Coastal Flood Study
Volume 1 of 2

Flood Study Report

Prepared by GHD for Brisbane City Council

April 2015

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Coastal Plan Implementation Study

Final Report

April 2015

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Cover Photo:

Breakfast Creek at Newstead during ex-TC Oswald, 28th January 2013 (B. Harper)

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Executive Summary

This study assesses the hazard posed by ocean storm tide to the Brisbane City Council (BCC) local government area, consistent with the aims of the Floodsmart Futures Strategy. It provides essential information needed to understand the extreme storm tide hazard. Both potential tropical cyclone and other large scale extra-tropical weather systems are considered in the context of present (nominally 2014) and projected future (2050 and 2100) climate and rising sea level conditions.

The study report focuses on the coastal margin from Hays Inlet south to Tingalpa Creek and also considers Moreton Island. It includes the Brisbane River upstream to Ipswich as well as its principal creek systems (Oxley, Norman, Breakfast and Bulimba) and the tidal limits of Kedron Brook, Nundah Creek, Cabbage Tree Creek, and parts of the South Pine River. Notwithstanding this focus, the analyses are necessarily based on numerical hydrodynamic and statistical models that encompass vast regions of the Coral Sea as this is the source of the extreme weather systems capable of generating extreme storm tide events in Moreton Bay.

The study has considered:

- The long-term historical record of tropical cyclones in the region, including preferred tracks, speeds, directions, sizes and intensities;
- The spatial and temporal characteristics of storm surge generated by tropical cyclones interacting with the complex coastal features;
- The broad-scale ocean response of extra-tropical and remote tropical cyclone influences as captured by the regional tide gauge records;
- Associated extreme waves and breaking wave setup and runup levels at the coastline;
- The astronomical tide, which varies considerably throughout the study region, and
- Fine-scale inundation modelling and mapping that includes the effects of local wind stress and time-varying ocean water levels.

The acceptable accuracy of the various models has been confirmed by comparison with available historical wind and storm surge data and also the published tide tables. The recent (Jan 2103) Ex-TC *Oswald* event that created a significant regional flood and storm tide impact has been used to demonstrate the predictive accuracy of the combined numerical modelling system, including the ability to reproduce the tidal characteristics. The statistical accuracy of the final water level **Annual Exceedance Probability (AEP)** estimates is underpinned by comparisons with long term wind data (which drives the storm tide response), historical storm statistics and empirical evidence taken directly from tide gauge records.

Climatologically, the Moreton Bay region lies towards the southern extremity of severe tropical cyclone influence and so is less susceptible to the types of potentially catastrophic storm tide inundation events that are possible in the northern regions of Queensland. Accordingly, extra-tropical and remote tropical cyclone impacts dominate the higher AEP (more common) water level events under present climate conditions up until about the 1% AEP. These then give way to (much rarer) tropical cyclone dominated events by the 0.5% AEP with an accompanying significant increase in the slope of the water level AEP curve.

The following table summarises the estimated long-term average **total storm tide** AEP levels (tide plus surge plus wave setup) at a selection of open coast sites and illustrates the likely variability of storm tide hazard across the study region:

Total Storm Tide Open Coast Levels – 2014 Climate Conditions

Location	Water Level in m AHD for varying % AEP events						
	20	5	2	1	0.2	0.05	0.01
Sandgate	1.64	1.74	1.84	1.91	2.35	2.73	3.18
Nudgee Beach	1.64	1.74	1.83	1.90	2.33	2.78	3.26
Brisbane Airport	1.67	1.77	1.86	1.93	2.29	2.78	3.23
Juno Point	1.67	1.77	1.86	1.93	2.30	2.77	3.27
Luggage Point	1.69	1.79	1.88	1.94	2.30	2.76	3.25
Fisherman Island	1.70	1.80	1.89	1.95	2.23	2.66	3.16
Wynnum	1.76	1.86	1.97	2.05	2.49	2.99	3.53
Lota	1.75	1.86	1.97	2.04	2.48	2.99	3.52
Bulwer	1.50	1.64	1.71	1.85	2.12	2.29	2.51
Cowan Cowan	1.47	1.58	1.64	1.68	1.69	1.71	1.93
Cape Moreton	1.60	2.10	2.40	2.60	2.99	3.26	3.41

It can be noted that the often adopted design water level of 2.5 m AHD for coastal infrastructure in the region represents approximately a 0.2% AEP event.

The storm tide hazard varies significantly across the Brisbane City region because:

- the open unpopulated eastern coast of Moreton Island is subject to relatively lower tide and surge influences owing to its adjacent deepwater environment, but is impacted by high levels of breaking wave setup and runup given its exposure to oceanic wave conditions;
- the inner sparsely-populated eastern coast of Moreton Island is significantly sheltered from oceanic wave impacts while experiencing a lower tide range and lower storm surge threat than Brisbane City;
- the highly-populated mainland coast of Brisbane City experiences amplification of both the ocean tide and any incoming storm surge in response to the relatively shallow waters of Moreton Bay and the narrowing bay planform, although it is sheltered from significant oceanic wave influences.

The influence of inter-decadal uncertainty on the above long-term average water level estimates has also been assessed and suggests that ENSO (El Niño Southern Oscillation) variability is of the order of ±3% above the 1% AEP event level and up to ±5% below that, when tropical cyclone events begin to dominate. Positive variability is associated with prolonged periods of La Niña, typically associated also with riverine flooding events, and negative variability is associated with prolonged El Niño periods, typically associated with drought conditions.

The specific storm tide hazard levels considered for fine scale inundation mapping of the metropolitan region are the 5%, 2%, 1%, 0.2% and 0.05% AEPs. This comprised a melding of the separate extra-tropical and tropical cyclone climate event surfaces to achieve the desired outcome of statistically robust mapped inundation extents. These inundation surfaces are not flat but rather reflect the dynamics of a possible storm tide episode that can locally amplify or attenuate water levels relative to the adjacent open coast levels. The interplay of storm tide levels with the Brisbane River is also represented and indicates (in the absence of a potential coincident flood) that water levels will vary in sometimes complex ways due to the dynamics. Estimates of breaking wave setup that can locally increase stillwater levels along the coastal margins are also included in the inundation mapping by an indicated zone of influence.

The inundation extents indicate that a 2% AEP event will begin to impact on the exposed nearshore Brighton-Sandgate properties with most of the low-lying areas affected by the 1% AEP event. Likewise, Wynnum foreshore property impact commences at the 1% event and the adjacent low-lying properties are mostly encompassed by the 0.2% event extending to Manly, Lota and Ransome. Other vulnerable areas include Nudgee Beach and parts of Shorncliffe and Deagon, which would be impacted by a 0.2% AEP event, as well as the Breakfast Creek precinct in Albion, parts of Norman Creek and industrial areas of Pinkenba. Boondall Entertainment Centre is impacted by the 0.05% AEP as well as the Hendra flats and the existing airport. Bulimba Creek impacts the Hemmant area by the 0.2% AEP and extends to low-lying parts of Tingalpa by the 0.05% AEP.

A detailed risk analysis that considers the vulnerability and exposure of properties (including their floor heights) and roads and other infrastructure, would be required to estimate the true impact of these hazard levels.

In future projected climates (2050 and 2100), whilst increases in tropical cyclone intensity are considered, the principal impact is estimated here to be due to an assumed mean global Sea Level Rise (SLR) of 0.3 m by 2050 and 0.8 m by 2100. As sea level rises, individual storm surge magnitude slightly reduces due to increasing depth. Additionally, the influence of breaking wave setup reduces at lower AEPs as low lying lands become increasingly inundated. Notwithstanding, slowly rising sea level alone represents a significant hazard and threat to the coastal margins over time if it continues to track near or above the current rates of increase. For example, by 2050, the current 1% AEP level is estimated to become approximately the 20% AEP level and by 2100 the 0.2% AEP, which as noted above has a very wide-reaching impact, will become approximately the 20% AEP event. These changes represent potential increases in frequency of storm tide impacts by a factor of 20 and 100 respectively.

While the full tracking of analysis uncertainty fell outside the present study scope, it is reasonable to expect that the estimated point AEP storm tide magnitude uncertainty is at least equal to that indicated by the inter-decadal ENSO variability analysis, which suggests a likely range of 3 to 5%. It should be noted that point-AEP estimates are merely "averages" in this context and are only realised over long time periods.

Notwithstanding this, the study has highlighted areas that would benefit from further detailed study if greater reliance is to be placed on estimates of higher AEP events, such as:

I. The influence of baroclinic processes;

II. The complexities of up-river storm tide propagation

Also, considering that techniques and knowledge continually improve, the data available for calibration and verification increases in quality and quantity and projected climate change effects are issued each 4 years, it is recommended that the study outcomes be reviewed within 5 years.

Guidance has also been provided on the interpretation of storm tide AEPs. Such interpretation is especially important in considering the overall risk to population, property and infrastructure and the practical (efficacy and economics) of any long-term adaptation strategy and plan.

Finally, it is noted that several older studies of storm tide risk exist for the immediate Moreton Bay region, and that in some cases predictions will vary. Whilst the present study methodology is the most recent and up to date, it has been developed in light of the older studies and the outcomes compared with them where possible. The final results presented here are deemed reconcilable with those earlier studies after consideration of the available information. The reader is referred to GHD (2014) for further details of why various studies might produce disparate results.

Acknowledgments and Team

This study was prepared by GHD for Brisbane City Council. The authors wish to acknowledge the full team who have assisted in preparing this report, along with Brisbane City Council, and the peer reviewers. The table below lists each of the key contributors.

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1. Introduction

This study assesses the hazard posed by ocean storm tide to the Brisbane City Council (BCC) local government area. It provides the essential information needed to understand the extreme storm tide hazard. Both potential tropical cyclone and other large scale extra-tropical weather systems are considered in the context of present (nominally 2014) and projected future (2050 and 2100) climate and sea level conditions.

The project aims (BCC 2013) are to establish storm tide levels for a range of “design events” and to refine the default conditions for storm-tide currently required by the Queensland Coastal Plan (DEHP 2013a). It considers the wide variety of ocean forcing that is possible (tides, coastal topography, foreshore inundation, over-bank flows from tidal watercourses and future sea level rise) to provide a better understanding of tidal, storm surge and associated coastal flooding within Moreton Bay.

The study outputs are designed to support the BCC Floodsmart Futures Strategy that considers:

- Impact assessment for tide and sea level rise with regard to coastal inundation and erosion on both short and long term;
- Development assessment;
- Land use planning;
- Development of the new city plan;
- Coastal adaptation planning;
- Maintenance regimes;
- Creek flood modelling
- Flood awareness in the community.

To inform future preparation of a comprehensive long-term coastal adaptation plan.

1.1 Background

Extreme coastal weather events in the Moreton Bay region can be associated with Tropical Cyclones (TCs), Sub-Tropical Lows (STLs), East Coast Lows (ECLs) and other mid-latitude low pressure systems, any of which can exert an impact in terms of storm surge, damaging winds and waves. Of the above, TCs are the rarest but potentially the more devastating if making landfall because they can generate extreme storm surge and associated flooding events. For example, recent history shows that the 1974 flood event in the Brisbane River was associated with ex-TC *Wanda* and the 2013 flood event with ex-TC *Oswald*. Projected climate change impacts may increase regional mean sea levels by as much as 1 m by 2100, relative to 1990 levels (IPCC 2013). The non-TC events are hereafter generically referred to as “extra-tropical” or “ex-tropical”.

Under existing State Government legislation, Local Government Authorities are required to adopt a Defined Storm Tide Event (DSTE) level for planning purposes, which by default in South East Queensland is the HAT + 1.5 m (DEHP 2013a). This level (approximately 3 m AHD) would, as subsequently shown in this study, represent approximately the 0.05% AEP water level in some localities. The DSTE level can influence development and planning for many decades, notwithstanding the compounding effects of slowly rising sea level and potential for changes in storm climatology. Additionally, Depth × Velocity hazard is an important aspect of risk assessment and is an especially complex metric in a coastal environment, as is the subsequent need to assess erosion prone zones.

1.2 Previous Studies

There have been a number of studies into the storm tide hazard within Moreton Bay, with one of the earliest prompted by planning for the relocation of the Eagle Farm airport to its present site (BBW 1979) and also an assessment of tide gauge records by the Bureau of Meteorology (Gourlay 1981). The State Government Beach Protection Authority had by then supported initial research by James Cook University (e.g. Harper et al. 1977) and later undertook comprehensive storm tide statistics studies (e.g. Harper 1985) that provided basic design ocean water levels, which were subsequently adopted by many coastal Councils in Queensland. Unfortunately Moreton Bay was not specifically targeted at that time (the focus then being on the Gold Coast and its beach erosion issues) but the important role of extra-tropical impacts in the SE Queensland and Northern NSW regions was identified even at that early stage. While these early numerical and statistical modelling studies suffered from very low resolution and simplistic storm representations, their estimates of open ocean storm tide hazards have been mostly vindicated by the more recent studies (e.g. GHD 2012), thus reflecting the broadscale nature of these phenomena.

Following the EPA's next initiative (Harper 1999) a need for further research into storm tide issues was raised and the *Queensland Climate Change and Community Vulnerability to Tropical Cyclones* study (QCC) subsequently received State and Federal funding, producing the influential Stage 1 "*Blue Book*" methodology (Harper 2001a). At around the same time AGSO (2001) also helped raise awareness of coastal hazards in SE Queensland with Councils. The Stage 3 QCC study (Hardy et al. 2004) then later produced the first high quality (but TC-only) storm tide assessment of Moreton Bay that is applicable to Brisbane City. At around the same time JWP (2004) considered potential storm tide in nearby Hays Inlet for Pine Rivers Council.

The later SEQDMAG initiative (GHD-SEA 2007) was an attempt to extend the QCC study methodology to include the equally important extra-tropical storm tide hazards in the SE Queensland context. Extensively quoted by the present study brief, this 2007 report listed all of the regional storm tide hazard studies that were available at that time and provided a critique in terms of best practice approaches. The SEQDMAG recommendations were then formed into a work specification for the Moreton Bay Storm Tide Hazard Study, which was later undertaken by CLT (2009) separately for Moreton Bay Regional Council, Logan City and Redland Shire Council.

In addition, SEA (2007) undertook a reassessment of storm tide hazard as part of the Houghton Highway upgrade and GHD (2012) subsequently undertook the Gold Coast Storm Tide Study, which necessarily encompassed Moreton Bay in order to correctly represent the hydraulic connectivity with the Broadwater.

1.3 Definitions Used in this Report

The total seawater level experienced at a coastal, ocean or estuarine site during the passage of any severe large scale ocean storm will be made up of relative contributions from a number of different effects, as depicted in Figure 1-1. The combined or total water level is then termed the *storm tide*, which is an absolute vertical level, referenced in this report to either Mean Sea Level (MSL) or Australian Height Datum (AHD) where applicable[1].

[1] Small adjustments at specific estuarine sites from MSL to AHD have been based on the interpolation of published offsets available from Maritime Safety Queensland (MSQ 2014) and are only approximate.

1.3.1 Components of a Storm Tide

It is important to understand the different water level components that can comprise the total storm tide at a specific site. These effects can vary throughout any given region in both time and space and depending on the local physical conditions.

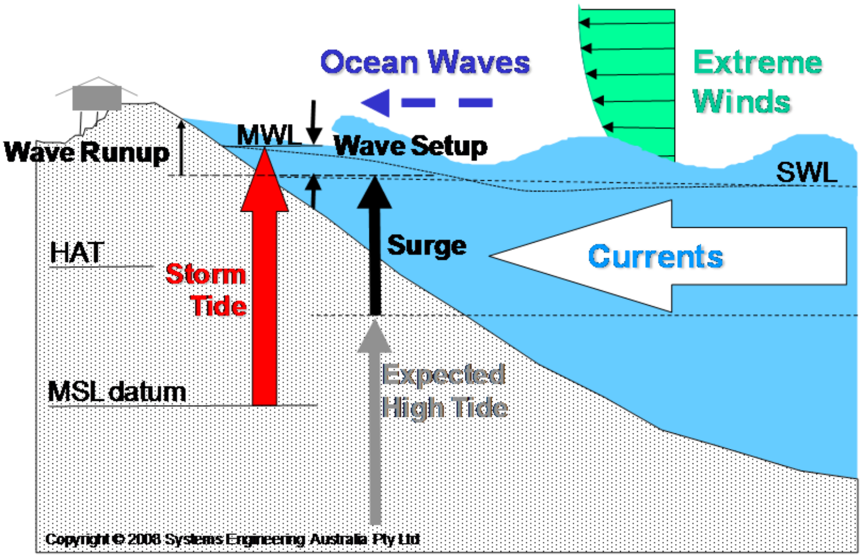

Figure 1-1 Water level components of an extreme storm tide

(a) The Astronomical Tide

This is the regular periodic variation in water levels due to the gravitational effects of the moon and sun, which can be predicted with generally very high accuracy at any point in time (past and present) if sufficient measurements are available. The highest expected tide level at any location is termed the Highest Astronomical Tide (HAT) and occurs once each 18.6 y period, although at some sites, high tide levels similar to HAT may occur several times per year and the level of HAT is often exceeded by the combination of a high tide and a non-astronomical weather-related event. The tidal plane variation within the region has been estimated based on published information (MSQ 2014) but storm-specific analyses and hydrodynamic modelling is also informed by direct analysis of historical tidal data.

(b) Storm Surge

This is the combined result of the severe atmospheric pressure gradients and wind shear stress of the storm acting on the underlying ocean. The storm surge is a long period “wave” capable of sustaining above-normal water levels over a number of hours or even days. The wave travels with and ahead of the storm and may be amplified as it progresses into shallow waters or is confined by coastal features. Typically the length of coastline that is severely affected by a TC storm surge is of order 100 km either side of the track although some lesser influences may extend many hundreds of kilometres. The magnitude of the surge is affected by several factors such as storm intensity, size, speed and angle of approach to the coast and the coastal bathymetry. Extra-tropical storm systems such as ECLs may have an extended (time and space) influence but normally at a magnitude lower than that from a severe TC.

(c) Breaking wave setup

Severe wind fields also create abnormally high sea conditions and extreme waves may propagate large distances from the centre of a storm as ocean swell. As the waves enter shallower waters they refract and steepen under the action of shoaling until their stored energy is dissipated by wave breaking either offshore or at a beach or reef. After breaking, a portion of the wave kinetic energy is converted into potential energy which, through the continuous action of many waves, is capable of sustaining shoreward water levels that are above the still-water level (SWL) further offshore. This increase in still-water level immediately after wave breaking occurs on a beach face is known as *breaking wave setup* and applies to most natural beaches and reefs. Wave setup is only associated with the rapid energy losses occurring during breaking and does not necessarily occur in river mouths, swampy lands or areas that suffer inundation to the extent that waves do not immediately break but rather are degraded more gradually through frictional or diffractive effects. Also, the presence of deep channels behind wave shoals is expected to limit the propagation of wave setup by providing return flows and the like. Accordingly the statistical water level modelling here assumes that vertical wave setup contributions cease when the tide plus surge level exceeds a nominal open coast “dune crest” elevation.

(d) Breaking wave runup

While much of the wave energy at the open coast prior to inundation occurring can be converted into wave setup, there remains some residual energy in the form of individual waves that will generate vertical *runup* and may cause localised intermittent impacts and erosion at elevations above that of the nominated storm tide level. These effects are best estimated with specific information about the land-sea interface, which may be changing in time as the storm tide increases in height. This includes the slope and porosity of the shoreline, vegetation and the incident wave height and period. In the present study the additional effects of wave runup on the open coast are estimated using empirical formulae.

(e) Still water level (SWL) and mean water level (MWL)

The storm surge, mainly caused by the interaction of the extreme wind-driven currents and the coastline, raises coastal water levels above the normally expected tide over a large area, producing the so-called still-water level or SWL. This is the highest water level at a point on the shoreline if all short period wind wave action is smoothed out.

Meanwhile, the extreme-wind generated ocean waves, combinations of swell and local seas, are driven before the strong winds and ride upon the SWL. As part of the process of wave breaking, a portion of their kinetic energy (momentum) can then be transferred into potential energy as vertical wave setup, yielding a higher localised mean water level (MWL). As previously mentioned, this effect is not always active (nor always effective) as it depends upon local beach and dune geometry.

(f) Overland inundation and wave penetration

When normally dry land becomes inundated during a severe storm tide episode, the sea begins to quickly flood inland as an intermittent “wave front”, driven by the initial momentum of the surge, products of wave setup and runup and the local surface wind stress. This flow then reacts to the local ground contours and the encountered hydraulic roughness due to either natural vegetation or housing and other infrastructure. It will continue inland until a dynamic balance is reached between the applied hydraulic gradients, wind stress and the land surface resistance or until it becomes constrained by elevation and creates ponding etc. As the storm surge abates or the tide reduces, a significant ebb flow can be created which is commonly responsible for much of the observed coastline scouring after such extreme inundation events.

(g) Specific effects not considered in this study

The present study is focussed on the estimation of storm tide elevation and the velocity of the encroaching storm tide flow over the land. However, as the new “stillwater” surface gradually reforms behind the propagating storm tide front, the exact extent to which individual unbroken or partially reformed ocean waves might further penetrate into a coastal region will be very site-specific. No over land wave modelling has been undertaken as part of this study.

There remain other related phenomena that are not addressed here but which can also have an effect on the local water level. These may include unsteady surf beat in specific high energy wave environments, and stormwater and/or river runoff. It is recommended that suitably qualified practitioners consider these effects on a case by case basis when designing specifically exposed facilities.

1.3.2 Statistical Concepts

The present study reports its findings in terms of the *Annual Exceedance Probability* (AEP) of storm tide levels. It is important to understand that the AEP is simply the expected average annual probability of equalling or exceeding a specified event level. However, the 1% AEP and 0.1% AEP event could both occur in the same year or one might occur twice in the same year, etc. Appendix **A** provides more explicit advice on the choice of AEP design levels in the context of encounter probability, which is a concept better suited for decision making leading to good planning.

1.4 Study Area and Modelling Domains

Figure 1-2 shows the study area along with the locations of water level and wave data of relevance to the analyses. While Moreton Bay is the focus of the investigation, the extent of the numerical modelling domain shown is necessarily significantly larger. GHD's model comprises approximately 2.27 million km^2 of the Coral Sea offshore from the Queensland Coast with its eastern boundary reaching New Caledonia or approximately 164ºE. Along the east coast, the modelling domain extends from 16ºS to 31ºS. The hydrodynamic modelling domains must be sufficiently large to encompass the extent of the applied ocean wind forcing and assimilate the global tidal forcing but also sufficiently fine-scale within Moreton Bay to resolve numerous banks and significant channels that exist. Even finer resolution is required to estimate the extent of overland flooding in association with the numerous coastal creeks. For this reason a series of complementary models have been developed.

1.5 Scope and Limitations

This document (the "Report"):

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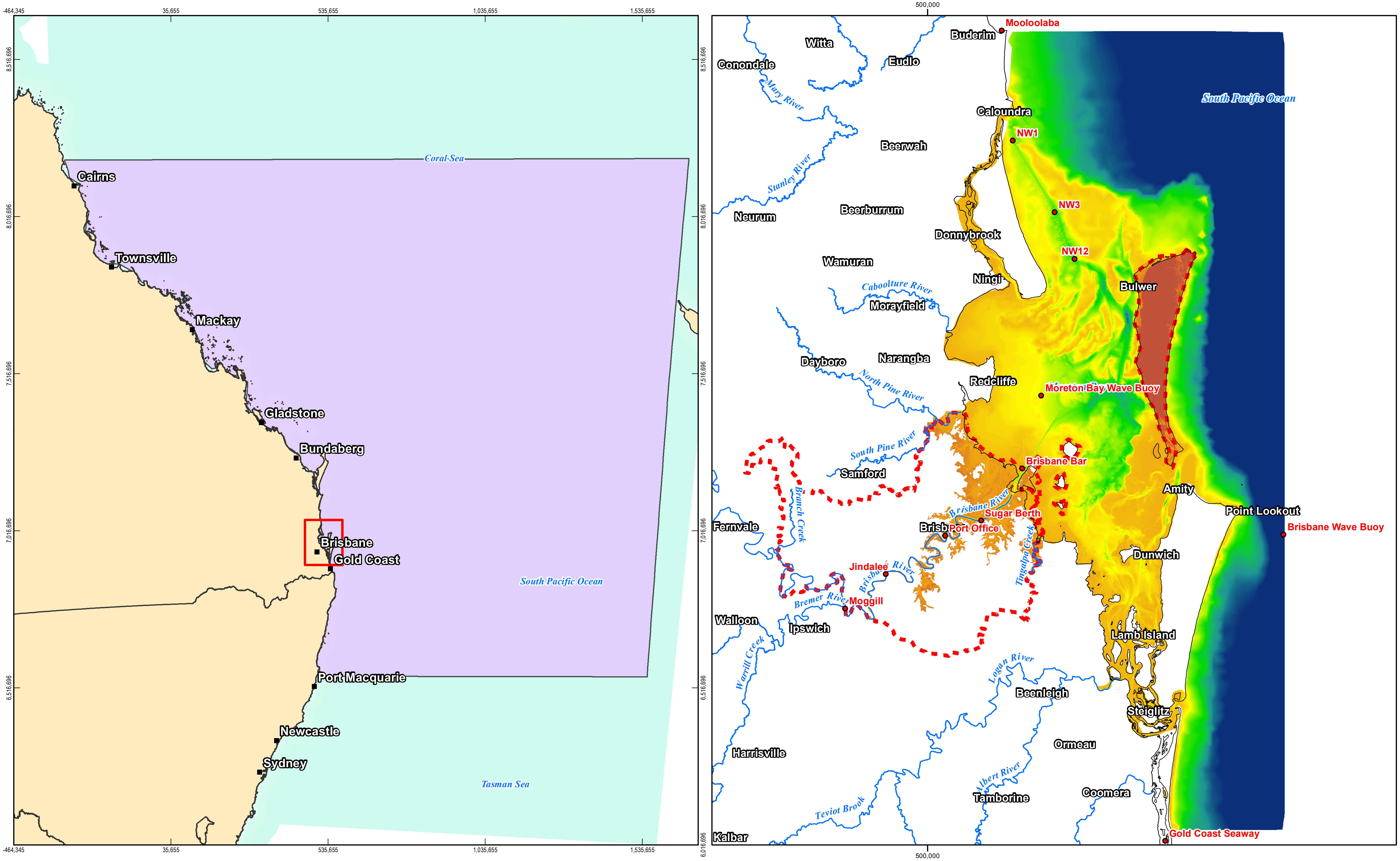

Paper Size A3

0 250 500

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 56

N

LEGEND

- Data Sites
- Watercourses
- Study Area
- RHM

LHM Extent

Bathymetry (m AHD)
High : 15
Low : -50

Brisbane City Council - City Projects Office
Brisbane City Coastal Planning Implementation Study

Job Number 41-27298
Revision A
Date 26 Sep 2014

Study Area

Figure 1.2

G:\41\27298\GIS\Maps\Deliverables\41_27298_001_revB.mxd

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

Data source: GHD: Model Extent (2014). DNRM: Locality, Mainlands, Watercourses (2014).

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2. Methodology Overview

This chapter outlines the study methodology, which is designed to capture the specific components of storm tide hazard in the region. Figure 2-1 provides an overall conceptual view of the methodology, the first part of which is based on the availability of data to describe the coastal and ocean geography, the historical TC and Extra-Tropical threat to the region and tide data for calibration for defining the regional astronomical tide characteristics. Data on regional winds is also used for model validation and Council-supplied land elevation and creek and river cross sections are used for defining the potential storm tide inundation areas.

2.1 The Geographical Setting

The Moreton Bay region lies towards the southern extremity of severe TC influence and so is less susceptible to the types of potentially catastrophic storm tide inundation events that are possible in the northern regions of Queensland, especially the Gulf of Carpentaria (e.g. Harper 2001a). Furthermore, the immediately adjacent oceanic region (Sunshine Coast to Gold Coast) is protected against significant wind-setup response by the presence of a narrow continental shelf with deep water relatively close to the coast. This same region is however greatly exposed to extreme waves emanating from a vast area of the Coral Sea and the breaking wave setup (and runup) effects on the exposed ocean coast are considerably greater in this area than those, say, behind the protection of the Great Barrier Reef further north.

Owing to the protection offered by Moreton Island and North Stradbroke Island, Moreton Bay itself is well protected from oceanic wave conditions and that, combined with the narrow continental shelf offshore, acts to attenuate storm tide influences that might otherwise propagate into the Bay from the open ocean. However Moreton Bay itself is relatively shallow (mostly < 10 m) and, depending on the wind direction and intensity, is capable of generating a localised storm surge response within and along its extensive low-lying coastal margins. The Bay also amplifies the astronomical tide and storm surge due to its narrowing planform, notwithstanding that the southern Bay is connected to the Broadwater and the Gold Coast Seaway. When water levels exceed local ground elevations, typically in association with the astronomical tide, the storm tide will propagate inland, driven by products of long-wave momentum and local surface wind stress.

Although TCs represent the more dangerous threat to life, it is well known that lesser-energetic but more frequent large-scale storm events can still have significant and damaging impacts. For example, sub-tropical cyclones (e.g. Ex-TC *Wanda* of 1974, TC *Roger* of 1993 and Ex-TC *Oswald* of 2013) can generate a modest storm surge in the Bay of the order 0.5 to 1 m, often with accompanying heavy rain and subsequent riverine flooding. A similar event in 1934 created the highest known storm surge in Moreton Bay of 1.2 m. Appendix D summarises the most significant known historical events. Continentally-linked East Coast Lows are also a specific feature of this area, producing persistent coastally-trapped wind fields that can also generate large waves and small storm surges. There are also influences from strong SE wind events generated by Tasman Sea high pressure systems that can create coastally-trapped long-waves and associated high seas. These extra-tropical systems typically produce slightly elevated ocean water levels over periods of many days and, although limited in magnitude, can dominate high AEP water level statistics because of their likely interaction with several tidal cycles.

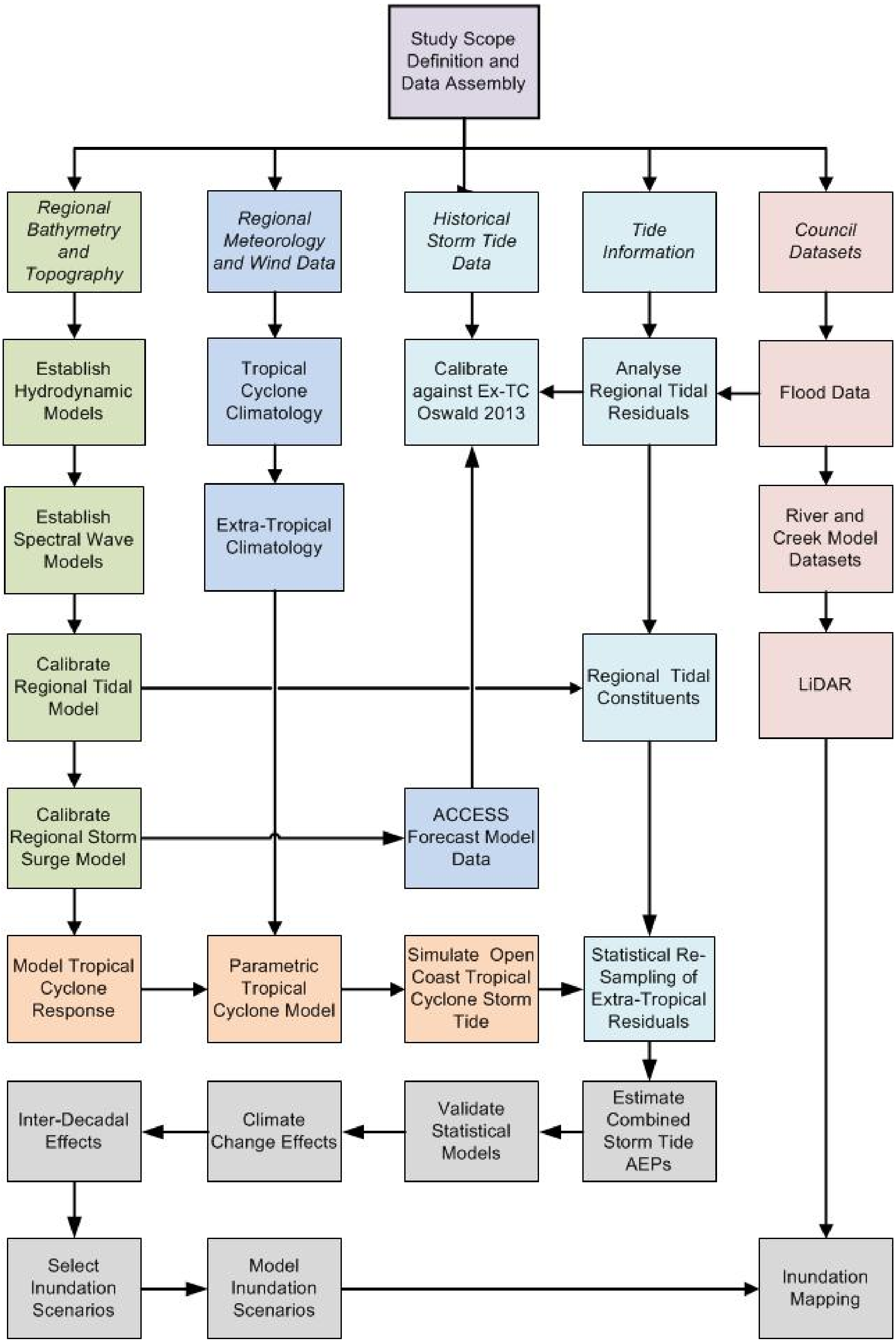


Figure 2-1 Overview of the Storm Tide Hazard Methodology

2.2 Numerical Model Development

A numerical hydrodynamic model is used to estimate the strength of the wind driven currents and resulting storm surge from the applied storm forcing, while a spectral wave model is used to estimate wave heights and periods, which contribute the breaking wave set-up water level component and wave runup. The models are constructed based on regional bathymetry data, comprising flexible mesh numerical grids to resolve the near-shore islands, capes, channels and bays. Details are given in Chapter 4.

The models have then been calibrated against local tidal data to prove the hydrodynamic accuracy of their regional representation and verified against the measured wind, surge and wave data available from the Ex-TC *Oswald* event of Jan 2013. Details of this process are given in Chapter 5.

2.3 Tropical Cyclone Storm Tide Hazard

Extreme storm tide levels caused by TCs cannot be estimated solely on the basis of historically measured water levels (Harper 2001a). This is because the available record of TCs affecting any single location on the coast is quite short, the resulting storm surge response is often complex and very site specific, and the final storm tide is dependent on the relative phasing with the astronomical tide. Hence, measured storm tide data alone is typically inadequate for extrapolation to very low AEP.

The methodology applied here closely follows the recommendations set out in the Government-sponsored Queensland Climate Change (QCC) investigations (e.g. Harper 2001, 2004). In particular, the so-called “hybrid” modelling philosophy has been implemented, whereby a range of numerical, analytical and statistical models are constructed to provide a basis for the estimation of storm tide risks and the extrapolation of their impacts to very low AEPs. A climatological assessment of the threat from TCs in the region is undertaken to obtain statistical descriptions that can be extrapolated to AEPs of interest. This includes statistics describing the expected variation in storm frequency, intensity, path and size within the region. Chapter 3 discusses the detailed climate analyses that have been required and Chapter 4 discusses the individual analytical and statistical models. Chapter 5 presents the calibration and verification of the various models.

2.4 Extra-Tropical and Remote Tropical Cyclone Storm Tide Hazard

The methodology so far described is targeted towards close-approach high energy TC events that might be expected to dominate the storm tide hazard well below the rarer 1% AEP. For more common AEP events (e.g. 5%, 10%) there are many more frequent yet possibly locally benign weather events that, while difficult to parameterise within a stochastic model, will influence the predicted levels and produce water levels that, for example, will likely exceed the Highest Astronomical Tide (HAT) level at AEPs above 5%. Indeed, many of these less energetic long-wave events are triggered by very complex baroclinic[2] ocean interactions of large scale forcing and/or large propagation distances, such that it would prove very difficult or impossible to numerically model them in any accurate or comprehensive manner. Likewise, remote TCs produce local coastal impacts that are similar to extra-tropical storms.

Accordingly, the present study methodology addresses the effect of these important extra-tropical and remote-tropical disturbances based on an analysis of measured tidal residuals. A robust empirical approach has been adopted that stochastically re-samples tidal residuals in order to

[2] This refers to the dynamic effects of stratification and mixing of ocean waters having different temperature and density, typically interacting with steep continental shelf bathymetry.

obtain the potential exceedance of water level variations caused by extra-tropical events down to approximately 0.1% AEP. Brisbane and Mooloolaba tidal records are used in concert to form the basis of this analysis (refer Chapter 4).

2.5 Combined Climate Storm Tide Hazards

The resulting statistics of the extra-tropical (and remote-tropical) events are then probabilistically combined with the results obtained from the close approach TC modelling to produce a single AEP estimate of all open coast storm tide levels. This assumes that the two storm event sets are fully independent of each other, which is achieved by the design of the analyses.

For example, if the analysis of each independent hazard shows that (say) a 1% AEP level is 2 m AHD, then combining the hazard probability would result in the 2 m AHD level becoming approximately the 2% AEP level.

Chapter 6 presents the results of the statistical modelling of storm tide for “present” climate conditions along the open coast.

2.6 Climate Variability and Change

The possible effects of long-term enhanced-greenhouse induced climate change and natural inter-decadal climate variability are considered in a subsequent step. Firstly, projected future climate scenarios impacting sea level rise, TC intensity and frequency are simulated and those results compared with the estimates for “present climate”. Secondly, the potential impacts of ENSO-induced short-term climate variability are considered (refer Chapter 7).

2.7 Coastal Inundation Modelling and Mapping

The preceding methods deliver robust estimates of storm tide water level statistics down to very low AEP that are applicable to open coast locations. It remains to transfer these impacts inland for regions that are subject to inundation to provide appropriate risk mapping.

To achieve this, fine scale inundation modelling is undertaken for a selection of both TC and Extra-Tropical climate hazards for the range of required AEPs, thus providing dynamically-forced flooding events that represent robust statistical surfaces for mapping. This also delivers Depth x Velocity estimates together with persistence of flooding.

Dynamic inundation mapping accounts for the fact that storm tide flooding events are not simply a horizontal projection of the open coast water levels inland (as often assumed in so-called “bathtub” simplistic mapping approaches). Rather, the combined effects of ocean momentum, surface wind stress over shallow inundated areas and the complex surface friction will allow modification and potential re-generation of the storm surge over land, interacting with the ground surface contours and creating favoured pathways. These analyses are described in Chapter 8.

2.8 Uncertainty

Storm tide events result from the occurrence of natural processes within a range of variability that can be estimated through a variety of techniques, each of which contain uncertainty in their estimates. It is important to recognise that uncertainty in such analyses results from:

1. The variability due to the random temporal and spatial fluctuations of natural (stochastic) processes – the *natural uncertainty*, and
2. The uncertainty with regard to data and measurements – the *data uncertainty*, and

3. The imperfect representation of natural processes by assumptions, analyses and models – the *model uncertainty*.

It is important that all types of uncertainty are addressed and ideally tracked in order to understand the overall reliability of the study outcomes.

In the present study the use of statistical simulation as the principal investigation tool has ensured that item (1) above is well represented as derived from the base data. In terms of item (2) the study is reliant on the many different sources of that data either publically available (Bureau of Meteorology, Geoscience Australia) or privately (e.g. BCC). Item (3) is addressed by a concerted effort in calibration and verification of the various statistical and numerical hydrodynamic models.

Notwithstanding these efforts it remains difficult to completely quantify the overall uncertainty of the study estimates of storm tide hazard. Throughout the report there are a number of insights provided into the likely variability both in AEP and hazard magnitude.

3. Regional Meteorology

This chapter discusses the regional atmospheric forcing that, in conjunction with the bathymetry, nearshore coastal geomorphology and astronomical tide forcing, is responsible for the storm tide hazard.

3.1 Tropical Cyclone Climatology

3.1.1 Tropical Cyclone Characteristics

The tropical cyclone (TC) is a large scale and potentially very intense tropical low pressure weather system that affects the Queensland region typically between November and April (Harper 2001a). In Australia, such systems are upgraded to *severe* tropical cyclone status (referred to as *hurricanes* or *typhoons* in some countries) when average, or sustained, surface wind speeds exceed 120 km h^{-1}. The accompanying shorter-period destructive wind gusts are often 30 to 50 per cent higher than the sustained winds, depending on the exposure. In the southern hemisphere, TC winds circulate clockwise around the centre, as seen in the spiral cloud patterns of the satellite image in Figure 3-1 for severe TC *Hamish* in 2009.

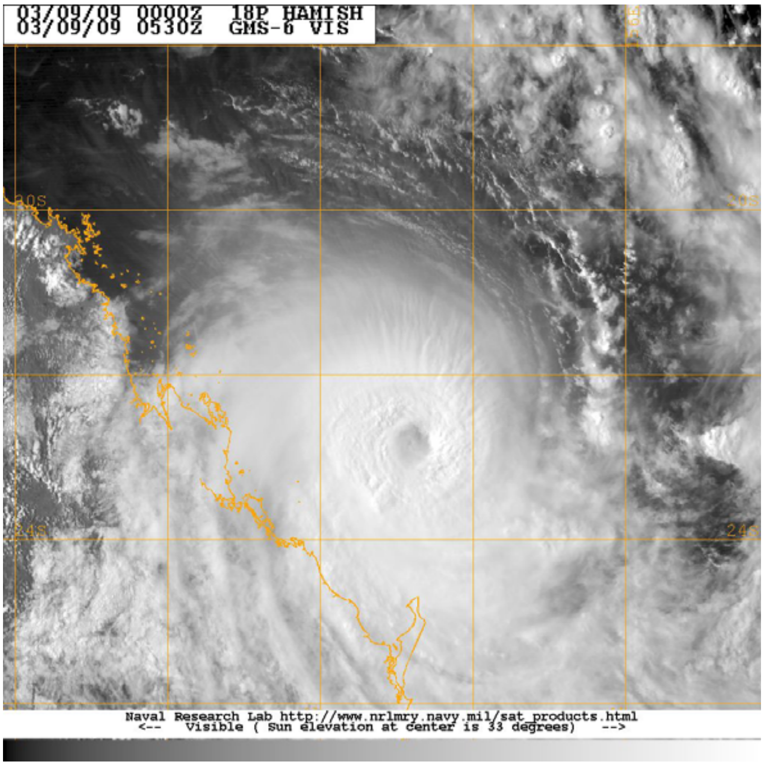


Figure 3-1 Severe TC *Hamish* at Category 4 intensity paralleling the Queensland coast offshore Fraser Island in March 2009. (US Navy processed image)

There are three components of a TC that combine to make up the total cyclone hazard - strong winds, intense rainfall and induced ocean effects, including extreme waves, currents, storm surge and resulting storm tide. The destructive force of cyclones is usually expressed in terms of the strongest wind gusts likely to be experienced. Maximum wind gust is related to the central pressure and structure of the system, whilst extreme waves and storm surge, are linked more closely to the combination of the *mean* surface winds, central pressure and regional bathymetry.

The Commonwealth Bureau of Meteorology (BoM) uses the five-category system shown in Table 3-1 for classifying TC intensity in Australia. “Severe” TC are those of Category 3 and above, approximately equivalent to “hurricane” and “typhoon” strength.

Table 3-1 Australian tropical cyclone category scale

Category	Maximum 3 s Wind Gust (km h-1)	Potential Damage
1	<125	minor
2	125-164	moderate
3	164-224	major
4	225-279	devastating
5	>280	extreme

The main structural features of a severe TC at the earth’s surface are the eye, the eye wall and the spiral rainbands. The eye is the area at the centre of the cyclone at which the surface atmospheric pressure is lowest. It is typically 20 to 50 km in diameter, skies are often clear and winds are light. The eye wall is an area of cumulonimbus clouds, which swirl around the eye. Tornado-like vortices of even more extreme winds may also occur associated with the eye wall and outer rain bands but are more likely at landfall. The rain bands spiral inwards towards the eye and can extend over 1000 km or more in diameter. The heaviest rainfall and the strongest winds, however, are usually associated with the eye wall.

For any given central pressure, the spatial size of individual TCs can vary enormously. Generally, smaller cyclones occur at lower latitudes and larger cyclones at higher latitudes but there are many exceptions. Large cyclones can have impacts far from their track, especially on waves and low levels of storm surge. For example, *David* crossed the coast near Yeppoon in 1976 and caused significant coastal impacts in south eastern Queensland; *Roger* in 1993 remained 300 km offshore of Sandy Cape but produced the highest recorded water levels in the Gold Coast Seaway in over 20 years and the highest recorded waves in over 30 years at the Brisbane waverider buoy offshore Point Lookout; *Justin* in 1997 offshore Cairns caused increased water levels along the entire east coast; *Yali* in 1998 passed 500 km east of Brisbane and caused increased water levels and beach erosion from the sunshine coast to Northern NSW.

Cyclonic winds circulate clockwise in the Southern Hemisphere and the wind field within a moving TC is generally asymmetric so that winds are typically stronger to the left of the direction of motion of the system (the “track”). This is because on the left-hand side the direction of storm movement and circulation tends to act together; on the right-hand side, they are opposed. During a coast crossing in the Southern Hemisphere, the cyclonic wind direction is onshore to the left of the eye (seen from the storm) and offshore to the right.

Given specifically favourable conditions, TCs can continue to intensify until they are efficiently utilising all of the available energy from the immediate atmospheric and oceanic sources. This maximum potential intensity (MPI) is a function of the climatology of regional sea surface temperature (SST) and atmospheric temperature and humidity profiles. When applying a thermodynamic MPI model for the Queensland coast (Holland 1997a, 1997b), indicative values for the MPI increase northwards from about 940 hPa near Brisbane to 880 hPa for regions north of Townsville. Thankfully, it is rare for any TC to reach its MPI because environmental conditions often act to limit intensities in the Queensland region. The present study however, makes allowance for this extreme condition.

3.1.2 Dataset Description

The study has considered all available records of TCs from official BoM records (National Climate Centre) as well as local Queensland Regional Office records in Brisbane. However, only those storms that entered within a 500 km radius of Cape Moreton have been included in the statistical analyses. The choice of a 500 km radius is based on capturing all events that would have been capable of directly affecting the Moreton Bay area within a 24 hour period and provides a sufficient sample of the statistical population to enable reasonably reliable estimates to be made of intensity, frequency of occurrence and track. The complete TC data set since the early 1900s shows a fluctuation in recorded occurrences of TCs that is due not just to the natural variability of these large scale storms, but also the often poor detection rate prior to the introduction of satellites in the late 1950's and early 1960's (Holland 1981). In order to ensure a stable and reliable statistical series for model extrapolation purposes, only data since 1959/60 onwards is used in the present study. This provides a total of 54 TC seasons up until 2012/2013, the latest year utilised.

The BoM TC data set consists of a series of estimated positions of the centre of each storm, together with the *estimated*[3] intensity described by the central pressure (hPa), at an interval of typically 6 hours. Little or no information about the size of the cyclone is normally available (except in recent years), so that the important radius to maximum winds is a parameter that has to be further estimated.

Appendix **B** provides a summary listing of all historical TCs considered in this study. It can be noted that ex-TC *Oswald* in Jan 2013 has been included in this list because of its very significant impact, even though it was not displaying TC features when in the region. This supports the fact that its effects have been excluded from the complementary extra-tropical climate analyses.

3.1.3 Analysis and Interpretation

A total of 50 TCs have occurred within the 54 season record and within the 500 km study region, averaging 0.92 storms per season but significantly weighted by the occurrence rate prior to the 1990s. The time history of the frequency of cyclone occurrence is shown in Figure 3-2, showing a fluctuation about a 5 year average value of between 0 to 3 storms per year. Some years indicate zero storms within the 500 km radius (1965/66, 1974/75, 1976/79, 1982/83, 1985/89, 1990/91, 1996/972004, 2005/08, 2009/12) while the maximum number during this time has been 4 storms in one season (1966/67, 1971/72, 1973/74 and 1975/76). Clustering of storm events in the past has resulted in significant coastal erosion episodes along the SE Queensland region.

The variability in TC occurrences over a 3 to 5 year span along the east coast of Queensland is known to be strongly associated with the so-called El Niño - Southern Oscillation (ENSO) phenomenon (e.g. Nicholls 1992, Basher and Zheng 2000). ENSO refers to a quasi-biennial oscillation of the sea surface temperatures (SST) and mixed-layer depths in the eastern tropical Pacific Ocean. During a so-called El Niño period, the SST is warmer than normal in the east and rainfall and TC activity in northern Australia tends to decrease. In the reverse situation, called La Niña, the SST in the eastern Pacific is cooler than normal and rainfall and TC activity increases along the east coast of Australia.

The Southern Oscillation Index[4] (SOI) is a measure of the strength of the ENSO episodes, derived from surface pressure data at Darwin and Tahiti. The SOI is also plotted on Figure 3-2, where it can be seen that a generally persistently negative SOI (El Niño) has been associated with a

[3] Fewer than 2% of all Australian tropical cyclone peak intensities are based on verified measurements of wind or pressure (Harper et al. 2008). The vast majority of intensity estimates are based on a satellite image analysis system developed in the mid-1970s (Velden et al. 2006) that has had limited validation in the Australian region.

[4] The SOI is simply 10 times the standard deviation from the mean of the Tahiti-Darwin MSL pressure difference.

decrease in TC occurrences over the past 30 years in the Moreton Bay region. Since 1959 though, the number of El Niño - La Niña cycles is approximately equal, although the strengths have varied (Pielke and Landsea 1999). This suggests that the long-term average frequency of occurrence of 0.92 storms per season for the statistical region could be reasonably reliable for the present epoch. However, it should be noted that ENSO fluctuations specifically alter the true likelihood of storm tide hazard in any particular year of exposure (refer Section 0). Some researchers (e.g. Power *et al.* 1999) suggested that the trends of the 1980s and 90s may have started reversing and that the western Pacific could enter a period of prolonged La Niña activity in the new millennia, but following years have seen only mild La Niña or near neutral conditions persisting. Even 2008/09, with a persistently high SOI, was not classed as a strong La Niña due to mixed SST signals. However 2010/11 established itself as one of the strongest La Niña events on record, ranking amongst the top 5 since 1900, and facilitating extensive and persistent flooding across much of Queensland, the January event that severely impacted Brisbane, and the occurrence of TC *Yasi* in Far North Queensland. This event is clearly seen in the very high SOI value for 2011 in Figure 3-2.

The corresponding time history of minimum storm central pressures is shown in Figure 3-3, illustrating the great variety possible in intensities. The lowest estimated TC central pressure in recent times within the 500 km radius is due to TC *Hamish* in 2009.

The tracks of TCs often appear random and chaotic but a more cohesive structure can be seen when the storms are grouped into what are believed to be common statistical populations that relate to areas of genesis and broad-scale movement. The present study assumes three basic track classes exist in this region, being *offshore moving*, *parallel to coast* and *onshore moving*. The 54 storm sample is split into these classes, with examples of typical storm tracks shown in Figure 3-4. The few over-land examples of the offshore class in this region are predominantly exiting decayed previously landfalling storms moving eastwards while the over-sea examples are relatively weak near-coast developing systems. The parallel class are concentrated about 200 to 500 km offshore but also contain examples of oblique coast-crossing events and some over-land storms.

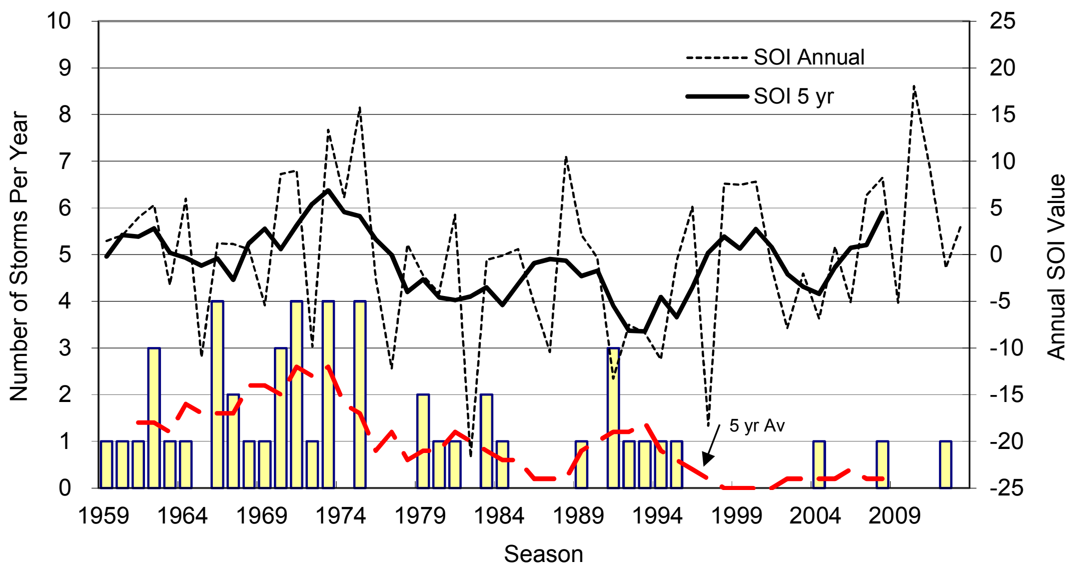


Figure 3-2 Time history of the frequency of TC occurrence within 500 km of Cape Moreton.

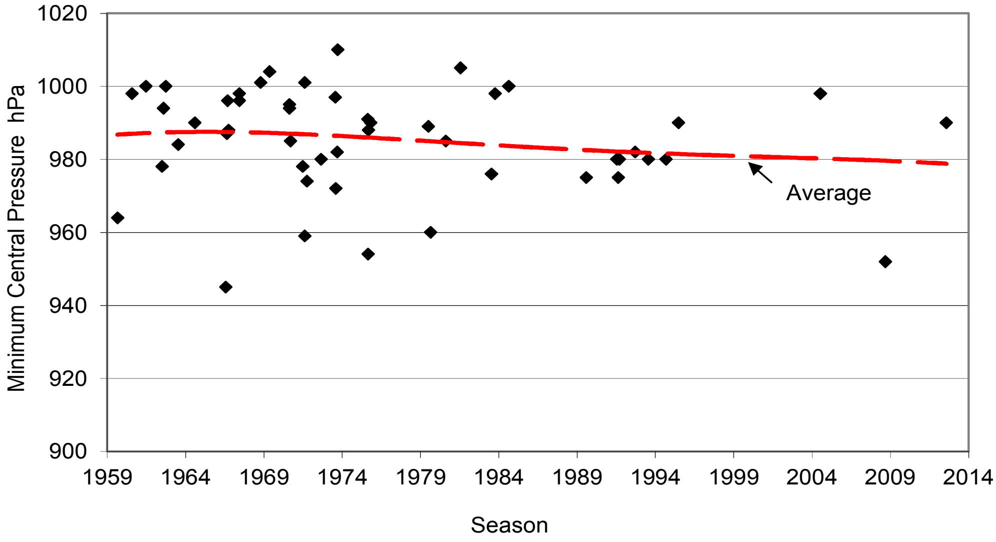


Figure 3-3 Time history of TC peak intensity within 500 km of Cape Moreton.

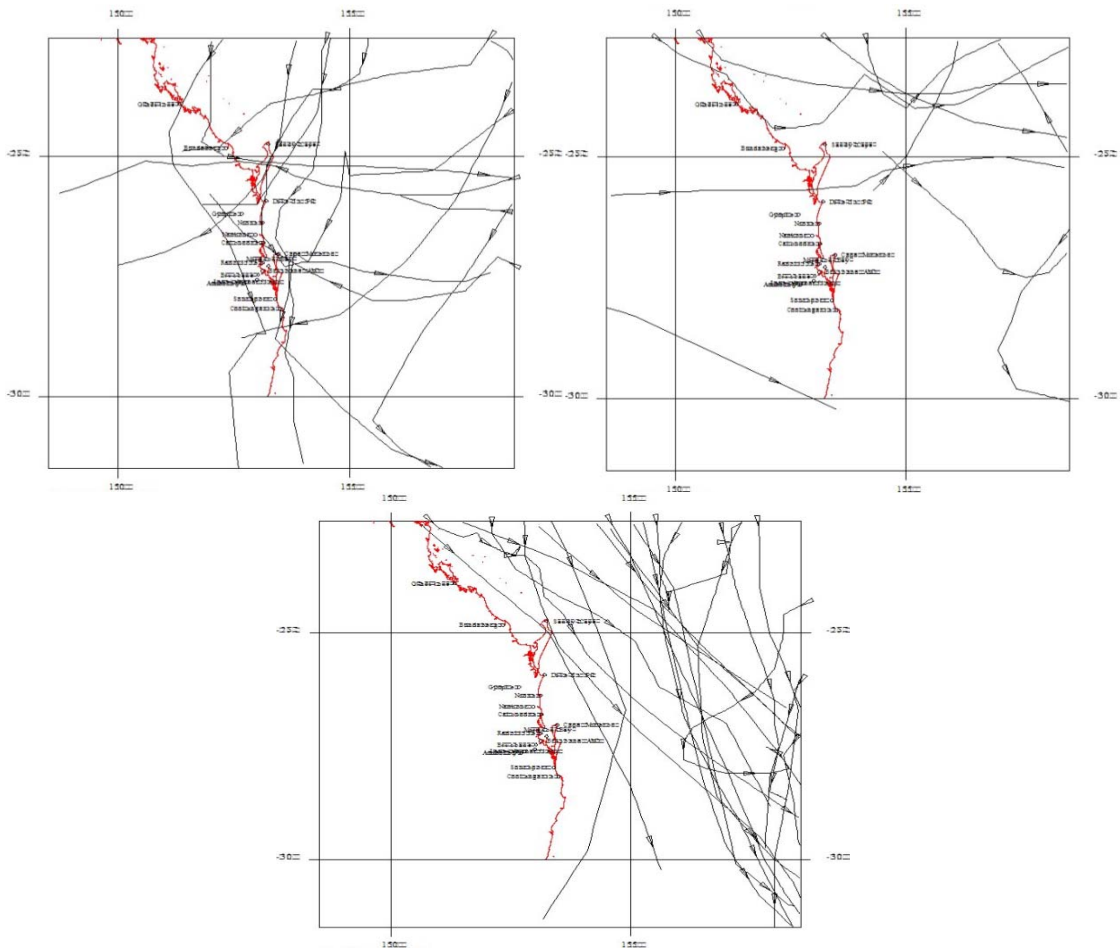


Figure 3-4 Tropical cyclone tracks capable of affecting the Moreton Bay Region classified into top left: offshore (20%), top right: parallel (54%) and bottom: onshore (26%).

The most significant parameter affecting regional storm tide is the intensity of the TC winds. This is typically indirectly represented by the central pressure of the storm but also depends in part on other scale parameters. The estimated minimum central pressure for each of the 54 storms is then statistically analysed using Extreme Value Theory (e.g. Benjamin and Cornell, 1970) to obtain the likelihood of particularly intense storms occurring anywhere within the 500 km radius region. The statistical analyses are undertaken firstly for each separate track class and then combined into a single regional prediction, summarised graphically in Figure 3-5 in terms of Annual Excedance Probability (AEP) and the approximate TC category. The most intense storms are contributed mainly by the onshore class, which typically represent fully mature storms in favourable steering currents.

Coupled with this theoretical (unbounded) analysis there needs to be a consideration of the maximum potential intensity (MPI) that might be sustained in any region. This is a function of a number of physical parameters but principally the sea surface temperature and the average upper atmosphere temperature and humidity profile. For the South East Queensland region the MPI is assessed as 940 hPa (Holland 1997a) – similar to the measured central pressure of *Dinah* when crossing Sandy Cape in 1967. Based on the present analysis, this MPI has an AEP of approximately 1.5% anywhere within 500 km of Cape Moreton, which indicates that a nominal Category 4 TC intensity or greater is not expected within the 500 km radius under present climate conditions.

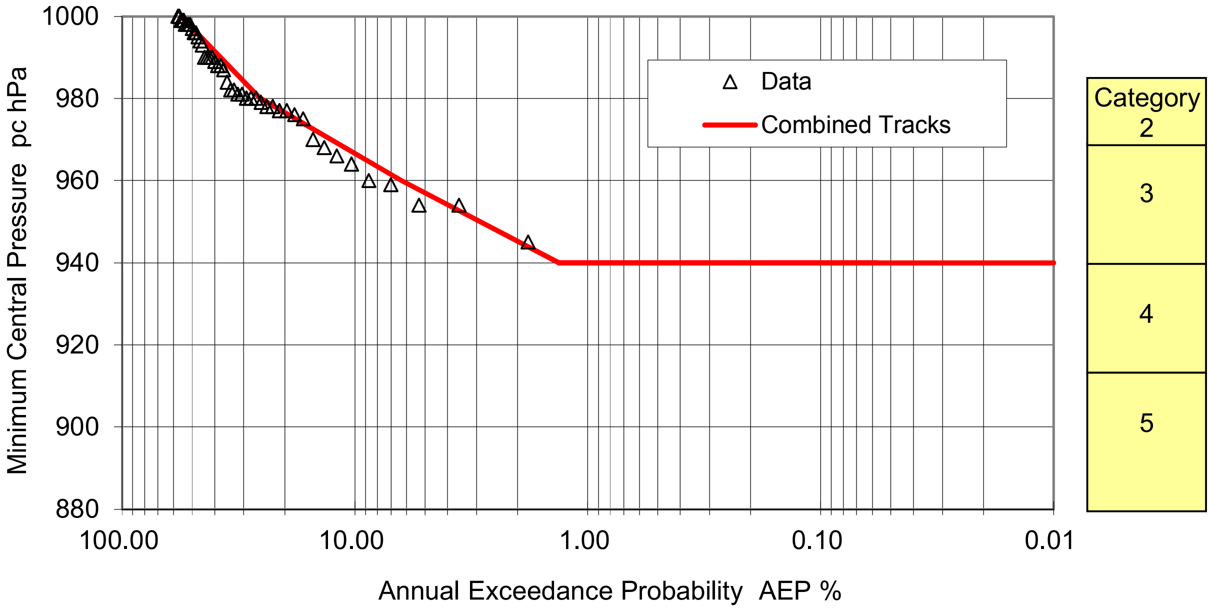


Figure 3-5 Extreme value analysis of cyclone intensity within 500 km of Cape Moreton.

Many other storm parameters are also extracted during the analysis phase. For example, the variation in forward speed, which adds to the strength of the cyclonic winds, the duration of storms, track bearing and the tendency for a proportion of storms to weaken (fill) as they move closer to the coast are based directly on the BoM data set. All of the above statistical estimates of TC behaviour and strength have been assembled for use by the statistical storm tide model SATSIM and used as a “template” to allow the generation of many thousands of synthetic storm events. The radius to maximum winds and Holland wind peakedness values are based on recommendations in Harper (2001b) for latitude 28°S and potential overland decay considerations have been neglected. Table 3-2 summarises the key model parameters for the 500 km radius statistical region used for this study.

Details of the modelling of TC-induced storm tide events are provided in Section 4.2.

Table 3-2 Key Statistical TC Climatology Parameters for the Moreton Bay Region

Track	Statistical Model Parameters			
Population	Name	Variable	Units	Value
	Ambient Pressure	pn	hPa	1007
	% This Track			20.0
	Average Number Per Year			0.19
	Gumbel Intensity	U	hPa	995.8
Offshore	Parameters	α		0.1379
Moving	Max Potential Intensity	MPI	hPa	990
		- std dev		60
	Radius to Max Wind	mean	km	76
		+ std dev	km	84
		- std dev		0.8
	Wind Peakedness	mean	-	0.9
		+ std dev	-	0.9
	% This Track			54.0
	Average Number Per Year			0.50
	Gumbel Intensity	U	hPa	990.9
Parallel	Parameters	α		0.0758
Moving	Max Potential Intensity	MPI	hPa	940
		- std dev		27
	Radius to Max Wind	mean	km	48
		+ std dev		80
		- std dev		0.9
	Wind Peakedness	mean	-	1.0
		+ std dev		1.3
	% This Track			26.0
	Average Number Per Year			0.24
	Gumbel Intensity	U	hPa	987.2
Onshore	Parameters	α		0.0944
Moving	Max Potential Intensity	MPI	hPa	940
		- std dev		27
	Radius to Max Wind	mean	km	48
		+ std dev		80
		- std dev		0.9
	Wind Peakedness	mean	-	1.0
		+ std dev		1.3

3.2 Extra-Tropical Storm Climatology

In the Moreton Bay region, the extra-tropical storm climatology is dominated by so-called East Coast Lows, although occasionally sub-tropical systems are present, together with extra-tropical transitioning cyclones. Historically the BoM TC database often (erroneously) included many of these sub- or transitioning tropical cyclone events but these have been removed in recent years. Ex-TC *Oswald* is actually an example of these types of complex (hybrid) storm systems (refer Section 5.2). Unfortunately there is not yet a fully complementary extra-tropical storm track dataset available from the BoM, although as noted below work continues in this space.

Much of the following material has been extracted from Harper (2001c) but updated based on more recent studies.

3.2.1 Features of East Coast Lows

East Coast Lows (ECLs), also known as *east coast cyclones*, *winter cyclones* or *easterly trough lows,* are one of a family of low pressure systems that most often develop during the winter months along the east coast of Australia between 25ºS and 40ºS (Holland et al. 1987, Hopkins and Holland 1997). These large scale storm systems often develop rapidly and can become quite intense, with storm-force winds extending over wide areas. These events contribute significantly to flooding and wind damage along the coastal margins as well as marine accidents, storm surge and beach erosion in south east Queensland. In the past some of these types of events were mis-classified as TCs because of their ability to produce widespread wind, storm surge and beach erosion impacts. They are however incapable of reaching “hurricane force” winds (TC Category 3) and most commonly produce “gale to storm force” impacts[5].

ECLs typically form after a low or deep trough intensifies in the upper atmosphere over eastern Australia. A low pressure system then develops at sea level near the coast to the east of the upper level system, often intensifying rapidly. These cells of low pressure are typically quite small relative to the broad synoptic features but can interact with developing high pressure systems to the south to produce severe gale conditions over periods of up to several days (Allen and Callaghan 2000, Callaghan 1986). These storm systems draw their energy from a combination of strong ocean temperature gradients, coastal convergence, uplift and a supply of moist sub-tropical air at the surface. The East Australian Current and the Great Dividing Range are principal players in the development of these storms, the circulation centres of which often track very close to the coast over considerable distances. An example of the tracks of several prominent systems is shown in Figure 3-6.

[5] This does not preclude the possibility of severe downbursts or tornadoes in specifically localised convective situations.

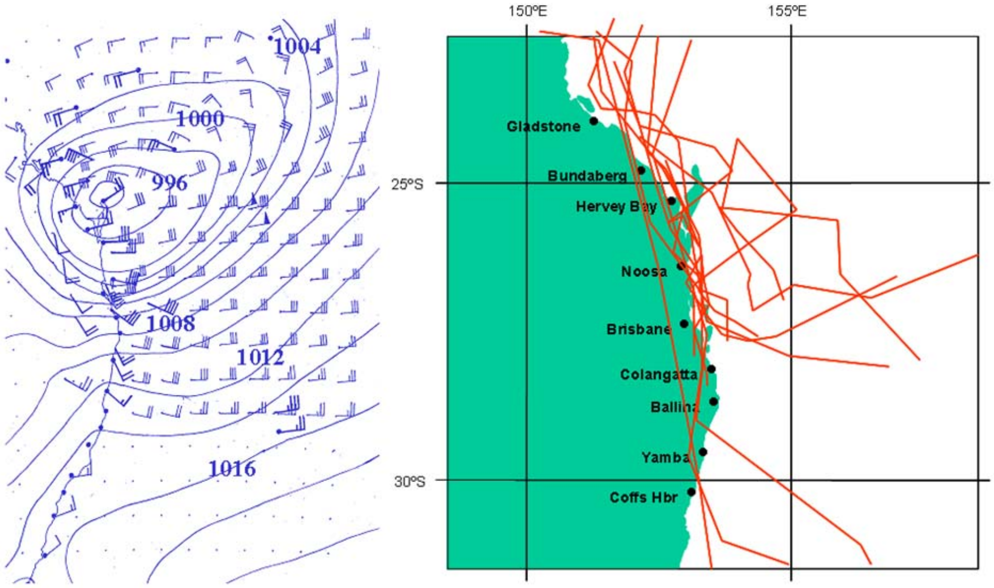


Figure 3-6 Example of an historical East Coast Low and some of the many ECL storm tracks affecting the Gold Coast region (after Harper 2001c)

Although the nominal storm centres may be close to the coast, their impacts extend over considerable distances, as can be seen in the example, where the steep gradients in the surface pressure fields and regions of strong onshore winds are indicated. The onshore flow is responsible for the heavy rains and, combined with the extended fetch regions over the ocean, the generation of high waves. Generally low but persistent storm surge impacts are also possible, whereby the strong clockwise winds create a net onshore flow at the surface causing a rise in water levels along the coast. The “inverted barometer” pressure effect can also be significant, with some ECLs having central pressures below 990 hPa. Wave setup caused by breaking wave processes at the coast also contributes to the total storm tide impact.

Prior to the introduction of satellite imagery in the early 1960s, many ECLs were classified as weak TCs. While their impacts may be similar or even possibly greater in some cases, the ECL has a different physical mechanism and a highly asymmetrical poleward cloud pattern where the heaviest rainfall frequently occurs. Another feature of ECL development is the tendency for clustering of events when conditions remain favourable. For example, near Brisbane, almost one third of events occur within 20 days of a preceding event (Allen and Callaghan 2000).

3.2.2 Climatology of East Coast Lows

There have been a number of studies into the frequency of occurrence and relative intensity of east coast lows. PWD (1985) addressed the coastal impacts of these systems on the NSW coastline, especially from a storm surge and wave setup perspective. Callaghan (1986) and Holland et al. (1987) considered the synoptic precursors to storm development as an aid to forecasting. Hopkins and Holland (1997) looked at the association between east coast lows and heavy-rain days. Allen and Callaghan (2000) considered the impacts of east coast lows on extreme wave heights in the SE Queensland coastal region.

Unfortunately, east coast lows have not been systematically recorded in the manner that TCs have been since the turn of the century. They are typically more complex systems and are often difficult to categorise. Accordingly, many of the studies have concentrated on detailed investigations of historical weather charts and station observations to reconstruct a time history of occurrences. The longest assembled record available (1880 to 1980) is from PWD (1985), which considered the region from Tweed Heads south to Gabo Island, near Bass Strait. This study classified the various storm systems into six categories, depending on the synoptic situation, as summarised in Kemp and Douglas (1981). Holland et al. (1987) considered the period 1970-1985 and used three broad classifications. Hopkins and Holland (1997) broadened this to 1958-1992 and Allen and Callaghan (2000) focussed on 1976-1997 when wave data was available.

In Harper (2001c) a composite data set was created based essentially on PWD (1985), using their categories E, S, I and C for the northern sector, and Allen and Callaghan (2000) using their type 1 and 2 events. Two additional heavy rain events from Hopkins and Holland (1997) were also included. This composite set covered the 118 year period 1880 – 1997 and considers only those east coast low events that had some impact on SE Queensland. On this basis the areal extent of the data set was within about a 500 km radius of Brisbane.

More recently, the Bureau of Meteorology initiated an attempt at a more comprehensive (albeit still subjective) study of maritime cyclones and related weather events affecting the NSW coastal areas - the NSW Maritime Low Database Project (MLD). This is of relevance to South East Queensland also because the study area extends northwards to Fraser Island and the data record ranges from 1959 to 2006 (Speer et al. 2009).

For the purposes of the present study, a further composite dataset from the MLD has been examined based on two factors;

- The Longitude and Latitude of the storms (within the nominal 500 km radius);
- The “Eastern Troughs” as classified in the original project.

These two storm classes were named NML 1 and NML 2 respectively.

This new composite dataset covered the 48 year period 1959 – 2006 and considers only those ECL events that had the potential for some impact on SE Queensland. Figure 3-7 presents a data set comparison showing the 10 year averaged number of storms, overlaid by a 10 year averaged Southern Oscillation Index Value (SOI), where “East Coast Lows” refers to Harper (2001c).

It is important to remember that, like TCs, the availability of regular satellite imaging revolutionised the monitoring of these types of weather events. In 1960, experimental satellite images became available. However, it was 1966 when two images per day could be obtained from the polar orbiting satellites. Prior to the availability of satellite imagery, significant under-sampling of ECLs is likely. On the contrary, it is interesting to note that regardless of NML 1 and NML 2 the east coast data displays an apparent sharp increase in the number of storms after the late 1960s. This is likely an artefact of the earlier subjective analyses that focused on impacts rather than occurrences. A new objective synoptic detection methodology by Pepler and Coutts-Smith (2013) for the period 1950 to 2008 uses global reanalysis datasets. This has identified a reasonably consistent average of about 50 days per year when ECLs are active. The variability with ENSO is also relatively low between La Niña and Neutral, but El Niño shows about an 8% reduction.

Details of the modelling of Extra-Tropical storm tide events are provided in Section 4.3.

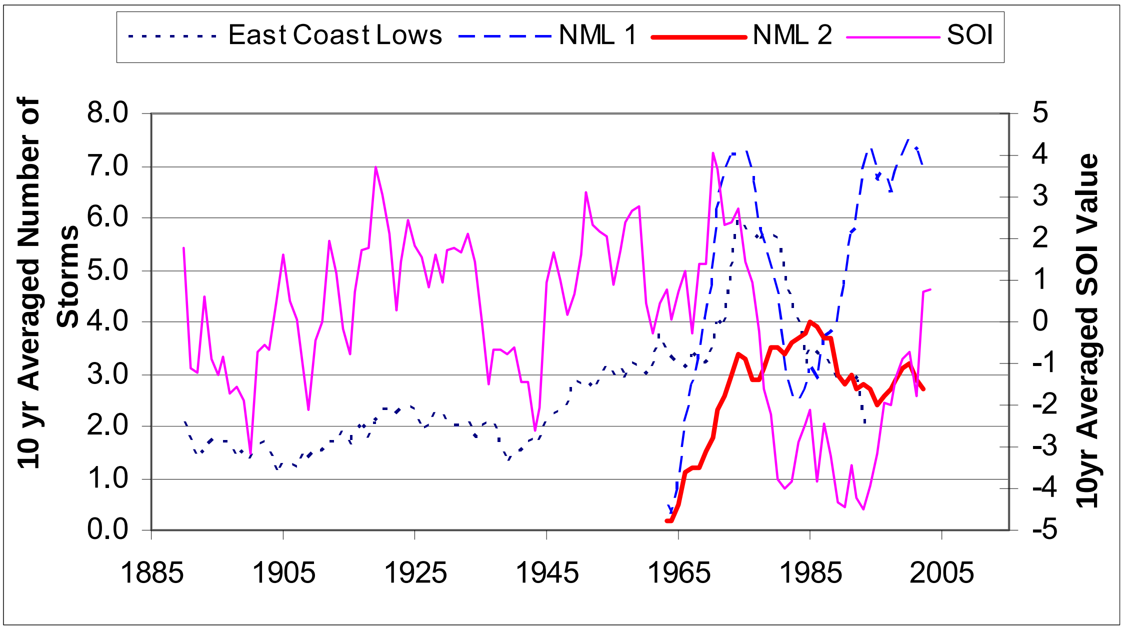


Figure 3-7 Composite Datasets of Damaging East Coast Lows Affecting SE Queensland

4. Numerical Model Development

This chapter describes the various numerical modelling components, such as the hydrodynamic models of tide, surge and waves, the TC wind and pressure model and the statistical water level simulation models adopted for the project. Examples of the outputs of each model are also presented.

4.1 Hydrodynamic Models

4.1.1 Model Domains

Two deterministic numerical hydrodynamic models were built using the 2-dimensional depth integrated finite-volume software package Mike21 (DHI 2014). These are:

- GHD's existing Regional Hydrodynamic Model (RHM) designed to encompass the large scale wind and pressure forcing from TCs as well as bathymetric detail within Moreton Bay; and
- A higher resolution, local-scale Local Hydrodynamic Model (LHM) representing Moreton Bay, the Brisbane River upstream to Ipswich, various creek systems and adjacent flood plains.

Each of the above models can be operated separately as hydrodynamic (HD) and spectral wave (SW) versions or in a coupled mode.

Figure 1-2 provides an overview of the relationship between the model extents.

The Regional Hydrodynamic Model (RHM)

An overview of RHM domain is shown in Figure 4-1, covering approximately 2.3 million square kilometres of the Coral Sea offshore from the Queensland Coast with its eastern boundary reaching 164ºE (approaching New Caledonia). Along the coast, the model extends south from 16ºS (Port Douglas) to 31ºS (Port Macquarie) and has around 17,000 elements and 9,000 nodes.

Selection of the flexible mesh size and model extent was based on the recommendations presented in the Government-sponsored Queensland Climate Change investigations (Harper 2001). Resolution varies from 40 km in open oceanic regions down to 100 m inshore. This ensures adequate resolution of a TC wind field, the large-scale forcing of the oceanic storm tide, the continental shelf features and the finer scale detail of channels within Moreton Bay.

Below HAT, the RHM model shares its bathymetry and resolution of tidal Moreton Bay with the LHM but only extends to the Brisbane River mouth and not upstream or overland. While, the RHM model extends south to Jumpinpin, the Gold Coast Seaway and Broadwater were not essential for the purposes of this study. This enabled increased resolution to be applied in other areas.

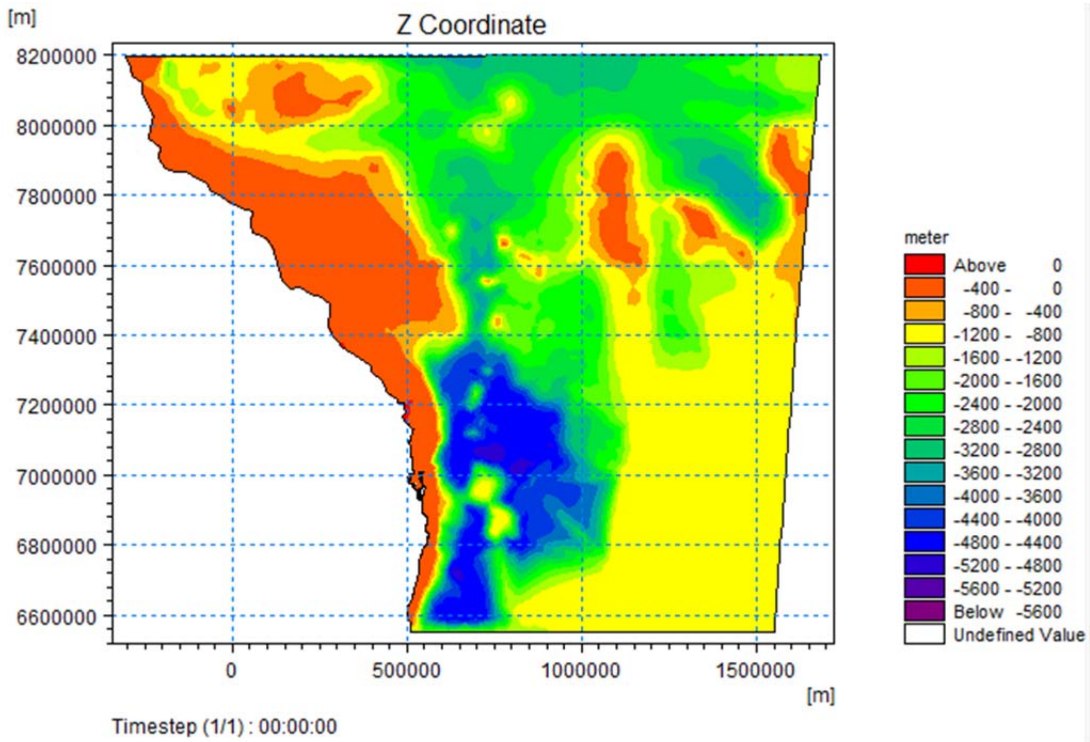


Figure 4-1 The Regional Hydrodynamic Model (RHM) extent and bathymetry

The Local Hydrodynamic Model (LHM)

The LHM model is designed to accept open boundary conditions from the RHM model and enables high resolution inundation modelling of the coastal margins within Moreton Bay, and more particularly the area within the Brisbane City boundary. For this purpose the Brisbane River is resolved upstream to the Bremer River confluence, together with its major tributaries (Oxley Creek, Norman Creek, Breakfast Creek and Bundamba Creek). Also resolved upstream to the extent of tidal influences are Kedron Brook, Nundah Creek, Cabbage Tree Creek, and the lower reaches of the South and North Pine rivers to the Bruce Highway. Surface elevation is represented up to 10 m AHD, as indicated in Figure 4-2, while Figure 4-3 and Figure 4-4 are examples of the spatial detail represented in the LHM.

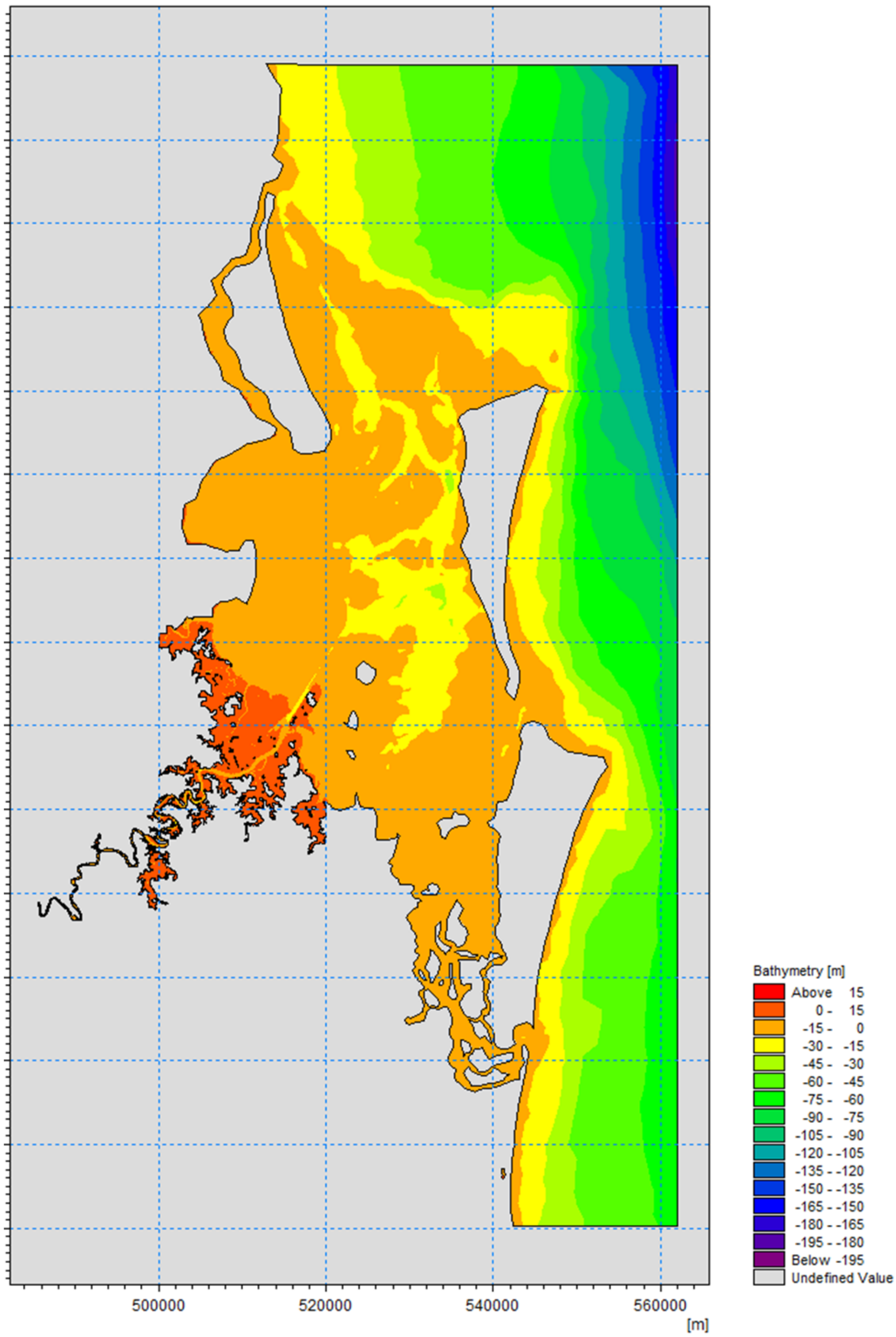


Figure 4-2 The Local Hydrodynamic Model (LHM) extent and bathymetry

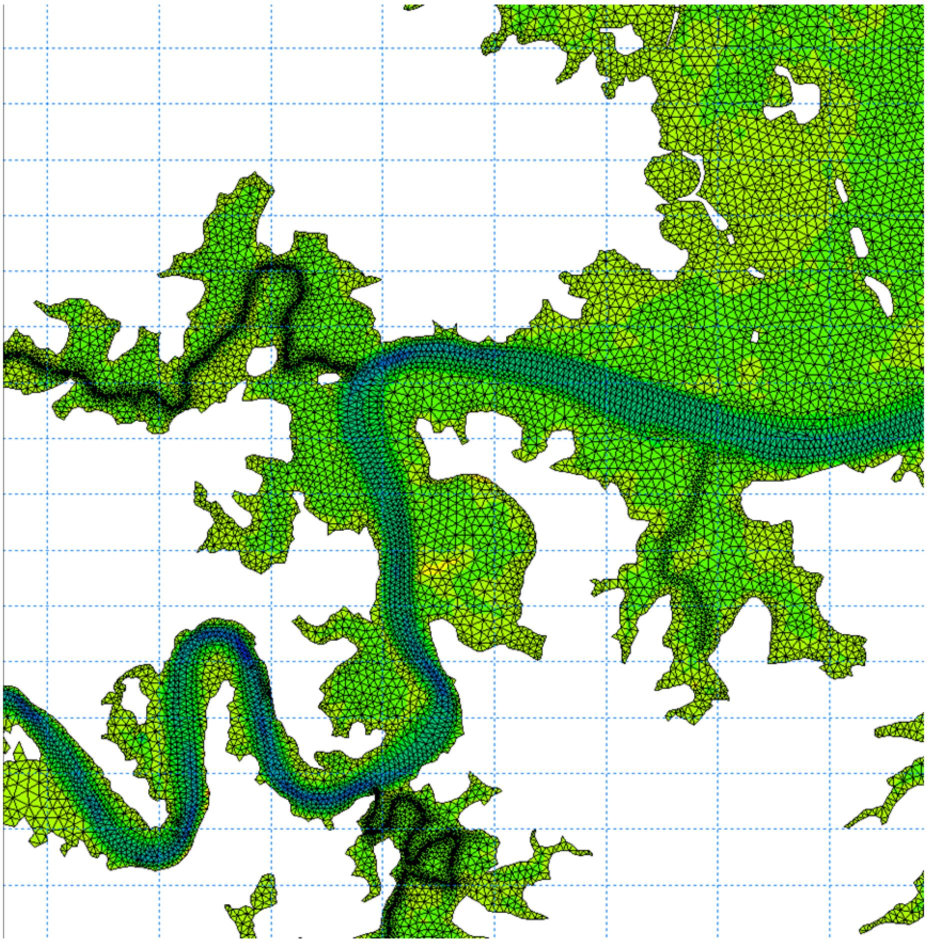


Figure 4-3 Detail of the Local Hydrodynamic Model of the Brisbane River downstream of the CBD in the vicinity of Norman, Breakfast and Bundamba Creeks

4.1.2 Bathymetric and Elevation Data

The base bathymetry and coastline information used in the models is derived from the Mike21 C-MAP utility and further augmented with supplied Maritime Safety Queensland and Port of Brisbane dredging survey data within Moreton Bay.

The land elevation data was provided by Brisbane City Council, comprising LiDAR and river and creek cross sectional data.

Table 4-1 lists by type and extent the key bathymetric and topographic datasets used in this study.

Table 4-1 Summary of Key Bathymetric and Topographic Datasets

Dataset (origin)	Extent	Type
Port of Brisbane approach channel (Port of Brisbane Corporation)	North Moreton Bay	XYZ triplets
Soundings and contours (Maritime Safety Queensland)	Moreton Bay, Brisbane River and 2014 updates of Aquarium Passage, Hamilton and Pinkenba	XYZ triplets and contours

Dataset (origin)	Extent	Type
BCC GIS datasets	Brisbane River Floodplain (Centenary Bridge to Gateway Bridge) and Moreton Island	LiDAR and aerial imagery
BCC DHI model topographic dataset	Brisbane City	Mike 21 dfs2 format
Brisbane River (BCC)	Karana Downs to Gateway Motorway	XYZ triplets
Brisbane River (BCC)	New Farm to Gateway MotorWay	XYZ triplets
Bald Hills Creek (BCC) – 2011 survey	Between Gympie Arterial Road and Gateway Motorway, lower reach missing	Cross-sections and XYZ triplets
Breakfast Creek (BCC)	Enoggera Reservoir to Brisbane River	XYZ triplets
Bulimba Creek (BCC) – circa 2002	Sunnybank Hills and Beenleigh Road to Brisbane River	cross-sections
Cabbage Tree Creek (BCC) – 2012 survey	Bunya and Everton Hills to Shorncliffe	cross-sections
Kedron Brook (BCC)	Entire catchment starting Upper Kedron and extending east to Brisbane Airport	XYZ triplets
Lota Creek (BCC)	Entire catchment extending from Chandler to Gumdale and Lota	XYZ triplets
Moggill Creek (BCC)	Upper Brookfield to Brisbane River via Brookfield and Kenmore Hills	cross-sections
Norman Creek (BCC)	Pacific Motorway to the southwest, Holland Park to the east and Brisbane River to the north	XYZ triplets
Nundah Creek (BCC)	Everton Park to the ocean via Stafford Heights, Chermside, Zillmere and Boondall wetlands	cross-sections
Oxley Creek (BCC)	Entire catchment from Edwards and Paradise Parks, Forestdale to Brisbane River	XYZ triplets and cross-sections
Pullen Pullen Creek (BCC)	Pullenvale	cross-sections
Wolston Creek (BCC) – sourced from the 1996 Wolston Creek Flood Study	Ipswich Motorway and Centenary Motorway to Brisbane River via Centenary Memorial Gardens	cross-sections
Wynnum Creek (BCC)	Manly West to ocean	XYZ triplets and cross-sections

4.1.3 Hydrodynamic Model Physical Parameters

Key parameters adopted for hydrodynamic modelling are detailed in Table 4-2.

Table 4-2 Hydrodynamic Model Parameters

Parameter	Value	Notes
Water Density	1025 (kg/m3)	A series of tests were also completed using differing density values during model verification.
Bed Friction	Refer Table 4-3.	Informed by the model calibration process (Section 5.1), a variable Mannings Coefficient (DHI 2014) is applied to ocean, waterways and floodplain as summarised in Table 4-3. The allocation of bed friction across the floodplain was based on a GIS impermeable surface layer supplied by BCC City Design
Wind Stress	Wind speed dependant (Pa)	The standard Mike21 formulation was overridden by the so-called “uncapped Wu” formulation (Harper 2001a) for consistency with previous TC calibration studies.
Flooding and Drying	0.005 m Drying Depth 0.05 m Flooding Depth 0.1 m Wetting Depth	
Horizontal Eddy Formulation	0.28	Smagorinsky formulation

Table 4-3 Adopted bed friction values for modelling

Type	Manning (M)	Manning (n)
Ocean	40	0.03
Waterway	33	0.03
Road	50	0.02
Urban	10	0.10
Floodplain	25	0.04

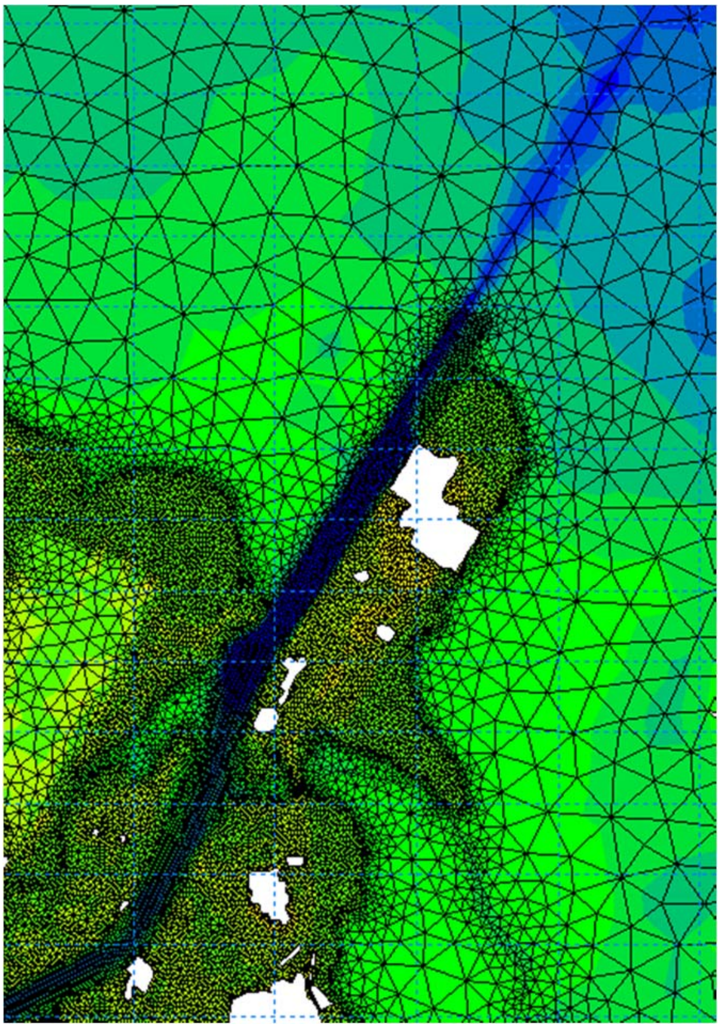


Figure 4-4 Detail of the Local Hydrodynamic Model in the vicinity of the Port of Brisbane

4.1.4 Open Boundary Conditions

RHM Model

The integrated Mike21 global tidal model at 0.25º x 0.25º resolution provides time histories of water-surface elevation along the open boundaries of the RHM model derived from 8 tidal constituents. These are the 4 major semi-diurnal (M2, S2, N2, K2) and the 4 major diurnal (K1, O1, P1, Q1).

LHM Model

The LHM receives open boundary conditions from the RHM model for TC forcing and regionally modified boundaries derived from Mooloolaba tide gauge for extra-tropical events. For further detail of the boundary development for extra-tropical events please refer to Section 5.2.3 – sub heading *Final Representation.*

4.2 Tropical Cyclone Model

The Tropical Cyclone model comprised a series of models describing the complex surface wind and pressures fields of a mature TC as well as the selection of storm parameter ranges derived from the climatology, the processing of the full scale model results and how the statistical model combines the various components. These are described in the following sections.

4.2.1 Wind and Pressure Model

The wind and pressure model is based on Holland (1980) and Harper and Holland (1999) as detailed in Harper (2001a). It has been used extensively throughout Australia and internationally to represent the broad scale wind and pressure fields of a mature TC. It relies on a series of parameters to describe a TC when it is over an open ocean environment, namely:

- The central Mean Sea Level pressure p_o
- The surrounding, or ambient, pressure p_n
- The radius to maximum winds R
- The wind field peakedness factor B; and
- The storm track (speed V_{fm} and direction θ_{fm})

The model generates estimates of the 10 minute average wind speed and direction at a height of 10 m above the ocean surface for supply to the hydrodynamic models for storm surge and waves. It also estimates the peak wind gust for comparison with long term wind records at regional sites such as Brisbane Airport. The MSL pressure is also supplied to the hydrodynamic model as it has an influence on the generation of the storm surge. An example of the model generated wind field is shown in Figure 4-5 for which occurred TC *Dinah* in 1967.

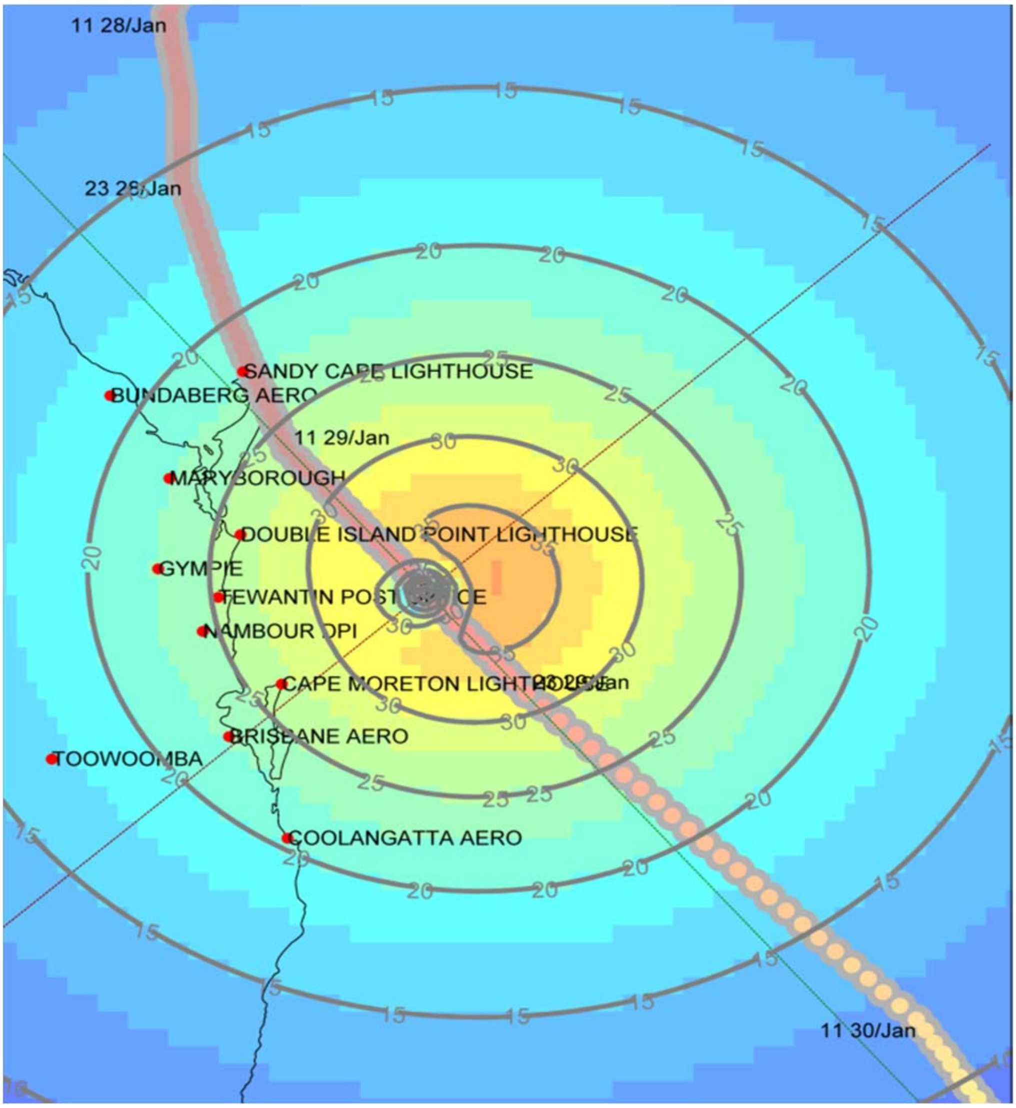


Figure 4-5 Example TC wind field (*Dinah* 1967) (m/s)

Tropical Cyclone Parameter Selection for Full Scale Modelling

The climatology assessment from Section 3.1.3 identified the principal TC parameter values likely to apply to the Moreton Bay region. These formed the basis of a series of conceptual straight-line and constant speed synthetic cyclone tracks, which when modelled systematically by the fully numerical (RHM) model, provide a response function for surge and waves that can be readily interpolated to provide output at any coastal location using the approach described in Harper (2001b).

Each of the conceptual cyclones is described by the same set of parameters as presented in Section 3.1.3, except that the pressure difference Δp is introduced to specify the storm intensity:

$$\Delta p = p_n - p_o$$

A total of 294 individual simulations were then used to form the “base” storm surge response and 189 simulations to form the wave response, as summarised in Table 4-4. These comprised three values each for intensity, radii, wind field peakedness factor *B*, forward speeds and angles of approach.

Table 4-4 Base TC Parameter Set for RHM Modelling

Δp	R	B	Vfm	θfm	Coastal Crossing Distance X		
hPa	km		ms-1	bearing˚	km		
					220˚	260˚	160˚
30	25	0.9	2	220	150	150	0 (0)
60	50	1.0	6	260	100	100	-50 (-100)
80	80	1.3	8	160	50 (200)	50 (200)	-100 (-200)
					0 (0)	0 (0)	-200
					-50 (200)	-50 (200)	
Totals							
3	3	3	3	3	5 (3)	5	4 (3)

The coastal crossing distance shown here is measured from Surfers Paradise, this being a convenient reference location used for the initial model development. The numbers in brackets refer to the wave model track selections, which were distributed more widely than the surge. Each simulation included an elapsed real time of 30 h, with the start of the storm being 18 h before "landfall" and continuing until 12 h afterwards. In the case of the parallel-moving storms, "landfall" is the time of closest approach to the reference location. Each model TC also underwent an initial 12 h build-up period, with the storm held stationary, to reduce numerical transient effects.

In addition to the base set of storms, a series of 6 special sensitivity tests (refer Table 4-5) were also undertaken to explore the surge and wave response at the upper and lower limits of the storm intensity ranges and to check linearity and scaling assumptions. These were completed using a selected range of fixed values for the other parameters.

Table 4-5 Additional TC Parameter Sensitivity Testing

Type	Δp	R	B	Vfm	θfm	X	Water Level
	hPa	km	-	ms-1	°	km	
Intensity	10	50	1.0	6	160	0	MSL
	105	50	1.0	6	220	50	MSL
					260	50	MSL
Water Level	60	50	1.0	6	160	0	-1.0m
					220	50	+1.0m
					260	50	

Finally, because all the base simulations were conducted at mean sea level (MSL), a further set of 6 sensitivity tests was undertaken at +1.0 m and -1.0 m, representative of the approximate tidal range in the region. These results were used to devise a surge-tide interaction function for the model (refer Section 4.2.3).

Each simulation provided a time history output of water elevation, wave height, period and direction at 10 minute intervals at 894 open coast locations from Caloundra to Point Danger.

4.2.2 Processing of the RHM Model Results

All full scale numerical model simulations were processed to extract the underlying regional and local storm surge and wave responses using an enhanced form of the SEA (2002) parametric surge and wave model. The model output for each track direction is condensed into a series of characteristic alongshore and offshore spatial profiles and a time history profile, all of which are scaled according to the intensity of the cyclone, its size and speed. Multiple track directions can be added as necessary to complete the description of the regional response. Additionally, each specific location is allocated a local response function that describes any localised changes in surge or wave height behaviour (including time differences) peculiar to that location. The method allows the rapid recreation of a storm surge or wave height response at any of the coastal locations based on a set of supplied storm parameters.

The parametric model is optimised for highest accuracy at the time of the predicted peak condition (surge or wave height) and typically reproduces the numerical model results to within about 5% for surge, within 0.5 m for wave height and within 2 s for peak spectral wave period.

An example of the regional storm surge parameterisation process is presented in Figure 4-6 showing the principal surge magnitude response as a function of Δp and the normalised spatial (cross-track or alongshore) response and the normalised time history response. At specific locations there are local modifiers that, together with the regional response, enable reconstruction of the original Mike21-modelled water level time response, as shown in Figure 4-7. It can be noted that the parametric model ignores negative surge, which at MSL inside Moreton Bay can theoretically be significant as seen by the Mike21 response only becoming positive near the time of the storm landfall (time = 0). Ignoring the prospect of potential negative surge is a slightly conservative modelling assumption but it acknowledges that the modelled offshore winds, which create the drawdown effect, are likely being overestimated.

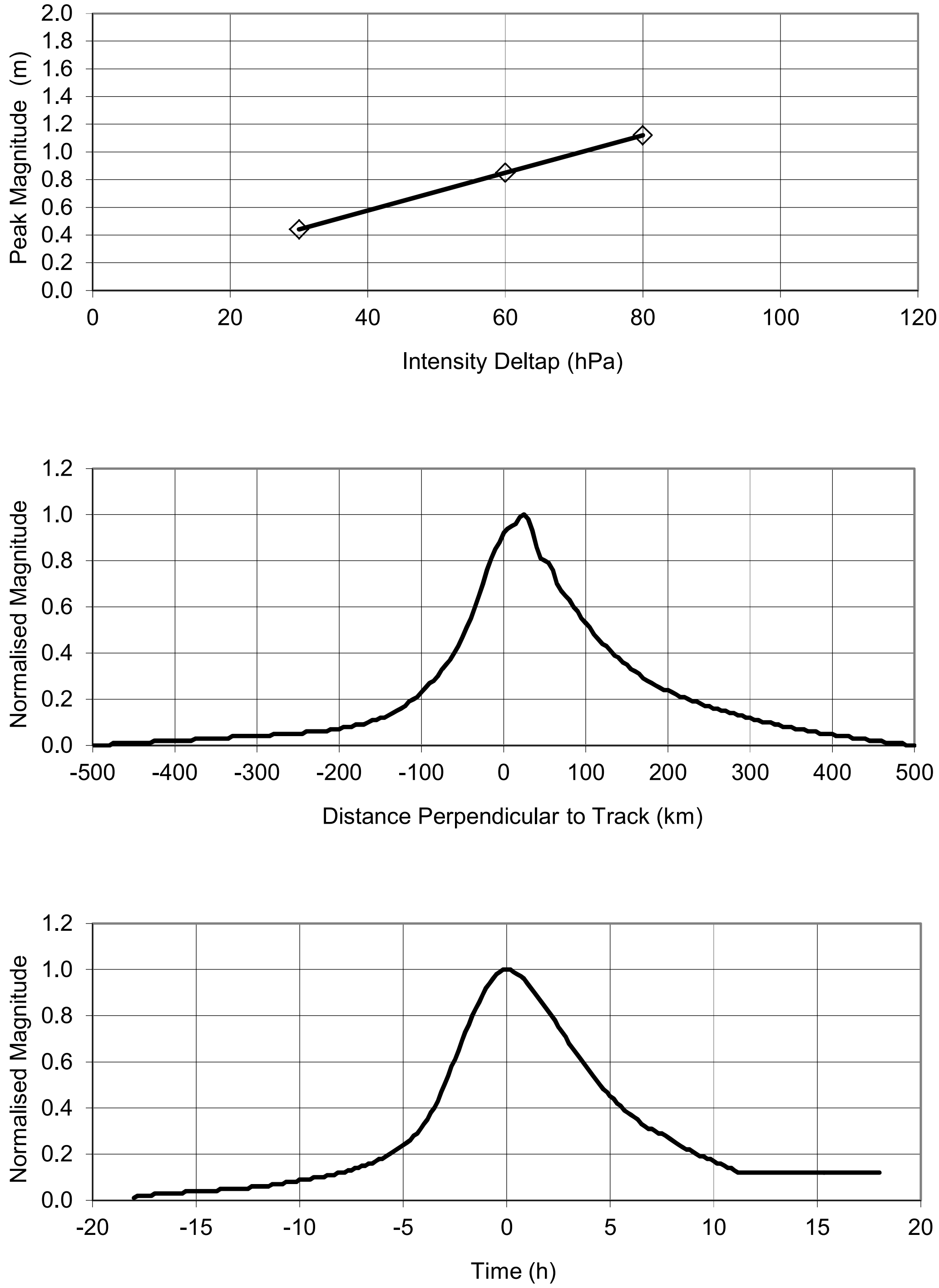


Figure 4-6 Example of the regional storm surge parameterisation for the 260° track angle; Top: Peak surge vs **Δ**p; Middle: Normalised alongshore spatial response; Bottom: Normalised time response.

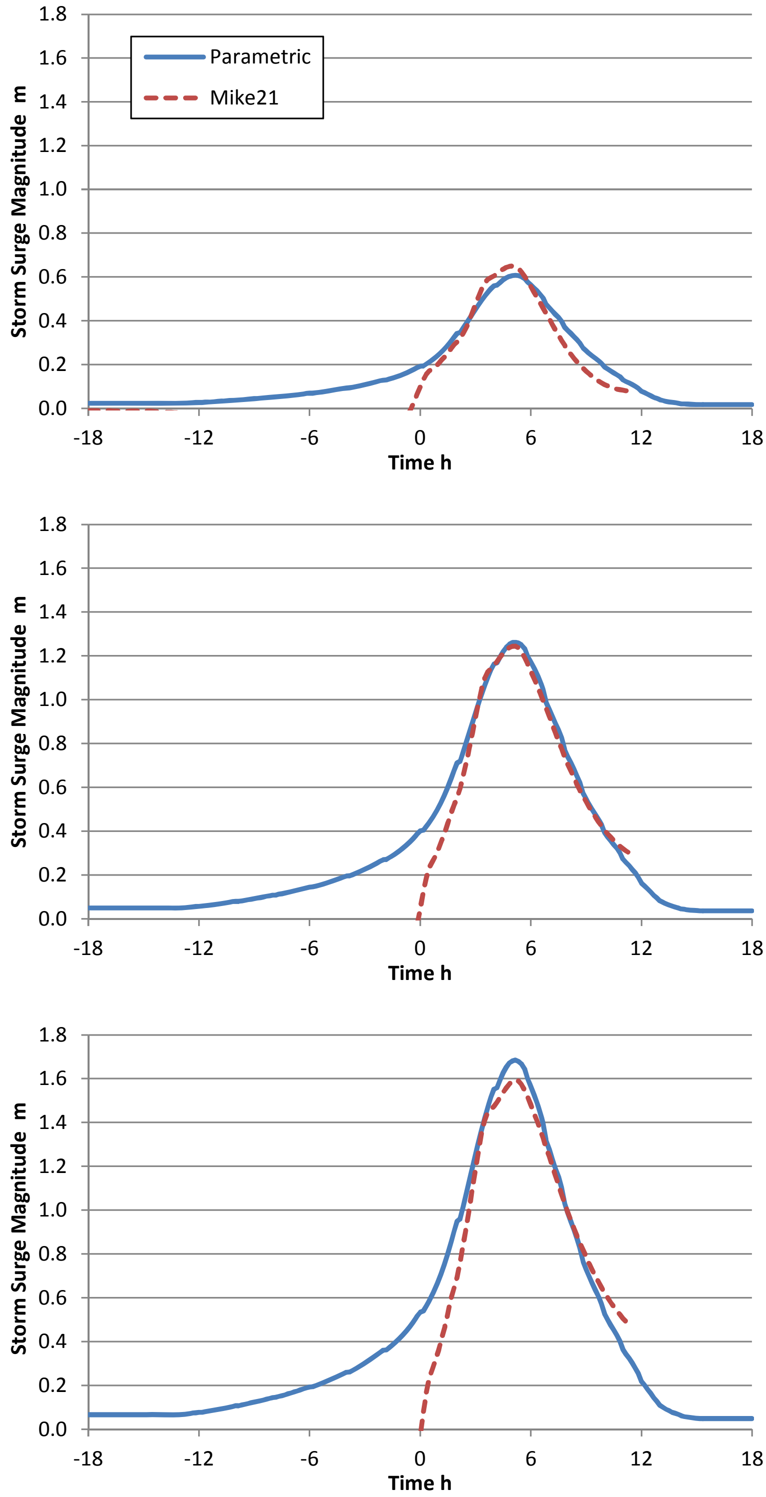


Figure 4-7 Example of a site-specific comparison of parametric and Mike21 storm surge; Top: 30 hPa **Δ**p; Mid: 60 hPa **Δ**p; Bottom: 80 hPa **Δ**p near Fisherman Islands

4.2.3 Simulation Modelling of Tropical Cyclone Impacts

Originally based on a method by Harper and McMonagle (1982), the statistical simulation model SATSIM (Surge and Tide Simulation) has been developed and refined over many years and successfully applied to a wide range of design projects. In summary, the model generates an artificial history of TCs based on the assumed parameter climatology. It maintains a clock that calculates the occurrence of the next event based on random number sequences and then allocates the necessary parameters, randomly sampled from the climatology distributions. Each storm's predicted wind, surge and wave response at each of the sites of interest is then generated by the parametric models, interpolating as necessary between the available modelled scenarios. The wave height and period estimate is converted into a breaking wave set-up height before being added to the surge and both are superimposed on a generated background astronomical tide for that date in time. Wave run-up height above the mean water level (excluding set-up) is also predicted at the 1% exceedance level. This is repeated for 50,000 years of synthetic storms and the exceedance statistics of the combined total water level at each site then forms the basis of the probabilistic storm tide level predictions.

Astronomical Tide Effects

The base simulation model astronomical tide is generated from 37 tidal constituents for Brisbane Bar (MSQ 2014). In order to provide for the variation in tide amplitude along the coast and within the complex waterways, a simple linear interpolation of tidal planes has been undertaken between the available data, leading to a set of "range ratios" relative to the standard port above. The tidal planes were based on published MSQ values but at many of the modelled sites, especially those in southern Moreton Bay, the range ratios are known to be only approximate. Tidal phase differences across the model domain are generally small and are not included as they simply represent a further random variation within the model.

Surge – Tide Interactions

As discussed earlier, special model tests were undertaken to determine the extent to which there might be non-linear interaction between the astronomical tide and the storm surge in the shallow water regions. Section 5.2.3 notes this effect in regard to observations during Ex-TC *Oswald*, which was an unusual near-steady-state wind event. That data suggests a variation in the surge level of about ±10%, whereby the surge magnitude was about 10% higher at low tide and 10% lower at low tide, consistent with the form of the inverse water level wind stress term in the hydrodynamic model equations. However, the model tests conducted for moving TCs with a MSL variation of ±1m were less conclusive, producing complex spatial and temporal variations across Moreton Bay. A nominal ±5% interaction was assumed in the subsequent statistical modelling to reflect the likelihood that there will be some non-linear modulation.

Wave Setup and Wave Runup

The total open coast water level is calculated on the basis of the modelled tide plus surge result, a breaking wave set-up component and a wave run-up estimate[6]. Both the wave set-up and run-up magnitudes are relative to the local still-water tide plus surge level.

It is emphasised that the accuracy of the provided tide plus surge estimates is considered inherently better reliable than those that include wave setup or wave runup. This is due to the likely wave interaction with very localised, small scale and potentially dynamic coastal features.

[6] Open ocean sites use Hanslow and Nielsen (1993) and Nielsen and Hanslow (1991). Moreton Bay sites use Stockdon et al. (2006).

An example of the SATSIM model site-specific output showing each of the simulated components of water level during TC-only forcing is given in Figure 4-8. The left-hand axis refers to all the water level components (some magnitudes only and some to AHD) while the right-hand axis is for the wave height curve only. At this location the assumed “dune crest” elevation is about 2.5 m AHD, which is where the various absolute water level estimates coalesce.

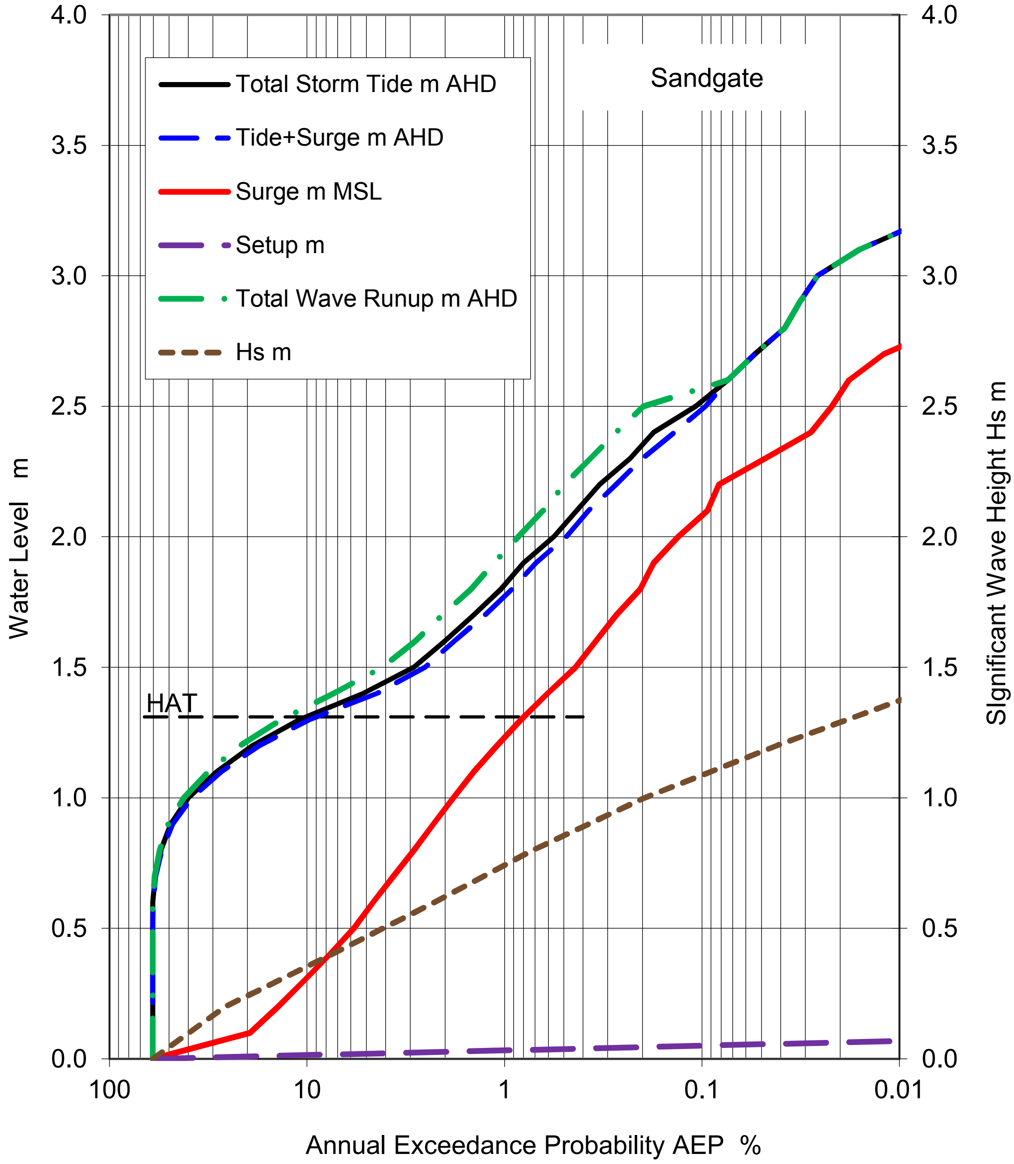


Figure 4-8 Example of the TC-only simulation of storm tide hazard for present climate

4.3 Extra-Tropical and Remote Tropical Cyclone Model

As discussed in Section 3.2, due to limited long-term meteorological data on these systems and also complex offshore baroclinic behaviour, it is problematical to model the climatology of these events, either atmospherically or oceanographically. The present study utilises an innovative empirical approach that bypasses the need for long-term deterministic climate modelling. Instead, the method utilises the recorded water level impacts directly, which as the data shows, are sufficiently numerous to argue that they can be used for reliable statistical analysis even though the period of reliably measured water level data from suitably located tide gauges is limited (refer below). Figure 4-9 provides a graphical overview of the analyses undertaken in this Section.

4.3.1 Tidal Residual Modelling

Modelling of the tidal residuals was undertaken by the Australian Maritime College Marine Modelling Unit (MMU) and follows the method briefly described in Hardy et al. (2004) used for estimating extra-tropical storm surge contributions in the Townsville region. Termed here the TRSSM (Tidal Residual Statistical Sampling Model), it is based on the re-sampling of the tidal residual event record from suitably long and reliable tide gauge records in the region of interest, which have occurred in random combination with the normally occurring tidal variation to produce the total storm tide level recorded by each gauge.

Because the incidence of the storms of interest is relatively frequent (averaging two or three per year of some significance as shown in Section 3.2) a data record of the order of 30 years is highly likely to have sampled close to the maximum ocean forcing possible from these events, whose intensity is typically limited to storm force only. Implicitly it is then assumed that the available record of ocean water levels from tide gauges has sufficiently captured the inherent range of variability of extra-tropical and remote TC storm surges in the region. It does not allow for any extrapolation of storm surge magnitudes beyond those already measured but, as the analysis shows, this is not a constraint on the effectiveness of the technique to represent water level statistics at higher AEPs where TC storm surge does not dominate.

4.3.2 Analysis of Tidal Data

Astronomical tide data was provided by the Tidal Unit of Maritime Safety Queensland, Department of Transport and Main Roads (DTMR) at the locations indicated in Table 4-6. The data consisted of tidal heights at hourly intervals. These have been recorded since digital data collection technology was introduced. Brisbane Bar has the longest digital record although not all of this data is able to be practically utilised.

Table 4-6 Astronomical tide station datasets

#	Tidal Station	Record	Years
1	Brisbane Bar	02/02/1966 - 31/12/2013	47
2	Mooloolaba	24/07/1979 - 31/12/2013	34
3a	Port Office	21/01/1985 - 31/12/2005	21
3b	Port Office	01/01/2007 - 30/07/2013	6

The analysis was carried out on the period 1985-2013. For this period, the Mooloolaba, Brisbane Bar and Port Office have relatively good quality overlapping tide gauge data[7]. The adopted approach yielded approximately 29 years of data for Mooloolaba and Brisbane Bar, and 27 years for the Port Office. The resulting tidal residuals are shown in Figure 4-10 and can be seen to be both positive and negative in magnitude. The tide predictions were based on 152 constituents derived from the raw tide data at each gauge site.

These three stations provide the perspective required to help identify the components of the broadscale extra-tropical storm surge response, namely:

[7] Analysis indicated that the early (pre-1985) Mooloolaba and Brisbane Bar data appears to have some timing errors and datum shifts and this has limited the useful record. Also the Port Office data had to be analysed in two parts due to problems around 2006.

- Mooloolaba, being located close to the open ocean, is deemed representative of the regional ocean response;
- Brisbane Bar is centrally located at the coastline of interest and represents the additional amplification of the tidal signal and the shallow water surge response within Moreton Bay;
- Brisbane Port Office, in addition to further tidal amplification, provides insight into the influence of riverine flooding on the local water levels.

As part of the analysis, periods of “flood” were removed from the Brisbane Bar and Port Office residuals, with a flood defined (by inspection) as a period when the difference between the Port Office and Mooloolaba residual is greater than 400 mm[8], although flow at Jindalee was also examined. It is noted that the filtering of flood events in such a way eliminates only a small amount of the total data (refer comparisons in Figure 4-10). Importantly, this filter removes the effects of Ex-TC *Oswald* in Jan 2013, the only “close approach” storm of significance during the data period. Accordingly, as mentioned earlier, it is treated separately as a modelled TC event to retain its statistical relevance.

It is noted that:

- Residuals at each station were first low-pass filtered using a 24 h cut-off to remove any small tidal signal remaining; and
- AHD was used as the datum for all analyses.

Further insight into the relative water level variation between these gauges over time can be seen in the graph of the differences in the filtered residuals relative to the Port Office in Figure 4-11. The long term variations evident can be attributed to the broadscale influence of ENSO and associated oceanic and atmospheric variability.

4.3.3 Simulation of Synthetic Water Level Time Histories

Tidal re-sampling simulation was conducted as outlined in Figure 4-12 using the tidal and residual records for each tidal station. A fundamental assumption of TRSSM is that the timing of the tide and the tide spring/neap cycle is uncorrelated to the residual but that there may be some correlation between the annual cycle of storm events and the annual patterns in the tide. It also assumes that the astronomical tide is largely predictable and that tide and residual can be linearly added to produce a combined result with only small errors.

[8] This is a nominal statistical separation unsupported by a rigorous flood event correlation but, as illustrated, it identifies the obvious flood events and suits the present purposes.

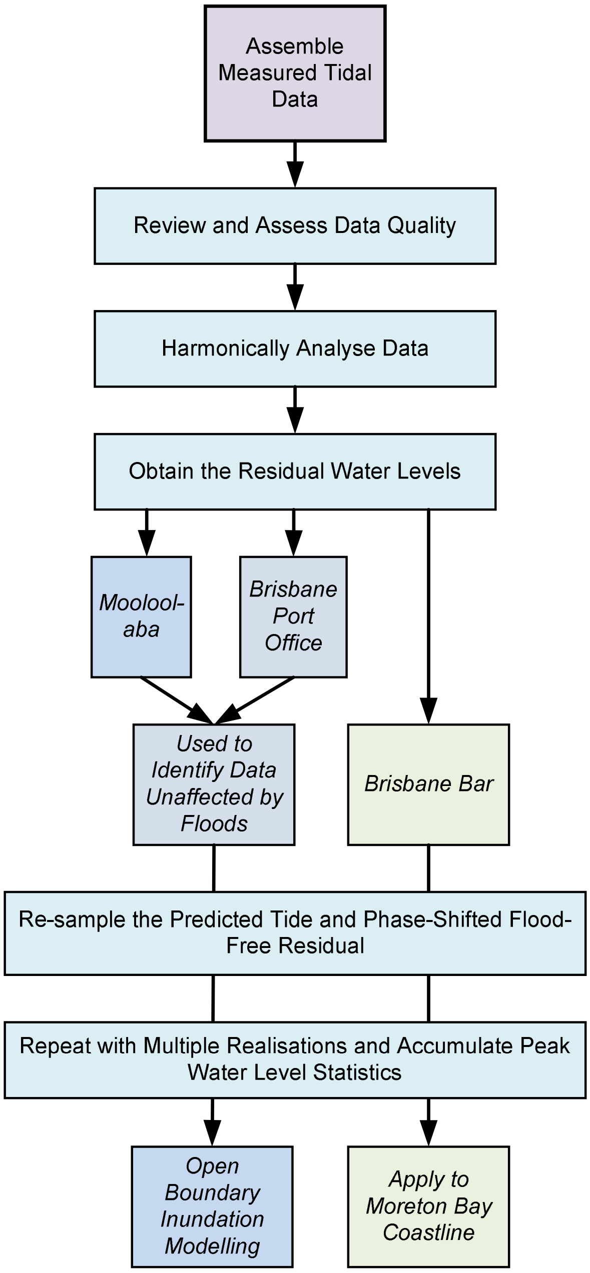


Figure 4-9 Overview of the Extra-Tropical and Remote Tropical Cyclone Methodology

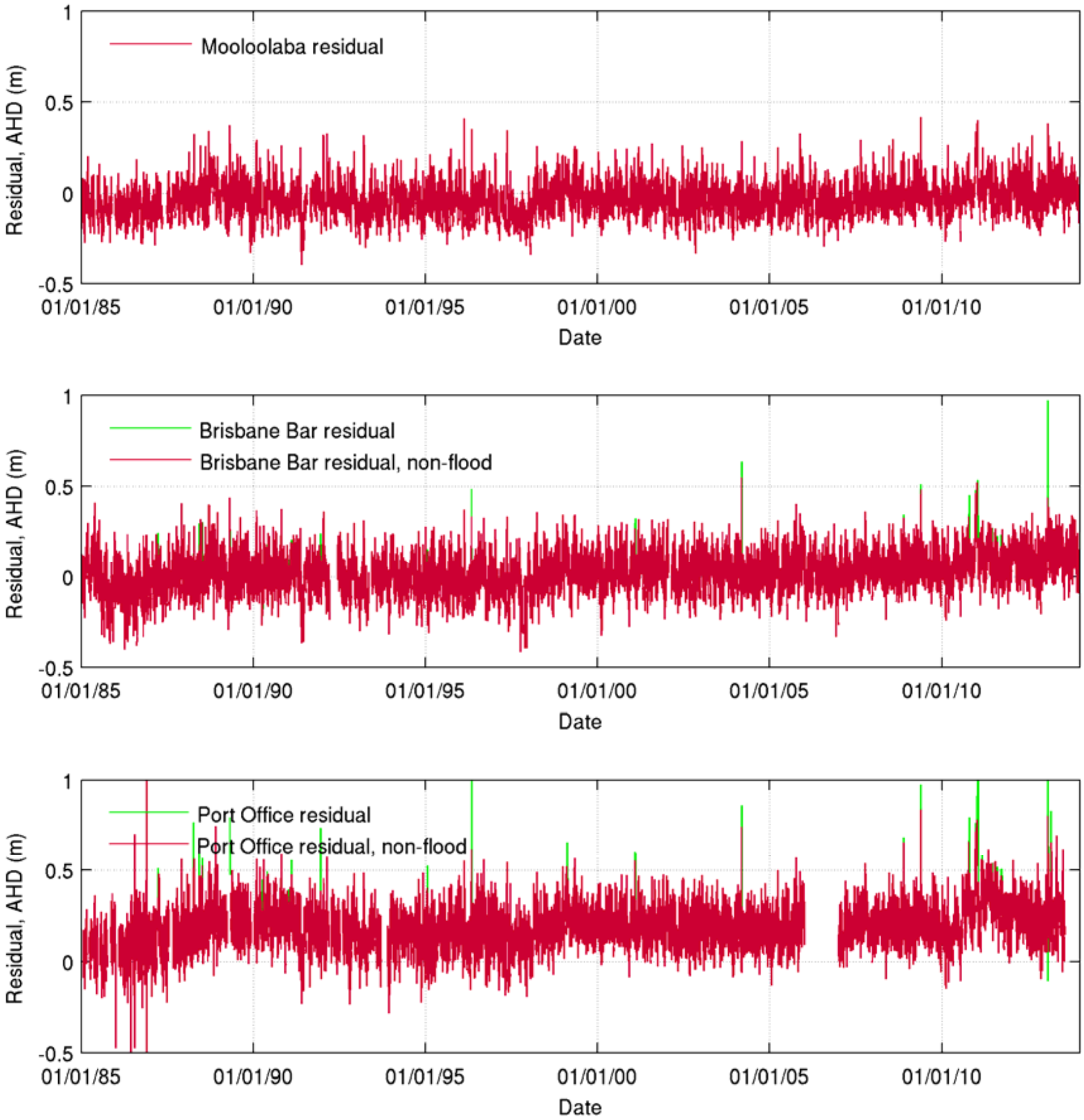


Figure 4-10 Mooloolaba, Brisbane Bar and Port Office Tidal Residual Records

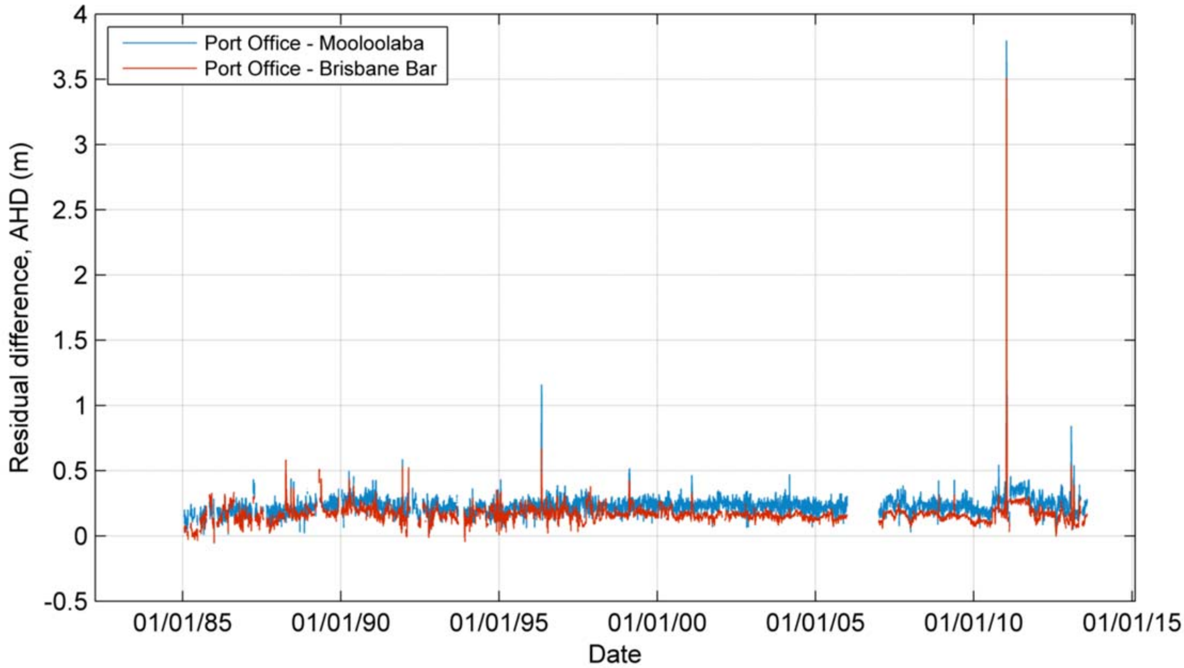


Figure 4-11 The Differences in Filtered Tidal Residual between the Port Office and Mooloolaba and Brisbane Bar

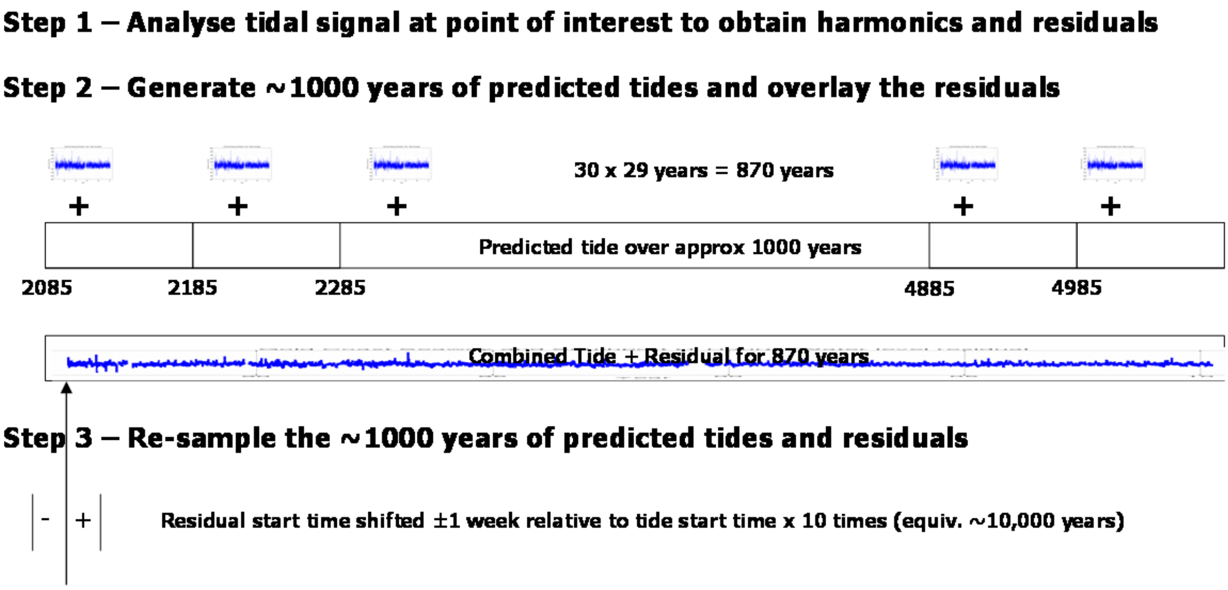


Figure 4-12 Overview of the Tidal Residual Re-sampling Process

Firstly, for each station, thirty separate 29 year long tidal predictions were generated with each prediction set arbitrarily one century apart starting in the 85th year of the century (e.g. 2085, 2185, ... 5085). This is simply a means of separating and sampling the natural tidal variability at the astronomical scale and providing a long timebase for overlaying the measured residuals.

Next, each 29 year tidal prediction was recombined with the measured 29 year residual but with the starting date of the residual randomly offset by up to 2 weeks (336 hours). The random offset was in whole hours equivalent to the time step of the original data and residuals and is small enough to ensure retention of the principle seasonal couplings between tide variability and the occurrence of storms of interest. Finally, this tide+residual recombination process was repeated 10 times with different time offsets to provide a synthetic water level record of almost 10,000 year. The yearly maxima were then extracted and ranked to produce the summary statistical plots as shown in Figure 4-13.

This result clearly reflects the differences in the tidal planes between each station, increasing from ocean to river, but also the shallow water storm surge response. Mooloolaba and Brisbane Bar predicted water levels can be seen to commence to asymptote by the 10,000 year Return Period but the Port Office still shows increasing tendency, likely still reflecting the effects of retention of some riverine flooding residuals in the data.

Of special note is that the level of HAT (1.5 m AHD at Brisbane Bar) is estimated to be experienced almost annually as a result of the non-astronomic atmospheric influences, rather than the 18.6 year astronomical interval.

The resampling method can be directly used to estimate the variability of the AEP estimates, as shown in Figure 4-14 for the 29 year data period. This shows, in dark blue, the same simulated estimate for Brisbane Bar from Figure 4-13 and, in black, the measured and ranked annual maximum tide gauge levels. In light blue are then the 300 re-sampled 29 year periods of tide and residuals, which together produce the (mean) dark blue line. The spread of the light blue around the dark blue indicates the sampled natural variability imposed on the system by the presence of tidal variation that is generally much larger than other components represented by the residual.

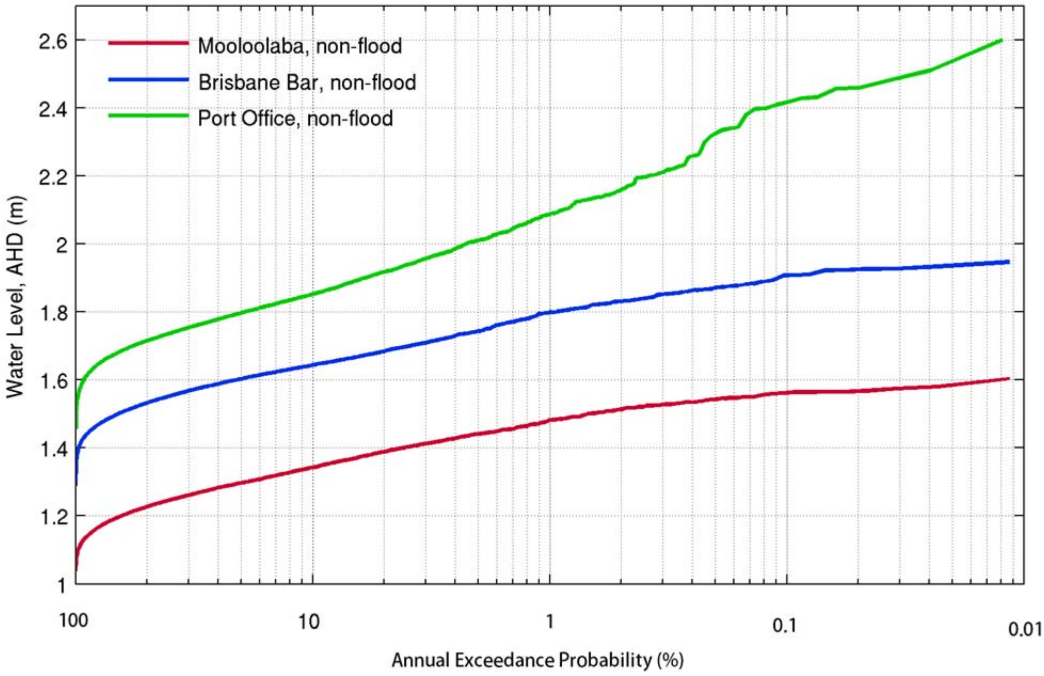


Figure 4-13 Simulated Extra-Tropical Water Annual Exceedance Probabilities

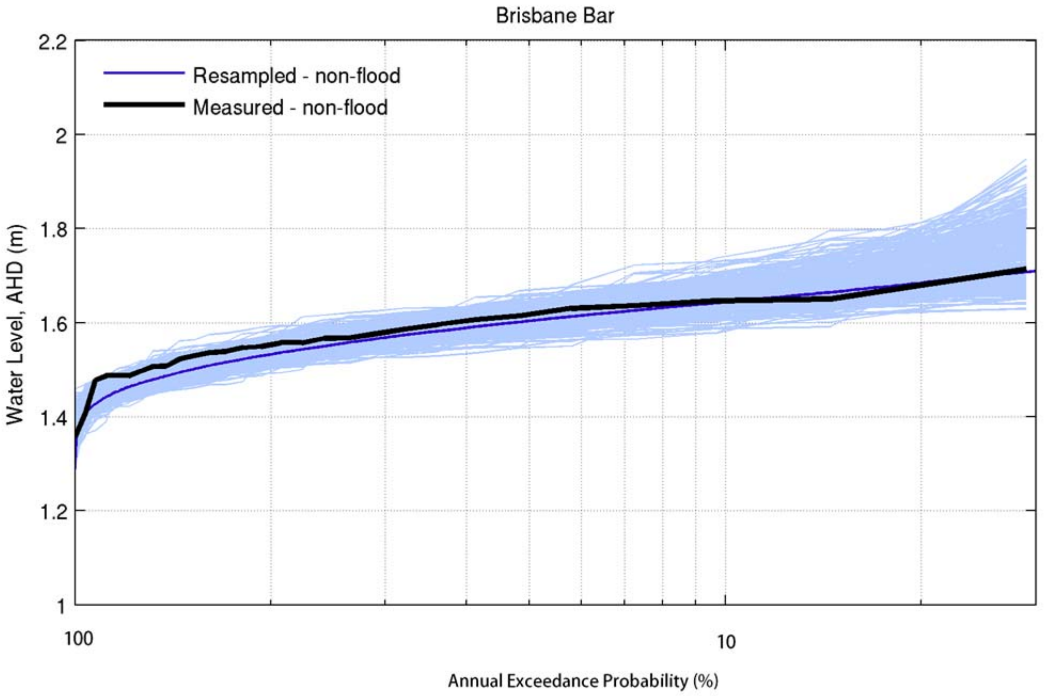


Figure 4-14 Example Annual Exceedance Variability at Brisbane Bar

4.3.4 Extra-Tropical and Remote Tropical Cyclone wave setup

The present methodology does not include spectral modelling of waves for these types of events, which for the same reasons discussed in regard to modelling of the storm surge, present challenges in terms of representation of wind fields and require significant computational effort. However, a series of spectral wave model tests was undertaken to show that wave conditions inside Moreton Bay are essentially independent of conditions outside and this permits simplification of the analyses for estimating the extra-tropical wave setup component inside the bay. The result of this systematic series of numerical tests is shown in Figure 4-15. It summarises the modelled differences in various spectral wave parameters between locations inside and outside of Moreton Bay when the model is forced with steady-state winds (20 ms^{-1}) from N, NE, E and S directions. These winds are representative of gale to storm force winds such as those experienced during Ex-TC *Oswald.* In each case the simulation has been conducted at MSL. The significant wave height (H_s), zero-crossing period (T_z) and peak spectral period (T_p) are shown and indicate, besides the clear attenuation in H_s, that the wave periods do not exceed the 6 s expected of the available inside-bay fetches and show that externally generated long period swell energy likely does not penetrate to these inside locations. While the model is merely a representation of the real conditions and the tests were done at a fixed water level, the results are considered robust. Tests at elevated Mean High Water Springs showed a similar response, suggesting that incoming wave energy is effectively dissipated by the extensive banks and shallows forming the northern entrance to the Bay. This can be expected to be an area where vigorous breaking wave setup will produce localised superelevation of the mean water level, which is then quickly redistributed as circulatory currents into and around the deeper channels that form the navigational entrance[9].

Inside Moreton Bay

In this case it is assumed that the wave setup component is formed by locally generated waves only, which are fetch-limited by the maximum dimension of the bay (approximately 40 km at its greatest). To provide a suitable relationship between wave height, period and AEP the long term mean wind data from Brisbane Airport (excluding periods when TCs are active was analysed (i.e. the opposite of the TC-only wind analysis in Section 5.4). Assuming omni-directional winds, which is conservative, these winds are used unadjusted to estimate Hs and Tp for the AEP winds of interest using Young and Verhagan (1996). These wave energy parameters are then used for the estimation of maximum shoreline wave setup[10] using Stockdon et al. (2006) to produce AEP estimates of the wave setup water level component on the open coast within Moreton Bay. In turn these are simply linearly (conservatively) added to the equivalent extra-tropical tide plus surge AEP water levels. The wave setup component estimated in this manner is relatively small, ranging from 0.10 m to 0.15 m over the AEP range required.

Outside Moreton Bay

It can be expected that extra-tropical storm systems will dominate wave setup on the open coast of Moreton island at high AEPs and so should be soundly based. This is achieved by considering the long-term data from the nearby State Government “Brisbane Waverider” located offshore of Point Lookout in approximately 80 m depth.

The readily available 21 year analysis of regional wave heights form this location by Allan and Callaghan (1999) was used for this purpose. This has the advantage that the analysis is presented

[9] Section 5.2.3 provides further commentary on the likely ability to accurately model the breaking wave setup in this region.

[10] A representative depth of 10 m and a beach slope of 0.06 was used in this calculation.

for “Total”, “Cyclonic” and “Non-Cyclonic” wave events using their stratification methodology. Using these results, a regression between the various components was developed and these relationships were applied to the results of the nearshore spectral wave modelling available from the SATSIM TC simulation model.

This permitted estimation of the likely extra-tropical and “combined” wave climate at the open coast sites based on the TC estimates alone, but with an allowance for wave breaking. Wave setup elevations were then estimated analogously to the TC method using Hanslow and Nielsen (1993)[11], assuming a fixed Tp value of 12 s, which is representative of the area. Although there is likely not a clear stratification between the event sets of Allen and Callaghan (1999) and the present study, it can be noted that their “non-cyclonic” storm subset tends to dominate the wave climate in this record and especially at higher AEPs.

In addition to consideration of the extra-tropical wave setup component, the tide plus surge level for such events is preferentially based on the Mooloolaba tidal residuals rather than the Brisbane Bar residuals, which contain the additional influence of wind setup within the bay.

The “Jason_Beach” model site on Moreton Island has been used as the nominal open coast site for estimating the combined tide plus surge plus breaking wave setup elevations that are listed in Table 6-2. These range from 0.7 m to 1.7 m over the AEP range required and have been linearly added to the matching tide plus surge AEP.

[11] Hanslow and Nielsen (1993) is used preferentially to Stockdon et al. (2006) for the exposed open coast sites.

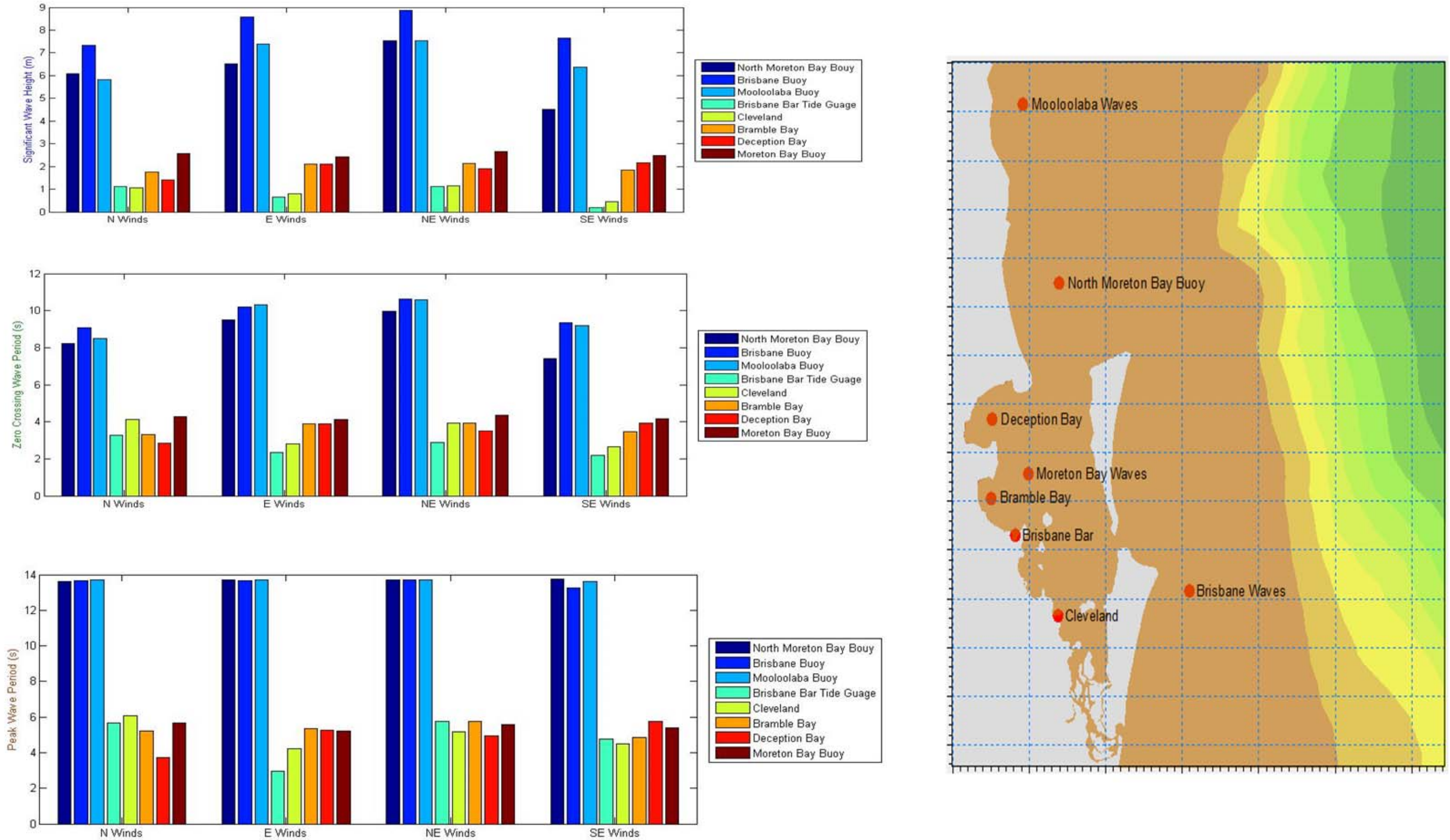


Figure 4-15 Summary of Spectral Wave Model Penetration Tests for Steady State Conditions

5. Model Calibration and Verification

This chapter outlines the various model calibration and verification activities that have been undertaken to demonstrate the suitability and accuracy of both the deterministic and probabilistic modelling components.

5.1 Astronomical Tide Calibration

Calibration of the hydrodynamic models against the astronomical tide was made possible through the availability of a reliable regional tide gauge dataset and long term records at the entrance to the Brisbane River (refer Section 4.3.2). This enabled consideration of the impact of bathymetric datasets and guided the selection of bed friction values to optimise the reliability of the modelled water levels within the measured tidal range.

Astronomical tides in the region are semi-diurnal with a marked diurnal inequality (a significant difference between heights of consecutive high or low tides). The Standard Port for the region is the Brisbane Bar, where the tidal planes are as shown in Table 5-1 (MSQ 2014).

Table 5-1 Tidal Planes at Brisbane Bar

Tidal Plane	Abbreviation	m AHD
Highest Astronomical Tide	HAT	1.49
Mean High Water Springs	MWHS	0.93
Mean Sea Level	MSL	0.03
Mean Low Water Springs	MLWS	-0.87
Lowest Astronomical Tide	LAT	-1.24

Tide predictions using the original eight RHM open boundary constituents only and also a shallow water enhanced set of 17 tidal constituents (Table 5-2) were adopted for Brisbane Bar, the Port Office and Mooloolaba for comparison with the RHM and LHM hydrodynamic model results.

Model sensitivity tests were undertaken using a variety of Mannings bed friction values and some modifications were made to the local Moreton Bay bathymetry as more detailed soundings became available.

The 17 constituent comparisons were accepted for the final comparisons as it is argued that the hydrodynamic model should be capable of generating many of the principal shallow water constituents that are detected from the harmonic analysis of the tide data.

Table 5-2 Tidal constituents adopted for model comparisons

Constituent	Local Phase (-10h) (deg)	Amplitude (m)
Q1	102.53	0.0246
O1	130.87	0.1191
P1	169.09	0.0588
K1	171.59	0.2143
N2	265.35	0.1372
M2	275.09	0.7017
S2	302.3	0.1917
K2	295.36	0.0582
M4	137.46	0.0139
MS4	155.05	0.0080
S4	118.74	0.0009
M6	141.43	0.0112
MK3	348.9	0.0067
MN4	119.52	0.0059
S6	338.32	0.0004
2SM2	117.39	0.0080
M8	313.82	0.0004

Extended Tidal Simulation

The period chosen for the model tidal calibration covers the seven months from January – August 2013 which includes that of Ex-TC *Oswald* in late January. Time histories of the modelled and predicted tides over the period surrounding *Oswald* are shown in Figure 5-1 and indicate a reasonably good level of agreement. This level of agreement is achieved over the full seven month period with a calculated RMSE of 0.066 m at Brisbane Bar.

Statistical Tide Comparisons

While the RMSE is acceptable and a visual comparison is instructive, it is important to consider the statistics of the correlations over the tidal range, as shown in Figure 5-2. These show a good comparison, especially at the key location of Brisbane Bar.

Ex-TC *Oswald* Event Peak Period Tides

Finally, Figure 5-3 presents the detail of the modelled and predicted tide signal during the peak of Ex-TC *Oswald*. Again the results are very acceptable, showing a maximum difference of only 0.05 to 0.10 m at any stage of the tide.

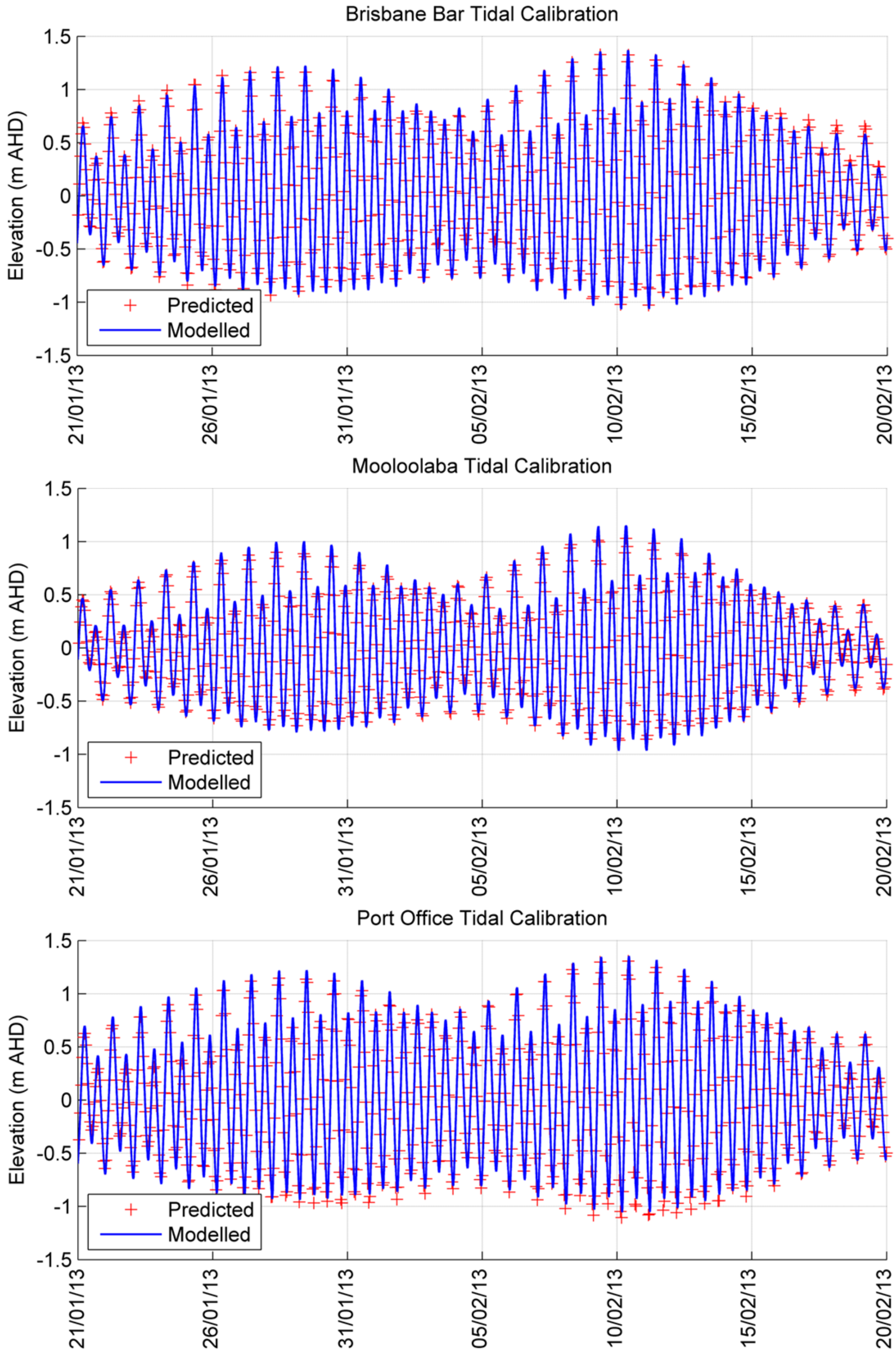


Figure 5-1 Time history comparison of modelled and predicted tides

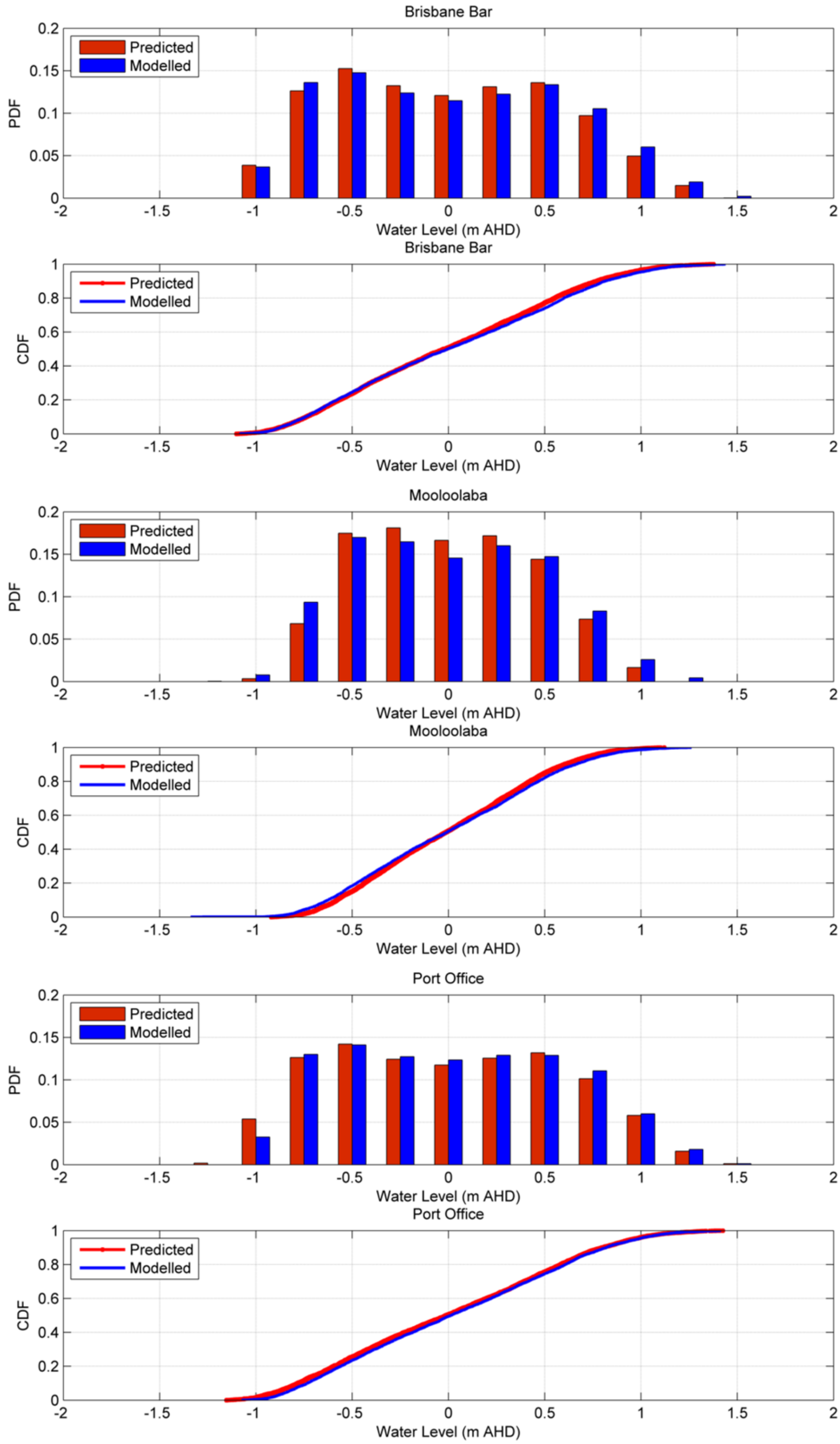


Figure 5-2 Statistical comparison of modelled and measured tide

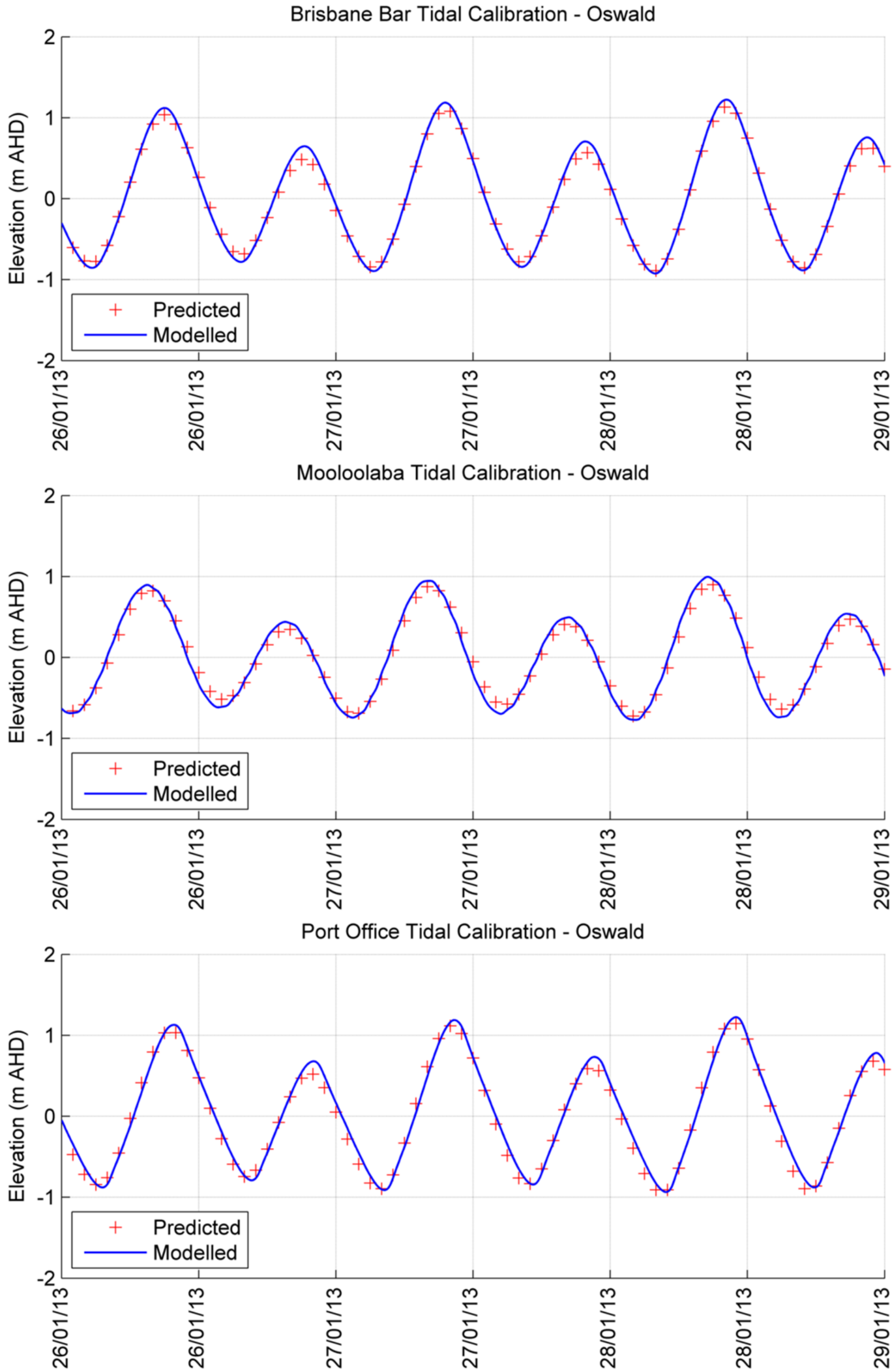


Figure 5-3 Tide modelling performance during peak of Ex-TC *Oswald*

5.2 Ex-TC *Oswald* Event Jan 2013

Given the significant impact of the January 2013 event within Moreton Bay and the ready availability of a wide range of data Ex-TC Oswald it was selected as the principal wind and pressure-forced model calibration storm for this study.

5.2.1 Meteorology and Broadscale Wind and Pressure Fields

A full description of this storm event has been provided by GHD's specialist sub-consultant meteorologist Mr Jeff Callaghan and is provided in Appendix C. This highlights the complex (transitioning) nature of this long-lived system from its formation as a deep monsoonal low in the southern Gulf of Carpentaria, its brief period of Category 1 tropical cyclone intensity at the time it crossed the Cape York coastline near Kowanyama on 21st January, and its subsequent southward movement just inland from the coast over the next several days. This relatively weak system maintained its broad circulation after crossing the coast, stalling inland from Rockhampton on Jan 25-26 (Figure 5-4), and intensified its effects over the ocean as it transformed into an ECL-like system, generating a period of sustained north-easterly gale force winds south of the Capricorn Coast. This is evident in the detailed satellite-derived scatterometer winds near the peak of the event (Figure 5-5) superimposed with measured land-based mean winds (gale force is 35 knots, or 17 m/s). Figure 5-6 additionally summarises peak winds at measuring sites in and around Moreton Bay at the same time (Note that Cape Moreton winds are topographically enhanced). Subsequently the system moved rapidly southwards and its effects dissipated relatively quickly.

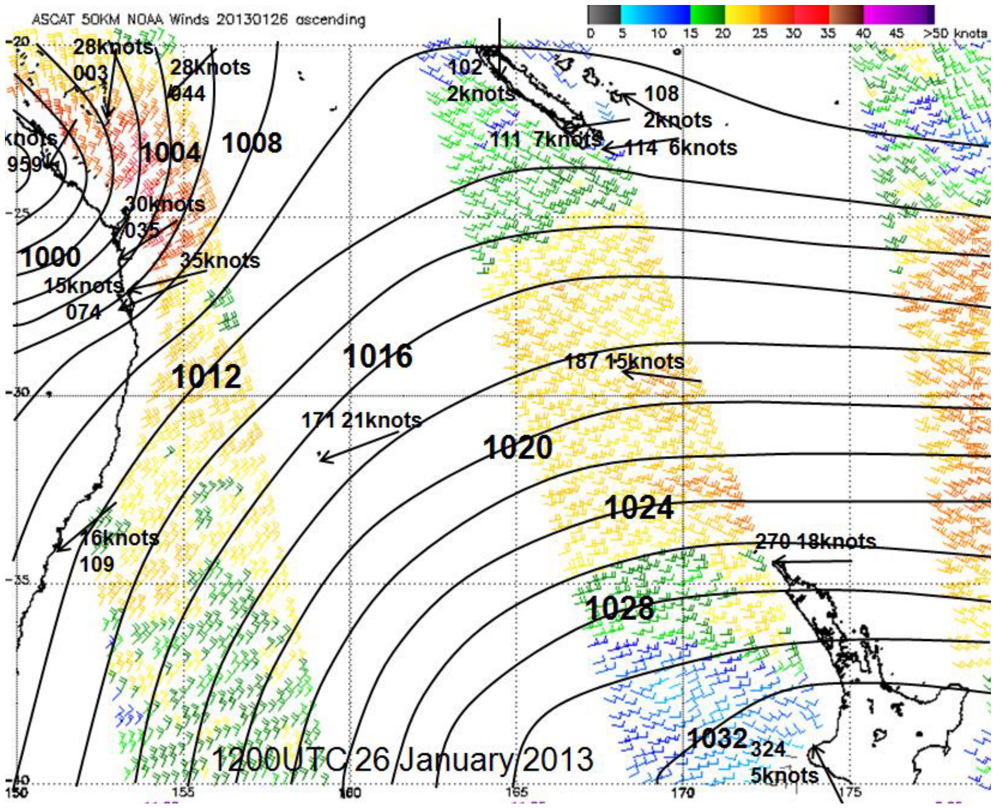


Figure 5-4 Synoptic NOAA-GFS numerical modelling and scatterometer winds near the peak of Ex-TC *Oswald*

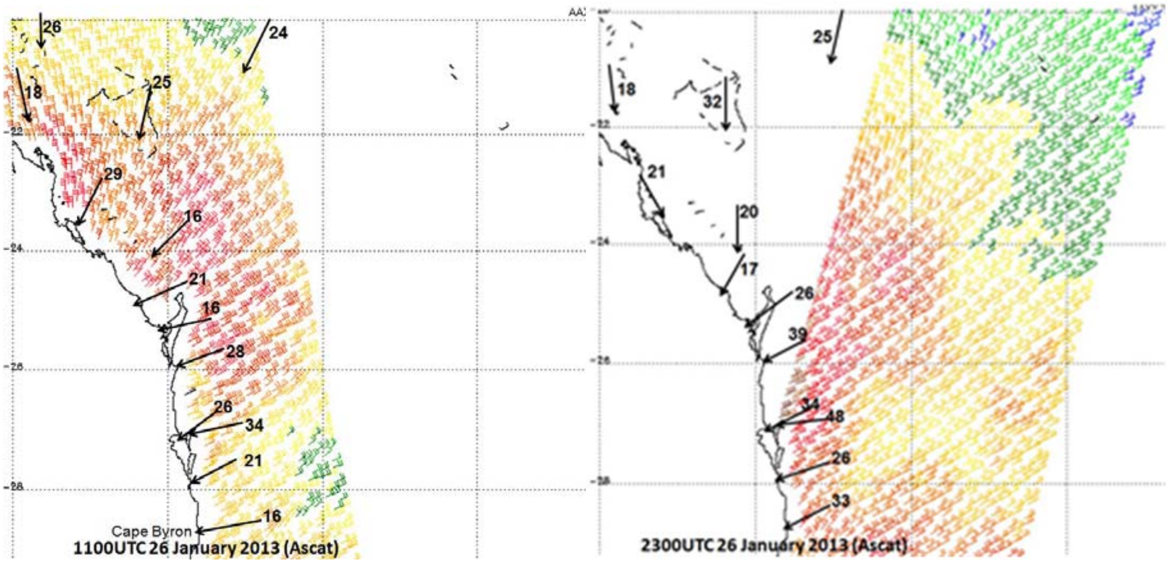


Figure 5-5 Satellite scatterometer winds and superimposed land-based winds during the peak of Ex-TC *Oswald* (knots)

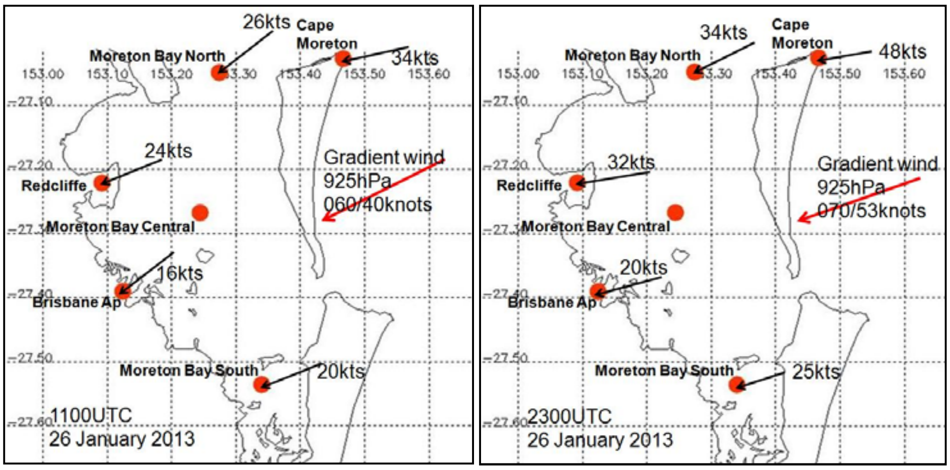


Figure 5-6 Land-based measured winds around Moreton Bay during the peak of Ex-TC *Oswald* (knots)

5.2.2 Model Wind and Pressure Forcing

As previously noted, these types of events have complex wind and pressure fields that are difficult to reproduce in any idealised manner and, without the detail now available from numerical weather models are almost impossible to reproduce. In this case the ACCESS R modelled wind and MSL pressure fields were obtained from BoM, which have a spatial resolution of about 10 km and represent nominally “surface +10m” mean wind speeds, available 6 hourly. These have been compared with measured surface winds and pressures at a total of 12 AWS (automatic weather stations) in the region of interest. This required topographic adjustment to winds at the elevated Cape Moreton sites, which were based on Ginger and Harper (2004). The results of these model and data comparisons are shown in Figure 5-7 for each AWS site. Figure 5-8 additionally provides the spatial context of the storm track and the AWS sites as well as error statistics.

It can be noted that the ACCESS model assimilates all of the data from these sites as well as available scatterometer data in its calculations, but this does not ensure a close matching, as is evident in the comparisons. After inspection, the graphed wind speeds shown were nominally adjusted upwards by 10% in order to better match the more reliable (better exposed) winds in the immediate vicinity of Moreton Bay, which includes Spitfire Channel (#9), Redcliffe Airport (#10) and Brisbane Airport (#12). This is a simple bulk adjustment well within the likely error range of the ACCESS model surface boundary layer approximation. In spite of this it can be seen that the model still underestimates peak winds at a number of regional AWS sites, notably Sunshine Coast Airport (#8) and Coolangatta Airport (#6). The mismatch at Cape Moreton is likely due to the model feeling some topographic effects. The MSLP are generally well matched at the peak of the event, as are the wind directions. The statistical summary in Figure 5-8 highlights some of these visual observations in the crossplots of wind speed, MSLP and direction. The RMS errors, bias and correlations are also shown for each station indicating the variability in the accuracy across the region, which is likely complicated by site specific issues that are beyond resolution within the present study scope. Peak modelled wind speeds generally appear to be within 2 to 3 m/s (approx. 10 to 15%) of the measured winds, except at Sunshine Coast Airport (#8), where there is no logical explanation for the consistent 5 to 8 m/s negative bias at this reasonably well exposed coast-adjacent site.

In summary, while the available ACCESS model pressure forcing appears accurate, there is an overall negative bias in the wind forcing even after a nominal +10% adjustment, which can translate into the resulting storm surge magnitude. Any further adjustments were deemed impractical and unjustifiable given the spatial and temporal complexity of the storm system.

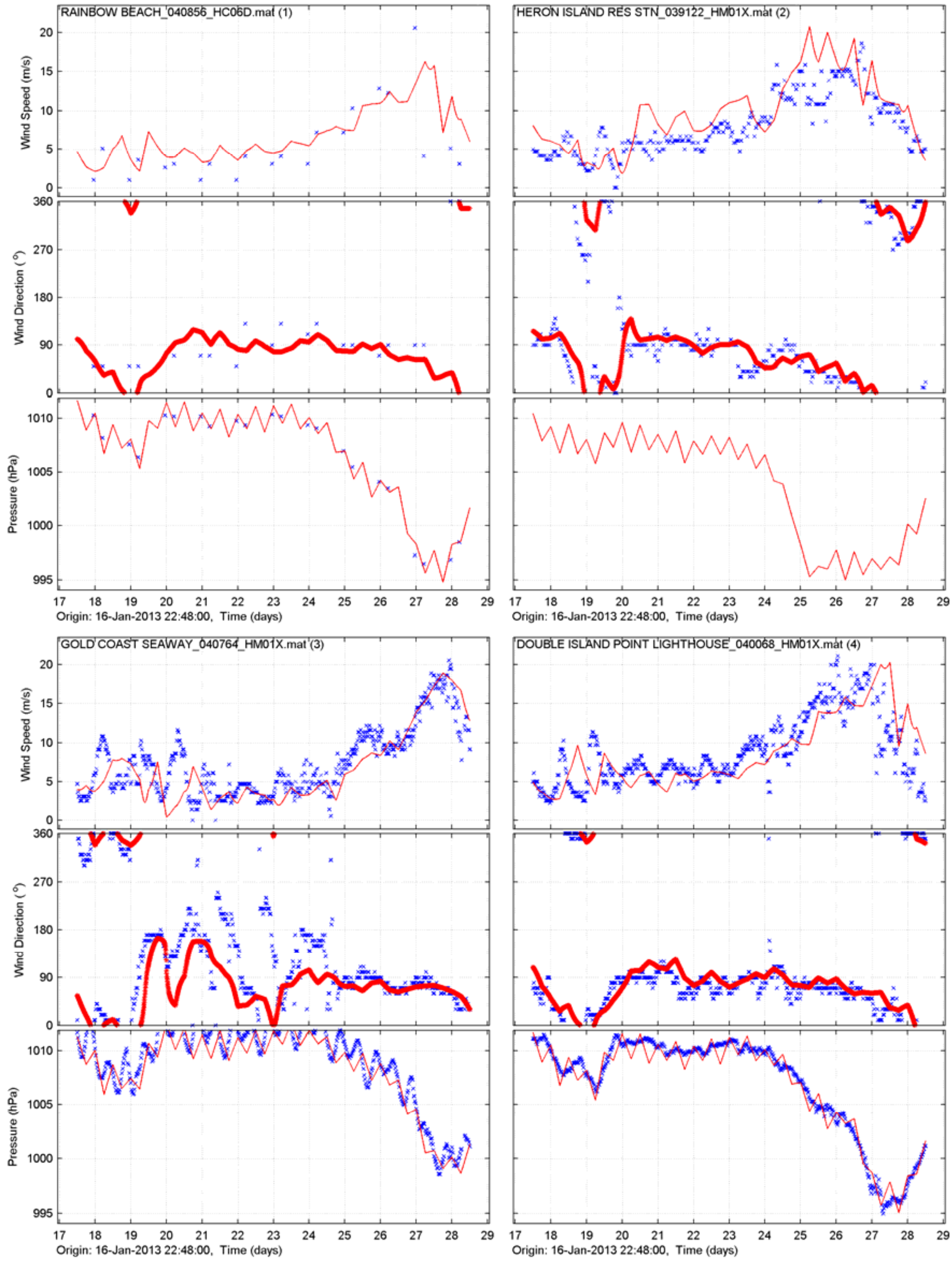


Figure 5-7 Comparison of measured vs modelled winds and pressures in the region of interest (blue is data, red is modelled).

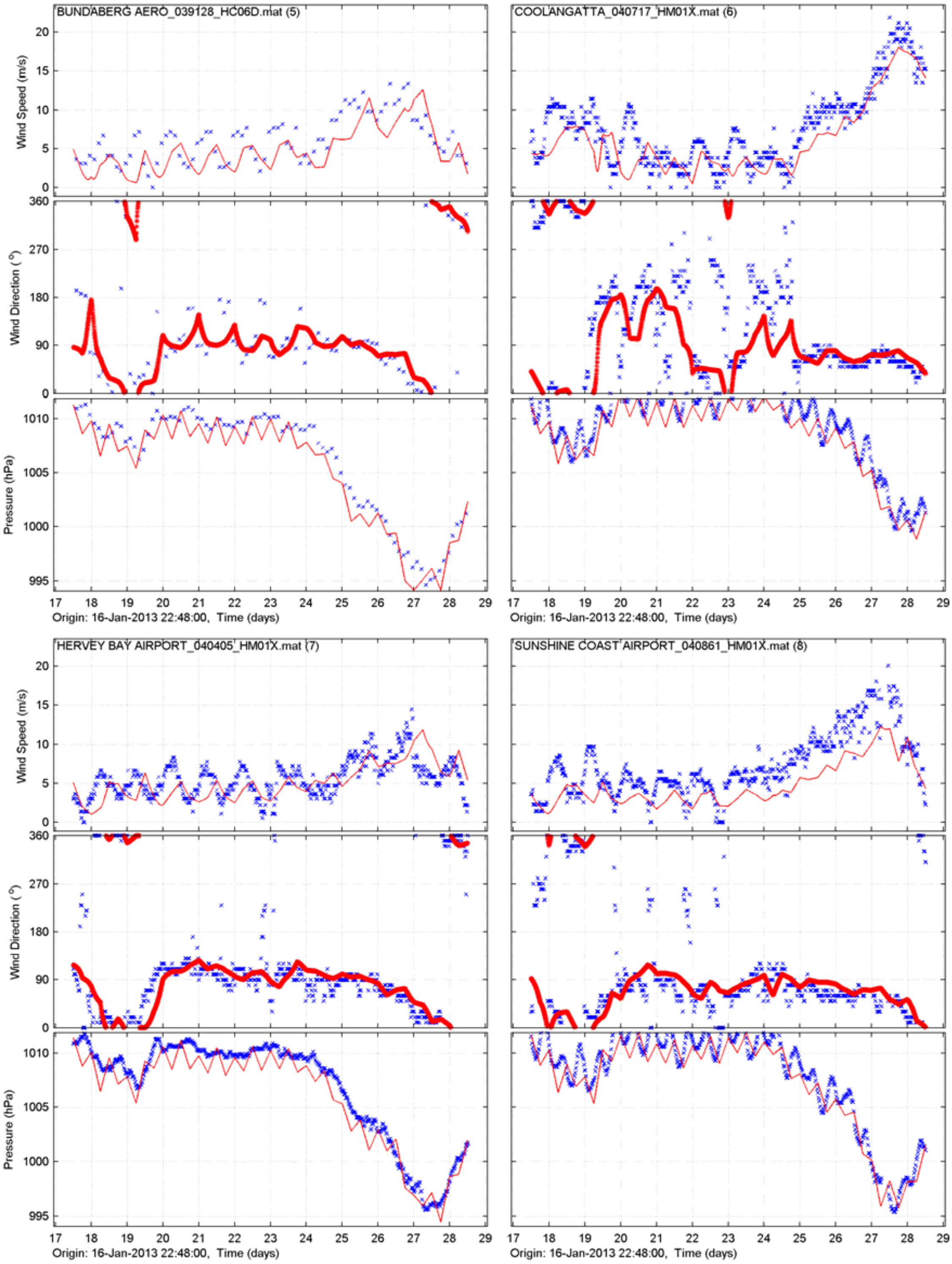


Figure 5-7 (contd.) Comparison of measured vs modelled winds and pressures in the region of interest.

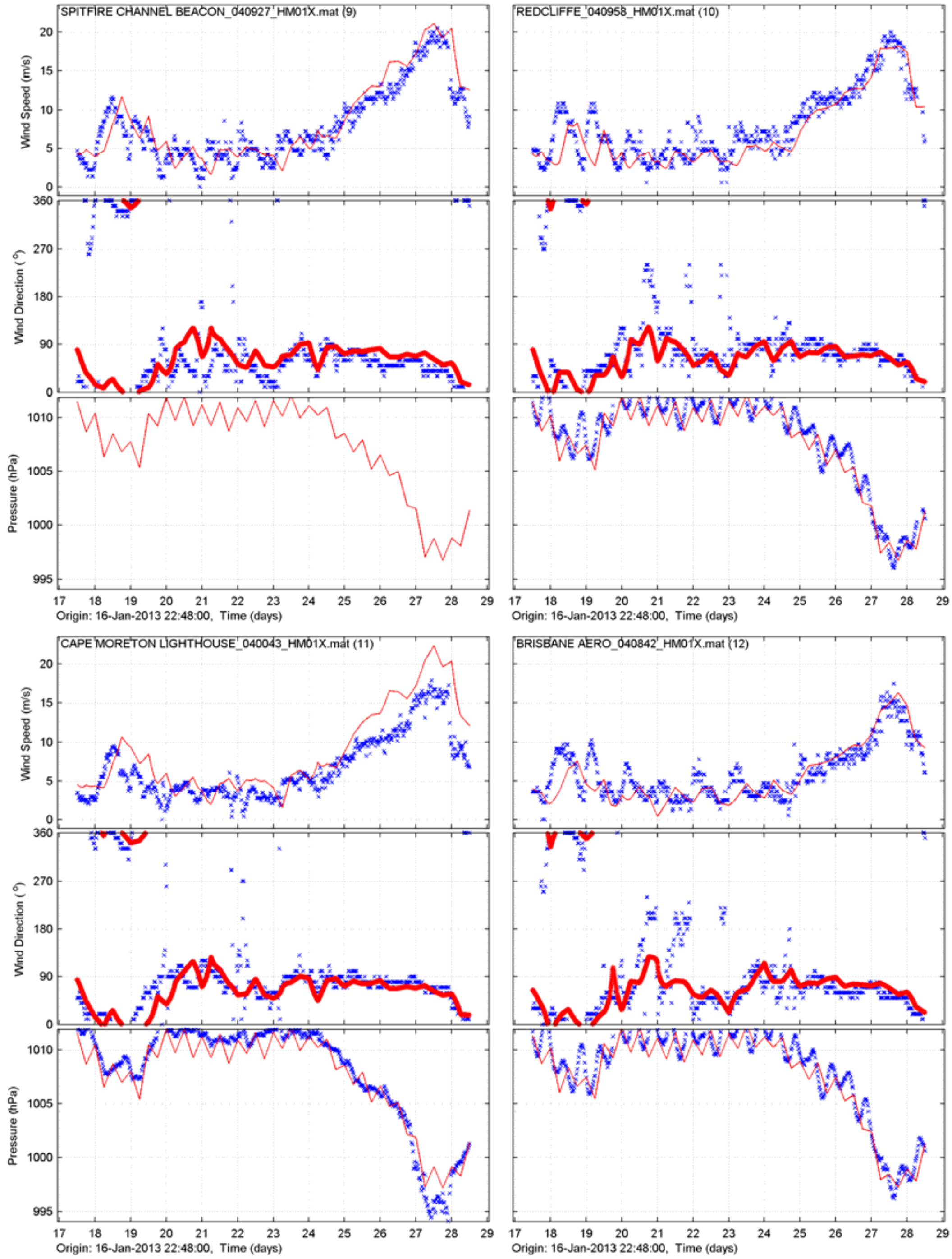


Figure 5-7 (contd.) Comparison of measured vs modelled winds and pressures in the region of interest.

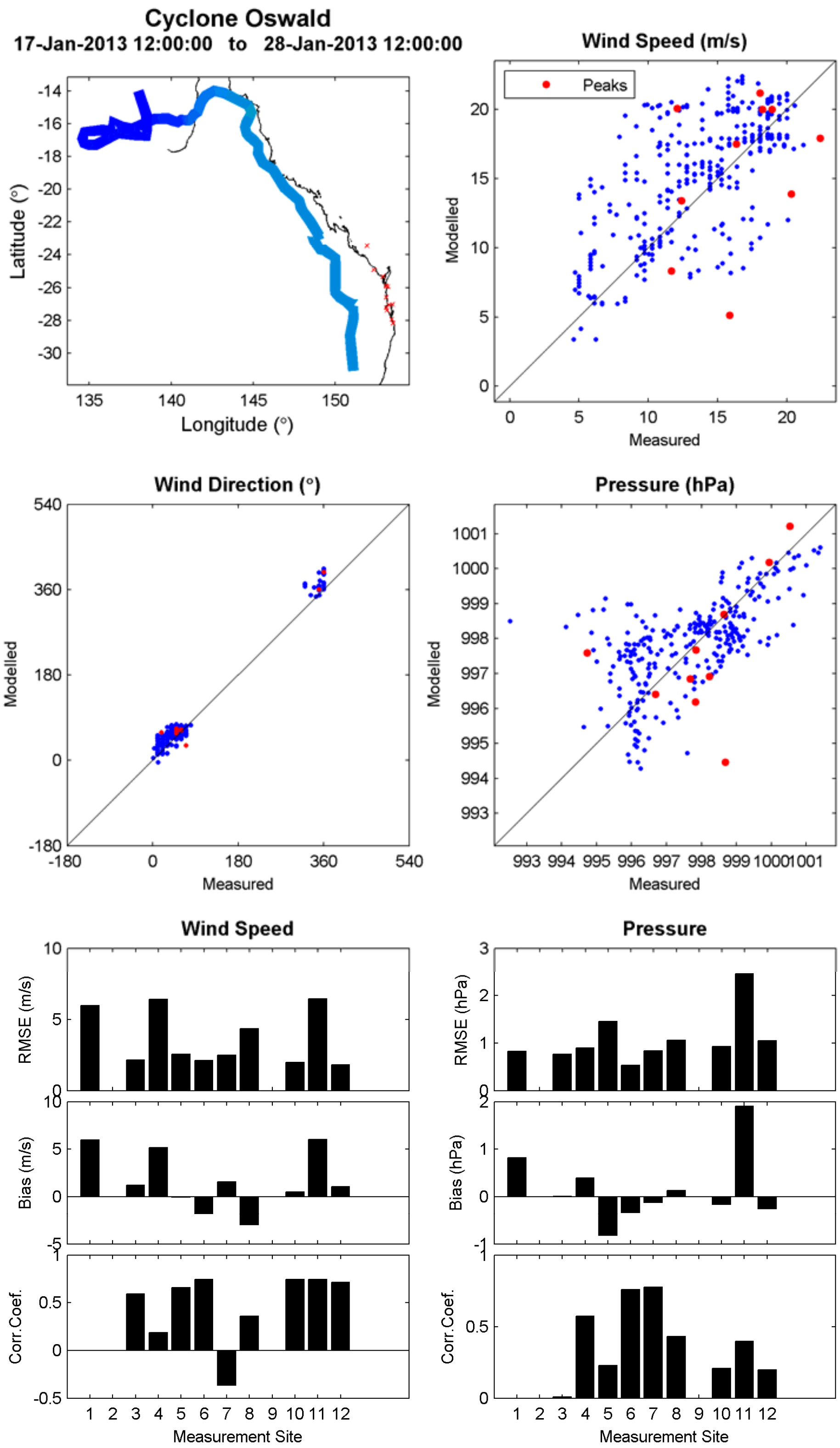


Figure 5-8 Summary of measured vs modelled winds and pressure statistics in the region of interest.

5.2.3 Hydrodynamic Modelling of Storm Surge, Waves and Storm Tide

The ACCESS wind and pressure fields over the period 16 Jan to 31 Jan 2013 described above were used to drive the Regional Hydrodynamic Model (RHM), with open boundaries provided from a global tidal model analysis having 8 constituents (refer Section 5.1).

Initial Trial Simulations

The results of the initial simulation are presented in Figure 5-9 for Mooloolaba and Brisbane Bar tide gauges, with the measured total water level shown in the background. It is clear that the model does not completely resolve the peak tidal residual (*aka* net storm surge), being about 0.2 m lower at Mooloolaba[12] and almost 0.4 m lower at Brisbane Bar. Comparisons at Tweed Offshore and Coffs Harbour similarly under-predicts the peaks. Some of this inaccuracy within Moreton Bay (about 0.05 to 0.10 m) can be attributed to the modelled tide not exactly matching the predicted tide, leading to modulation of the surge(as discussed previously) and this is likely responsible for the observed phase shifts in the residual. Some of the under-prediction can also be logically assigned to the previously discussed deficiencies in the applied wind field[13]. While in absolute terms these differences are relatively small, they are significant proportions of the tidal residual and the temporal and spatial scale suggests that the model is lacking the ability to generate the full measured ocean response at these two sites.

Unfortunately this is a familiar outcome in the numerical barotropic modelling of similar magnitude storm tide events in the region, i.e. storm to gale force conditions generated by large scale ECLs or remote TCs. Examples from past investigations include TC *Dinah* (GHD 2012), a close but parallel to coast event, and the remote TC *Roger* (Stewart et al. 2010). In the latter research study a barotropic model of similar characteristics to the present RHM was extensively tested over a range of possible parameter ranges (wind speed, wind stress, tidal amplitude, wave coupling etc) and failed to reproduce the measured tide gauge responses over a wide area and to a similar difference in magnitude. Stewart et al. (2010) recommended more investigation using 2D or even 3D models and more offshore instrumentation.

A similar range of sensitivity testing was conducted for the present study, especially targeting the assertion and reliance from earlier studies (CLT 2009) that regional breaking wave setup is responsible for the mismatch. This was discounted by Stewart et al. (2010) and likewise here. Although including coupled wave and hydrodynamic modelling in the RHM does produce an increased residual response it remains an unconvincing outcome due to (a) the clear lack of wave-scale resolution in the RHM at the entrances to Moreton Bay, (b) the presence of modelled wave setup inside, for example, the Gold Coast Seaway where measurements indicate (P. Nielsen, personal communication) none occurs, and (c) modelled wave setup cannot explain the mismatch at the Mooloolaba gauge and the Tweed Offshore gauge during such events. Also, some wave-coupled tests produced unexpected and unusual results that could not be reasonably accepted. Also, a 3D barotropic model test using the RHM for Ex-TC *Oswald*, for example, did not yield more convincing results.

[12] The RHM does not resolve the actual location of the Mooloolaba tide gauge but it is assumed that this gauge, which is in close proximity to the river entrance channel, has sufficient connectivity to regard its data as representative of the open ocean. The possibility of this data being flood affected during this time has also been considered but deemed likely to have had little impact.

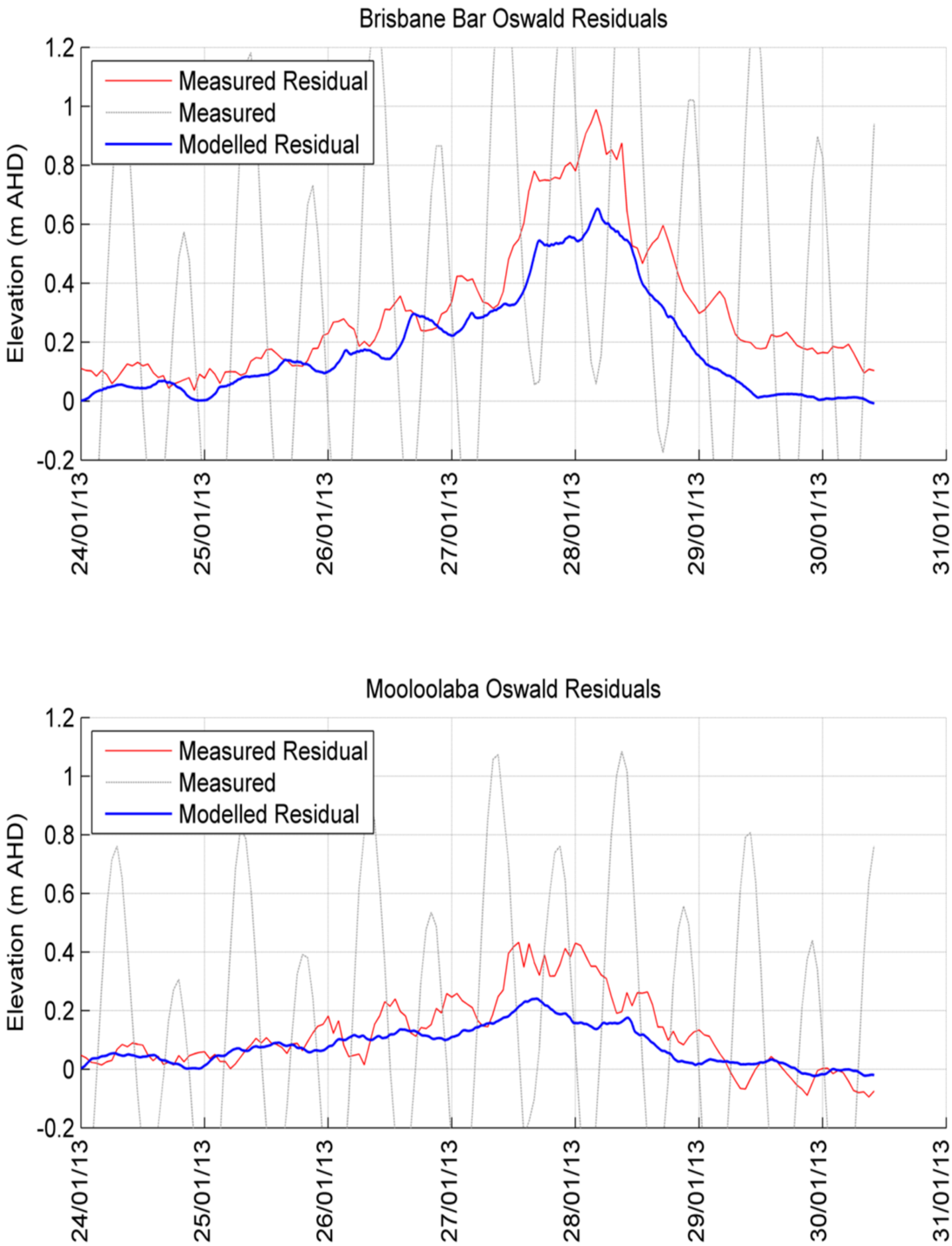
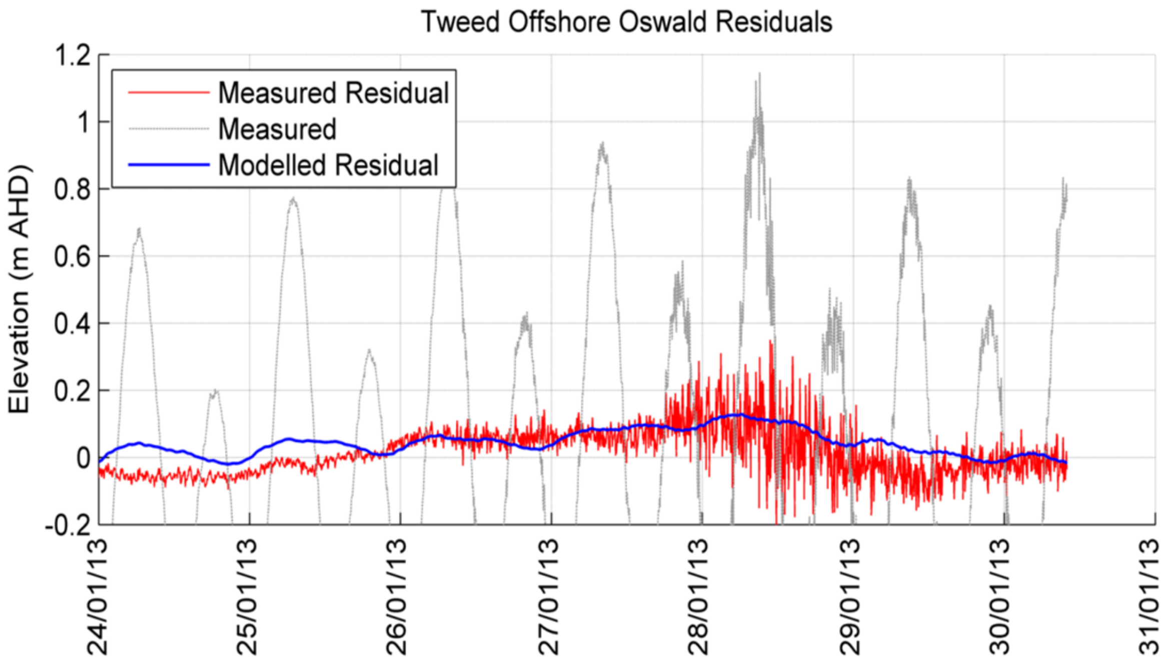


Figure 5-9 Measured and initial RHM-modelled tidal residuals during Ex-TC *Oswald*



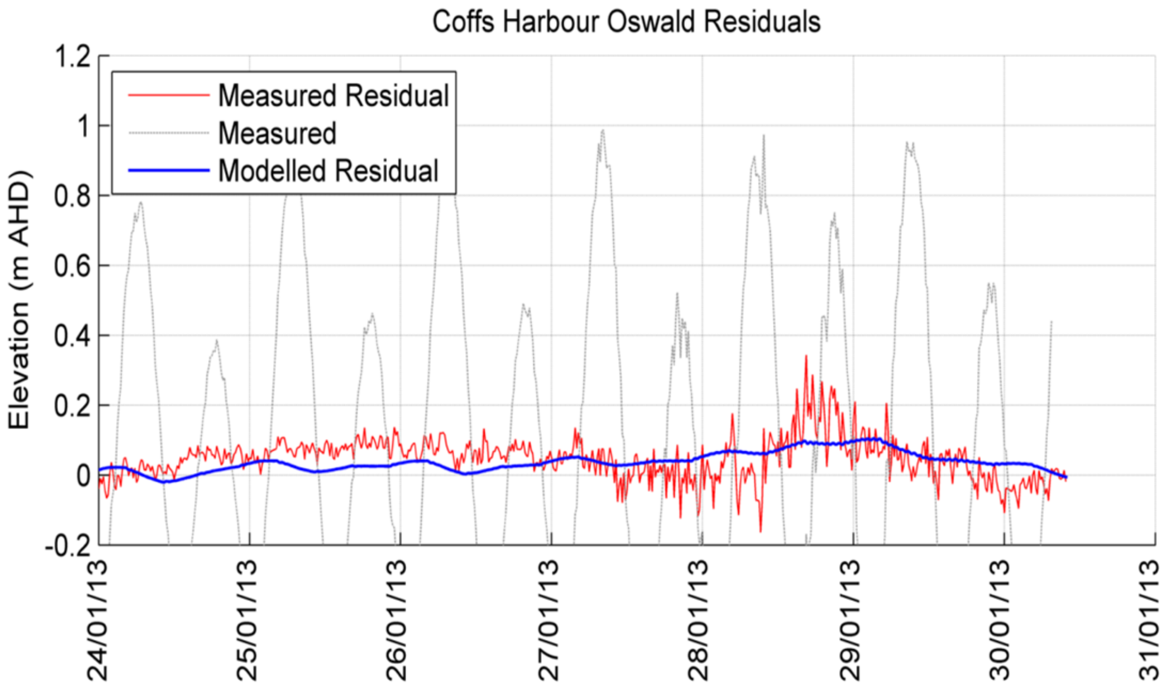


Figure 5-9 (contd.) Measured and initial RHM-modelled tidal residuals during Ex-TC *Oswald*

Final Representation

Based on the present experience and numerous previous investigations, it is hypothesised that the observed lack of response to these types of events in this region derives essentially from energetic baroclinic processes that are simply not being represented by 2D or 3D numerical barotropic modelling. Although Coriolis forcing is represented, and is capable of generating a Kelvin wave response on the adjacent coast, it is well known that upwelling events on steep continental shelves, combined with non-linear tidal forcing, can generate free waves that propagate widely. This, combined with the complex initial conditions of the adjacent Coral Sea as depicted in Figure 5-10, likely is responsible for the mismatches that accompany such investigations.

These complex warm and cold eddy fields forming the East Australian Current (EAC) are in meta-stable geostrophic balance that can be distorted by the applied wind stress and impinge on the shelf break. Even with a 3D baroclinic model, initialisation alone would remain a significant challenge and such models are deemed impractical for these types of investigations.

As a practical and reasonable alternative, the *Oswald* event has been re-modelled on the reduced LHM domain that includes open boundary forcing equivalent to the measured tidal residual at Mooloolaba[14]. This approach accepts that the barotropic model cannot generate the observed wide scale but low level (deemed baroclinic) response of the order of 0.2 m to 0.3 m that accompanies the peak barotropic response.

This outcome is illustrated in Figure 5-11, where the Mooloolaba comparison simply reflects the fact that it is close to the imposed open boundary residual, which has been smoothed for this purpose. However the calculated response at Brisbane Bar is significantly improved, yet still imperfect at the time of the peak, being of the order of about 0.2 m lower still. Also, the modelled surge drops more quickly than the measured residual, with both these effects likely affected by the quality of the modelled wind field. The unusual rise to the peak of the measured residual could also be a very localised effect associated with river outflow[15] or may be a subtle 3D effect. Project constraints prevent further investigation of these possible effects.

Given the combined complexity of the event this result is deemed reasonable, with scope for further improvement perhaps given a research-grade budget. Importantly, regional breaking wave setup is not considered a significant contributing factor in this event, but rather the lack of baroclinic forcing is considered to be the principal influence. This is consistent with the present methodology for simulating the extra-tropical storm tide using the empirical sampling approach rather than a direct dynamic modelling approach, as baroclinic processes undoubtedly dominate the lower energy response.

Although it cannot be demonstrated with present models or data, it is considered unlikely that this hypothesised low energy baroclinic response persists to the same extent under a strong (hurricane force wind) response that presents with a TC event. This assumes that the higher energy event will essentially introduce mixing and dispersion of the density structures near the shelf break and lessen their influence. Accordingly the alleged “missing” but small baroclinic residual component will not be “added” to modelled TC responses from the 2D barotropic model (refer Section 6.1).

[14] Use of the Tweed Offshore residual on the southern boundary with linear interpolation north to Mooloolaba was also trialled but was less successful. Further trials with a non-linear boundary could yet improve the outcome.

[15] Some tests were undertaken with an estimate of the river discharge included and also reduced salinity (density), which did result in small additional increases in levels.

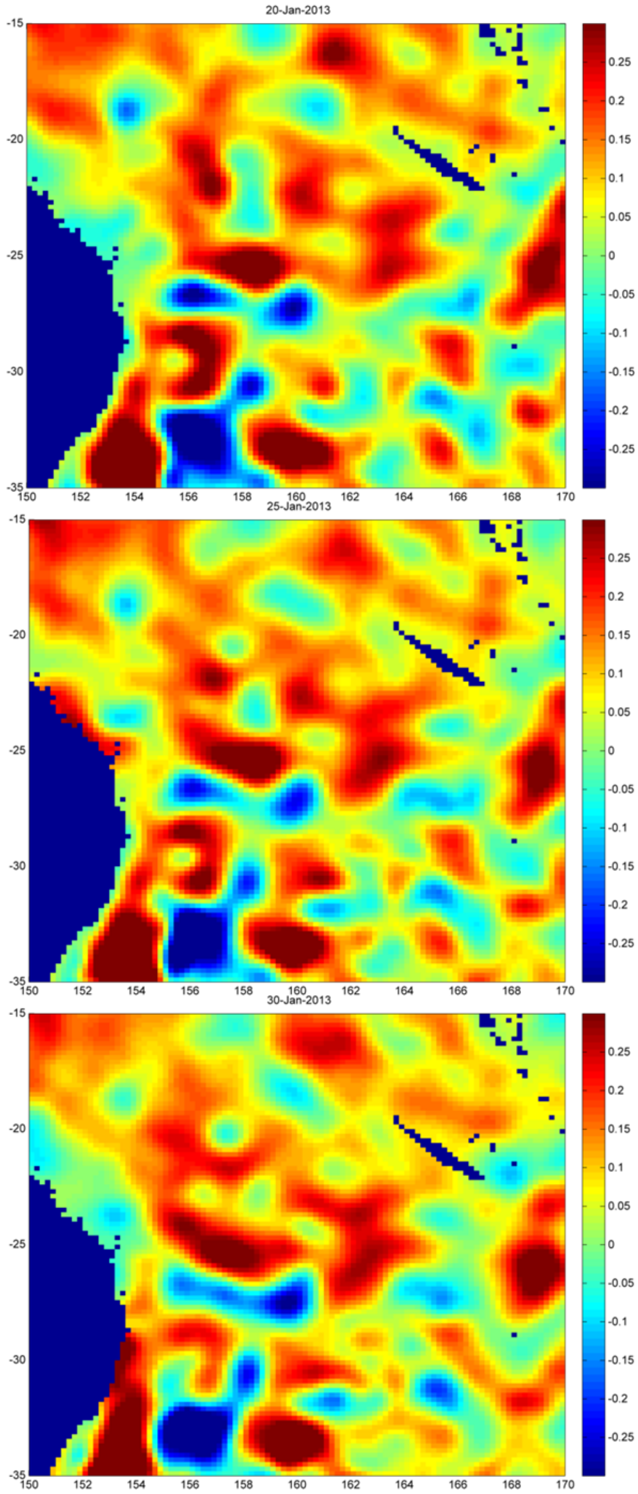


Figure 5-10 Estimated Coral Sea surface height anomalies (m) during Ex-TC *Oswald* from IMOS

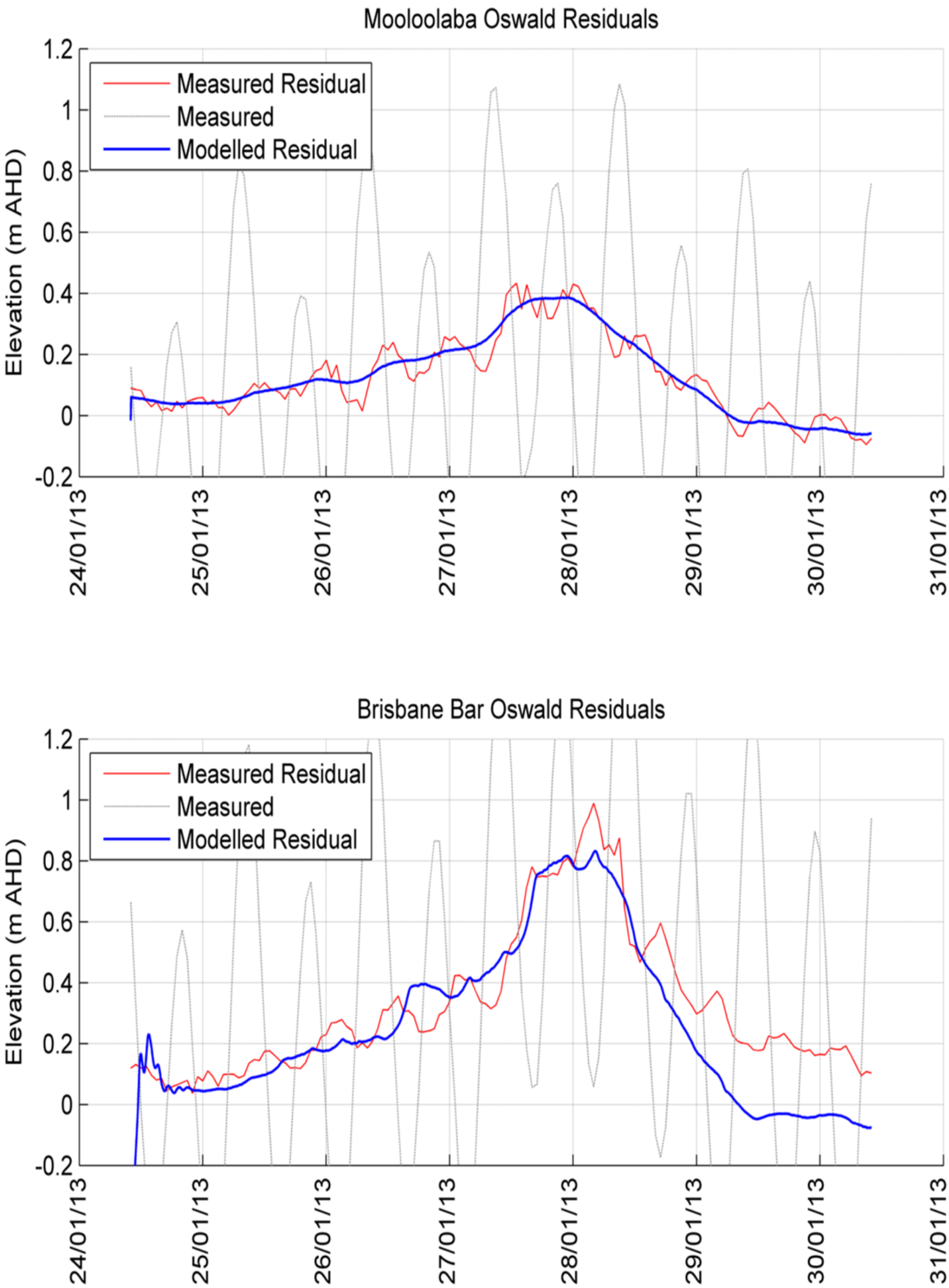


Figure 5-11 Measured and final LHM-modelled tidal residuals during Ex-TC *Oswald*

Spectral Wave Modelling

In addition to the storm tide modelling of *Oswald*, spectral wave modelling was also undertaken, both hydrodynamically uncoupled and coupled (as mentioned in the previous discussion).

The results are presented in Figure 5-12 for the Mooloolaba Buoy, Figure 5-13 for the North Moreton Buoy, Figure 5-14 for the Brisbane Buoy and Figure 5-15 for the Gold Coast Buoy. The location of all these waverider sites, presented north to south, is indicated on Figure 1-2.

Each figure shows the significant wave height Hs (top), the peak spectral period Tp (middle) and the mean wave direction θm (bottom). The red line is the measured data and the blue line is the modelled. All sites show a reasonable agreement with all parameters, noting that the measured Tp values are rather erratic early in the period prior to the onset of significant forcing. Some data errors are also evident.

In each case the Hs is arguably slightly overpredicted, while the Tp and θm are generally quite good at least during the peak of the event. These reflect the quality of the wind field quite directly but do show some structural features throughout the modelled responses that do not necessarily exactly mimic the measured data response.

Overall this is an extremely good result that shows the high coherence of the modelled wind field across the region of interest and the model’s capacity to reliably reproduce measured data.

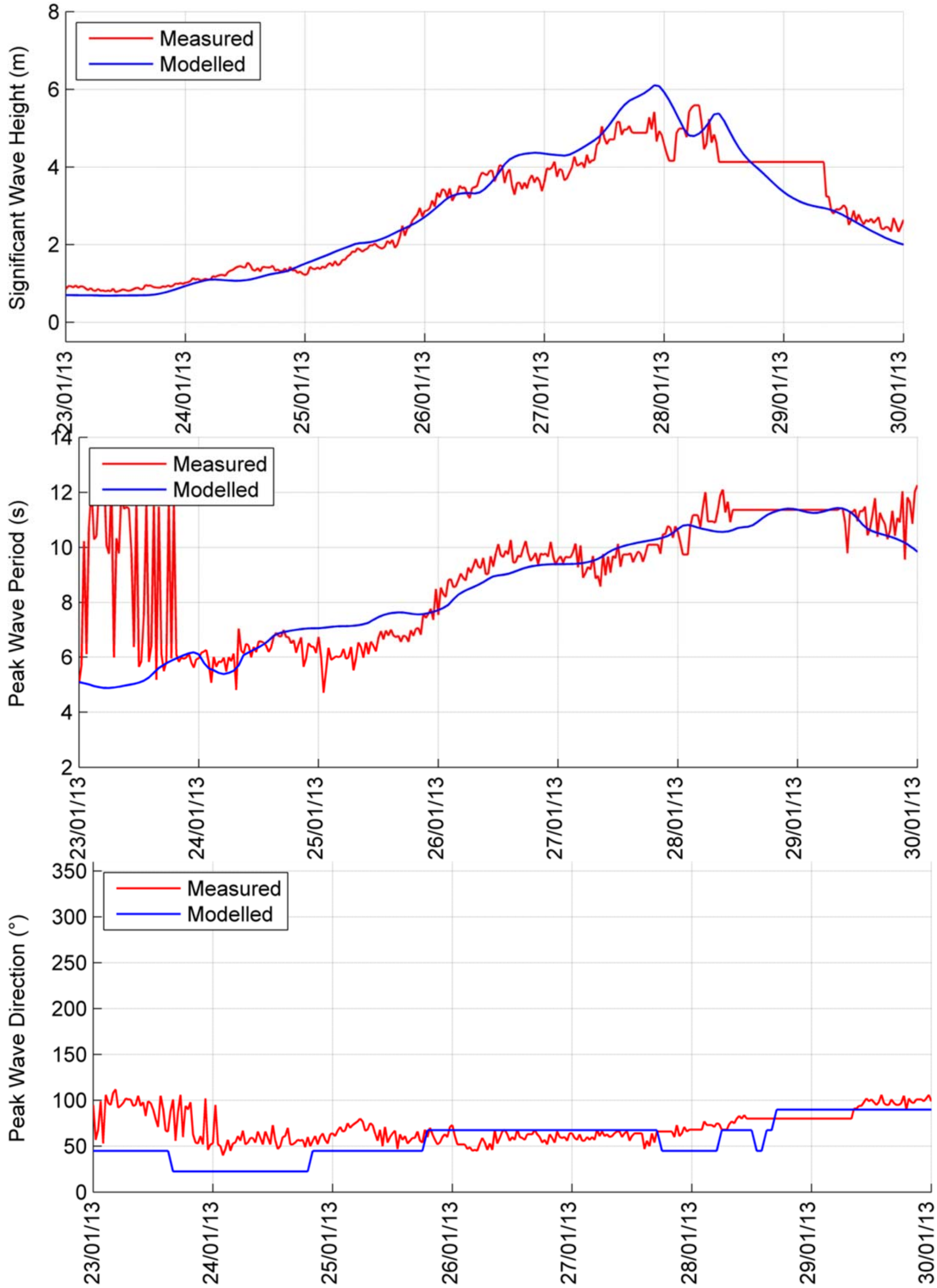


Figure 5-12 Measured and modelled RHM waves at Mooloolaba Buoy during Ex- TC Oswald

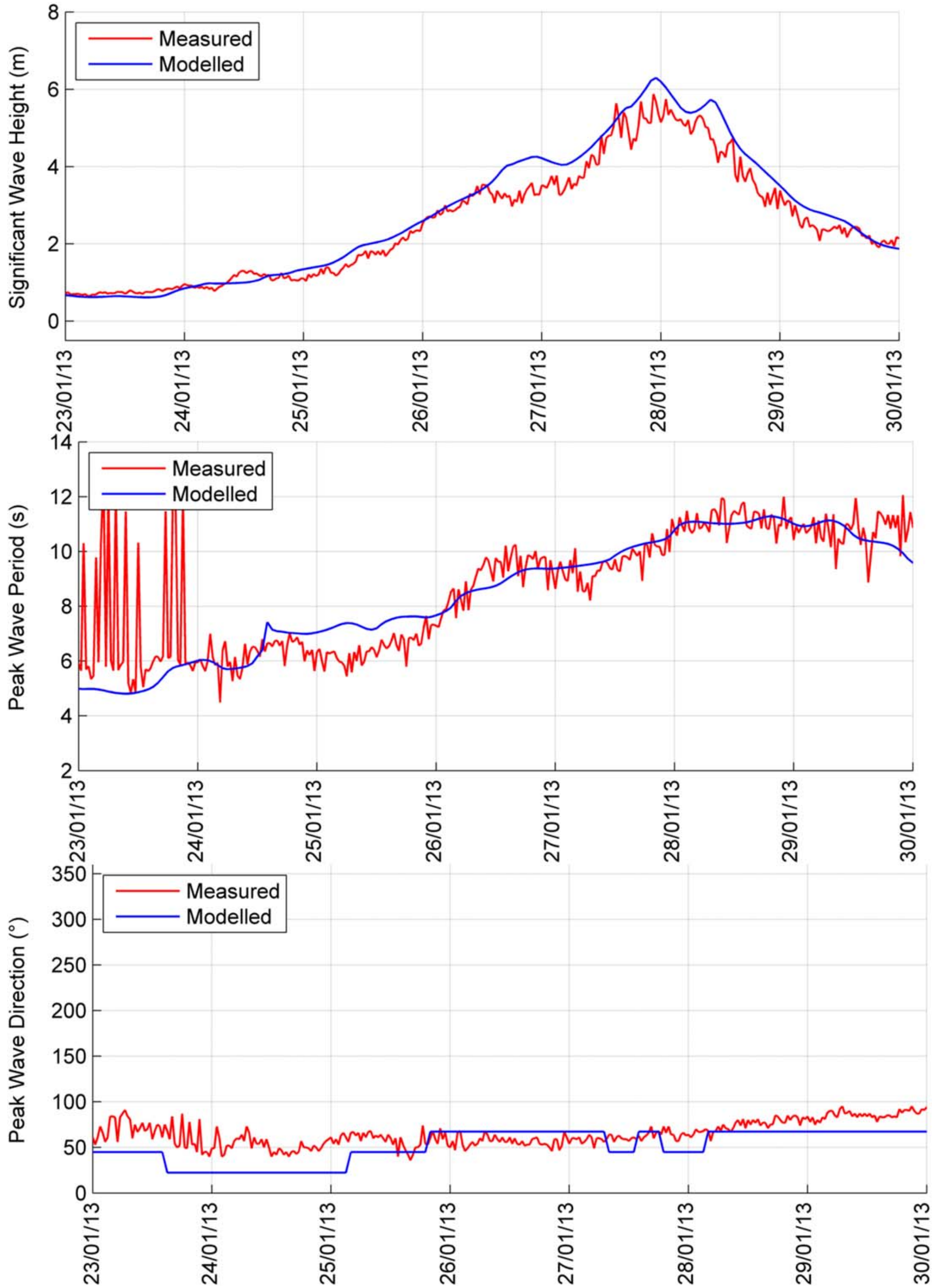


Figure 5-13 Measured and modelled RHM waves at North Moreton Buoy during Ex-TC *Oswald*

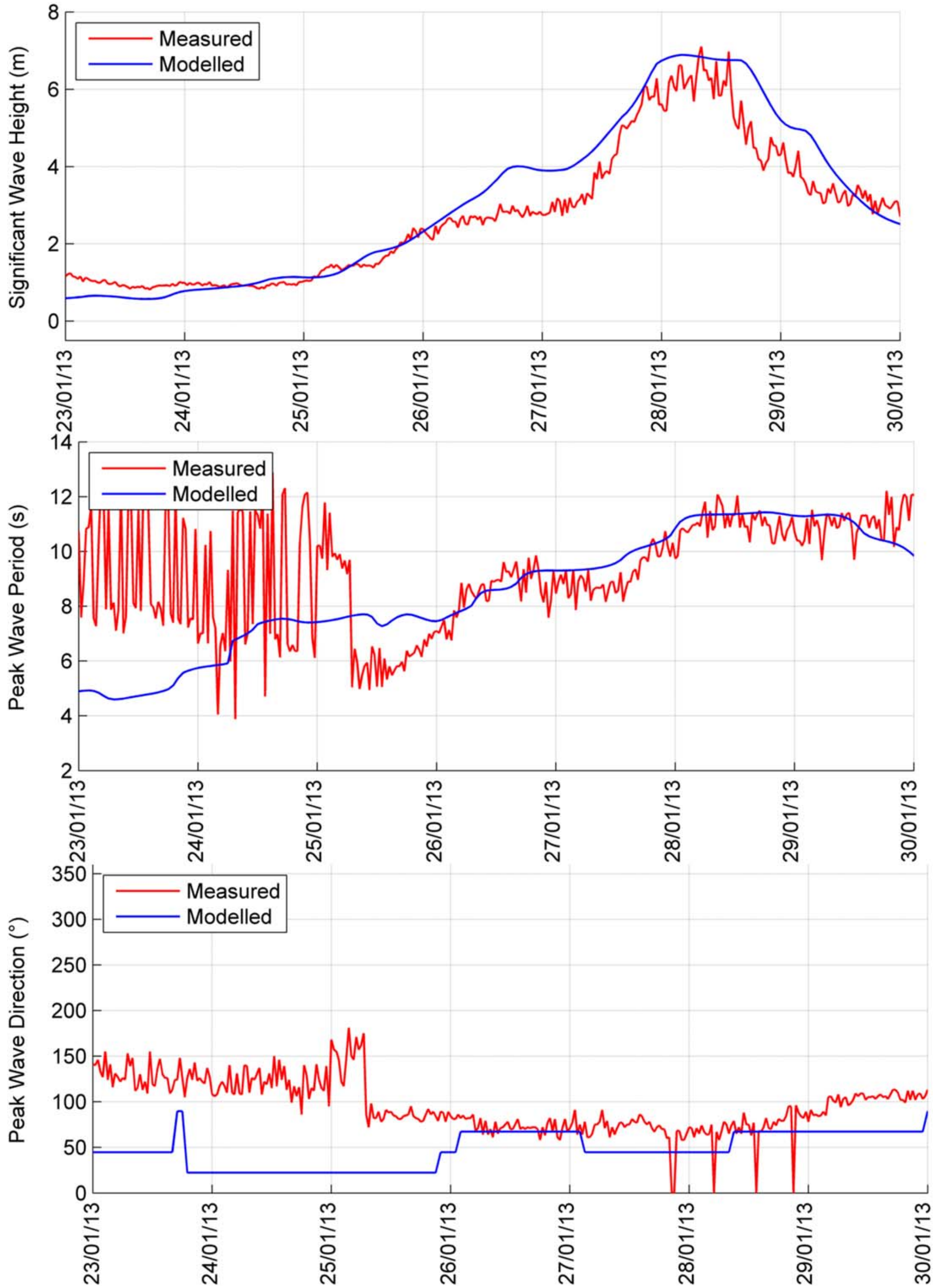


Figure 5-14 Measured and modelled RHM waves at Brisbane Buoy during Ex-TC *Oswald*

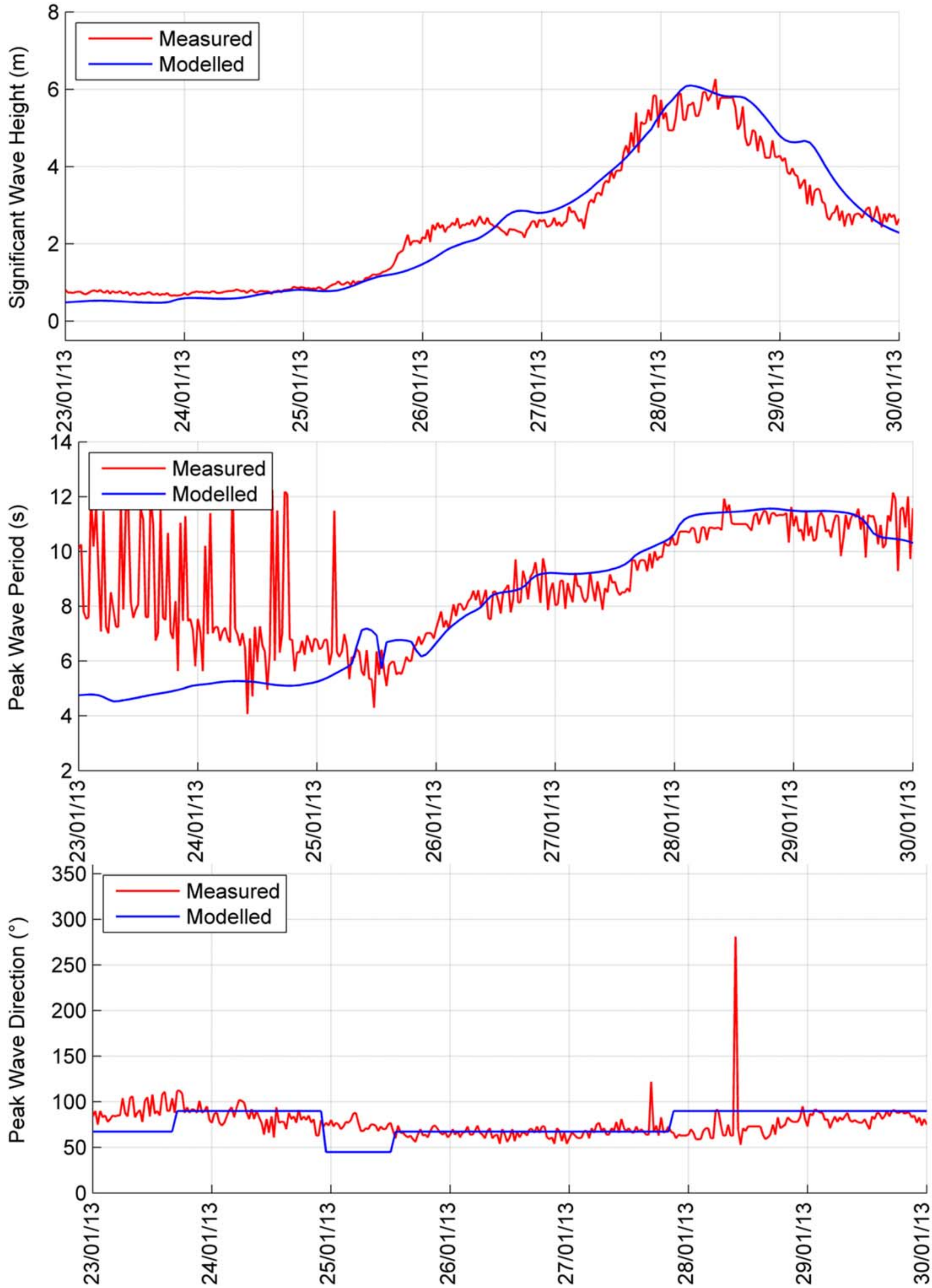


Figure 5-15 Measured and modelled RHM waves at Gold Coast Buoy during Ex-TC Oswald

5.3 Deterministic Verification of the Tropical Cyclone Model

The deterministic accuracy of the regional numerical wind, wave and storm tide models has previously been tested by demonstration hindcasts of the effects of *TC 1954* and TC *Dinah 1967*, although a lack of quantitative data restricted the extent to which comparisons could be made (GHD 2012). Meanwhile, the verification above with Ex-TC *Oswald* using BoM-modelled wind fields, proves the wind and pressure-forced hydrodynamic performance of the model.

5.4 Statistical Verification of the Tropical Cyclone Simulation Model

There is no clear method by which the statistical aspects of the model can be verified, other than ensuring that the various component parts of the model are performing correctly. The statistical checks that can be done relate to the model's re-creation of the astronomical tide statistics and a comparison of its wind speed predictions with available long term regional values.

Figure 5-16 shows the modelled statistics of high astronomical tides at Brisbane Bar compared with the specified HAT tidal plane of 1.49 m AHD. Normally, HAT is associated with an 18.6 y tidal cycle; hence it should fall at around the 5% AEP value if the time is fully sampled. However, the statistical model only samples 6 months of each year (the nominal TC season from November to April) and so the apparent AEP of HAT here has been essentially halved. The remaining differences are due to the use of a half-hour tidal sample, a 0.1 m vertical discretisation level in the model and a reduced set of tidal constituents (the principal 37 only) being used. On this basis, the model is deemed to be correctly sampling the astronomical tide.

The next test considers the model's prediction of mean and gust wind speeds when compared with an analysis of up to 50 years of gust wind speed data from Brisbane Airport, which is the longest record available in the region, and also 32 years of data from the more exposed Cape Moreton. Peak daily wind gust wind data has been chosen in preference to the available synoptic (3 hourly 10 min means) because of the more reliable daily peak sampling, which leads to a more temporally homogeneous record that avoids the potential undersampling at discrete synoptic intervals.

The raw wind data was obtained from the Bureau of Meteorology and analysed to extract the peak winds occurring only during periods when a TC was within a 300 km radius of the site so that the effects of other severe weather such as isolated local thunderstorms were likely excluded or significantly reduced. While the Brisbane Airport data is of a higher precision than the Cape Moreton data due to its longer instrumented period, the Cape Moreton site is more representative of the open ocean winds that the model seeks to represent. Importantly though, the high and steep elevation of Cape Moreton necessitates an adjustment for significant topographic effects, which has been based here on the wind tunnel testing of the site reported in Ginger and Harper (2004). This reduces reported winds at the site by up to 50% from some directions.

Additionally, the gust wind speeds have been adjusted in an attempt to further improve their homogeneity, following the investigation into the response of the Dines anemometer instrument as reported by Holmes and Ginger (2012). This relates to the discrepancy between modern digital-sampling 3-cup anemometer systems, introduced by the BoM from the late 1980s onwards, compared with the earlier analogue Dines instruments. The Dines-recorded gusts are now known to be typically around 10% higher than those now being recorded, with both traditionally referred to as "peak 3s gusts". In order to standardise on the re-named Dines-equivalent "0.2s gust" metric used in engineering design by AS1170.2 (SA 2011), the Brisbane Airport data has been Dines-adjusted post-1987[16]. It can be noted also that the Brisbane Airport instrumentation has undergone many significant changes in location over the past 30 y period but the present analysis has not attempted to assess the possible impacts of that. The best available long-term wind data is therefore not without flaws but provides the only possible independent check on the statistical model TC wind prediction performance.

The peak wind data were also windowed over a 7 day period to ensure independent samples were obtained and are ranked in Figure 5-17 using traditional quantile plotting techniques. The SATSIM predictions for mean and gust wind speeds based on a 50,000 y simulation are then overlaid, with the model assuming a nominal gust factor of 1.3[17]. The comparison between the modelled and measured gusts is of interest, whereby the model tends to follow the more exposed Cape Moreton gust data below 10% AEP. This is the desired result, given that the Brisbane Airport site is thought to suffer attenuation in high offshore winds due to the effects of Moreton Bay (J. Callaghan, personal communication). The mean (600s or 10min) wind comparison at both sites is less impressive, suggesting that the model overestimates this metric. However the potential for under-sampling of the peak of the synoptic wind data is also likely a factor. For reference, the design wind speed gust applicable to Brisbane from AS1170.2 is also shown. This includes allowance for severe thunderstorm wind gusts at high AEP and does not consider an upper bound, but is sympathetic to the slope of the modelled TC-only result.

Overall, this shows a very favourable comparison; the model generally following the trend of the better exposed data, and is a good verification of the model's capabilities in probabilistic space.

5.5 Statistical Verification of the Extra-Tropical Simulation Model

As discussed in Section 4.3.3, the TRSSM model is fully empirical. Accordingly there is no calibration context and the accuracy of the predictions depends solely on the appropriateness of the assumptions regarding the sufficient sampling of the residual extremes.

Although the period of data utilised is only of order 30 years, the potential frequency of storm events is of the order of 50 per year, giving a sample of approximately 1500 events in total, which are then expanded to nearly 10,000 years via the recombination with the deterministic tide variability. This is significantly greater than the base statistical data used for the extreme value analysis that underpins the TC-only simulation.

[16] Based on BoM weather station metadata records for Cape Moreton it is likely that prior to Aug 1995 there was no fixed wind speed instrumentation, although hand-held instruments may have been used by observers. For example, a small portable venturi device was available for use at Norah Head Lighthouse on the Central Coast of NSW in the late-1970s but was not normally being used by the Observer (B. Harper personal communication). Unless taken at height even these would potentially be underestimates at the site. It is also possible that qualitative Beaufort sea-state wind estimates were being made preferentially. Because the top 6 of the 9 peak TC gusts are all pre-Aug 1995 the reliability of the higher wind speeds reported during the period 1980 to 1995 is most uncertain. Hence, although there was never a Dines instrument at Cape Moreton, its gust data record has been Dines-adjusted for consistency with the Brisbane Airport.

[17] This is based on the equivalent $G_{0.2,600}$ gust factor for "at sea" exposure following the method of Harper et al. (2010), discounting the normally recommended "off sea" turbulence intensity because of the high (+100m) elevation and deep ocean exposure at the site for the more extreme wind condition.

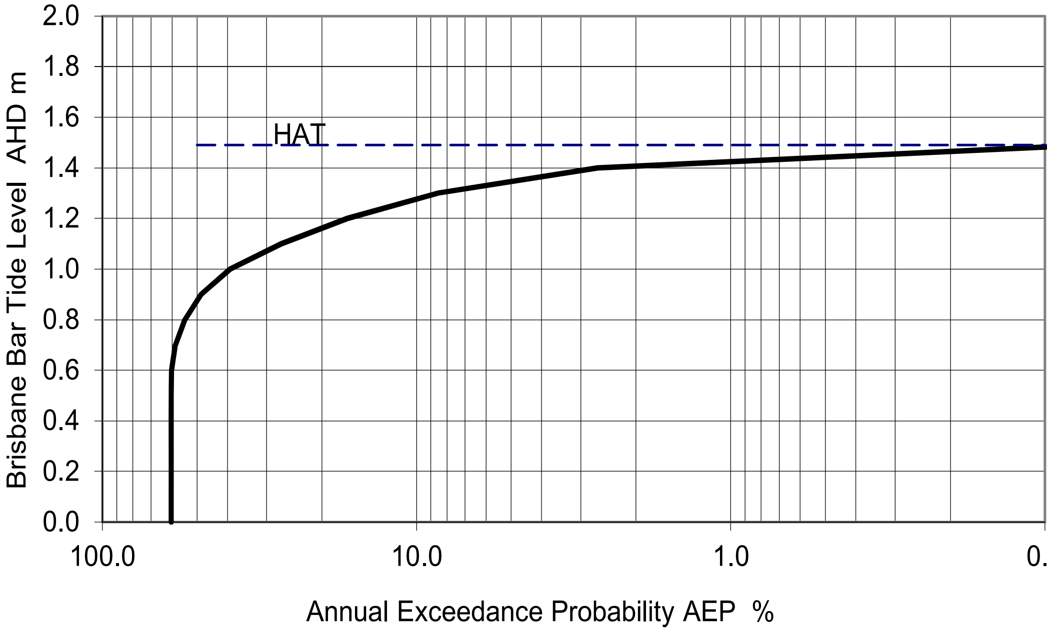


Figure 5-16 Verification of the generated HAT tidal plane at Brisbane Bar

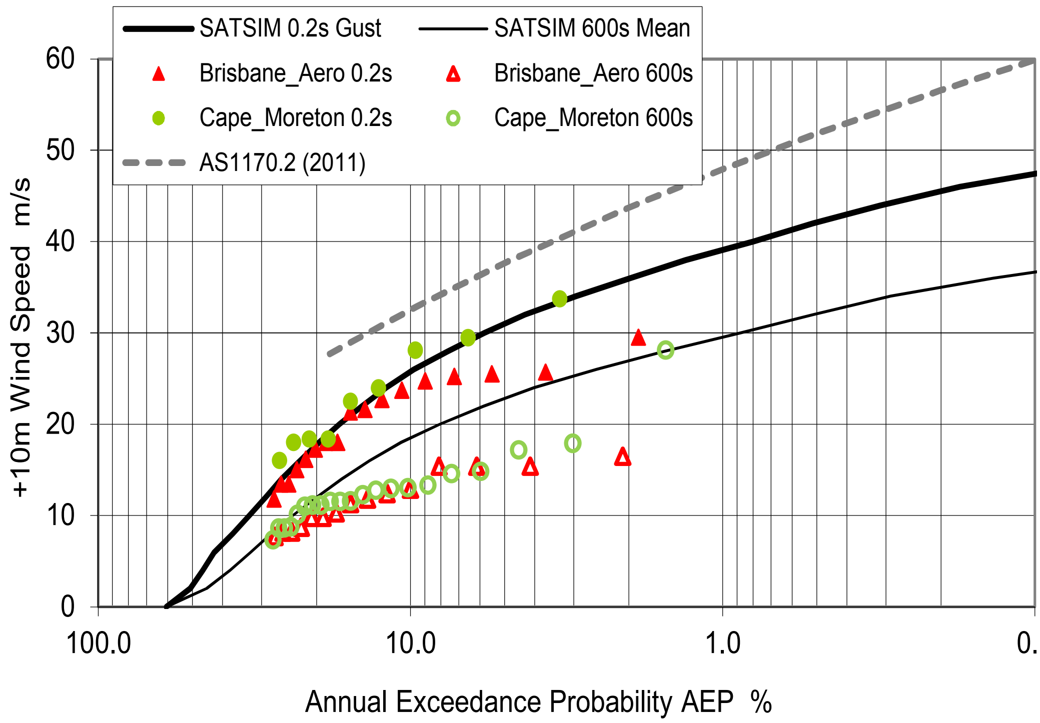


Figure 5-17 Statistical prediction of regional TC-only wind speeds

6. Storm Tide Hazard in the Present Climate

This chapter considers so-called "open coast" storm tide hazard estimates that are obtained directly from the statistical simulation models (SATSIM and TRSSM). This refers to locations that, under normal conditions, are representative of the expected storm tide elevation at the natural shoreline. Subsequent chapters extend these estimates inland through dynamic inundation modelling that can further modify these levels at inland locations (increase or decrease) relative to the open coast.

Study results are presented as a series of tables and graphs providing the probabilistic curves for tide plus surge, total storm tide and wave runup estimates at a selection of sites.

6.1 Combining the Climate Hazard Estimates

As described in the preceding chapters, the present study methodology is predicated on the ability to separate the two principal climatological forcing components – TC and extra-tropical storm events. The analyses ensure that these two contributions are statistically independent and this permits a final recombination to obtain the full-climate storm tide hazard estimate for present climate conditions. This takes the form of merging the site-specific TC storm tide hazard (e.g. Figure 4-8) with the site-appropriate extra-tropical water level hazard (e.g. Figure 4-13). The latter extra-tropical component, which strictly applies only at the location of the respective tide gauge, is modulated during the statistical blending process according to the assigned site-specific tidal range ratio used in the SATSIM model.

6.2 Tide plus Surge Hazard

The results of this combination of the tide plus surge levels (no wave setup) are tabulated in Table 6-1 for a selection of open coast sites (refer Figure 6-1) for the mapped location of these sites).

A selection of these results is shown graphically in Figure 6-2 and illustrates that the transition between extra-tropical-dominance and TC-dominance occurs in the AEP range 1.0% to 0.5%. This also shows that the hazard levels tend to increase southwards along the coast in this area.

The level of HAT (nominally 1.5 m AHD at Brisbane Bar) is also indicated, and, as noted previously, this is estimated to be experienced almost annually as a result of the non-astronomic atmospheric influences, rather than at the 18.6 y astronomical interval.

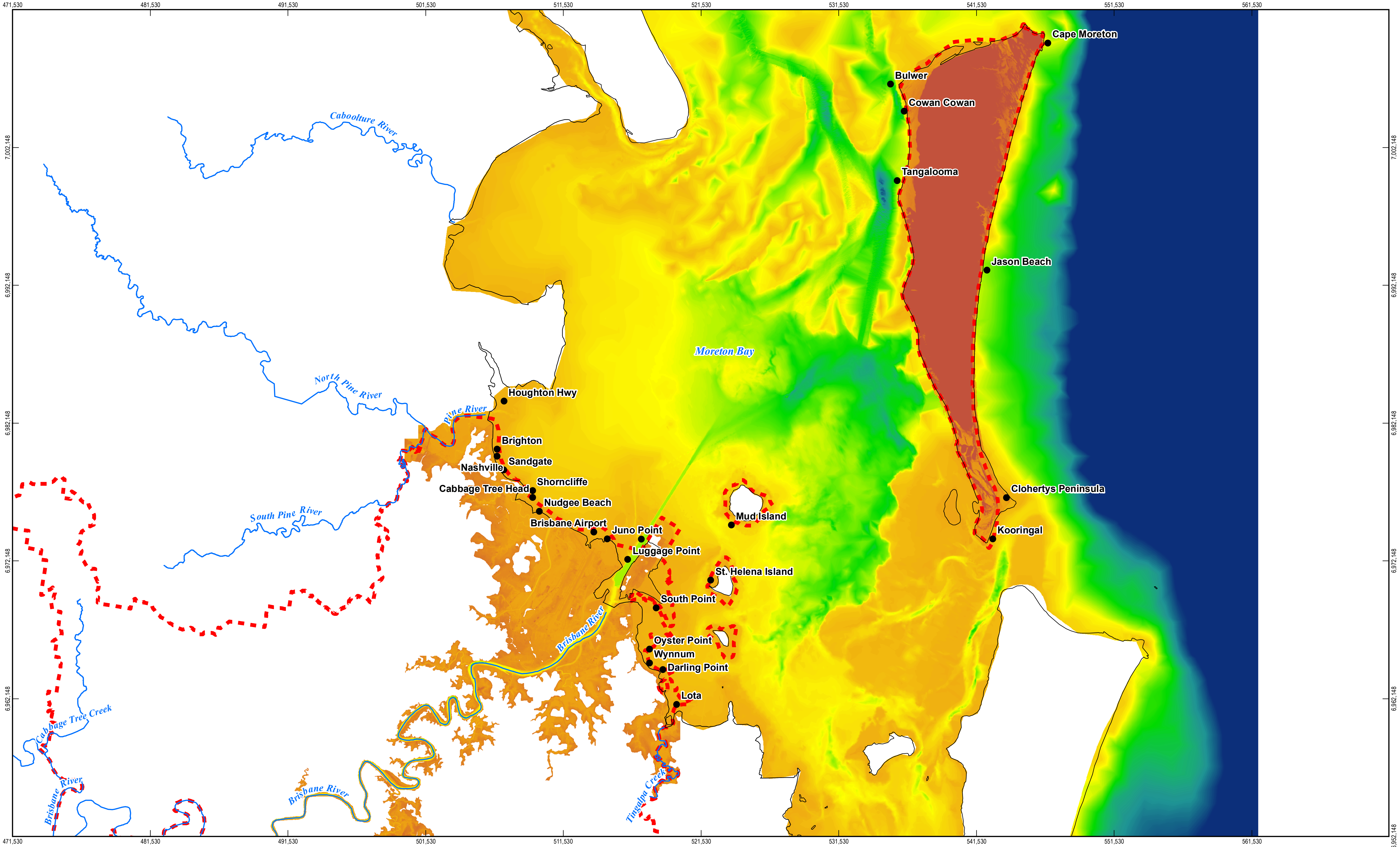
6.3 Total Storm Tide Hazard

The analogous results for the total storm tide (including wave setup) are tabulated in and the variability is graphed in Figure 6-3.

These results represent a small increase in estimated levels for locations that have a finite "dune crest" but tend to asymptote to the tide plus surge result at lower AEP where the models assume that the wave setup component dissipates after inundation occurs.

6.4 Total Breaking Wave Runup Hazard

The analogous results for the (nominal 1%) total breaking wave runup levels (tide plus surge plus wave runup) are tabulated in Table 6-3 and the variability is graphed in Figure 6-4. Wave runup is limited by the declared "dune crest" elevation and is indicative only.



Paper Size A3

0 5 10

Kilometers

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 56

N

LEGEND

- Open Coast Reporting Locations
- Watercourses
- Study Area

LHM Extent

Bathymetry (m AHD)

High : 15

Low : -50

Brisbane City Council - City Projects Office
Brisbane City Coastal Planning Implementation Study

Job Number 41-27298
Revision A
Date 26 Sep 2014

Open Coast Reporting Sites

Figure 6.1

G:\41\27298\GIS\Maps\Deliverables\41_27298_002_revA.mxd

145 Ann Street Brisbane QLD 4000 Australia T 61 7 3316 3000 F 61 7 3316 3333 E bnemail@ghd.com W www.ghd.com

Data source: GHD: Model Extent (2014). DNRM: Mainlands, Locality, Watercourses (2014).

For Information Only. Not Council Policy

Table 6-1 Combined-Climate Tide plus Surge Open Coast Levels – 2014 Climate Conditions

Location	Latitude (deg)	Longitude (deg)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	1.52	1.61	1.70	1.76	2.12	2.49	2.91
Brighton	-27.3008	153.0680	1.54	1.64	1.73	1.81	2.27	2.67	3.11
Nashville	-27.3053	153.0680	1.54	1.64	1.73	1.82	2.28	2.70	3.11
Sandgate	-27.3143	153.0730	1.54	1.64	1.73	1.82	2.30	2.73	3.17
Shorncliffe	-27.3278	153.0940	1.54	1.64	1.74	1.82	2.30	2.74	3.17
Cabbage Tree Head	-27.3323	153.0940	1.54	1.64	1.74	1.82	2.30	2.75	3.21
Nudgee Beach	-27.3414	153.0990	1.54	1.64	1.74	1.83	2.33	2.78	3.26
Brisbane Airport	-27.3549	153.1390	1.57	1.67	1.77	1.85	2.29	2.78	3.23
Juno Point	-27.3594	153.1490	1.57	1.67	1.77	1.85	2.30	2.77	3.27
Luggage Point	-27.3729	153.1640	1.59	1.68	1.78	1.86	2.30	2.76	3.25
Fisherman Island	-27.3594	153.1740	1.60	1.70	1.79	1.85	2.22	2.66	3.16
South Point	-27.4045	153.1850	1.64	1.73	1.83	1.89	2.30	2.73	3.22
Oyster Point	-27.4316	153.1800	1.64	1.74	1.84	1.93	2.44	2.91	3.44
Wynnum	-27.4406	153.1800	1.65	1.76	1.86	1.96	2.49	2.99	3.53
Darling Point	-27.4451	153.1900	1.65	1.75	1.86	1.94	2.44	2.93	3.45
Lota	-27.4677	153.2000	1.65	1.76	1.86	1.96	2.47	2.99	3.51
Mud Island	-27.3502	153.2400	1.68	1.77	1.85	1.91	2.11	2.47	2.85
St. Helena Island	-27.3864	153.2250	1.68	1.78	1.86	1.92	2.20	2.61	3.01
Bulwer	-27.0611	153.3560	1.37	1.46	1.52	1.56	1.62	1.66	1.70
Cowan Cowan	-27.0789	153.3660	1.37	1.46	1.52	1.56	1.62	1.66	1.70
Tangalooma	-27.1243	153.3610	1.37	1.46	1.52	1.56	1.63	1.68	1.86
Kooringal	-27.3588	153.4320	1.30	1.39	1.44	1.48	1.54	1.57	1.62
Clohertys Peninsula	-27.3317	153.4420	1.30	1.39	1.44	1.48	1.54	1.57	1.62
Jason Beach	-27.1828	153.4270	1.30	1.39	1.44	1.48	1.54	1.57	1.62
Cape Moreton	-27.0337	153.4710	1.23	1.29	1.34	1.38	1.44	1.48	1.51

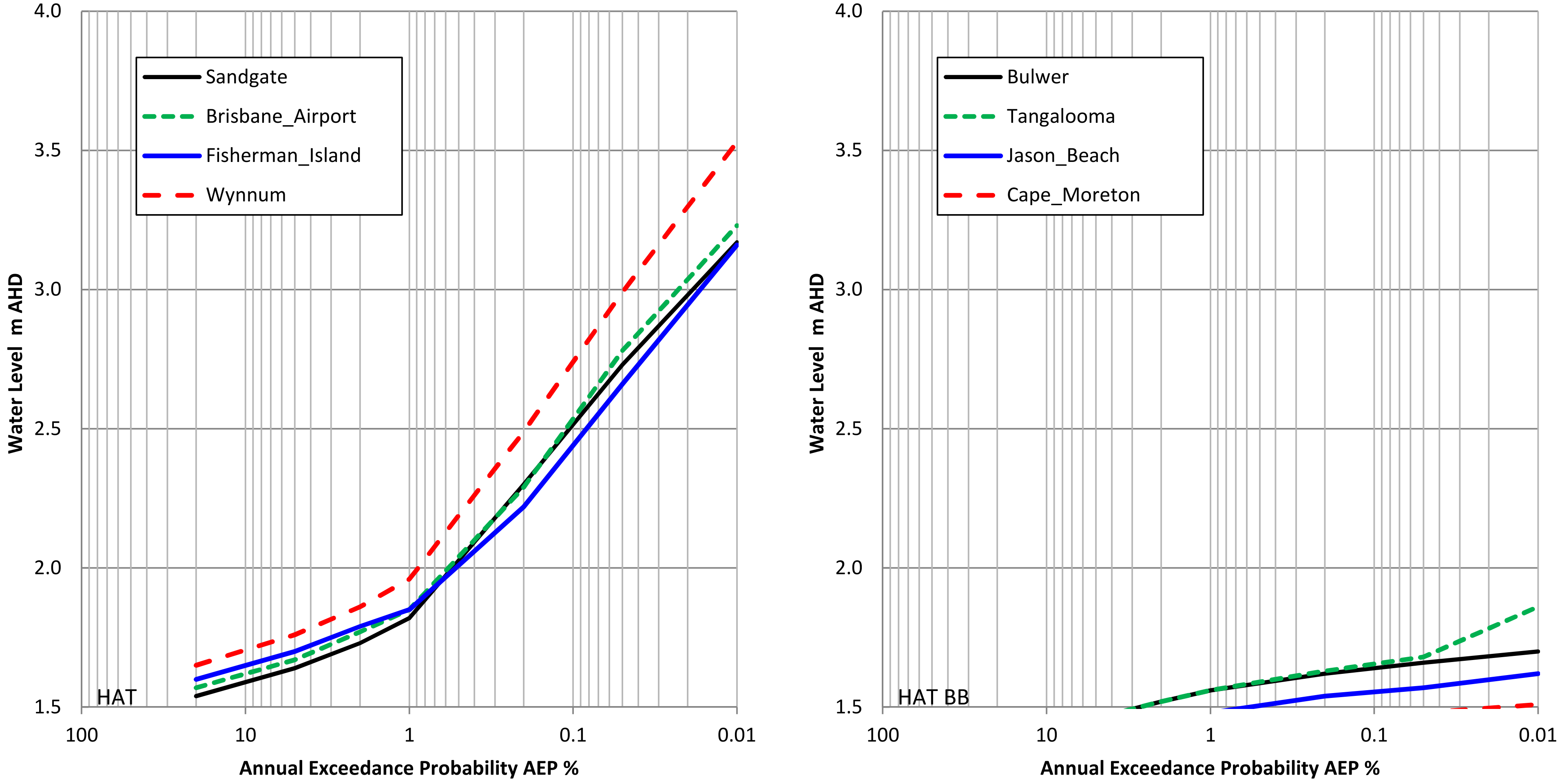


Figure 6-2 Combined climate tide plus surge estimates at selected sites[18]

[18] BB = Brisbane Bar.

Table 6-2 Combined-Climate Total Storm Tide Open Coast Levels – 2014 Climate Conditions

Location	Latitude (deg)	Longitude (deg)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	1.62	1.71	1.80	1.86	2.12	2.49	2.91
Brighton	-27.3008	153.0680	1.64	1.74	1.84	1.91	2.32	2.67	3.11
Nashville	-27.3053	153.0680	1.63	1.73	1.83	1.89	2.28	2.70	3.11
Sandgate	-27.3143	153.0730	1.64	1.74	1.84	1.91	2.35	2.73	3.18
Shorncliffe	-27.3278	153.0940	1.64	1.74	1.84	1.92	2.36	2.74	3.17
Cabbage Tree Head	-27.3323	153.0940	1.64	1.74	1.84	1.91	2.34	2.75	3.21
Nudgee Beach	-27.3414	153.0990	1.64	1.74	1.83	1.90	2.33	2.78	3.26
Brisbane Airport	-27.3549	153.1390	1.67	1.77	1.86	1.93	2.29	2.78	3.23
Juno Point	-27.3594	153.1490	1.67	1.77	1.86	1.93	2.30	2.77	3.27
Luggage Point	-27.3729	153.1640	1.69	1.79	1.88	1.94	2.30	2.76	3.25
Fisherman Island	-27.3594	153.1740	1.70	1.80	1.89	1.95	2.23	2.66	3.16
South Point	-27.4045	153.1850	1.74	1.84	1.93	1.99	2.30	2.73	3.22
Oyster Point	-27.4316	153.1800	1.74	1.84	1.95	2.02	2.44	2.91	3.43
Wynnum	-27.4406	153.1800	1.76	1.86	1.97	2.05	2.49	2.99	3.53
Darling Point	-27.4451	153.1900	1.76	1.86	1.96	2.04	2.44	2.93	3.45
Lota	-27.4677	153.2000	1.75	1.86	1.97	2.04	2.48	2.99	3.52
Mud Island	-27.3502	153.2400	1.79	1.89	1.96	2.03	2.17	2.47	2.85
St. Helena Island	-27.3864	153.2250	1.79	1.89	1.97	2.04	2.21	2.61	3.01
Bulwer	-27.0611	153.3560	1.50	1.64	1.71	1.85	2.12	2.29	2.51
Cowan Cowan	-27.0789	153.3660	1.47	1.58	1.64	1.68	1.69	1.71	1.93
Tangalooma	-27.1243	153.3610	1.47	1.58	1.65	1.69	1.70	1.85	2.07
Kooringal	-27.3588	153.4320	2.45	2.80	2.95	3.05	3.19	3.27	3.34
Clohertys Peninsula	-27.3317	153.4420	2.45	2.80	2.95	3.05	3.19	3.27	3.34
Jason Beach	-27.1828	153.4270	2.46	2.81	2.96	3.06	3.20	3.29	3.36
Cape Moreton	-27.0337	153.4710	1.60	2.10	2.40	2.60	2.99	3.26	3.41

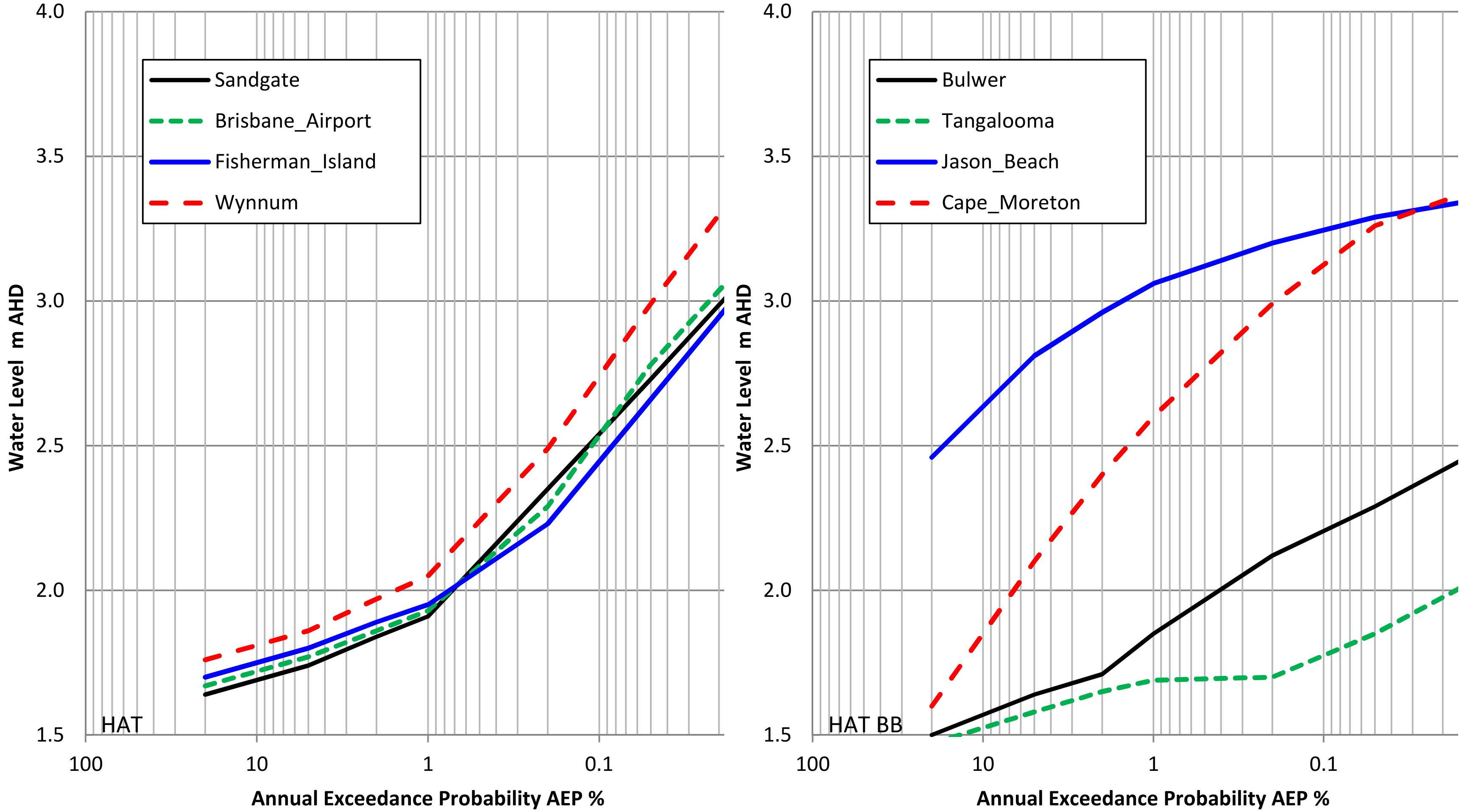


Figure 6-3 Combined climate total storm tide estimates at selected sites[19]

[19] BB = Brisbane Bar.

Table 6-3 Combined-Climate Total Breaking Wave Runup Open Coast Levels – 2014 Climate Conditions

Location	Latitude (deg)	Longitude (deg)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	1.80	1.92	2.00	2.08	2.24	2.49	2.91
Brighton	-27.3008	153.0680	1.82	1.95	2.05	2.12	2.44	2.67	3.11
Nashville	-27.3053	153.0680	1.82	1.94	2.03	2.11	2.30	2.70	3.11
Sandgate	-27.3143	153.0730	1.82	1.95	2.06	2.13	2.50	2.73	3.18
Shorncliffe	-27.3278	153.0940	1.82	1.95	2.06	2.14	2.50	2.74	3.16
Cabbage Tree Head	-27.3323	153.0940	1.82	1.95	2.05	2.12	2.45	2.75	3.22
Nudgee Beach	-27.3414	153.0990	1.82	1.94	2.04	2.11	2.33	2.78	3.26
Brisbane Airport	-27.3549	153.1390	1.86	1.98	2.07	2.15	2.33	2.78	3.23
Juno Point	-27.3594	153.1490	1.86	1.98	2.07	2.15	2.33	2.77	3.27
Luggage Point	-27.3729	153.1640	1.87	2.00	2.09	2.17	2.35	2.76	3.25
Fisherman Island	-27.3594	153.1740	1.89	2.02	2.13	2.20	2.44	2.94	3.36
South Point	-27.4045	153.1850	1.93	2.06	2.15	2.23	2.40	2.73	3.22
Oyster Point	-27.4316	153.1800	1.93	2.07	2.17	2.25	2.45	2.91	3.43
Wynnum	-27.4406	153.1800	1.95	2.09	2.19	2.27	2.49	2.99	3.53
Darling Point	-27.4451	153.1900	1.95	2.08	2.19	2.27	2.46	2.93	3.46
Lota	-27.4677	153.2000	1.95	2.08	2.19	2.27	2.48	2.99	3.51
Mud Island	-27.3502	153.2400	1.99	2.11	2.20	2.28	2.42	2.51	2.85
St. Helena Island	-27.3864	153.2250	1.99	2.12	2.21	2.29	2.43	2.61	3.01
Bulwer	-27.0611	153.3560	1.83	2.43	2.87	3.18	3.77	4.13	4.37
Cowan Cowan	-27.0789	153.3660	1.68	1.81	1.89	1.96	2.07	2.15	2.32
Tangalooma	-27.1243	153.3610	1.68	1.81	1.89	1.96	2.07	2.17	2.45
Kooringal	-27.3588	153.4320	4.37	5.22	5.58	5.79	6.10	6.29	6.43
Clohertys Peninsula	-27.3317	153.4420	4.37	5.22	5.58	5.79	6.10	6.29	6.43
Jason Beach	-27.1828	153.4270	4.43	5.27	5.63	5.85	6.21	6.54	7.01
Cape Moreton	-27.0337	153.4710	4.89	6.99	7.00	7.00	7.00	7.01	7.01

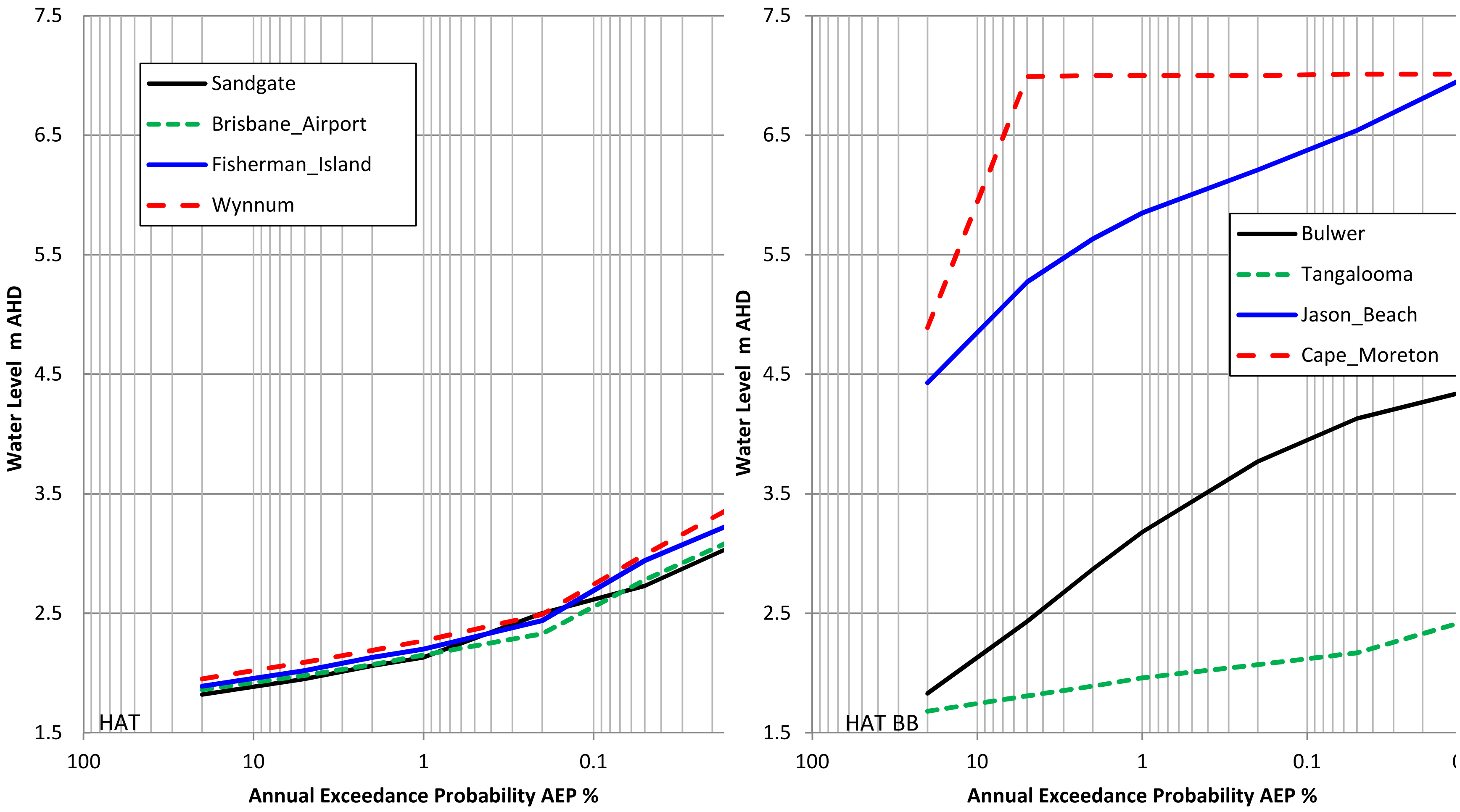


Figure 6-4 Combined climate breaking wave runup estimates at selected sites[20]

[20] BB = Brisbane Bar.

7. Climate Change and Climate Variability

This chapter considers the potential impacts of statistically non-stationary climate forcing, which contrasts with the basic assumption in the preceding analyses that the averaged statistical experience derived from available data represents the “best” or “expected” estimate. It addresses the effects of projected secular sea level rise and potential changes in extreme ocean forcing events (*aka* “climate change”) and also the observed inter-decadal variability of these phenomena that are deemed not specifically linked with projected secular climate change.

7.1 The Enhanced Greenhouse Effect

Over the past two decades there has been a growing awareness of the potential impacts that human-induced global climate change may have, and especially its possible effects on the coastal environment (NCCOE 2012). The estimated Annual Exceedance Probabilities for storm tide levels in the present study rely on the assumption that the natural environment, although highly variable, remains statistically static and that probability distributions for TCs and sea level are unchanging with the passage of time within timescales of practical interest (i.e. the planning horizon). However, the proven rise in atmospheric carbon dioxide levels and an increasing trend in mean air temperatures and rising sea levels points to the likelihood of the Earth being subject to an enhanced "greenhouse" effect, which means that these static assumptions will be in error to some extent. Consequently, some consideration of the possible impacts of future climate change on modifying the present storm tide estimates is addressed in this section. The effect that these possible gradual climate changes might have already had on the past historical data is not able to be quantified and is therefore neglected at this time, although MSQ tidal plane data has been continuously adjusted in response to measured sea level changes.

7.1.1 Potential Sea Level Rise

Global sea levels are expected to rise as a consequence of enhanced greenhouse warming of the earth (IPCC 2013; AR5). The observed rate of global average sea level rise measured by TOPEX/Poseidon satellite altimetry during the 20 y period 1993 to 2012 was 3.2 ± 0.4 mm p.a., although there are large regional differences. This is close to the estimated total of 2.8 ± 0.7 mm p.a. for the following climate-related contributions, in order of decreasing impact:

- An accelerating thermal expansion throughout the 21st century;
- The melting of glaciers;
- Retreat of the Greenland ice shelf;
- Antarctic ice losses; and
- Land water storage.

The official projections of global average sea level rise by 2100 (relative to 1990) are in the range 0.28 to 0.98 m (IPCC 2013, nominally representing the 5% to 95% confidence levels for five greenhouse gas emission scenarios). These represent increases in both the upper and lower limits of about 0.2 m over the previous IPCC (2007; aka AR4) assessment and exceed those currently recommended by DEHP (2013a,b) by about 25%. The presently projected sea level trends are displayed in Figure 7-1. Although the year 2100 is normally quoted, it is important to note that if greenhouse gas concentrations were stabilised (even at present levels), sea level is nonetheless projected to continue to rise for hundreds of years.

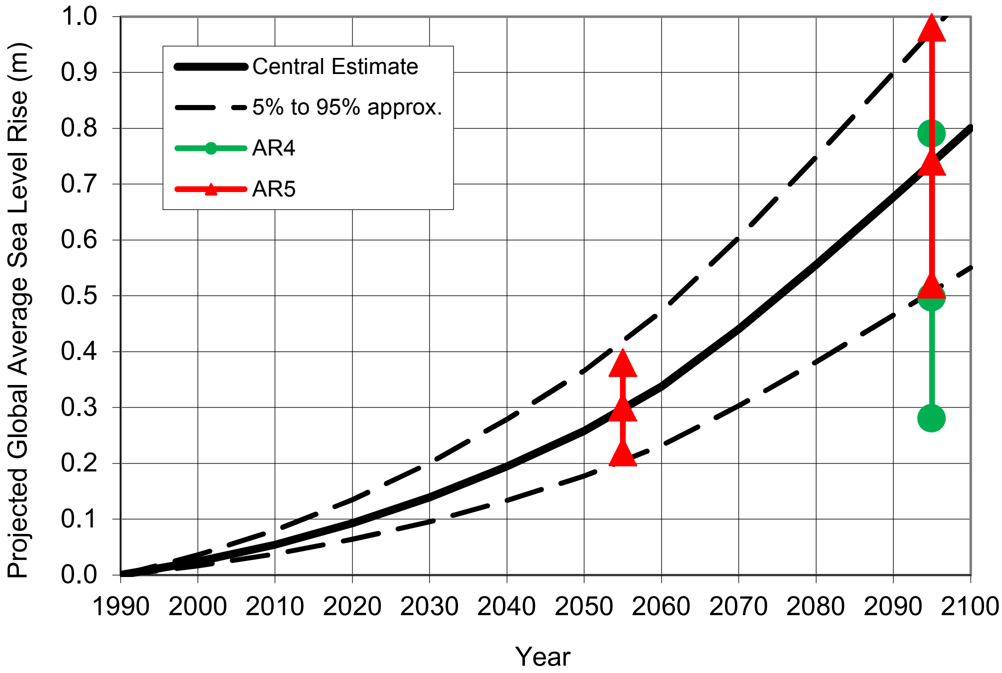


Figure 7-1 Projection of Global Average Sea Level Rise (after NCCOE 2012)

7.1.2 Possible Changes to Extreme Weather Systems Driving Storm Tide

(a) Potential changes in Future Tropical Cyclones

IPCC (2013) notes that climate model projections for the 21st century show it is likely that the global frequency of TCs will either decrease or remain essentially unchanged, but there may be an increase in both global mean TC maximum wind speed and rain rates. This is a significant change from IPCC (2007), which did not have the benefit of a World Meteorological Organization consensus statement (WMO 2006) formed in late 2006.

Subsequently, a WMO-endorsed study by Knutson et al. (2010) summarised the status of current research in this area and it was concluded that there is an agreed likely increase in the Maximum Potential Intensity (MPI) of TCs as the mean global temperature rises, of 3 to 5% per degree Celsius. Assuming a 2 to 4 °C temperature range is possible, this may lead to an upper level increase of as much as 20% in central pressure deficit by (say) 2100. This could translate into a 10% increase in peak wind speeds.

(b) Potential changes in Future Tropical Cyclone Frequency and Track

Knutson et al. (2010) also reports that the consensus from many advanced modelling studies is actually for a potential reduction in the global number of TCs, although regional differences can be high. Regarding tracks, the most likely change might be a slight poleward movement in some regions. For sub-tropical regions like Moreton Bay, if this does occur it could be reasonably significant, but this may simply be offset by the projected large decrease in numbers of TCs, which is 6 to 34% globally, and up to ±50% or more in individual basins by 2100. Regarding tracks, there is a stated low confidence in estimates of changed areas of genesis or tracks. Accordingly no changes are adopted here for the year 2050, but a nominal precautionary allowance for a +10% change due to poleward movement has been assumed by the year 2100.

(b) Potential changes in Extra-Tropical Storms

There is no specific advice available in this regard, although previous modelling studies have provided conflicting evidence. McInnes et al. (2007) is the most comprehensive climate change assessment available for the NSW coast and utilises outputs from a number of CSIRO climate models, focusing on Wooli and Batemans Bay as indicative coastal environments. Although the study attempted to provide indications of future trends for 2030 and 2070, the results are highly variable across a range of parameters. Taking the higher estimates of change in each case, the study suggested that the 1% AEP storm surge magnitude might increase by as much as 4% by 2030 or 2070 at Wooli, but actually decrease at Batemans Bay by as much as 3% by 2070. Significant wave height estimates were also highly variable between models and sites, with a range of up to 9% at Wooli by 2100 and 32% at Batemans Bay for storms from the SSE direction. Taken as a whole, these analyses are considered to be too variable to be regarded as reliable indicators for the Moreton Bay region.

It is concluded that there is no basis for applying a climate change signal to the Extra-Tropical storm climatology, other than the projected sea level rise.

7.1.3 Tropical Cyclone Climate Change Scenarios Considered for this Study

In light of the above scientific projections and assumptions, the climate change scenarios considered in this study are summarised below in Table 7-1. In regard to these assumptions:

a. A rise in mean sea level (MSL) will also lead to a rise in HAT and the tidal characteristics may also change slightly as a result, but this effect is ignored. Also, although AHD is based on MSL, it is assumed here that the AHD datum will remain where it is now.

b. An increase in tropical cyclone MPI is not a straightforward concept to apply to the statistical description of individual TC central pressure values. The interpretation made here is that the most intense of cyclones may increase their intensity but that not all TCs will be more intense. The way that this is applied is shown in Figure 7-2, whereby the potential pressure % increase (relative to Δp) is blended into the present climate description used by the statistical model.

Table 7-1 Enhanced Greenhouse Scenarios for Future Tropical Cyclones

Scenario Year	Increase in Extra-Tropical Storm Surge Magnitude	Increase in Frequency of TC Occurrence	Increase in TC Maximum Potential Intensity (MPI) Pressure Deficit	Increase in Mean Sea Level (DEHP 2013a)
	%	%	%	m
2050	0	0	10	0.30
2100	0	10	20	0.80

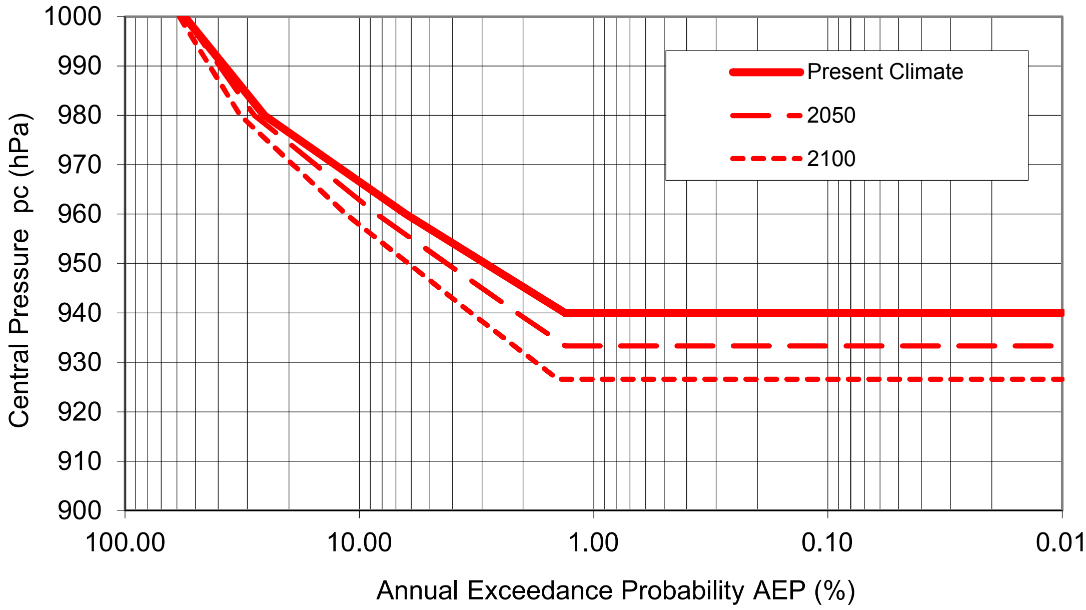


Figure 7-2 Assumed Possible Changes in the Intensity of TCs under Future Climate Change Projections within 500 km of the Gold Coast.

7.1.4 Effects of the Projected Climate Change Scenarios

Only the TC simulation has an applied change in storm intensity, whereas both the TC and Extra-Tropical simulations include the projected sea level rise from Table 7-1.

The results are presented analogously to the present climate estimates, namely a 2050 tide plus surge tabulation (Table 7-2) and graph (Figure 7-3), followed by a total storm tide tabulation (Table 7-3) and graph (Figure 7-4) and Breaking wave runup tabulation (Table 7-4) and graph (Figure 7-5).

This is repeated for the 2100 climate projection in Table 7-5, Figure 7-6, Table 7-6, Figure 7-7, Table 7-7 and Figure 7-8.

It is evident in these presentations that the projected sea level rise is the dominating influence, although there is also an attenuating trend at low AEP due to the increasing encroachment of the sea onto the low lying lands.

As detailed in Sections 6.3 and 6.4, total storm tide and wave runup estimates at lower AEPs are a function of the locally estimated dune crest height, as tide plus surge water levels exceeding the dune crest will tend to ‘overtop’ the dune. This overtopping and thus capping of wave runup and setup components becomes more prevalent for the 2050 and 2100 climates as the dune crest height relative to mean sea level is reduced.

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Table 7-2 Combined Tide plus Surge Open Coast Levels – Projected 2050 Climate Conditions

Location	Latitude (degree)	Longitude (degree)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	1.81	1.90	2.00	2.07	2.51	2.92	3.38
Brighton	-27.3008	153.0680	1.83	1.93	2.03	2.14	2.67	3.13	3.57
Nashville	-27.3053	153.0680	1.83	1.93	2.03	2.14	2.68	3.14	3.61
Sandgate	-27.3143	153.0730	1.83	1.93	2.03	2.14	2.70	3.17	3.65
Shorncliffe	-27.3278	153.0940	1.83	1.93	2.04	2.15	2.70	3.18	3.68
Cabbage Tree Head	-27.3323	153.0940	1.83	1.93	2.04	2.15	2.71	3.18	3.67
Nudgee Beach	-27.3414	153.0990	1.83	1.93	2.04	2.16	2.73	3.25	3.77
Brisbane Airport	-27.3549	153.1390	1.87	1.97	2.07	2.18	2.71	3.23	3.76
Juno Point	-27.3594	153.1490	1.87	1.97	2.07	2.18	2.72	3.24	3.78
Luggage Point	-27.3729	153.1640	1.89	1.99	2.09	2.19	2.70	3.21	3.77
Fisherman Island	-27.3594	153.1740	1.91	2.00	2.10	2.18	2.63	3.10	3.66
South Point	-27.4045	153.1850	1.94	2.04	2.14	2.23	2.70	3.18	3.71
Oyster Point	-27.4316	153.1800	1.94	2.05	2.16	2.28	2.87	3.43	3.95
Wynnum	-27.4406	153.1800	1.96	2.07	2.18	2.31	2.92	3.48	4.06
Darling Point	-27.4451	153.1900	1.96	2.07	2.18	2.29	2.87	3.41	3.96
Lota	-27.4677	153.2000	1.96	2.07	2.19	2.32	2.92	3.49	4.04
Mud Island	-27.3502	153.2400	2.00	2.09	2.18	2.24	2.51	2.92	3.32
St. Helena Island	-27.3864	153.2250	2.00	2.10	2.19	2.25	2.62	3.05	3.51
Bulwer	-27.0611	153.3560	1.68	1.78	1.83	1.87	1.94	1.97	2.02
Cowan Cowan	-27.0789	153.3660	1.68	1.78	1.83	1.87	1.94	1.97	2.02
Tangalooma	-27.1243	153.3610	1.68	1.78	1.83	1.88	1.95	2.01	2.18
Kooringal	-27.3588	153.4320	1.60	1.69	1.74	1.78	1.84	1.87	1.91
Clohertys Peninsula	-27.3317	153.4420	1.60	1.69	1.74	1.78	1.84	1.87	1.91
Jason Beach	-27.1828	153.4270	1.60	1.69	1.74	1.78	1.84	1.87	1.92
Cape Moreton	-27.0337	153.4710	1.46	1.53	1.57	1.62	1.67	1.72	1.74

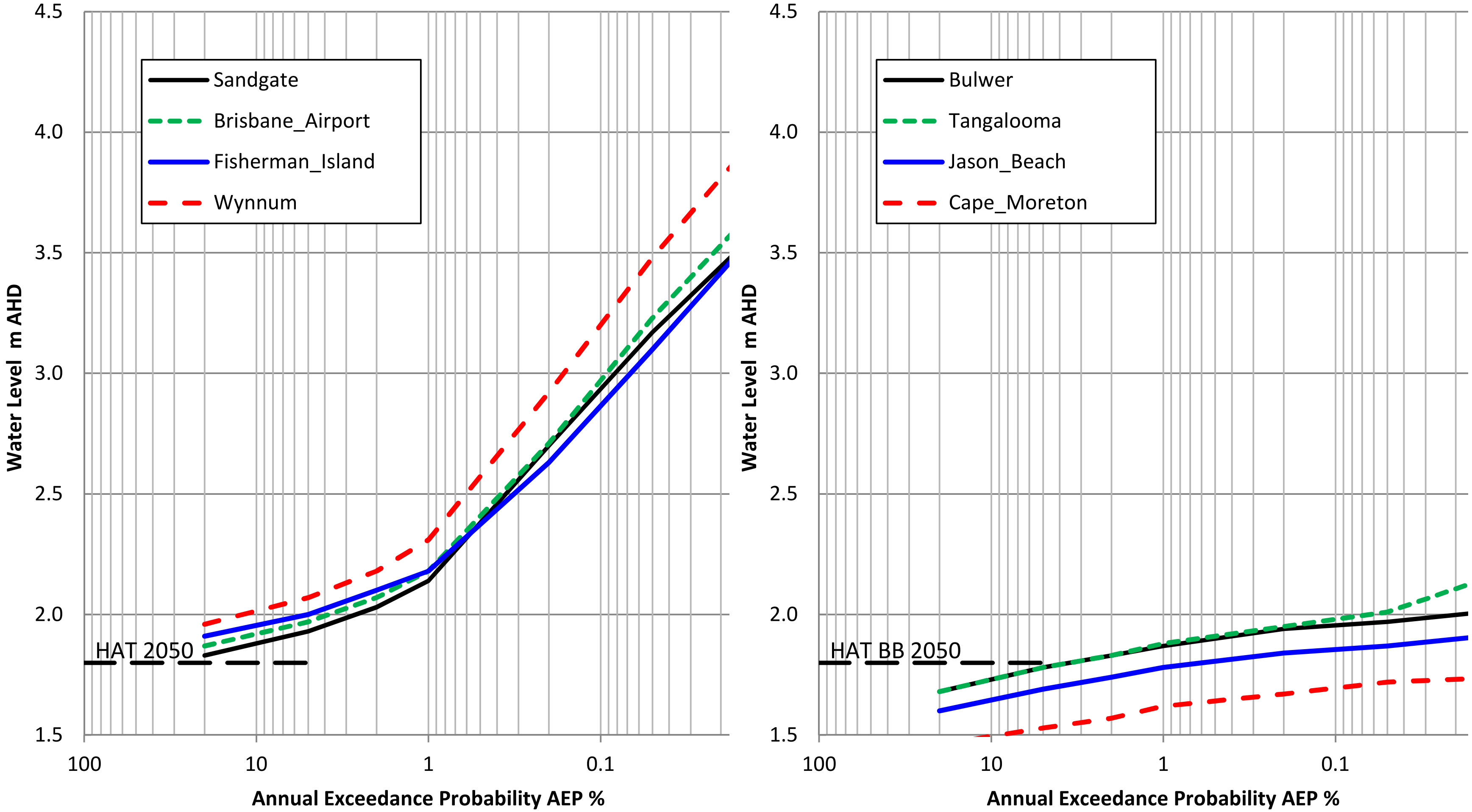

Figure 7-3 Combined 2050 climate tide plus surge estimates at selected sites[21]

[21] BB = Brisbane Bar.

Table 7-3 Combined Total Storm Tide Open Coast Levels – Projected 2050 Climate Conditions

Location	Latitude (degree)	Longitude (degree)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	1.90	2.00	2.09	2.16	2.51	2.92	3.38
Brighton	-27.3008	153.0680	1.92	2.03	2.14	2.23	2.67	3.13	3.57
Nashville	-27.3053	153.0680	1.92	2.02	2.13	2.21	2.68	3.14	3.61
Sandgate	-27.3143	153.0730	1.92	2.03	2.14	2.23	2.70	3.17	3.65
Shorncliffe	-27.3278	153.0940	1.92	2.03	2.14	2.25	2.70	3.18	3.67
Cabbage Tree Head	-27.3323	153.0940	1.92	2.03	2.14	2.23	2.71	3.18	3.66
Nudgee Beach	-27.3414	153.0990	1.92	2.03	2.13	2.22	2.73	3.25	3.77
Brisbane Airport	-27.3549	153.1390	1.96	2.07	2.17	2.25	2.71	3.23	3.76
Juno Point	-27.3594	153.1490	1.96	2.07	2.17	2.25	2.72	3.24	3.78
Luggage Point	-27.3729	153.1640	1.98	2.09	2.19	2.26	2.70	3.21	3.77
Fisherman Island	-27.3594	153.1740	2.00	2.10	2.20	2.27	2.64	3.11	3.66
South Point	-27.4045	153.1850	2.04	2.15	2.25	2.32	2.70	3.18	3.71
Oyster Point	-27.4316	153.1800	2.04	2.15	2.27	2.36	2.87	3.43	3.96
Wynnum	-27.4406	153.1800	2.06	2.17	2.29	2.38	2.92	3.48	4.06
Darling Point	-27.4451	153.1900	2.06	2.17	2.28	2.37	2.87	3.41	3.96
Lota	-27.4677	153.2000	2.06	2.18	2.29	2.39	2.92	3.49	4.04
Mud Island	-27.3502	153.2400	2.10	2.20	2.29	2.35	2.52	2.92	3.32
St. Helena Island	-27.3864	153.2250	2.10	2.20	2.29	2.36	2.62	3.05	3.51
Bulwer	-27.0611	153.3560	1.81	1.94	2.01	2.13	2.42	2.61	2.83
Cowan Cowan	-27.0789	153.3660	1.79	1.90	1.96	2.00	2.01	2.02	2.23
Tangalooma	-27.1243	153.3610	1.79	1.90	1.96	2.00	2.02	2.16	2.42
Kooringal	-27.3588	153.4320	2.74	3.10	3.25	3.34	3.49	3.57	3.64
Clohertys Peninsula	-27.3317	153.4420	2.74	3.10	3.25	3.34	3.49	3.57	3.64
Jason Beach	-27.1828	153.4270	2.75	3.11	3.26	3.35	3.50	3.59	3.72
Cape Moreton	-27.0337	153.4710	1.86	2.38	2.70	2.89	3.28	3.54	3.73

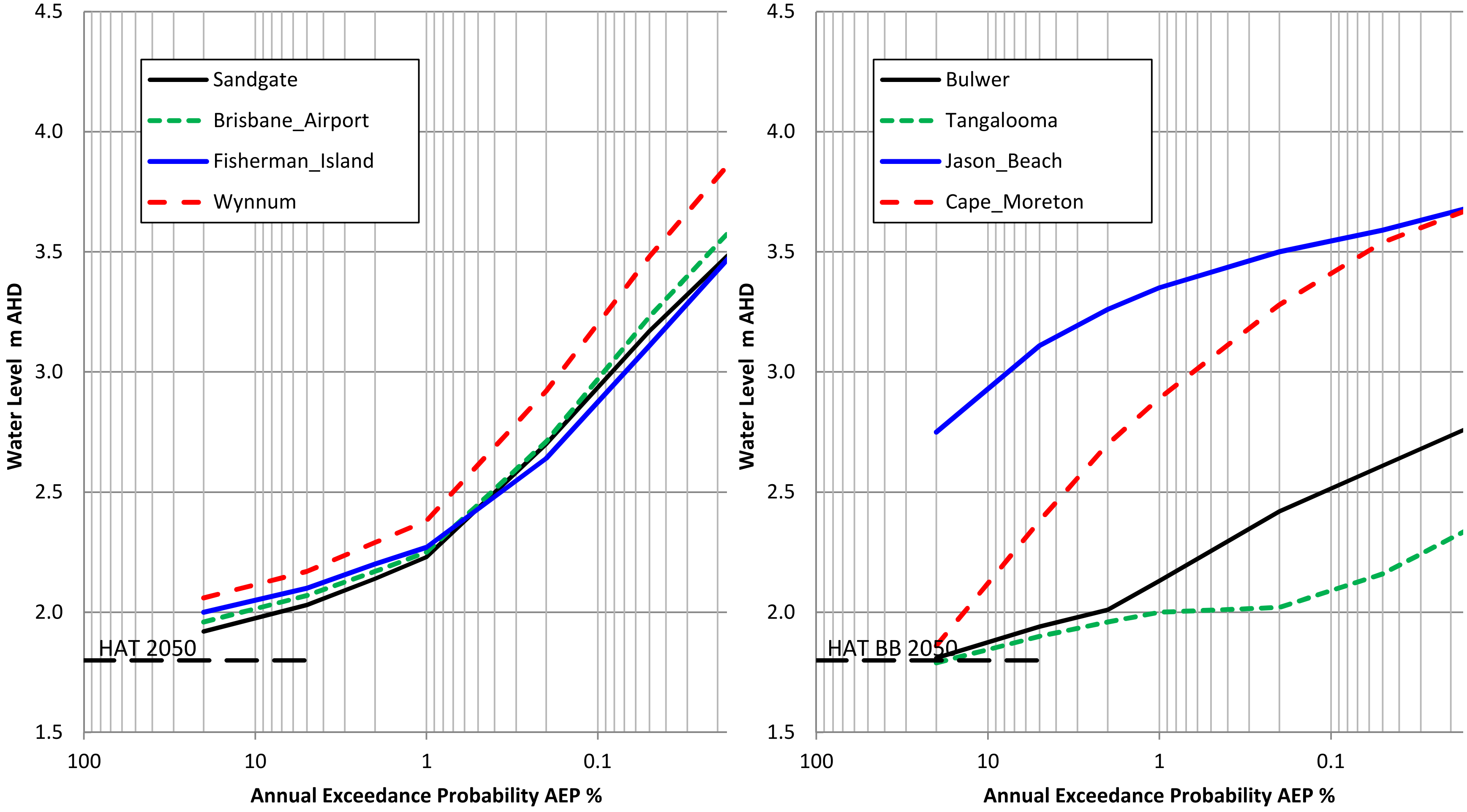

Figure 7-4 Combined 2050 climate total storm tide estimates at selected sites[22]

[22] BB = Brisbane Bar.

Table 7-4 Combined Breaking Wave Runup Open Coast Levels – Projected 2050 Climate Conditions

Location	Latitude (degree)	Longitude (degree)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	2.08	2.20	2.29	2.37	2.55	2.92	3.38
Brighton	-27.3008	153.0680	2.11	2.23	2.35	2.43	2.67	3.13	3.57
Nashville	-27.3053	153.0680	2.11	2.23	2.33	2.40	2.68	3.14	3.61
Sandgate	-27.3143	153.0730	2.11	2.24	2.35	2.43	2.70	3.17	3.65
Shorncliffe	-27.3278	153.0940	2.11	2.24	2.36	2.44	2.70	3.18	3.67
Cabbage Tree Head	-27.3323	153.0940	2.11	2.23	2.35	2.43	2.71	3.18	3.67
Nudgee Beach	-27.3414	153.0990	2.11	2.23	2.33	2.41	2.73	3.25	3.77
Brisbane Airport	-27.3549	153.1390	2.15	2.27	2.37	2.45	2.71	3.23	3.76
Juno Point	-27.3594	153.1490	2.15	2.27	2.37	2.45	2.72	3.24	3.78
Luggage Point	-27.3729	153.1640	2.17	2.30	2.40	2.47	2.70	3.21	3.77
Fisherman Island	-27.3594	153.1740	2.20	2.32	2.43	2.52	2.86	3.38	3.86
South Point	-27.4045	153.1850	2.24	2.36	2.46	2.54	2.74	3.18	3.71
Oyster Point	-27.4316	153.1800	2.24	2.37	2.48	2.56	2.87	3.43	3.96
Wynnum	-27.4406	153.1800	2.26	2.39	2.50	2.58	2.92	3.48	4.06
Darling Point	-27.4451	153.1900	2.26	2.39	2.50	2.58	2.87	3.41	3.97
Lota	-27.4677	153.2000	2.26	2.39	2.50	2.58	2.92	3.49	4.04
Mud Island	-27.3502	153.2400	2.30	2.43	2.52	2.60	2.75	2.92	3.32
St. Helena Island	-27.3864	153.2250	2.30	2.43	2.52	2.60	2.77	3.05	3.51
Bulwer	-27.0611	153.3560	2.12	2.75	3.20	3.51	4.10	4.46	4.67
Cowan Cowan	-27.0789	153.3660	1.99	2.13	2.21	2.27	2.38	2.47	2.66
Tangalooma	-27.1243	153.3610	1.99	2.13	2.21	2.27	2.39	2.49	2.81
Kooringal	-27.3588	153.4320	4.67	5.52	5.88	6.09	6.40	6.59	6.73
Clohertys Peninsula	-27.3317	153.4420	4.67	5.52	5.88	6.09	6.40	6.59	6.73
Jason Beach	-27.1828	153.4270	4.74	5.58	5.95	6.16	6.53	6.94	7.42
Cape Moreton	-27.0337	153.4710	5.27	6.98	6.98	6.98	6.99	6.99	7.00

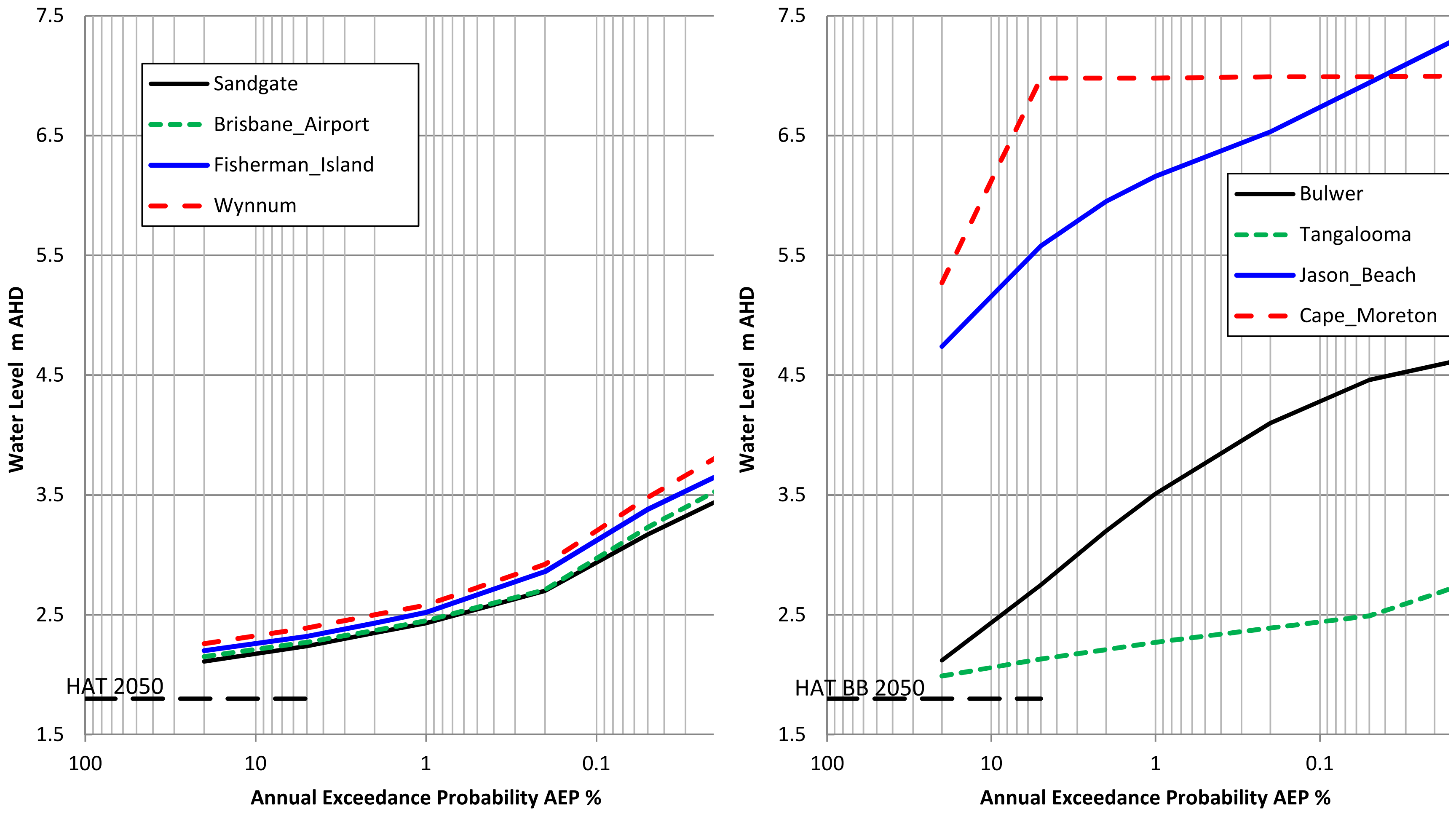

Figure 7-5 Combined 2050 climate breaking wave runup estimates at selected sites[23]

[23] BB = Brisbane Bar.

Table 7-5 Combined Tide plus Surge Open Coast Levels – Projected 2100 Climate Conditions

Location	Latitude (degree)	Longitude (degree)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	2.29	2.38	2.49	2.61	3.15	3.61	4.11
Brighton	-27.3008	153.0680	2.31	2.42	2.53	2.71	3.32	3.85	4.34
Nashville	-27.3053	153.0680	2.31	2.42	2.53	2.72	3.33	3.87	4.37
Sandgate	-27.3143	153.0730	2.31	2.42	2.53	2.72	3.35	3.89	4.41
Shorncliffe	-27.3278	153.0940	2.31	2.42	2.54	2.74	3.36	3.91	4.42
Cabbage Tree Head	-27.3323	153.0940	2.31	2.42	2.54	2.73	3.35	3.91	4.43
Nudgee Beach	-27.3414	153.0990	2.31	2.42	2.54	2.76	3.40	4.00	4.51
Brisbane Airport	-27.3549	153.1390	2.36	2.47	2.59	2.76	3.36	4.00	4.47
Juno Point	-27.3594	153.1490	2.36	2.47	2.59	2.77	3.38	4.02	4.47
Luggage Point	-27.3729	153.1640	2.38	2.49	2.61	2.76	3.39	3.96	4.44
Fisherman Island	-27.3594	153.1740	2.41	2.51	2.62	2.73	3.29	3.82	4.34
South Point	-27.4045	153.1850	2.45	2.56	2.67	2.80	3.37	4.00	4.51
Oyster Point	-27.4316	153.1800	2.46	2.57	2.70	2.90	3.55	4.19	4.71
Wynnum	-27.4406	153.1800	2.48	2.60	2.73	2.94	3.62	4.25	4.81
Darling Point	-27.4451	153.1900	2.48	2.59	2.72	2.91	3.58	4.19	4.75
Lota	-27.4677	153.2000	2.48	2.60	2.73	2.95	3.65	4.25	4.81
Mud Island	-27.3502	153.2400	2.52	2.62	2.72	2.79	3.17	3.63	4.11
St. Helena Island	-27.3864	153.2250	2.52	2.63	2.73	2.82	3.29	3.78	4.31
Bulwer	-27.0611	153.3560	2.21	2.30	2.36	2.40	2.46	2.50	2.55
Cowan Cowan	-27.0789	153.3660	2.21	2.30	2.36	2.40	2.46	2.50	2.57
Tangalooma	-27.1243	153.3610	2.21	2.30	2.36	2.40	2.47	2.54	2.77
Kooringal	-27.3588	153.4320	2.10	2.19	2.24	2.28	2.34	2.37	2.43
Clohertys Peninsula	-27.3317	153.4420	2.10	2.19	2.24	2.28	2.34	2.37	2.43
Jason Beach	-27.1828	153.4270	2.10	2.19	2.24	2.28	2.34	2.37	2.43
Cape Moreton	-27.0337	153.4710	1.85	1.91	1.96	2.00	2.07	2.11	2.23

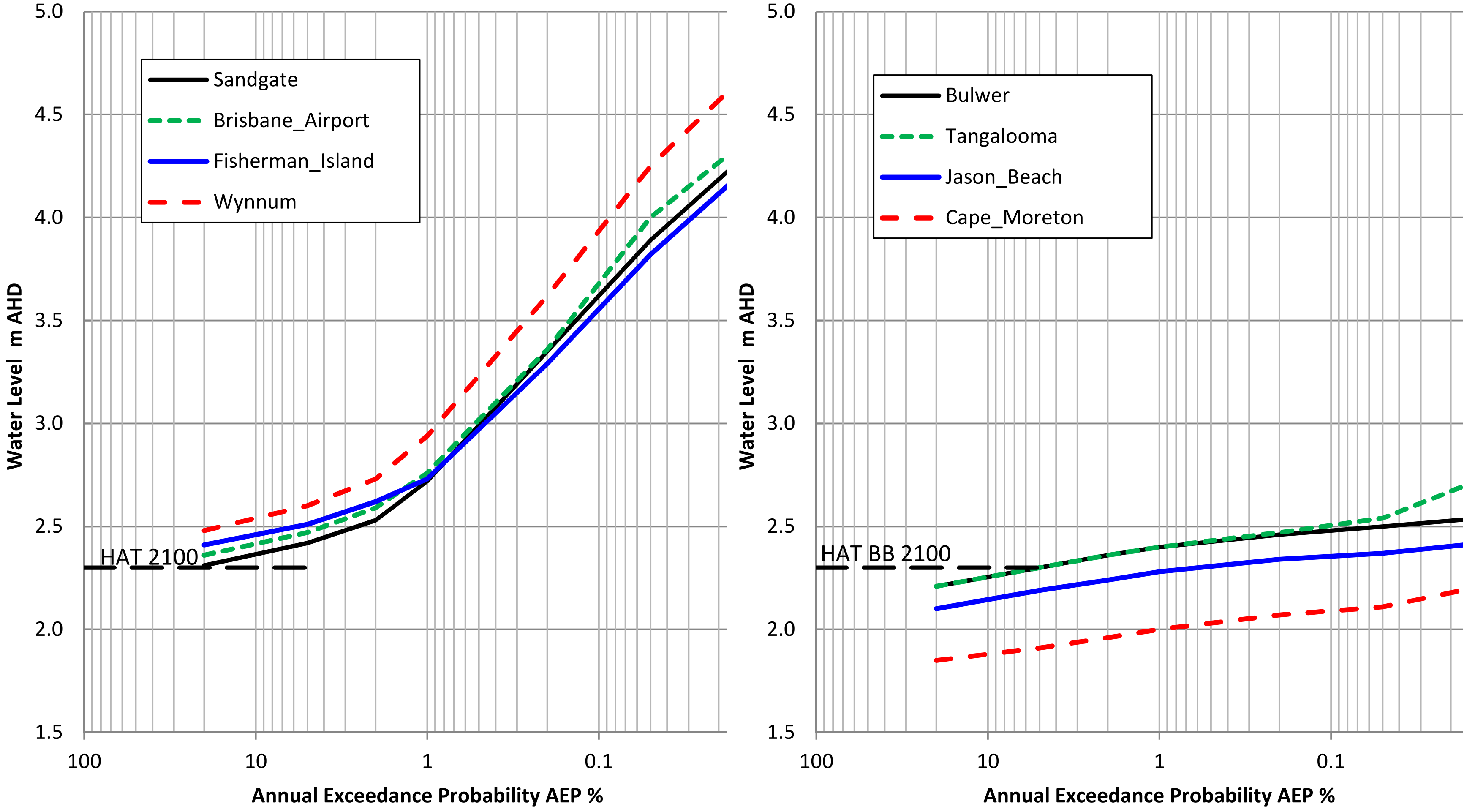

Figure 7-6 Combined 2100 climate tide plus surge estimates at selected sites[24]

[24] BB = Brisbane Bar.

Table 7-6 Combined Total Storm Tide Open Coast Levels – Projected 2100 Climate Conditions

Location	Latitude (degree)	Longitude (degree)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	2.38	2.48	2.58	2.66	3.15	3.61	4.11
Brighton	-27.3008	153.0680	2.40	2.51	2.63	2.74	3.32	3.85	4.34
Nashville	-27.3053	153.0680	2.40	2.51	2.62	2.75	3.33	3.87	4.37
Sandgate	-27.3143	153.0730	2.40	2.51	2.63	2.75	3.35	3.89	4.41
Shorncliffe	-27.3278	153.0940	2.40	2.52	2.63	2.76	3.36	3.91	4.41
Cabbage Tree Head	-27.3323	153.0940	2.40	2.52	2.63	2.75	3.35	3.91	4.44
Nudgee Beach	-27.3414	153.0990	2.40	2.51	2.63	2.77	3.40	4.00	4.51
Brisbane Airport	-27.3549	153.1390	2.45	2.56	2.68	2.80	3.36	4.00	4.47
Juno Point	-27.3594	153.1490	2.45	2.56	2.68	2.80	3.38	4.02	4.47
Luggage Point	-27.3729	153.1640	2.48	2.59	2.70	2.81	3.39	3.96	4.44
Fisherman Island	-27.3594	153.1740	2.50	2.61	2.72	2.81	3.30	3.84	4.34
South Point	-27.4045	153.1850	2.55	2.66	2.77	2.87	3.37	4.00	4.51
Oyster Point	-27.4316	153.1800	2.55	2.67	2.79	2.92	3.55	4.19	4.70
Wynnum	-27.4406	153.1800	2.58	2.70	2.82	2.96	3.62	4.25	4.82
Darling Point	-27.4451	153.1900	2.58	2.69	2.82	2.94	3.58	4.19	4.74
Lota	-27.4677	153.2000	2.58	2.70	2.82	2.96	3.65	4.25	4.81
Mud Island	-27.3502	153.2400	2.62	2.73	2.82	2.89	3.17	3.63	4.11
St. Helena Island	-27.3864	153.2250	2.62	2.73	2.84	2.91	3.29	3.78	4.31
Bulwer	-27.0611	153.3560	2.33	2.45	2.53	2.58	2.88	3.10	3.32
Cowan Cowan	-27.0789	153.3660	2.32	2.42	2.48	2.52	2.53	2.54	2.78
Tangalooma	-27.1243	153.3610	2.32	2.43	2.49	2.52	2.53	2.70	2.96
Kooringal	-27.3588	153.4320	3.24	3.60	3.75	3.84	3.99	4.07	4.14
Clohertys Peninsula	-27.3317	153.4420	3.24	3.60	3.75	3.84	3.99	4.07	4.14
Jason Beach	-27.1828	153.4270	3.25	3.61	3.76	3.85	4.00	4.10	4.25
Cape Moreton	-27.0337	153.4710	2.30	2.85	3.16	3.36	3.78	4.00	4.30

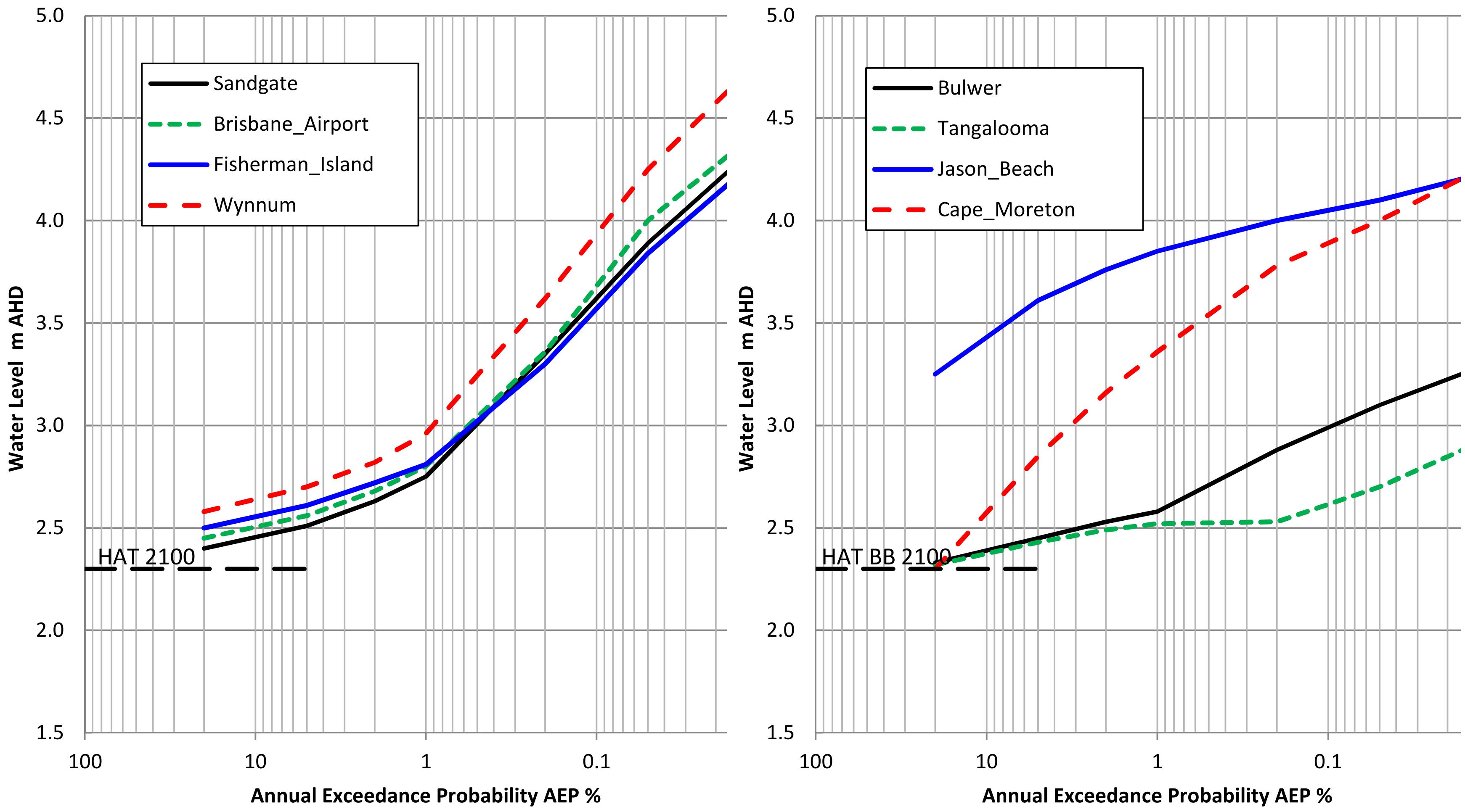

Figure 7-7 Combined 2100 climate total storm tide estimates at selected sites[25]

[25] BB = Brisbane Bar.

Table 7-7 Combined Breaking Wave Runup Open Coast Levels – Projected 2100 Climate Conditions

Location	Latitude (degree)	Longitude (degree)	Water Level in m AHD for various AEP						
			20.00%	5.00%	2.00%	1.00%	0.20%	0.05%	0.01%
Houghton Hwy	-27.2692	153.0730	2.56	2.68	2.78	2.85	3.15	3.61	4.11
Brighton	-27.3008	153.0680	2.59	2.71	2.82	2.90	3.32	3.85	4.34
Nashville	-27.3053	153.0680	2.59	2.71	2.82	2.91	3.33	3.87	4.37
Sandgate	-27.3143	153.0730	2.59	2.71	2.82	2.91	3.35	3.89	4.41
Shorncliffe	-27.3278	153.0940	2.59	2.71	2.83	2.91	3.36	3.91	4.41
Cabbage Tree Head	-27.3323	153.0940	2.59	2.71	2.83	2.91	3.35	3.91	4.44
Nudgee Beach	-27.3414	153.0990	2.59	2.71	2.83	2.92	3.40	4.00	4.51
Brisbane Airport	-27.3549	153.1390	2.64	2.77	2.88	2.97	3.36	4.00	4.47
Juno Point	-27.3594	153.1490	2.64	2.77	2.88	2.97	3.38	4.02	4.47
Luggage Point	-27.3729	153.1640	2.67	2.80	2.91	2.99	3.39	3.96	4.44
Fisherman Island	-27.3594	153.1740	2.70	2.83	2.96	3.05	3.54	3.93	4.33
South Point	-27.4045	153.1850	2.75	2.88	2.99	3.07	3.37	4.00	4.51
Oyster Point	-27.4316	153.1800	2.75	2.88	3.00	3.09	3.55	4.19	4.71
Wynnum	-27.4406	153.1800	2.78	2.91	3.03	3.13	3.62	4.25	4.81
Darling Point	-27.4451	153.1900	2.78	2.91	3.03	3.12	3.58	4.19	4.75
Lota	-27.4677	153.2000	2.78	2.91	3.04	3.13	3.65	4.25	4.82
Mud Island	-27.3502	153.2400	2.83	2.95	3.05	3.13	3.30	3.63	4.11
St. Helena Island	-27.3864	153.2250	2.83	2.96	3.06	3.14	3.34	3.78	4.31
Bulwer	-27.0611	153.3560	2.63	3.25	3.71	4.04	4.58	4.92	5.15
Cowan Cowan	-27.0789	153.3660	2.52	2.65	2.73	2.79	2.90	2.99	3.13
Tangalooma	-27.1243	153.3610	2.52	2.65	2.73	2.79	2.91	3.02	3.32
Kooringal	-27.3588	153.4320	5.17	6.02	6.38	6.59	6.90	7.09	7.23
Clohertys Peninsula	-27.3317	153.4420	5.17	6.02	6.38	6.59	6.90	7.09	7.23
Jason Beach	-27.1828	153.4270	5.25	6.09	6.46	6.67	7.04	7.41	8.01
Cape Moreton	-27.0337	153.4710	5.97	6.99	6.99	6.99	6.99	7.00	7.00

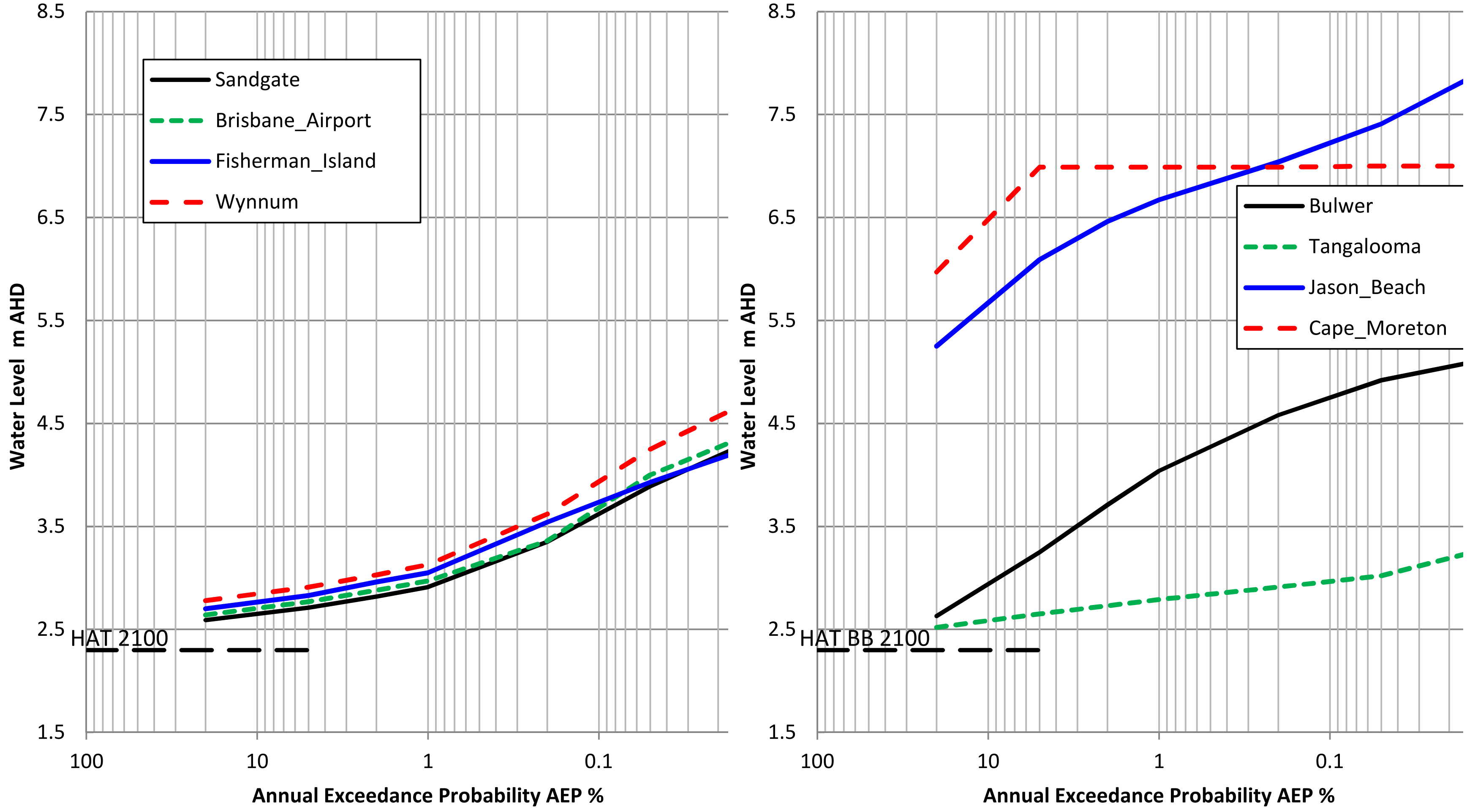

Figure 7-8 Combined 2100 climate breaking wave runup estimates at selected sites[26]

[26] BB = Brisbane Bar.

The increasing potential impact indicated by projected climate change is highlighted by Figure 7-9, which summarises the modelled results for Sandgate. For example, by 2050, the current 1% AEP level is estimated to approximate the 20% AEP level and by 2100 the 0.2% AEP, which as noted above has a very wide-reaching impact, will become approximately the 20% AEP event. These changes represent potential increases in frequency of storm tide impacts by a factor of 20 and 100 respectively.

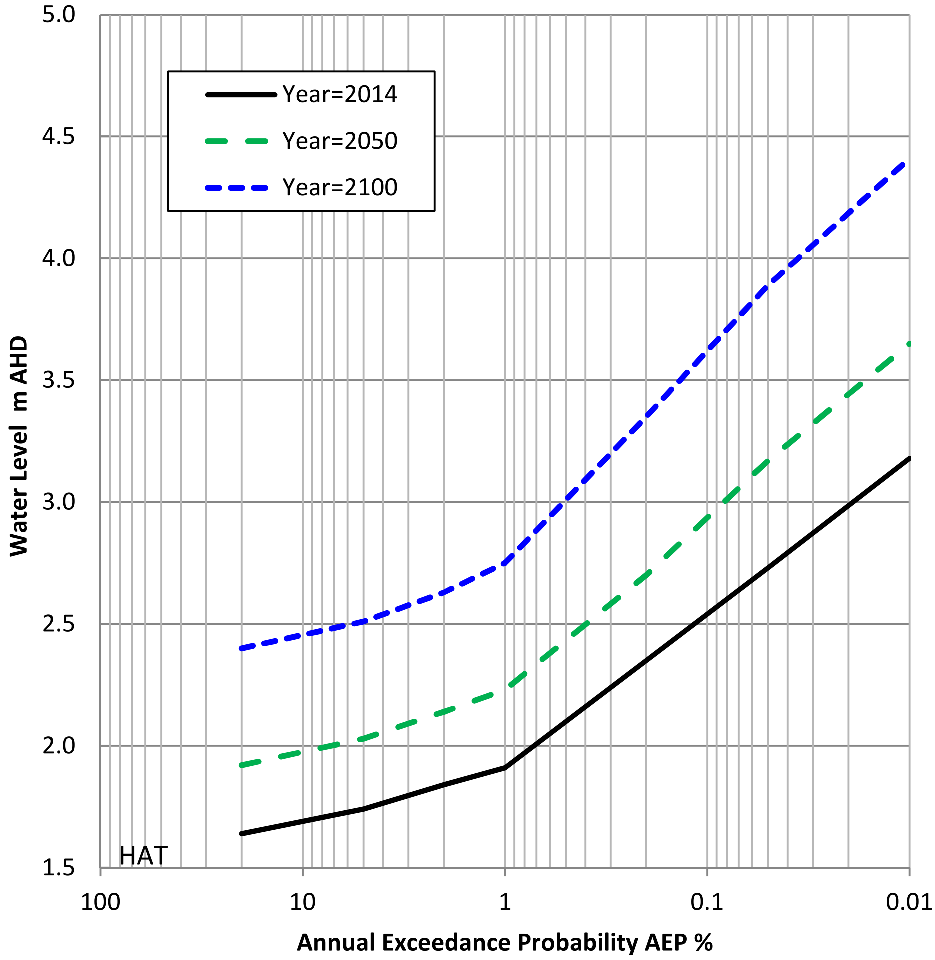

Figure 7-9 Comparison of Impacts of Projected Climate Change on Estimated total storm tide levels at Sandgate.

7.2 Inter-Decadal Climate Variability

The preceding analyses that consider the amalgamation of the available historical data into a single dataset implicitly “averages out” shorter period fluctuations in the intensity and frequency of occurrence of extreme events – whether that be TC occurrences or tide gauge anomalies. The predicted storm tide level AEPs are then simply the “average” or “expected” outcomes over a long period of time (i.e. a time period at least as long as the original dataset).

However, as discussed in Section 3.1, the variability in TC occurrences over a 3 to 5 year span along the east coast of Queensland is known to be strongly associated with the so-called El Niño - Southern Oscillation (ENSO) phenomenon. This refers to a quasi-biennial oscillation of the sea surface temperatures (SST) and mixed-layer depths in the eastern tropical Pacific Ocean. During a so-called El Niño period, the SST is warmer than normal in the east and rainfall and tropical TC activity in northern Australia tends to decrease. In the reverse situation, called La Niña, the SST in the eastern Pacific is cooler than normal and rainfall and tropical TC activity increases along the east coast of Australia. Besides its influence on TC occurrence, the ENSO state also directly impacts the mean sea level variability as a result of both ocean temperature changes and changed large scale geostrophic current patterns, like the East Australian Current. These mean sea level changes are evident in the tidal residual analyses.

The ENSO phenomenon has been a developing area of knowledge over the past few decades and there have been a variety of metrics proposed to define when and how strong the ENSO effect might be at any time. The metric chosen here to classify the ENSO state extremes has been based on the so-called “Niño 3.4” monthly ocean temperature anomaly index provided by the US NOAA/NCEP[27]. In order to represent the Southern Hemisphere interests (which is the reverse of the traditional US-perspective), an annual index has been calculated based on the April-March average of the monthly Niño 3.4 anomaly. This is graphed in Figure 7-10 below for the data period of interest. Also plotted is the Southern Oscillation Index (SOI), which is another (cruder) measure of the strength of ENSO states, derived from surface pressure data differences between Darwin and Tahiti. Note that the SOI is shown in reverse[28], whereby a negative SOI corresponds to a “warm” Niño 3.4 anomaly. It is the “cold” Niño 3.4 anomaly or “high” SOI that is termed a La Niña state and indicates a likely enhanced period of TC activity and higher mean sea levels on the east coast of Queensland because this is the “locally warm” anomaly. The reverse or El Niño state typically shows reduced TC activity and lower mean sea levels as this is the “locally cold” anomaly. Variability between the indicated “warm” and “cold” anomaly boundaries is described as the “neutral” ENSO state.

The following analyses seek to explore how the ENSO inter-decadal variability influences the estimated long-term storm tide AEP averages and therefore provides an indication of the level of uncertainty of the predictions.

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27 http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/detrend.nino34.ascii.txt

28 No attempt has been made here to correlate the Niño 3.4 anomaly and the SOI by adjusting the scales, although it is clear visually that there is a high correlation.

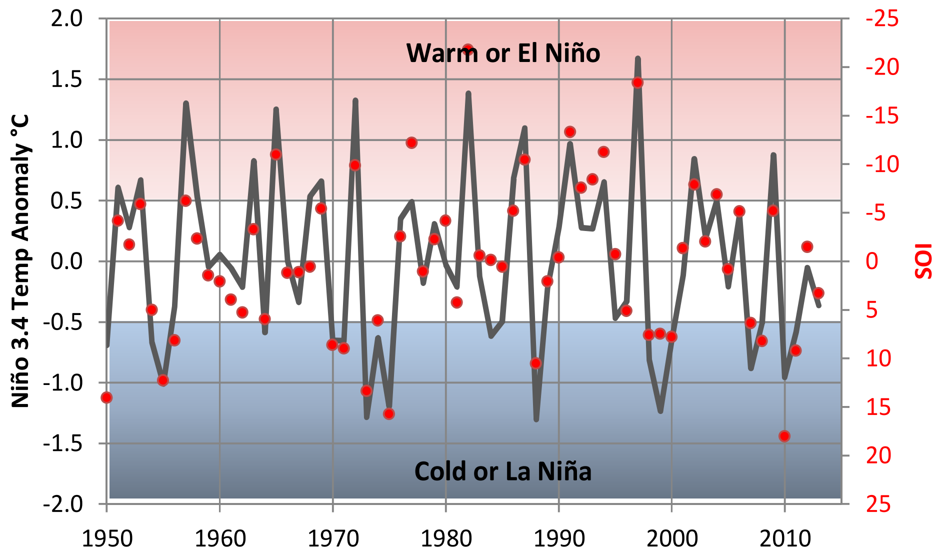

Figure 7-10 ENSO state variability over the data period of interest.

7.2.1 ENSO Effects on Tropical Cyclone Storm Tide Hazard

Because of the relatively short record of TC data, separation of the data set into ENSO state subsets and track subsets tends to negate the statistical value. Accordingly, a simplified approach to estimate the impact of the ENSO variability is adopted here. It is assumed that the principal difference between ENSO states relates to the relative proportion of TC track types (offshore moving, parallel and onshore) but that the intensity distribution of TCs remains relatively constant according to the track class[29].

For the present purposes, modified frequency of occurrence parameters have been derived that broadly describe the observed variation in track class proportions when TCs in each year are assigned to particular ENSO states. These are presented in summary form as Figure 7-11, where the “average” line shows the combined data set that forms the basis of the long term storm tide predictions. The Neutral and El Nińo lines are similar and closest to the average, whereas the La Nińa line shows a very significant change. La Niña states are associated with about a doubling of the damaging "onshore" storm class relative to the other states (from 20% of total tracks to 40%) and a corresponding halving of the parallel class, i.e. storms that might ordinarily tend to run parallel to the coast are more inclined to cross the coast.

These modified average occurrence values have then been used in SATSIM sensitivity tests in place of the long-term average track proportions to gauge the impact of "long term averages of each of the ENSO states”. The true system behaviour then can be considered to likely vary between the ENSO extremes. The current ENSO state or SOI and its forward seasonal trend can therefore be interpreted to consider the possible variation in hazard levels over the coming months or year relative to simply assuming the long term average hazard level.

[29] An analysis of the estimated peak TC intensities grouped purely on ENSO state, without regard to track class, shows that there is indeed little difference between the intensity probability distributions. This supports the practical observation that, even during “quiet” seasons, intense TCs can develop. The recent TC *Ita* was just such an example.

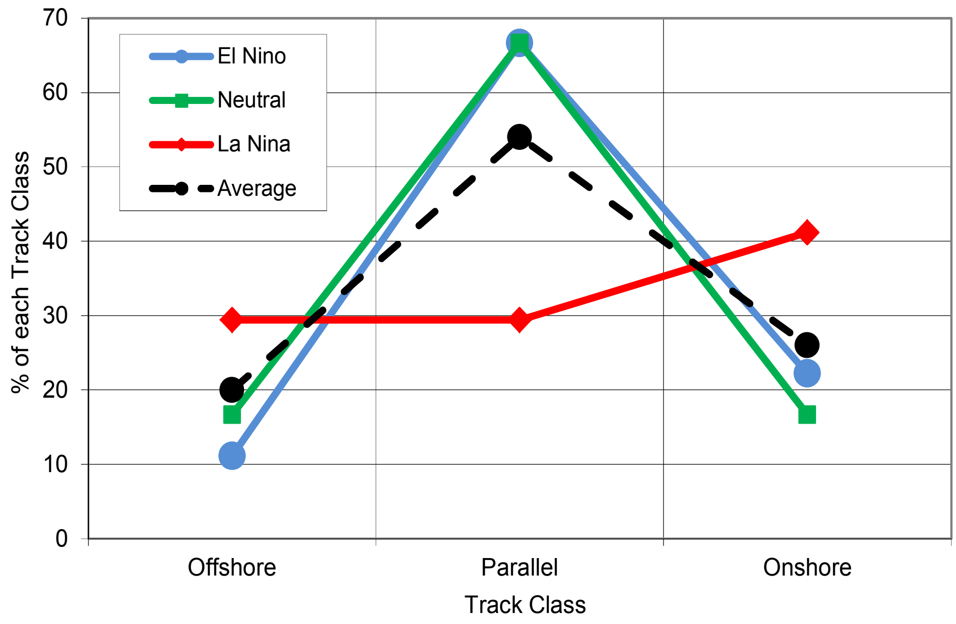

Figure 7-11 Change in adopted model TC track class counts according to ENSO state.

The results of the climate simulations with the above “ENSO biased” perspectives are summarised in Figure 7-12 in terms of the average change in the total storm tide level along the BCC coastline on the western side of Moreton Bay. This has been limited to the AEPs below the Extra-Tropical dominance level determined earlier. It can be seen that La Niña state dominates with an increase in water level ranging between 2% and 8% across the AEP range, averaging a 5% increase overall. The El Niño case is almost identical to the combined climate case. The Neutral state produces a variation almost opposite to that of the La Niña, averaging -5% across the AEP range. These changes are likely driven by the small differences in the number of “onshore” track storms represented in each of the biased climates.

The overall ENSO variability on total storm tide levels due to TC events is of the order of ±5%.

7.2.2 ENSO Effects on Extra-Tropical Storm Tide Hazard

The analyses of Section 4.3 were repeated here after stratifying the measured residual data at the Brisbane Bar into annual periods according to the designated Niño 3.4 ENSO state.

Figure 7-13 summarises the results of this analysis, limited to the higher AEP range mostly dominated by Extra-Tropical events. This shows that La Niña periods also result in increases in the mean Surge plus Tide level at the Brisbane Bar ranging from 2% to 5%. El Niño periods show a reverse response, slightly attenuated, and Neutral periods are similar to the Combined Residual response for high AEP but trend towards the E Niño response at lower AEP. It is possible that the indicated La Niña response is influenced by some river flooding artefacts, but the overall Extra-Tropical ENSO variability is of the order of ±3%.

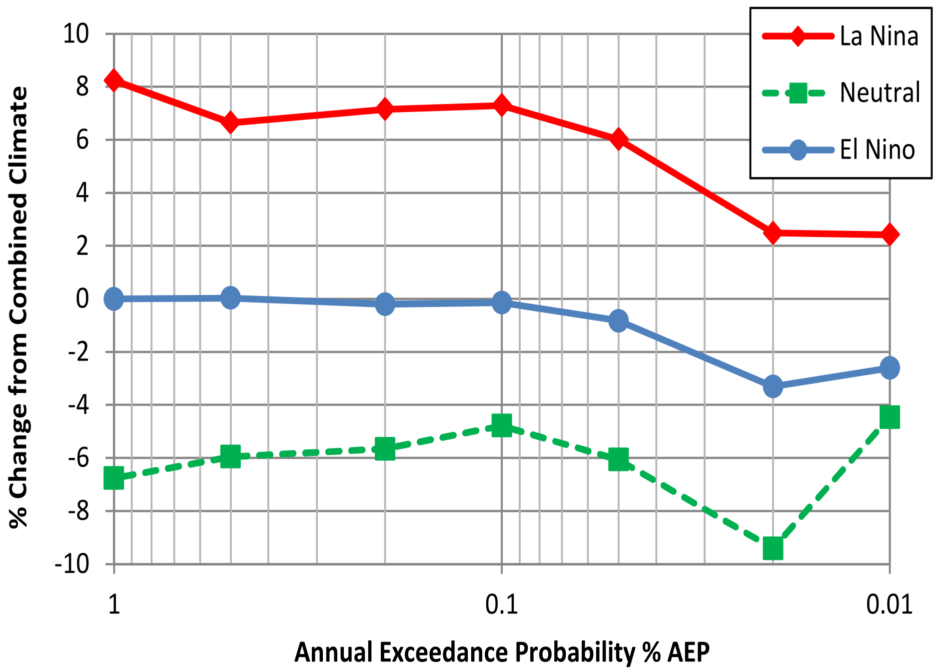

Figure 7-12 Change in estimated total TC storm tide levels for the BCC coastline according to each persistent ENSO state.

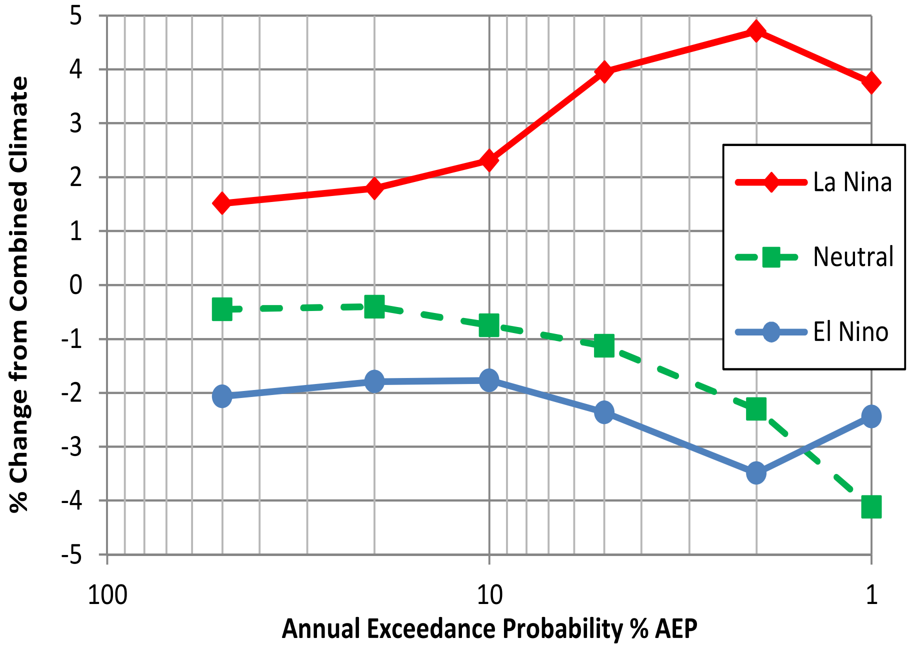

Figure 7-13 Change in estimated Extra-Tropical tide plus surge levels for the Brisbane Bar after annual stratification of tidal residuals according to each ENSO state.

8. Inundation Modelling and Mapping

This chapter describes the fine scale dynamic inundation modelling undertaken using the LHM to allow the preparation of statistically robust mapping of storm tide extents for a range of AEPs, depth x velocity estimates and to calculate persistence of flooding under the 2014, 2050 and 2100 climate projections considered.

8.1 Inundation Modelling

Dynamic overland inundation mapping aims to account for the fact that storm tide flooding events are not simply a horizontal projection of the open coast water levels inland. Rather, the combined effects of ocean momentum, surface wind stress over the shallow inundated areas and the complex surface friction will allow modification and potential re-generation of the storm surge over land, interacting with the ground surface contours and creating favoured pathways.

The technique is one of selecting a suitable sample of previously modelled open coast stochastic events (Extra-Tropical and TC) that, when re-modelled in the fine-scale hydrodynamic context, will be representative of the equivalent inundation impacts. The sampled individual event modelled inundation surfaces are then averaged to obtain the expected parameters of interest; namely extent, depth x velocity and persistence.

Key deliverables of the inundation modelling phase include GIS surface development for the 5%, 2%, 1%, 0.2% and 0.05% AEPs and hardcopy mapping of the 1% AEP. This required melding of the separate Extra-Tropical and TC climate event surfaces to achieve the desired outcome of statistically robust mapped inundation extents. The methods for storm selection and model development are detailed in the following sections.

8.1.1 Storm Selection

The tide plus surge and total storm tide shoreline estimates detailed in Chapters 6 and 7 were developed based on the simulation of many thousands of stochastic ‘events’ using the SATSIM and TRSSM models . However, use of the high resolution Mike21 FM model precluded the modelling of similarly large numbers of storms, owing to the significant runtime involved. Accordingly, a sample of 6-11 storms was run for each required AEP, and for each climate that approximated the resulting levels at the open coast. This led to the simulation of over 200 individual events selected from the SATSIM and TRSSM event suites.

As detailed in Chapters 6 and 7 water levels for AEP events lower than the 0.5 % are dominated by high energy close approach TCs while more frequent AEPs are derived from extra-tropical systems. To correctly capture the dynamics of these differing systems, inundation events have been selected from the SATSIM and TRSSM storm populations as follows:

- The 0.2 % and 0.05 % AEP were selected from the SATSIM stochastic set; and
- The 5 %, 2 % and 1 % AEP have been developed from the TRSSM dataset.

To ensure adequate time for tidal build-up, storm peak and relaxation to lower levels, a period of 3 to 4 days surrounding the event was simulated.

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8.1.2 Inundation Model Setup Tropical Cyclone

The model setup adopted for TC inundation modelling is consistent with the approach described in Chapter 4 by which the LHM receives tide and surge model boundaries from the large-scale RHM and wind and pressure fields from the Double Holland TC model.

8.1.3 Inundation Model Setup Extra-Tropical and Remote TCs

The Extra-Tropical and remote TC inundation modelling were completed in a manner consistent with the Section 5.2.3 – sub heading *Final Representation* whereby the measured residuals from Mooloolaba are applied to the boundaries of the LHM in concert with astronomical tidal inflows from the RHM. For each 'event' the period of predicted tide and historical residual was replicated based on the tidal prediction and residual periods used in the TRSSM.

A spatially constant but temporally varying wind and pressure field was applied to the LHM based on the long-term wind records at Brisbane Airport, which were deemed to be representative of conditions within the study area. The period of wind applied to the model was consistent with the residual period selected from the 29 year residual record. A correlation between the Brisbane Airport wind speeds and the Spitfire Banks was developed to ensure a more representative over-water wind field over Moreton Bay.

8.1.4 Verification to Open Coast/Shoreline Estimates

Initially, maximum water levels were extracted for each run with the set averaged for each AEP. When compared to the shoreline estimates, the average peak water levels from the envelope of runs were found to be less than 10 % for TCs and less than 5% of the Extra-Tropical derived levels. Differences are likely due to the overland and Brisbane River representation within the LHM as well as slight timing issues between the time and angle of landfall within the SATSIM dataset. It is likely that if many more storms were run i.e. 50, that the average levels would converge on the shoreline estimates.

To ensure consistency with the statistically robust shoreline estimates, the peak results of each inundation run were factored at all locations based on the difference in levels between Luggage Point and the modelled peak at this location. The resulting inundation surfaces have then been averaged to produce probabilistic inundation surfaces for each AEPs considered.

These probabilistic inundation surfaces have then been utilised to develop a series of digital mapping surfaces for future planning and emergency management.

8.1.5 Brisbane River Influences

The Brisbane River is a significant modifier of long wave activity (tidal and storm surge) that propagates in from Moreton Bay. In addition to the reducing planform moving upstream, there are increasing frictional effects, complex bathymetry and curvature that introduce some specific numerical modelling challenges. A feature of all shallow water/estuary areas is that the non-linear influence of bed friction tends to flatten out the ebb tidal response relative to the peak flood response and this creates a slight increase in the Mean Sea Level (MSL) moving upstream. Also, the finite wavelength of incoming tide and surge events means that they may not have sufficient time to propagate fully up-river by the time the tailwater level is already falling at the mouth. This will tend to produce a "mounded statistical water level surface" at some intermediate chainage along the river. The published MSQ tidal planes illustrate these influences at a number of sites, although the present veracity of these is unknown, given that instrumentation and processing has likely varied over the years.

While the model tidal calibration comparisons (Section 5.1) show a good agreement with the Port Office, there are a number of complex issues that have not been able to be specifically considered within the present study scope. These manifest as an apparent slight underestimation of the modelled storm tide levels when moving up river, as compared with the empirical resampling results from the TRSSM shown in Figure 4-13 applicable to the Port Office.

Firstly, the empirical TRSSM method applies a linear recombination of tide and measured residuals, which ignores frictionally-forced harmonics and baroclinic (e.g. salinity) effects that could tend to attenuate the potentially higher residual events. Also the Port Office data was necessarily analysed in two separate segments because of datum shifts (and anecdotally in response to instrument changes) that produced some differences in the derived zero offsets and also in the longer period constituent amplitudes. When re-combining to produce the Port Office response (green line in Figure 4-13), the characteristics of the (shorter) later period were preferentially used rather than the former as river dredging and the like can also influence this site. There is also still some possibility of small flood-flow influences on the residual levels. In short, the TRSSM storm tide levels may tend to overestimate the true Port Office hazard.

Secondly, although the LHM model open boundaries were specified using 17 tidal constituents, which was adequate for the open coast Brisbane Bar reference location, it has not been able to reproduce all of the shallow water harmonics that are evident from the MSQ harmonic analysis of the Port Office tide gauge. For example, the difference in peak tidal amplitude at the Port Office between using 17 constituents and then including the remaining (approximately 30) can generate an additional 0.1 to 0.2 m water level. There are a number of possible reasons why the LHM does not reproduce these effects fully. Principal among these might be the need for a closer examination of bed friction variability or bathymetric accuracy. However other factors that cannot be represented by a 2D barotropic model like the LHM are equally likely to influence the outcome. These other factors include 3-dimensionality of the river flow (especially due to the serpentine morphology and the depth variability) and salinity gradients.

Thirdly, the adopted open coast inundation scenario selection process may not have yielded an unbiased sample of the range of possible events that contribute to the subtlety of up-river flooding. This could only be guaranteed by modelling a much larger set of events than has been possible within the present timeframe.

In keeping with the above, BCC provided some intermediate water level data for a number of tidal events along the river for the purposes of creating an operational “lookup table”. The table will provide a basis for comparing statistical water levels at the Brisbane Bar with those at other locations. It is noted that the provided BCC data leads to a higher level of amplification up-river than that derived from the MSQ data.

Although it is clear that above the Hamilton Reach the flood hazard will be dominated by fluvial events, it is recommended that further research, data collection and modelling be undertaken if there is a need for more accurate mapping of the along-river storm tide variation.

8.2 Inundation Mapping

Storm tide inundation elevation and depth surfaces for the 5%, 2%, 1%, 0.2% and 0.05% AEPs and depth x velocity surfaces for the 1%, 0.2% and 0.05% AEPs have been developed by processing the hundreds of inundation and open coast modelling results with a suite of GHD-developed GIS modelling toolboxes. These GIS toolboxes are similar to those used for earlier studies (GHD/SEA 2007, 2009; GHD 2010, 2012) whereby hydrodynamic model results are mapped to a high resolution DEM (here 5 m horizontal) in order to more accurately represent small scale depressions and waterways in the final mapping product.

- The average tide plus surge model results are used to interpolate/extrapolate levels to the extent of a provided Digital Elevation Model (DEM).
- For regions likely to be affected by wave setup, the approximate position of the frontal dune has been digitised based on available aerial photography and where possible, this location has been verified based on provided topographic data.
- Total storm tide levels have been mapped within a region 200 m adjacent to the digitised coastline with *total storm tide* levels mapped directly on the coastline linearly decreasing to *tide plus surge* only levels at the edge of the nominal wave setup zone.

In addition to depth and water level surface development, mapping of the 1% AEP for each climate considered has been developed consistent with BCC's mapping framework and is provided as Appendix E. The digital GIS datasets have been provided in ESRI geodatabase format on the MGA, Zone 56 grid projection and to AHD.

8.3 Water Level Persistence

To provide an indication of likely periods of disruption due to flooding by storm surge for consideration in emergency response and planning, an assessment of tide plus surge flood duration was undertaken. The term "water level persistence" refers to the length of time that a storm tide water level likely exceeds a particular elevation. Estimates of water level persistence to the nearest 0.5 hr are directly available from the SATSIM model which accumulates the water level exceedance statistics throughout the 50,000 years for each simulation.

The results are expressed in terms of a cumulative exceedance distribution of persistence, which is graphed in Figure 8-1 for a modelled location near the mouth of the Brisbane River. The series of curves shown are for different AEP total water levels, which can be seen to vary only slightly. The average persistence is therefore indicative of the overall response, whereby there is a 90% chance at any AEP level that it will be exceeded for about 0.5 hr. The average persistence is around 2.5 hr with the 10%-only exceeded persistence around 5 hr.

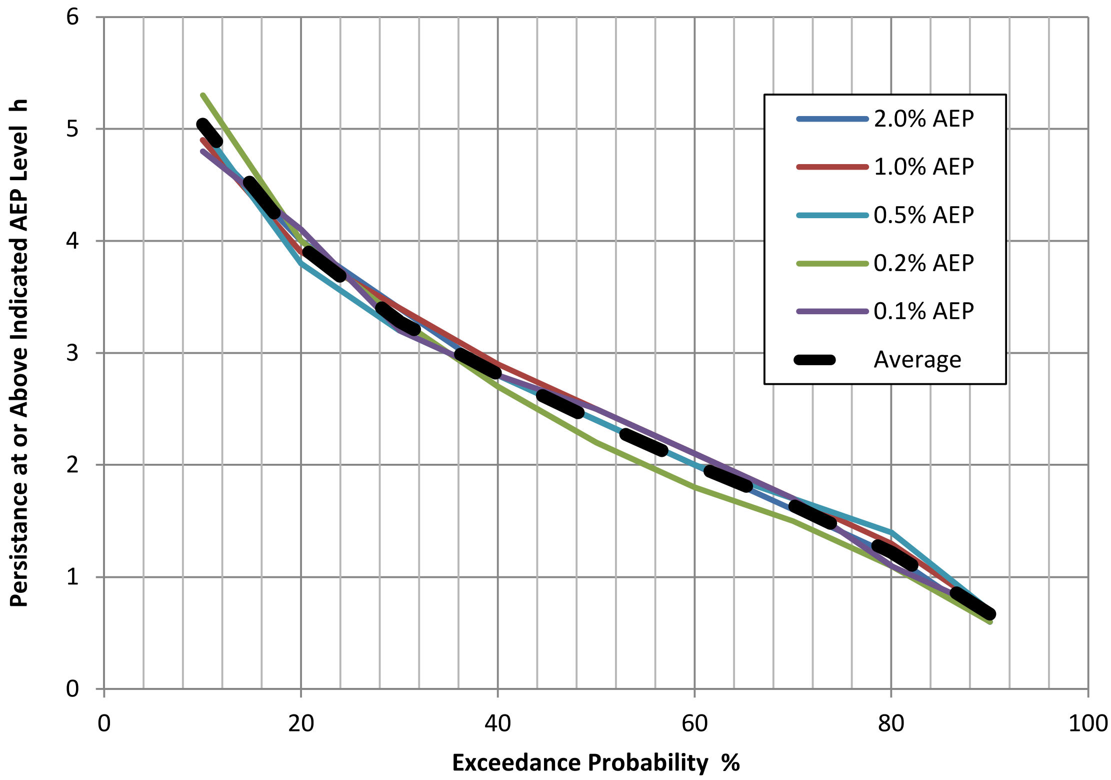

Figure 8-1 Estimated Water Level Persistence for TC Events

8.4 Commentary

The inundation extents indicate that a 2% AEP event will begin to impact on exposed nearshore Brighton-Sandgate properties and that most of the low-lying areas will be affected by the 1% AEP event. Likewise, Wynnum foreshore property impact commences at the 1% event with the adjacent low-lying properties mostly encompassed by the 0.2% event extending to Manly, Lota and Ransome. Other vulnerable areas include Nudgee Beach and parts of Shorncliffe and Deagon, which would be impacted by a 0.2% AEP event, as well as the Breakfast Creek precinct in Albion, parts of Norman Creek and industrial areas of Pinkenba. The Boondall Entertainment Centre is impacted by the 0.05% AEP as are the Hendra flats and Brisbane Airport. Bulimba Creek impacts the Hemmant area by the 0.2% AEP extending to low-lying parts of Tingalpa for the 0.05% AEP. A risk analysis that considers the vulnerability and exposure of individual properties (including their floor heights), roads and other infrastructure, would be required to estimate a more detailed impact of these hazard levels.

The projected influences of future climate change do not change this situation, although slowly rising sea level alone represents a significant hazard and threat to the coastal margins over time (particularly if sea level rise continues to track near or above the current rates of increase). For example, by 2050 the current 1% AEP level is estimated to equate approximately to the 20% AEP level. By 2100 the 0.2% AEP, which as noted above has a very wide-reaching impact, will approximate the 20% AEP event. These changes represent potential increases in frequency of storm tide impacts by a factor of 20 and 100 respectively.

9. Conclusions

A comprehensive assessment has been completed of the storm tide hazard in the Brisbane City Council coastal region due to the possible effects of severe tropical cyclones and other large scale extra-tropical weather systems that combine with the regular tidal variability. The coastal margin includes the region from Hays Inlet south to Tingalpa Creek and east to Moreton Island. It includes the Brisbane River upstream to Ipswich as well as principal tributaries (Oxley Ck, Norman Ck, Breakfast Ck and Bulimba Ck) and the tidal limits of Kedron Brook, Nundah Creek, Cabbage Tree Creek, and parts of the South Pine River. Both present (2014) climatic conditions and projected future possible climate and sea level conditions have been considered (for the years 2050 and 2100), as well as the underlying natural climate variability on inter-decadal timescales.

Historical data analysis, detailed numerical hydrodynamic modelling and state-of-the-art statistical modelling have been combined to provide enhanced understanding, assessment and quantification of the storm tide hazard that can impact population, property and infrastructure in the region. The analyses are necessarily based on a number of assumptions and the possible influence of these on the accuracy of the storm tide estimates as discussed throughout the report. Experience and knowledge gained from numerous previous studies was used in designing the specialised methodology needed for this project.

(a) Scope and Outcomes

The study provides an estimate of likely open coast water level AEPs (Annual Exceedance Probabilities) and the extents, depths and velocities of potential inundation events. Such information can also inform fluvial flooding studies where suitable ocean tailwater levels need to be defined.

Within the limits of the available data, resources and timescale, the study has considered:

- The long-term historical record of tropical cyclones in the region, including preferred tracks, speeds, directions, sizes and intensities;
- The spatial and temporal characteristics of storm surge generated by tropical cyclones interacting with the complex coastal features;
- The broad-scale ocean response of extra-tropical and remote tropical cyclone influences as captured by the regional tide gauge records;
- Associated extreme waves and breaking wave setup and runup levels at the coastline;
- The astronomical tide, which varies considerably throughout the study region, and
- A range of fine-scale inundation extents dynamically modelled with imposed wind stress and time-varying boundary conditions, which are then statistically combined.

The accuracy of the various models has been confirmed by comparison with available historical wind and storm surge data and also through reference to published tide tables. The recent (Jan 2103) Ex-TC *Oswald* event that created a significant regional flood and storm tide impact has been used to demonstrate the deterministic accuracy of the combined numerical modelling system, including the ability to reproduce the tidal characteristics. The probabilistic accuracy of the final water level AEP estimates is underpinned by comparisons with long term wind data (which drives the storm tide response), historical storm statistics and empirical evidence taken directly from the tide gauge records.

While the principal prediction of extreme storm tide levels has been undertaken within the concept of “present” climate as determined from interpretation of historical climate and impact records, additional guidance on the possible influence of projected future “climate change” has been included based on current scientific opinion.

It is emphasised that the provided tide plus surge water level estimates are considered inherently more reliable than those that include wave setup or wave runup. This is due to an intrinsic lack of fine scale coastal detail, the noted scatter in the empirical functions available to provide the estimates, and likely wave interaction with very localised and possibly dynamic coastal features. Water levels that include wave setup and/or wave runup should therefore be regarded as indicative and hence it is a matter of sound professional practice that any detailed risk assessment or design of facilities within indicated wave setup or runup zones should be based on additional and specific local analyses.

The storm tide hazard has been shown to vary significantly across the Brisbane City region:

- The open unpopulated eastern coast of Moreton Island is subject to relatively low tide plus surge influences owing to the adjacent deepwater environment, but is impacted by high levels of breaking wave setup and runup through exposure to oceanic wave conditions
- The inner sparsely-populated eastern coast of Moreton Island is significantly sheltered from oceanic wave impacts while experiencing a lower tide and lower storm surge threat than Brisbane City
- The highly-populated mainland coast of Brisbane City experiences amplification of both the ocean tide and any incoming storm surge given the relatively shallow waters of Moreton Bay (mostly < 10m) and the narrowing bay planform, although it is sheltered from significant oceanic wave influences.

> Climatologically, extra-tropical and remote tropical cyclone impacts dominate the higher AEP water level events under present climate conditions up until about the 1% AEP. These then give way to TC-dominated events by the 0.5% AEP with a significant increase in the slope of the water level AEP curve.

(b) Inundation Mapping

The fine scale inundation mapping of the metropolitan region has been provided for specific storm tide hazard levels of 5%, 2%, 1%, 0.2% and 0.05% AEPs. The mapping comprises a melding of the separate extra-tropical and tropical cyclone climate event surfaces to achieve the desired outcome of statistically robust mapped inundation extents. These inundation surfaces are not flat but rather reflect the dynamics of a possible storm tide episode that can locally amplify or attenuate water levels relative to the adjacent open coast levels. The interplay of storm tide levels with the Brisbane River is also represented and indicates (in the absence of a potential coincident flood) that water levels will vary in sometimes complex ways due to the dynamics. Estimates of breaking wave setup that can locally increase stillwater levels along the coastal margins are also included in the inundation mapping by an indicated zone of influence.

The inundation extents indicate that a 2% AEP event will begin to impact on the exposed nearshore Brighton-Sandgate properties and most of the low-lying areas there will be affected by the 1% AEP event. Likewise Wynnum foreshore property impact commences at the 1% event and the adjacent low-lying properties are mostly encompassed by the 0.2% event extending to Manly, Lota and Ransome. Other vulnerable areas include Nudgee Beach and parts of Shorncliffe and Deagon, which would be impacted by a 0.2% AEP event, as well as the Breakfast Creek precinct in Albion, parts of Norman Creek and industrial areas of Pinkenba. The Boondall Entertainment Centre is impacted by the 0.05% AEP as well as the Hendra flats and Brisbane Airport. Bulimba Creek impacts the Hemmant area by the 0.2% AEP and extends to low-lying parts of Tingalpa by the 0.05% AEP. A detailed risk analysis that considers the vulnerability and exposure of properties (including their floor heights), roads and other infrastructure, would be required to estimate the full impact of these hazard levels.

The projected influences of future climate change do not change this situation, although slowly rising sea level alone represents a significant hazard and threat to the coastal margins over time if it continues to track near or above the current rates of increase. For example, by 2050, the current 1% AEP level is estimated to become approximately the 20% AEP level. By 2100 the 0.2% AEP, which as noted above has a very wide-reaching impact, will approximate the 20% AEP event. These changes represent potential increases in frequency of storm tide impacts by a factor of 20 and 100 respectively

(c) Uncertainty

While the full tracking of analysis uncertainty has been outside of the present scope, it is reasonable to expect that the estimated point AEP storm tide magnitude uncertainty is at least equal to that indicated by the inter-decadal ENSO variability analysis, which suggests a likely range of 3 to 5%. It should be noted that point-AEP estimates are merely “averages” in this context and are only realised over long time periods.

(d) Comparison with Previous Studies

As noted in Section 1.2 there have been a number of studies over the past 35 years that have sought to estimate storm tide hazard in the Moreton Bay region. The referenced studies mentioned have been re-examined as a part of the present study methodology development and the present results compared with the results of those earlier studies. Notwithstanding increases in computational power and technical knowledge, there are many reasons why studies produce different results. This was recently the subject of a detailed critique and analysis undertaken by GHD for DSITIA (GHD 2014) for the entire Queensland coast that considers only the most recent storm tide studies.

Principally, some studies are not comprehensive in including both TC and extra-tropical influences. Some do not always provide sufficient detail of their methodology or data to enable a thorough critique. Others do not always provide robust verification or validation analyses and some provide erroneous process and statistical advice. The final results presented here are deemed reconcilable with those earlier studies after consideration of the available information. The interested reader is referred to GHD (2014) for further details.

(e) Future Studies

Taken as a whole, the study results provide a very comprehensive and robust quantitative estimation of storm tide hazard throughout the Brisbane City Council local government region. Notwithstanding this, the study has highlighted areas that would benefit from further detailed study if greater reliance is to be placed on estimates of higher AEP events, such as:

I. The influence of baroclinic processes;

II. The complexities of up-river storm tide propagation

Also, considering that techniques and knowledge continually improve, the data available for calibration and verification increases in quality and quantity and projected climate change effects are issued each 4 years, it is recommended that the study outcomes be reviewed within 5 years.

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Appendices

Appendix A - A Note on the Interpretation of Annual Exceedance Probability

This study has presented its analyses of risk in terms of the Annual Exceedance Probabiility (AEP) of equalling or exceeding the indicated storm tide elevations. At less than the 10% AEP, the AEP is approximately equal to 100 times the inverse of the so-called *Return Period* (or Average Recurrence Interval *ARI*).

The Return Period is the "average" number of years between successive events of the same or greater magnitude. For example, if the 100-year return period storm tide level is 3.0 m AHD then on average, a 3.0 m AHD level storm tide *or greater* will occur due to a single event once every 100 years, but sometimes it may occur more or less frequently than 100 years. It is important to note that in any "N"-year period, the "N"-year return period event has a 63% chance of being equalled or exceeded. This means that the 3.0 m storm tide has a better-than-even chance of being exceeded by the end of any 100-year period. If the 100-year event were to occur, then there is still a finite possibility that it could occur again soon, even in the same year, or that the 1000 year event could occur, for example, next year. Clearly if such multiple events continue unchecked then the basis for the estimate of the 100 year event might then need to be questioned, but statistically this type of behaviour can be expected.

A more consistent way of considering the above (NCCOE 2012) is to include the concepts of "design life" and "encounter probability" which, when linked with the Return Period, ARI or AEP, provide better insight into the problem and can better assist management risk decision making. These various elements are linked by the following formula (Borgman 1963):

$Tr = - L / \ln [1 - p]$ and $AEP = 100 [1-\exp(-1/Tr))$

where	p	=	encounter probability	$0 \leq 1$
	L	=	the design life	(years)
	Tr	=	the return period	(years)

This equation describes the complete continuum of risk when considering the prospect of at least one event of interest occurring. More complex equations describe other possibilities such as the risk of only two events in a given period or only one event occurring.

Figure A-1 illustrates the above equation graphically. It presents the variation in probability of at least one event occurring (the encounter probability) versus the period of time considered (the design life). The intersection of any of these chosen variables leads to a particular AEP and a selection of common AEP is indicated. For example, this shows that the 0.5% AEP has a 40% chance of being equalled or exceeded in any 100-year period.

The level of risk acceptable in any situation is necessarily a corporate or business decision. Table A-1, based on Figure A-1, is provided to assist in this decision making process by showing a selection of risk options. Using Table A-1, combinations of design life and a deemed acceptable risk of occurrence over that design life can be used to yield the appropriate AEP to consider. For example, accepting a 5% chance of occurrence in a design life of 50 years means that the 0.1% AEP should be considered. A similar level of risk is represented by a 1% chance in 10 years. By comparison, the 1% AEP is equivalent to about a 10% chance in 10 years. AS1170.2 (Standards Australia 2011), for example, dictates a 10% chance in 50-year criteria or the 0.2% AEP as the minimum risk level for wind speed loadings on engineered structures.

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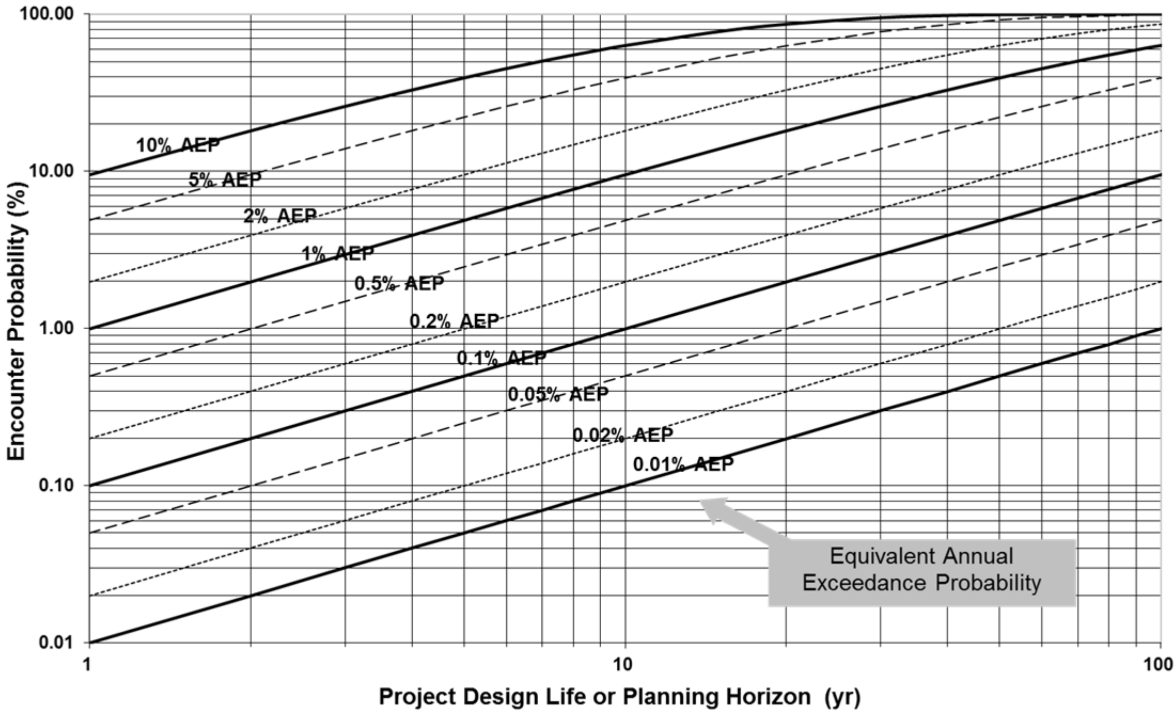

Figure A-1: Relationship between AEP and Encounter Probability

Table A-1: Risk selection based on encounter probability concepts.

Considered Design Life or Planning Horizon	Chosen Level of Risk of at Least One Event Occurring % Chance					
y	1	2	5	10	20	30
	Equivalent AEP (%)					
10	0.10	0.20	0.51	1.05	2.21	3.50
20	0.05	0.10	0.26	0.53	1.11	1.77
30	0.03	0.07	0.17	0.35	0.74	1.18
40	0.03	0.05	0.13	0.26	0.56	0.89
50	0.02	0.04	0.10	0.21	0.45	0.71

Appendix B - Tropical Cyclone Dataset Summary

Name	Start Date	Lat deg	Long deg	Finish Date	Lat deg	Long deg	At Maximum Intensity Within Radius p0 hPa	Date	Dist km	Bear deg	Vfm m/s	Theta deg	At Closest Approach p0 hPa	Date	Dist km	Bear deg	Vfm m/s	Theta deg
CY0288_1960	27-Feb-60	-16.7	155.3	3-Mar-60	-28.7	158.3	964	1-Mar-60	462	60	4.3	161	978	2-Mar-60	449	89	2.6	169
CY0296_1961	26-Jan-61	-14.3	161.2	1-Feb-61	-31.7	162.0	998	31-Jan-61	497	63	3.9	158	998	31-Jan-61	494	69	3.9	158
CY0304_1961	22-Dec-61	-16.7	148.7	25-Dec-61	-25.3	159.7	1000	24-Dec-61	469	21	6.0	120	1000	24-Dec-61	463	31	6.0	120
Cy310_1962	29-Dec-62	-17.7	150.8	31-Dec-62	-26.0	151.7	978	31-Dec-62	123	337	6.0	270	978	31-Dec-62	123	337	6.0	270
CY0317_1963	3-Feb-63	-16.0	151.5	6-Feb-63	-32.0	161.3	994	5-Feb-63	415	36	12.5	169	997	5-Feb-63	299	80	12.0	168
CY0323_1963	30-Mar-63	-22.3	153.0	2-Apr-63	-24.3	165.0	1000	31-Mar-63	421	11	3.9	121	1000	31-Mar-63	399	24	7.7	113
Audrey_1964	6-Jan-64	-10.2	141.5	14-Jan-64	-30.4	153.9	984	13-Jan-64	453	251	24.1	116	986	14-Jan-64	316	209	24.1	116
Judy_1965	25-Jan-65	-11.6	133.0	5-Feb-65	-31.5	164.5	990	3-Feb-65	459	90	4.5	217	991	3-Feb-65	406	107	3.2	196
Dinah_1967	22-Jan-67	-12.7	163.8	31-Jan-67	-35.2	161.5	945	28-Jan-67	418	350	5.3	164	950	29-Jan-67	122	51	5.9	141
Barbara_1967	17-Feb-67	-13.1	163.5	21-Feb-67	-28.8	152.6	987	21-Feb-67	174	185	3.3	252	988	21-Feb-67	166	168	7.0	257
Elaine_1967	13-Mar-67	-14.7	149.3	19-Mar-67	-32.0	164.0	996	17-Mar-67	441	20	13.2	159	996	17-Mar-67	288	68	12.7	158
Glenda_1967	26-Mar-67	-12.5	155.3	5-Apr-67	-31.7	159.3	988	4-Apr-67	474	99	5.2	169	988	4-Apr-67	474	99	5.2	169
Cy562_1967	6-Dec-67	-15.5	151.6	10-Dec-67	-27.7	163.7	996	8-Dec-67	402	76	5.5	138	998	8-Dec-67	350	56	6.6	134
Cy563_1967	9-Dec-67	-24.9	154.5	12-Dec-67	-21.9	156.4	998	10-Dec-67	290	76	2.5	146	1002	9-Dec-67	242	43	8.3	133
Cy680_1969	11-Apr-69	-10.6	164.9	16-Apr-69	-31.5	160.0	1001	15-Apr-69	474	44	6.9	195	1002	15-Apr-69	299	88	10.3	177
Cy575_1969	14-Nov-69	-20.1	154.0	15-Nov-69	-32.4	152.5	1004	15-Nov-69	250	19	9.6	163	1004	15-Nov-69	130	99	16.3	192
Dora_1971	10-Feb-71	-19.5	152.7	17-Feb-71	-25.7	151.9	995	17-Feb-71	74	123	7.6	302	995	17-Feb-71	6	127	7.6	302
Fiona_1971	16-Feb-71	-16.0	140.8	28-Feb-71	-20.8	161.8	994	21-Feb-71	322	334	2.3	90	995	22-Feb-71	302	349	2.9	79
Lena_1971	13-Mar-71	-12.4	154.8	19-Mar-71	-24.0	167.8	985	15-Mar-71	463	9	4.3	160	990	16-Mar-71	369	24	1.4	42
Althea_1971	19-Dec-71	-10.9	159.0	29-Dec-71	-34.8	164.7	978	27-Dec-71	217	28	5.2	78	988	27-Dec-71	153	353	5.6	84
Wendy_1972	4-Feb-72	-16.0	165.2	9-Feb-72	-25.8	156.0	1001	9-Feb-72	453	76	4.2	270	1001	9-Feb-72	287	61	4.9	288
Daisy_1972	5-Feb-72	-14.9	150.0	13-Feb-72	-27.4	158.1	959	10-Feb-72	399	18	2.4	270	996	12-Feb-72	5	219	4.3	147
Emily_1972	27-Mar-72	-11.0	157.5	4-Apr-72	-34.4	153.2	974	1-Apr-72	450	336	6.8	204	1005	2-Apr-72	89	252	10.4	159
Kirsty_1973	24-Feb-73	-14.6	157.4	1-Mar-73	-34.3	160.6	980	27-Feb-73	350	39	9.9	169	982	27-Feb-73	268	77	8.9	168
Wanda_1974	20-Jan-74	-17.7	148.8	25-Jan-74	-27.3	149.9	997	24-Jan-74	173	347	4.2	222	998	24-Jan-74	141	317	3.8	227
Pam_1974	3-Feb-74	-19.9	163.1	6-Feb-74	-29.9	157.8	972	5-Feb-74	469	92	5.3	194	974	5-Feb-74	456	106	8.7	182
Zoe_1974	6-Mar-74	-18.8	154.3	14-Mar-74	-32.0	158.8	982	10-Mar-74	478	11	4.1	180	982	12-Mar-74	11	67	2.9	151
Alice_1974	21-Mar-74	-22.6	154.3	22-Mar-74	-29.7	161.1	1010	21-Mar-74	498	9	10.0	145	1010	21-Mar-74	356	50	8.0	140
Beth_1976	13-Feb-76	-16.5	149.9	22-Feb-76	-24.9	151.3	991	20-Feb-76	480	30	4.4	256	996	21-Feb-76	277	332	4.2	263
Colin_1976	25-Feb-76	-10.3	155.5	4-Mar-76	-33.8	158.9	954	1-Mar-76	470	28	4.1	186	959	2-Mar-76	261	78	4.7	168
Dawn_1976	3-Mar-76	-17.4	145.6	6-Mar-76	-30.4	155.7	988	5-Mar-76	405	335	9.7	133	990	5-Mar-76	77	66	10.1	155
Watorea_1976	25-Apr-76	-9.5	152.6	28-Apr-76	-27.1	158.9	990	28-Apr-76	324	30	22.1	127	990	28-Apr-76	322	37	22.2	126
Paul_1980	2-Jan-80	-15.1	137.1	8-Jan-80	-30.0	159.6	989	7-Jan-80	346	35	11.2	141	989	7-Jan-80	333	52	11.2	141
Simon_1980	21-Feb-80	-17.0	153.8	28-Feb-80	-30.5	160.5	960	24-Feb-80	498	336	1.5	70	974	27-Feb-80	160	49	6.9	137

Name	Start Date	Lat deg	Long deg	Finish Date	Lat deg	Long deg	At Maximum Intensity Within Radius p0 hPa	Date	Dist km	Bear deg	Vfm m/s	Theta deg	At Closest Approach p0 hPa	Date	Dist km	Bear deg	Vfm m/s	Theta deg
Cliff_1981	**9-Feb-81**	**-11.1**	**171.6**	**15-Feb-81**	**-26.0**	**146.5**	**985**	**13-Feb-81**	**447**	**70**	**4.8**	**257**	**985**	**14-Feb-81**	**182**	**18**	**6.8**	**287**
Abigail_1982	**22-Jan-82**	**25.7**	**154.3**	**5-Feb-82**	**-26.2**	**166.5**	**1005**	**22-Jan-82**	**495**	**30**	**4.7**	**11**	**1007**	**22-Jan-82**	**169**	**29**	**4.8**	**42**
Grace_1984	**11-Jan-84**	**-18.5**	**148.5**	**20-Jan-84**	**-23.4**	**163.0**	**976**	**17-Jan-84**	**497**	**23**	**2.2**	**118**	**980**	**17-Jan-84**	**495**	**28**	**3.3**	**90**
Lance_1984	**4-Apr-84**	**-13.5**	**153.4**	**7-Apr-84**	**-23.7**	**159.3**	**998**	**7-Apr-84**	**525**	**355**	**30.3**	**103**	**998**	**7-Apr-84**	**499**	**13**	**30.4**	**103**
Pierre_1985	**18-Feb-85**	**-11.8**	**143.3**	**24-Feb-85**	**-23.8**	**160.0**	**1000**	**22-Feb-85**	**438**	**340**	**4.8**	**102**	**1001**	**22-Feb-85**	**383**	**6**	**4.8**	**96**
Nancy_1990	**28-Jan-90**	**-18.3**	**156.0**	**4-Feb-90**	**-34.5**	**155.0**	**975**	**1-Feb-90**	**384**	**60**	**8.4**	**266**	**980**	**2-Feb-90**	**32**	**95**	**3.6**	**187**
Betsy_1992	**10-Jan-92**	**-19.5**	**160.0**	**14-Jan-92**	**-27.6**	**160.0**	**980**	**13-Jan-92**	**492**	**69**	**7.0**	**143**	**980**	**13-Jan-92**	**492**	**69**	**7.0**	**143**
Daman_1992	**15-Feb-92**	**-13.1**	**168.5**	**19-Feb-92**	**-31.6**	**157.0**	**975**	**18-Feb-92**	**402**	**97**	**7.0**	**215**	**975**	**18-Feb-92**	**354**	**119**	**5.8**	**207**
Fran_1992	**9-Mar-92**	**-18.6**	**168.3**	**17-Mar-92**	**-25.5**	**159.0**	**980**	**15-Mar-92**	**449**	**340**	**5.6**	**180**	**987**	**16-Mar-92**	**208**	**4**	**5.2**	**95**
Roger_1993	**12-Mar-93**	**-10.0**	**157.0**	**21-Mar-93**	**-21.3**	**160.9**	**982**	**17-Mar-93**	**391**	**36**	**1.5**	**180**	**985**	**17-Mar-93**	**365**	**39**	**2.1**	**0**
Rewa_1993	**28-Dec-93**	**-9.5**	**165.5**	**21-Jan-94**	**-29.0**	**158.0**	**980**	**19-Jan-94**	**488**	**343**	**4.7**	**150**	**985**	**21-Jan-94**	**231**	**66**	**7.7**	**122**
Violet_1995	**3-Mar-95**	**-16.0**	**152.5**	**8-Mar-95**	**-29.2**	**155.1**	**980**	**7-Mar-95**	**381**	**156**	**4.8**	**318**	**990**	**7-Mar-95**	**174**	**159**	**5.8**	**128**
Gertie_1995	**17-Dec-95**	**-13.2**	**125.5**	**24-Dec-95**	**-23.0**	**163.0**	**990**	**24-Dec-95**	**488**	**46**	**14.4**	**79**	**994**	**23-Dec-95**	**123**	**15**	**11.9**	**102**
Kerry_2005	**8-Jan-05**	**-18.2**	**159.8**	**18-Jan-05**	**-27.5**	**157.8**	**998**	**15-Jan-05**	**264**	**98**	**2.1**	**180**	**998**	**15-Jan-05**	**264**	**98**	**2.1**	**180**
Hamish_2013	**10-Mar-09**	**-24.2**	**154.8**	**11-Mar-09**	**-24.3**	**155.0**	**952**	**10-Mar-09**	**334**	**40**	**1.9**	**93**	**970**	**10-Mar-09**	**329**	**36**	**0.7**	**318**
Oswald_2013	**27-Jan-13**	**-26.8**	**150.6**	**28-Jan-13**	**-27.9**	**151.1**	**990**	**27-Jan-13**	**285**	**275**	**2.9**	**110**	**990**	**28-Jan-13**	**246**	**264**	**41.7**	**172**

Appendix C – The Meteorology of Ex-TC *Oswald*

Provided by J. Callaghan, edited and abridged by B. Harper.

C.1 Ex-TC *Oswald*- A Severe Monsoon Low

Despite being classified as an ex-tropical cyclone, the weather system code-named *Oswald* had an impact comparable with land-falling Severe Tropical Cyclones. As a consequence the meteorology of how this system moved down into subtropical areas and intensified is important to understand. This meteorological summary describes how that occurred.

There is a history of Severe Monsoon Lows originating from Northern Australia impacting on Southern sub-tropical regions of Australia and despite tracking overland these systems sometimes increase their intensity while moving south. We investigate below how this occurs.

The weather system *Oswald* generated a significant storm surge in Moreton Bay and the large scale wind pattern is examined using Ascat Satellite wind data. The sub-tropical east coast region is then considered using Ascat and Oscat Satellite wind data combined with Automatic Weather Station (AWS) wind data to identify flow patterns into the Moreton Bay region from the 24 to 28 Jan 2013. The localised winds through Moreton Bay during the peak storm surge period are then discussed taking advantage of the relatively dense network of AWS. Finally the structure of *Oswald* as it passed to the west of Moreton Bay is discussed, showing the asymmetry of the wind and precipitation fields.

Unfortunately this event resulted in seven fatalities. A fishing boat sank near Port Alma, one man was found on an island and one believed drowned. A young boy died after a tree fall on beside Kedron Brook at Gordon Park Brisbane around 8.30am Monday 28 Jan. A motor cyclist was drowned at Oxley Creek Brisbane Monday 28 Jan. A man was drowned at Bundaberg on Monday as well as another man at Gympie on the same day. Two missing men were found drowned in a creek near Gatton on 30 Jan.

The Insurance Council of Australia (ICA) damage statistics showed ex-TC *Oswald* caused over a billion dollars damage as follows: Queensland $977,000,000 and Northern NSW $121,300,000. This compares with Severe Tropical Cyclone *Yasi* (Category 5) having ICA damage statistics of $1,412,239,000 or only $313,939 more than Ex-TC *Oswald*.

C.2 The Influence of the Madden Julian Oscillation on the Development of TC *Oswald*.

The Madden-Julian Oscillation (MJO) is a global-scale feature of the tropical atmosphere that is the major fluctuation in tropical weather on weekly to monthly timescales. The MJO can be characterized as an eastward moving "pulse" of cloud and rainfall near the equator that typically recurs every 30 to 60 days. MJO effects are most evident over the Indian Ocean and western equatorial Pacific Ocean. Tropical Cyclones often develop in association with the MJO, which is associated with variations in wind, cloudiness, and rainfall. Most tropical rainfall comes from tall thunderstorms, which have very cold “tops” and emit only low levels of longwave radiation as a result. Satellite measurements of outgoing long wave radiation (OLR) can therefore be effectively used to identify areas of cloudiness (low OLR) within the tropics.

In the Figure below, the active part of the MJO (blue region) can be seen moving across Northern Australia and out into the Coral Sea from 11 – 27 Jan 2014. *Oswald* formed on the 22 Jan 2013, likely triggered by the regionally-enhanced convection environment provided by the MJO.

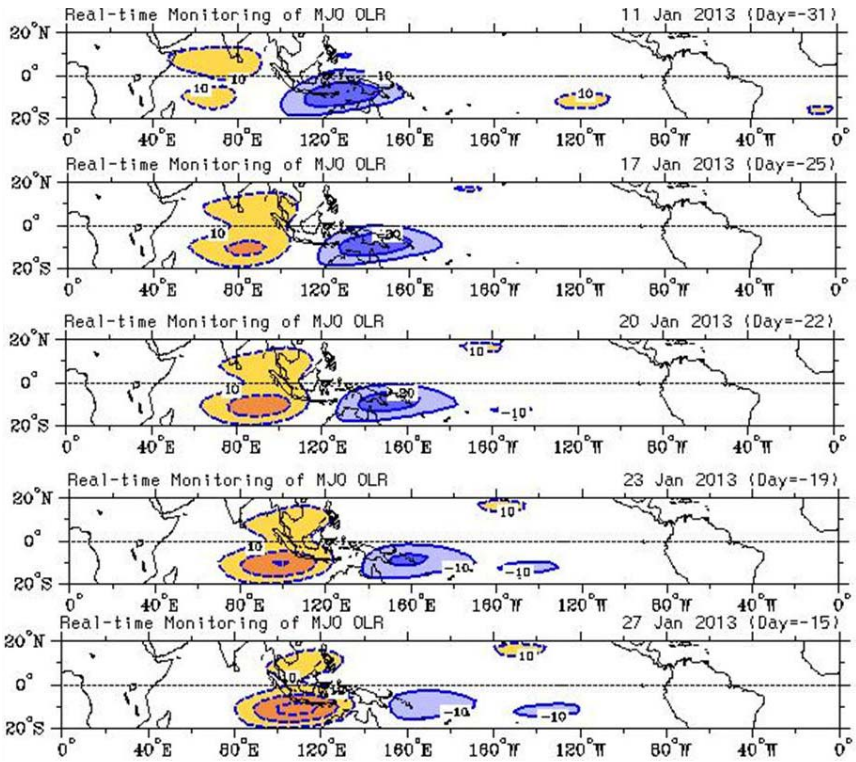

Figure C-1. The blue region shows the active part of the MJO moving eastward across Northern Australia from 11 Jan to 27 Jan 2013.

C.3 Track of TC *Oswald*

In Figure C-1 the official BoM track shows *Oswald* made landfall on the eastern Gulf of Carpentaria Coast while moving towards the northeast. It then turned towards the southeast and subsequently tracked just inland from the coast before taking a more southerly track south of Mackay. Notice how the movement slowed after 2000UTC 24 Jan 2013 (6am 25 Jan EST) until around 1500UTC 26 Jan 2013 (1am 27 Jan EST) which was a period when very heavy prolonged rain fell in the Capricorn - Burnett Districts.

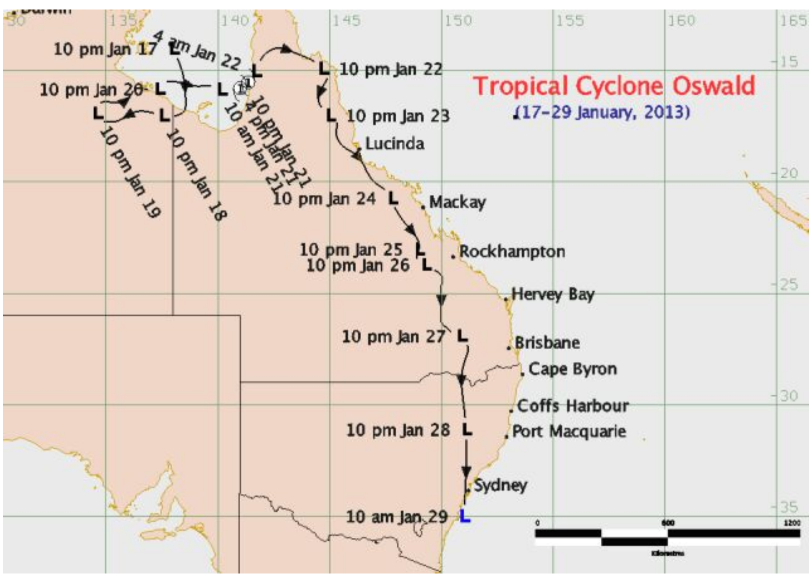

Figure C-2 BoM Track of *Oswald* showing its brief life as a Category 1 Tropical Cyclone, followed by its path inland from the coast south to Sydney.

C.4 Movement and Intensification over Southeast Queensland

Due to its ready availability the NOAA Global Forecast System (GFS) numerical weather prediction system high resolution analyses are used, which are available from http://nomad1.ncep.noaa.gov/cgi-bin/pdisp_gfs0.5.sh.

In Figure C-3 the southerly movement at 0000UTC 26 Jan is indicated by the strongest winds between the 850 hPa and 500 hPa levels being northerly. Twenty four hours later at 0000UTC 27 Jan (Figure C-4), the northerly winds increased on average over all three levels and this was the period the southerly rate of movement increased after its stalling in Central Queensland. This occurred as a trough was evident moving up towards *Oswald* at the 500 hPa level. Interaction with this trough increased the 850 hPa winds over a wide area and this was the period severe winds storm surge and large waves began to impact over Southeast Queensland. The 850 hPa to 500 hPa winds at both times show northeast winds in the southeast sector turn northerly with height and this wind structure helps produce large scale ascent and the extreme rainfall experienced in that sector. This large scale ascent associated with winds turning anticlockwise with height was evident from the Brisbane soundings (noting that some observations were missed due to the difficulty of the radar tracking the balloon in the extreme rainfall):

0500UTC 26Jan 850 hPa 055/34 kts; 700 hPa 050/31 kts; 500 hPa 025/16 kts
1700UTC 26Jan 850 hPa 050/49 kts; 700 hPa 035/38 kts; 500 hPa 005/38 kts
2300UTC 26Jan 850 hPa 050/55 kts; 700 hPa 045/54 kts; 571 hPa 025/48 kts;
1200UTC 27Jan 850 hPa 040/59 kts; 710 hPa 030/26 kts.

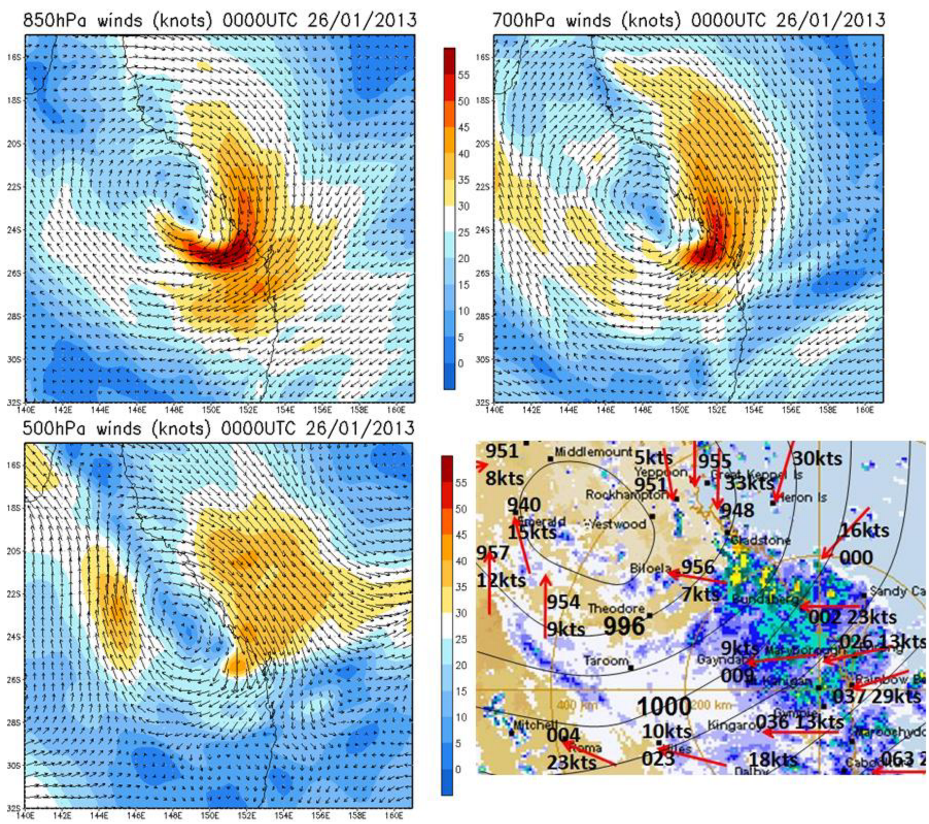

Figure C-3 High resolution GFS wind analyses together with mean sea level analyses near time of wind analyses for 0000UTC 26 Jan 2013 (10am 26 Jan EST). The mean sea level charts show observations with the mean 10 min wind speed and direction and the last three digits of mean sea level pressure to tenths of hPa where 023 is 1002.3 hPa.

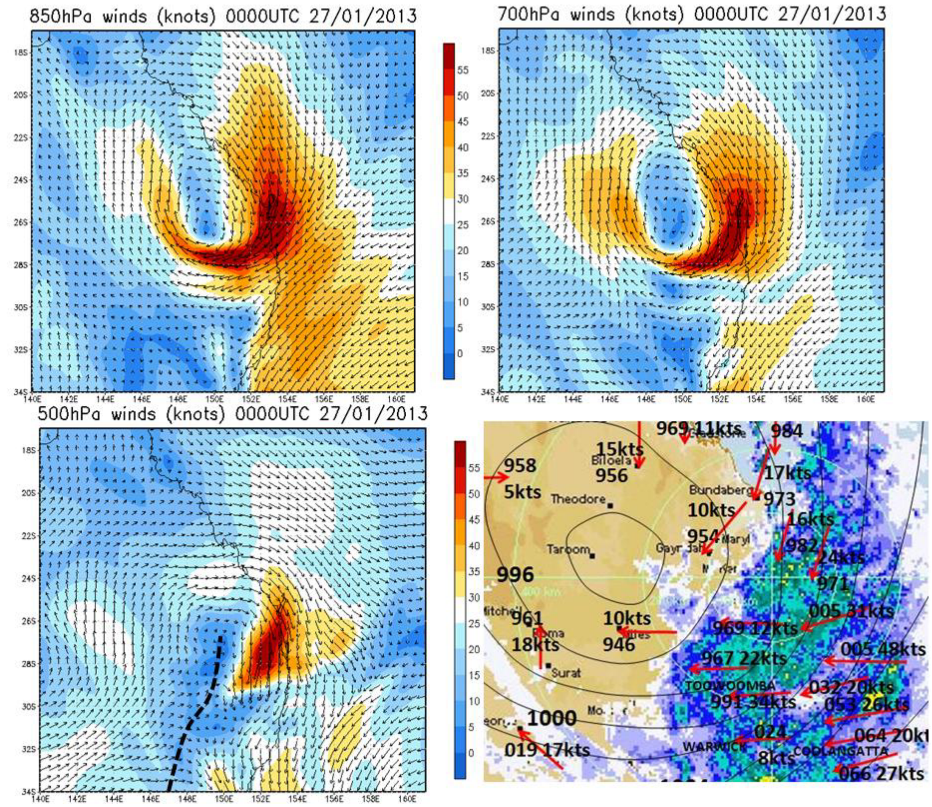

Figure C-4 As per Figure C-3 except for 0000UTC 27 Jan 2013 (10am 27 Jan EST). Dashed line indicates the 500 hPa trough.

The same sequence at the upper 200 hPa level (Figure C-5) gives an indication of the source of the energy that maintained and intensified *Oswald* as it moved over land. On each GFS synoptic field is plotted actual observations from the BoM upper atmosphere sounding network that supports the veracity of the model output. The high latitude source of energy to help develop low pressure systems comes from a tropopause undulation marked by “U”. The centre of *Oswald* remained well removed from downstream of the undulation such that it received little energy from this system up to 0000UTC 28 Jan. So the primary mechanisms for the development overland of *Oswald* as it neared Moreton Bay came from the high moisture content of the air being advected from the Coral Sea combined with the forced ascent associated with the turning winds with height that were generated by the mid to upper level trough.

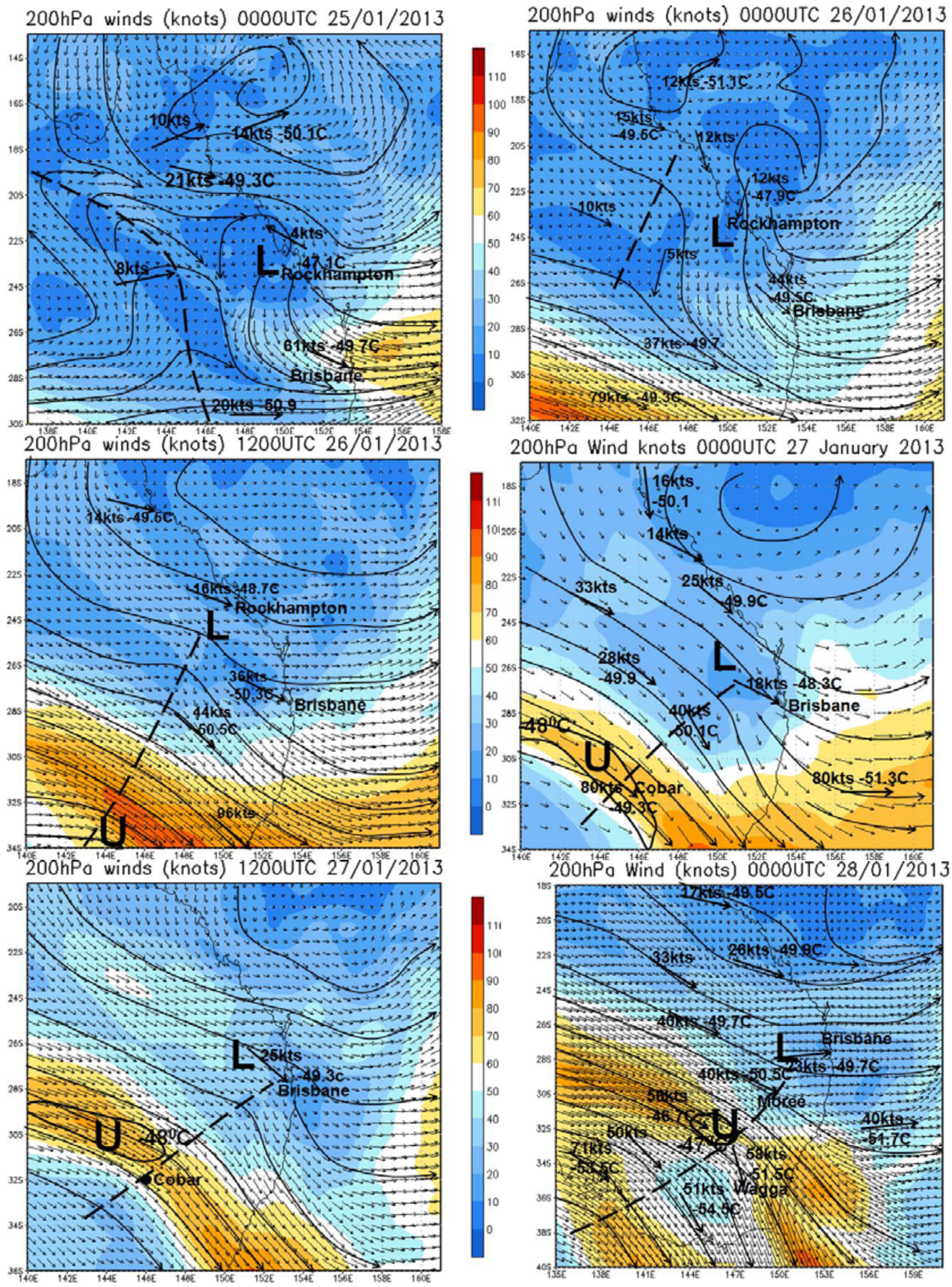

Figure C-5. GFS wind analyses (kts) at 200 hPa 0000UTC 25 Jan 2013 (top left), 0000UTC 26 Jan 2013 (top right), 1200UTC 26 Jan 2013 (centre left), 0000UTC 27 Jan 2013 (centre right) and 1200UTC 27 Jan 2013 (lower left) and 0000UTC 28 Jan 2013 (lower right). The figure shows an upper trough (dashed line), tropopause Undulation (denoted by "U") and the centre of the MSL position of *Oswald* is marked by the "L". 1200UTC 27 Jan 2013 (lower left) Actual observations of wind and temperature are plotted where available.

C.5 Mean Sea Level Analyses with Scatterometer Winds

Scatterometers on satellites operate by transmitting a pulse of microwave energy towards the Earth's surface and measuring the reflected energy. The backscattered energy depends on the wind speed and direction and both Ascat and Oscat satellite data is shown, available from: - http://manati.star.nesdis.noaa.gov/datasets/ASCATData.php. These are low-flying polar-orbiting satellites having staggered swaths.

In Figure C-6 and C-7 the large scale environment of Southeast Queensland coastal areas is examined covering the period of the large storm surge in Moreton Bay. The pressure distribution was obtained from the GFS high resolution output which assimilates the observations into its solution. The low pressure system (Ex TC *Oswald*) is shown moving down to the west of Moreton Bay by 0000UTC 28 Jan 2013, while the other main feature is a strong high pressure system over New Zealand. In between both systems a very strong pressure gradient is evident over Southeast Queensland generating north to northeast gale force winds.

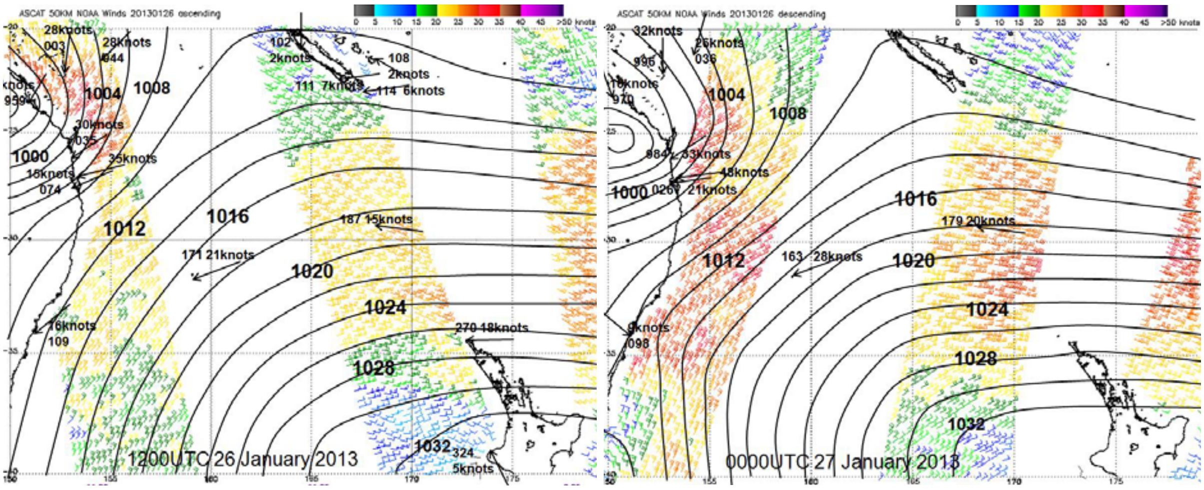

Figure C-6. Mean Sea level analyses with arrows indicating wind direction and the point of the arrow at the station location with 10 min wind speed indicated in kts overlaid on Ascat wind observations in left frame for 1200UTC 26 Jan (10pm 26th EST) and in right frame for 0000UTC 27 Jan (10am 27th EST).

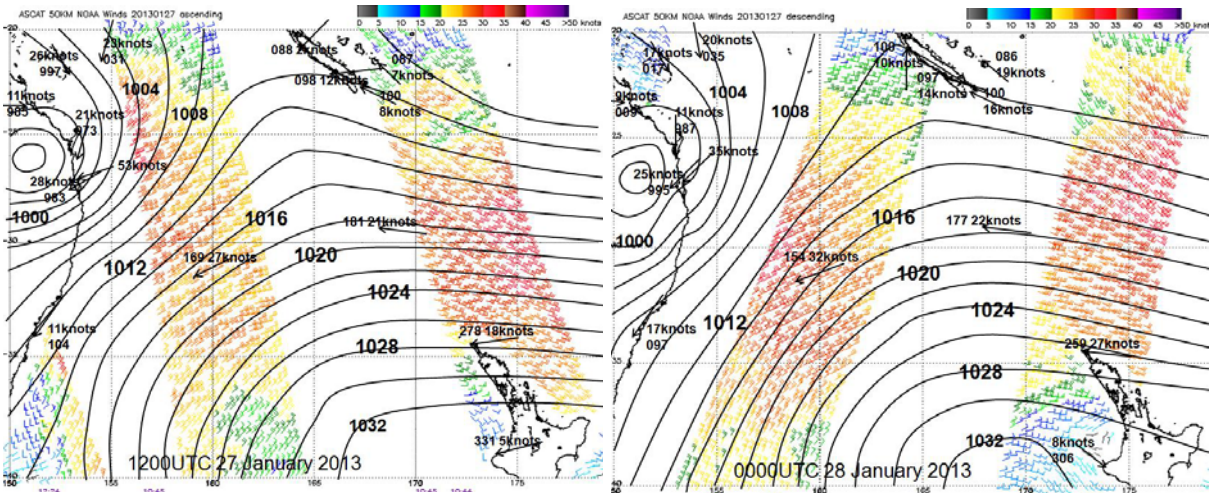

Figure C-7. Mean Sea level analyses with arrows indicating wind direction and the point of the arrow at the station location with 10 min wind speed indicated in kts overlaid on Ascat wind observations in left frame for 1200UTC 27 Jan (10pm 27th EST) and in right frame for 0000UTC 28 Jan (10am 28th EST).

C.6 Wind Analyses over the Sub-Tropics using Scatterometer and AWS Data

Figure C-8 displays the high resolution Ascat and Oscat imagery together with available AWS wind data. At 1100UTC 23 Jan (Figure C-8 top left) mostly moderate NE winds were reported north of Fraser Island turning more easterly to the south.

At 2300UTC 23 Jan stronger NE winds from *Oswald* began moving into the northern region from Ascat (Figure C-8 top right) supported by mean winds of 28 kts and 27 kts at Creal and Frederick respectively. The strong wind zone crept further south at 1100UTC 24 Jan (Figure C-8 centre left) and Ascat showed a large area of NE near gale force winds being directed towards the Emu Park region (north of Rundle Island) supported by 10 min average wind observations of 33 kts (Creal Reef), 32 kts (Gannet Cay), 29 kts (Frederick Reef) and 39 kts (Rundle Island)

Twelve hours later no decent scatterometer winds were available however gales were reported from Gannet and Rundle Island at 2300UTC 24 Jan (Figure C-8 centre right). Shortly after this at 0100UTC 25th the Emu Park waverider reported significant wave heights (Hs) of 4.0 m from ENE with peak period (Tp) 9 s. Maximum wave heights (Hm) reached 7.4 m, which is the second highest wave height recorded at that station.

By 1400UTC 25 Jan the Oscat data (Figure C-8 lower left) indicated the strong to gale force winds extended down to the Sunshine Coast with a long fetch extending out beyond 156E. By this time the Hs at the Mooloolaba Buoy had exceeded 3 m from the NE with Tp 9 s. The Ascat imagery at 2300UTC 25 Jan (Figure C-8 lower right) showed strong winds were maintained along the South Coast.

A more expansive Ascat pass at 1100UTC 26 Jan (top left frame Figure C-9) shows the strong NNE winds in the north turning ENE in the south. The Brisbane Buoy Hs was just under 3 m from the ENE and starting to increase. Mooloolaba had reached Hs 4 m from the ENE with Tp 10 s.

Gales were directed onto the coast south of Fraser Island by 2300UTC 26 Jan (top right frame Figure C-9) and the Ascat [ass showed that strong to gale force ENE winds extended out about 500 km from Cape Moreton. Hs at Mooloolaba buoy had reached 5 m by 0200UTC 27 Jan, when the Oscat and AWS data (centre left Figure C-9) showed N to NNE strong to gale force winds down to Fraser Island and ENE strong to gale force winds further south. On the high tide that morning the Central Moreton Bay buoy had Hm exceeding 4.4 m from the NE with Tp 9 to 10 s. By 0500UTC 27th the offshore Brisbane Buoy had exceeded Hs of 5 m and was increasing with waves from ENE with Tp 10 s and increasing .

By 1100UTC 27 Jan gale force ENE to NE winds lashed the coast south of the Sunshine Coast and Ascat showed the stronger winds extending out past 156E (centre right Figure C-9). Around this time the offshore Brisbane Buoy recorded a Hm of around 10 metres. The Northern Moreton Bay Buoy recorded its largest Hs of 5.9 m over this period at 1200UTC 27 Jan and Hm of 10.3 m at 1330UTC 27 Jan with both these creating new records. The Oscat pass at 1400UTC 27 Jan (lower left Figure C-9) showed the gales extending well out to sea and at 2130UTC 27 Jan the Brisbane Buoy recorded its peak wave heights for the event as 7.1 m Hs and 12.1 m Hm. Around 1900UTC 27 Jan the Moolooolaba Buoy recorded its peak wave heights for the event as Hs 5.6 m (ranked 2nd) and Hm 10.5 m (ranked 2nd).

Between 2300UTC 27 Jan and 0200UTC 28 Jan (lower right Figure C-9 and left frame Figure C-10) the ENE to NE gales contracted south of Cape Moreton and by 1100UTC 28 Jan (right frame Figure C-10) south of the Gold Coast.

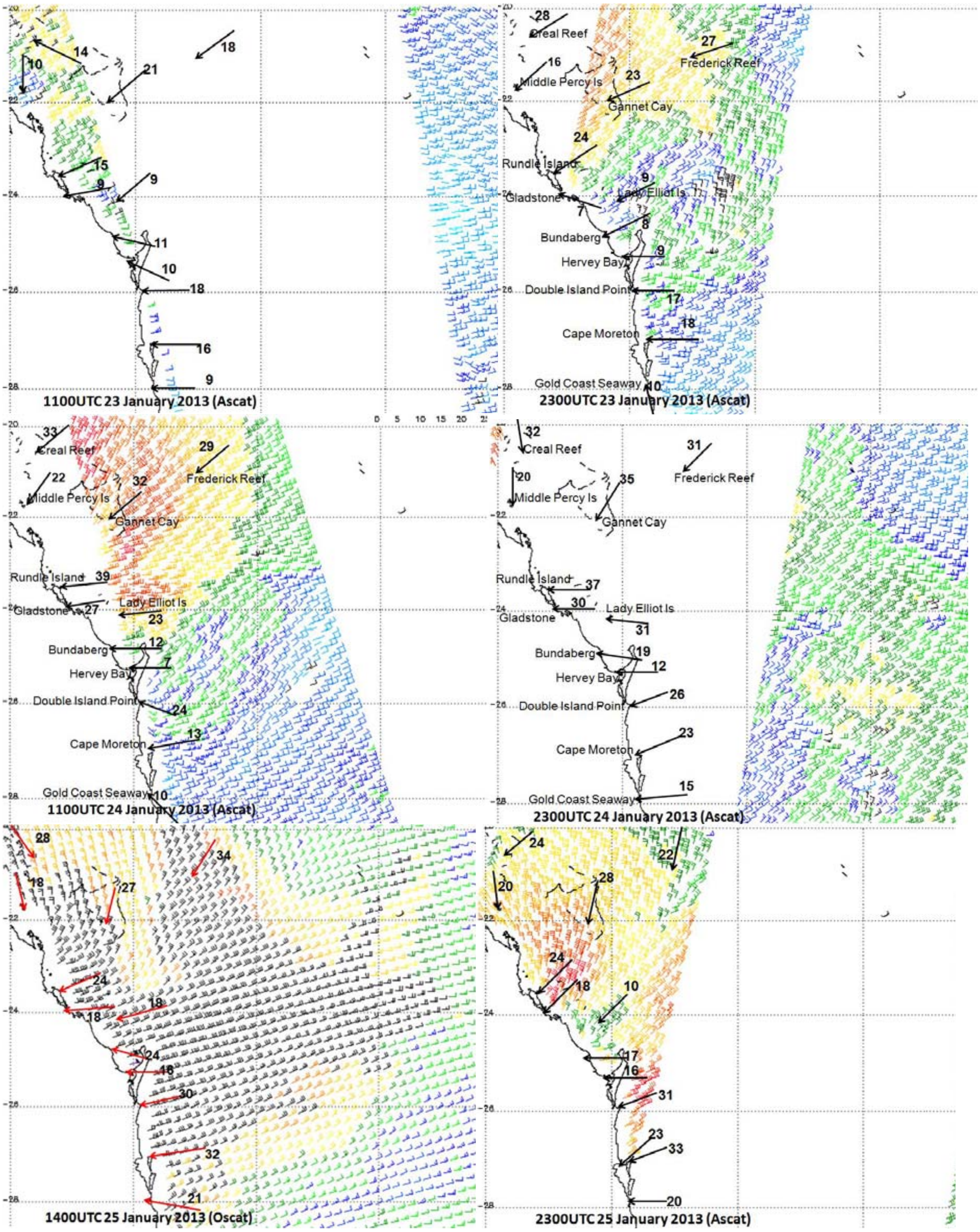

Figure C-8. AWS and Scatterometer winds from 1100UTC 23 Jan to 0200UTC 26 Jan.

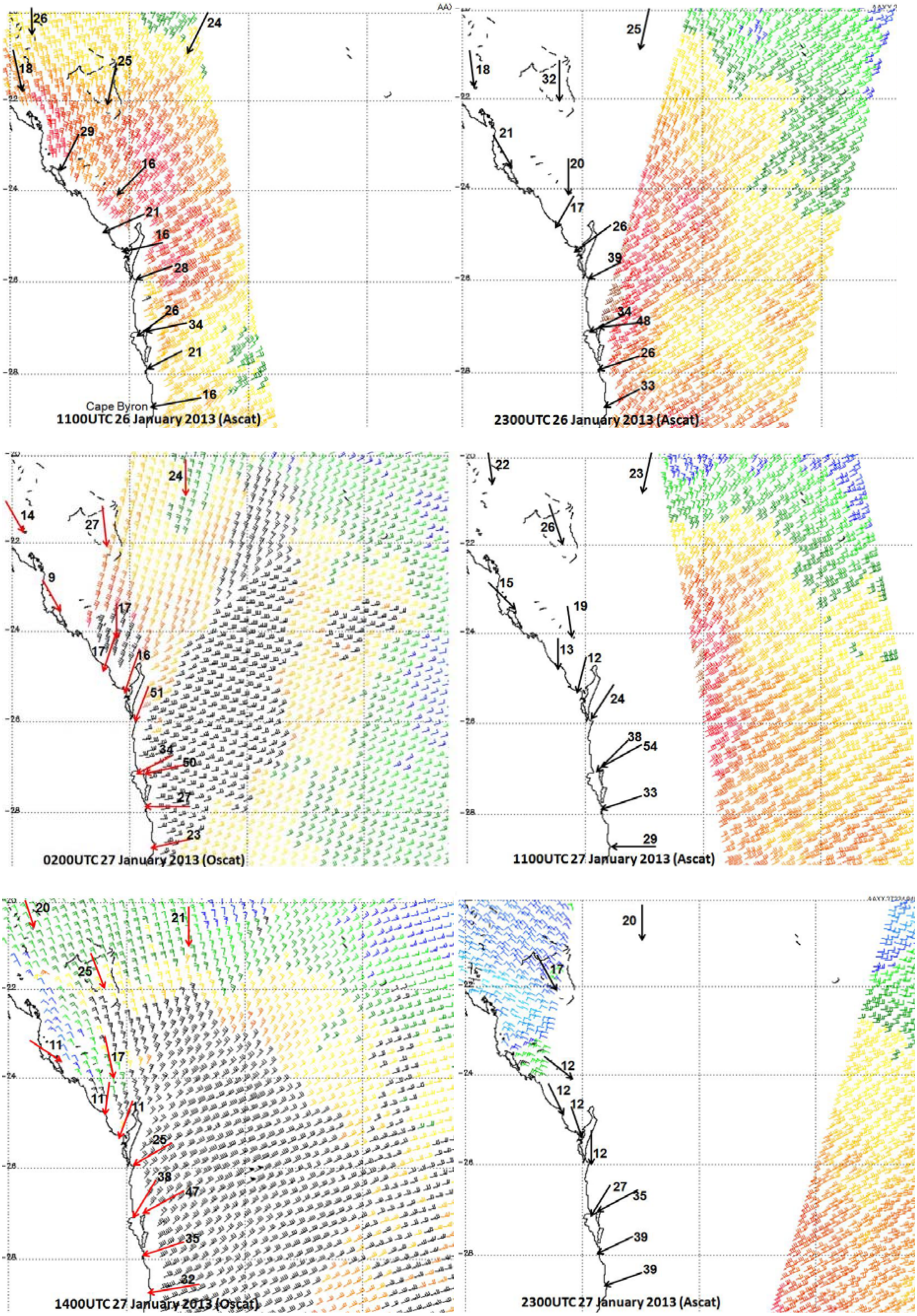

Figure C-9. AWS and Scatterometer winds from 1100UTC 26 Jan to 2300UTC 27 Jan.

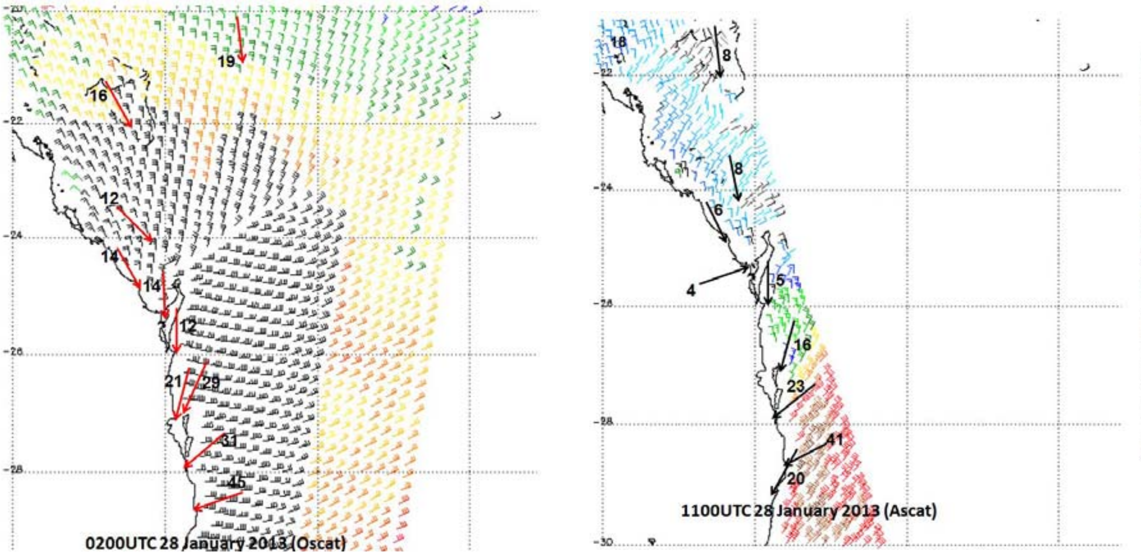

Figure C-10. AWS and Scatterometer winds for 0200UTC 28 Jan (left) and 1100UTC 28 Jan (right).

C.7 Winds and Storm Surge over Moreton Bay

In the following figures the dense network of AWS observations are used to illustrate the wind flow changes across Moreton Bay as *Oswald* passed to the west. In Figure C-11 ENE to NE winds increase over Moreton Bay to gale force over northern waters by 2300UTC 25 Jan to 0200UTC 27 Jan.

Figure C-12 illustrates the period of strongest winds over Moreton Bay from 0500UTC to 2000UTC 27 Jan with average ENE to NE winds speeds reaching 54 kts at Cape Moreton, 38 kts at Moreton Bay North, 37 kts at Redcliffe and 34 kts at Moreton Bay South.

The final period in Figure C-13 shows wind speeds easing from 2300UTC 27 Jan 2013 to 1100UTC 28 Jan 2013.

The maximum storm surge at the mouth of the Brisbane River was about 0.8 to 0.9 m (the latter on low tide) during Monday 28 Jan (high tide around 0019UTC 28 Jan), and then dropped sharply to about 0.4 m between about 0000UTC to 0200UTC 28 Jan when the winds dropped quickly. The anomaly was above 0.3 m for almost 48 hours - early morning Sunday 27 to about 10pm Monday 28 (1200UTC 28th).

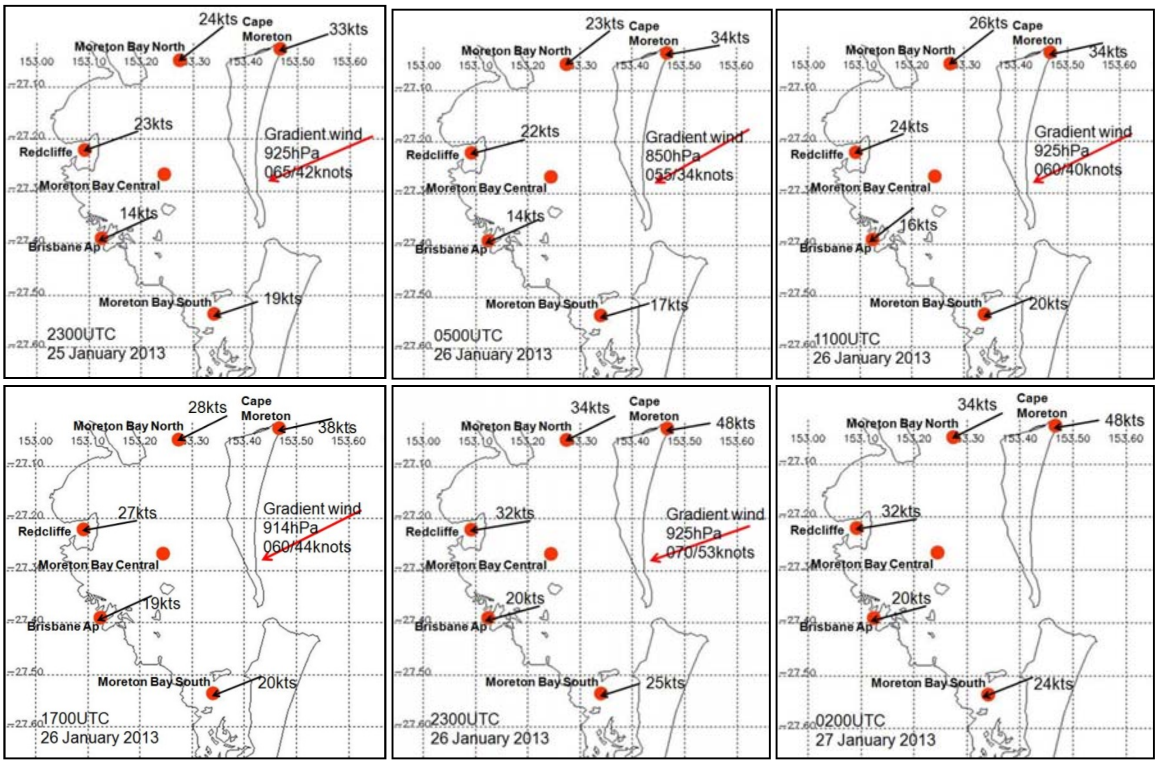

Figure C-11. 10 min average wind speeds over Moreton Bay from AWS observations 2300UTC25 Jan 2013 to 0200UTC 27 Jan 2013.

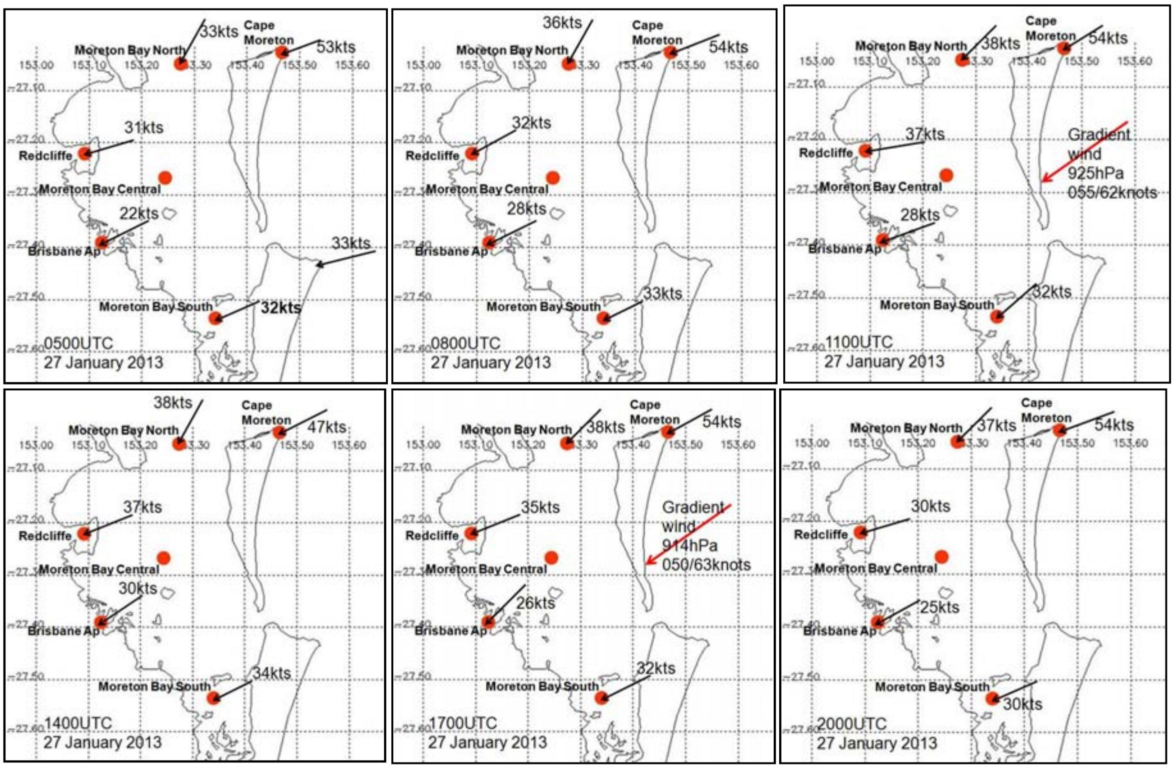

Figure C-12. 10 min average wind speeds over Moreton Bay from AWS observations 0500UTC27 Jan 2013 to 2000UTC 27 Jan 2013.

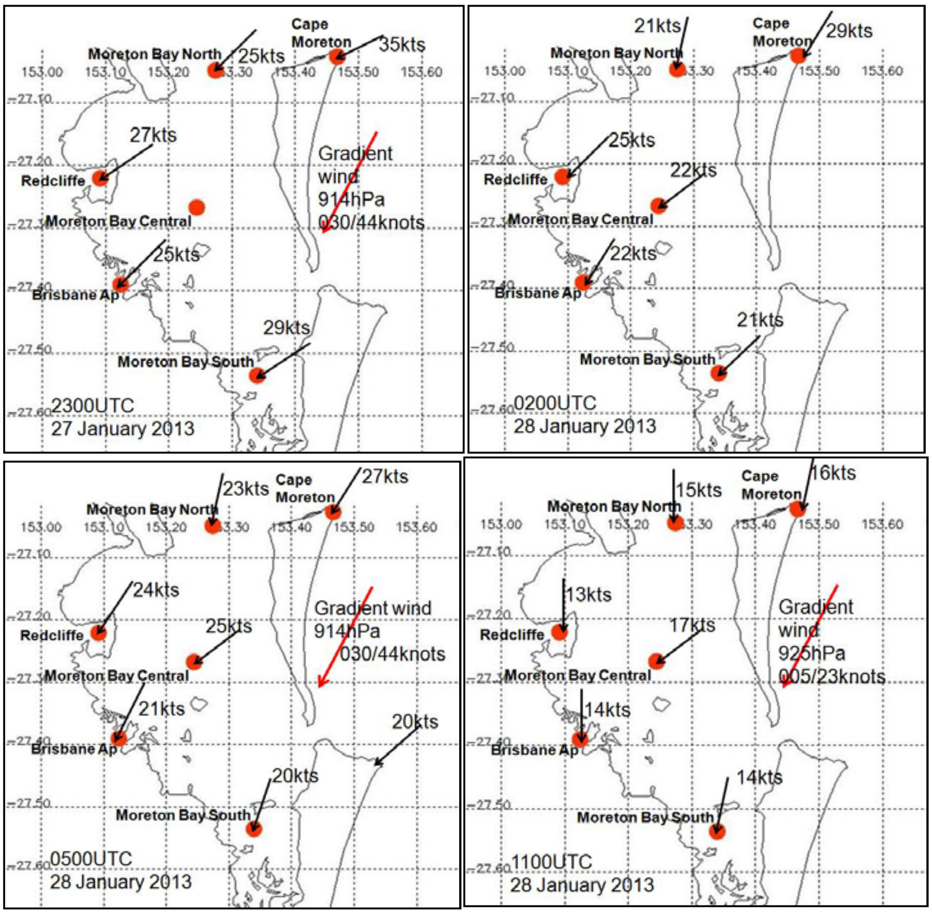

Figure C-13. 10 min average wind speeds over Moreton Bay from AWS observations 2300UTC 27 Jan 2013 to 1100UTC 28 Jan 2013.

C.8 Mean Sea Level Analyses and Rain Structure

In the figures below mean sea level analyses are carried out and overlaid on radar imagery to gain insight into the structure of *Oswald* as it impacted on Moreton Bay.

From 2300UTC 25 Jan to 1100UTC 26 Jan the MSL analyses on the Mt Kanigan radar image (256 km range Figure C-14) shows *Oswald* moved down to the west of Biloela with rain extending down to its southeast. Gales were reported from the elevated Cape Moreton site while strong ENE winds were reported in Moreton Bay (Redcliffe 23-24 kts).

The analyses in Figure C-15 are overlaid on the Marburg radar images at 128 km range and show the centre of *Oswald* become distorted near Dalby with a strong pressure gradient developed over the Brisbane – Moreton Bay region with average winds at Cape Moreton 48-53 kts and Redcliffe 31- 32 kts. Pressures dropped to around 998 hPa over Moreton Bay adding to the storm surge level.

The analyses from 1200UTC-1700UTC 27 Jan in Figure C-16 are still on the Marburg radar (range 128 km) and the centre remained distorted on the Darling Downs with the strongest pressure gradient over Moreton Bay with average winds at Redcliffe 35-37 kts and Cape Moreton 54-55 kts. Rain had eased over Southeast Queensland. Pressures remained low over the period on Moreton Bay mostly below 1000 hPa.

The final analyses (Figure C-17) also on Marburg at range 128 km show *Oswald* developing a new centre over Northern NSW where the strongest pressure gradient lies, reflected by average winds of 37-45 kts at Cape Byron. Winds eased over Moreton Bay but turned NNE and remained strong with pressures generally below 1000 hPa.

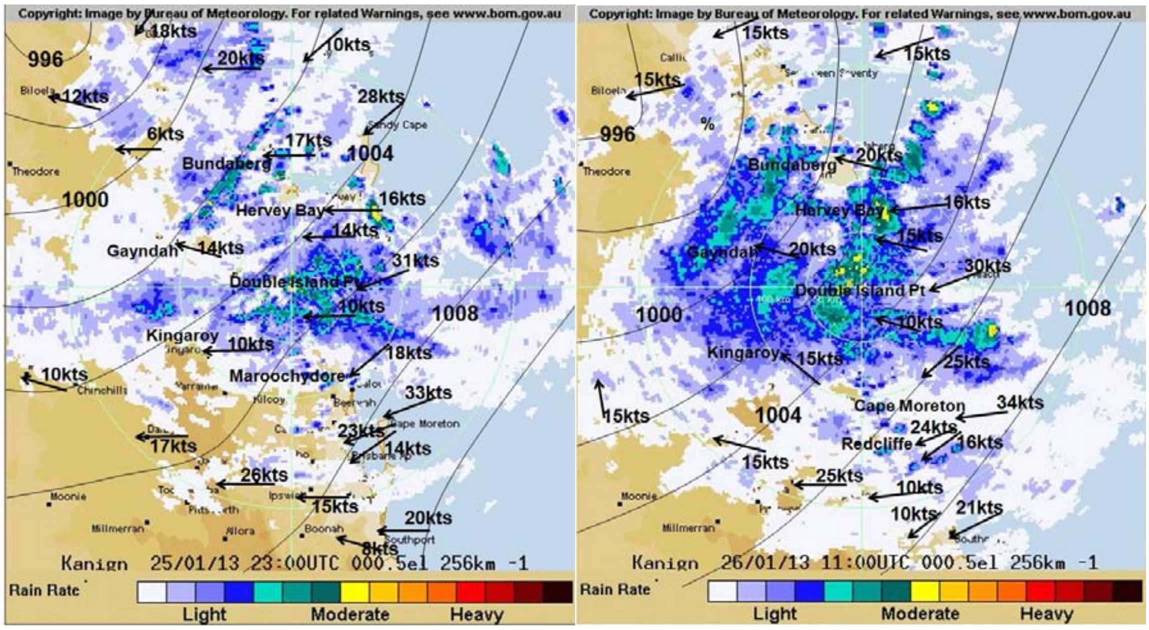

Figure C-14 Mean Sea level analyses with arrows indicating wind direction and the point of the arrow at the station location with 10minute wind speed indicated in kts overlaid on Kanign Radar imagery in left frame for 2300UTC 25 Jan (9am 26th EST) and in right frame for 1100UTC 26 Jan (9pm 26th EST).

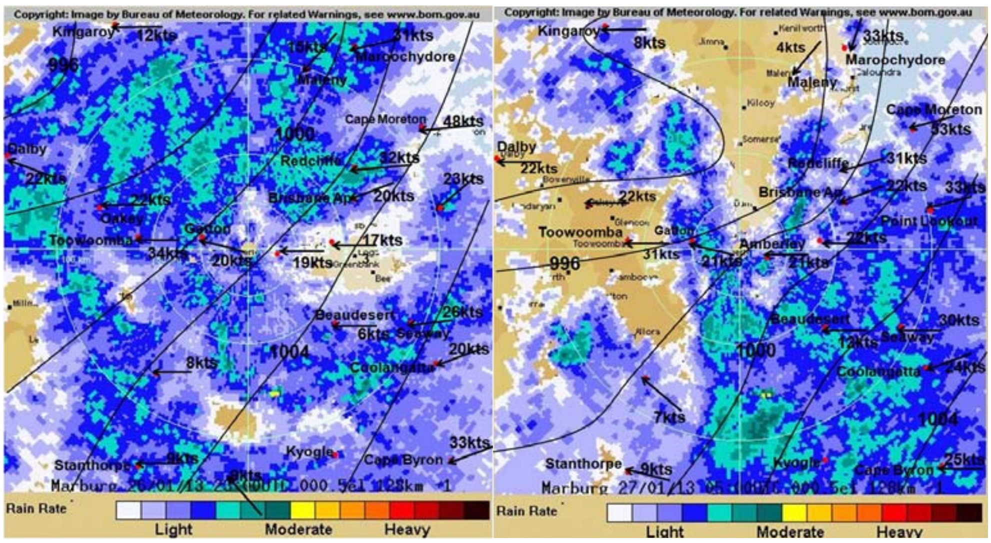

Figure C15 Mean Sea level analyses with arrows indicating wind direction and the point of the arrow at the station location with 10minute wind speed indicated in kts overlaid on Marburg Radar imagery in left frame for 2300UTC 26 Jan (9am 27th EST) and in right frame for 0500UTC 27 Jan (3pm 27th EST).

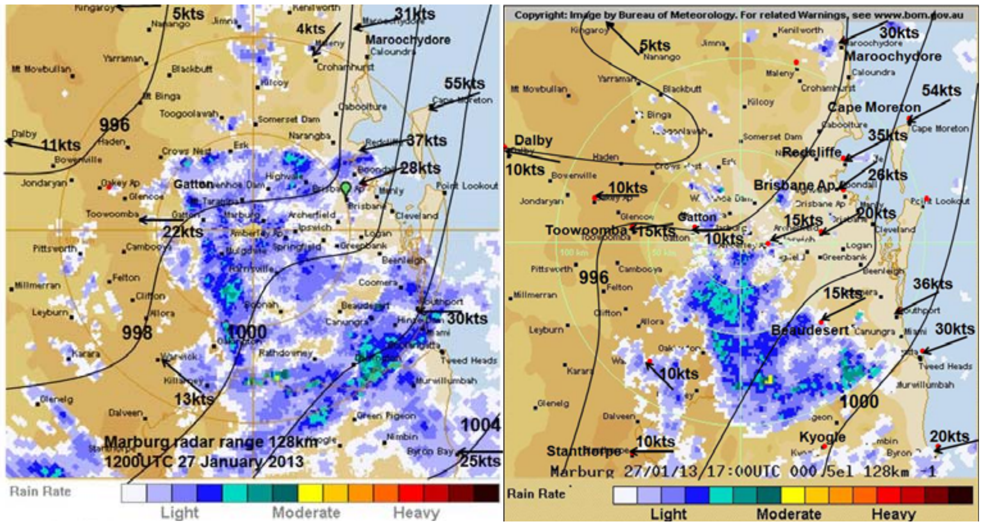

Figure C-16 Mean Sea level analyses with arrows indicating wind direction and the point of the arrow at the station location with 10minute wind speed indicated in kts overlaid on Marburg Radar imagery in left frame for 1200UTC 27 Jan (10pm 27th EST) and in right frame for 1700UTC 27 Jan (3am 28th EST).

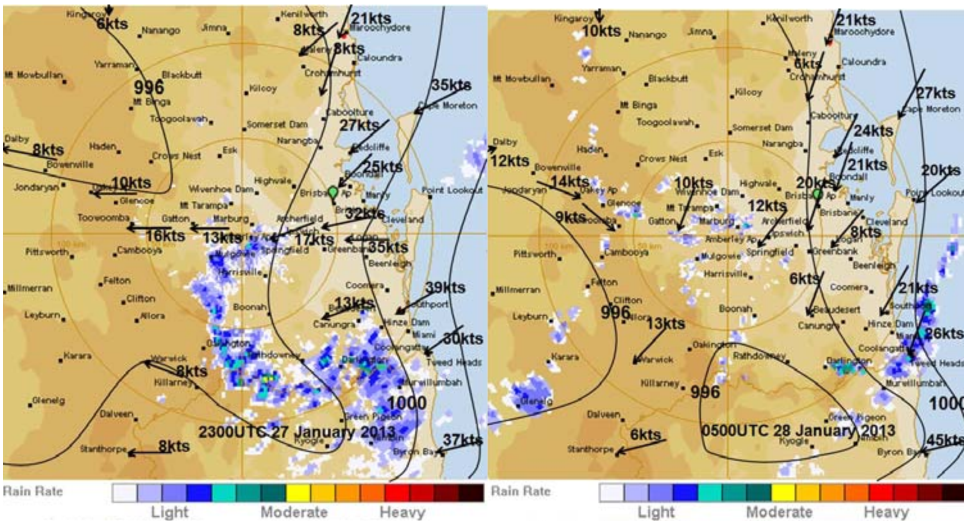

Figure C-17 Mean Sea level analyses with arrows indicating wind direction and the point of the arrow at the station location with 10minute wind speed indicated in kts overlaid on Marburg Radar imagery in left frame for 2300UTC 27 Jan (9am 28th EST) and in right frame for 0500UTC 26 Jan (3pm 28th EST).

C.9 Automatic Weather Station Statistics

Severe wind gusts 1400UTC 25 Jan 2013 to 1400UTC 26 Jan 2013 (midnight to midnight local time)

Rundle Island 91 km/h (49 kts mean 360/37 kts) at 10:42pm;
Cape Moreton 89 km/h (49 kts mean 080/42 kts) at 11:30pm;
Double Island Point 100 km/h (54 kts mean 060/39 kts) at 10:00am;

Severe wind gusts 1400UTC 26 Jan 2013 to 1400UTC 27 Jan 2013 (midnight to midnight local time)

Heron Island 100 km/h (54 kts mean 360/41 kts) at 02:34am;
Bundaberg Aero 91 km/h (49 kts mean 050/31 kts) at 01:30am;
Rundle Island 93 km/h (50 kts mean 360/35 kts) at 00:00am;
Cape Moreton 126 km/h (68 kts mean 070/60 kts) at 2:46pm;
Double Island Point 122 km/h (66 kts mean 020/57 kts) at 10:46am
Archerfield 89 km/h (48 kts mean 060/38 kts) at 7:49pm;
Coolangatta 91 km/h (49 kts mean 060/34 kts) at 10:00pm;
Gold Coast Seaway 95 km/h (52 kts mean 090/37 kts) at 8:00pm;
Brisbane Aero 93 km/h (50 kts mean 050/31 kts) at 8:13pm;
Sunshine Coast Airport 87 km/h (47 kts mean 040/35 kts) at 1:00pm;
Banana Bank 91 km/h (49 kts mean 060/35 kts) at 6:11pm;
Spitfire Channel Beacon 98 km/h (53 kts mean040/39 kts) at 9:30pm;
Redcliffe 95 km/h (51 kts mean 060/39 kts) at 10:30pm;
Toowoomba Airport 93 km/h (50 kts mean 090/33 kts) at 2:00pm;
Roma 91 km/h (49 kts mean 190/32 kts) at 12:47pm;
Cape Byron 87 km/h (47 kts mean 070/34 kts) at 5:00pm;

Severe wind gusts 1400UTC 27 Jan 2013 to 1400UTC 28 Jan 2013 (midnight to midnight local time)

Cape Moreton 128 km/h (69 kts mean 070/57 kts) at 08:00am;
Archerfield 93 km/h (50 kts mean 070/32 kts) at 09:00am;
Coolangatta 82 km/h (44 kts mean 030/35 kts) at 3:41pm;
Gold Coast Seaway 95 km/h (52 kts mean 060/40 kts) at 08:00am;
Brisbane Aero 93 km/h (50 kts mean 050/39 kts) at 08:43am;
Banana Bank 93 km/h (50 kts mean 060/31 kts) at 04:30am;
Spitfire Channel Beacon 96 km/h (52 kts mean 030/40 kts) at 00:30am;
Redcliffe 93 km/h (50 kts mean 060/38 kts) at 01:00am;
Cape Byron 128 km/h (69 kts mean 060/55 kts at 4:30pm;

Wind run in the 24 hours to 9am 26 Jan 2013 (2300UTC 25 Jan)

1234km (51.4 km/h) Cape Moreton
1223 km (51.0 km/h) Double Island Point
1124 km (46.8 km/h) Rundle Island
1015km (42.3 km/h) Heron Island
927km (38.6 km/h) Redcliffe
922km (38.4 km/h) Toowoomba Airport
907km (37.8 km/h) Gladstone Radar
901km (37.5 km/h) Lady Elliot Island
850km (35.4 km/h) Gold Coast Seaway
829km (34.5 km/h) Bundaberg

Wind run in the 24 hours to 9am 27 Jan 2013 (2300UTC 26 Jan)

1560km (65.0km/h) Cape Moreton
1392km (58.0 km/h) Double Island Point
1288km (53.7 km/h) Heron Island
1227km (51.1 km/h) Rundle Island
1097km (45.7 km/h) Redcliffe

1085km (45.2 km/h) Toowoomba Airport
1072km(44.7 km/h) Sunshine Coast Airport
960km (40.0 km/h) Cape Byron
905km (37.7 km/h) Bundaberg
874km (36.4 km/h) Gold Coast Seaway

Wind run in the 24 hours to 9am 28 Jan 2013 (2300UTC 27 Jan)

2216km (92.3 km/h 50 kts)) Cape Moreton
1517km (63.2 km/h 38 kts) Redcliffe
1426km (59.4 km/h 32 kts) Gold Coast Seaway
1225km (51.0 km/h 28 kts) Cape Byron
1163km (48.5 km/h 26 kts) Brisbane Aero
1129km (47.0 km/h 25 kts) Coolangatta
1048 km (43.7 km/h 24 kts) Toowoomba Airport
1011km (42.1 km/h 23 kts) Archerfield
952km (39.7 km/h 22 kts) Ballina
945km (39.4 km/h 21 kts) Double Island Point
909km (37.9 km/h 20 kts) Amberley

Wind run in the 24 hours to 9am 29 Jan 2013 (2300UTC 28 Jan)

1591km (66.3 km/h 36 kts) Cape Byron
947km (39.5 km/h 22 kts) Ballina
834km (34.8 km/h 19 kts) Coolangatta
809km (33.7 km/h 18 kts) Gold Coast Seaway
759km (31.6 km/h 17 kts) Cape Moreton t

Appendix D – Historical Large Storm Surge Events in Moreton Bay

Prepared by J. Callaghan.

Intense east coast low 17-20 July 1889: The flats behind Shorncliffe and around Cabbage Tree Creek were one big lake, in some places 2 or 3 ft deep.

8-9 Jun 1891 tropical low pressure system passed to the west of Brisbane: The Brighton flat was one stormy sea, with huge waves rolling over it. Large trees were thrown on the road, fences washed down, the embankment at the back of the sea wall washed out in great holes, and the remains of boats and bathing-houses were lying all over it. Bathing Houses were swept away.

The 1931 Tropical Cyclone: A tropical cyclone tracked down to Hervey Bay. At Redcliffe much damage was done to the sea wall. At Sandgate police rescued families in the submerged areas. Old Pile Light storm surge was 0.76 m 0100UTC 5 Feb when storm tide was 3.14 m and which was the observed highest tide and a record value for Moreton Bay.

Inland from the Gulf 31 Jan 1934 to 2 Feb 1934 (similar to Oswald): Record storm surge Old Pile Light 1.16 m 1200UTC 1 Feb with storm tide 2.71 m (also observed highest tide).

Tropical Cyclone recurved seawards of Fraser Island 22 Mar 1936: Storm tide came over retaining walls at Cribb Island, Nudgee Beach, Shorncliffe and Flinders Parade Sandgate. Houses were wrecked at Cribb Island. At Sandgate the sea flooded along 9th Avenue, Griffith St and Murray St. At Redcliffe Sea walls and beach buildings were damaged. The sea broke over the sea walls at Wynnum flooding the Esplanade and damaging boats.

Large tropical cyclone 17 to 20 Jan 1938: Waves came over retaining walls in Moreton Bay on Wed19 Jan:- Roads and the yards of some houses were flooded by tidal waters at Sandgate and Cribb Island. Pile Light tide gauge measured 0.52 m storm surge at noon 20th when the predicted highest tide was 2.07 m.

The Sydney Cyclone of 16-19 Jan 1950: A storm surge of 0.58 m was recorded on Moreton Bay gauge. Shops and houses flooded at Sandgate with houses evacuated. Sea water up to 5 ft deep was reported to have invaded the houses at Sandgate. Bishop Island tide gauge measured 0 .58 m storm surge at 9am 18th when the predicted highest tide was 2.32 m (Storm tide of 2.90 m).

The Great Cyclone Feb 20 1954: Storm surge measurement at the Laid Up Plant (near mouth of Brisbane River) was 0.64 m at 1400UTC 20 Feb 1954 (storm tide then 2.5 m which was the highest tide). Mountainous seas had hurled more than 30 vessels on to the banks at Beachmere. When the water receded, some were left balanced precariously on treetops, others lay in tangled telephone and powerlines, and the rest were scattered in broken heaps alone the grassy banks. Eleven prawn trawlers washed ashore at Bribie Island near Beachmere were spread over an area of seven miles. Massive shoreline erosion from Sandgate to Northern Bay.

Tropical Cyclone Dinah 29 Jan 1967: The area from Sandgate to Cribb Island was flooded when storm surge overtopped seawalls and dunes. This brought water up to 1.5 m deep into some houses. More than one hundred homes were flooded at Sandgate and at Cribb Island one house was washed into the sea while several others were nearly lost. At Cribb Island the water rose over man-made barriers 2 m high.

Remote tropical cyclone Pam Feb 1974: The storm surge measured at the Brisbane Bar on 7 Feb it was 0.63 m. It occurred coincident with a spring high tide and produced the highest storm tides (equal to the 1931 Cyclone) in Brisbane flooding roads and disrupting Bus services. It seemed best explained as a Kelvin Wave surge.

Tropical Cyclone David 18-20 Jan 1976: A storm surge at Beachmere on Moreton Bay cut all roads into the town.

8 Apr 1984 Extra-Tropical Transition of Tropical Cyclone Lance: There was damage to boats on the western side of offshore Islands in storm force westerlies and 20 boats were driven ashore on Moreton Island.

TC Roger 17 Mar 1993: Large storm surge Northern Moreton Bay (Beachmere). Storm surge tide gauge readings were 0.62 m Pumicestone Passage (The Farm); 0.74 m Caloundra Public jetty.

Appendix E – Inundation Mapping – 1% AEP

Note: Appendix E is provided as a separate A3 landscape portfolio.

Appendix F – Data Files

GEODATABASE	STORM	FILENAME	SURFACE TYPE	ARI	CLIMATE	LOCALITY
Non_Cyclonic.gdb	Non Cyclonic	TPS2014020_TST2014020_Depth	Depth	20	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050020_TST2050020_Depth	Depth	20	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100020_TST2100020_Depth	Depth	20	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014020_TST2014020_WL	Water Level	20	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050020_TST2050020_WL	Water Level	20	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100020_TST2100020_WL	Water Level	20	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014020_TST2014020_Extent	Water Level Extent	20	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050020_TST2050020_Extent	Water Level Extent	20	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100020_TST2100020_Extent	Water Level Extent	20	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014020M_TST2014020M_Depth	Depth	20	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050020M_TST2050020M_Depth	Depth	20	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100020M_TST2100020M_Depth	Depth	20	2100	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2014020M_TST2014020M_WL	Water Level	20	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050020M_TST2050020M_WL	Water Level	20	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100020M_TST2100020M_WL	Water Level	20	2100	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2014020M_TST2014020M_Extent	Water Level Extent	20	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050020M_TST2050020M_Extent	Water Level Extent	20	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100020M_TST2100020M_Extent	Water Level Extent	20	2100	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2014050_TST2014050_Depth	Depth	50	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050050_TST2050050_Depth	Depth	50	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100050_TST2100050_Depth	Depth	50	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014050_TST2014050_WL	Water Level	50	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050050_TST2050050_WL	Water Level	50	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100050_TST2100050_WL	Water Level	50	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014050_TST2014050_Extent	Water Level Extent	50	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050050_TST2050050_Extent	Water Level Extent	50	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100050_TST2100050_Extent	Water Level Extent	50	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014050M_TST2014050M_Depth	Depth	50	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050050M_TST2050050M_Depth	Depth	50	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100050M_TST2100050M_Depth	Depth	50	2100	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2014050M_TST2014050M_WL	Water Level	50	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050050M_TST2050050M_WL	Water Level	50	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100050M_TST2100050M_WL	Water Level	50	2100	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2014050M_TST2014050M_Extent	Water Level Extent	50	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050050M_TST2050050M_Extent	Water Level Extent	50	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100050M_TST2100050M_Extent	Water Level Extent	50	2100	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2014100_TST2014100_Depth	Depth	100	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050100_TST2050100_Depth	Depth	100	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100100_TST2100100_Depth	Depth	100	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014100_TST2014100_WL	Water Level	100	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050100_TST2050100_WL	Water Level	100	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100100_TST2100100_WL	Water Level	100	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	DV_2014_100	Depth Velocity Product	100	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	DV_2050_100	Depth Velocity Product	100	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	DV_2100_100	Depth Velocity Product	100	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014100_TST2014100_Extent	Water Level Extent	100	2014	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2050100_TST2050100_Extent	Water Level Extent	100	2050	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2100100_TST2100100_Extent	Water Level Extent	100	2100	BCC
Non_Cyclonic.gdb	Non Cyclonic	TPS2014100M_TST2014100M_Depth	Depth	100	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050100M_TST2050100M_Depth	Depth	100	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100100M_TST2100100M_Depth	Depth	100	2100	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2014100M_TST2014100M_WL	Water Level	100	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050100M_TST2050100M_WL	Water Level	100	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100100M_TST2100100M_WL	Water Level	100	2100	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2014100M_TST2014100M_Extent	Water Level Extent	100	2014	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2050100M_TST2050100M_Extent	Water Level Extent	100	2050	Moreton Island
Non_Cyclonic.gdb	Non Cyclonic	TPS2100100M_TST2100100M_Extent	Water Level Extent	100	2100	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2014500_TST2014500_Depth	Depth	500	2014	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2050500_TST2050500_Depth	Depth	500	2050	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2100500_TST2100500_Depth	Depth	500	2100	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2014500_TST2014500_WL	Water Level	500	2014	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2050500_TST2050500_WL	Water Level	500	2050	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2100500_TST2100500_WL	Water Level	500	2100	BCC
Tropical_Cyclone.gdb	Cyclonic	DV_2014_500	Depth Velocity Product	500	2014	BCC
Tropical_Cyclone.gdb	Cyclonic	DV_2050_500	Depth Velocity Product	500	2050	BCC
Tropical_Cyclone.gdb	Cyclonic	DV_2100_500	Depth Velocity Product	500	2100	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2014500_TST2014500_Extent	Water Level Extent	500	2014	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2050500_TST2050500_Extent	Water Level Extent	500	2050	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2100500_TST2100500_Extent	Water Level Extent	500	2100	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS2014500M_TST2014500M_Depth	Depth	500	2014	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2050500M_TST2050500M_Depth	Depth	500	2050	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2100500M_TST2100500M_Depth	Depth	500	2100	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2014500M_TST2014500M_WL	Water Level	500	2014	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2050500M_TST2050500M_WL	Water Level	500	2050	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2100500M_TST2100500M_WL	Water Level	500	2100	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2014500M_TST2014500M_Extent	Water Level Extent	500	2014	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2050500M_TST2050500M_Extent	Water Level Extent	500	2050	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS2100500M_TST2100500M_Extent	Water Level Extent	500	2100	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS20142000_TST20142000_Depth	Depth	2000	2014	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS20502000_TST20502000_Depth	Depth	2000	2050	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS21002000_TST21002000_Depth	Depth	2000	2100	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS20142000_TST20142000_WL	Water Level	2000	2014	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS20502000_TST20502000_WL	Water Level	2000	2050	BCC

GEODATABASE	STORM	FILENAME	SURFACE TYPE	ARI	CLIMATE	LOCALITY
Tropical_Cyclone.gdb	Cyclonic	TPS21002000_TST21002000_WL	Water Level	2000	2100	BCC
Tropical_Cyclone.gdb	Cyclonic	DV_2014_2000	Depth Velocity Product	2000	2014	BCC
Tropical_Cyclone.gdb	Cyclonic	DV_2050_2000	Depth Velocity Product	2000	2050	BCC
Tropical_Cyclone.gdb	Cyclonic	DV_2100_2000	Depth Velocity Product	2000	2100	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS20142000_TST20142000_Extent	Water Level Extent	2000	2014	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS20502000_TST20502000_Extent	Water Level Extent	2000	2050	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS21002000_TST21002000_Extent	Water Level Extent	2000	2100	BCC
Tropical_Cyclone.gdb	Cyclonic	TPS20142000M_TST20142000M_Depth	Depth	2000	2014	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS20502000M_TST20502000M_Depth	Depth	2000	2050	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS21002000M_TST21002000M_Depth	Depth	2000	2100	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS20142000M_TST20142000M_WL	Water Level	2000	2014	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS20502000M_TST20502000M_WL	Water Level	2000	2050	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS21002000M_TST21002000M_WL	Water Level	2000	2100	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS20142000M_TST20142000M_Extent	Water Level Extent	2000	2014	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS20502000M_TST20502000M_Extent	Water Level Extent	2000	2050	Moreton Island
Tropical_Cyclone.gdb	Cyclonic	TPS21002000M_TST21002000M_Extent	Water Level Extent	2000	2100	Moreton Island
DEM.gdb	Digital Elevation Model	BCC_5mDEM	Digital Elevation Model (5m)			BCC and Moreton Island
DEM.gdb	Digital Elevation Model	MoretonIsland_5mDEM	Digital Elevation Model (5m)			Moreton Island

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