Southeast Queensland Storm Tide Response to Ex. Tropical Cyclone Oswald

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Abstract

Although a significant body of work exists, previous storm tide studies within Moreton Bay have consistently underestimated observed peak tide gauge levels by up to 40%. There remains scientific debate regarding the source of this “missing” contribution, which is hypothesised to be resultant from either disturbance of regional oceanic density structure, wave radiation stress gradients due to wave breaking on the Spitfire Banks or the need to improve the current parameterisation of wind stress into the water column. To support or disprove these hypotheses, this study investigates the regional surge response during the passage of Ex. Tropical Cyclone Oswald in January 2013 through the application of a series of integrated hydrodynamic and spectral wave modelling experiments. Overall, the shape and magnitude of the experiments with wave radiation stresses activated provide a better match (~27% peak underestimate) to measured residuals compared with tide plus surge only experiments (~47% underestimate) supporting the theory of wave-surge interaction. During the twenty-hour period of greatest wind speeds however, there is a consistent ~25% underestimation that tends to support a call to improve the implementation of model physics at the air-sea interface, while the effects of 3D regional ocean contributions needs to be revisited when improved model boundaries are available and this aspect cannot be dismissed.

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I certify that the ideas, designs and experimental work, results, analysis and conclusions set out in this dissertation are entirely my own efforts, except where otherwise indicated and acknowledged.

I further certify that the work is original and has not been previously submitted for assessment in any other course or institution, except where specifically stated.

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2nd of November, 2015.

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Dr Bruce Harper - External Supervisor - Systems Engineering Australia

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Mr Toby Devlin – BMT-WBM

Dr Matthew Barnes – BMT-WBM

Dr Jason McConochie – Shell, The Hauge

Dr Dave Callaghan - University of Queensland

The author would also like to thank the on-going work of the following organisations, which without the data they collect and provide it would not have been possible to complete studies such as this.

- The Queensland Department of Science, Information Technology, Innovation and the Arts;
- Maritime Safety Queensland;
- Manly Hydraulics Laboratory;
- The Bureau of Meteorology; and
- The U.S National Centre for Environmental Prediction.

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1 Introduction

1.1 Outline

Although a body of work exists, there remains debate amongst the scientific community regarding the relative contribution of region-scale oceanic circulation and surface wind-wave processes on observed storm tide levels across Southeast Queensland during remote and close approach Tropical Cyclone (TC) events.

This research project investigates the near and offshore oceanic response during the passage of Ex. TC Oswald in January 2013. The study utilises a series of numerical models to represent surface wind fields, ocean surface waves and ocean hydrodynamics in assessing the behaviour and interaction of the:

- astronomical tide;
- regional mean ocean level anomalies and currents;
- wind field and pressure forcings; and
- wave breaking;

on measured water levels at a number of locations in Southeast Queensland. Notably, the primary focus of this study is the -hindcasting and reproduction of measured storm tide levels at Brisbane Bar.

The aim of this study is to improve our existing understanding of these events to assist coastal planning, coastal hazard adaptation, disaster management and operational flood and storm tide forecasting.

1.2 The Problem

Tropical Cyclones (TCs) and oceanic storms regularly lead to loss of life, damage and disruption to those in the coastal zone with storm surge and flooding typically being the more significant hazards associated with the passage of these systems. *Hurricane Katrina*, one of the deadliest storms to affect the United States in recent history, resulted in a storm surge of 7.5 - 8.5 m over 32 km of coastline. Reaching up to 19 km it caused over $108 billion in damages and killed over 1,500 persons with many hundreds more missing (*Event History - Tropical 2000s - Storm Surge and Coastal Inundation* n.d.). In the Australian context – *TC Yasi, TC Tracy and TC Althea* are examples of systems that caused significant damage and cost to the economy.

In Northern Queensland, it is common to experience large storm surges due to the interplay between intense TC events and the wide shallow seas of the continental shelf.

Southeast QLD however, lies in a transition zone between the tropical and higher latitudes where mature TCs are less frequent and the continental shelf is much less pronounced. Notwithstanding these limitations, there have been numerous storm surges experienced in Southeast QLD over the past 60 y. These surges are usually the result of remote approach TCs that recurve or track offshore, or due to the impacts of tropical depressions moving over-land.

In order to understand the likely magnitude and frequency of storm tide occurrence in our coastal communities, numerical modelling is required due to the complexity and scale of the processes being investigated. With the high-energy events experienced in Northern QLD, traditionally a two-dimensional (2D) approach that does not consider ocean density variations (barotropic) has been remarkably good at hindcasting observed storm surge events. There are however, a growing number of studies in Southeast QLD that have underestimated by up to 40% the observed (albeit relatively low) storm surge levels during events such as *TC Dinah*, *TC Rodger* and recently *Ex. TC Oswald* using conventional 2D barotropic modelling. This indicates that these techniques are omitting or under-representing important physical processes responsible for the generation of storm surge in the region.

1.3 Tropical Cyclone Oswald

The following account are largely extracts from reports of the event provided by the (Bureau of Meterology 2013) and (Harper & Maher 2013).

Tropical Cyclone Oswald formed in the Gulf of Carpentaria on the afternoon of the 21st January 2013 and made landfall as a category 1 system six hours later near Kowanyama, on the west coast of Cape York Peninsula. The cyclone rapidly weakened after landfall and was downgraded to a tropical low on the morning of 22nd January. The low tracked eastwards across Cape York Peninsula and was positioned to the west of Cooktown on the 23rd of January. The system then took a turn to the south and tracked inland almost parallel to the QLD coast to be positioned inland from Townsville on the 24th of January. The moist northeast flow around the southern flank of the low pressure system combined with a firm ridge that extended along the QLD coast, from a high pressure system to the south of Victoria, to produce an enhanced band of rainfall on its southern side. The high pressure system moved eastwards allowing the low pressure system to move south during the 25th of January to be positioned near Emerald in Central QLD. The tropical low then stagnated in that area over the 25th and 26th of January. Moist northeast to easterly winds around the eastern side of the low coincided with enhanced low level convergence brought about by a strong low level jet, and resulted in very heavy rainfall across the Capricornia, *Wide Bay and Burnett regions at this time. Tornadoes were also observed on radar and reported. Rainfall totals of more than 400 to 500 millimetres in 24 hours were recorded during this period with several sites exceeding the 1% ARI for 3 to 72 hour. By the 27th of January 2013, the low pressure system had resumed a steady southwards track to be centred near Dalby on the 28th of January, enticed southwards by a vigorous mid level trough over south-eastern Australia. This movement brought the intense area of rainfall to the southeast corner of QLD where falls up to 750mm in 24 hours were recorded in some parts, particularly about the ranges. The system then accelerated southwards through northern New South Wales before moving offshore near Sydney on the 29th of January, but not before producing heavy rainfall across north-eastern parts of the state. The track of Oswald as a Tropical Cyclone and Tropical Low is shown in* Figure 1-1

The low pressure system was associated with strong winds, with numerous sites experiencing gusts in excess of 100 km/h and several tornadoes sighted and reported. Rough seas, large waves and coastal storm surge also resulted from the system. The majority of the 25 storm tide gauges throughout the state observed water levels within 0.5 m of HAT. The peak recorded surge at Brisbane Bar during the event was ~ 1 m with surges of 0.4 m measured at Mooloolaba, 0.25 m at Tweed Offshore and 0.84 m at Southport Marine Operations. Extreme waves within the top ten highest recorded were observed at a number of sites. The highest waves during the event were recorded at the Brisbane Wave Buoy that recorded the third highest significant wave height 7.11 m in 37 years of data collection on the morning of the 28th of January. The peak wave recorded during this period was 12.11 m.

There are few close precedents in the last 50 years for the track of Ex-Tropical Cyclone Oswald. While a number of former tropical cyclones have moved far enough south to have significant impacts on New South Wales, most such systems have either originated over the Coral Sea and not approached the QLD coast until south of the Tropic of Capricorn (e.g. Zoe 1974, Nancy 1990), or moved south from the Gulf of Carpentaria and tracked through western QLD (e.g. Audrey 1964).

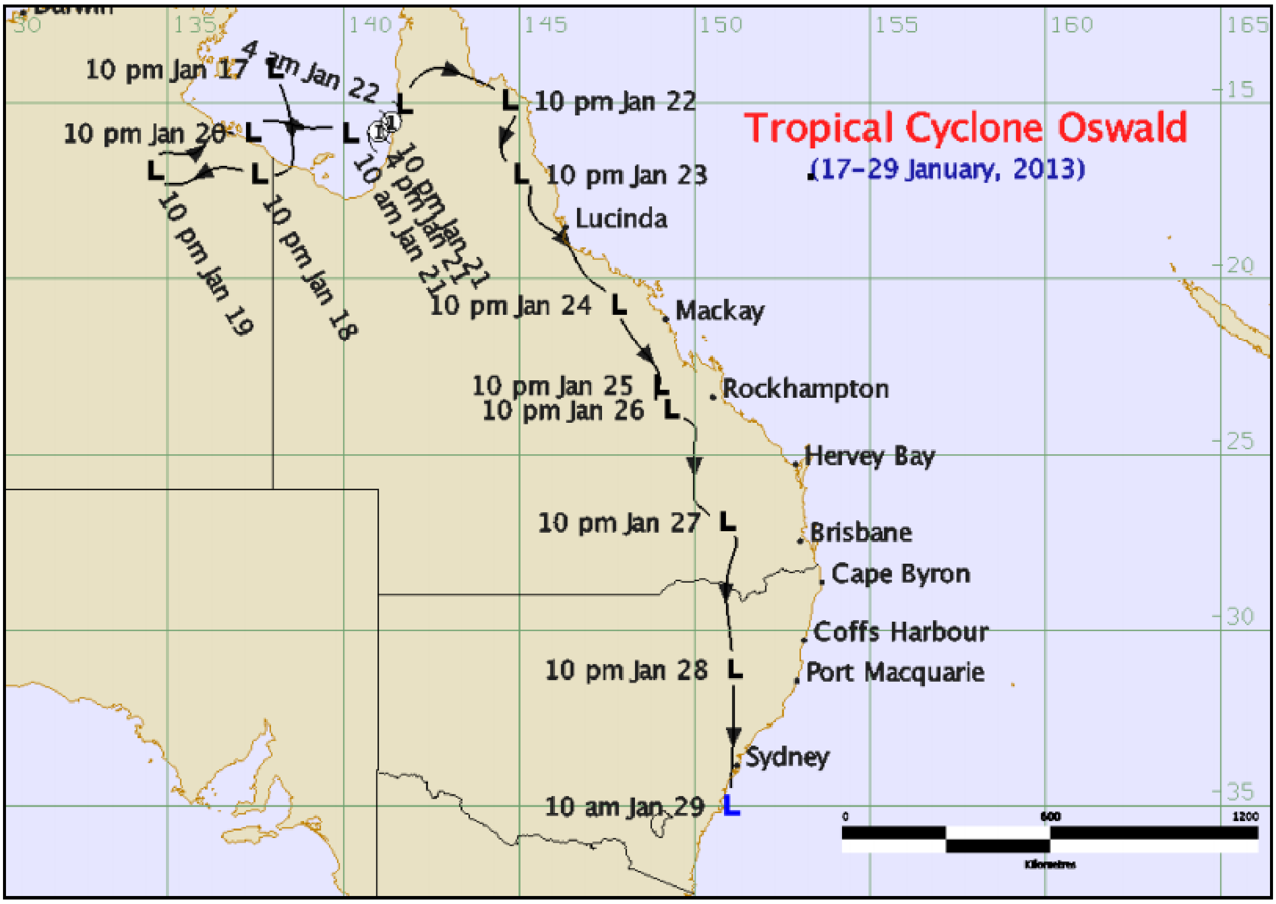

Figure 1-1 Tropical Cyclone Oswald Track (Source BOM, 2013)

1.4 Research Objectives

This study hypothesises that three-dimensional (3D) density driven (baroclinic) processes propagating from deep water across the continental shelf are responsible for a component of observed storm surge levels within the Southeast QLD region. To test this hypothesis, the study utilises the hydrodynamic modelling package TUFLOW FV (WBM, 2013) in-concert with the spectral wave model SWAN ((Booij, Holthuijsen & Ris 1996) to hindcast the passage of Ex. Tropical Cyclone Oswald and compare modelled results to those observed at tide and storm tide gauges within Southeast QLD. If it can be shown that these processes contribute to the overall water levels during *Ex. Tropical Cyclone Oswald*, it may be inferred that modelled baroclinic effects may explain the negative biases found in similar studies in the region.

The specific objectives are:

- Collate available meteorological, oceanographic and topographic data required to setup a series of model experiments;
- Ensure that the available meteorological datasets are representative of observed conditions during *Ex. TC. Oswald*;
- Develop and test the hydrodynamic model TUFLOW FV. Prepare a model domain and set of parameters that are suitable for storm tide assessment;
- Develop and test a series of spectral wave models using SWAN. Prepare a model domain and set of parameters that are suitable for storm tide assessment;
- Calibrate the TUFLOW FV model to accurately represent the astronomical tides for the month of January 2013;
- Calibrate the SWAN model to accurately represent wave conditions for the month of January 2013;
- Complete a series of two-dimensional, depth-averaged hindcasts of Ex. TC Oswald, by varying the input forcing's: astronomical tide, meteorological and wave input;
- Complete a series of three-dimensional, depth-averaged hindcasts of Ex. TC Oswald, by varying the input forcing's: astronomical tide, meteorological and wave input;
- Undertake sensitivity testing on the effects of model resolution;
- Identify scope for further research.

1.5 Report Summary

Key items investigated and undertaken for this study include:

- Literature Review: Review of applicable physical processes, relevant local and international studies (refer Chapter 2).
- Study Methodology (refer Chapter 3).
- Data Collation and Analysis: An analysis and overview of the comprehensive data collation process completed (refer Chapter 4).
- Model Setup: Configuration and details of the TUFLOW FV hydrodynamic and SWAN spectral wave model (refer Chapter 5);

- Model Calibration: The astronomical tide and wave calibration process and results (refer Chapter 6)
- Experimental Hindcast Runs: Design and rationale of each experimental run conducted (refer Chapter 7).
- Results and Discussion: Presentation and discussion of the model Experimental Hindcast Runs (refer Chapters 8 and 9).

2 Literature Review

This section provides an overview of three main areas:

- The physical processes involved in the generation of coastal storm surge;
- Review of recent storm tide studies within the Southeast QLD region; and
- Investigation of relevant studies in the area of tropical cyclone and three dimensional ocean modelling.

2.1 Physical Processes

2.1.1 Introduction

The passage of synoptic-scale meteorological systems such as Tropical Cyclones, Extra-Tropical Systems and East Coast Lows bring with them heavy rainfall, destructive winds and affect the ocean on a range of spatial scales (Harper et al. 2001). From a coastal management perspective, coastal inundation and erosion associated with the storm surge and extreme waves generated by these events are of primary concern.

The following sections provide an overview of the main dynamic and static physical processes that contribute to the generation and propagation of storm tide hazard within the Queensland (QLD) region including:

- Synoptic scale oceanic storm systems;
- Ocean bathymetry, coastal morphology and topography;
- The astronomical tide;
- Ocean density structure, internal waves, coastal currents and seasonal ocean setup; and
- Offshore and near-shore surface wave processes including wave shoaling, wave setup, run-up and overland wave propagation.

Each of the aforementioned factors contribute in a non-uniform manner to observed water levels measured during coastal storm events. Importantly, these factors act to influence each other in a complex non-linear fashion over the large temporal and spatial scales they act upon.

2.1.2 Overview of Storm Tide Components

Figure 2-1 provides an overview of the major storm tide components.

- Astronomical tide plays an important role in determining the depth of water to generate surge or wave attack during a storm.
- Wind driven surge: Transfer of momentum from wind shear stress is imparted to the water column. The leads to the generation of currents and in regions adjacent to the coastline, water can ‘heap’ up against the coast. The shallower the water, the higher surge that can occur.
- Pressure surge: This is also known as the so-called inverse-barometer effect that results in about 1cm rise for every hPa mean sea level pressure drop. Usually not as significant as the wind driven surge.
- Extreme winds acting on the ocean surface generate wind waves. As these wave propagate into shallow water they begin to shoal and break. Some of the kinetic and potential energy associated with wave forms an onshore current component. This onshore component of breaking wave energy results in a increased mean water level at the beach face known as wave setup (Longuet-Higgins & Stewart 1964).
- The storm tide is the combination of the astronomical tide, wind and pressure surge and wave setup.
- In addition to storm tide, residual energy from the runup of individual waves and surf beat can result in intermittent water levels above the wave setup level due to wave action. These waves can propagate inland causing significant damage to coastal structures and infrastructure.

Storm tide is often measured using the tidal residual, or the difference between the measured water level and the predicted tide as follows:

$$Tidal\ Residual\ (m) = Measured\ Water\ Level - Predicted\ Tide$$

Figure 2-1 provides a schematic of each storm tide component. The term SWL refers to the so-called ‘still water level’ and represents the level that the storm surge would reach without surface gravity wave processes. The mean water level (MWL) is the elevated water levels experienced adjacent to the beach due to wave setup, which acts on top of the SWL. The storm tide can be measured above the Australian Height Datum (AHD) or at times the Lowest Astronomical Tide datum and this is often a cause of confusion. The term HAT stands for the Highest Astronomical Tide and represents the maximum height at which the astronomical tide can reach at a given location due to just gravitation forces alone, however due to the effects of weather it is regular exceeded. HAT is an important level as generally dwellings and public infrastructure are constructed above it and therefore storm tide exceeding HAT can have disastrous effects on the community.

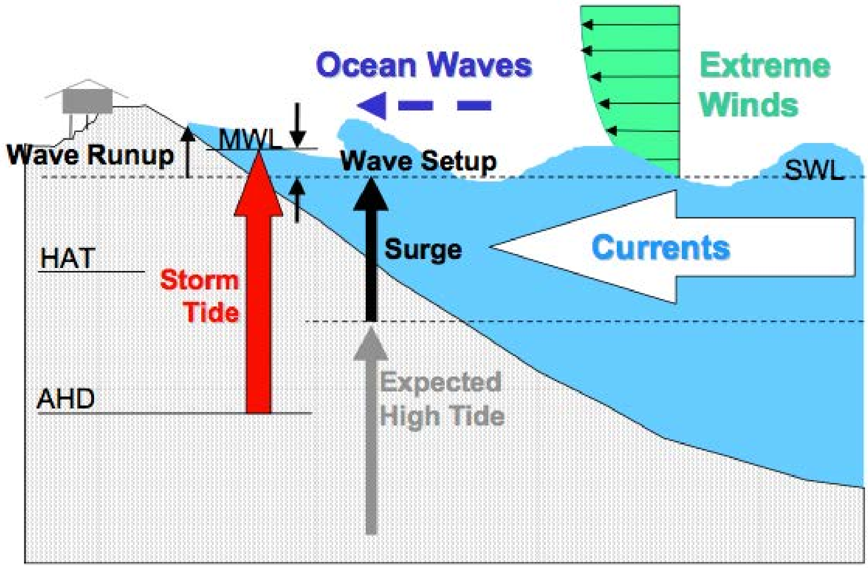

Figure 2-1 Storm Tide Components. Reproduced with permission (Harper et al. 2001)

2.1.3 Equations of Motion

The physical response of the ocean to external and internal forces can be simplified and modelled through the usage of the so-called Non-Linear Shallow Water Long Wave equations. These equations are derived from the viscous Reynolds equations (Harper et al. 2001) assuming hydrostatic and Boussinesq approximations as follows:

- Hydrostatic approximation: This assumes that the horizontal scale is large compared to the vertical scale and that the vertical pressure gradient is a product of the density and gravitation acceleration (buoyancy)(*Hydrostatic balance - AMS Glossary* n.d.) .
- Boussinesq approximation: Assumes that density differences (in a given layer) are small enough to be neglected and that density differences only affect the acceleration due to gravity (buoyancy term).
- The fluid is incompressible, vertical accelerations can be ignored and density variation affect the buoyancy of the fluid only

The shallow water equations rely on the principals of conservation of momentum and mass, here reproduced in Cartesian form in the reference system (x,y,z):

The momentum equation in the x direction:

$$\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{t}} + \boldsymbol{\nabla_h} \cdot (\boldsymbol{uu}) + \frac{\partial(\boldsymbol{wu})}{\partial \boldsymbol{z}} + \boldsymbol{fk} \times \boldsymbol{u} = -\boldsymbol{\nabla_h}[\boldsymbol{g}(\boldsymbol{\eta} - \overline{\boldsymbol{\eta}}) + \boldsymbol{P_s}/\boldsymbol{\rho_w}] + \frac{\partial}{\partial \boldsymbol{z}}\left(\boldsymbol{K_m}\frac{\partial \boldsymbol{u}}{\partial \boldsymbol{z}}\right) + \boldsymbol{F}$$

The conservation of mass (continuity equation):

$$\frac{\partial \boldsymbol{\eta}}{\partial \boldsymbol{t}} + \boldsymbol{\nabla_h} \cdot \boldsymbol{u} + \frac{\partial \boldsymbol{w}}{\partial \boldsymbol{z}} = \boldsymbol{0}$$

Where:

$\boldsymbol{\nabla_h} = \langle \frac{\partial}{\partial x}, \frac{\partial}{\partial y} \rangle$

g = gravitational acceleration

f = Coriolis parameter

t = time

u = (u,v)

ρ_w= water density

k = local gradient unit vector

w = vertical velocity component.

η = water level surface (with reference to mean sea level)

$\bar{\eta}$ = equilibrium tide due to external astronomical forcing

F = Additional horizontal forces

The action of wind stress within the ocean can be explained through a control volume analysis with the control volume as depicted by the rectangle in Figure 2-2. As wind ‘blows’ across the surface of the ocean, it exerts a shear stress at the water surface. A component of the wind momentum is transferred vertically into the water column (Callaghan, Nielsen & Baldock 2012) and to balance this momentum an increase is water level must occur.

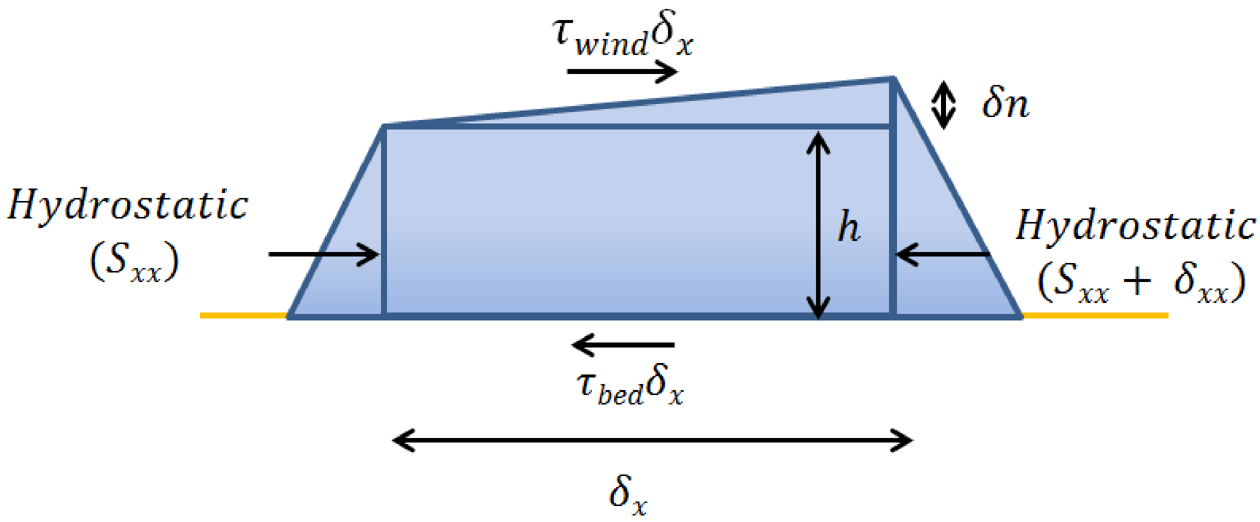

Figure 2-2 Control volume force analysis for wind stress in the x direction

2.1.4 Surface Wind and Pressure

Surface wind and pressure forcing is the main driver of observed coastal storm surge. Unfortunately, under the extreme conditions experienced during tropical cyclones, the surface winds remain poorly understood (Bode & Hardy 1997). Within Southeast QLD, the extreme storm climatology is composed of both tropical and sub-tropical systems, mainly Tropical Cyclones and East Coast Lows.

2.1.4.1 Tropical Cyclones

Tropical Cyclones (TCs) are the most destructive weather events experienced on the Queensland coast, usually occuring in the region between November and April. These systems can affect the coast over hundreds of kilometres for periods of several days. The Australian Bureau of Meteorology (BoM) defines a TC as:

"A non-frontal low pressure system of synoptic scale developing over warm waters having organised convection and a maximum mean wind speed of 34 knots or greater extending more than half-way around near the centre and persisting for at least six hours".

In Australia, TCs typically develop from low pressure disturbances over warm waters associated with the Monsoon trough, a region of tropical convergence where simultaneous favourable environmental factors can exist to allow TC development. These conditions accorded to (Gray 1968) include:

(1) Sufficient ocean heat energy to drive convection This generally requires sustained sea surface temperatures (SST) of over 26^{o} C to a depth of at least 60m;

(2) Enhanced humidity through the mid-troposphere and conditional instability;

(3) Enhanced lower troposphere relative vorticity;

(4) Weak vertical wind shear; and

(5) Formation needs to be far enough from the equator to allow sufficient Coriolis deflection and rotation (typically greater than 5 degrees of latitude although there have been exceptions).

A mature TC is characterised by largely symmetrical 'core' with winds rotating clockwise (anti-clockwise) in the southern (northern) hemisphere around an inner 'eye' which is typically 30-50 km in diameter (Harper et al. 2001). This eye region is associated with the lowest atmospheric pressure and is relatively calm compared to the violent and destructive winds within the convective cumulonimbus clouds of the 'eye-wall' that surround the eye (refer to the purple and red colouration in the left panel of Figure 2-3 and as shown in Figure 2-4). For TCs approaching the QLD east coast from offshore, the maximum wind speeds are usually experienced to the south of the system where both the forward speed component of the moving storm and the wind direction act together. Outside of the eye-wall a series of convergent spiral rainbands can trail out for many hundreds of kilometres.

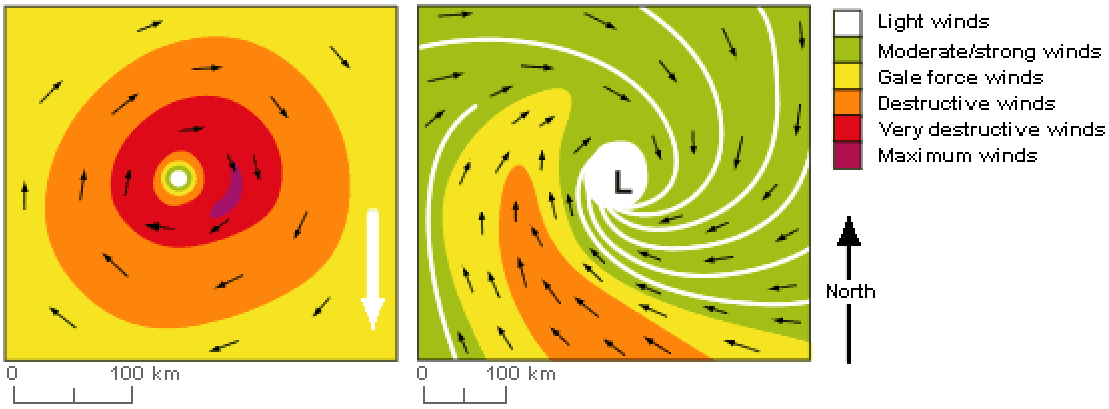

Figure 2-3 Mature Tropical Cyclone symmetrical form (left) and hybrid system (right) Source: (Bureau of Meterology n.d.))

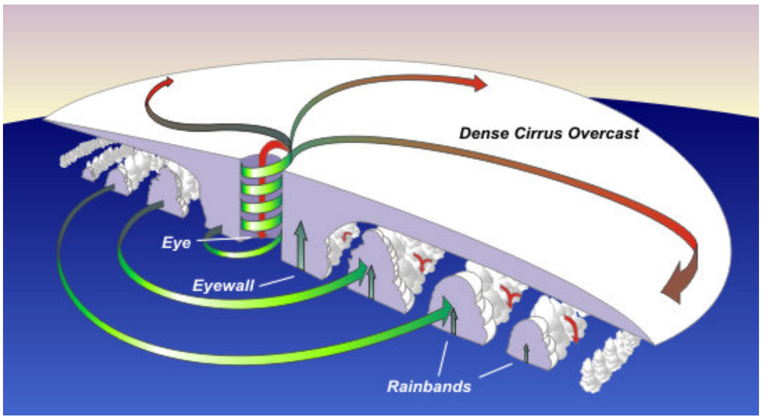

Figure 2-4 Cross section of a mature hurricane Source: (US National Weather Service n.d.)

The intensity of TCs in Australia is assigned using a five-category scale based on estimated maximum wind gust as shown in Table 2-1. For any given central pressure, the form and movement of TCs varies considerably. For example Figure 2-5 shows the structure of the mature *TC Yasi (left)* as it approached the Queensland coast in 2011 and *TC Marcia* (right) in 2015. Both systems were estimated to have a minimum central pressure of approximately 930 hPa[1] and were classified as Category 4-5 status. The red and green arrows within Figure 2-5 shows the limit of the main convective zone for Marcia and Yasi respectively, highlighting the significant difference in size between the two systems. Although of similar intensity, *TC Yasi* due to its size also had a much greater overwater fetch length available for the generation of waves and resulting in a significant storm surge of approximately 5.33 m at Cardwell (Queensland Government, 2012). At the time of writing, a field report stating the impacts of *TC Marcia* was being prepared by the State Government, however from available levels the surge footprint was much smaller than that associated with *TC Yasi.*

[1] The intensity associated with Tropical Cyclone Marcia may be revised down following further investigation by the Bureau of Meteorology.

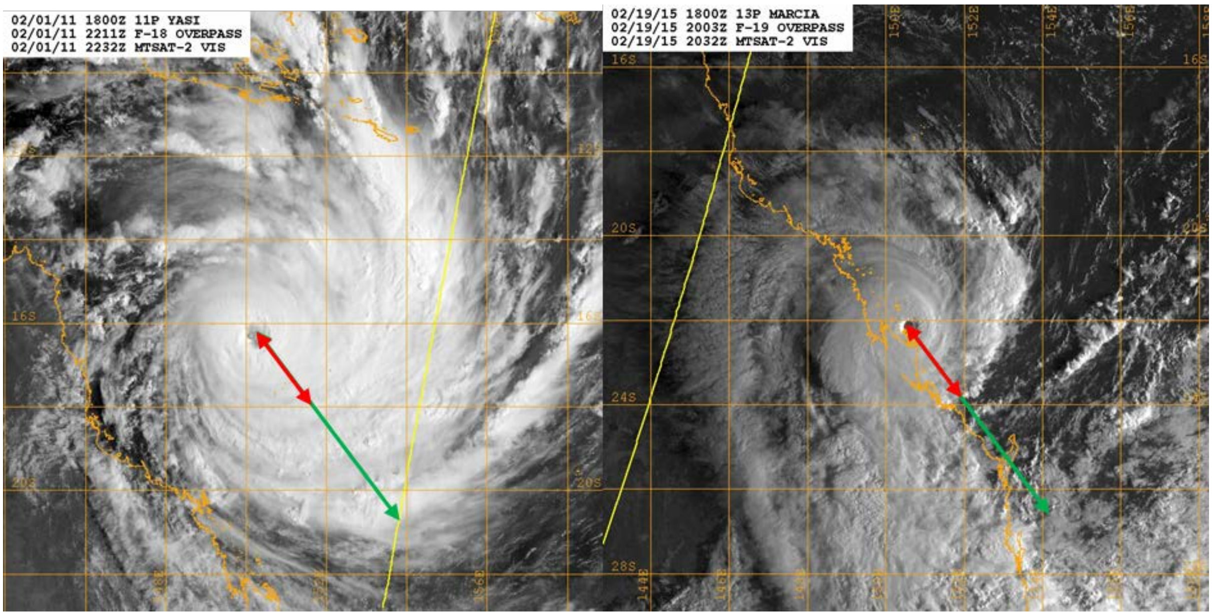

Figure 2-5 Structure of Tropical Cyclone Yasi (left) and Marcia (right) approaching the Queensland coastline in 2011 and 2015 respectively (NRL, 2015).

Whilst many of the impacts associated with TCs are experienced in Northern Queensland (on average 4.7 per year (BoM, 2015a)) approximately one system per year tracks within 500 km of Brisbane (GHD, 2007). Southeast QLD resides in a transition zone between tropical and extra-tropical systems and as a result, many of the systems that do move south tend to be large but decaying systems. As these systems track south, they often interact with upper level synoptic features that move them parallel to the coast in a north-west to south-easterly direction as highlighted in the right panel of Figure 2-6.

Table 2-1 Tropical Cyclone Category Scale

Category	Maximum 3-sec Wind Gust (km/hr)	Potential Damage
1	<125	Minimal house damage. Damage to some crops, trees and caravans.
2	125-170	Minor house damage. Significant damage to signs, trees and caravans. Heavy damage to some crops. Risk of power failure.
3	170-225	Some roof and structural damage. Some caravans destroyed. Power failure likely.
4	225-280	Significant roofing and structural damage. Many caravans destroyed and blown away. Dangerous airborne debris and power failures.

Category	Maximum 3-sec Wind Gust (km/hr)	Potential Damage
5	>280	Extremely dangerous with widespread destruction.

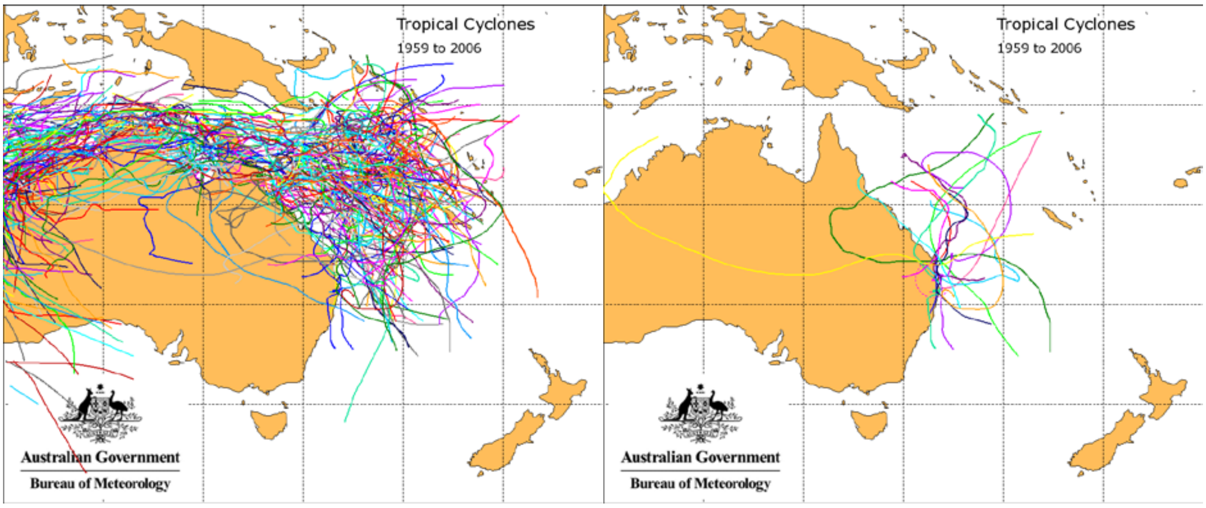

Figure 2-6 Tropical Cyclones affecting the within the QLD region (left) and within 200km of Brisbane (right) for the period 1959-2006. Source: BoM, 2015b

2.1.4.2 East Coast Lows

As detailed in (GHD, 2007), East Coast Lows (ECLs) are large-scale intense low pressure systems that form off the Queensland and New South Wales east coast, typically forming in the winter months. In Southeast QLD, ECLs are much more frequent occurring then Tropical Cyclones with an average of 3.7 systems occurring per year since 1960 with up to 12 systems occurring in some years.

Unlike tropical systems which draw much of their energy from latent heat, ECLs draw their energy from strong ocean temperature gradients. Due to this differing forcing mechanism, ECLs can never be as intense as TCs although they have been observed to have central pressures as low 990 hPa.

The passage of ECLs is often accompanied by heavy rain, minor storm surge and large waves. These systems can remain quasi-stationary and result in extensive coastal erosion such as occurred during the ECL of May 2015 which affected the Sydney and Central Coast regions of New South Wales (NSW) over a three day period.

2.1.4.3 Sub-Tropical, Extra-Tropical and Hybrid Systems

(Granger and Hayne, 2001) also detail a number of other systems contribute to the ocean storm climatology in Southeast QLD including:

- Sub-Tropical Cyclones: Intense low-pressure systems that don't quite make it to TC intensity. They do not have the extreme eye wall winds required to be classed as TCs however due to large fetch lengths, they can still lead to large wave and surge events. Such systems can transform into extra-tropical systems or east coast lows.
- Decaying or south moving Tropical Cyclones can often interact with the passage of trough systems resulting in or extra-tropical transition or the so-called 'weather bombs'. Rather than decaying as a tropical system, the gain further energy through interaction with other systems. This can result in rapid intensification.
- Finally, a storm can be in the form of a 'hybrid' system with structure similar to that provided in the right panel of Figure 2-3. These systems can be hard to classify and much of the convection can be to the south of the system.

TC Oswald was an unusual system to classify in that after making landfall as a 'true' Category 1 TC in the Gulf of Carpentaria, *Ex-TC Oswald* passed almost entirely overland through QLD and NSW as an intense inland low, affecting almost the entire east coast of Australia.

2.1.5 Astronomical Tide

The astronomical tides are primarily the result of the gravitation forces of the moon and sun upon the earth; and the centrifugal forces produced by the earth and moon and earth and sun around their common centre of gravity (NOAA, 2013).

Normal to the earth's surface, the gravity component of the earth is approximately nine million times stronger than that exerted by the moon. Thus the moon does not pull vertically, but tides propagate horizontally and act to 'pile up' water due to the horizontal component of the gravitation force, known as the Tractive Force. This results in a series of gravitationally driven sine waves that continuously sweep around the earth following the position of the moon (and sun).

Land masses act as a barrier to tidal wave propagation. Topography can also create local effects or restrain the tide acting to significantly change the speed of propagation. As the depth of the water shallows, the speed of forward movement of a traveling tidal wave is modified due to frictional forces of the bed and ocean current that act to slow the advance of tide.

The astronomical tide component of observed water levels can be represented as a linear combination of sine waves known as tidal constituents. These components can be extracted from a measured time history of sufficient length to extract tidal phase, amplitude and frequency for each of the main 37 different tidal constituents using Fourier Analysis (Pawlowicz, Beardsley & Lentz 2002). The eight major diurnal and semi-diurnal constituents for Brisbane Bar and the tidal planes are provided in Table 2-2 and Table 2-3 respectively (Department of Transport and Main Roads 2014)

Table 2-2 Brisbane Bar Tidal Constituents

Constant	Definition	Amplitude (m)	Phase (^{o})
M^2	Principal lunar semidiurnal constituent	0.707	275.0
S^2	Principal solar semidiurnal constituent	0.193	302.2
N^2	Larger lunar elliptic semidiurnal constituent	0.138	265.3
K^2	Lunisolar semidiurnal constituent	0.058	294.2
K^1	Lunar diurnal constituent	0.212	171.1
O^1	Lunar diurnal constituent	0.117	131.4
P^1	Solar diurnal constituent	0.060	169.0
Q^1	Larger lunar elliptic diurnal constituent	0.024	103.0

Whether a given region has diurnal (one high tide per day) or semi-diurnal (two high tide per day) can be classified based on the tidal 'Form Factor', a relationship between the major diurnal and semi diurnal constants. When F is less than or equal 0.5 the tide is semi-diurnal, if greater than 0.5 the tide is primarily diurnal (PCTMSL 2014). As shown in the equation below this indicates that Brisbane Bar and the Moreton Bay region can be classified as a semi-diurnal tide.

$$F = \frac{K^1 + O^1}{M^2 + S^2} = \frac{0.212 + 0.117}{0.707 + 0.193} = 0.37$$

Where the tidal constants are previously described in Table 2-2

Table 2-3 2015 Brisbane Bar Tidal Planes

Constant	Level (mLAT)	Level (mAHD)
Lowest Astronomical Tide	0	-1.24
Mean Low Water Springs	0.37	-0.87
Mean Low Water Neaps	0.76	-0.48

Constant	Level (mLAT)	Level (mAHD)
Mean Sea Level	1.27	0.03
Australian Height Datum	1.243	0.00
Mean High Water Neaps	1.78	0.54
Mean High Water Springs	2.17	0.93
Highest Astronomical Tide	2.73	1.49

2.1.6 Bathymetry and Coastal Morphology

The underlying ocean bathymetry and coastal morphology determine the propagation of the astronomical tides and storm surges from deep water into coastal near-shore regions. The bathymetry of the QLD Coast south from Townsville is characterised by a large continental shelf extending up to 200 km offshore reducing sharply east of Bundaberg and then tapering to approximately 40 km at the QLD/NSW border (refer Figure 2-7). The presence of the continental shelf in northern QLD has allowed the formation of the Great Barrier Reef that acts as an important barrier in the dissipation of offshore wave energy, reducing the threat of wave attack during extreme events. Although reducing wave attack, the shallow water region of the Great Barrier Reef Lagoon at its widest enhances the threat of extreme storm surge to our Northern Coastal communities.

The exposed coastline of the Gold Coast, the Sunshine Coast and the barrier islands of Stradbroke, Moreton, Bribie and Fraser Islands are all subject to high-energy wave attack and this has resulted in the iconic beaches that we observe on these stretches of coast. While Moreton Bay is largely sheltered by extreme wave effects by the Barrier Islands, the region represents a relatively shallow coastal embayment with much of the bathymetry between 0 to 10 m below Mean Sea Level (MSL). Due to its shallow nature it is more vulnerable to storm surge than the aforementioned beach regions.

Major river systems that empty into Moreton Bay include the Caboolture, Pine, Brisbane, Logan and Albert Rivers that in flood can introduce a significant amount of freshwater and sediment.

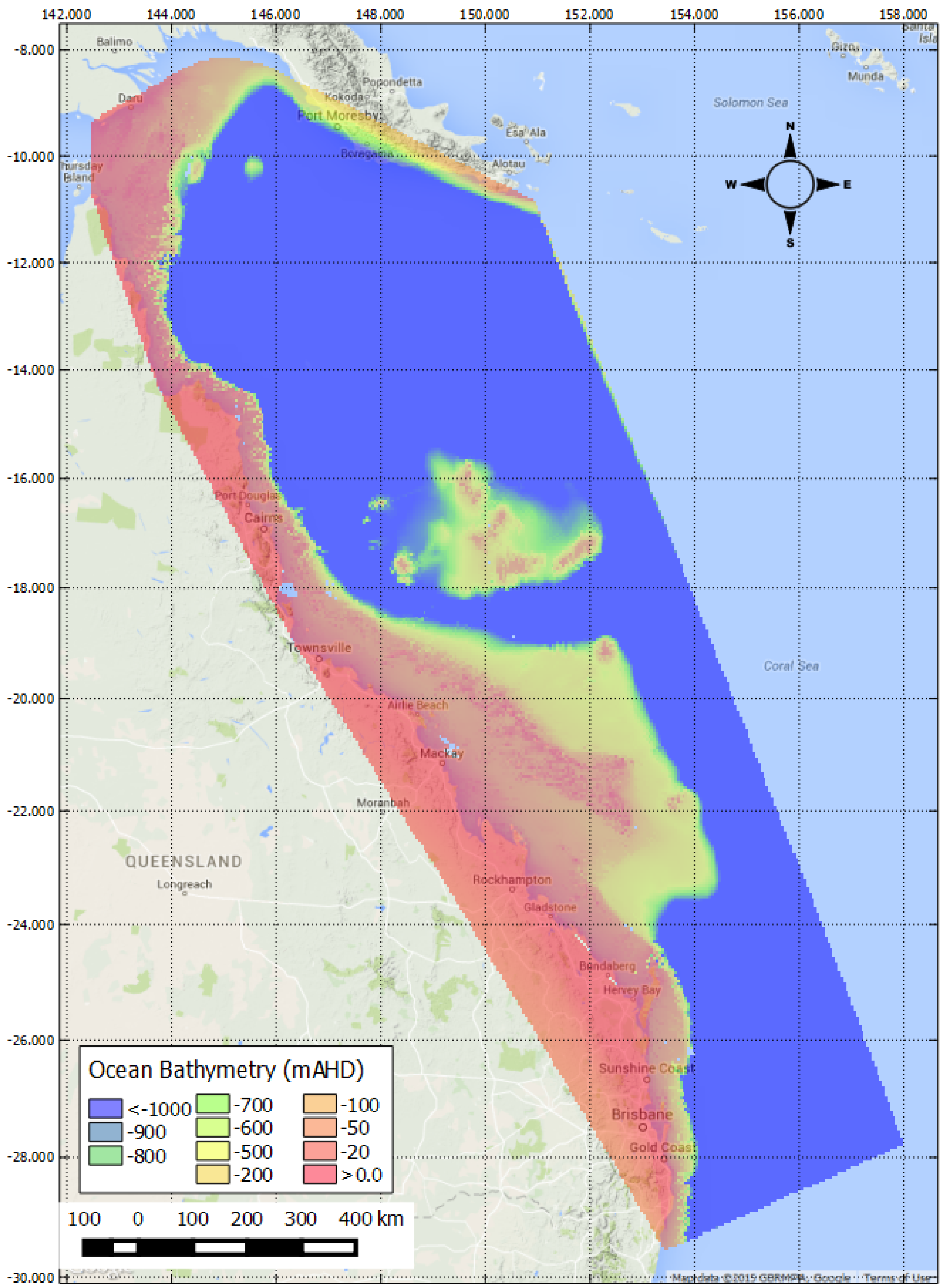

Figure 2-7 Queensland Coastal Bathymetry

2.1.7 Storm Surge

Storm surges are a result of meteorological forcing on the ocean surface. They manifest as surface long waves that can cause persistent increased water levels to those usually associated with the astronomical tide (Harper et al., 2001). During extreme wind events such as TCs, ECLs and Extra-Tropical Systems, the magnitude of the surge is primarily forced by surface wind shear stress with atmospheric pressure forming a lesser component of the overall surge.

As a storm system approaches the coast, the storm surge at a given location is influenced by a complex combination of factors such as:

- The approach speed, intensity, direction and size of the storm;
- The phase of the astronomical tide during the passage of the system;
- The shape and scale of the coastal bathymetry and morphology. i.e. the presence and slope of the continental shelf, shallow coastal embayment's, beaches, coastal lowlands, offshore reefs, barrier islands and riverine systems; and
- The role of surface gravity (wind driven) waves and interaction between the atmosphere and ocean at the air-sea interface.

2.1.8 Surface Wind Waves

In deep water, surface wind waves play an important role in the mixing of the upper ocean through turbulence and oscillatory motion. In shallow regions, wave shoaling can act to impart energy into the water column resulting in wave induced currents and the wave setup component of storm tide.

Wind waves and swell are essentially a form of gravity wave generated through the shearing effects of the wind on the ocean surface. As the wind begins to blow it produces random pressure fluctuations that build very small waves (Stewart 2008). As the wind continues to blow these small waves grow in size which creates larger pressure differences and the waves grow rapidly. As these waves grow they begin to interact producing waves of longer wavelengths (Hasselmann et al. 1973) that propagate away from the generation site. For a given wind speed, duration, fetch and water depth wave heights will continue to grow until the reach a state of equilibrium known as a 'fully arisen sea'.

By nature waves are inherently non-linear (Stewart 2008) however we can approximate real wave behaviour through linear wave theory. This leads to fundamental expressions for wave height, wave period, frequency, number, celerity, dispersion, phase and group velocity and wave energy which are not repeated here.

In reality, the waves we observe at the beach are a complex combination of semi-random energy waves that advect energy across surface and through the upper ocean, each with their own frequency, direction and source. There is still on-going research into the propagation of waves however which with some simplifications, can be assessed using the concept of a wave spectrum (Stewart 2008). This study will use a so-called third generation wave model (SWAN) to model the evolution and decay of the directional wave spectrum F(f,θ) where f is frequency and θ is the direction of propagation ((Harper et al. 2001).

Waves transfer momentum to the water column through an excess pressure force and horizontal momentum flux known as wave radiation stress (Longuet-Higgings and Stewart 1964). Radiation stresses can occur in both deep and shallow waters however for the purposes of storm tide assessment and coastal morphological studies the action of waves for the latter can become significant. Waves start to be affected by bed friction when the depth is approximately half the wavelength, as the depth becomes shallower the waves increase in steepness, shoal and eventually break. The ensuing energy imparted by radiation stresses lead to wave induced currents, wave setup, surf beat and wave run-up.

Inside the surf zone radiation stresses decrease rapidly as you approach the shore due to the depth limited wave heights. The process of breaking wave setup is highlighted in Figure 2-8 whereby an elevated mean water level can be maintained through the surf zone according to the following relationship:

$$\frac{\partial \eta}{\partial x} = \frac{1}{\rho g h} \cdot \frac{\partial S_{xx}}{\partial x} + \frac{1}{\rho g h} \cdot (\tau_{wind} - \tau_{bed})$$

Where:

$\bar{\eta}$ = Level above mean sea level (m)

ρ = Water Density (kg/m^3)

g = Gravitational acceleration (m/s^2)

h = Water depth (relative to mean water sea level (m)

S_{xx} = Wave radiation stress (Pa)

τ = (Pa)

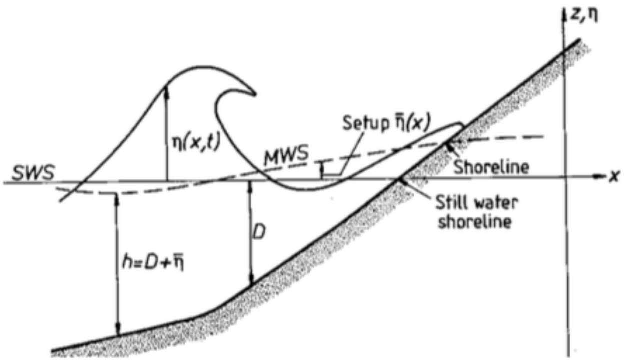

Figure 2-8 Wave setup at the shoreline (after (Hanslow & Nielsen 1992)

2.1.9 Limitations in our current understanding of wave-surge physics

The review of (Bode & Hardy 1997) made a number of observations with regard to the status of storm tide modelling and model physics which almost twenty years later remain areas of intense research focus. Two key points were in relation to the need to include surge-wave interactions. Importantly:

- The current method of specifying surface stress as a function of wind speed only, underestimates the role of surface waves. Waves are the roughness element and they move in both space and time and that the physics at the air interface is very complex and poorly understood, particually at extreme wind speeds;
- If the wind speed and direction is known, which is very unlikely most of the time, the surface drag coefficient is the single most important factor in determining the transfer of momentum to the water column.

So it is possible that limitations to our current implementation of these important physical processes is responsible for a component of the 'missing' storm tide levels observed within the region.

2.1.10 Ocean Vertical Structure

The vertical state of the ocean establishes the kind of disturbances that can propagate through the internal ocean. As this study is looking at the potential for density driven effects along the continental shelf during the passage of extreme weather events, the three-dimensional state prior and the likely mixing during the event are explored.

Vertically, the ocean can be described by three main regions:

- The mixed boundary layer: The surface region of ocean subject to atmospheric forcing and the ocean currents driven by wind stress and pressure gradients. Salinity and temperature are close to constant in this layer (Stewart 2008);
- The thermocline: The region below the mixed layer where there is a rapid change in temperature and thus density; and
- The deep ocean: The region below the thermocline typically less than 1500 m below sea level.

Seawater density is a function of pressure, salinity and temperature that is calculated using the equation of state. In most oceanic situations, and in particular in the upper 1500 m of the ocean, the effect of the vertical salinity gradient on density is much smaller than the effect of the vertical temperature gradient (Tomczak & Godfrey 2003).

Figure 2-9 shows vertical profiles of salinity and temperature measured offshore of Moreton Island on the 3rd of January, 2013, approximately one month before the passage of *Ex. TC Oswald,* collected by an Argo float. These devices drift through the ocean at a depth of ~1000m for up to nine days. After this period they descend to 2000 m and once at this depth they slowly ascend at ~0.1 m/s to the surface taking temperature and salinity measurements. Focusing on the left and middle panels of Figure 2-9 the mixed layer of the ocean can be observed over a depth of approximately 60 m prior to a rapid reduction in temperature associated with the thermocline.

These profiles are in the vicinity of the East Australian Current (EAC), which is a significant western boundary current that flows in a mean north to south direction along the east coast of Australia as a result of topographical and Coriolis deflection of trade wind driven currents from the central and western Pacific. The current is a major propagator of heat energy to the South and has observed gyres that occur off the NSW coastline. (Ridgway & Dunn 2003). The effects of the EAC can be observed in the top and bottom right panel of Figure 2-9. These panels show the high sea surface temperatures and sea level anomalies associated with the passage and gyres of the EAC adjacent the QLD coastline.

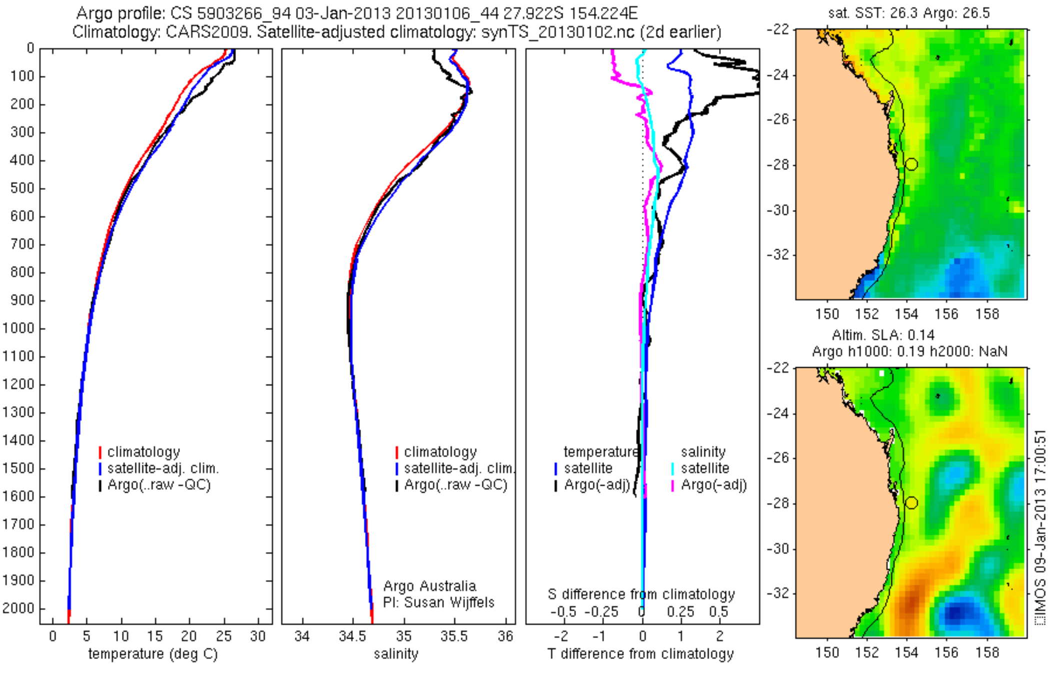

Figure 2-9 Argo ocean temperature and salinity profile and gridded sea surface temperature and sea level anomaly from IMOS.

The ocean can be described as either *barotropic* or *baroclinic* dependent on the vertical density composition as follows:

- Barotropic: Oceanic isobars (lines of equal pressure) and (lines of equal density) are always parallel. Barotropic flow is sometimes referred to as depth averaged or depth independent flow; or
- Baroclinic: Isobaric and isopycnal surfaces are at angles to each other and density may vary with depth (Stewart 2008).

Under baroclinic conditions large gradients in density or vertical stratification can arise. The degree of stratification can be inferred through calculation of the Brunt-Vaisala frequency N, defined as:

$$N = \sqrt{-\frac{g}{\rho} \cdot \frac{d\rho}{dz}}$$

Where p is the potential density and higher N values indicate larger density gradients through the vertical. For example, calculated values of N experienced off the Southeast QLD from the profile in Figure 2-9 range from 0.002 to 0.02.

During the passage of extreme weather, waves and currents within the mixed layer can act to disturb the thermocline through turbulence and interaction with the continental shelf break. The turbulence can result in the upwelling of colder water and deepening of the thermocline. The mixed layer can also overturn if winds are strong enough. The potential for overturning and instability in the mixed layer can be estimated through calculation of the dimensionless Richardson Number, a relationship between current shear and buoyancy as follows:

$$Ri \equiv \frac{N^2}{(\partial u/\partial z)^2}$$

If the Richardson Number is greater than 0.25 everywhere the layer is stable, less than 0.25 unstable and likely for overturning to occur.

2.1.11 Oceanic Long Waves

Kelvin and Rossby Waves are two oceanic-scale energy transfer mechanisms that lead to observed water level anomalies in the Southeast QLD region. The main differences between these two different wave types is the restoring mechanism; with Kelvin Waves restored by gravity and Rossby Waves by the conservation of relative vorticity. A storm surge event with be comprised of a mixture of these types of fundamental wave motions.

2.1.11.1 Kelvin Waves

Coastal Kelvin Waves (or coastally trapped waves) can travel on the surface (Barotropic) or as internal waves (Baroclinic) and balance the Coriolis Force against a topographic boundary. In the Southern Hemisphere they always propagate with the coast on the left. Coastally trapped waves as a result of TCs have been investigated at length in the Australian region by the likes of (Tang & Grimshaw 1995), (Woodham et al. 2013), (Eliot & Pattiaratchi 2010) which have shown that waves move around the continent as continuous features with their amplitude modulated by the width of the continental shelf (Waves travel faster with greater continental shelf width). The amplitude of a coastal Kelvin wave is at maximum at the coast and negligible at a distance defined by the Rossby Radius of deformation, which defines the distance over which Coriolis forces start to become as important as buoyancy and gravitation wave speed processes. In a Barotropic ocean the Rossby Radius of Deformation is defined by:

$$\frac{\sqrt{gH}}{f}$$

where g = gravitational acceleration;

H = water depth; and

f = $2\Omega\sin\phi$ or Coriolis Parameter (approx.. 0.66E-06 for the Brisbane region).

Table 2-4 provides a summary of calculated Rossby Radii of Deformation at different depths off the Southeast QLD coast and shows that there is a considerable distance that a current must travel prior to be deflected, particularly in deep water. Baroclinic waves can be deflected over relatively shorter lengths, due largely to the smaller difference in density between ocean layers. As defined in (Chelton et al. 1998), away from the tropics, i.e. less than ±5^{o} latitude the baroclinic Rossby Radius of Deformation is computed from the baroclinic gravity-wave phase speed, c, and the Coriolis parameter, f, as follows:

$r = \frac{c}{f}$ Where: $c = \sqrt{g\frac{\Delta\rho}{\rho}\frac{H1H2}{H1+H2}}$ Baroclinic wave celerity

where H1 and H2 represent the top and bottom of the ocean layer considered respectively.

Table 2-4 Barotropic and Baroclinic Rossby Radii of Deformation off Southeast QLD

Depth	Barotropic Rossby Radius of Deformation (km)	Baroclinic Rossy Radius of Deformation (km)
50	140	30-50 km
100	320	
250	650	
500	910	
1000	1290	

2.1.11.2 Rossby Waves

Rossby Waves form due to the requirements to conserve potential vorticity. In a Barotropic ocean as water is pushed eastward over a reducing depth, to conserve potential vorticity the relative vorticity must increase. In the Southern Hemisphere, as depth decreases there is an anticlockwise rotation of the water column. Equally as water flows equator-ward under constant depth the Coriolis parameter decreases to there must be a increase in vorticity leading to anti-clockwise flow.

$$\Pi = \frac{f}{\rho} \cdot \frac{\partial \rho}{\partial z} = \frac{\xi + f}{H}$$

Where f is the Coriolis Parameter

p is the water density

H is the total water depth

z is the water depth

ξ is the relative vorticity

2.1.12 Internal Waves

Internal waves propagate within the interior of the ocean, typically within the thermocline at the interface of differing density layers (refer Figure 2-10). They can be thought of as similar to surface gravity waves (Thorpe 1999). As stated in (Dukhovskoy, Morey & O'Brien 2009), internal wave frequencies can range from an upper limit of the Brunt-Vaisala frequency to a minimum of the Coriolis frequency, however they generally span from a few tens of cycles per hour to one cycle per Coriolis period. The internal response of the ocean over a shelf to a cyclone depends on the characteristics of the cyclone (intensity, track, translation speed), but also on the latitude, shelf geometry and water stratification. The interplay between these parameters is characterized by a scaling called the Burger number (LeBlond and Mysak, 1978):

$$Bu = \left(\frac{Ri}{L}\right)^2 = \left(\frac{NH}{fL}\right)^2$$

where: Ri = radius of deformation, L is the length scale over which the current or wave occurs, H is the average water depth of the region and f and N are the Coriolis parameter and Buoyancy frequency as previously defined. When the Burger number is much less than 1 the shelf responds to large-scale weather systems as a barotropic ocean (Clarke and Brink, 1985). When Bu much greater than one, the shelf response should predominantly be baroclinic.

Figure 2-10 Observed Internal Waves off Southeast QLD (Jackson & Apel 2004)

2.2 Review of Recent Local Storm Tide Investigation

There have been numerous storm tide studies conducted within Southeast QLD. This review will concentrate on recent studies (post 2000) that have included hindcasting of TC storm surge events.

2.2.1 Moreton Bay and Logan/Redland Storm Tide Study

Two separate 'sister' studies were completed for Moreton Bay Regional and Logan Redland City Council's (Carno Lawson and Treloar 2009). The studies investigated *TC Daisy* (1972), *TC Dinah* (1967) and a Tropical Low in 2004 and also a regional wave event during July 2001.

Due to the historical nature of the events, a major source of uncertainty during the hindcasts were the applied wind fields and where possible, various attempts to correct to observed data within acceptable practise were completed

For the *TC Daisy* hindcast, initially the model skill was assessed using a tide plus wind-only comparison to measured residuals. This provided a reasonable match at Mooloolaba however at Brisbane Bar, residual levels at the peak of the event were underestimated by up to 70% (0.2m vs total surge of 0.7m) The study argues that the negative bias during *TC Daisy* was due to 'regional wave setup' as a result of wave breaking on the Spitfire Banks. It also stated that regional wave set-up *has long been recognised as an important component of the observed storm surge inside Moreton Bay. The calibration process has shown that during particular storm events, there is a residual water level inside Moreton Bay that cannot be attributed to either inverse barometer or conventional wind set-up processes.* Residuals were observed to be highest during the ebbing tide and it was postulated that wave-current interactions on the Spitfire Banks essentially led to a blocking or control of tidal outflows due to wave momentum flux.

Reported comparisons to measured residuals during *TC Dinah* where limited to modelling results including regional wave setup only, and as such it is difficult to infer the contribution that wave related effects vs. surge alone contributed to observed levels. Notwithstanding the additional regional wave setup applied, there remained negative biases at the peak of the event at both Brisbane Bar and Sandgate. Similar negative biases were modelled during the Tropical Low of 2004 with tide plus surge only results 55% lower at 0.3 m (of total surge of 0.7 m) while with regional wave setup results were approximately 0.6 m.

To remove uncertainties associated with wind and pressure forcings during an extreme event, the study also investigated a regional wave event resulting from an intense low in the Tasman Sea in July 2001. It was concluded that the surge of 0.19 m observed at Brisbane Bar occurred at the time of peak wave heights offshore, which further supported the assumption of regional wave-surge interaction.

2.2.2 Tropical Cyclone Rodger (Stewart, Callaghan & Nielsen 2010)

This investigation was undertaken as part of a Masters Thesis and hindcasted *TC Rodger* and found a negatively consistent bias of 30 to 40 % for a range open coast and protected sites from Mooloolaba to Northern New South Wales.

The study included a number of sensitivity tests including increasing the wind drag coefficient by 30 % to better match observed surge levels. The paper also explored other potential reasons for the surge mismatch including potential for wave setup and riverine flooding. Unlike the Cardno study, 'regional wave setup' was not proposed to be the contributing factor to observed residual levels and the study suggested the need for further work on wind stress momentum transfer and for offshore current meters to be installed.

Both (Stewart, Callaghan & Nielsen 2010) and (Callaghan, Nielsen & Baldock 2012) adapted the model of (Tilburg & Garvine 2004) to produce a simplified model of the continental shelf off the Gold Coast. This work has been reproduced here to illustrate the effects of wind forcing and Coriolis on a conceptualised shelf during the peak of winds in Moreton Bay during from the passage of *Ex. TC Oswald*. (Tilburg & Garvine 2004) explored both the onshore and along shelf component of wind driven surge through:

$$\eta_c = \frac{fLU_x}{g}\sqrt{\frac{\rho_a C_D U}{\rho C_B |U_x|}} - \frac{\rho_a C_D U_y U}{\rho g \alpha}\ln\left(\left|1+\frac{\alpha L}{h_o}\right|\right)$$

Where:

η_c = peak surge (m)

f = Coriolis Frequency

L = Width of the continental shelf (m)

U, Ux and Uy= Wind speed (m/s) and x and y components of wind speed.

g = Gravitational acceleration (m/s^2)

ρ_a= Density of air (kg/m^3)

ρ = Density of Sea Water (kg/m^3)

Cd and Cb = The wind and bottom drag coefficients

α = slope

h_o= cutoff depth (m)

Both Stewart and Callaghan showed that this simplified steady state approach on a conceptual shelf could reproduce surge to within 5-10% of full non-linear modelling. Unlike Rodger whereby winds affecting the coast were largely from the east and southeast, during the passage of *Ex. TC. Oswald* the mean wind direction tended more east to east-northeast. Using the model of Tilburg and Garvine a maximum surge 0-0.05 m is estimated (refer green line Figure 2-11 for 90 degree wind direction) which is much less than observed surge levels at both Mooloolaba and Brisbane Bar. For complex coastal areas such as Moreton Bay this highlights the need to use modelling approaches that can better represent coastal features and dynamic processes. An interesting outcome of Figure 2-11 is the possibility that when winds are coming from the north and east Coriolis deflection would lead to currents moving offshore and a negative surge with potential coastal upwelling.

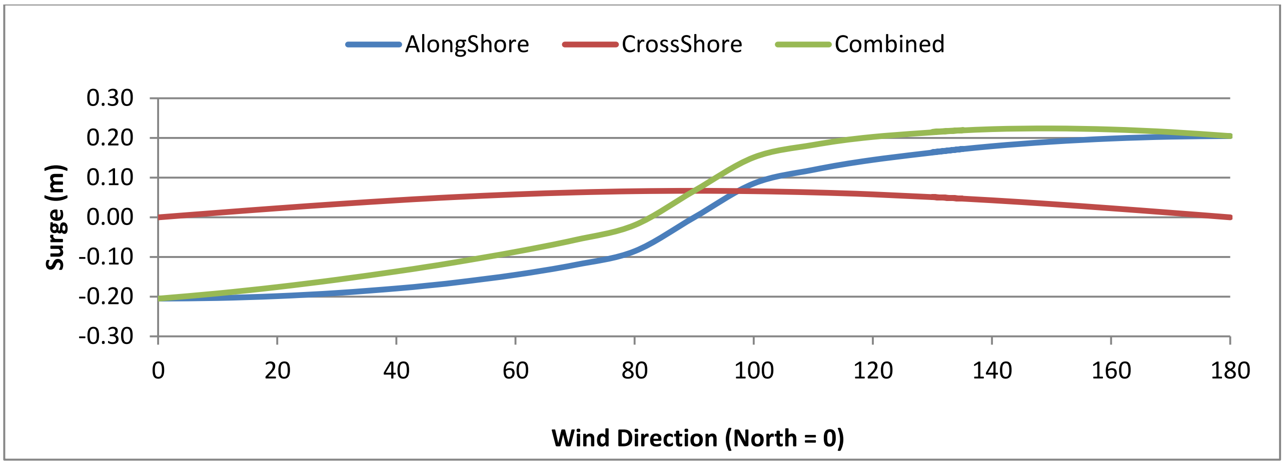

Figure 2-11 Alongshore, cross shore and combined surge due to constant wind speed of 20 m/s following from (Tilburg and Garvine, 2004)

2.2.3 Gold Coast Storm Tide Study

This study attempted to assess the surge associated with *TC Dinah* and the *TC 1954* Cyclone Also underestimated the surge (Harper, personal communication).

For both *TC Dinah* and *TC 1954* despite modelled winds and pressures being acceptable during the event and consistency with anecdotal observations during the event, actual storm surge levels at Brisbane Bar were in the order of 0.3 to 0.4 m higher than those modelled. It is also stated that due to the study being focused on the Gold Coast and not Moreton Bay, that some of this difference may have been due to lack of model detail in Moreton Bay. It is stated that ‘broadscale’ or regional effects are also likely responsible for the under prediction .

2.2.4 Brisbane Coastal Planning and Implementation Study.

This study was completed by GHD for Brisbane City Council and is currently in Draft form within BCC and the author of this paper was also involved in undertaking this study. *TC Oswald* was investigated and with a tide plus surge only 2D approach the *TC Oswald* storm surge was underestimated by up to 40 % (0.4 m) at Brisbane Bar and also by up to 50% (~0.25 m) at Mooloolaba. A key hypothesis of the study calibration was that the observed lack of response was due to energetic baroclinic processes that are not represented within 2D or 3D barotropic modelling that doesn't consider density effects. It postulated that upwelling events and interactions within the steep slope of the continental shelf break can act to generate internal and surface wave energy that can propagate across the shelf to the coast.

In an attempt to allow for these regional long wave and continental shelf processes, the measured tidal residual sampled from Mooloolaba was deemed representative of conditions outside of Moreton Bay and was added to the open boundaries of the hydrodynamic model. It is noted that other sites such as Southport were not included due to poor model resolution in the area. This approach improved the calibration but the peak remained 20% below the peak residual at Brisbane Bar. The study investigated but dismissed the likelihood of regional wave setup as claimed by Cardno, Lawson and Trealor.

2.2.5 Callaghan et al. (2012)

In response to the additional wind drag coefficients required to obtain reasonable matches to offshore approaching Tropical Cyclones in Southeast QLD, (Callaghan, Nielsen & Baldock 2012) compared momentum transfer using two approaches:

- The traditional 'air-side' quadratic drag law drag coefficients; and
- A formulation that provided momentum values similar to those observed during the wave height growth experiments of (Cavaleri & Zecchetto 1987)

Key findings and arguments put forward included:

- Measuring wind stress above the water and assuming it is applied to the ocean surface shows that wave growth data indicates 2-3 times more momentum than that estimated using the 'air side' approach.
- Investigated *TC Rodger* and also February 1996 East Coast Low.

- Compared the wind side and wave momentum using a modified model of that developed by (Tilburg & Garvine 2004). Wind side undestimed while the wave side approach resulting in overesimatation of peak surge levels.
- Posed the question why is it still acceptable momentum based on air side wind stress? Suggested that there needs to be a plausible and physical link between wave growth and input of momentum to the water column in depths greater than the shallow water limit.

2.3 Other Relevant Literature

The study of (Orton et al. 2012) modelled Hurricane Irene in 2011 and an extra-tropical 'nor-easter' of March 2010 using a series of modelling experiments completed by turning off various input forcings which is a similar experimental approach to that adopted for this study. They found that:

- Remote wind and pressure forcing beyond 250km led to reductions in measured residuals of 7-17%;
- Neglecting water density variations i.e. running in Barotropic model accounted for up to 1-13% of the observed residual;
- Parameterisation of wind drag due to wave steepness 3-12%;
- Atmospheric pressure gradient 3-11%;
- Freshwater river inputs accounted for only a 2% variation in surge at the open coast.

The findings of this study are of relevance to the current study:

- The addition of considering water density variations and wind drag steepness increased modelled surge levels by up to 20%. While this does not represent the 30-40% 'missing' during remote approach events in Southeast QLD, it does highlight that they play a role in increasing surge levels; and
- The influence of modelling freshwater river input was found to have a limited impact. Although in differing coastal regions, both 'The Battery' and Brisbane Bar tide gauges lay at the mouth of significant river systems. This is an interesting finding given one potential source of uncertainly associated with *Ex. TC Oswald* is the effect of the freshwater river flows on measured surge during the event. With accurate flow and timing information of flood flows from the Brisbane River these effects could be investigated further in future research.

With regards to vertical current mixing during a TC, (Mitchell et al. 2005) and (Teague et al. 2007) reviewed and reported on the data collected from an array of Acoustic Doppler Current Profilers (ADCPs) in depths ranging from 60 to 1000m during the passage of Hurricane Ivan in the Gulf of Mexico, which should be noted the bathymetric conditions are much shallower than offshore of Southeast Queensland. Key findings of the study included:

- During the Hurricane approach the current structure was frictionally dominated, with surface and bottom Ekman layers. All moorings in less then 90 m depth measured onshore advection with offshore advection at depth due to down-dwelling; and
- During eyewall passage, surface friction almost dominated barotropic behaviour through 60m. Offshore sites in 90m stayed strongly Baroclinic,

This study highlighted that during the passage of extreme TCs, surface frictional/shear stresses tend to dominate close to shore in comparison to regional scale oceanic processes such as geostrophic behaviour associated with Rossby and Kelvin waves. Given that peak wind speeds associated with *Oswald* were approximately half Ivan, surfaces stresses to promote vertical mixing would be expected to be four times less and thus it could be expected that vertical mixing may be significantly less pronounced. This behaviour is explored with reference to local ADCP data in Section 4.6.

3 Research Methodology

Key items to be investigated and undertaken for this study are provided in Figure 3-1 and include:

1. Development of suitable hydrodynamic and spectral wave models using the TUFLOW FV and SWAN modelling packages.
2. Confirm astronomical tide calibration (predicted tide vs modelled) at Mooloolaba and Brisbane Bar during the passage of Ex TC. Oswald.
3. Confirm wind and pressure data matches measured observations.
4. Confirm wave calibration at available offshore and nearshore wave buoys.
5. Assess preliminary surge calibration vs. measurements at Brisbane Bar and Mooloolaba (Hydrodynamic model run with only astronomical tide boundaries and an applied windfield from point 3). Run in both 2D and 3D mode to assess model sensitivity and response to the differing numerical methods.
6. Apply HYCOM ocean boundaries to the 3D hydrodynamic model. Assess preliminary surge calibration vs measurements at Brisbane Bar and Mooloolaba. Compare results with those from Step 5.
7. Apply wave forcings to the models within steps 5 and 6 and compare results. The ability to model waves under 3D forcing may be subject to computing availability and model runtimes as determined in Step 1.
8. Report on the literature review, input datasets, model setup, simulation results and key findings and compare to previous studies.
9. Provide a series of recommendations for additional research.

The agreed Project Specification is also provided in Appendix A.

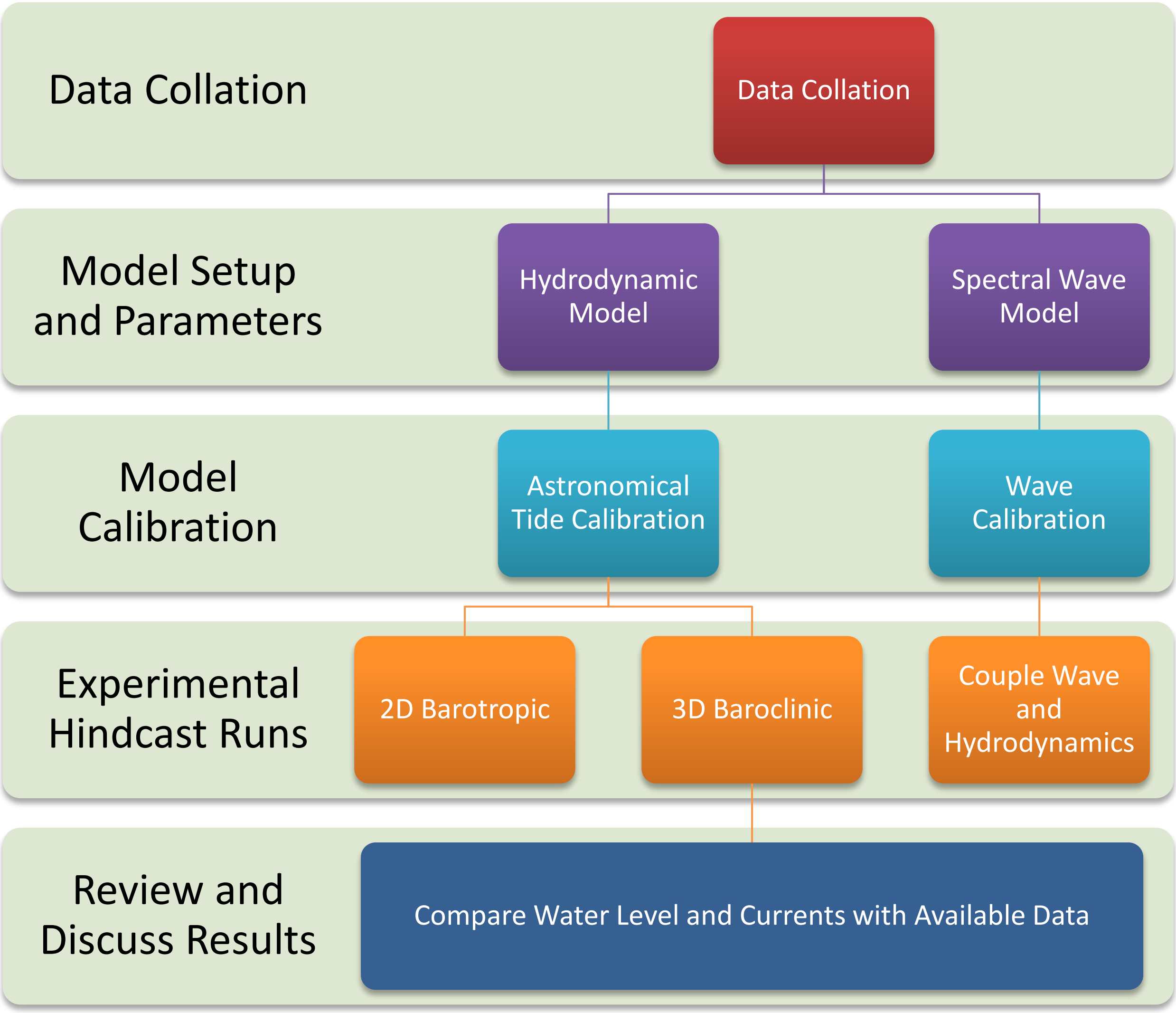

Figure 3-1 Project Methodology Overview

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4 Data Collation

To force and evaluate the performance of the hydrodynamic and wave models a significant data collation process was completed comprising oceanic and metrological sources. Details of the various datasets are provided in the following sections with reference to tabulation and figures showing the extent and quality of each source.

4.1 Bathymetry and Topography

Bathymetric and topographic data was sourced from existing BMT WBM hydrodynamic models of QLD (refer Figure 2-7) and Moreton Bay. These datasets comprised a combination of admiralty chart and hydrographic survey and were deemed suitable for the current study.

4.2 Meteorological Data

4.2.1 Synoptic Observations

Ten minute mean wind speed, direction and mean sea level pressure synoptic data was collected for QLD coastal sites during the passage of *Ex-TC Oswald.* Figure 4-2 provides a time series from the 17-29th of January at Brisbane Airport, Cape Moreton, Spitfire Channel Beacon and the Gold Coast Seaway. The datasets highlight the strong and consistent north-east to easterly flow that affected Southeast QLD over the period 24-29th of January allowing a significant over water fetch length to generate surge and extreme waves. The mean wind speed and direction at the peak of the event is provided in Figure 4-1.

4.2.2 ACCESS and CFSv2

Gridded surface wind and pressure data at 0.11º resolution was sourced via the BoM ACCESS atmospheric forecast numerical model. This provided six houry analyses over the study area and was later used to force the hydrodynamic and wave models. Figure 4-1 shows a scalar plot of peak mean wind speed at 4am EST on the 28th of January that are consistent with the meteorological analysis taken at the time (Callaghan, 2014). Figure 4-2 show comparisons of the ACCESS model parameters and those measured at the surface showing a good level of agreement. Statistics comparing the modelled and measured wind speed data at key sites adjacent Moreton Bay are provided in Table 4-1. A full set of timeseries results are provided in Appendix A.

One interesting observation that may have a bearing on measured surge within Moreton Bay is the difference in measured and modelled wind direction at the Spitfire Banks (top left panel of Figure 4-1). The measured data (blue) is up to 30^{o} more northerly than the modelled data, which is likely due to topographic interaction with Cape Moreton that is not picked up in the ACCESS model. It is possible that a longer northerly fetch length could lead to increased surge within southern and central Moreton Bay.

Air temperature, relative humidity, incoming and outgoing solar radiation and precipitation gridded data was obtained from the NCEP CFSv2 forecasts at hourly temporal and 0.25 ^{o} spatial resolution for the study period. The primary purpose of these synoptic inputs were to force the heat module within TUFLOW FV.

Table 4-1 Measured vs. Modelled Wind Speed

Location	Measured Peak (m/s)	Modelled Peak (m/s)	Peak Error (m/s)	Mean Error (m/s)
Gold Coast Seaway	20.0	18.9	-1.1	1.2
Double Island Point Lighthouse	13.9	20.3	6.5	5.1
Bundaberg Airport	13.4	12.4	-1.0	0.0
Coolangatta Airport	21.2	18.1	-3.7	-1.9
Hervey Bay Airport	8.3	11.7	1.4	1.6
Sunshine Coast Airport	20.1	12.1	-8.0	-3.0
Redcliffe	20.0	18.2	-1.8	0.5
Cape Moreton Lighthouse (Corrected)	17.9	22.4	4.5	6.0
Brisbane Airport	17.5	16.3	-1.2	1.0

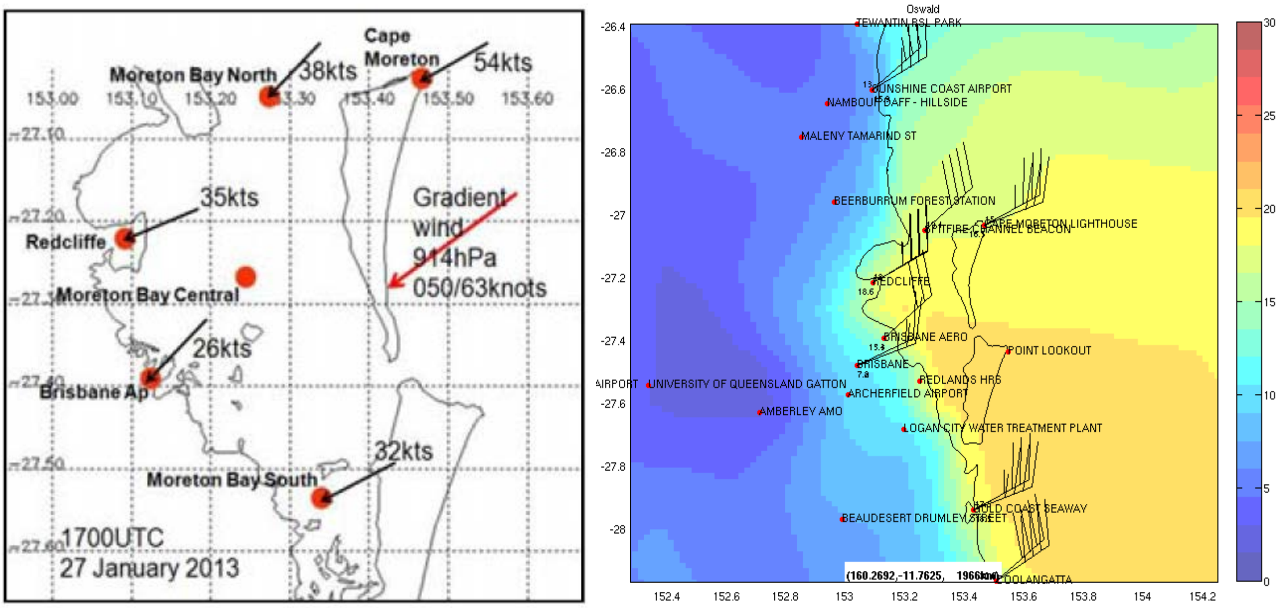

Figure 4-1 Mean wind speeds at 4am, 28th January in Moreton Bay (Callaghan, 2014) (left) and modelled wind speeds and direction barbs (m/s)

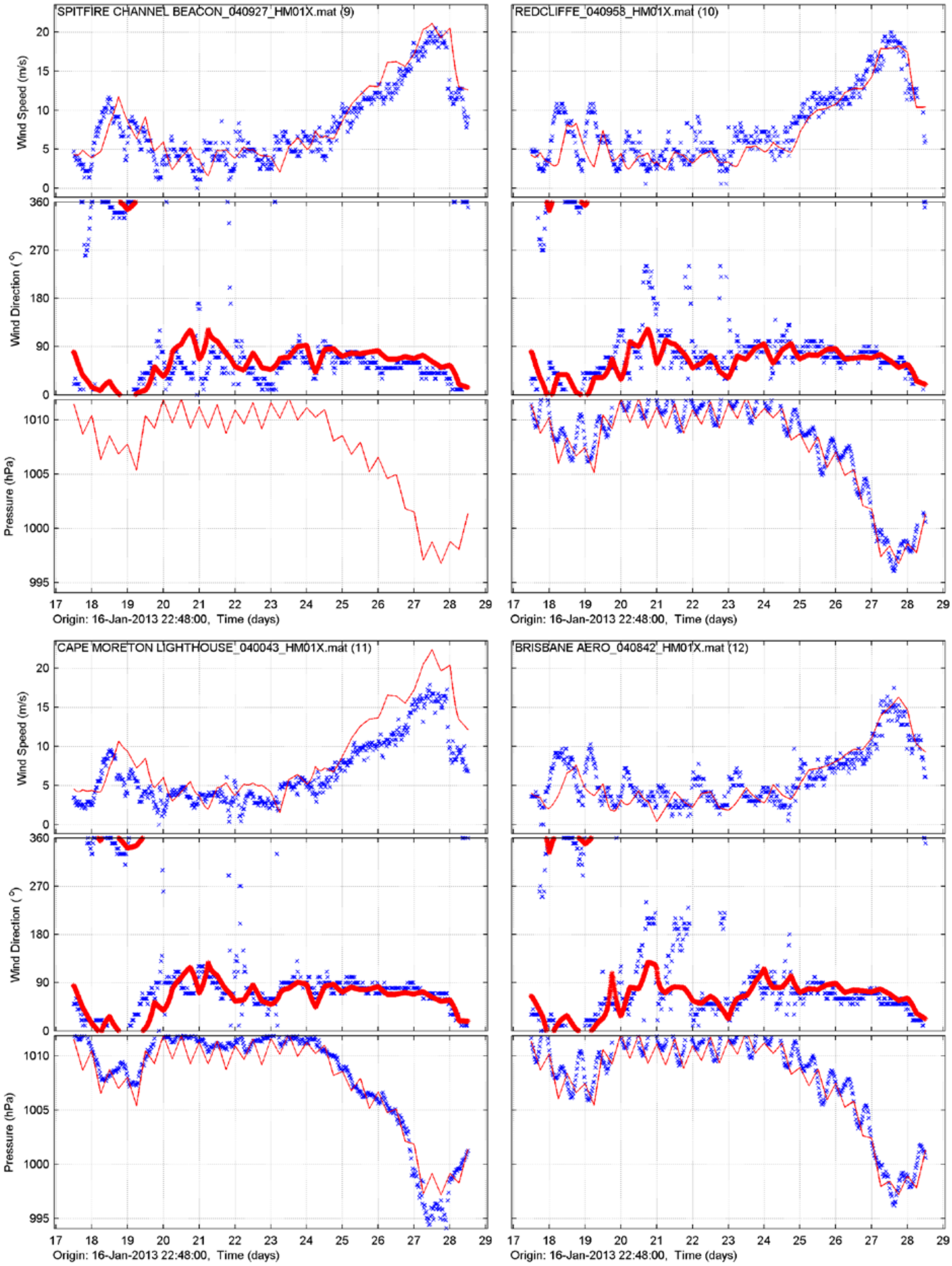

Figure 4-2 Observed and modelled wind speed, wind direction and pressure at Moreton Bay sites (Time zone UTC). Red are modelled fields and blue measured.

4.3 Gridded Ocean Data

4.3.1 HYCOM

To initialise the three-dimensional structure and external boundaries of the hydrodynamic model the global circulation model HYCOM was downloaded and applied. This model provides daily fields of sea surface height anomaly, u and v current velocity and salinity and temperature data over 33 vertical depths ranges to a depth of 5,500 m. The sea surface anomaly and current fields predicted by the HYCOM model for the 27th of January are provided in Figure 4-3 below and shows the strong anti-cyclonic gyre immediately adjacent the continental slope and also the strong north to south currents associated within the East Australian Current. To reference the below sea surface heights with respect to mean sea level, 0.49 m should be subtracted from the values provided.

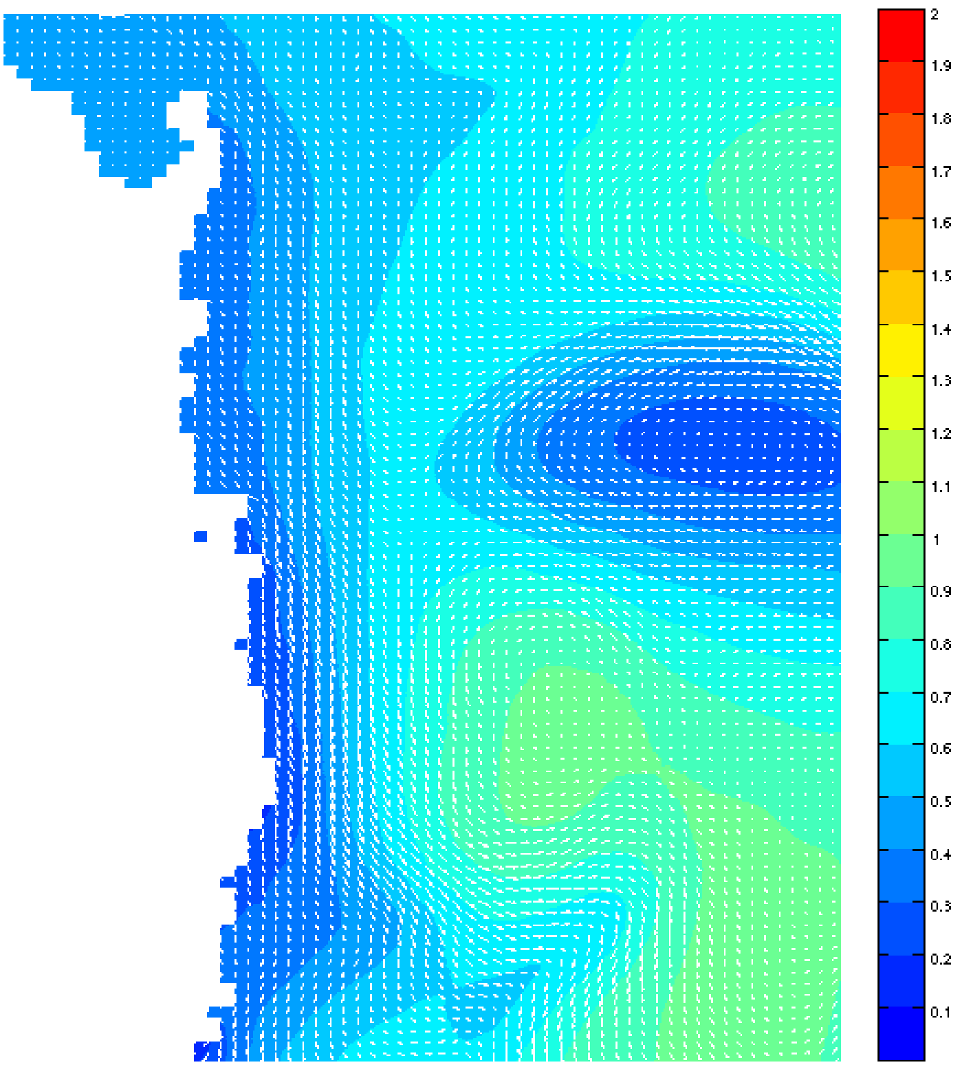

Figure 4-3 HYCOM Modelled Ocean Surface Anomaly and Current Vector Field (m)

4.3.2 NOAA Wavewatch III

Wavewatch III is a third generation wave model (Tolman 1999) used for global wave forecast modelling and for weather prediction services. The model behaves in a similar manner to the SWAN spectral wave model which is discussed in detail in Section 5.2. Global wave simulations provide hourly estimates of significant wave height, wave direction and period that have been applied as swell inputs to the regional spectral wave model.

4.3.3 Astronomical Tide Model

To provide tidal prediction estimates offshore the Topex Tidal Constituent database (Egbert, Bennett & Foreman 1994) was utilised to provide offshore water level estimated from 10 tidal constituents.

4.4 Water Level Observations and Predictions

Measured tide gauge data was collected from Maritime Safety Queensland (MSQ), the Queensland Department of Science, Innovation, Information Technology and the Arts (DSITIA) and the Manly Hydraulics Laboratory (MHL) for Mooloolaba, Brisbane Bar, Southport and the Tweed Offshore. The location and temporal resolution obtained for each site is provided in Table 4-2 and Figure 4-4

At each of the aforementioned locations tidal predictions have been calculated at 15-minute increments using the 113 available constituents for each site. Figure 4-5 provides a times series for each site with measured levels (black) astronomical tide predictions (blue) and tidal residuals (red crosses) shown for the period 24th January to 2nd of February 2013. This highlights the storm surge experienced of approximately 1.0, 0.5 and 0.85 m at Brisbane Bar, Mooloolaba and the Southport during *Ex-TC Oswald*.

Table 4-2 Tide Gauge Locations

Location	X	Y	Temporal Resolution (mins)	Data Period[2]
Brisbane Bar	153.1667	-27.3667	60	1996-2014
Mooloolaba	153.1341	-26.6684	60	1996-2014
Tweed Offshore	153.6000	-28.1702	5	2012-2013
Southport	153.4240	-27.9700	10	1999-2014

4.5 Wave Observations

Significant wave height (Hs), peak wave period (Tp) and wave direction (Wdir) was collected for a range of sites offshore and within Moreton Bay for the period immediately prior and following the passage of *Oswald.* The location of each site, water depth and data period is provided in Table 4-3 and the location is plotted in Figure 4-4.

Table 4-3 Collated Wave Observation Data

Location	X	Y	Depth (m)	Temporal Resolution (mins)	Data Period
Brisbane	153.6317	-27.4872	70	30	30/10/1976 -
Gold Coast	153.4426	-27.9652	17	30	20/02/1987 -
Mooloolaba	153.1812	-26.5660	32	30	20/04/2000 -
North Moreton Bay	153.2788	-26.8985	35	30	08/03/2010 -

[2] As available on the Queensland Government Data Portal https://data.qld.gov.au/dataset/

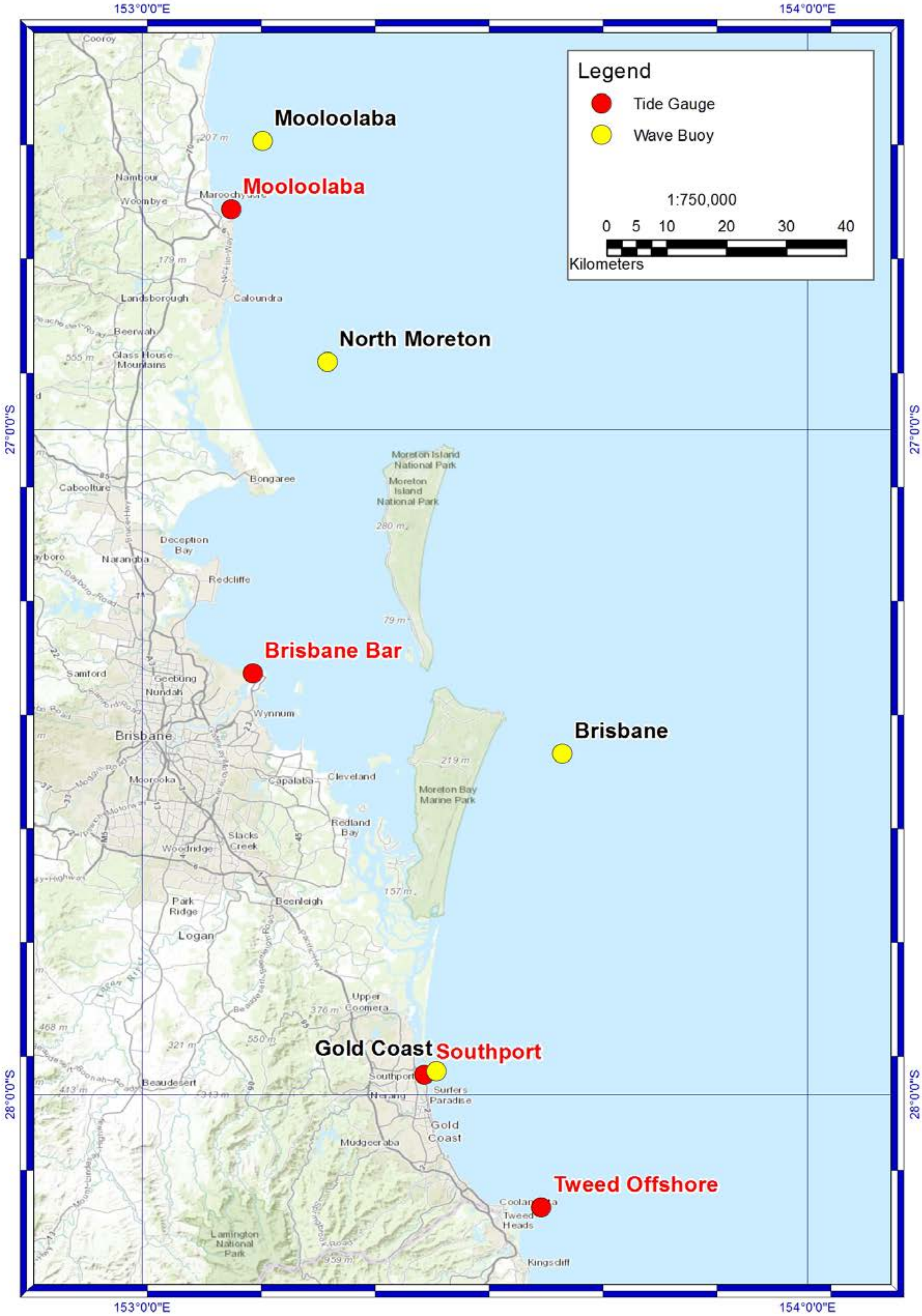

Figure 4-4 Wave and Tide Gauge Locations

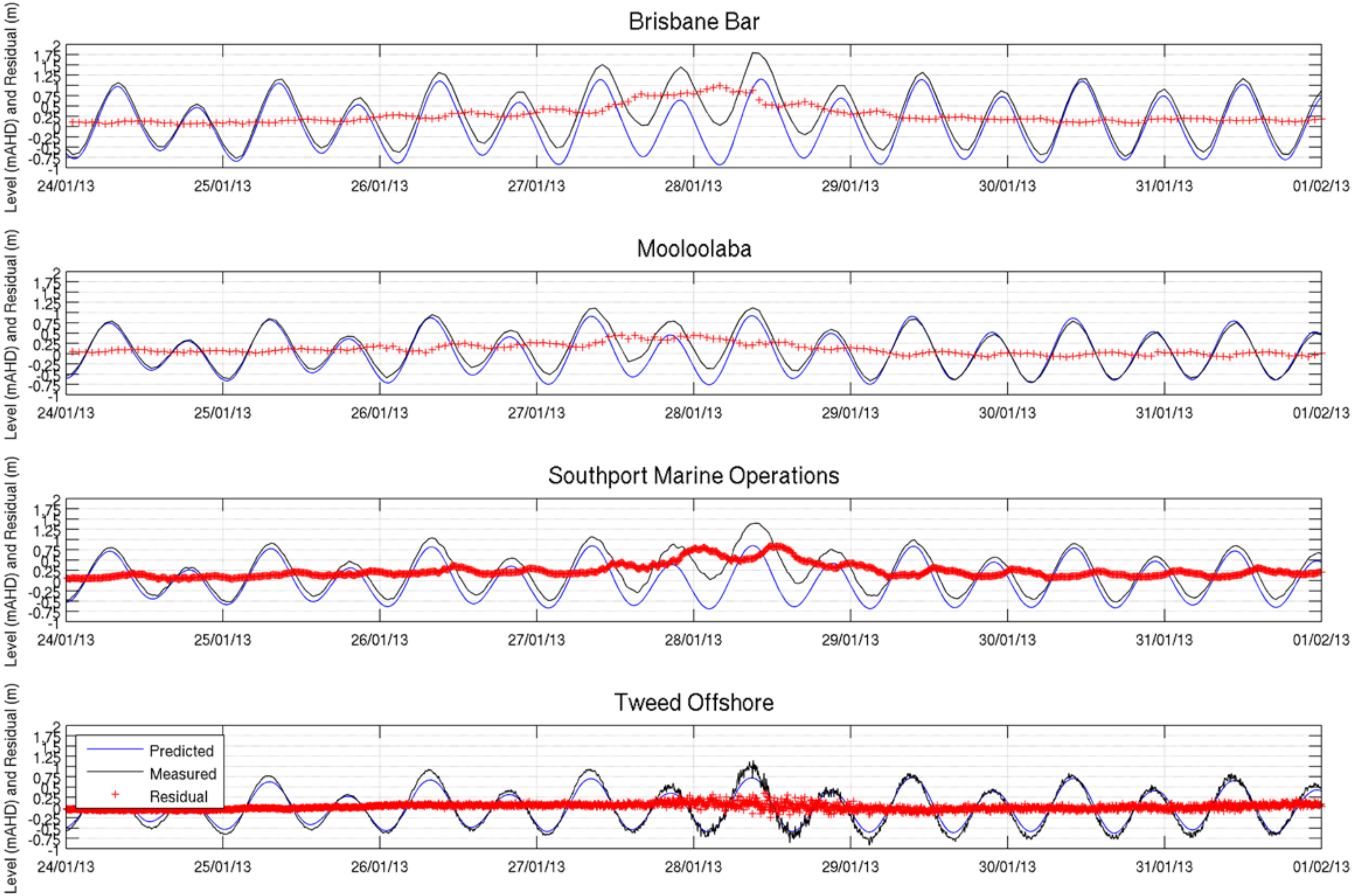

Figure 4-5 Measured and Predicted Water Levels 24/01/2013 - 01/02/2013

4.6 Current Data

To provide an indication of the 3D ocean velocity structure during Oswald, Acoustic Doppler Current Profiler (ADCP) data was obtained online from IMOS (*IMOS-OceanCurrent* n.d.) for sites offshore of North Stradbroke Island in depths ranging from 65 to 200. U and V current velocities in 65m of depth are provided in Figure 4-6.

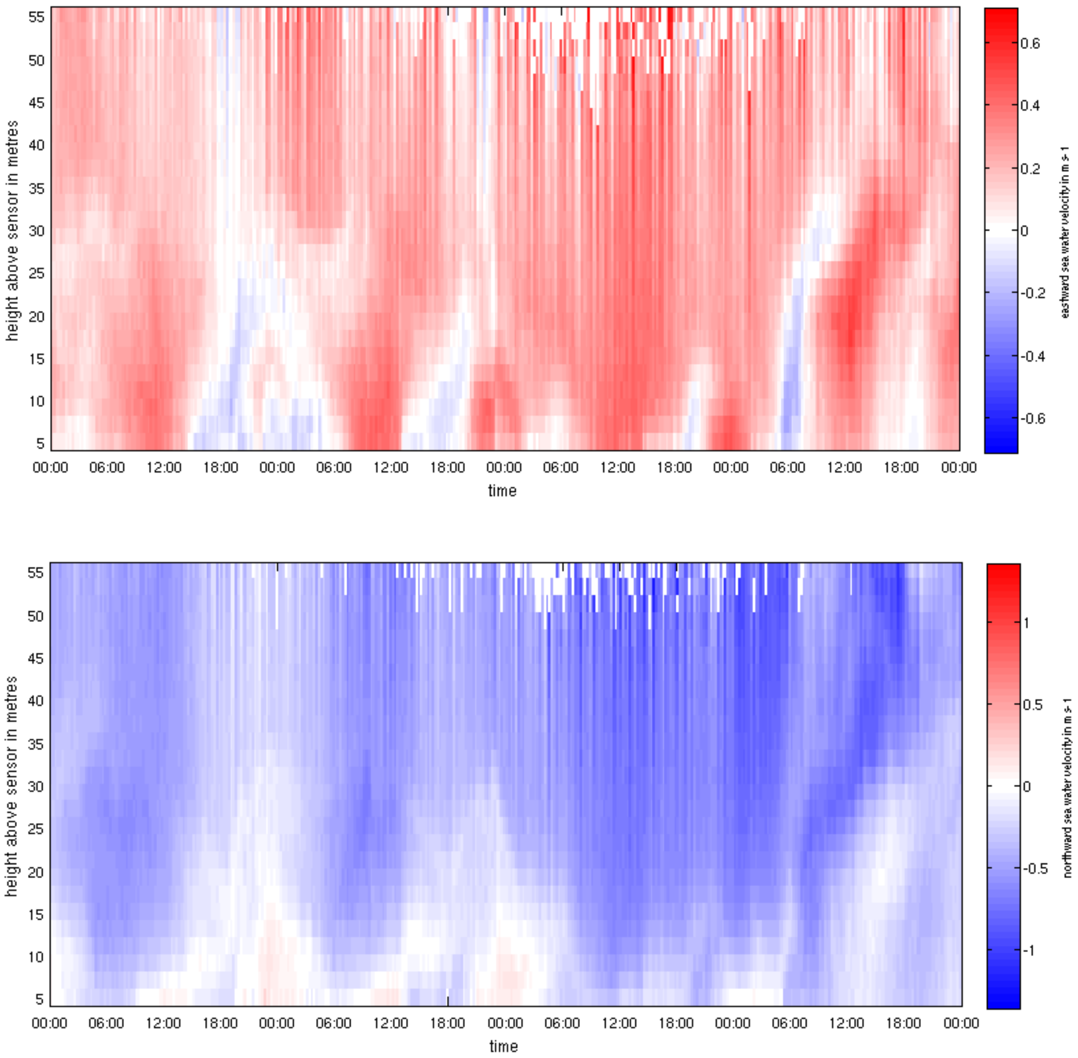

Figure 4-6 U and V current velocity at IMOS National Reference Station – Depth = 65 m from 25th – 29th of January 2013.

5 Model Setup

This Chapter provides an overview of the TUFLOW FV hydrodynamic and SWAN spectral wave models and their experimental setup. Key technical parameters and assumptions are also detailed.

5.1 TUFLOW FV Hydrodynamic Model

TUFLOW FV is a numerical hydrodynamic model developed by BMT WBM that is used to solve both the two and three-dimensional non-linear shallow water equations. TUFLOW FV is highly suited to estuarine and oceanic modelling, however it can also be used for riverine and floodplain assessments (BMTWBM 2015). The hydrodynamics can be run in either barotropic mode or with baroclinic pressure gradients optionally switched on, allowing density gradients as a function of salinity, temperature and sediment to be assessed. Atmospheric inputs such as heat flux and surface forcings can be simulated and the model can be extended for usage in cohesive/non-cohesive sediment transport and advection dispersion.

5.1.1 TUFLOW FV Implementation of the Non-Linear Shallow Water Equations

TUFLOW FV uses a finite volume approach to solve the non-liner shallow water equations including viscous and non-viscous terms in first or second order. These equations are solved on a numerical mesh, which can be a combination of triangular and quadrilateral elements (elements can also be referred to as cells). The flow or mass (flux) from across element boundaries from one element to another is conserved using a Finite-Volume numerical scheme as follows:

$$\frac{\partial \boldsymbol{U}}{\partial t} + \nabla \cdot \boldsymbol{F}(\boldsymbol{U}) = \boldsymbol{S}(\boldsymbol{U})$$

Where:

- $\boldsymbol{U} = \begin{bmatrix} h \\ hu \\ hv \end{bmatrix}$ are the conserved variables for depth (h), x-momentum (hu) and y-momentum (hv)
- inviscid fluxes $(\boldsymbol{F}_x^I, \boldsymbol{F}_y^I, \boldsymbol{F}_z^I)$ represent the directly resolved flux of mass and momentum between adjacent elements; and
- viscous fluxes $(\boldsymbol{F}_x^V, \boldsymbol{F}_y^V, \boldsymbol{F}_z^V)$ represent the “mixing” of mass and momentum that is not directly resolved as advection within the numerical model;

The x, y and z components of the inviscid and viscid fluxes are therefore defined by:

$$\boldsymbol{F}_x^I = \begin{bmatrix} hu \\ hu^2 + \frac{1}{2}gh^2 \\ huv \end{bmatrix},\ \boldsymbol{F}_x^V \approx \begin{bmatrix} 0 \\ -hK_v\frac{\partial u}{\partial x} \\ -hK_v\frac{\partial v}{\partial x} \end{bmatrix} \boldsymbol{F}_y^I = \begin{bmatrix} hv \\ huv \\ hv^2 + \frac{1}{2}gh^2 \end{bmatrix},\ \boldsymbol{F}_y^V \approx \begin{bmatrix} 0 \\ -hK_v\frac{\partial u}{\partial y} \\ -hK_v\frac{\partial v}{\partial y} \end{bmatrix} \boldsymbol{F}_z^I = \begin{bmatrix} hw \\ hwu \\ hwv \end{bmatrix},\ \boldsymbol{F}_z^V \approx \begin{bmatrix} 0 \\ -\nu_t\frac{\partial u}{\partial z} \\ -\nu_t\frac{\partial v}{\partial z} \end{bmatrix}$$

Put simply, these equations define that the flux of momentum and mass from one cell to another is conserved in that any decrease in mass and/or momentum in a given cell must be balanced by increases in mass and/or momentum flux in an adjacent cell. To allow for a change in mass and/or momentum the element must be acted upon by any one or a combination of the source terms as outlined below:

$$\boldsymbol{S} = \begin{bmatrix} gh\frac{\partial z_b}{\partial x} + fvh - \frac{h}{\rho_0}\frac{\partial p_a}{\partial x} - \frac{hg}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial x}dz - \frac{1}{\rho_0}\left(\frac{\partial \boldsymbol{s}_{xx}}{\partial x} + \frac{\partial \boldsymbol{s}_{xy}}{\partial y}\right) + \frac{\boldsymbol{\tau}_{sx}}{\rho_0} - \frac{\boldsymbol{\tau}_{bx}}{\rho_0} \\ gh\frac{\partial z_b}{\partial y} - fuh - \frac{h}{\rho_0}\frac{\partial p_a}{\partial y} - \frac{hg}{\rho_0}\int_z^\eta \frac{\partial \rho}{\partial y}dz - \frac{1}{\rho_0}\left(\frac{\partial \boldsymbol{s}_{yx}}{\partial x} + \frac{\partial \boldsymbol{s}_{yy}}{\partial y}\right) + \frac{\boldsymbol{\tau}_{sy}}{\rho_0} - \frac{\boldsymbol{\tau}_{by}}{\rho_0} \end{bmatrix}$$

where:

- $\frac{\partial z_b}{\partial x}, \frac{\partial z_b}{\partial y}$ are the x- and y-components of bed slope;
- $f = 2\Omega_r\phi$ is the Coriolis coefficient;
- ρ is the local fluid density, ρ_0 is the reference density and p_a is the mean sea level pressure;
- $\boldsymbol{s}_{ij}$ is the short-wave radiation stress tensor; and
- $\boldsymbol{\tau}_s$ and $\boldsymbol{\tau}_b$ are respectively the surface and bottom shear stress terms (where applicable).

For a full specification of the equations utilised please refer to the TUFLOW FV User Manual (BMTWBM 2015).

5.1.2 Hydrodynamic Model Domains

During the experimental process, a series of three hydrodynamic model domains were developed:

- Hydrodynamic Domain A (HD Domain A);
- Hydrodynamic Domain B (HD Domain B); and
- Hydrodynamic Domain C (HD Domain C).

Initial testing was completed on HD Domain A (refer Appendix Figure C-1). This model achieved a suitable level of astronomic tidal calibration and surge results in two-dimensional mode. A number of three-dimensional test runs were also completed however, during three-dimensional testing the model produced poor results. On closer inspection of current behaviour it was postulated that this lack of performance was due to the southeastern boundary obliquity across the continental shelf in a region of Eastern Australia that is also characterised by some of the highest East Australian Current velocities. Due to these factors HD Domain A was abandoned for a larger model domain (HD Domain B) with boundaries well away from the area of interest.

HD Domain B (refer Figure 5-1 and Appendix Figure C-2) was used for the majority of the experimental test cases and comprised a combination of triangular and quadrilateral elements with resolutions spanning 25 to 7000 m. Spatially, the model extends from approximately Coffs Harbour to Indian Head on Fraser Island along the coast and up to 200 km offshore to a depth exceeding 4000m. This offshore depth was adopted to allow sufficient representation of the transition from deep water (>2000 m) to near-shore bathymetry. Figure 5-1 highlights the transition from coarse resolution offshore moving to high spatial resolution in areas of interest and of high bathymetric and hydraulic gradients. This capability provides shows one of the major strengths of using a flexible mesh approach in complex coastal areas.

For the three-dimensional modelling, TUFLOW FV has the capability to discretise the water column vertical using a hybrid sigma- zlayer approach whereby a top portion of the water column (in this case from the water surface to -3 mAHD) can be modelled using a series of sigma layers (here 4 layers) with a transition to vertical z-grid layering beneath. The vertical z layering was discretised using a series of 45 layers to a depth of 2500 m (refer Appendix D.3). This level of discretisation was deemed suitably fine to capture the physical processes of vertical stratification, mixing and potential overturning during *Oswald* without being overly prohibitive in terms of computational runtimes.

Hydrodynamic Model Domain C was developed with a similar extent to that of B, however the spatial resolution at the Spitfire Banks was increased from approximately 600m to 100m (refer Appendix Figure C-3). This mesh was used for the series of resolution sensitivity tests.

Model Setup

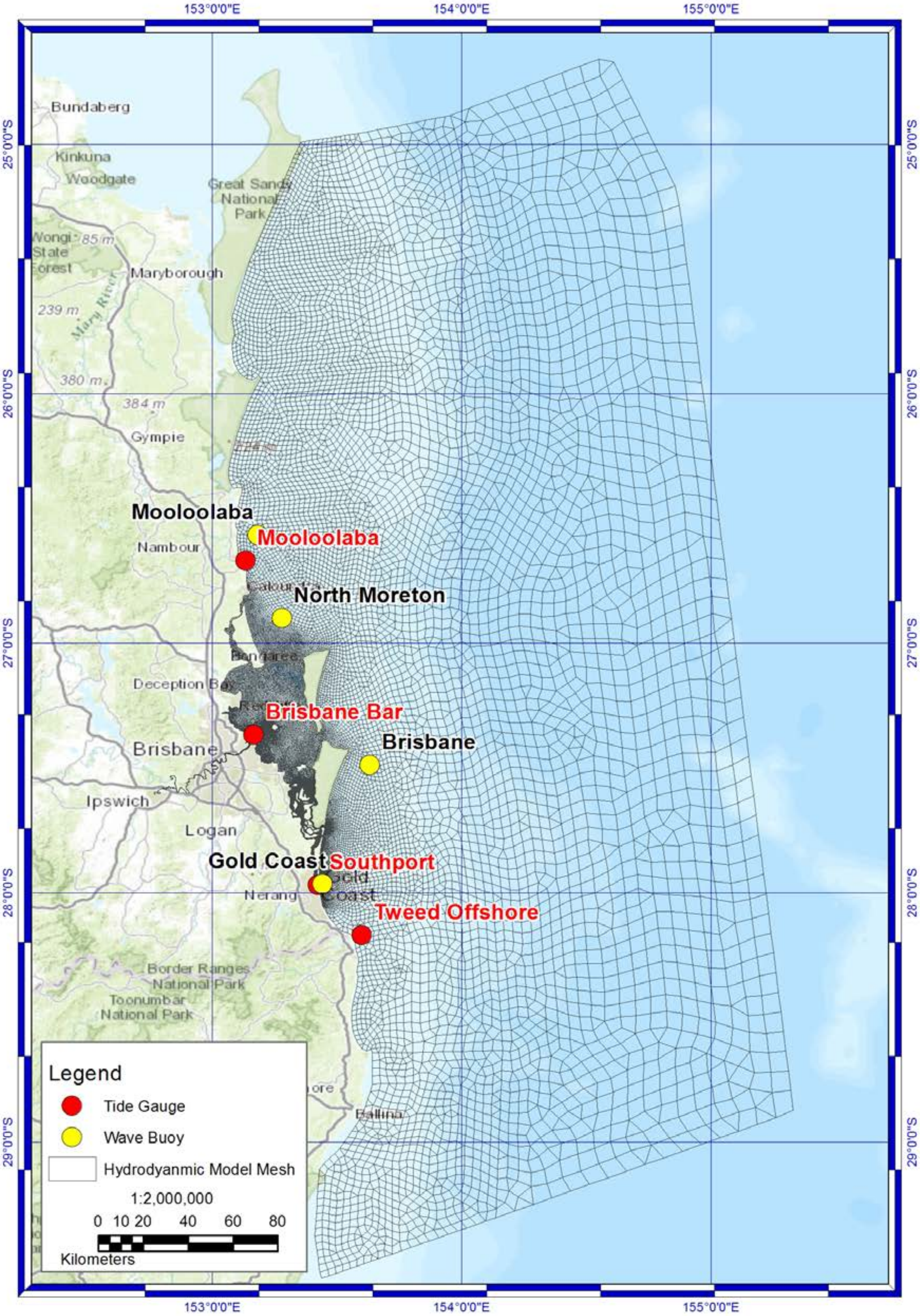

Figure 5-1 Hydrodynamic Model Domain B

5.1.3 Simulation Period and Initial Conditions

Each wind model experiment, tide only and waves were run for the period 10:00am 05/01/2013 – 10:00am 02/01/2013. This allowed an extended period of 20 days prior to the passage of Ex. TC Oswald for model currents and water levels to be 'built up' and provided suitable initial conditions for the storm event.

For the first time step of each 3D experiment the model was initialised using gridded HYCOM boundary fields of sea surface anomaly, depth varying salinity, temperature and u and v current components. 2D numerical experiments assumed zero velocity at model start-up and the initial water level was selected to match mean astronomical tidal levels at the model start time of 10am on the 5th of January 2015.

5.1.4 Open Boundary Conditions

Depending on the experimental scenario being completed TUFLOW FV was forced at the northern, southern and eastern open boundaries using:

- Time and spatially varying water levels generated using the TOPEX Tidal Constituent database (Egbert, Bennett & Foreman 1994) also accounting for inverse barometer effects; and/or
- Time, spatially and depth varying gridded HYCOM sea surface anomaly, salinity and temperature data.

Notably, no river inflows were applied to the model, however with the possible exception of the Brisbane River at Brisbane Bar it is expected that these effects would be negligible on the storm tide observed in Moreton Bay.

The volume-force and surface-stress boundary conditions, again dependant on the experiment being completed, utilised the following forcing:

- Six-hourly gridded wind and mean sea level pressure fields from the ACCESS weather model; and/or
- Wave radiation stress gradients derived from SWAN as an additional momentum source term. These wave radiation stress gradients were applied as an x and y force per unit volume component derived from the D001, D002 and E001 SWAN domains.

The wind drag coefficient adopted for this study used the formulation of (Wu 1980) that varies the applied coefficient as a function of the 10 m mean wind speed. Insert Wu values here.

- $\boldsymbol{\tau}_{sw} = \rho_a c_{dw} \mathbf{u}_w |\mathbf{u}_w|$

Wave fields are supplied from SWAN as spatially and temporally varying inputs and are applied at the cell centres of the numerical grid according to:

$\int_{\Omega} \left(\frac{\partial s_{xx}}{\partial x} + \frac{\partial s_{xy}}{\partial y}\right) \partial\Omega$ Where Omega represents the cell volume.

5.1.5 Physical Parameters

A sample of the hydrodynamic setup files are provided in Appendix D that reference the key physical parameters adopted for the 2d and 3d modelling. The commands and default values can be cross-compared with documented features within the TUFLOW FV User Manual (BMTWBM 2015). Initial testing was completed using both first and second order spatial discretisation. Review of model results using both solution schemes indicated limited differences between the two methods. Therefore the less computationally demanding first order scheme has been adopted.

5.2 SWAN Spectral Wave Model

The SWAN spectral wave model is a third generation wave modelling package developed by Delft University in the Netherlands (Booij, Holthuijsen & Ris 1996). SWAN includes the ability to represent wind forcing's, bed friction; wave refraction, frequency-direction wave development and propagation and wave dissipation such as white capping. The modelling system can utilise the powerful feature of grid domain nesting, whereby a larger coarse domain can provide open boundary wave spectra conditions to a 'nested' finer resolution grid, which in turn can provide boundary conditions to a mesh nested within it. The wave model has been used extensively and is an industry standard wave-modelling package.

Importantly, the main purpose of the SWAN modelling was to provide wave radiation stresses to the hydrodynamic model.

5.2.1 Model Domains

Five wave model domains were setup to ensure coverage of the B Hydrodynamic Domain and details of each are provided in Table 5-1 and Figure 5-2.

Particular care was taken to ensure that the Spitfire Banks were resolved to within 25 -100 m using the D and E level grids. This was undertaken to provide high-resolution wave radiation stresses to the hydrodynamic model in the region of high wave energy gradients.

Table 5-1 Wave Model Domains

Domain	Resolution	Purpose
Regional	800 m	Provide Boundary Conditions to the RWQM Domain
RWQM	400 m	Calibration and Boundary Conditions for D001 and D002 Wave Domains
D001	100 m	North Moreton Bay – Provide Boundary Conditions to E001
D002	100 m	Passage between North Stradbroke and Moreton Islands
E001	25 m	Coverage of the Spitfire Banks

5.2.2 Open Boundary Conditions

Swell and sea wave energy from the global ocean wave model, Wavewatch III were downloaded and applied to the Regional domain. A series of spectral nests were then completed to provide staged boundary conditions to the RWQM, D001, D002 and E001 as detailed in the 'Purpose' column of Table 5-1.

To allow for variation in water depth due to the astronomical tides, water level and current fields were provided to SWAN. Wind data from the ACCESS model was applied to each model domain to allow for local sea wave growth.

5.2.3 Model Parameters

The wave spectral energy domain was discretised using twenty-four frequencies while the directional resolution was thirty-six 10^{o} segments of the compass. Key spectral wave parameters adopted were the default values provided with SWAN. The model setup files are provided in Appendix E.

5.2.4 Wave Radiation Output

For wave experiments conducted in this study, wave radiation stress gradients are being applied from a combination of the D001, D002 and E001 domains. Testing was competed in an attempt to also apply wave radiation stresses from the RWQM domain. Testing showed that this approach led to unstable conditions in the TULFOW-FV simulation. Closer inspection revealed the cause of these instabilities was due to differences in the near shore resolution and bathymetry of the SWAN and TUFLOW FV meshes. For example, in a number problematic locations, the fine-scale mesh of the TULFOW-FV model had significantly shallower depths then within SWAN at the same location resulting in non-physical forces being provided as input to TUFLOW FV.

As the D001, D002 and E001 models provide high quality inputs for Moreton Bay results at Brisbane Bar are unlikely to be affected by this omission. At Mooloolaba and Southport results are only presented for Surge only or Tide plus Surge experiments. The effects of wave radiation stresses at Mooloolaba and Southport could certainly be investigated in future research, however it is recommended either the wave model resolution be increased or the bathymetry of the wave model be modified in problematic locations to better reflect the bathymetry within the hydrodynamic model.

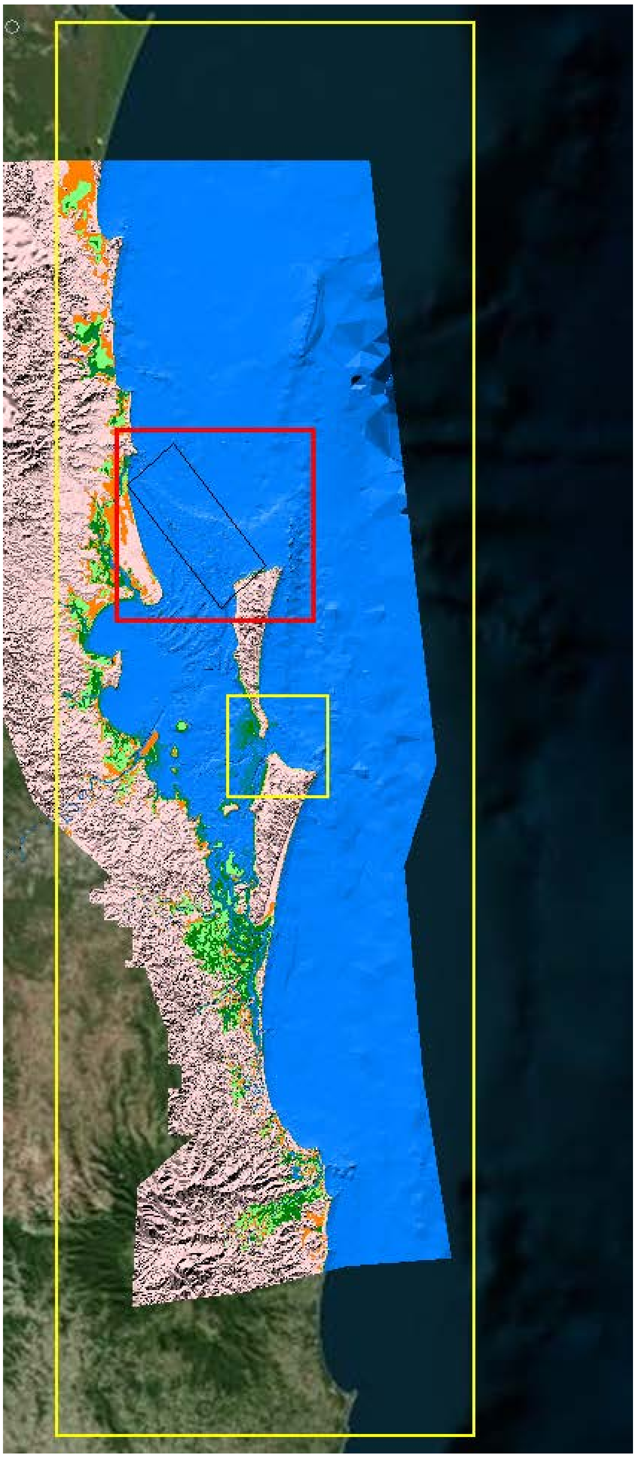

Figure 5-2 SWAN Spectral Model Domains. RWQM (outer yellow), D001 (red), D002 (inner yellow) and E001 (black).

6 Astronomical Tide and Wave Calibration

To verify that both TUFLOW FV, SWAN and their respective input boundary conditions could produce reliably reproduce the astronomical tide and wave energy during the passage of *Oswald* an extended calibration was completed for the month of January 2013. This Chapter outlines the calibration process and results.

6.1 Astronomical Tide Calibration

The performance of the hydrodynamic model in reproducing tidal predictions at Mooloolaba Brisbane Bar, Southport and Tweed Offshore is shown Appendix Figure F-1 for the B Hydrodynamic Domain. To achieve this level of agreement the main calibration parameter utilised was slight modifications to bed roughness coefficients within Moreton Bay. The final set of roughness coefficients as well as full model setup files are provided in Appendix D.

Based on visual inspection, overall the tide can be viewed as well represented both in terms of amplitude and phase during both spring and neap tide periods, although on closer inspection there is a tendency for tidal phase to be out by approximately 30 mins. Figure 6-1 provides the results at Brisbane Bar zoomed into the period 26-30th of January. It can be seen that there are some differences in the shape and phase of the modelled outgoing tide for all three model mesh calibrations. It is possible that these differences are due to the differing number of constituents being used to generate the model boundary condition predictions (10 constituents) compared with over 100 constituents used to develop the compared tidal predictions at Brisbane Bar. Notwithstanding these differences, HD Domain A performs best to the peak of the tide on each cycle while both HD Domain B and C tend to slightly over predict the tide.

In additional to qualitative inspection, model performance can be quantified using the Root Mean Square Error (RMSE) metric, a relationship between the modelled and predicted tide as per the below equation. Tabulated RMSE values are provided in Table 6-1 and indicate a good match for the purposes of defining the water depth available for surge generation under the various experimental runs for all three model domains investigated.

$$\boldsymbol{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(x_i - \hat{x}_i)^2}{\boldsymbol{N}}}$$

Where x_i is the predicted tide, $\hat{x}_i$ is the modelled tide and N is the sample size.

Table 6-1 Tidal Calibration Root Mean Square Error

Location	Domain A RMSE (m)	Domain B RMSE (m)	Domain C RMSE (m)
Brisbane Bar	0.05	0.06	0.05
Mooloolaba	0.05	0.05	0.06
Southport	0.04	0.05	0.05
Tweed Offshore	0.09	0.10	0.10

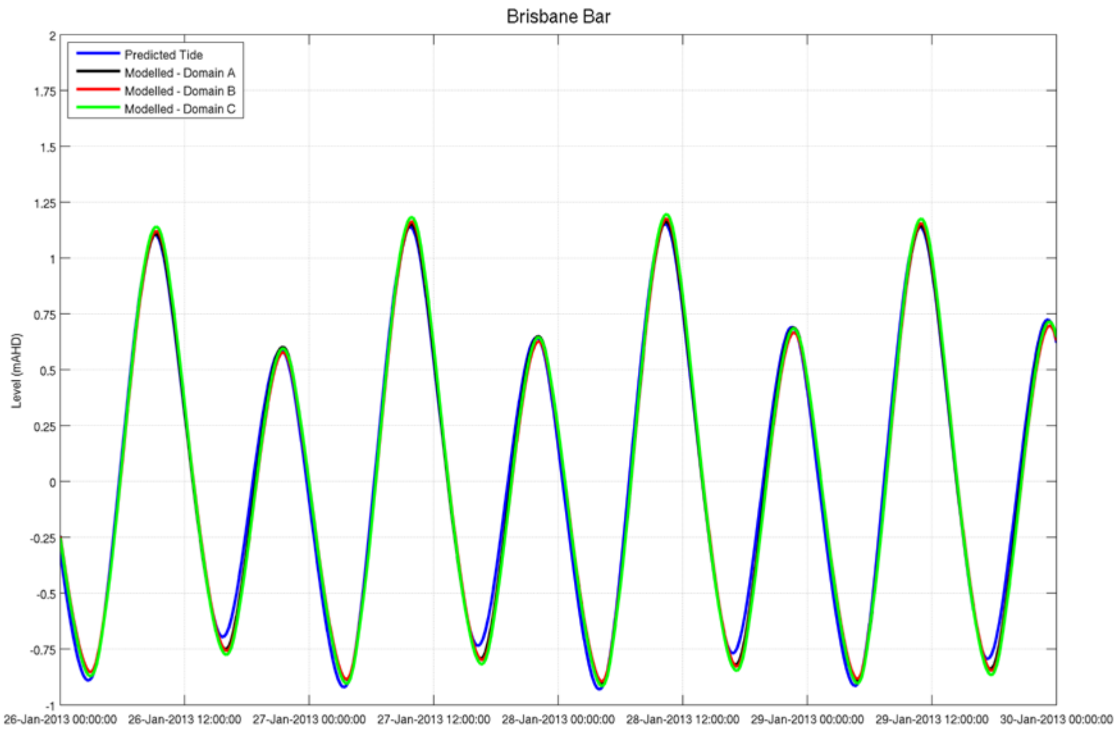

Figure 6-1 Astronomic Tide Calibration – Brisbane Bar 26-30th January, 2013

6.2 Wave Calibration

The performance of the spectral model in reproducing measured wave conditions at Mooloolaba, North Moreton Bay, Brisbane and Gold Coast is presented in Appendix Figure F-2 for key wave parameters Significant Wave Height (Hs) and Peak Wave Period (Tp). Differences between measured and modelled Peak Hs values and time of peaks are presented in Table 6-2. Fortunately these results were achieved by running SWAN with the default parameters and setup as outlined previously. This again highlights the quality of the ACCESS wind model used to drive SWAN and overall this is deemed an excellent match for the purposes of applying wave radiation stresses to the hydrodynamic model. Wave direction was also visually inspected and provided an equally suitable match to wave buoy observations.

It is noted, that the modelled wave heights at the Brisbane Wave Buoy tend to stay elevated or lag behind the measurements during the twenty-four hour period 12pm 28th to 12pm 29th of January. It is possible that this is an artefact of the six-hourly wind fields being linearly interpolated during this period however it is interesting that the Gold Coast and North Moreton wave buoys do not seem to be affected by the same issue.

Table 6-2 Measured and Modelled Peak Significant Wave Heights

Location	Observed Hs (m)	Observed Time	Modelled Hs (m)	Modelled Time
Mooloolaba	5.59	28/01/2013 5:30am	5.69	27/01/2013 10:00pm
North Moreton Bay	5.88	27/01/2013 10:00pm	5.66	27/01/2013 11:00pm
Brisbane Bar	7.11	28/01/2013 7:30am	6.71	28/01/2013 4:00am
Gold Coast	6.27	28/01/2013 10:30am	5.94	28/01/2013 05:00am

7 Experimental Hindcasts

This section details the experimental design and the intended purpose of each experiment.

7.1 Experimental Design

A series of 8 model experiments were designed with the aim of addressing the specific questions:

1. Is a component of observed storm tide due to the behaviour geostrophic offshore gyres and currents and water level anomalies associated with regional ocean conditions such as the East Australian Current?
2. Do wave-radiation stress gradients due to wave breaking on the Spitfire Banks and in the passage between Moreton and North Stradbroke Island contribute to elevated levels in Moreton Bay?
3. If so, what is the effect of hydrodynamic and wave model resolution over the Spitfire Banks?
4. With consideration of Questions 1-3 above, do the models still under-predict observed storm tide at Brisbane Bar, and if this is the case what else could be considered?

To explore these questions, the TUFLOW FV model was run either stand-alone in 2D or 3D mode with boundary forcing selectively included or excluded for each experiment as detailed in the following sections.

7.2 3D Baroclinic Experiments

7.2.1 Development of 3D Experiments

Two 3D model experiments were prepared as follows:

- **Experiment 1**: 3D model initialised with HYCOM gridded 3D data and open boundaries. No other forcing was applied.
- **Experiment 2**: 3D model initialised with HYCOM gridded 3D data and open boundaries. Astronomical tide plus ACCESS gridded wind and pressure fields applied.

The two experiments were initially attempted by externally forcing Hydrodynamic Model Domain A (refer Appendix Figure C-1) with gridded 3D initial and open boundary conditions from HYCOM. This resulted in rapid destabilisation of the initial condition vertical structure, significant cold-water upwelling and an accompanying water level set-down adjacent to the coast that was not representative of conditions during the January 2013 period.

On closer inspection of the HYCOM dataset it was observed the bathymetry assumed by HYCOM was on average 20-40 m (in depths of 40 m i.e. 50% different) shallower than surveyed bathymetry across the continental shelf. In an attempt to assess the impact of bathymetry differences the TUFLOW FV model bathymetry was modified to mimic the HYCOM bathymetry. Following these tests it was observed that the upwelling and poor model performance continued.

It was postulated that the location of the HD Domain A open boundaries were too close to the area of interest and were affecting the model behaviour. This was also thought to be exacerbated by the obliquely aligned southeastern section of the boundary across the continental shelf, a region where the eddies and accompanying energy of the EAC are greatest during January 2013. To remove the potential for boundary effects the model domain was expanded leading to the development of HD Domain B and HD Domain C as provided in Figure 5-1.

Even with the extension of the model boundary well offshore, north and south of the area of interest the upwelling was still modelled but did not occur as quickly or as significantly as with HD Domain A. The modelled currents and water levels appeared more realistic, but there was negligible surge reproduced. These findings finally led to a comparison of the model input from HYCOM with satellite altimetry composites collected during the period leading up to Oswald's passage (*IMOS-OceanCurrent* n.d.) . As can be seen in

Figure 7-1 and Figure 4-3 there are significant differences between the HYCOM and observed mean water level conditions during the event.

7.2.2 Outcomes of 3D Experiments

A fundamental assumption of the project proposal was that the HYCOM global ocean model would provide suitable boundary conditions, given its successful use on several other recent projects within the Australian region (BMT WBM, 2014 and 2015). However, following a series of model test cases and comparisons to measured data, it was shown that the HYCOM boundary conditions provided a poor near-shore representation of ocean conditions in the period leading up to, during and following the passage *Ex. TC Oswald* in the Southeast QLD region.

Apart from the obvious bathymetric differences, it is possible that the sources of data assimilation being implemented in HYCOM are not being as heavily weighted in the Australian region in comparison to the other regions of the model, such as the Gulf of

Mexico were HYCOM has been tested and used extensively. It is recommended that the 3D modelling experiments be revisited when the latest CSIRO BRAN (BlueLink 3) experimental runs are made publically available (expected 2016, pers. comm. CSIRO) which will focus more heavily on data sources from the Australian region.

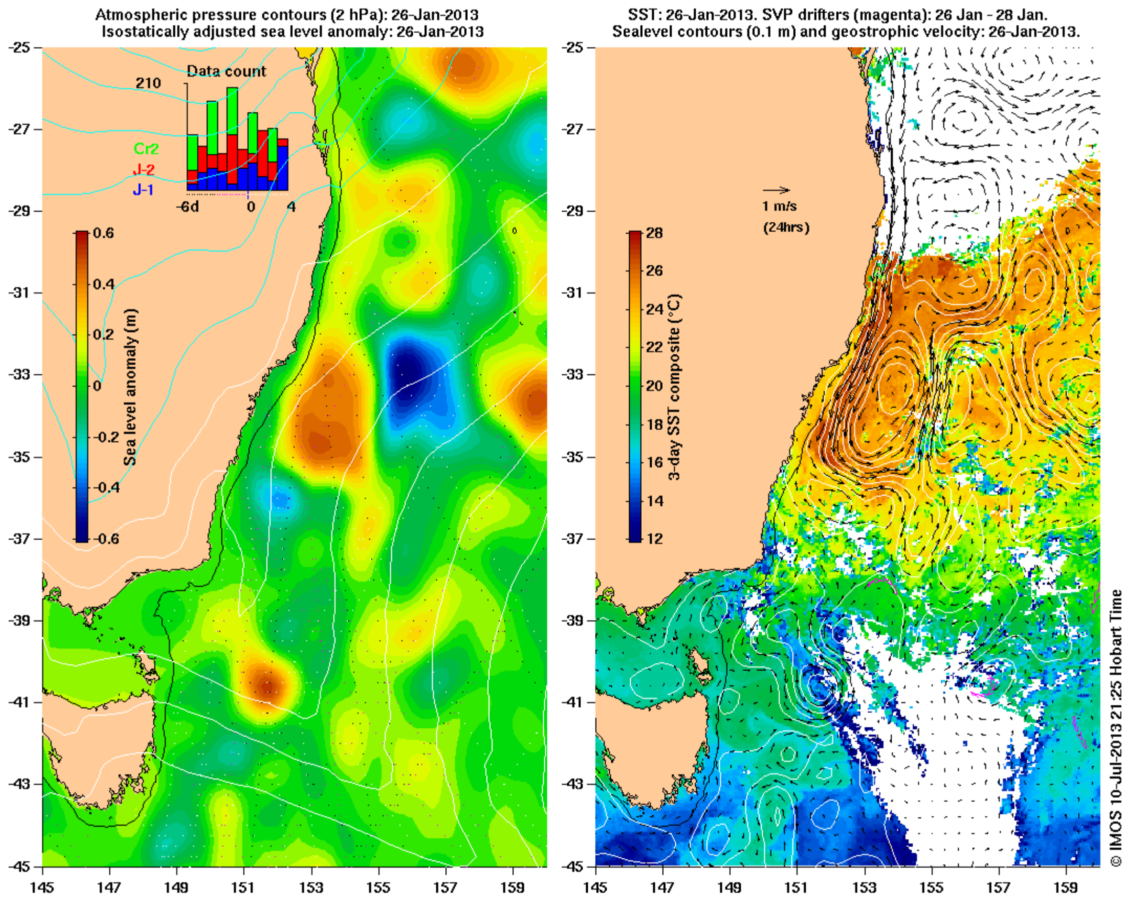

Figure 7-1 Ocean Level Anomaly, sea surface temperature and currents (*IMOS-OceanCurrent* n.d.)

7.3 2D Experiments

Although the 3D modelling was abandoned for reasons outlined above a more detailed investigation of potential wave-surge interactions between Moreton Bay and the Spitfire Banks was then commenced.

7.3.1 Development of 2D Experiments

Six 2D model experiments were completed, three using the HD Domain B investigating tide, wind and wave impacts on surge and another three using the HD Domain C, explicitly investigating the effects of model resolution on results. The experiments are detailed as follows:

HD Domain B

- **Experiment 3 - Surge Only:** Run with an initial water level of zero and with no tidal boundaries applied, this simulation was to assess the impact of ACCESS model wind and pressure fields.
- **Experiment 4 - Tide plus Surge:** Run identically to Experiment 3, however the astronomical tidal boundaries were activated. This simulation was run to assess the impact of the astronomical tide on modelled surge.
- **Experiment 5 - Tide plus Surge plus Waves:** This simulation was run identically to Experiment 4, however the wave radiation stresses were activated. At each cell centre within the model domain, wave radiation stresses were applied from either the Regional, RWQM, D001, D002 or E001 spectral wave models. In regions of overlap the highest resolution model was applied. This simulation was run to assess the potential for wave-surge interactions in Moreton Bay. As discussed in Section 5.2.4, due to the coarse wave models applied at Mooloolaba, Southport and Tweed offshore during Experiment 5, results are presented and discussed only for Brisbane Bar.

HD Domain C

- **Experiment 6 - Hi Res HD Tide plus Surge:** This simulation was to examine the effects of model resolution on tide plus surge results. It has the same inputs as Experiment 4 but using a higher resolution model domain.
- **Experiment 7 - Hi Res HD Tide plus Surge plus Waves (100m Wave Grid):** This simulation was to examine the effects of both hydrodynamic and wave model resolution. This model was similar to Experiment 5 with HD Domain C but without the E001 (25m) wave inputs. It will be compared with both Experiments 5 and 8.
- **Experiment 8 - Hi Res HD Tide plus Surge plus Waves (25m Wave Grid):** This simulation was to examine the effects of model resolution on tide plus surge plus wave results. It is the same as Experiment 5 but on the higher resolution HD Domain C.

For Experiments 6-8, as the sensitivity tests were centred on Moreton Bay, results are presented and discussed only for Brisbane Bar.

A summary of the model inputs for all experiments is provided in Table 7-1.

Table 7-1 – Summary of Experimental Model Inputs

No.	Mesh	Mod e	HYCOM	Tide	Met.	Wave	Purpose
1	B	3D	**Y**	N	N	N	Assess TUFLOW FV model capability to reproduce 3D density fields and currents of the HYCOM model
2	B	3D	**Y**	**Y**	**Y**	N	Assess the 3D response to tide plus surge inputs
3	B	2D	N	N	**Y**	N	Response of the system to wind and surge only inputs
4	B	2D	N	**Y**	**Y**	N	Investigate the effect of water level variation on storm surge levels
5	B	2D	N	**Y**	**Y**	**Y**	Investigate the potential for wave breaking effects on the Spitfire Banks to surge generation at Brisbane Bar
6	C	2D	N	**Y**	**Y**	N	Investigate the effect of water level variation on storm surge levels and model resolution.
7	C	2D	N	**Y**	**Y**	**Y**	To test the sensitivity of hydrodynamic and 100 m wave model spatial resolution on wave radiation stress.
8	C	2D	N	**Y**	**Y**	**Y**	To test the sensitivity of hydrodynamic and 25 m wave model spatial resolution on wave radiation stress

8 Results

The chapter provides the outcomes of the eight experiments completed.

8.1 Method of Presentation and Analysis

The model results and discussion presented in this Chapter rely on comparisons of modelled and measured data with the aim to reproduce as closely as possible the peak levels, shape and timing of the storm tide during Ex. TC Oswald.

The two main metrics that have been used to assess the performance of each experiment include:

1. **Water Levels:** Modelled water level vs. observed absolute water levels; and
2. **Residuals:** Modelled residuals vs. observed residuals. Modelled residuals have been post-processed using the following formula:

$$Residual_{\ Modelled}(m) = Water\ Level_{\ ExperimentX} - Water\ Level_{Tide\ Only}$$

Where *ExperimentX* is the given experiment being investigated and *Tide Only* are water levels from the astronomical tide calibration presented in Chapter 6.

Results for both modelled water levels and residuals are presented as a combination of time-series and tabulations. Due to the noise associated with measurements at Tweed Offshore, comparisons are presented for Mooloolaba, Brisbane Bar and Southport only. All results presented are in Australian Eastern Standard Time (AEST).

8.2 3D Model Results – Experiments 1 and 2

Although later abandoned, the results of Experiment 1 and 2 are provided in Appendix Figure H-1 for completeness. The results of Experiment 1 with modelled residuals close to zero at all sites, provides further evidence to highlight that HYCOM did not provide boundary conditions representative of those observed by satellite or at tide gauges throughout the region. The modelled residual associated with Experiment 2 is due to the wind and pressure inputs applied. Interestingly, the modulation of the surge due to the tide can also be observed in the Experiment 2 results. This is because the ability of the wind to generate a storm surge response that is inverse to the water depth. As the tide recedes from Moreton Bay, the shallower water allows a greater surge and the opposite is the case at high tide.

8.3 2D Model Results – HD Domain B - Experiments 3 to 5

8.3.1 Experiment 3 - Surge Only

This was run at zero water level to test the effects of the ACCESS model wind and pressure fields and the peak residual results for Experiment 3 are presented in Table 8-1. As the tide in for this simulation, there is no value in comparing to observed water levels and so they have been omitted. The results show negative biases of -45, -53 and -74 % for Brisbane Bar, Mooloolaba and Southport respectively.

Time series of residual water levels are presented in Appendix Figure H-2 for the three sites and also within Figure 8-1 for Brisbane Bar only. Review of the Brisbane Bar timeseries shows the general surge shape is captured, however the modelled results are consistently lower than those measured. The timing of the peak surge is estimated at approximately 12am on the 28th of January, coinciding with the peak wind modelled wind speeds at the Spitfire Channel, Redcliffe and 2-3 prior to peak modelled winds at Brisbane Airport.

Table 8-1 Experiment 3 - Surge Only Residual Results

Location	Measured	Modelled	Diff (m)	Diff (%)
Brisbane Bar	0.99	0.54	-0.45	-45
Mooloolaba	0.49	0.23	-0.26	-53
Southport	0.84	0.22	-0.62	-74

8.3.2 Experiment 4 - Tide plus Surge

This experiment included astronomical tide inputs in addition to the ACCESS model wind and pressure fields. Peak water level and residual results for Experiment 4 are presented in Table 8-1. The results show negative biases with peak residuals of -47, -51 and -69 % for Brisbane Bar, Mooloolaba and Southport respectively. These are similar to the results of Experiment 3.

As expected, the modulation of the surge due to astronomical tidal variation can be observed within the time series of Figure 8-1. During high tide the modelled surge is lower than the surge only case and this is reversed at low tide although the differences are minor between the two cases.

Peak water levels for the three locations vary from 7-14 % below observed levels.

Table 8-2 Experiment 4 - Tide plus Surge Water Level and Residual Results

Location	Water Levels				Residuals			
	Measured	Measured	Diff (m)	Diff (%)	Measured	Modelled	Diff (m)	Diff (%)
Brisbane Bar	1.79	1.66	-0.13	-7	0.99	0.52	-0.47	-47
Mooloolaba	1.45	1.25	-0.20	-14	0.49	0.24	-0.25	-51
Southport	1.4	1.21	-0.19	-14	0.84	0.26	-0.58	-69

8.3.3 Experiment 5 - Tide plus Surge plus Waves

Experiment 5 included the activation of wave radiation stresses over the Spitfire Banks and passage between Moreton Island and South Stradbroke Islands.

This resulted in a peak-modelled residual of 0.72 m at Brisbane Bar, a 27% underestimate. With peak water levels providing an excellent match. Review of the residual time series shows a reasonable match to shape and amplitude in the period prior to 10am on the 27th and following 10am 28th with the model results with wave radiation stresses activated providing a significantly better match to observation than Experiments 3 and 4.

Table 8-3 Experiment 5 - Tide plus Surge plus Waves Water Level and Residual Results

Location	Water Levels				Residuals			
	Measured	Measured	Diff (m)	Diff (%)	Measured	Modelled	Diff (m)	Diff (%)
Brisbane Bar	1.79	1.78	-0.01	-1	0.99	0.72	-0.27	-27

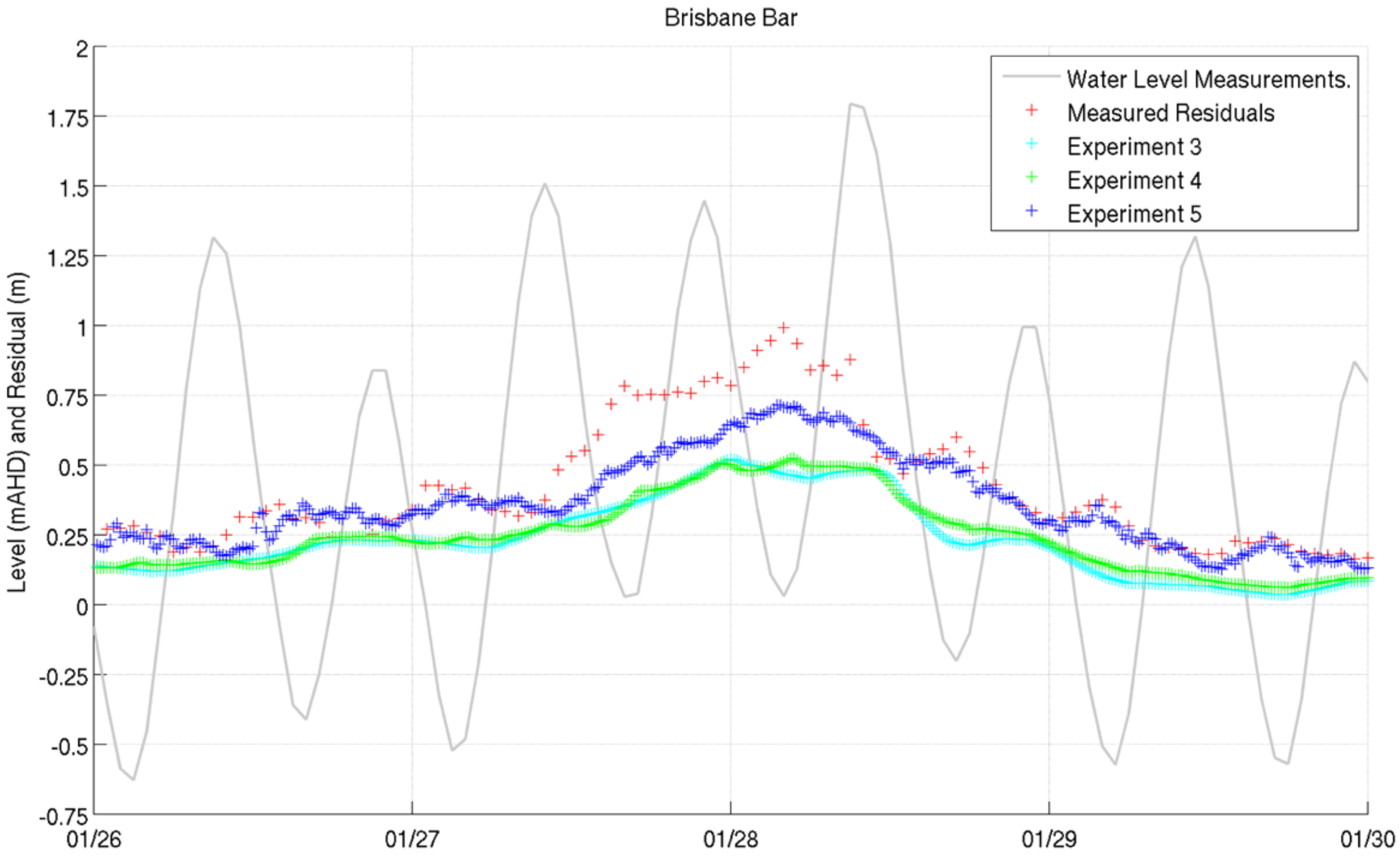

Figure 8-1 Mesh B Experiments 3-5

8.4 2D Model Results – HD Domain C - Experiments 6 to 8

8.4.1 Experiment 6 - Hi Res HD Tide plus Surge

Experiment 6 investigated the effects of increased model resolution of Tide plus Surge results at Brisbane Bar. Peak water level and residual results are provided in Table xx and for ease of comparison results from Experiment 4 are also repeated. Interestedly, the increase in model resolution on the Spitfire Banks leads to negligible changes in modelled surge levels at Brisbane Bar. The slight increase in peak-modelled water levels between Experiments 4 and 6 is due to the differences in the astronomic tide between the two cases.

Table 8-4 Tide plus Surge Resolution Sensitivity Results

Location	Water Levels				Residuals			
	Measured	Measured	Diff (m)	Diff (%)	Measured	Modelled	Diff (m)	Diff (%)
Brisbane Bar Ex.6	1.79	1.68	-0.11	-6	0.99	0.53	-0.46	-46
Brisbane Bar Ex.4	1.79	1.66	-0.13	-7	0.99	0.52	-0.47	-47

8.4.2 Experiment 7 and 8 - Hi Res HD Tide plus Surge plus Waves

Experiments 7 and 8 aimed at assessing the impact of resolving wave radiation stress gradients on the Spitfire Banks. The results of the two experiments are provided in Table 8-5 and for ease of comparison, the results of Experiment 5 are repeated. Key observations include:

- Experiment 7 leads to a 3% and -28% difference from observed peak water levels and residuals respectively;
- Experiment 8 leads to marginally improved residuals (compared to Ex. 7) with 2% and -26% differences for water levels and residuals; however
- A comparison of the three results indicates that there are negligible differences (> 2%) due to increases in both hydrodynamic and spectral wave models.

Table 8-5 – Tide plus Surge plus Waves Resolution Sensitivity Results

Location	Water Levels				Residuals			
	Measured Total Water Level	Measured Total Water Level	Diff (m)	Diff (%)	Measured	Modelled	Diff (m)	Diff (%)
Brisbane Bar – Ex.7	1.79	1.84	0.05	3	0.99	0.75	-0.28	-28
Brisbane Bar – Ex.8	1.79	1.83	0.04	2	0.99	0.73	-0.26	-26
Brisbane Bar – Ex.5	1.79	1.78	-0.01	-1	0.99	0.72	-0.27	-27

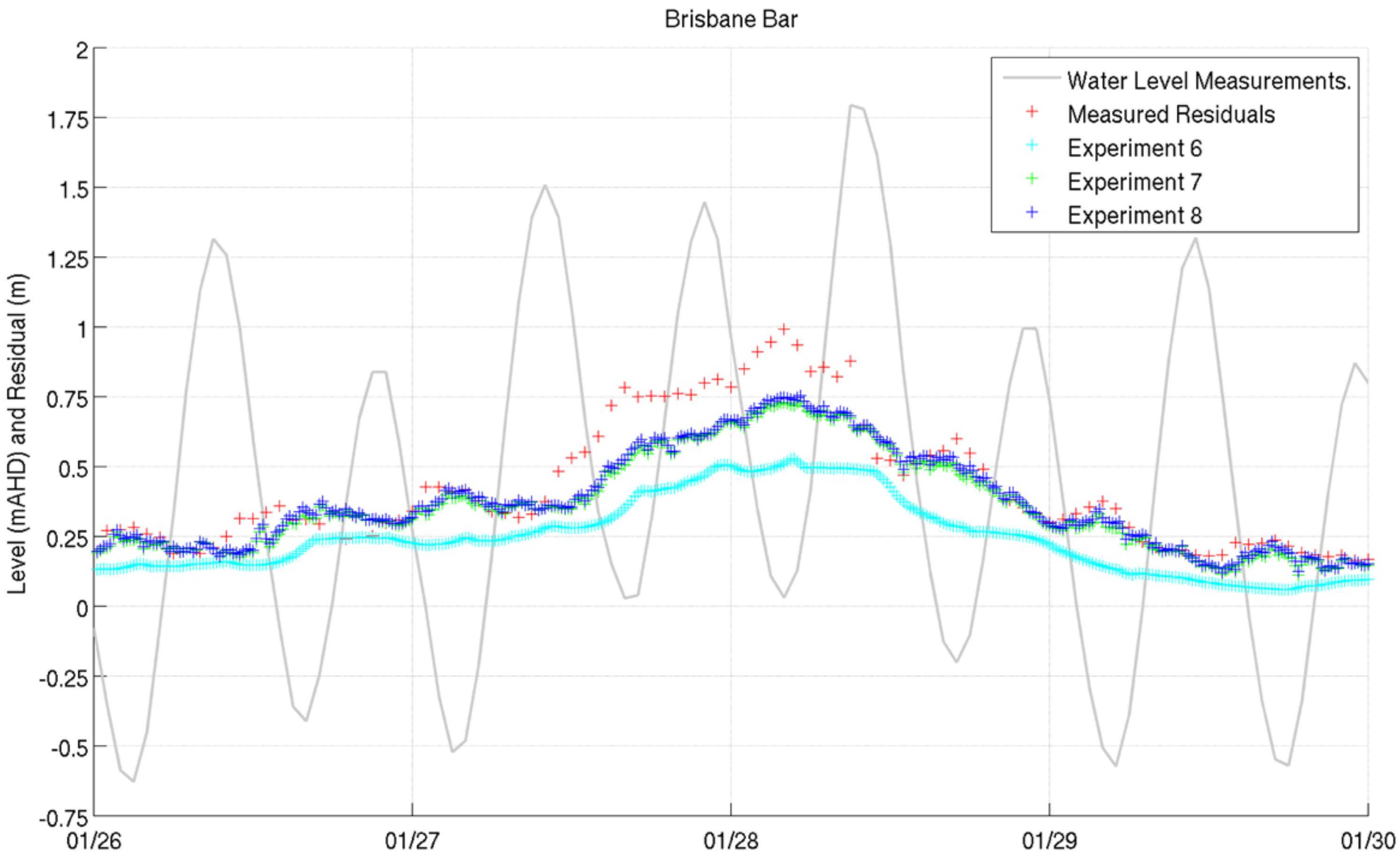

Figure 8-2 Mesh C Experiments 6-8

Table 8-6- Summary of Experimental Results at Brisbane Bar (26th-30th of January 2013)

Ex. No.	Details	Peak Water Level				Peak Residual			
		Observed (mAHD)	Modelled (mAHD)	Diff** (m)	Diff (%)	Observed (m)	Modelled (m)	Diff** (m)	Diff (%)
1	3D HYCOM Only	1.79	NA			0.99	0.06	-0.93	-93
2	3D HYCOM plus Tide plus Surge	1.79	1.57	-0.23	-13	0.99	0.56	-0.43	-43
3	2D Surge Only	1.79	NA			0.99	0.54	-0.45	-45
4	2D Tide plus Surge	1.79	1.66	-0.13	-7	0.99	0.52	-0.47	-47
5	2D Tide plus Surge plus Waves:	1.79	1.78	-0.01	-1	0.99	0.72	-0.27	-27
6	2D Hi Res HD Tide plus Surge	1.79	1.68	-0.11	-6	0.99	0.53	-0.46	-46
7	Hi Res HD Tide plus Surge plus Waves (100m Wave Grid)	1.79	1.84	0.05	3	0.99	0.75	-0.28	-28
8	Hi Res HD Tide plus Surge plus Waves (25m Wave Grid)	1.79	1.83	0.04	2	0.99	0.73	-0.26	-26

**Differences are (modelled – measured). i.e. positive values indicate the model is higher than that measured and vice-versa.

9 Discussion

9.1 Study Hypothesis and Research Questions

At the study proposal stage, the main hypothesis posed was that the disturbance of existing offshore geostrophic currents by *Ex. TC Oswald* was responsible for a component of observed storm surge levels within the Southeast Queensland region. Throughout the course of the project additional questions were posed resulting in the following four main research items:

1. Is a component of observed storm tide due to the behaviour of geostrophic offshore gyres and water level anomalies associated with regional ocean conditions or the East Australian Current?
2. Do wave-radiation stress gradients due to wave breaking on the Spitfire Banks and in the passage between Moreton and North Stradbroke Island contribute to elevating levels in Moreton Bay?
3. If wave-surface interaction contributes, what is the effect of hydrodynamic and wave model resolution in resolving wave breaking processes on the Spitfire Banks?
4. With consideration of Questions 1-3 above, do the models still under-predict observed storm tide at Brisbane Bar, and if this is the case what else could be considered?

9.2 3D Assessment

A 3D assessment was required to investigate Question 1 and as outlined at length in Section 7.2 the available boundary conditions did not adequately resolve offshore conditions during January 2013. Although the 3D modelling has been postponed awaiting the CSIRO BRAN dataset release, the exercise was still useful and resulted in a number of important lessons learnt that may save others from repeating the mistakes here.

Although these may seem like obvious conclusions, care should be taken prior to using 3D gridded oceanic model data, particularly in areas where large eddies and bathymetric gradients are experienced (as is the case off Southeast Queensland). Time spent reviewing these fields early on in the process would have saved considerable energy and resources in the delivery of this project.

It should be noted that the HYCOM model does assimilate data from offshore data sources such as floats, fixed ADCPs and satellite altimetry. The fundamental flaw here was the assuming that such datasets in the Australian region would be incorporated sufficiently to provide suitable ‘nudging’ and represent observed conditions, this was however not the case. It is likely that bathymetric differences between HYCOM and surveyed levels also played some role however with both the large bathymetric differences and non-representation of offshore conditions, it was unlikely that the 3D assessment was going to be successful.

A by-product of the poor 3D boundary conditions was that a more thorough investigation of wave-surge interactions was then conducted.

9.3 Contribution of Surge, Tide and Waves at Brisbane Bar

This section discusses Question 2 and 4 from Section 9.1.

Oswald, due to its relatively constant wind speed and direction provided an excellent candidate storm for assessing interactions of tide, surge and waves within Moreton Bay. From review of the collated wind, wave and tide gauge observations a number of statements regarding the magnitude and timing of the event can be inferred:

Discussion of Measured Data

- With reference to Figure 9-1, mean 10min 10m wind speeds at Brisbane Airport and the Spitfire Banks were at their maximum (greater than 15m/s) during the twenty-four hours from 10am 27th of January to 10 am 28th of January, with the peak wind speeds marginally exceeding 20 m/s at approximately 4am on 27th of January. As shown in the top panel of Figure 9-1 via the green double-ended arrow, this period immediately following 10am on resulted in a rapid increase in the measured residual of approximately 0.5 m (from ~0.3 to ~0.8m) on the afternoon outgoing tide.
- During the incoming tide on the late evening on the 27th, residual levels stayed relatively steady. On the outgoing tide early on the 28th the peak residual occurred at 4am, coinciding with low tide. This peak occurred 2-3 hours prior to the observed peak Hs at both Mooloolaba (530am) and Brisbane Wave Buoy (730am) (refer Table 4-3). Interestingly the peak wave heights at North Moreton Bay were recorded at 10:00pm the previous evening on the 27th, however they did remain relatively constant throughout the 12hr period that followed so significant wave action was still occurring throughout this entire period on the Spitfire Banks. This earlier peak in Hs at North Moreton may have been a result of its northerly exposure and potentially some refraction and dissipation effects of due to Moreton Island and the Spitfire Banks when the winds turned more easterly. The orange double-ended arrow within Figure 9-1 shows the period when Hs exceeded 5m at the Brisbane Wave Buoy.

- Although wind direction stayed north to north-east during the 28th, once wind speed dropped below 15 m/s on the 28th the measured residual dropped 0.3-0.4m. While this occurred during the high tide, significant wave energy was still impacting the Spitfire Banks. This rapid drop in residuals is likely a combination of two factors, the wind surface stress being reduced and also the depth of water in Moreton Bay increasing. It was also during this period that the highest water levels associated with Oswald were recorded at Brisbane Bar, with the level of 1.79 mAHD leading the flooding issues in the Lower Brisbane River and Brisbane CBD.
- (Treloar, Taylor & Prenzler 2011) through work on the Moreton Bay Storm Tide Study, argued that some form of wave surge or ‘blocking’ on the outgoing tide led to increased surge in the bay. The rapid increase in residuals observed on the outgoing tides followed by periods of relatively steady residual on the incoming tide certainly does suggest that on the outgoing tide there is some mechanism at work to increase water levels throughout Moreton Bay.

Discussion of Model Results

- Outside of the period associated with peak winds (orange double ended arrow) the modelling results provide a much better fit to measured data when wave radiation stresses are activated (Experiments 7 and 8) as opposed to the tide plus surge case (Experiment 6). These model results support the findings of (Treloar, Taylor & Prenzler 2011) but should be viewed in light of the discussion within Section 9.6.
- During the period of maximum winds there is a lack of response from the modelled residual (when run either with or without wave radiation stresses) equating to approximately 0.25 m or 25% of the peak residual. This lack of response is particularly obvious on the outgoing tides of the afternoon of the 27th and early morning the 28th. This tends to suggest that notwithstanding the activation of wave radiation stresses there remains something ‘missing’. This missing component provides support to the arguments of (Bode & Hardy 1997) and (Callaghan, Nielsen & Baldock 2012) for improved surge generation physics, and also the possibility of offshore regional oceanic shelf wave energy impacts that requires further investigation. Although there were freshwater outflows from the Brisbane River also during this time, the main flood peak from the Brisbane River occurred later during the 29th and therefore it is assumed here to be a minor contributor to the error at the peak of the event.

- Although peak modelled and measured total water level results provide a very good match (refer bottom panel Figure 9-1), closer inspection shows a slight phase shift when compared to the measurements. This shift is a remnant of the phase error within the astronomical tide calibration. This phase shift is approximately 30 mins and does not effect the calculation of tidal residuals during the event, as the same modelled tide is applied to the experimental runs.

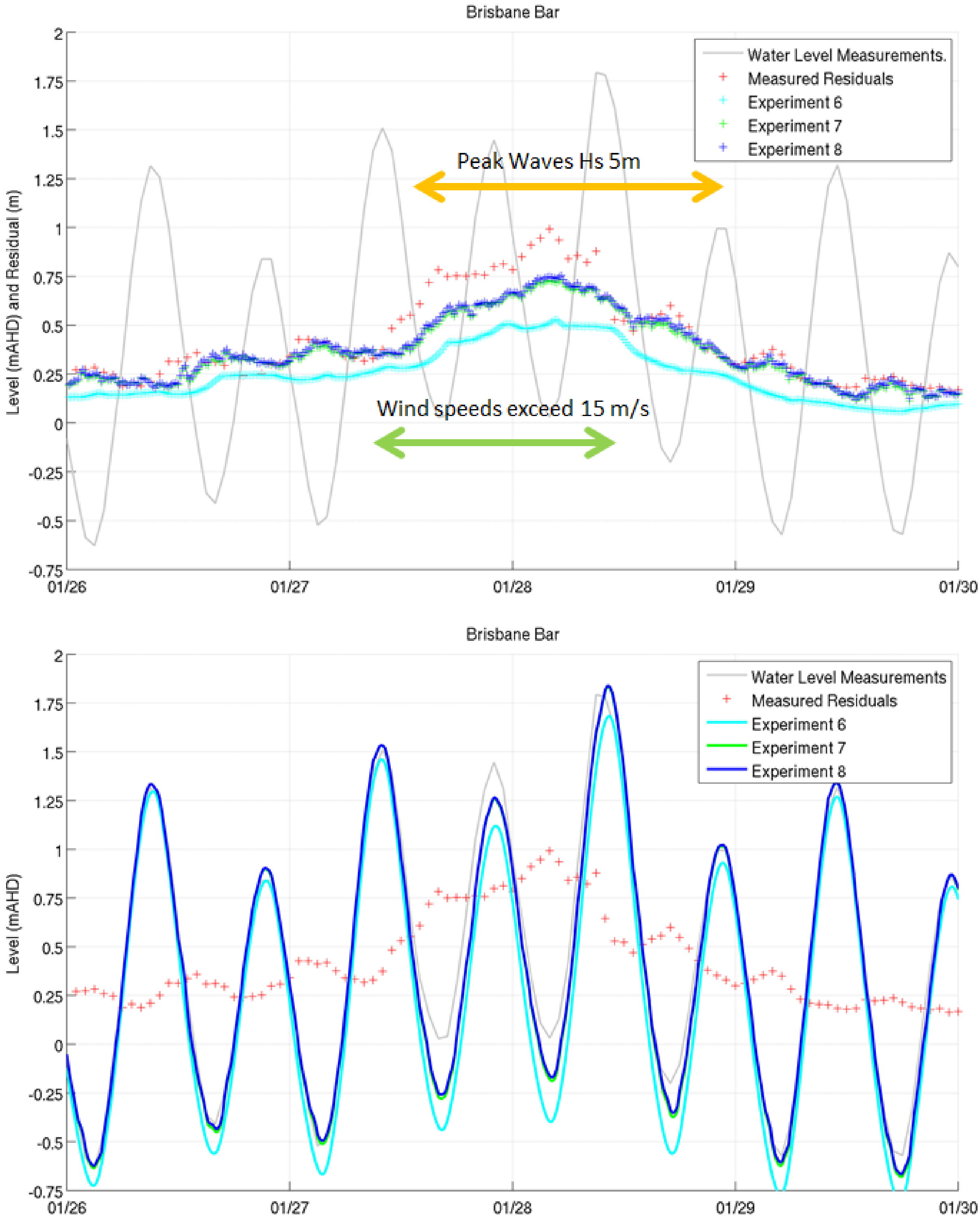

Figure 9-1 Ex TC. Oswald Total Water Level and Surge Discussion

9.4 Results at Mooloolaba and Southport

Results at Mooloolaba were 53 % and 51% below observed for the surge only and tide plus surge cases (refer Table 8-1 and Table 8-2) which equates to a miss-match of approximately 0.25 m. Generally the shape of the modelled residual matches that of the measurements although the response is not as pronounced (refer Appendix Figure H-2).

There are a number of factors that could be leading to the underestimate. The mesh generation at Mooloolaba is judged here to be suitable to represent conditions offshore, however the Harbour in which the tide gauge is located has not been represented in detail, so a component may be due to very local scale effects. It is possible that wave-surge interaction (which have not been modelled at Mooloolaba) may also be leading to elevated levels inside the harbour, however given the trained harbour entrance, this would be at odds with the findings of (Hanslow & Nielsen 1992). It is also possible, that freshwater flood flows are influencing behaviour inside the harbour and finally, regional ocean effects could also be contributing.

To test these possibilities, it is recommended that when further 3D work is completed that the representation of Mooloolaba Harbour is improved and sensitivity testing be completed on freshwater flood inflows from the Mooloolah River.

Overall, results at Southport are the least successful, with the shape of the surge wave matched rather poorly during the 28th of January. Peak residual under-estimates of approximately 0.6 m or 69 to 74 % (refer Table 8-1 and Table 8-2) were achieved. To improve this match, future work with need to consider the effects of flood flows within the Broadwater and the significant canal system of the Gold Coast.

This lack of performance at the Gold Coast is unlikely to detract from the main objective of this study which was the estimation of levels at Brisbane Bar, however if further work is completed it would be beneficial to investigate flood interaction further. This will likely need detailed hydrology and hydraulic inputs from the various river and creek systems flowing into the Broadwater and improved representation of the waterways and flood storage areas in the hydrodynamic model mesh.

9.5 Sensitivity to Model Resolution

The following statements can be made regarding the effects of model resolution:

- While certainly the activation of wave radiation stresses increased levels in Moreton Bay, the application of 25 or 100 m resolution showed limited difference in results at Brisbane Bar. A more significant finding was that reduction of the hydrodynamic model mesh from ~600 m to ~100 m also had limited benefit.
- It should be recognised that the wave model resolution of 100 m is already much finer than previous work completed in the area and one might question the validity of applying 25 m wave radiation results to a 100 m hydrodynamic model. In retrospect, an improved sensitivity test would have been to look at the effects of using a similar wave and surge model resolution combination (500 m) to that of the work of (Carno Lawson and Treloar 2009) to see if this lead to artificially elevated levels at Brisbane Bar . Although not a major research item for future work, it is recommended that further sensitivity testing be completed, to determine at what resolution results at Brisbane Bar start to become distorted.
- An unfortunate trend has emerged with the increase in computer hardware performance, allowing models to be run with increasingly finer model mesh resolution. This study shows very similar results were achieved by running a model with a mesh of 600-700 m as with 100 m on the Spitfire Banks. The model run time was increased by a factor of three using HD Domain C (compared with HD Domain B) for limited benefit. It is likely we are reaching a point of diminishing returns with respect to model resolution due to unknowns in model bathymetry and survey density (pers commun B.Harper). These unknowns are exacerbated by the fact that during an extreme event, the morphology (sand bars) of the Spitfire Banks are dynamically responding to wave forcing. This exercise highlights the importance of completing model mesh sensitivity testing during project start-up allowing optimisation of mesh size and computation runtimes.

9.6 Outcomes

Key outcomes from the study include:

- With waves, tide and surge forcing activated there remains a 26% under prediction at Brisbane Bar. Without the inclusion of wave radiation stresses the miss-match is considerable worse at -47 % (refer Table 8-6).
- Outside the twenty-four hour period from 10am the 27th to 10am the 28th of January, experiments with wave radiation stresses activated result in an improved match to both the shape and magnitude of observed residuals. However, during the period of maximum wind speeds there is a missing response of ~ 25%.
- Modelled results with wave radiation stresses activated provide an excellent match to peak water levels, however the timing of the high tide is such that the surge event was starting to recede. Had the higher tide on the 28th occurred six hours earlier, it is likely that the peak water levels would not have been captured as well as they have been. So from a disaster management perspective, the match of peak results here is somewhat fortunate.
- The work that has been completed variously supports what have been opposing thoughts on the surge generations in Moreton Bay. From the modelling results it can be inferred that both wave-surge and air-sea physics could play a role in surge generation at Brisbane Bar, while 3D effects cannot be discounted. However, without the ability to investigate a reliable fully three-dimensional assessment it is difficult to draw conclusions about the relative contribution of each. It is speculated that that all three factors (wave-surge, air-sea physics and 3D effects/regional ocean behaviour) play an important role.
- Model resolution increases on the Spitfire Banks in both the TUFLOW FV and SWAN models appears to have limited impact on the modelled residuals in Moreton Bay for the resolutions tested. Importantly at some reduced resolution there would certainly be impacts on the results and it is recommended that sensitivity testing during the model setup stage be completed to optimise performance.

9.7 Implications of Research

- The study shows just how challenging storm tide assessments in Moreton Bay can be. The Bay forms a complex coastal embayment that is bordered by the high-energy processes occurring over the continental shelf such within the gyres and associated mean sea level anomalies of the East Australian Current. When extreme wind events occur, the shape and magnitude of measured and modelled tidal residuals are a function of the non-linear interaction between the astronomical tides, waves-surge current interactions and regional ocean processes propagating internally and as surface wave energy along the continental shelf.

- Southeast Queensland is within a transition zone between tropical and mid-latitude weather systems. An unfortunate (or perhaps fortunate depending on one's perspective) consequence is that it is rarely affected by "direct hit" events and none are available within the recent record to gain better understanding on the likely contribution of strong surge generation mechanisms. It also means that for the majority of surge events in Moreton Bay, surface friction due to extreme winds does not dominate the surge response as occurs in Northern Queensland. Here the effects of waves and regional ocean processes play a more pronounced role and this study supports that these factors need to be considered when undertaking assessments in the region.
- Due to the complexity and non-linearity of these interactions the usage of numerical models is required. Importantly numerical modelling needs to be supported with reliable data and be also needs to reproduce the experimental findings of other studies conducted within the area. There remains tremendous opportunely for further research and collaboration in this space to meld the findings of measured data experiments and those modelled.

10 Conclusions and Recommendations

10.1 Conclusions

A comprehensive investigation of Moreton Bay has been undertaken to assess the likely contributors to total recorded water levels and tidal residuals during the passage of *Ex. Tropical Cyclone Oswald* in January 2013. The driver for this assessment has been the systematic 30-60% under-prediction of storm tide levels at Brisbane Bar within five previous independent assessments completed by a combination of both industry and academia.

The reasons for this under-estimation has been hypothesised as derived from three main effects:

- Regional surge-wave interactions as a result of wave radiation stress gradients due to wave breaking on the Spitfire Banks, a region of large underwater sandbanks at the northern opening of Moreton Bay (Treloar, Taylor & Prenzler 2011);
- The need to improve our implementation of the physics at the ocean/atmosphere interface, (Bode & Hardy 1997), (Stewart, Callaghan & Nielsen 2010), (Nielsen, Callaghan & Baldock 2011) and (Callaghan, Nielsen & Baldock 2012); and
- The potential for ocean meso-scale eddies propagating as internal and surface wave energy across the continential shelf following wind forcing of the mixed layer and thermocline in an active region of the East Australian Current (pers commun B.Harper).

Due to the complexity of the processes involved, a series of integrated numerical models have been developed within the TUFLOW FV hydrodynamic and SWAN spectral wave modelling packages. This has required a significant collation of available topographic, bathymetric, oceanographic and meteorological data sources from various agencies to drive the models and to allow comparison to available observations.

To ensure the TUFLOW FV models could adequately reproduce astronomical tide and that the SWAN model could reproduce wave conditions, an extended calibration for the period of January 2013 was completed. The models were both able to reproduce excellent results and provided confidence that the models were suitable for further experimentation.

In order to question the three previously stated hypotheses a series of 8 numerical modelling experiments were prepared. The first two of these experiments involved three-dimensional modelling, however after exhaustive testing it was decided that the open boundary conditions available from the global HYCOM model were not sufficiently representative of nearby measured data, ultimately meaning that the three-dimensional runs could not be deemed reliable. It is hoped that the soon to be released CSIRO ocean reanalysis will provide improved representation of offshore water level and density gradients allowing this work to be revisited.

Experiment 3, 4 and 5 investigated model response under different input forcings for the model configured in a two-dimensional depth averaged mode. Experiment 3 was run with wind and pressure inputs only, Experiment 4 with both the astronomical tide and wind and pressure forcing applied and Experiment 5 with wave radiation stresses additionally applied. To ascertain the effect of model spatial resolution Experiments 6, 7 and 8 essentially repeated Experiments 4 and 5 with the model resolution on the Spitfire Banks increased from approximately 600-700 m to 100 m.

The modelling results were primarily compared with peak tidal residuals at Brisbane Bar although further complementary comparisons were made at Mooloolaba and Southport. The peak-measured residual at Brisbane Bar was recorded at 4am on the 28^{th} of January at 0.99m at low tide and close to the peak wind speeds recorded at both Brisbane Airport and the Spitfire Beacon.

With waves, tide and surge forcing activated it was estimated that there is a 26% under prediction of peak residual levels at Brisbane Bar (Experiments 5, 7 and 8). Without the inclusion of wave radiation stresses the mismatch was considerably worse at -47 % (Experiments 4 and 6). The effect of increasing model resolution was found to be negligible.

Overall, the shape and magnitude of the water levels with wave radiation stresses activated provided a good match to measured residuals outside of the period 10am the 27^{th} of January to 10am the 28^{th} of January, which was also the period of highest wind speeds within Moreton Bay. This tends to support the theory for of wave radiation stress gradients interacting with the tide/surge generated water levels and currents, which may be due to some form of ‘blocking’ effect on tidal outflows. During the twenty-four hour period of greatest wind speeds however, there is a consistent ~25% underestimation of water levels that tends to support a call for improved implementation of model physics at the air-sea interface, while the effects of 3D regional ocean contributions cannot be dismissed.

A number of items for further research, outside the current scope of work have been recommended including investigation of other events, numerical mass balance assessments of Moreton Bay, further sensitivity testing on wind data inputs, model mesh resolution improvements and freshwater inflows assessment at both Mooloolaba and

Southport. What can be stated though is that this study has addressed and gone well beyond the requirements outlined in the Project Specification (Appendix A) given consideration of available datasets. It should provide an important resource for others completing studies in the region.

This study highlights just how challenging storm tide assessments in Moreton Bay can be and there remains tremendous opportunity for further research and collaboration in this space to meld the findings of data driven and analytical experiments and those of the numerical models completed here.

10.2 Limitations and Recommendations for Future Research

Although this study has completed a rigorous investigation given the scope of work (refer Appendix A) there are a number of limitations, some of which can be addressed in the future through further investigation, while others are inherent due to uncertainties associated with data. Key limitations of the present study include:

- The lack of suitable 3D modelling boundary conditions. This should be revisited and revised as improved boundary conditions become available. Another benefit of 3D modelling is the ability to better represent return flows at depth in the key passages into Moreton Bay that are not resolved in 2D depth averaged mode. This omission remains a significant limitation of the current study. While the 2D modelling with waves certainly shows improved results, to have similar results reflected in a 3D solution would allow for stronger conclusions regarding surge generation mechanisms.
- The wave coupling method adopted for Experiments 5, 7 and 8 allows wave generation within SWAN to be influenced by water levels and currents from the tide plus surge runs (either experiments 4 and 6 dependant on the HD Model Domain) and TUFLOW FV is in turn driven with radiation stresses from SWAN. Additionally this coupling can be completed on a fully two-way dynamic basis such that the hydrodynamic and waves models influence each other. It is recommended that future work investigate the sensitivity of completing this dynamic two- way coupling approach.
- Although the wind field is one of the best that the author has worked with to date in terms of reproducing wind speed and direction over a wide range of sites, there remains some uncertainly regarding wind direction at the northern entrance of Moreton Bay. Measured wind direction at the Spitfire Banks (refer Appendix Figure B-3) is consistently more northerly than the ACCESS model at

this location, which may be due to topographic interaction with Moreton Island. It is recommended that sensitivity testing be completed by manually modifying the ACCESS wind field within Moreton Bay to be more northerly and inspect possible increased in surge at Brisbane Bar.

- The current work could be strengthened by conducting a series of experiments in the SWAN model applying differing wind speeds from the northeast. This could help determine if there is a critical offshore wave height that starts to result in increased modelled surge levels in Moreton Bay.
- To improve understanding of dynamics of surge generation, the current work could be improved with additional reporting on the mass balance within Moreton Bay. This would be achieved by extracting flow fluxes profiles across major entrances and exits to Moreton Bay and should be completed when 3D modelling is conducted in future.
- The representation of Mooloolaba Harbour and the full Gold Coast Broadwater system has likely affected the results at these locations. This can be improved with greater focus on these sites in future work.
- To a lesser extent at Mooloolaba and Brisbane Bar but certainly at the Gold Coast, the effects of freshwater inflows warrant further investigation.
- Future work should incorporate comparison of measured data from sources not investigated here, such as Acoustic Doppler Current Profiler and offshore temperature and salinity measurements. Additional tide gauge data for Southeast Queensland such as Caloundra and Pine Rivers may also add weight to the investigation.
- The -26% result (0.26 m) is approaching the limits of model accuracy. i.e. uncertainties with data may be playing a role. Although not quantified here, storm tide assessments typically aim to be within ±5% of those measured. Should improved bathymetric data become available, the models should be updated and reassessed to determine the model sensitivity to these changes.
- Finally, only one event has been investigated within the study although, as previously mentioned, Ex TC Oswald remains an excellent test candidate. It would certainly be of value to investigate other available surge events within the period that matches the available 3D model record.

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Appendix A Project Specification

For: Mitchell Smith

Topic: SEQ Storm Tide Response to Ex Tropical Cyclone Oswald

Supervisors: Dr Md Jahangir Alam (USQ), Dr Ian Teakle (BMTWBM) and Dr Bruce Harper (SEA)

Enrolment: ENG4111 S1 2015 - ENG4111 S2 2015

Project Aim: To investigate the effects of regional ocean currents and mean surface anomalies on the total storm tide level observed during Ex. Tropical Cyclone Oswald in Moreton Bay.

Sponsership: BMT WBM Pty Ltd

Programme: Issue B, 26 March 2015

1. Undertake model testing, data collation and model application.
2. Preparation of astronomical tide, wind and pressure calibrations at Mooloolaba and Brisbane Bar during the passage of Ex TC. Oswald.
3. Assess preliminary model results of storm surge (Hydrodynamic model run with only astronomical tide boundaries and an applied windfield). Run in both 2D and 3D mode to assess model sensitivity and response to the differing numerical methods. If time permits undertake sensitivity testing on the number of layers to model in 3D and model parameters.
4. Apply HYCOM ocean boundaries to the 3D hydrodynamic model and compare preliminary surge results for calibration at Brisbane Bar and Mooloolaba. Compare results with those from Step 3.
5. Review the model results and analyse the contribution of to the total water level from each of the astronomical tide, regional ocean currents and mean surface anomalies at Brisbane Bar.
6. Establish correlations between the factors with storm surge and key research findings.
7. Analyse the impact of Ex. TC. Oswald on coastal waters.

As Time Permits

8. Apply wave forcing to model the effect of wave breaking on the storm surge. The ability to model waves under 3D forcing may be subject to computing availability and model runtimes as determined in Step 1.
9. Apply Bluelink ocean boundaries to the 3D hydrodynamic model and assess the preliminary surge calibration at Brisbane Bar and Mooloolaba to evaluate whether the model inputs from the BoM lead to more reliable results at Brisbane Bar.

AGREED:

Mitchell Smith (Student), Dr Bruce Haper, Dr Ian Teakle, Dr Md Jahangir Alam (Supervisors)

30th of March 2015.

Appendix B ACCESS Model Performance

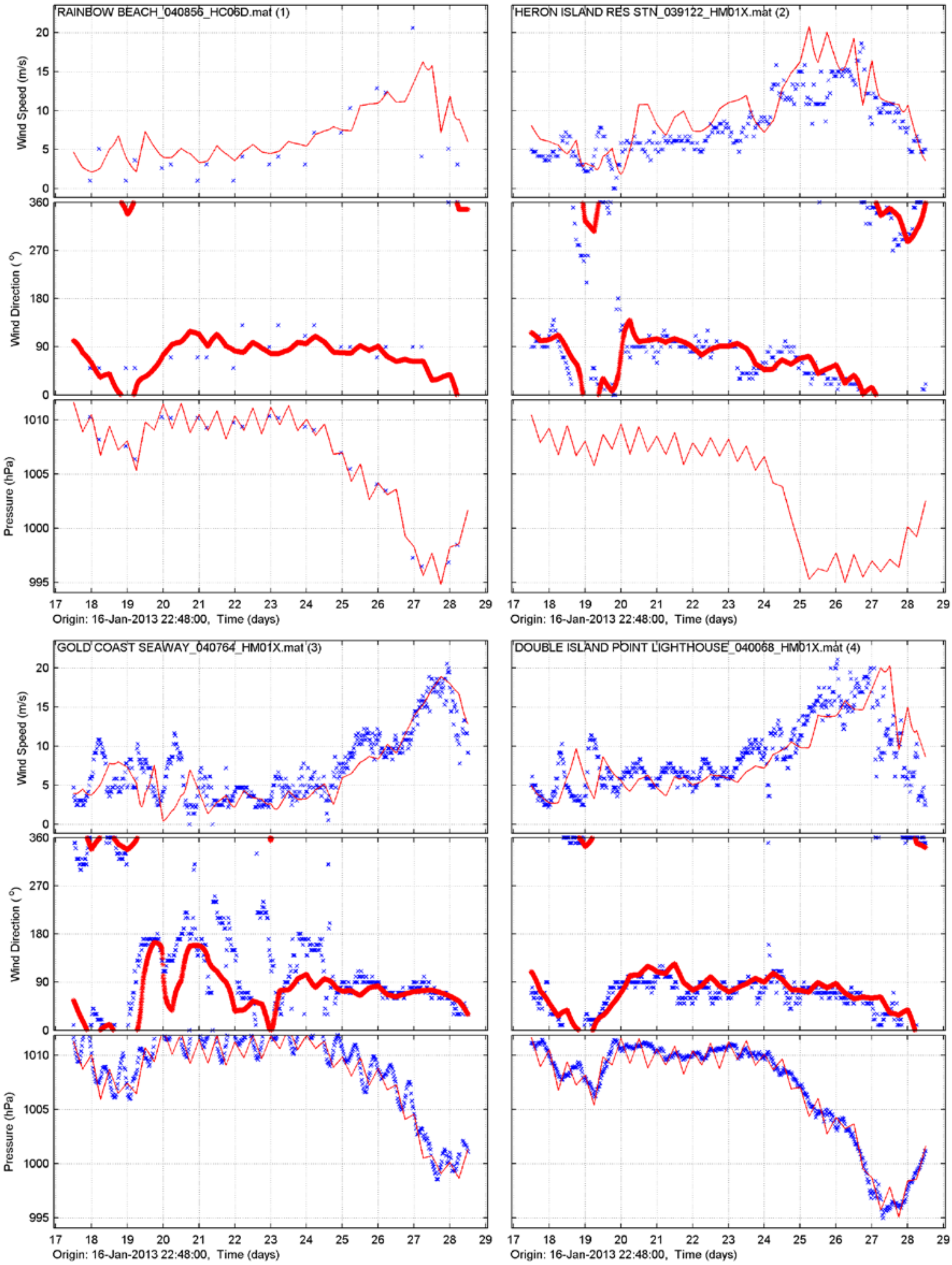

Figure B-1 Rainbow Beach, Heron Island, Gold Coast Seaway and Double Island Point, modelled (red) and measured (blue) 10m 10 minute wind speed, direction and mean sea level pressure.

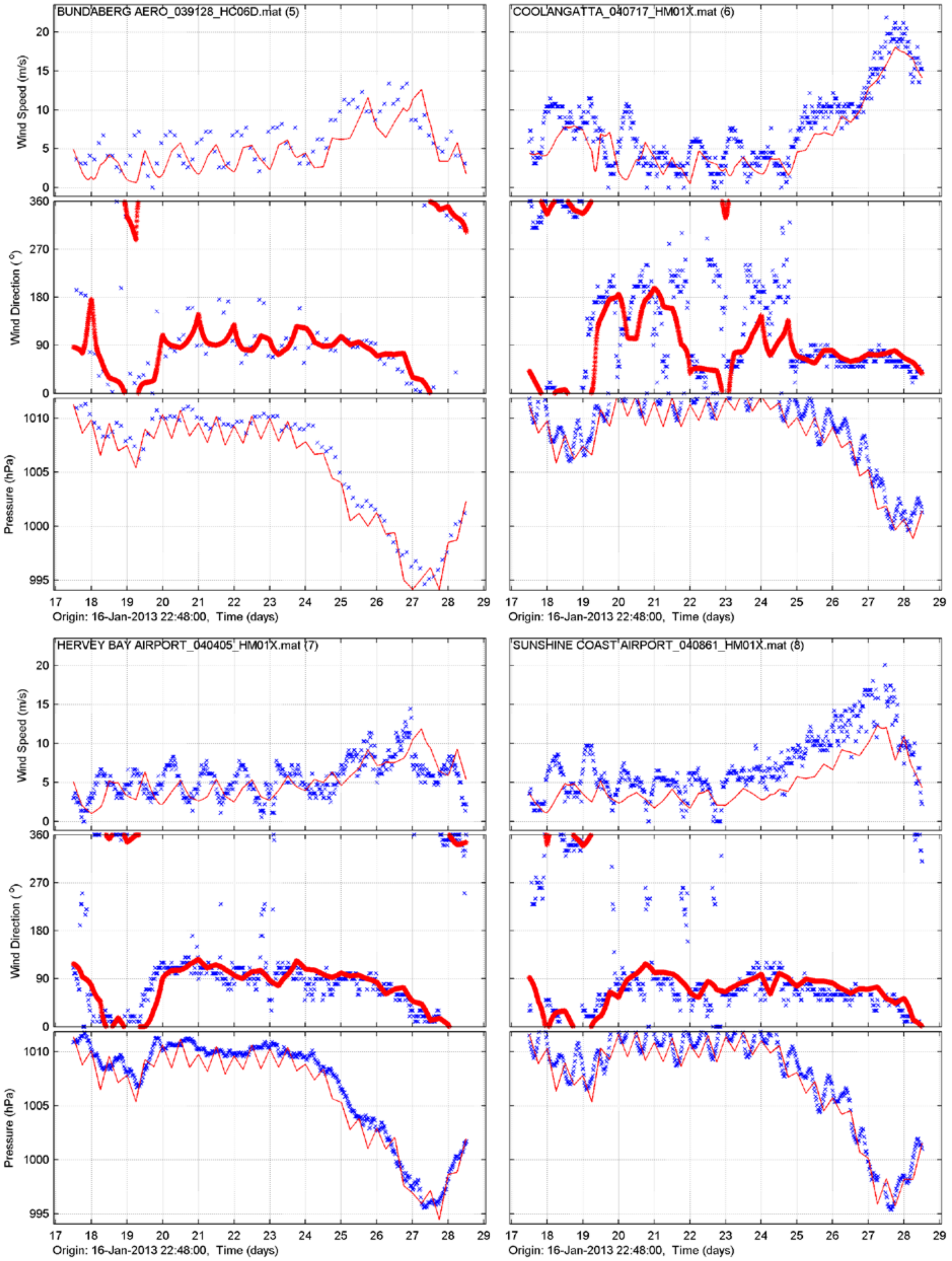

Figure B-2 Bundaberg, Coolangatta, Hervey Bay and Sunshine Coast Airport, modelled (red) and measured (blue) 10m 10 minute wind speed, direction and mean sea level pressure.

ACCESS Model Performance

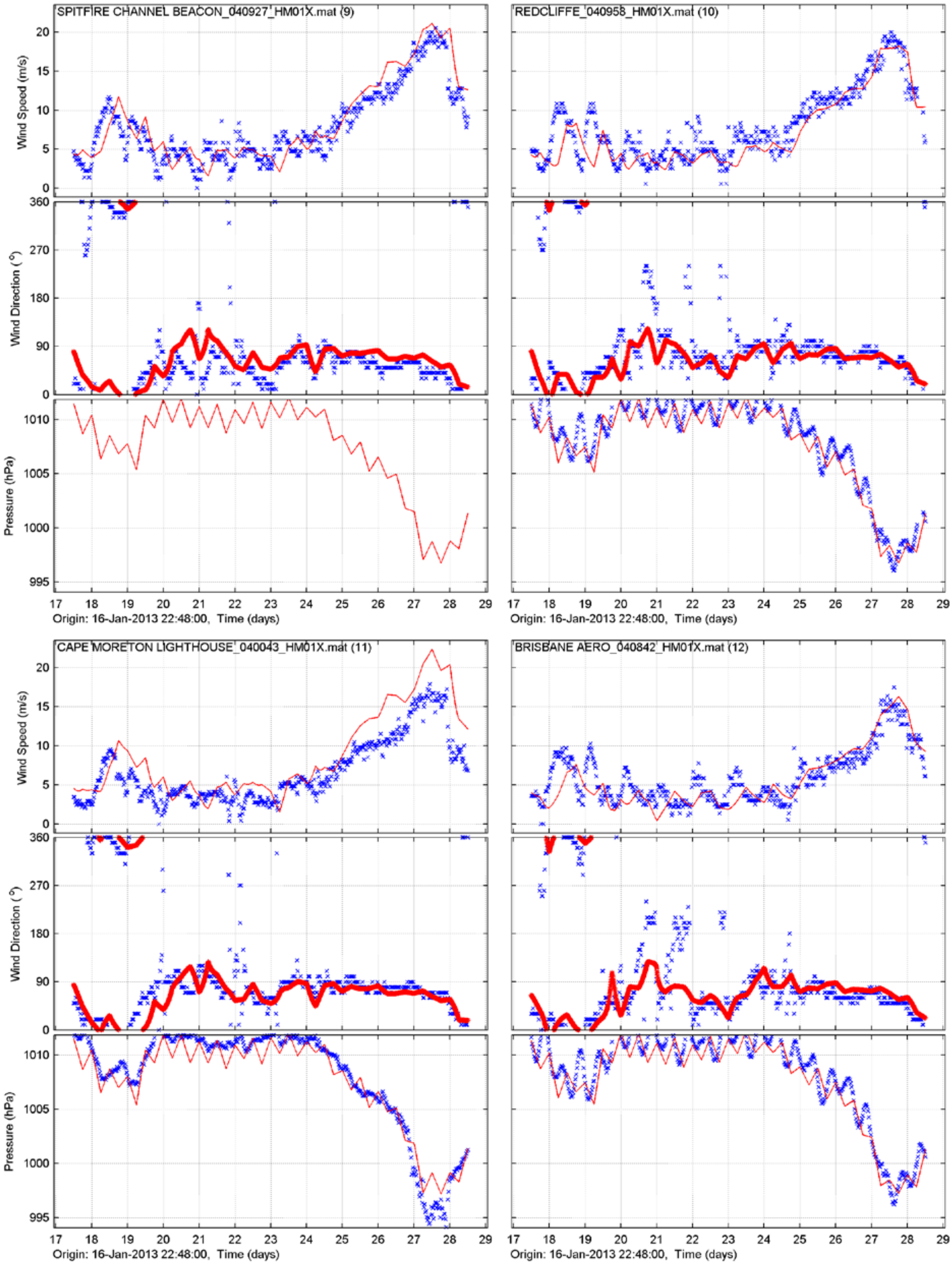

Figure B-3 Spitfire Channel, Redcliffe, Cape Moreton and Brisbane Airport, modelled (red) and measured (blue) 10m 10 minute wind speed, direction and mean sea level pressure.

Appendix C Hydrodynamic Model Domains

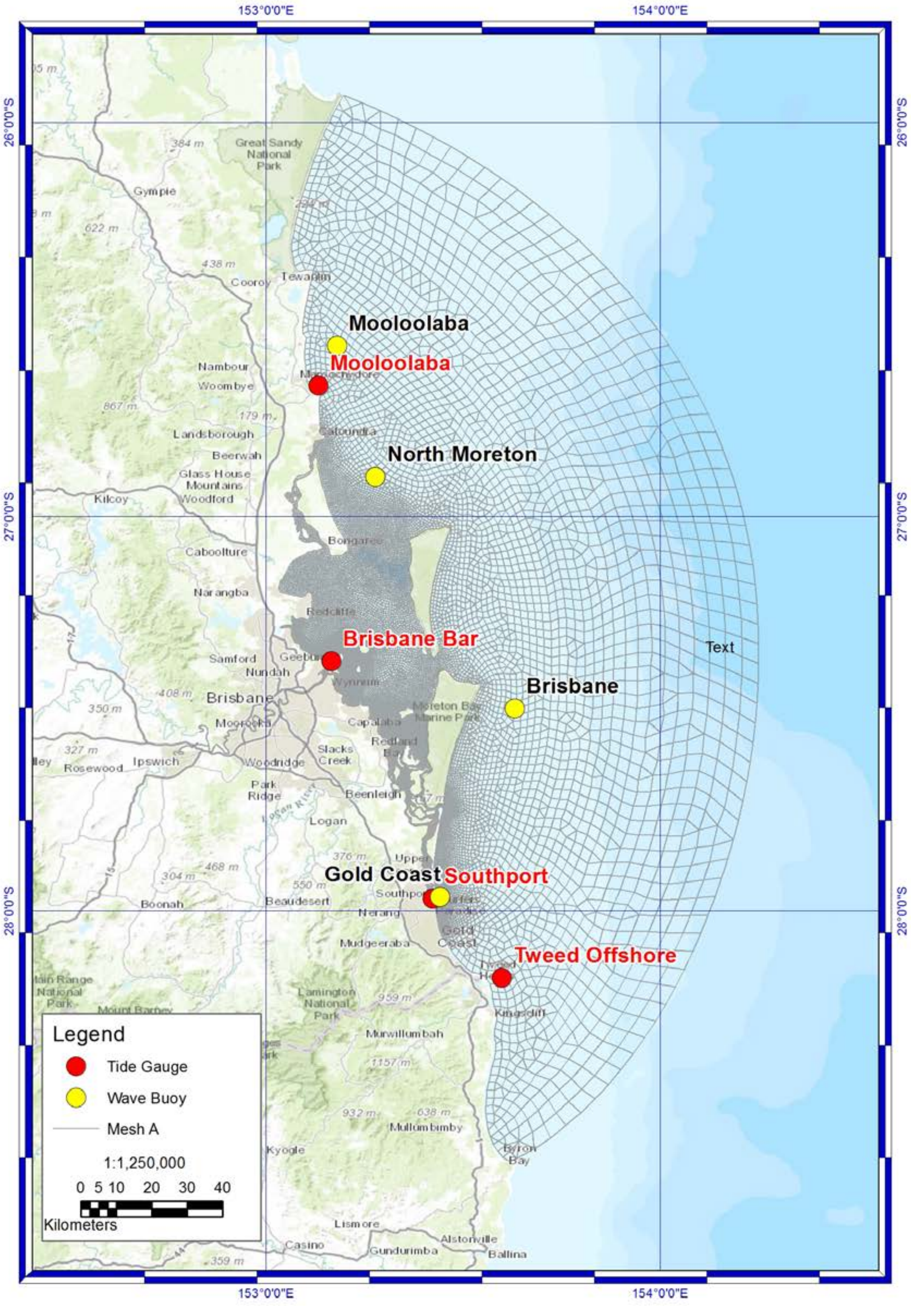

Figure C-1 Hydrodynamic Model Domain A

Hydrodynamic Model Domains

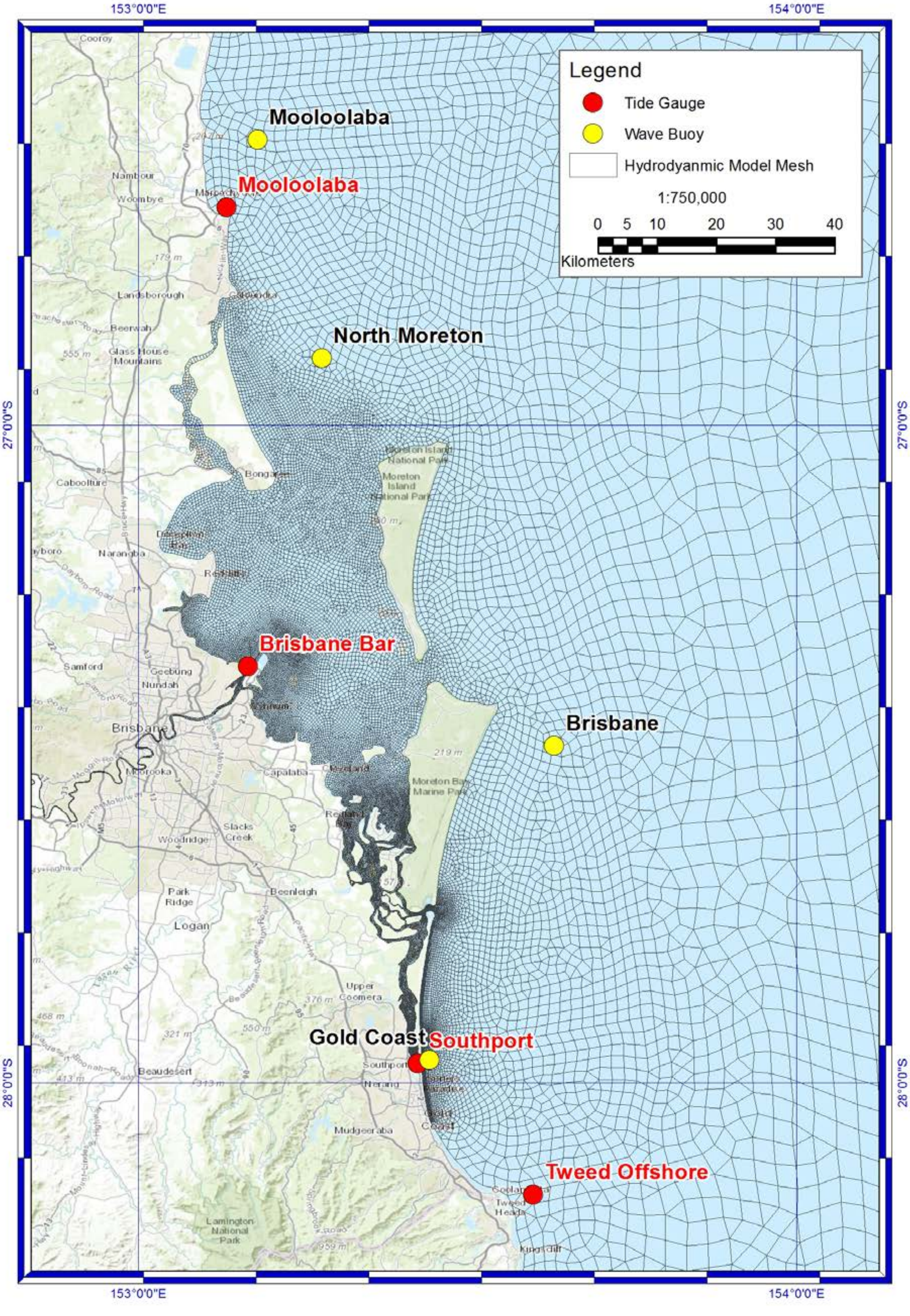

Figure C-2 Hydrodynamic Model Domain – Mesh B Zoom

Hydrodynamic Model Domains

Figure C-3 Increased Resolution of Hydrodynamic. Domain B (top) Domain C (bottom)

Appendix D TUFLOW FV Model Parameters

D.1 Overview

The following outlines the TUFLOW 2D model tide plus surge setup used for the Experiment 4 and 3D Setup for Experiment 2. It provides the key inputs and parameters utilised by the TUFLOW FV model. For full details of each parameter and also the defaults please refer to the TULFOW-FV User Manual available @ http://www.tuflow.com/Download/TUFLOW_FV/Manual/FV-UserManual-2014.01.pdf

D.2 2D Control File and Inputs

```
! 2D MODEL CONTROL FILE - EX TC. OSWALD.

! SIMULATION CONFIGURATION
!_________________________________________________________________
spherical == 1
momentum mixing model == Smagorinsky
scalar mixing model == Smagorinsky
vertical mixing model == External
bottom drag model == ks
spatial order == 1,1
equation of state == UNESCO


!TIME COMANDS
!_________________________________________________________________
cfl external == 0.7
cfl internal == 0.7
time format == ISODATE
start time == 05/01/2013 10:00:00
end time ==   01/02/2013 10:00:00
display dt == 900.
timestep limits == 0.1, 15.
turbulence update dt == 300.

!MODEL PARAMETERS
!_________________________________________________________________
stability limits == 10.,10.
cell wet/dry depths == 5.0e-3, 1.0e-1
cell 3d depth == 1.0
reference density == 1025.0
reference salinity == 35.0
reference temperature == 26.0
kinematic viscosity == 1.0e-6
global horizontal eddy viscosity == 0.5
global horizontal eddy viscosity limits == 1.0, 9999.0
global horizontal scalar diffusivity == 0.2
global horizontal scalar diffusivity limits == 1.0, 9999.0
global vertical eddy viscosity limits == 1.0e-4, 1.0
global vertical scalar diffusivity limits == 0., 1.0

!STRUCTURE SPECIFICATIONS
!_________________________________________________________________
```

```
!GEOMETRY
!___________________________________________________________________
geometry 2d == ..\geo\MortonBay_DEV_006.2dm
cell elevation file ==
..\geo\cell_centres\MortonBay_DEV_006celcent_ins3.csv
global bed elevation limits == -9999, 9.9
global bottom roughness == 0.02


!MATERIAL SPECIFICATIONS
!___________________________________________________________________
material == 1        !default
end material

material == 2        !bunded off canals
  inactive == 1
end material

material == 3        !rivers and channels
  bed elevation limits == -9999, -2.5
end material

material == 4        !canals
  bed elevation limits == -2.5, -2.5
end material

material == 5        ! rivers and channels deep
  bed elevation limits == -9999, -3.5
end material

material == 6        !flow restrictions
  bed elevation limits == -0.25, 0.25
end material

material == 7      !Bris River
  bed elevation limits == -7, -7
end material

material == 8      !Sand Banks
  bottom roughness == 0.001
end material
```

```
material == 9      !maintained depth 14
  bed elevation limits == -15.3, -15.3
end material

material == 10       !maintained depth 9.1
  bed elevation limits == -10.4, -10.4
end material


!BOUNDARY CONDITIONS

! ncep
!include == ..\bc\cfsv2\BC_ncep_JanDec2013.fvc

! hycom
!include == ..\bc\hycom\BC_hycom.fvc

! tides
include == ..\bc\tide\BC_tide_2D.fvc

! wind
include == ..\bc\cycal\BC_cycal.fvc

! waves
!include == ..\bc\wave\bc_wave_nc_500m_jun_oct13.fvc



!INITIAL CONDITIONS
!_________________________________________________________________
!initial condition ogcm
!initial condition quiescent
!restart ==
log/GLAD_EXT_SEDI_HIND_2D_015_019_spliced_20131113_000018.rst

!OUTPUT COMMANDS
!_________________________________________________________________
output dir == /scratch2/Z_Mitch_Thesis/TUFLOW-FV/output/

output == netcdf
  output parameters == H,V,w10,mslp,Taus,Taub
  output interval == 900.
  output compression == 1
```

```
end output

!output == transport
!  output interval == 900.
!  output compression == 1
!end output

write restart dt == 24.0
```

```
! ASTRONOMICAL TIDE INPUT - EX TC. OSWALD.
! Tides
bc == WL_CURT, 1, MoretonBay_006_TPX7pnt2_AEST.nc
  sub-type == 1
  bc header == TIME,NS1_Chainage,dummy,NS1_WL
  bc update dt == 60.
  bc time units == hours
  bc reference time == 01/01/1990 00:00
  includes MSLP == 0
end bc
```

```
! WIND AND PRESSURE INPUT - EX. TC OSWALD
! WIND ACCESS data
grid definition file == Oswald.nc
grid definition variables == lon,lat
grid definition label == cycal_wind
end grid

bc == W10_GRID, cycal_wind, Oswald.nc
  bc header == valid_time,zonal_wnd,merid_wnd
  bc update dt == 600.
  bc reference time == 01/01/1990 00:00
  end bc

! MSLP CFSv2 data
grid definition file == Oswald.nc
grid definition variables == lon,lat
grid definition label == cycal_mslp
end grid
bc == MSLP_GRID, cycal_mslp, Oswald.nc
  bc header == valid_time,mslp
  !bc scale == 0.01
  bc update dt == 600.
  bc default == 1013.25
  bc reference time == 01/01/1990 00:00
  end bc
```

```
! WAVE RADIATION STRESS INPUTS - EX. TC OSWALD

! waves regional 800m
grid definition file ==
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_REG_006A_001.nc
  grid definition variables == longitude,latitude
  grid definition label == wave_grid_coarse
end grid
bc == wave, wave_grid_coarse,
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_REG_006A_001.nc
  bc header == time,hs,tps,theta0,ubot,tmbot,dummy,dummy
  bc scale == 1.,1.,1.,1.414,1.,1.,1.
  bc reference time == 01/01/1970 00:00
  bc time units == seconds
  bc update dt == 900.
end bc


! waves regional 400m
grid definition file ==
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_RWQM_006A_001.nc
grid definition variables == longitude,latitude
grid definition label == wave_grid_rwqm
end grid
bc == wave, wave_grid_rwqm,
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_RWQM_006A_001.nc
  bc header == time,hs,tps,theta0,ubot,tmbot,dummy,dummy
  bc scale == 1.,1.,1.,1.414,1.,1.,1.
  bc reference time == 01/01/1970 00:00
  bc time units == seconds
  bc update dt == 900.
end bc


! waves local 100m  - North Moreton
grid definition file ==
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D001_006A_001.nc
grid definition variables == longitude,latitude
grid definition label == wave_grid_d001
end grid
bc == wave, wave_grid_d001,
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D001_006A_001.nc
  bc header == time,hs,tps,theta0,ubot,tmbot,xforce,yforce
```

```
  bc scale == 1.,1.,1.,1.414,1.,1.,1.
  bc reference time == 01/01/1970 00:00
  bc time units == seconds
  bc update dt == 900.
end bc


! waves local 100m  Straddie - Moreton
grid definition file ==
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D002_006A_001.nc
grid definition variables == longitude,latitude
grid definition label == wave_grid_d002
end grid
bc == wave, wave_grid_d002,
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D002_006A_001.nc
  bc header == time,hs,tps,theta0,ubot,tmbot,xforce,yforce
  bc scale == 1.,1.,1.,1.414,1.,1.,1.
  bc reference time == 01/01/1970 00:00
  bc time units == seconds
  bc update dt == 900.
end bc

! waves local 25m
grid definition file ==
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_E001_006A_001.nc
  grid definition variables == longitude,latitude
  grid definition label == wave_grid_e001
end grid
bc == wave, wave_grid_e001,
/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_E001_006A_001.nc
  bc header == time,hs,tps,theta0,ubot,tmbot,xforce,yforce
  bc scale == 1.,1.,1.,1.414,1.,1.,1.
  bc reference time == 01/01/1970 00:00
  bc time units == seconds
  bc update dt == 900.
end bc
```

D.3 3D Model Control File and Z-Layering

```
! 3D MODEL CONTROL FILE - EX TC. OSWALD.

! SIMULATION CONFIGURATION
!_________________________________________________________________
spherical == 1
include salinity == 1,1
include temperature == 1,1
!include sediment == 1,0
include heat == 1
momentum mixing model == Smagorinsky
scalar mixing model == Smagorinsky
vertical mixing model == External
bottom drag model == ks
spatial order == 1,2
equation of state == UNESCO


!TIME COMANDS
!_________________________________________________________________
cfl external == 0.5
cfl internal == 0.5
time format == ISODATE
start time == 05/01/2013 10:00:00
end time ==   01/02/2013 10:00:00
display dt == 900.
timestep limits == 0.1, 15.
turbulence update dt == 300.

!MODEL PARAMETERS
!_________________________________________________________________
stability limits == 10.,10.
cell wet/dry depths == 5.0e-3, 1.0e-1
cell 3d depth == 1.0
reference density == 1025.0
reference salinity == 35.0
reference temperature == 26.0
kinematic viscosity == 1.0e-6
global horizontal eddy viscosity == 0.5
global horizontal eddy viscosity limits == 1.0, 9999.0
global horizontal scalar diffusivity == 0.2
global horizontal scalar diffusivity limits == 1.0, 9999.0
global vertical eddy viscosity limits == 1.0e-4, 1.0
global vertical scalar diffusivity limits == 0., 1.0
```

```
!STRUCTURE SPECIFICATIONS
!_________________________________________________________________

!WB wall
!structure == nodestring,13
!flux type==wall
!end structure


!GEOMETRY
!_________________________________________________________________
geometry 2d == ..\geo\MortonBay_DEV_006.2dm
cell elevation file ==
..\geo\cell_centres\MortonBay_DEV_006celcent_ins2.csv
global bed elevation limits == -9999, 9.9
global bottom roughness == 0.02

vertical mesh type == z
layer faces == ..\geo\zfaces\Moreton_zlayer_002.csv
sigma layers == 4
min bottom layer thickness == 0.5

!MATERIAL SPECIFICATIONS
!_________________________________________________________________
material == 1        !default
end material

material == 2        !bunded off canals
  inactive == 1
end material

material == 3        !rivers and channels
  bed elevation limits == -9999, -2.5
end material

material == 4        !canals
  bed elevation limits == -2.5, -2.5
end material

material == 5        ! rivers and channels deep
  bed elevation limits == -9999, -3.5
end material
```

```
material == 6        !flow restrictions
  bed elevation limits == -0.25, 0.25
end material

material == 7      !Bris River
  bed elevation limits == -7, -7
end material

material == 8      !Sand Banks
  bottom roughness == 0.001
end material

material == 9      !maintained depth 14
  bed elevation limits == -15.3, -15.3
end material

material == 10       !maintained depth 9.1
  bed elevation limits == -10.4, -10.4
end material

!material == 11      !maintained depth 9.1
!  bed elevation limits == -10.4, -10.4
!  inactive == 1
!end material

material == 12       ! Deep Water Hack
  bottom roughness == 0.02
!  spatial reconstruction == 0
end material

!BOUNDARY CONDITIONS

! ncep
include == ..\bc\cfsv2\BC_ncep_JanDec2013.fvc

! hycom
include == ..\bc\hycom\BC_hycom.fvc

! tides
include == ..\bc\tide\BC_tide.fvc

! wind
```

```
include == ..\bc\cycal\BC_cycal.fvc

! waves
!include == ..\bc\wave\bc_wave_nc_500m_jun_oct13.fvc



!INITIAL CONDITIONS
!_________________________________________________________________
initial condition ogcm
!initial condition quiescent
!restart ==
log/GLAD_EXT_SEDI_HIND_2D_015_019_spliced_20131113_000018.rst

!OUTPUT COMMANDS
!_________________________________________________________________
output dir == /scratch2/Z_Mitch_Thesis/TUFLOW-FV/output/

output == netcdf
  output parameters == H,V,Sal, Temp, Rhow,w10,mslp,Taus,Taub
  output interval == 900.
  output compression == 1
end output

!output == transport
!  output interval == 900.
!  output compression == 1
!end output

write restart dt == 24.0
```

```
! 3D Z FACES LAYERING
Z
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
-14.5
-16
-17.5
-19
-21
-23
-25
-30
-40
-50
-60
-70
-80
-90
-100
-125
-150
-200
-250
-300
-350
-400
-450
-500
-600
-700
-800
-1000
-1250
-1500
```

-1750
-2000
-2250
-2500

```
! HEAT INPUTS for 3D - EX. TC OSWALD

grid definition file == NCEP_Reanalysis_CoralSea_JanDec2013_temp.nc
grid definition variables == lon, lat
grid definition label == ncep
end grid
bc == AIR_TEMP_GRID, ncep,
NCEP_Reanalysis_CoralSea_JanDec2013_temp.nc
  bc header == time,temp
  bc update dt == 3600.
  bc time units == hours
  bc reference time == 01/01/1990 00:00
end bc

bc == SW_RAD_GRID, ncep, NCEP_Reanalysis_CoralSea_JanDec2013_dswr.nc
  bc header == time,dswr
  bc update dt == 3600.
  bc time units == hours
  bc reference time == 01/01/1990 00:00
end bc

bc == LW_RAD_GRID, ncep, NCEP_Reanalysis_CoralSea_JanDec2013_dlwr.nc
  bc header == time,dlwr
  bc update dt == 3600.
  bc time units == hours
  bc reference time == 01/01/1990 00:00
end bc

!bc == PRECIP_GRID, ncep,
NCEP_Reanalysis_CoralSea_JanDec2013_rain.nc
!  bc header == time,rain
!  bc update dt == 3600.
!  bc time units == hours
!  bc reference time == 01/01/1990 00:00
!end bc

bc == REL_HUM_GRID, ncep,
NCEP_Reanalysis_CoralSea_JanDec2013_rhum.nc
  bc header == time,rhum
  bc update dt == 3600.
  bc time units == hours
  bc reference time == 01/01/1990 00:00
end bc
```

Appendix E SWAN Model Parameters

E.1 Overview

The following outlines the SWAN setup files used for each of the nested spectral wave provides the key inputs and parameters utilised.. For full details of each parameter and also the defaults please refer to the SWAN User Manual available @ http://falk.ucsd.edu/modeling/swanuse.pdf

```
PROJECT 'Mitch' '006A'
'REG'
'ex-TC Oswald'

SET 0.00 90.0 0.05 200 2
MODE NONSTATIONARY TWODIMENSIONAL
COORDINATES SPHERICAL

CGRID REGULAR 153.004 -29.996 0.0 2.4 5.4 300 750 CIRCLE 36 0.05
1.00

INPGRID BOTTOM REGULAR 153.004 -29.996 0.0 300 750 0.008 0.0072
EXCEPTION -5.00
READINP BOTTOM +1 '..\geo\swan_regional_001_refdat.out' 5 0 FORMAT
'((20f10.4))'

INPGRID WIND REGULAR 145.0 -32.0 0 200 170 0.1 0.1 NONSTATIONARY
20130102.100000 10 MIN 20130201.100000
READINP WIND +1 '/proj_coastal/Z_Mitch_Thesis/SWAN/wind/Oswald.txt'
3 0 FREE

BOUND SHAPESPEC PM PEAK DSPR DEGREES
BOUNDSPEC SIDE E CONSTANT FILE
'..\bc\NWW3\SEQ_Dec2012_Jun2013_AEST.txt'

GEN3
FRICTION COLLINS

PROP BSBT
NUMERIC ACCUR 0.02 0.02 0.02 98.0 NONST 1 0.1 DIRIMPL 0.5 4

$ Nesting file (boundary conditions for nested model)
NGRID 'RWQM' 153. -28.7 0. 0.86 2.7432
NESTOUT 'RWQM'
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_REG_nest.out' OUTPUT
20130105.010000 1 HR

$ netCDF OUTPUT
BLOCK 'COMPGRID' NOHEADER
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_REG_006A_001.nc' &
LAY-OUT 3 HSIGN TPS DIR PDIR DEPTH FORCE UBOT TMBOT WIND OUTPUT
20130105.010000 1 HR
```

```
$ Points OUTPUT
POINTS 'BRI'  153.632 -27.487
POINTS 'MOO'  153.181 -26.566
TABLE 'BRI' HEADER '..\output\points\MORT_REG_006A_001_BRI_BUOY.out'
&
HSIGN TMM10 TPS DIR PDIR DSPR DEPTH OUTPUT 20130105.010000 1 HR
TABLE 'MOO' HEADER '..\output\points\MORT_REG_006A_001_MOO_BUOY.out'
&
HSIGN TMM10 TPS DIR PDIR DSPR DEPTH OUTPUT 20130105.010000 1 HR

$ Simulation period
INITIAL DEFAULT
COMPUTE NONSTATIONARY 20130105.010000 0.5 HR 20130201.010000

STOP
```

```
PROJECT 'B17436' '001'
'RQM3 Swan Model'
'Swell propagation simulation 001'
$
SET 0.00 90.0 0.05 200 2
MODE NONSTATIONARY TWODIMENSIONAL
COORDINATES SPHERICAL
$
CGRID REGULAR 153. -28.7 0. 0.86 2.7432 215 762 CIRCLE 24 0.05 1.00
24
$
INPGRID BOTTOM REGULAR 153. -28.7 0. 215 762 0.004 0.0036 EXCEPTION
-5.00
READINP BOTTOM +1 '..\geo\RWQM_SWN_DEV_004_GEO_refdat.out' 5 0
FORMAT '((20f10.4))'
$
INPGRID WIND REGULAR 145.0 -32.0 0 200 170 0.1 0.1 NONSTATIONARY
20130102.100000 10 MIN 20130201.100000
READINP WIND +1 '/proj_coastal/Z_Mitch_Thesis/SWAN/wind/Oswald.txt'
3 0 FREE

$
INPGRID WLEV REGULAR 153.0000000 -28.7000000 0 215 762 0.0040 0.0036
&
NONSTATIONARY 20130105.100000 0.250 HR 20130201.100000
READINP WLEV +1
'/proj_coastal/Z_Mitch_Thesis/SWAN/hydros/OSWALD_2D_010_waterlevels_
grid.txt' 1 0 FREE

$
INPGRID CURRENT REGULAR 153.0000000 -28.7000000 0 215 762 0.0040
0.0036 &
NONSTATIONARY 20130105.100000 0.250 HR 20130201.100000
READINP CURRENT +1
'/proj_coastal/Z_Mitch_Thesis/SWAN/hydros/OSWALD_2D_010_currents_gri
d.txt' 1 0 FREE

$
BOUN NEST '/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_REG_nest.out'
$
GEN3
FRICTION COLLINS 0.025
$
```

```
PROP BSBT
NUMERIC ACCUR 0.02 0.02 0.02 98.0 NONST 1 0.1 DIRIMPL 0.5 4


$ Nesting file (boundary conditions for nested model) North Moreton
Bay
NGRID 'D001' 153.128 -27.1196 0. 0.40 0.349
NESTOUT 'D001'
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D001_nest.out' OUTPUT
20130105.010000 1 HR

$ Nesting file (boundary conditions for nested model) Stad to
Moreton
$NGRID 'D002' 153.36 -27.4654 0. 0.2 0.18
$NESTOUT 'D002'
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D002_nest.out' OUTPUT
20130105.010000 1 HR

$ netCDF OUTPUT
BLOCK 'COMPGRID' NOHEADER
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_RWQM_006A_001.nc' &
LAY-OUT 3 HSIGN TPS DIR PDIR DEPTH FORCE UBOT TMBOT WIND OUTPUT
20130105.010000 1 HR

$ Points OUTPUT
POINTS 'BRI'  153.632 -27.487
POINTS 'MOO'  153.181 -26.566
TABLE 'BRI' HEADER
'..\output\points\MORT_RWQM_006A_001_BRI_BUOY.out' &
HSIGN TMM10 TPS DIR PDIR DSPR DEPTH OUTPUT 20130105.010000 1 HR
TABLE 'MOO' HEADER
'..\output\points\MORT_RWQM_006A_001_MOO_BUOY.out' &
HSIGN TMM10 TPS DIR PDIR DSPR DEPTH OUTPUT 20130105.010000 1 HR

$ Simulation period
INITIAL DEFAULT
COMPUTE NONSTATIONARY 20130105.010000 0.5 HR 20130201.010000

STOP
```

```
PROJECT 'B17436' '001'
'Nest D Moreton North Swan Model'
'Swell propagation simulation 001'
$
SET 0.00 90.0 0.05 200 2
MODE NONSTATIONARY TWODIMENSIONAL
COORDINATES SPHERICAL
$
CGRID REGULAR 153.128 -27.1196 0. 0.40 0.349 400 349 CIRCLE 24 0.05
1.00 24
$
INPGRID BOTTOM REGULAR 153.128 -27.1196 0. 400 349 0.001 0.001
EXCEPTION -5.00
READINP BOTTOM +1 '..\geo\swan_d_001_refdat.out' 5 0 FORMAT
'((20f10.4))'
$
INPGRID WIND REGULAR 145.0 -32.0 0 200 170 0.1 0.1 NONSTATIONARY
20130102.100000 10 MIN 20130201.100000
READINP WIND +1 '/proj_coastal/Z_Mitch_Thesis/SWAN/wind/Oswald.txt'
3 0 FREE

$
INPGRID WLEV REGULAR 153.128 -27.1196 0 400 349 0.0010 0.0010 &
NONSTATIONARY 20130105.100000 0.250 HR 20130201.100000
READINP WLEV +1
'/proj_coastal/Z_Mitch_Thesis/SWAN/hydros/waterlevels_grid_d001.txt'
1 0 FREE

$
INPGRID CURRENT REGULAR 153.128 -27.1196 0 400 349 0.0010 0.0010 &
NONSTATIONARY 20130105.100000 0.250 HR 20130201.100000
READINP CURRENT +1
'/proj_coastal/Z_Mitch_Thesis/SWAN/hydros/currents_grid_d001.txt' 1
0 FREE

$
BOUN NEST '/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D001_nest.out'
$
GEN3
FRICTION COLLINS 0.025
$
PROP BSBT
NUMERIC ACCUR 0.02 0.02 0.02 98.0 NONST 1 0.1 DIRIMPL 0.5 4
```

```
$ Nesting file (boundary conditions for nested model) North Moreton
Bay
NGRID 'E001' 153.136 -26.8640 -50. 0.3125 0.125
NESTOUT 'E001'
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_E001_nest.out' OUTPUT
20130105.010000 1 HR


$ netCDF OUTPUT
BLOCK 'COMPGRID' NOHEADER
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D001_006A_001.nc' &
LAY-OUT 3 HSIGN TPS DIR PDIR DEPTH FORCE UBOT TMBOT WIND OUTPUT
20130105.010000 1 HR


$ Simulation period
INITIAL DEFAULT
COMPUTE NONSTATIONARY 20130105.010000 0.5 HR 20130201.010000

STOP
```

```
PROJECT 'B17436' '001'
'Nest D Moreton North Swan Model'
'Swell propagation simulation 001'
$
SET 0.00 90.0 0.05 200 2
MODE NONSTATIONARY TWODIMENSIONAL
COORDINATES SPHERICAL
$
CGRID REGULAR 153.36 -27.4654 0. 0.2 0.18 200 180 CIRCLE 24 0.05
1.00 24
$
INPGRID BOTTOM REGULAR 153.36 -27.4654 0. 200 180 0.001 0.001
EXCEPTION -5.00
READINP BOTTOM +1 '..\geo\swan_d_002_refdat.out' 5 0 FORMAT
'((20f10.4))'
$
INPGRID WIND REGULAR 145.0 -32.0 0 200 170 0.1 0.1 NONSTATIONARY
20130102.100000 10 MIN 20130201.100000
READINP WIND +1 '/proj_coastal/Z_Mitch_Thesis/SWAN/wind/Oswald.txt'
3 0 FREE

$
INPGRID WLEV REGULAR 153.3600000 -27.4654000 0 200 180 0.0010 0.0010
&
NONSTATIONARY 20130105.100000 0.250 HR 20130201.100000
READINP WLEV +1
'/proj_coastal/Z_Mitch_Thesis/SWAN/hydros/OSWALD_2D_010_waterlevels_
grid_d002.txt' 1 0 FREE

$
INPGRID CURRENT REGULAR 153.3600000 -27.4654000 0 200 180 0.0010
0.0010 &
NONSTATIONARY 20130105.100000 0.250 HR 20130201.100000
READINP CURRENT +1
'/proj_coastal/Z_Mitch_Thesis/SWAN/hydros/OSWALD_2D_010_currents_gri
d_d002.txt' 1 0 FREE

$
BOUN NEST '/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D002_nest.out'
$
GEN3
FRICTION COLLINS 0.025
$
```

```
PROP BSBT
NUMERIC ACCUR 0.02 0.02 0.02 98.0 NONST 1 0.1 DIRIMPL 0.5 4


$ netCDF OUTPUT
BLOCK 'COMPGRID' NOHEADER
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_D002_006A_001.nc' &
LAY-OUT 3 HSIGN TPS DIR PDIR DEPTH FORCE UBOT TMBOT WIND OUTPUT
20130105.010000 1 HR


$ Simulation period
INITIAL DEFAULT
COMPUTE NONSTATIONARY 20130105.010000 0.5 HR 20130201.010000

STOP
```

```
PROJECT 'B17436' '001'
'Nest D Moreton North Swan Model'
'Swell propagation simulation 001'
$
SET 0.00 90.0 0.05 200 2
MODE NONSTATIONARY TWODIMENSIONAL
COORDINATES SPHERICAL
$
CGRID REGULAR 153.136 -26.8640 -50. 0.3125 0.125 1250 500 CIRCLE 24
0.05 1.00 24
$
INPGRID BOTTOM REGULAR 153.136 -26.8640 -50. 1250 500 0.00025
0.00025 EXCEPTION -5.00
READINP BOTTOM +1 '..\geo\swan_e_001_refdat.out' 5 0 FORMAT
'((20f10.4))'
$
INPGRID WIND REGULAR 145.0 -32.0 0 200 170 0.1 0.1 NONSTATIONARY
20130102.100000 10 MIN 20130201.100000
READINP WIND +1 '/proj_coastal/Z_Mitch_Thesis/SWAN/wind/Oswald.txt'
3 0 FREE

$
INPGRID WLEV REGULAR 153.1360000 -26.8640 -50 1250 500 0.00025
0.00025 &
NONSTATIONARY 20130105.100000 0.250 HR 20130201.100000
READINP WLEV +1
'/proj_coastal/Z_Mitch_Thesis/SWAN/hydros/waterlevels_grid_e001.txt'
1 0 FREE

$
INPGRID WLEV REGULAR 153.1360000 -26.8640 -50 1250 500 0.00025
0.00025 &
NONSTATIONARY 20130105.100000 0.250 HR 20130201.100000
READINP CURRENT +1
'/proj_coastal/Z_Mitch_Thesis/SWAN/hydros/currents_grid_e001.txt' 1
0 FREE

$
BOUN NEST '/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_E001_nest.out'
$
GEN3
FRICTION COLLINS 0.025
$
```

```
PROP BSBT
NUMERIC ACCUR 0.02 0.02 0.02 98.0 NONST 1 0.1 DIRIMPL 0.5 4

$ netCDF OUTPUT
BLOCK 'COMPGRID' NOHEADER
'/scratch2/Z_Mitch_Thesis/SWAN/output/MORT_E001_006A_001.nc' &
LAY-OUT 3 HSIGN TPS DIR PDIR DEPTH FORCE UBOT TMBOT WIND OUTPUT
20130105.010000 1 HR


$ Simulation period
INITIAL DEFAULT
COMPUTE NONSTATIONARY 20130105.010000 0.5 HR 20130201.010000

STOP
```

Appendix F Model Calibration Results

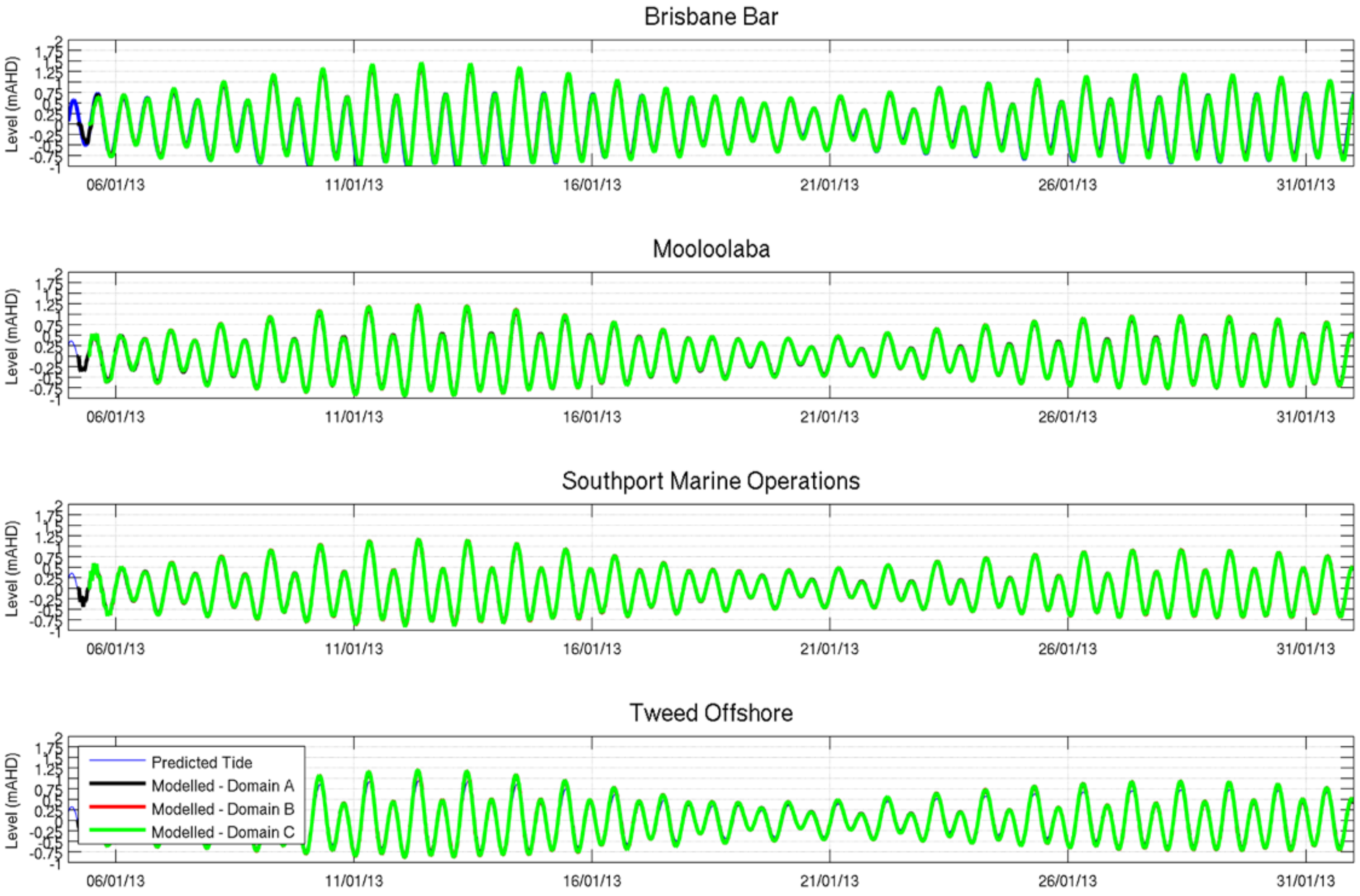

Figure F-1 Astronomical Tide Calibration 05/01/2013 – 01/02/2013

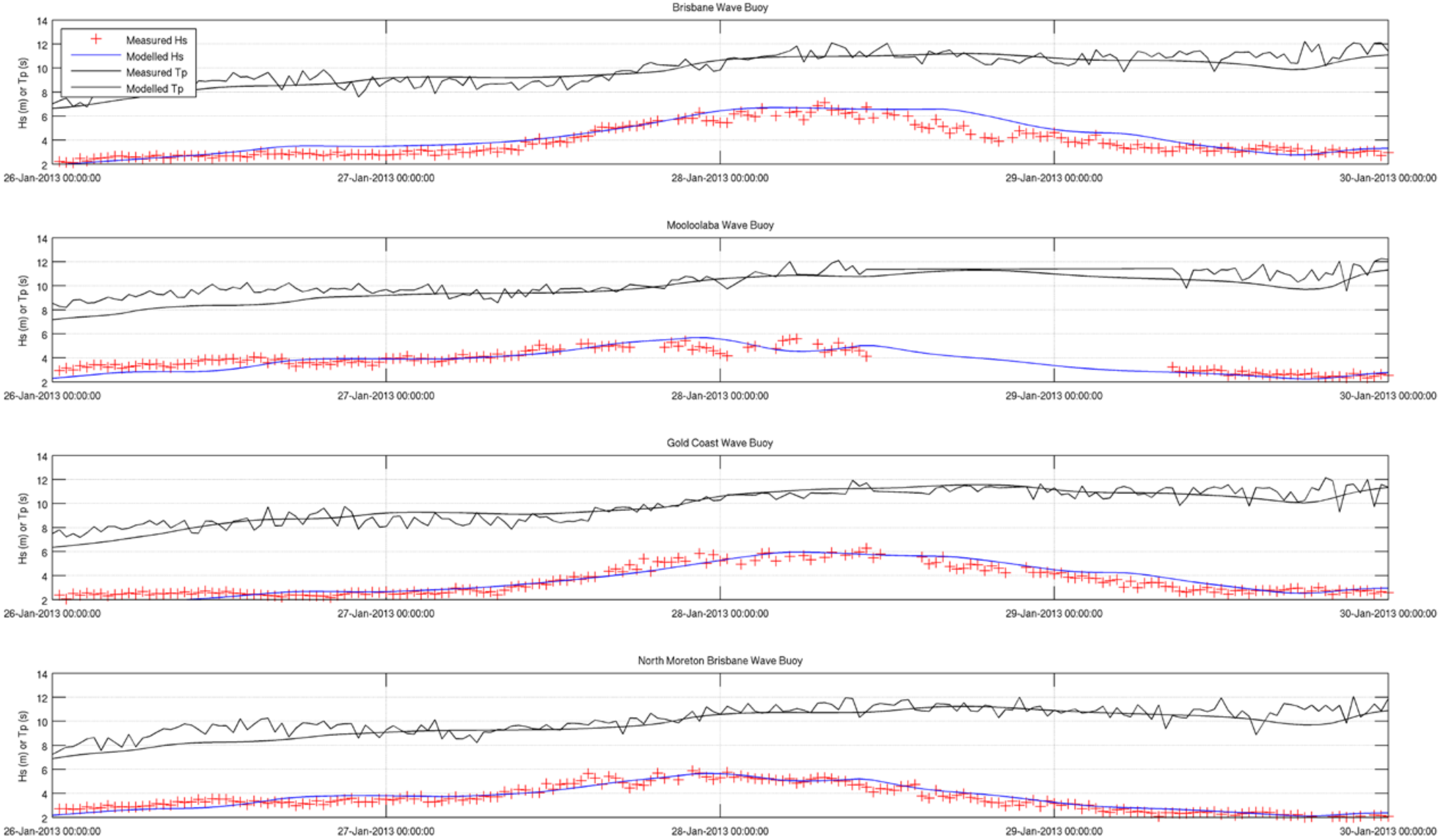

Figure F-2 Wave Calibration 26/01/2013-30/02/2013 AEST

Appendix G Experimental Total Water Level Results

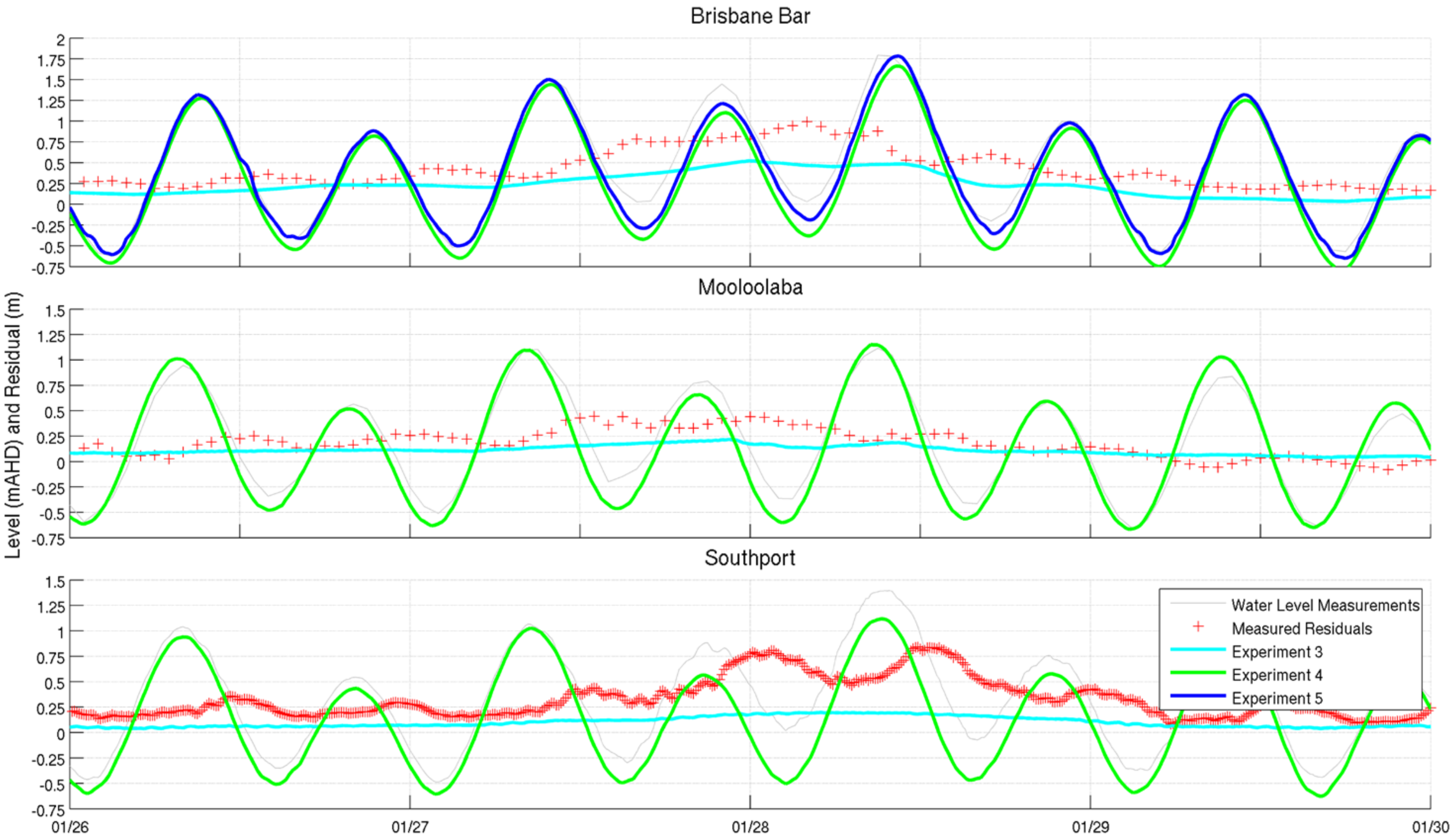

Figure G-1 Water Level Time-series 26/01/2013 – 01/03/2013 AEST Experiments 3, 4 and 5 at Brisbane Bar, Mooloolaba and Southport Tide Gauges

Experimental Total Water Level Results

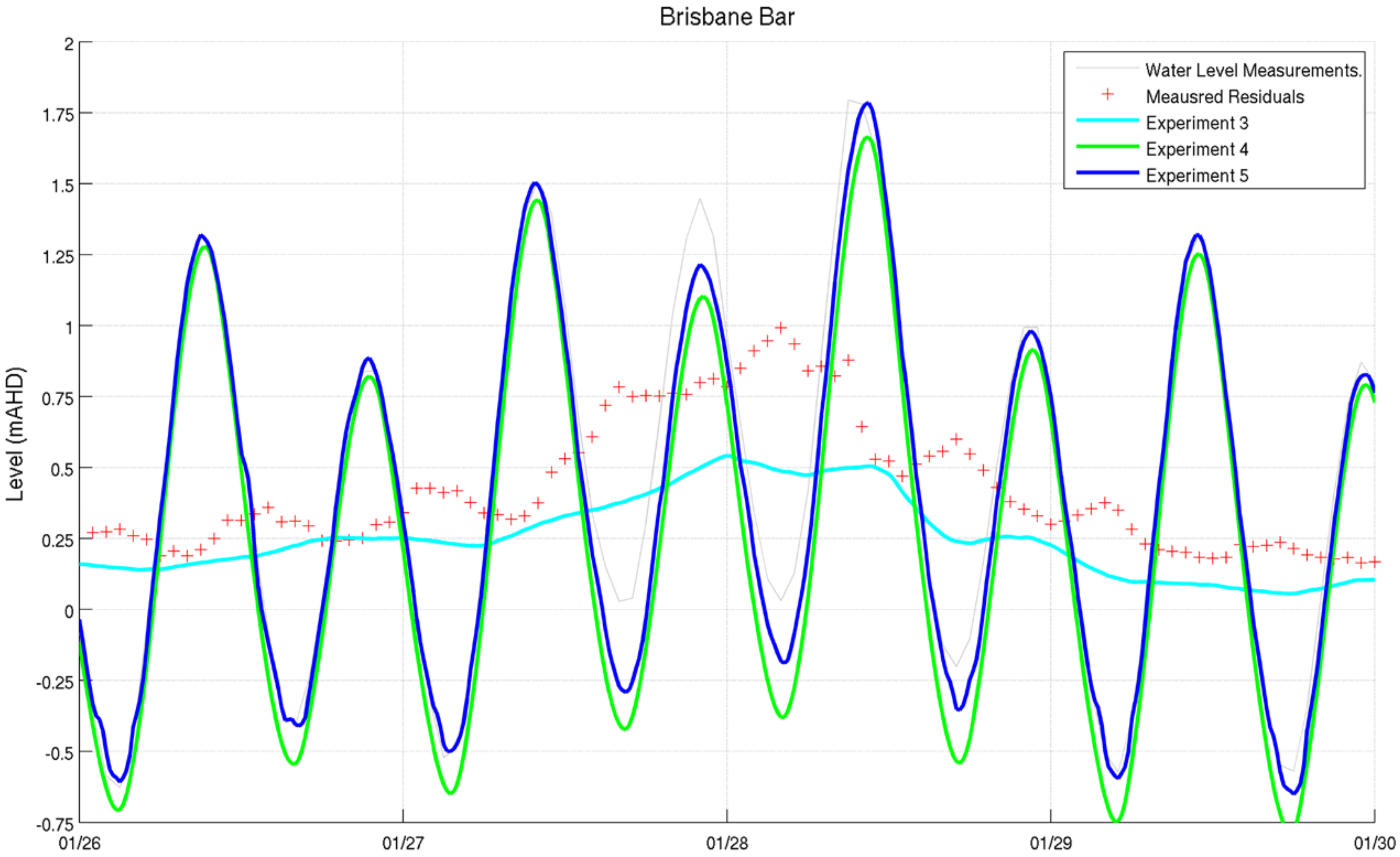

Figure G-2 Water Level Time-series 26/01/2013 – 01/03/2013 AEST Experiments 3, 4 and 5 at Brisbane Bar

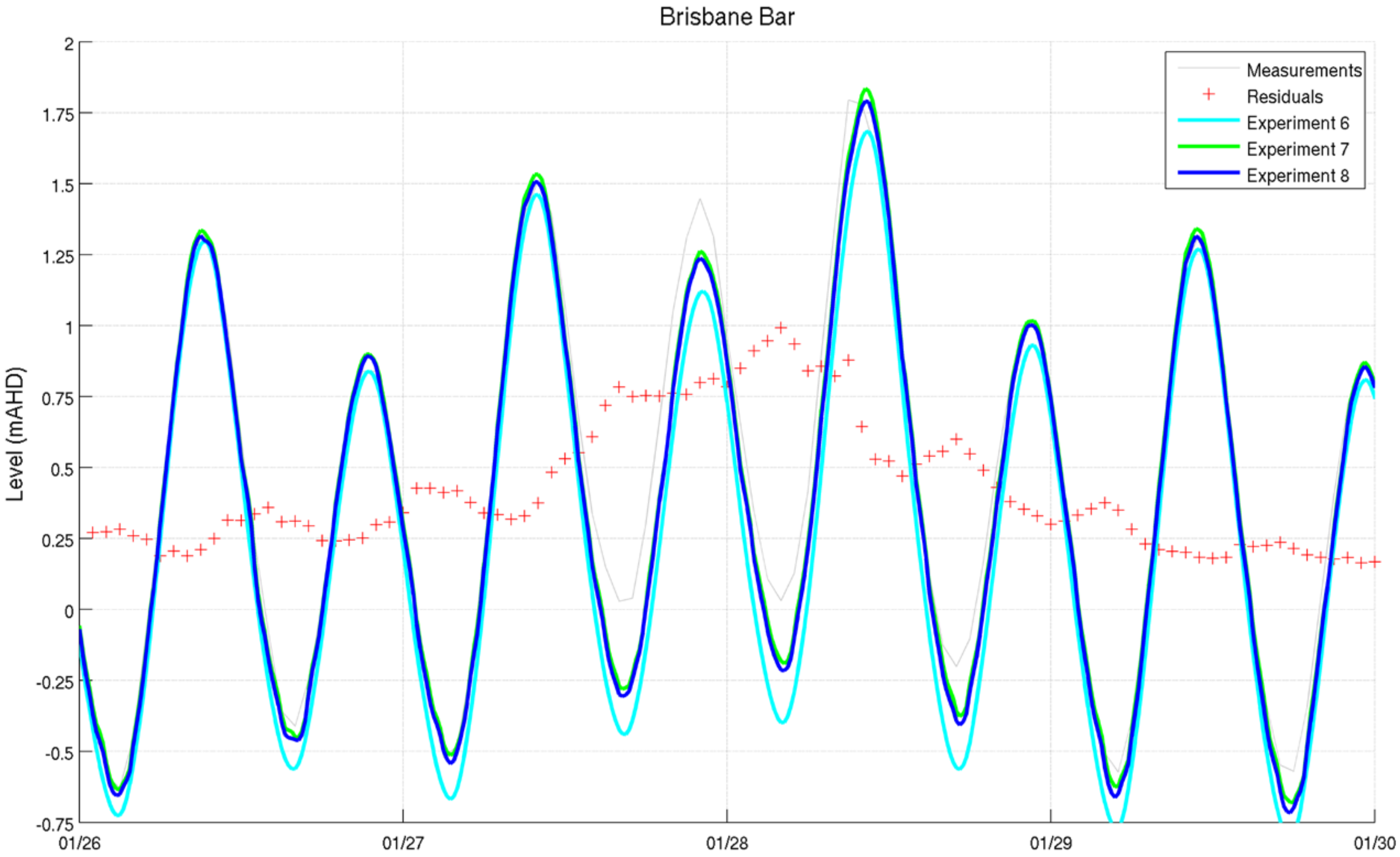

Figure G-3 Water Level Time-series 26/01/2013 – 01/03/2013 AEST Experiments 6, 7 and 8 at Brisbane Bar

Appendix H Experimental Modelled Residual Results

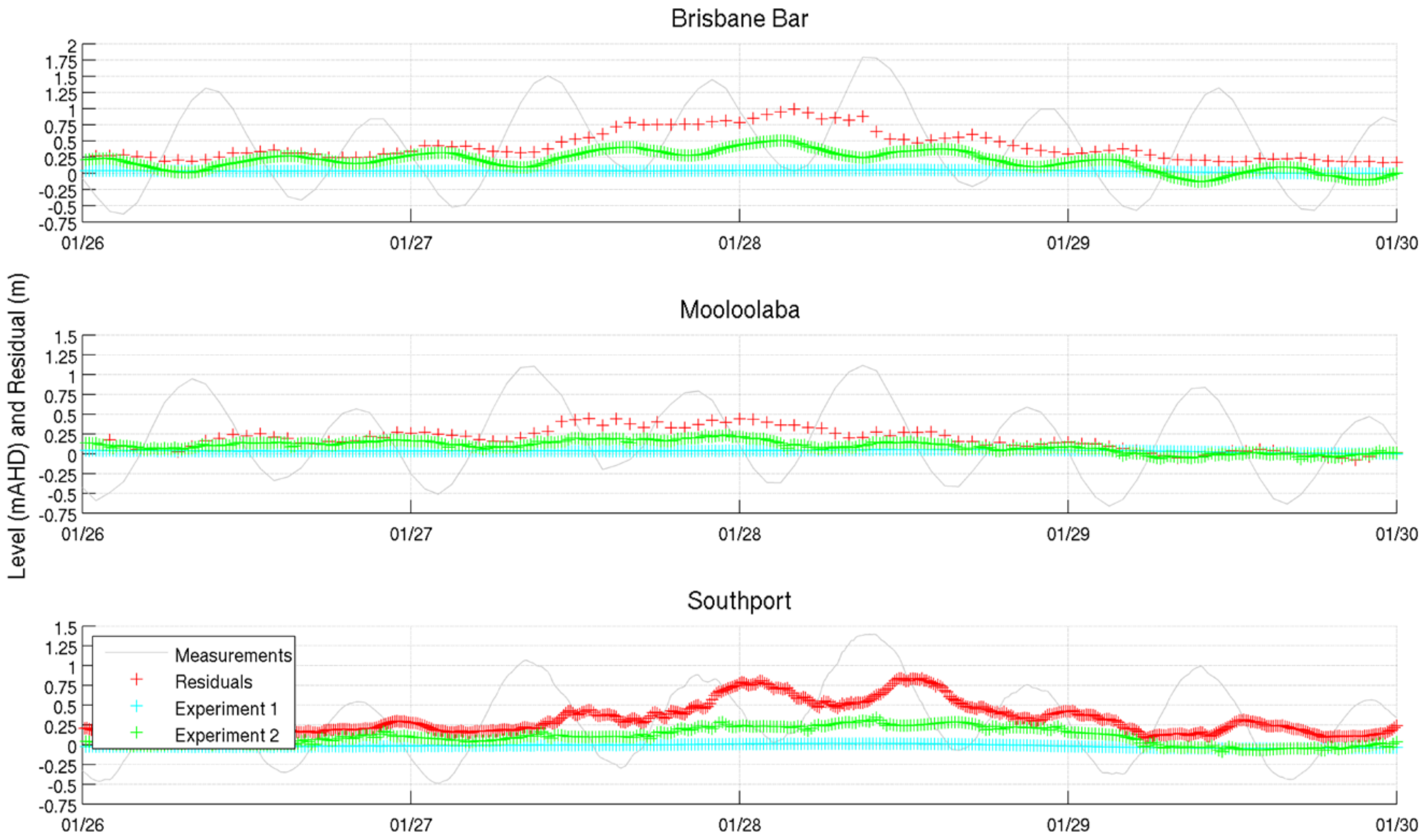

Figure H-1 HYCOM 3D Experiment Results

Experimental Modelled Residual Results

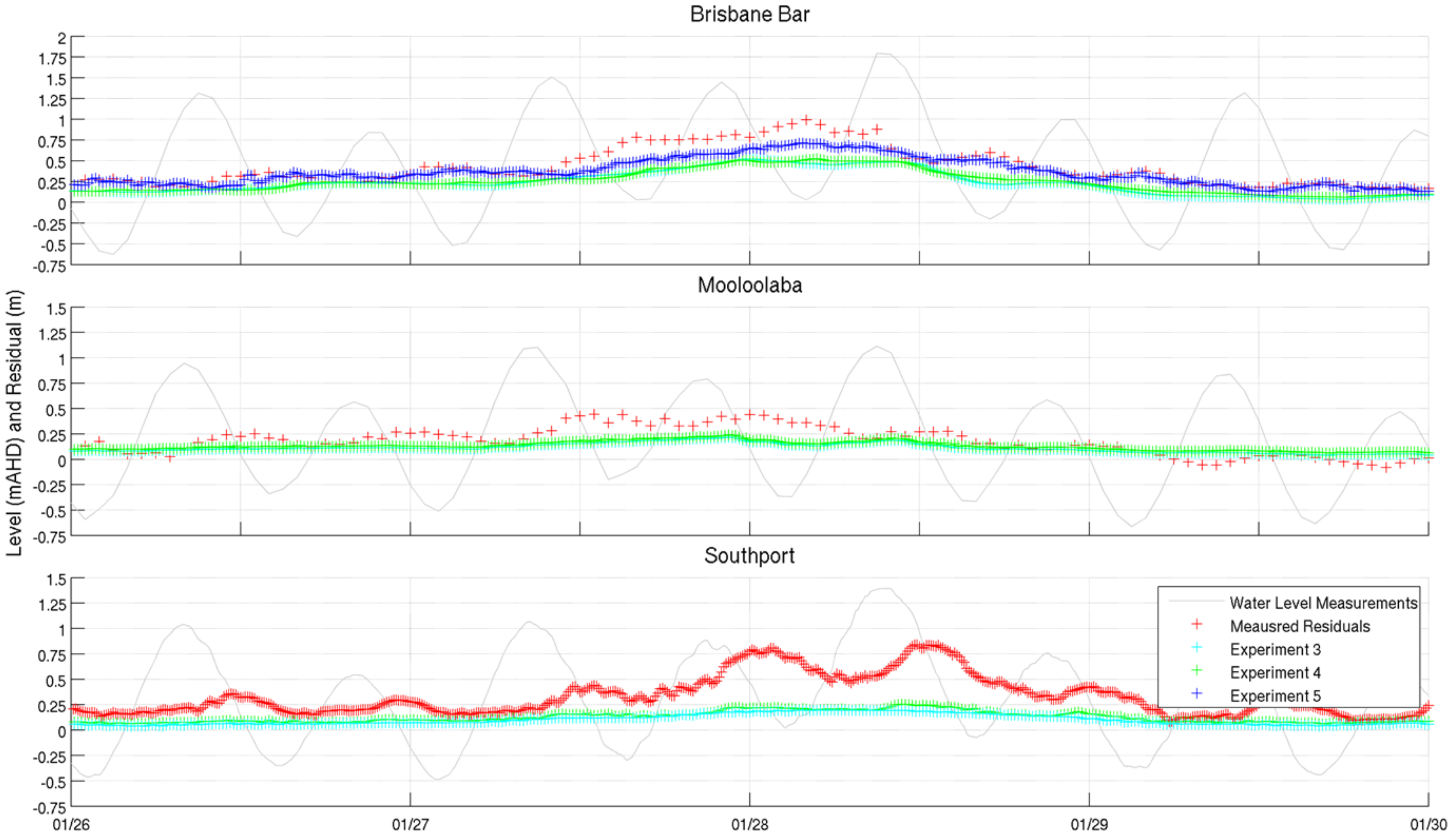

Figure H-2 Mesh B Experiments 3-5