temperature. The high spatial variability in current speed over the NWS means that spatial resolution issues play an important role when performing direct comparisons between spatially averaged data and point source information.

It is also important to note that although the BLUElink data did not reproduce the observed current conditions at NRA, it was only used to force the model initially on the 6th of February and thereafter only at the open boundaries. Therefore the dynamics occurring at NRA were a direct result of the ROMS computation, as dominated by winds during the cyclone event and density gradients within the flow field. For this reason, the low correlation between the current information was not considered to have a significant impact on the accuracy of the model results.

### 5.3 Domain Modification

Initial attempts to improve the models computational stability were aimed at further smoothing the BLUElink input file and removing steep bathymetry slopes in the model solution. Most of these modifications proved to be unsuccessful and it was only after severe modification to the deeper bathymetry, where the computation and model output were not a particular focus of the study, that a complete run was produced.

As before, the more significant smoothing was applied to layers below 400 m since the minor topographic variations below these regions were expected to have little impact on the dynamics occurring at NRA. The maximum depth of 1000 m that was set over the domain
was done to enable smooth forcing of the BLUElink data through the water column at the northwest and southwest boundaries. The initial results indicated that large variations in bathymetry near the forcing boundaries were resulting in numerical instability, which rapidly amplified and caused the model to become unstable. Figure 28 illustrates the computationally improved bathymetry near the boundaries, as indicated by the horizontal sigma coordinate layers at the deepest sections of the model, where the most highly variable BLUElink information was being applied.

The close proximity vertically of the sigma layers was also believed to produce truncation errors in the horizontal pressure gradient term, resulting in a numerical induced instability that caused the model to become unstable near the boundaries. To reduce the topographic sensitivity of the sigma-coordinate system, as described in section 3.1.2, the number of sigma coordinate layers was reduced from 40 to 25. Reducing the number of sigma layers in this manner was not expected to significantly alter the reproduction of the cyclone induced dynamics within the model solution. In the deeper shelf regions, where water depths were approximately 200 m, there would be a layer approximately every 8 m which is enough to resolve the vertical dynamics given the length of the horizontal grid scale.

5.4 ROMS Results

Although the tidal range during the neap tide conditions were underestimated by the model, during the spring tides, when the largest currents are generated, the modelled tide was within 0.1 m of the measured tidal range. This was particularly important for the period before the cyclone event and after the cyclone event, when the tides are expected to dominate the dynamics through the water column (Katsumata 2006).

As illustrated in Appendix C.4, there was little difference observed between the four different turbulence closure schemes that were successfully implemented. All of the schemes appear to react slower to the cyclone than the field results at NRA. They remained near-well mixed at NRA for a much longer period and reverted back to the ambient stratification at a much slower rate after the cyclone event. It was, however, during this
relaxation period after the cyclone event that a slight variation in the temperature profile between these different schemes was observed.

The K-omega scheme appeared to be significantly slower, and hence more dissipative, than the other methods at reverting back to the conditions prior to the cyclone event. Since this was least reflective of the actual conditions at NRA it was not selected as the most accurate mixing scheme for this study. For the other methods there was little difference observed, except for the K-epsilon and Mellor-Yamada schemes which appeared to show a slightly larger variation in the near-seabed temperature than the K-tao closure scheme. In the end the Mellor-Yamada method was selected as it was the most widely used amongst previous cyclone modelling studies and considered the least dissipative amongst the successfully implemented schemes (Keen & Glenn 1998).

The fact that only moderate differences were observed between the different turbulence closure schemes can be related to the fact that they relate to subgrid scales, not resolvable by the model. These schemes directly relate to the smaller scale processes occurring within the flow field, and even if the most effective closure scheme is incorporated, its reliability when compared to field data will directly relate to the scale in which the model resolves the circulation dynamics.

5.4.1 Cyclone Influence on Temperature Stratification and Mixing

The model results at NRA show that the level of mixing induced by the cyclone was replicated by the model, however, the duration of the mixing event and the rate of mixing and subsequent re-stratification were underestimated. The fact that the observed temperature profile reestablished the original stratification characteristics faster means that it is most likely the smaller subgrid-scale processes, not resolved by this model, that are acting to rebalance the system. It is also undoubtedly influenced by the non-hydrostatic processes and the highly non-linearity of the internal waves in the vicinity of NRA, which are not being replicated in the ROMS hydrostatic computations. The strong density stratification, tidal forcing and progression to shallower bathymetry that is characteristic of the shelf break
region near NRA also has all the elements required to observe non-hydrostatic internal wave breaking, which would significantly influence the regional dynamics (Van Gastel, Ivey & Antenucci 2007).

Due to the low horizontal spatial variability of temperature within the water column, and the relatively large spatial scales over which the cyclone is acting, scale issues are expected to have little implication on these results. The 2°C variation in temperature at the 5 and 30 m ASB locations, before the cyclone is present, is a direct result of the same variation that was observed between the BLUElink and field observations in section 4.2.3. This does not, however, explain the reduction in temperature, particularly near the seabed in the four days before the cyclone event. As illustrated in Appendix C.4, this was common amongst all the mixing schemes and for this reason it likely indicates the presence of a near-seabed, localised cold water intrusion into the region around NRA.

The daily sinusoidal fluctuations in the temperature profile, particularly at the surface layer during the initialisation period and after the cyclone event, can be attributed predominantly to the tidal forcing, with a secondary near surface response to radiative heat fluxes across the air-water interface. The measured data at NRA appears to exhibit similar daily fluctuations during these periods, however, they appear to be much larger and have a higher frequency component. Possible reasons for this are the idealised bathymetry, structures not resolvable within the model solution and the discrepancy that was observed between the BLUElink output and that measured at NRA during the ambient conditions.

As expected, all the other locations appeared to have a different response time to the cyclone, due to the spatially varying wind speeds of Cyclone Monty as it passed their respective locations. Loc 4, 5 and 6, however, appeared to all revert back to the pre-cyclone stratification at a much faster rate than at the NRA location, with the profiles fluctuating significantly in the immediate days following the event as a result of inertial oscillations in the wake of the cyclone. This could again indicate that non-hydrostatic processes, not resolved by the model, are affecting the dynamics occurring at NRA.
Discussion

One anomaly that existed in the model results related to the level of mixing evident at Loc 2 and 3. As indicated in Table 4, the level of mixing that was evident at Loc 2, the shallower water body, exceeded that at Loc 3, even though the magnitude of the winds were significantly greater at Loc 3. This can be attributable to the level of stratification that exists within the water bodies of different depths. As indicated by the temperature profile plots of Loc 2 and Loc 3, shown in Appendix C.1, the temperature range is much larger at Loc 3, indicative of stronger stratification. This demonstrates that the mixing depth is directly correlated with the strength of the stratification within the water body for a given level of wind stress.

5.4.2 Cyclone Influence on Subsurface Currents

Under ambient conditions, the spatial variability of currents makes a reliable comparison between field data and model results difficult, as identified in section 3.8.1. Under cyclone conditions, however, the scale of the cyclones influence is large compared to the grid size and the fact that it dominates the dynamics through the water column means that it was possible to make a direct comparison with the field data. For this reason, the main focus when examining the comparison plots presented in Figure 34 were those during the cyclone event.

As indicated in Figure 34 there is a subsurface peak in the velocity predicted by the model at a depth of approximately 15 m ASB. Unfortunately, since there are no current meters at this location, it was not possible to determine whether this is in fact a real occurrence. What can be observed, however, is that the results at the 30 m ASB current meter location are not reproduced by the model. Where the field observations illustrated a constant transition between the slowest currents at the seabed and the fastest at the surface, the model results showed that the current speed at 30 m ASB was near equivalent to the currents at 5 m ASB, near the seabed. The most likely reason for this is the eddy-like system identified in Figure 37, which is further discussed in section 5.4.3 below.
This eddy-like system does not explain the double peak present in the near-surface results at NRA. The cause of this is observed in the horizontal plots of the near-surface current speeds provided in Appendix C.5. As illustrated in the plots, the magnitude of the cyclone induced surface currents significantly increases as the cyclone winds increase. These currents appear to be much larger and more spatially variable than those occurring near the seabed and are generated as a direct result of the wind stress applied, rather than effects of a local density gradient.

It is clear from the plots of current speed at the other locations, shown in Appendix C.2, Figure 35 and Figure 36, that cyclones dominate the dynamics throughout the water column during cyclone events. This is illustrated by the model output at Loc 2, which shows that as soon as the cyclone reaches a Category 1 phase it has the dominant influence on the magnitude of the subsurface currents throughout the entire water column. The output at Loc 4 shows that even in the deeper regions off the shelf break, the cyclone is still the dominant energy contributor in the generation of near-seabed currents.

Loc 5 experienced the largest near-seabed currents at approximately 1.3 ms$^{-1}$ at 5 m ASB, as illustrated in Figure 36. This is approximately double the maximum observed current speed at NRA of 0.8 ms$^{-1}$ at 5 m ASB. This is another result of the eddy-like system identified in Figure 37, with the implications discussed below.

### 5.4.3 Anticlockwise Vorticity Response to the Cyclone

It was the generation of this anticlockwise vorticity response that explains most of the large near-seabed currents that are experienced, particularly at NRA and Loc 5 and 6. As indicated in Figure 37, the current speed of 1.3 ms$^{-1}$ measured at Loc 5, was a direct result of the passing, high velocity seaward side of the eddy-like system at 12 pm on the 29$^{th}$ of February. This eddy-like system also illustrates the reason for the drop in the near-seabed current speed at NRA, since this occurred at approximately 9 am on the 29$^{th}$ of February, which was approximately the same time that the centre of the system passed NRA.
The containment or trapping of the eddy-like system to the near-seabed region, as illustrated in Figure 38, was expected due to the fact that this system was most likely generated and driven by a local density gradient induced by the cyclone. This density gradient exists due to the localised mixing induced by the cyclone, coupled with the reduction in atmospheric pressure that causes the water to expand beneath the cyclone and in its immediate wake. The conservation of potential vorticity will no doubt play a role in the generation of this eddy-like system, however, a full analysis of this was beyond the scope of this study (Cushman-Roisin 1994).

Another interesting feature of this eddy-like system, as identified in section 4.7, was the fact that the northern, offshore side was significantly higher in magnitude than the other sides of the system. There are a number of possible reasons for this. One is the shear interaction with the bottom topography in the shallower regions that would cause a reduction of the current velocity near the seabed. Another, and perhaps more realistic reason, is the presence of a geostrophic inflow directed towards the shore, as illustrated in Figure 40 and Figure 41, which results in an intensification of the velocity field forming a jet-like flow on its seaward side. Finally, requirements of the conservation of potential vorticity were also expected to play a role (Cushman-Roisin 1994).

5.5 Comparison with Previous Studies

There have been only a few papers to study in detail the impact that a real cyclone event has through the water column, particularly when considering the generation of near-seabed currents. The main distinguishing feature between this study and those prior to it, was the level of simplification applied to the model and the focus of the model output.

Comparing the near-seabed currents obtained in this study, the maximum current speed of 0.68 ms\(^{-1}\) at 5 m ASB produced was slightly below the 0.92 ms\(^{-1}\) current produced at the same depth in Sullivan (2006). The reason for this discrepancy is related to the fact that Sullivan (2006) focused on idealised cyclones, with the results presented here produced by an idealised cyclone event that best resembled Cyclone Monty’s characteristics as it passed
near NRA. It had an average peak wind speed of 52 ms\(^{-1}\), slightly larger than the 48.9 ms\(^{-1}\) maximum in the CycWind dataset, and straight line path traveling at 2 ms\(^{-1}\), compared to Cyclone Monty’s approximate cyclone speed of 2.57 ms\(^{-1}\) as it passed near NRA, as indicated in Appendix A.1. Both of these discrepancies would result in more momentum transfer through the water column and hence a larger current being experienced near the seabed. The results did, however, show that the water column mixed to approximately 26\(^{0}\)C, as reflected in this study.

Consistent with the Keen and Glenn (1998) study, this study confirmed that the Mellor-Yamada 2.5 scheme was one of the most effective turbulence closure schemes to use within the model. The conclusion that a less dissipative scheme would more accurately represent the dynamics occurring during cyclone events was also confirmed by the results of this study. This was inferred in section 5.4, where a lower amount of dissipation within the model was believed to enable a more rapid rate of mixing through the water column, enabling the model to more accurately reproduce the field measurements for temperature at NRA.

The study was also consistent with historical qualitative analyses on tropical cyclones on the NWS. As with the Holloway and Nye (1984) study, it demonstrated that as the magnitude of the winds increased, and propagation speed of Cyclone Monty slowed, the magnitude of the subsurface currents increased. This is simply as a result of the larger time period that momentum is able to transfer into the local water column. This is particularly prevalent for the current speeds generated at Loc 5 and Loc 6, illustrated in Appendix C.2 and Figure 36, at 12 am on the 1\(^{st}\) of March, when the cyclone slowed to approximately 1 ms\(^{-1}\), as indicated in Appendix A.1.

The study by Hearn & Holloway (1990) had quite different objectives to this study. One similarity, however, related to the stability criteria of the model performance. This study, like the Hearn & Holloway (1990), found that altering the barotropic and baroclinic timesteps within the model had a significant impact on the stability of the model computation. The final runs performed in this study were achieved through reducing the barotropic timestep by 3 seconds and increasing the baroclinic by 80 seconds, enabling the
slower 3D processes to be computed at a lower resolution and the faster 2D processes to be resolved at a much higher resolution.

The Davidson and Holloway (2003) study demonstrated the most similarities with the current study, in terms of the type of model used and the realistic cyclone wind and boundary forcing. Only a few of the objectives, however, were similar, relating to the level of mixing and density instabilities induced by the cyclone. As with the Davidson and Holloway (2003) study, the level of cyclone induced mixing, was most abrupt in the shallow waters, around 125 metres deep, than in deeper water over 300 metres deep. This is indicated by the different levels of mixing observed between Loc 4 and NRA, illustrated in Appendix C.1 and Figure 31 respectively. The density instabilities observed were those responsible for the generation of the near-seabed eddy system, shown in Figure 37.

5.6 Limitations of the Study

Over the course of this project a number of problems were encountered which can be categorised as follows.

5.6.1 Internal and External Model Forcing

The main problems relating to the external forcing of the model was associated with the reliability of the BLUElink and CycWind solution. The ability of BLUElink to accurately resolve the mesoscale structures evident on the NWS and the reliability of the temperature and salinity profiles used to force the model on the open boundaries undoubtedly had a significant effect on the model results. The ambient winds that were neglected from the model computation, as described in section 3.5, would have also played a role in the stratification and near-surface current generation, however, these synoptic winds were included during the cyclone event.


Described in section 3.5 were the radiative heat fluxes used to force the model. Missing values within the dataset were determined using straight line interpolation. The use of this type of interpolation may have been inaccurate, with large variations likely to occur near the cyclone event due to cloud cover and precipitation. These radiative heat fluxes, however, were considered a secondary process in the dynamics occurring, even during ambient conditions when tides dominate.

Internal forcing issues related to the BLUElink dataset. The problems encountered when interpolating the BLUElink z-coordinate data onto the ROMS sigma coordinate domain were believed to have a significant impact on the accuracy of the model results, particularly during ambient conditions before the cyclone event. This was seen to have a significant influence on the generation of artificially induced lateral density gradients, which was the main reason for the model instability during the early stages of the project.

### 5.6.2 Field Data for Comparison

The main limitation with the comparative analysis that was performed related to the reliability of the field data and the manner in which this data was processed for simplification. Gaps in the meteorological field data, such as those in the wind data set illustrated in Figure 31, made a comparison over the entire modelled period difficult, and for radiative heat flux, may have slightly impeded the accuracy of the model solution. There was also the lack of available field data in other regions in which to make a more effective evaluation of the model results and forcing data. Although the data supplied at NRA was comprehensive at providing an indication of the oceanographic conditions at that point source, it did not give evidence to the likely conditions elsewhere on the shelf. This lack of other sources for comparison also made assessment of the model accuracy heavily reliant on the conditions recorded at NRA, which may have been inaccurate itself.

The filtering of the observational data, for ease in comparison, was also observed to slightly dampen the larger oscillations present in the field results. Although the aim of this filter was to remove some of the structure not resolved by the model it also removed some of the
cyclone induced characteristics. For the current speed, it was ensured that the extent of this dampening was small (less than 5% decrease in magnitude) and that the cyclone induced dynamics were preserved in the field.

5.6.3 The ROMS Model

Spatial and temporal scales of the model domain and the resulting minimum resolvable structures reproduced by the model had a significant bearing when comparing the model results to that observed in the field. This is common to most modelling studies and was the reason the results focus was on the ability of the model to resolve the dominant processes occurring. The impact of this is evident in the temperature profile plots at NRA, in Figure 31, which shows that the magnitude of the daily oscillations were significantly underestimated by the model during ambient conditions. The models ability to reproduce the cyclone conditions, however, was far more accurate.

When determining the most appropriate vertical mixing scheme to adopt, it was assumed that the most accurate was the one that best represented the field results at NRA. This again related to the risk associated with having a large reliability on the NRA oceanographic data, detailed in section 5.6.2.
6.0 Conclusions

This study has demonstrated that whilst the generation of subsurface currents can be relatively accurately represented within the model, the vertical mixing induced by the cyclone is not well reproduced as a result of subgrid scale and non-hydrostatic processes not being resolved by the model. Analysis of a number of turbulence closure schemes found that there was little difference observed at NRA under each of the schemes successfully incorporated into the model. This was expected as the schemes tend to only become important when the smaller scale processes are resolved by the model. The Mellor-Yamada 2.5 scheme was employed in the final solution as it was considered to most rapidly revert back to the ambient stratification after the cyclone had passed, reflective of the field observations. Under these forcing conditions, and using the Mellor-Yamada turbulence closure scheme, ROMS was able to determine subsurface currents through the water column at NRA with an average discrepancy of approximately 22.3%. More accurate current speeds were produced near the surface and seabed, where discrepancies between the field results were approximately 0.01 ms\(^{-1}\) (0.72%) and 0.12 ms\(^{-1}\) (15%) respectively.

Evaluation of the model wind forcing showed that CycWind was relatively effective at replicating observed winds at NRA, however, it did slightly under-predict the cyclone induced wind speeds. The boundary forcing produced by the BLUElink solution also demonstrated a slight deviation in temperature through the water column and an even more significant deviation in current speed and direction. This was found to have an effect predominantly during ambient conditions, before and after the cyclone event. The main focus of this study, however, was during the cyclone event, where the dynamics in the vicinity of NRA were dominated by the ROMS computation and less influenced by the boundary forcing.

The most difficult problems experienced during the study related to the interpolation of the BLUElink z-coordinate system onto the ROMS sigma coordinate grid. In order to enable a successful run to be performed the resolution of the domain was significantly reduced which meant that the interpolated boundary conditions were applied at a much lower resolution.
Conclusions

than the initially provided BLUElink solution. It was ensured, however, that the most significant domain restructuring was applied to the deeper regions of the model, where the instabilities were being generated and the dynamics not considered to affect those occurring at NRA.

The large vorticity response that was observed in the wake of the cyclone near the seabed, although not confirmed real due to a lack of spatial field data, was predicted to play a significant role in the generation of large near-seabed currents, particularly in the vicinity of the shelf break region. This eddy-like system was responsible for the near-seabed current speeds of 1.3 ms\(^{-1}\) generated at loc 5, a location approximately 40 km northwest of NRA on the shelf break where water depth is approximately 240 m. A cyclone-induced density instability throughout the water column was believed to produce the eddy-like system which generated and dissipated during the maximum intensity stages of the cyclone.
7.0 Recommendations for Further Research

This study has contributed to an improved understanding of the impact that cyclones have on the subsurface oceanographic environment, with particular reference to the NWS. Further analysis, however, is required to improve the accuracy of results and to confirm the presence of specific features in the model solution, such as the near-seabed vorticity response in the wake of the cyclone. Some recommendations, beyond the scope of this study, are detailed below and relate to possible methods of improving model performance and the reliability of the model solution.

The main restriction encountered in the model related to the subgrid scale processes that were not being resolved in the model computation. One solution to this could be to increase the resolution of the model, or incorporate a nested domain, of higher resolution, in the vicinity of NRA. Another option is to couple ROMS with a non-hydrostatic model, such as the Suntans (Stanford Unstructured Non-hydrostatic Terrain-following Adaptive Navier–Stokes Simulator) model. Using these more advanced models may enable the non-linearity that exists in internal waves and non-hydrostatic oceanic processes, such as internal wave breaking, to be resolved in the model. This would enable the physics of the entire multiscale internal wave energy cascade to be represented in the model solution (Fringer, Gerritsen & Street 2006).

Although our results illustrated a discrepancy between the observed data and that produced by BLUElink, a comparison should be made with other measuring locations before any conclusions may be made with regards to the accuracy of the BLUElink solution. A particular focus on field observation in deeper waters would enable a much more comprehensive analysis to be performed, as in these regions tides would play a much smaller role in the generation of subsurface currents and stratification variations.

Another paramount aim should be to successfully employ a lower energy dissipative scheme in the model. The schemes that were not able to be employed, such as the LMD scheme, may have been less dissipative and therefore more applicable to this study, where the level
of energy dissipation is expected to have a significant impact on the model results (Keen & Glenn 1998). Incorporating ambient winds before and after the cyclone event could also improve the accuracy of the model solution. This will enable comparisons to also be made during non-cyclonic periods, which would play a direct role in the ability of the model to reproduce the oceanographic response during the cyclone event.

In a more general sense, reevaluation of these results would be required to assess the impact of climate change on temperature stratification and storm patterns (Poloczanska et al. 2007). As seen with Hurricane Katrina, a small variation in the surface temperature can have a significant impact on the dynamics of the cyclone and its impact through the water column (Graumann et al. 2006).
8.0 References


References

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Van Gastel, P., Ivey, G. N. & Antenucci, J. P. 2007, The seasonal variability of the nonlinear internal wave field on the Australian North West Shelf, School of Environmental Systems Engineering, University of Western Australia, Crawley, WA.


Zhu, S. & Imberger, J. 1996, 'Computer-simulated current responses to cyclones on the
APPENDIX A
Wind Field Information
### A.1 Meteorological Information on Cyclone Monty

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### A.2 Extracted Radius to Maximum Wind and Central Location Information from the CycWind Data Set

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Appendices

A.3 Spatial Wind Fields plots CycWind after Interpolation onto the ROMS Model Domain

Spatial Wind Speed (m/s) and Direction Plot for the 26-Feb-2004 at 10:00 PM

Spatial Wind Speed (m/s) and Direction Plot for the 27-Feb-2004 at 10:00 PM

Spatial Wind Speed (m/s) and Direction Plot for the 28-Feb-2004 at 10:00 AM

Spatial Wind Speed (m/s) and Direction Plot for the 28-Feb-2004 at 10:00 PM

The maximum wind speeds on this plot were 16.6538 m/s at -18.9038N 120.8662E
The maximum wind speeds on this plot were 27.5059 m/s at -19.3775N 118.9813E
The maximum wind speeds on this plot were 33.3805 m/s at -19.225N 117.7077E
The maximum wind speeds on this plot were 37.9008 m/s at -19.3057N 116.6672E
Appendices
APPENDIX B
BLUElink Analysis Results
B.1 BLUElink Temperature Comparison Plots

1. Plot of observed temperature data at NRA against BLUElink for 05-Feb-2004
   - Depth (m) vs. Temperature (°C)

2. Plot of observed temperature data at NRA against BLUElink for 12-Feb-2004
   - Depth (m) vs. Temperature (°C)

3. Plot of observed temperature data at NRA against BLUElink for 16-Feb-2004
   - Depth (m) vs. Temperature (°C)

4. Plot of observed temperature data at NRA against BLUElink for 24-Feb-2004
   - Depth (m) vs. Temperature (°C)
B.2 BLUElink Current Speed Comparison Plots
Appendices
B.3 BLUElink Current Direction Comparison Plots
APPENDIX C
ROMS Results
C.1 Temperature Time-Series Plots
Appendices
C.2 Current Speed Time-Series Plots
C.3 Computation of Percentage Difference between Modelled and Measured Maximum Current Speed at NRA

Equation used to calculate percentage difference:

\[
\% \text{ Difference} = \left( \frac{v_{\text{FIELD}} - v_{\text{MODEL}}}{v_{\text{FIELD}}} \right) \times 100\%
\]

Results:

<table>
<thead>
<tr>
<th>Current Meter Depth (m)</th>
<th>Field Measurement</th>
<th>Model Results</th>
<th>% difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>117</td>
<td>1.38</td>
<td>1.37</td>
<td>0.72%</td>
</tr>
<tr>
<td>75</td>
<td>1.28</td>
<td>0.92</td>
<td>28.13%</td>
</tr>
<tr>
<td>60</td>
<td>1.10</td>
<td>0.72</td>
<td>34.55%</td>
</tr>
<tr>
<td>30</td>
<td>0.97</td>
<td>0.65</td>
<td>32.99%</td>
</tr>
<tr>
<td>5</td>
<td>0.80</td>
<td>0.68</td>
<td>15.00%</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>22.28%</td>
</tr>
</tbody>
</table>
C.4 Alternate Turbulence Closure Scheme Temperature Time-Series Plots
C.5 Near-Surface Cyclone Induced Currents (2 sigma layers below the surface)