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DEVELOPING BETTER PREDICTIONS FOR EXTREME WATER LEVELS

Annual project report 2015-2016

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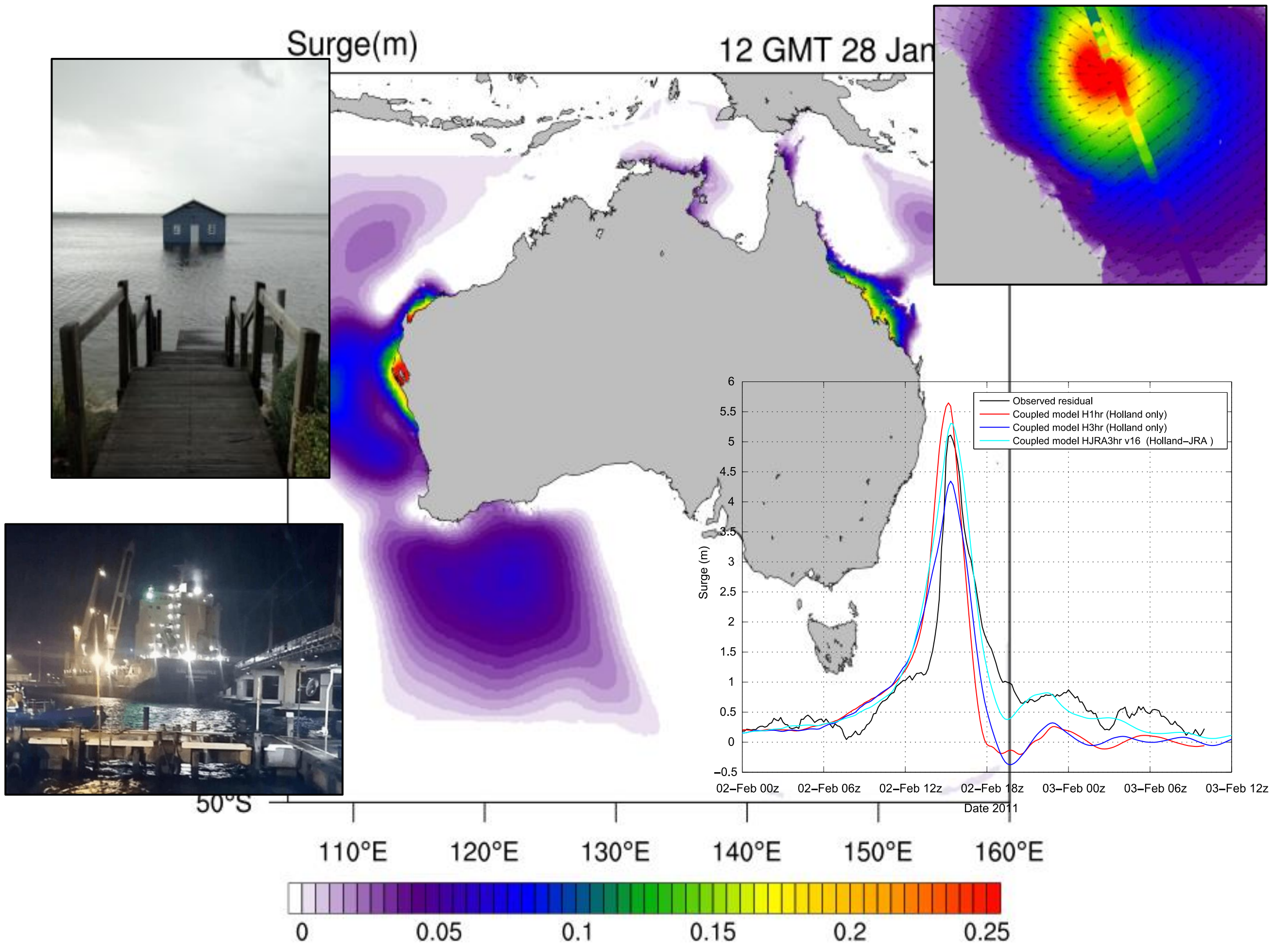

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EXECUTIVE SUMMARY

The occurrence of extreme water level events along low-lying, highly populated and/or developed coastlines can lead to devastating impacts on coastal infrastructure. Therefore it is very important that the probabilities of extreme water levels are accurately evaluated to inform flood and coastal management and for future planning. The aim of this study is to provide estimates of present day extreme total water level exceedance probabilities (including the action of surface gravity waves) around the whole coastline of Australia, arising from combinations of mean sea level, astronomical tide and storm surges generated by both extra-tropical and tropical storms.

Significant progress has been made in the four main areas of investigation. In particular, the modelling system now incorporates and combines the main 3 areas of development detailed in the project aims (wave-set-up, extra-tropical transition, continental shelf waves). Simulations are currently being undertaken with the use of an unstructured grid for the Australian region at a 100m resolution at the coastline. Model validations, through comparison with field measurements have been completed for specific events including: Tropical cyclones in WA (TC George) and Queensland (TC Yasi) , Extratropical Transition event in WA (TC Alby) and, Extra-tropical storms in WA and SA (winter 2007), and Continental Shelf Waves. Simulations have also been undertaken for the recent east coast low event in New South Wales in June 2016.

Work on meteotsunamis has continued and been extended beyond the initial study undertaken in Western Australia, associated with the ship accident in Frementle Port, to cover the whole of Australia and over 200 events were identified from the tide gage records over the past 5 years.

Discussions with end-users have continued to develop final products. In addition, discussions with Bureau of Meteorology are ongoing to develop synergies with the work that the BNHCRC project team is undertaking and the Bureau developments for an operational storm surge warning system for Australia.

END USER STATEMENT

Martine Woolf, Geoscience Australia

This project continues to work towards delivering high quality science to improve our ability to model extreme water levels around the coastline. Given the concentration of the Australian population and infrastructure in coastal areas, this understanding is key to managing the risk from inundation. An improved understanding of the likelihood and severity of extreme water level heights along the coast as a national dataset remains a high priority issue across jurisdictions. End-users have significant expectations from this project. Some focus will continue to be required to ensure that the expectations are managed, and outputs will be delivered in the appropriate format to ensure accessibility and useability.

INTRODUCTION

The major hazard in coastal regions is inundation through extreme water levels generated in the ocean through different mechanisms such as storm surges and tsunamis or through a combination of effects such as a relatively small storm surge coinciding with high astronomical tides. The impacts of seismic tsunamis (generated through underwater earthquakes) have been highlighted by the recent mega-tsunamis in the Indian Ocean (2004) and Pacific Ocean (2011). These events were accompanied by large loss of life and extreme damage to coastal infrastructure. Similarly, the effects of storm surges have had significant affects such as those due to major storms: *Katrina* in New Orleans; *Sandy* in New York City and *Haiyan* in the Philippines. These events also highlighted the effects of coastal inundation with major impact on coastal infrastructure albeit a significant smaller number of casualties mainly due to lead times associated with storm propagation.

Throughout history, coastal settlers have had to adapt to periodic coastal flooding. However, as a society we have become increasingly vulnerable to extreme water level events as our cities and our patterns of coastal development become more intricate, populated and interdependent. In addition to this, there is now a real and growing concern about rising sea levels. Over the last 150 years, global sea levels have on average risen by about 25 cm [1] and it is predicted that this rise will continue over the 21st century (and beyond) at an accelerated rate. With rises in sea level, given water levels will be exceeded more and more frequently as progressively less severe storm conditions are required to achieve that water level [2]. In some coastal regions, extreme water levels could be amplified further by changes in storminess, such as more intense tropical cyclones, although there are still significant uncertainties regarding possible future changes in tropical and extra-tropical storm activity [3].

Therefore it is very important that the exceedance probabilities of extreme water levels are accurately evaluated to inform flood and erosion risk-based management and for future planning. This study is aimed at estimating present day extreme sea level exceedance probabilities due to storm surges, tides and mean sea level (including wind-waves) around the whole coastline of Australia.

The project will increase the accuracy of extreme water level predictions in selected regions of Australia by the inclusion of physical processes not previously considered. Research will include the application of a hydrodynamic model of the Australian continental shelf region to determine annual maximum water levels that will be used to estimate exceedance probabilities around the coastline. The following processes are the focus of the work to be undertaken:

(1) The importance of surface gravity waves (wave-set-up) to extreme sea levels.

(2) Improved parameterisation of the wind fields when tropical cyclones move into higher latitudes, interact with other weather systems and transition to extra-tropical systems.

(3) Continental shelf waves (CSW) which are generated by both tropical and extra-tropical systems but travel around the coast influencing the regions outside the immediate storm system. The resonance conditions between

the storm systems and shelf wave can occur when their propagation systems are similar leading to extreme conditions.

(4) The influence of meteorological tsunamis, which are large-amplitude sea level oscillations created by meteorological disturbances that are similar to tsunamis generated by seismic activity.

PROJECT BACKGROUND

Potential impacts and hazards of extreme water level events along our coasts are increasing as populations continue to escalate and the mean sea levels rise. To better prepare, coastal engineers and managers need accurate estimates of average exceedance probabilities for extreme water levels. The occurrence of extreme water levels along low-lying, highly populated and/or developed coastlines can lead to considerable loss of life and billions of dollars of damage to coastal infrastructure. Therefore it is vitally important that the exceedance probabilities of extreme water levels are accurately evaluated to inform risk-based flood management, engineering and future land-use planning. This ensures the risk of catastrophic structural failures due to under-design or expense due to over-design are minimised. Coastal regions experience rise and fall of sea level which vary at timescales of hours, days, weeks, months, annually and so on, governed by the astronomical tides, meteorological conditions, seismic events, local bathymetry and a host of other factors. The meteorological conditions lead to extreme events through the generation of (1) storm surges both locally and remotely (through the generation of continental shelf waves [4]; (2) generation of surface gravity waves which increases the mean water level at the coastline through wave set-up); and, (3) meteorological-tsunamis generated during thunderstorm activity.

In a previous related study, we estimated, for the first time, present day probabilities of extreme water levels around the entire coastline of Australia from tropical and extra-tropical storm systems [2]. A high-resolution depth averaged hydrodynamic model was configured for the entire Australian continental shelf region and forced with tidal levels from a global tidal model, seasonal and inter-annual sea level variation from satellite altimeter data and meteorological fields from a global reanalysis database to generate a 61-year hindcast of water levels. Output from this model was successfully validated against measurements from 30 tide gauge sites. At each numeric coastal grid point, extreme value distributions were fitted to the derived time series of annual maxima and the several largest water levels each year to estimate exceedance probabilities. This provided a reliable estimate of water level probabilities around southern Australia; a region mainly impacted by extra-tropical cyclones [5]. The study was then extended to include the influence of tropical cyclones. Initially, an analysis of tide gauge records were used to assess the characteristics of tropical cyclone induced surges around Australia. However, given the dearth (temporal and spatial) of information around much of the coastline, and therefore the inability of these gauge records to adequately describe the regional climatology, an observationally based stochastic tropical cyclone model was been developed to synthetically extend the tropical cyclone record to 10,000 years (Figure 1). Wind and pressure fields derived for these synthetically generated events were used to drive a hydrodynamic model of the Australian continental shelf region with annual maximum water levels extracted to estimate exceedance probabilities around the coastline. Over 76,000 individual model runs were completed. To validate this methodology, selected historic storm surge events were simulated and resultant storm surges compared with tide gauge records. Predicted 61-year water level time series data were analysed using extreme value theory to construct return period curves for both the water level hindcast and synthetic tropical cyclone modelling (Figure 2). These return period curves were then combined by taking the highest water level at each return period

(Haigh et al., 2013b). This is most comprehensive study of extreme sea levels undertaken for the whole of Australia to date. The results of the study data are available through the www.sealevelrise.info for whole of Australia. The advantages of this study was that the same methodology was used to estimate the extreme water levels around Australia to enable direct comparisons between regions as well as those regions located away from water level monitoring stations: the model output was able to provide synthetic time series at 10 km (model resolution) intervals around the coastline Australia.

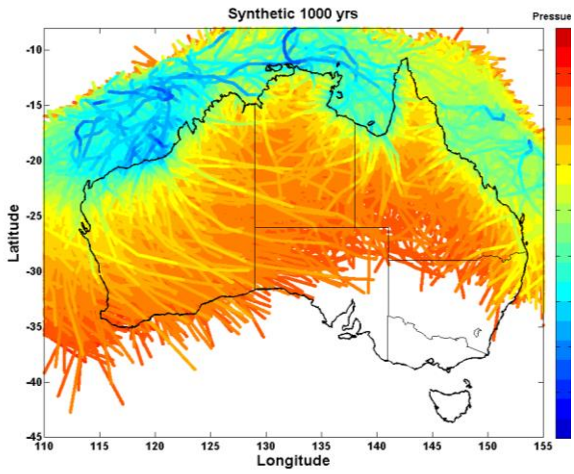

Figure 1: Paths of synthetic tropical cyclones predicted over a period of 1000 years (Haigh et al., 2012)

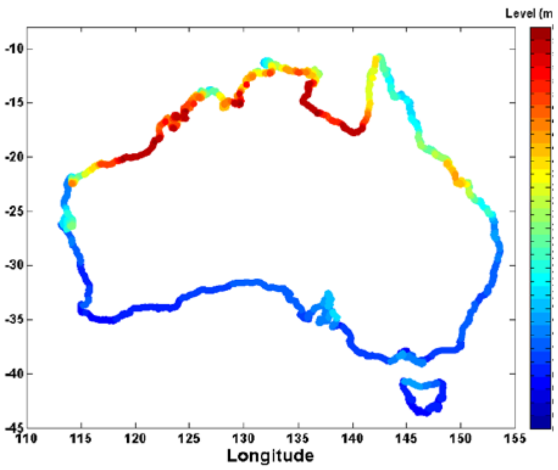

Figure 2: 1:1000 annual recurrence interval extreme water levels for Australia (Haigh et al., 2012)

The studies described above led to a significant advance in the knowledge, methodology and communication of results (through a web interface) for extreme water levels around Australia. After the completion of the study, we have now discovered four major areas in which we can improve the predictions of the extreme water levels by the inclusion of the following processes which were not explicitly included in the original studies and would increase the accuracy of extreme sea level predictions in selected regions of Australia.

These processes include: (1) changes in mean water level due to surface gravity waves (wave-set-up); (2) improved parameterisation of the wind fields when the system transitions from a tropical to an extra-tropical system; (3) continental shelf waves (CSW) which are generated by both tropical and extra-tropical systems but travel around the coast influencing the regions outside the immediate storm system. The resonance conditions between the storm systems and shelf wave can occur when their propagation systems are similar leading to extreme conditions; and, (4) the influence of meteorological tsunamis. These processes are described below with reference to their contribution to extreme water levels and work to be undertaken as part of this project.

(1) ***Wave set-up***: is the increase in mean water level due to the presence of waves. Wave setup is not included in prediction of storm surges as it is usually

calculated as a separate component to water rise that must be calculated by accurately forecasting waves generated by the storm system (e.g. tropical cyclone) and then calculating the wave setup at a specific coastline location. Depending on the tropical cyclone and local bathymetry the wave set-up component can be significant. For example with hurricane Opal, which hit the Florida Panhandle in 1995, wave setup was estimated to be ~3 m whilst the storm surge from onshore winds and inverse barometer was ~2.7m. Here, it is proposed that the magnitude of the wave set-up component be defined at particular locations around Australia to estimate its importance to total water levels. This will be undertaken using a numerical model which includes the effects of waves on mean sea levels.

(2) ***Transition from tropical to extra-tropical cyclones***: Tropical Cyclones are initiated in regions where sea surface temperatures are > 27° Celsius and once they are formed travel onto higher latitudes. Occasionally a decaying tropical cyclone interacts with a cold front and evolves into an intense, larger fast-moving system. These systems can produce a range of destructive phenomena from intense rainfall, storm surges and large waves and provide conditions conducive to the spread of bushfires. Examples of such systems include TC *Alby* in 1978 the most destructive system to impact on the south-west Australia to-date and Hurricane *Sandy* which caused significant coastal inundation in New York City in October 2012. Currently, we do not include these transitions in the numerical models used to predict storm surges resulting in underestimate of the predicted storm surge. The tropical cyclone wind fields are currently predicted using the 'Holland' model which defines the wind speeds generated by the cyclone based on the central pressure and maximum wind radius. Here, it is proposed that atmospheric model data be collected from tropical cyclones which have been identified to undergone the transition from tropical to extra-tropical cyclones in an attempt to develop parameterisations which may be included in numerical models.

(3) ***Continental shelf waves***: Storm surges are generated by a combination of atmospheric phenomena including barometric effect and wind set-up. The storm surge is greatest at the coast and as an atmospheric system crosses a coast wind stress on the water surface is removed releasing the mass of water accumulated in the storm surge. For a sloping continental shelf this releases energy in the form of continental shelf wave. These waves travel with the coastline on its left in southern hemisphere and on the right in the northern hemisphere. They have a low rate of decay and may propagate extended distances. For example, waves generated off Broome in the Kimberley can be identified off Tasmania, 2-3 days later. These waves are common along the west, south and east coasts of Australia and are well documented [4]. The largest shelf waves are generated by tropical cyclones particularly originating in the north-west region which travels along the WA coast and the influence of the wave is over a period of 10 days. Thus the effects of the tropical cyclone can exist long after the generating cyclone has dissipated. If the propagation speed of the tropical cyclone matches the speed of the shelf wave then a resonance condition may develop resulting in large amplitude waves and there are many instances of this happening. A most recent example of a continental shelf wave which could have caused large scale flooding of the Perth region is the shelf wave generated by category 4 TC *Bianca* in 2011. The path of TC *Bianca* was such that subsequent to generating the shelf wave in the north-west shelf it travelled offshore and was then was predicted to cross the coast in the Perth

region. The peak of the shelf wave, the local storm surge to be generated by the TC *Bianca* winds as well as high tide were to occur simultaneously resulting in a maximum water level 0.5m higher than that recorded in the Perth region. However, TC *Bianca* encountered strong wind shear 2 hours prior to coastal impact and rapidly dissipated. Although a high water level was reached flooding many low lying areas in the Perth region, wide spread flooding did not occur. Here, it is proposed that models used for estimating extreme sea levels around Australia [5] be modified to include the effects of continental shelf waves.

(4) ***Meteorological tsunamis***: Meteorological tsunamis (or meteo-tsunamis) are large-amplitude sea level oscillations similar to those generated by tsunamis of seismic activity but are generated by meteorological disturbances. These events have been documented from different regions globally and cause localised coastal inundation. Analysis of a decade of tide gauge records from different locations along the coastline of Western Australian (WA), from Carnarvon to Esperance, revealed regular occurrence of these events of non-seismic origin. The events corresponded with meteorological data and the larger events (amplitude > 0.25 m) were found to be associated with summer thunderstorms and could be classified as meteo-tsunamis. The maximum wave heights recorded during these events frequently exceed the maximum wave heights recording during seismic tsunamis (e.g. [6]). Also the highest water level ever recorded in June 2012 at Fremantle, where the tidal record extends over 110 years, can be attributed to a meteo-tsunami. The regular occurrence of these events (2-3 events per annum at a given location) in Western Australia over a large spatial area: for example a single system can influence water levels over a region several hundreds of kilometers as the thunderstorm travels along the coast. Occurrence of these events around Australia is unknown as no detailed analysis of tidal records has been undertaken. In the US, work is currently underway to develop an early warning system to predict the occurrence of these events. The success gained by numerical simulations of these systems allows us to develop such predictive systems in Australia. Here, it is proposed that the analyses undertaken in Western Australia to be extended to other regions of Australia to identify the occurrence of these events and to define the magnitude of the hazard from meteo-tsunamis.

WHAT THE PROJECT HAS BEEN UP TO

The project started off in January 2014. Initially, there was a delay in recruitment of personnel but now the project is up to date with milestones. Two post-doctoral researchers were recruited with Dr Yasha Hetzel starting in August 2014 and Dr Ivica Janekovic starting in April 2015. Significant progress has been made in the 4 specific areas detailed in the Project Background and are summarised below. In particular, the modelling system incorporates and combines the main 3 areas of development detailed in the project aims (wave-set-up, extra-tropical transition, continental shelf waves). Simulations are currently being undertaken with the use of an unstructured grid for the Australian region at a 100m resolution at the coastline (Figure 3). Model validations, through comparison with field measurements have been completed for specific events including: Tropical cyclones in WA (TC George) and Queensland (TC Yasi) , Extratropical Transition event in WA (TC Alby) and, Extra-tropical storms in WA and SA (winter 2007), and Continental Shelf Waves. Simulations have also been undertaken for the recent east coast low event in New South Wales in June 2016).

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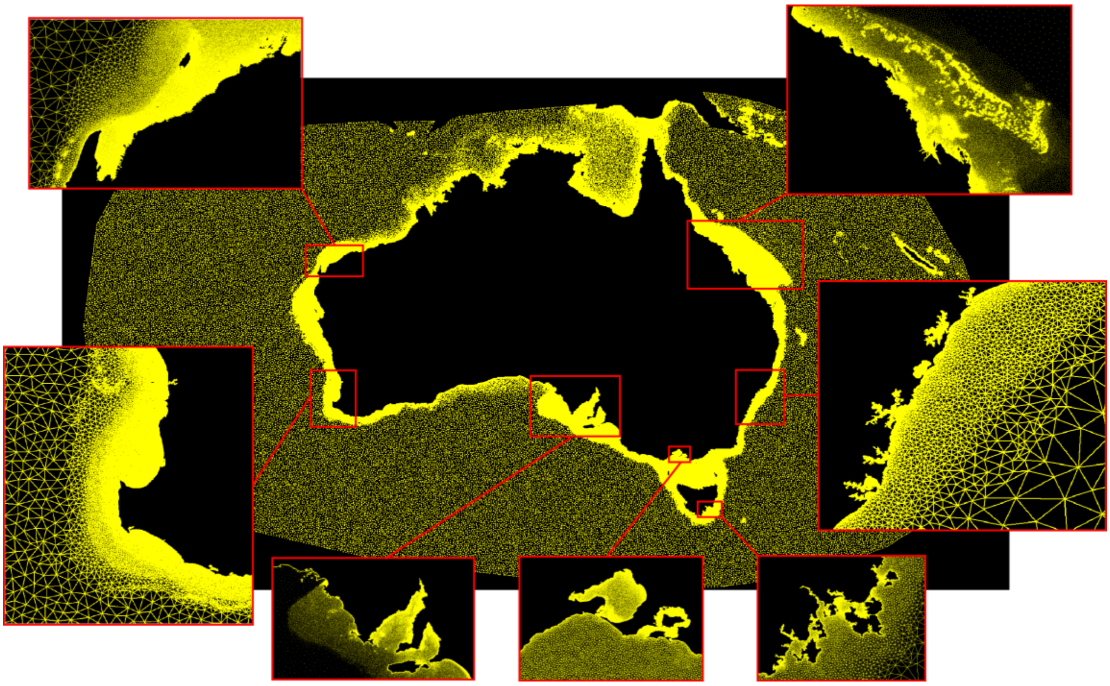

Figure 3. Australia-wide mesh grid showing the large domain and varying resolution, from tens of kilometres in the open ocean to approximately 100m at the coastline.

WAVE SETUP

Wave set-up is the increase in mean water level due to the presence of waves. In general, wave setup is not included in prediction of storm surges as it is usually calculated as a separate component to water level increase that must be calculated by accurately forecasting waves generated by the storm system (e.g. tropical cyclone) and then calculating the wave setup at a specific coastline location. This component when added to already high water levels during storm conditions can significantly increase the risk of flooding, erosion, and structural damage in coastal regions. The original project proposed that current computing resources available to perform a 60-year simulation of wave climate at the high resolution required for resolving wave set-up in coastal regions was not possible. Rather high resolution wave models were proposed to apply for different regions so that regions where wave set-up was important could be identified. However, recent developments in computer models and adopted by the project will allow us to run coupled wave and storm surge models for whole of Australia. Initial model runs of the coupled sytem, including recently released atmospheric hindcast datasets have shown to more accurately reproduce the dynamics of exteme storm surges than what has previously been available.

A detailed case study was performed for Cyclone Yasi that struck the coast in Northern Queensland in February 2011, causing substantial damage to infrastructure with storm surges up to 5.3 m and waves up to 8 m at the coast. Calculating the difference between coupled and uncoupled model runs resulted in a measure of wave setup that consisted of the transfer of momentum from breaking waves into vertical change in water level

For TC Yasi, maximum wave setup of 0.25-0.4 m slightly preceded maximum surges at all sites and coincided with maximum wave heights. In the hours before landfall this accounted for 30-35% of the total surge. Around the time of landfall the proportion of the surge related to wave setup dropped to around 6-20% due to the increase in surge from the strong winds and decrease in pressure. The high spatial and temporal variability of the wave setup component of the surge was mostly determined by two factors: wave height and the cross shelf depth profile, which varied greatly over the region.

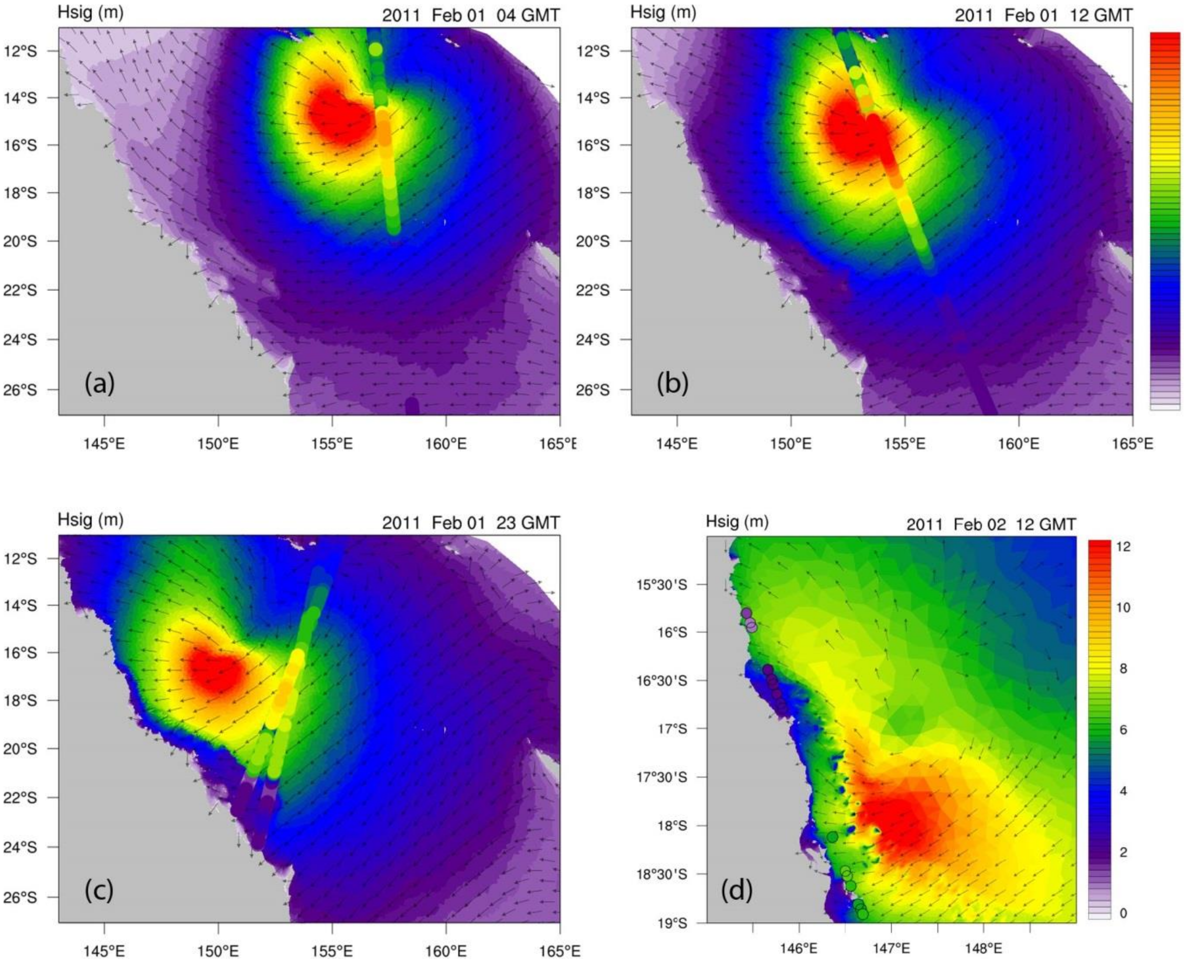

Figure 4. Modelled significant wave height (H_s) with satellite derived measurements of H_s within a two hour window plotted on top as coloured circles. A zoomed in view at 12 (GMT) on 2 February (d) shows a satellite pass over the nearshore region around Cardwell as Yasi made landfall.

TRANSITION FROM TROPICAL TO EXTRA-TROPICAL CYCLONES

As tropical cyclones move toward the poles they can interact with the surrounding environment causing the tropical cyclone to lose tropical characteristics and become more extratropical in nature – this is known as Extratropical Transition, or ET [7]. These systems are sometimes referred to as ex-tropical or post tropical cyclones. Storms that undergo ET pose a serious threat by extending tropical cyclone–like conditions over a larger area and to latitudes that do not typically experience such events. They often evolve into fast-moving and occasionally rapidly intensifying extratropical cyclones that produce intense rainfall, very large waves, and tropical cyclone intensity winds.

For simulating Cyclone Alby (SWWA 1978), the best documented extratropical transition event in Australia, we found the Japanese 55 Year Reanalysis (JRA-55) [8] wind and pressure resulted in surprisingly accurate estimates of surge levels along the coast, given the generally accepted assumption that coarse resolution reanalyses underestimate the intensity of tropical cyclones. Initial comparisons of wind speeds indicated that the JRA-55 wind speeds were comparable with the limited observations as the storm transitioned into an extratropical storm. The question remains whether other ET events will behave the same as TC Alby, however it is clear from our simulations that coarse reanalyses can provide superior forcing than parametric cyclone models since ET storms no longer behave as tropical cyclones.

Review and testing of the different forcing parameters in the model revealed that the JRA55 model predicted higher wind speeds away from the storm centre and more accurately reproduced winds nearer to the coast compared to parametric wind models. This formulation is used in the current forcing of the modellling system as the resulting simulated water levels closely fit observations.

CONTINENTAL SHELF WAVES

A coastally trapped wave is defined as a wave that travels parallel to the coast, with maximum amplitude at the coast and decreasing offshore. Examples of these waves include continental shelf waves (CSWs) and internal Kelvin waves, which are governed through vorticity conservation. Coastally trapped waves need a shallowing interface and may develop a range of modes according to the shelf structure. They travel with the coast to the left (right) in the southern (northern) hemisphere. Along the Australian coast, shelf waves propagate anti-clockwise relative to the landmass. All these wave types propagate along the coastal boundary, with the wave signal reducing in amplitude with distance offshore. Continental shelf waves (CSWs) depend on only the cross-shelf bathymetry profile and the vertical density profile controls the structure of an internal Kelvin wave. The alongshore component of wind stress usually generates CSWs that propagate anti-clockwise along the south coast of the Australian continent over a maximum distance of 4000 km at speeds of 5–7 ms^{-1}.

A series of simulation were undertaken for Cyclone Bianca (2011) using both the SELFE/SCHISM model (without density effects) and the Regional Ocean Modeling Systems (ROMS) (including density effects) to understand the requirements for modeling CSWs. While both models were able to recreate the CSW the ROMS simulation more closely matched observations, particularly as the CSW propagated south of Carnarvon/Shark Bay. This result indicated that to properly result shelf waves traveling around the coast it is necessary to use a full three-dimensional baroclinic model that includes density effects. It appeared that the energy of the continental shelf waves dissipated too quickly in regions of with varying bathymetry unless allowed to transform into other modes that required vertical density stratification to propagate. This result would likely repeat itself around the coastline at specific locations and these results will inform what is the best approach for modelling storm surges where shelf waves are important.

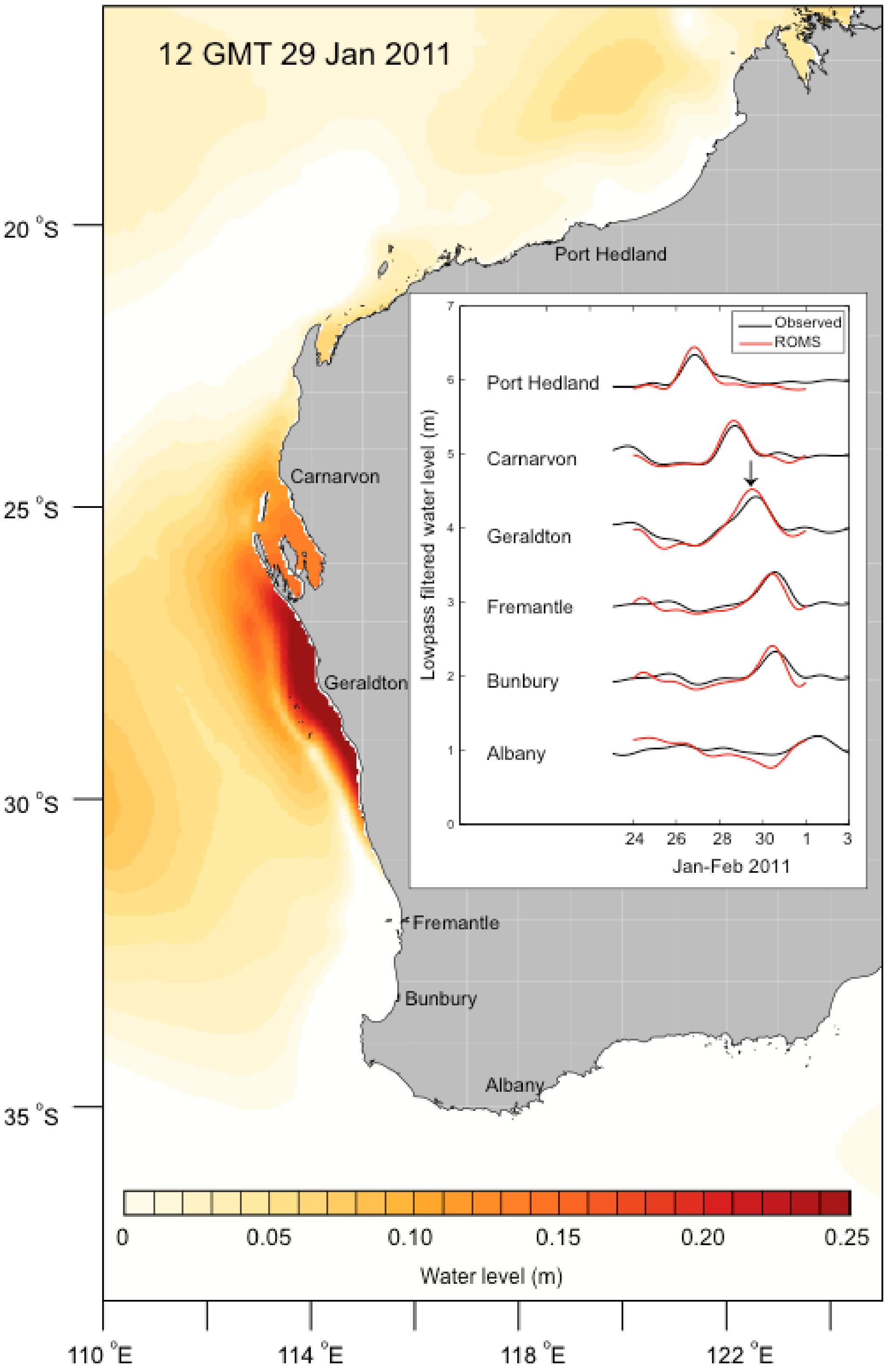

Figure 5. Simulated water levels from ROMS model run for Bianca (2011). Colour represents the water level (no tides). Inset shows time series of water levels at selected sites along the coast with the arrow marking the time and place of the water levels shown in the map.

METEOTSUNAMIS

The major hazard in coastal regions is inundation through extreme water levels generated in the ocean through different mechanisms such as storm surges and tsunamis or through a combination of effects such as a relatively small storm surge coinciding with high astronomical tides. The impacts of seismic tsunamis (generated through underwater earthquakes) have been highlighted by the recent mega-tsunamis in the Indian Ocean (2004) and Pacific Ocean (2011). These events were accompanied by large loss of life and extreme damage to coastal infrastructure. Similarly, the effects of storm surges have had significant affects such as those due to major storms: *Katrina* in New Orleans; *Sandy* in New York City and *Haiyan* in the Philippines. These events also highlighted the effects of coastal inundation with major impact on coastal infrastructure albeit a significant smaller number of casualties mainly due to lead times associated with storm propagation.

Meteorological tsunamis (meteotsunamis) are water level oscillations that are similar to waves generated by seismic activity ('tsunami waves'), except they have a meteorological origin and are not generated through seismic activity, volcanic explosions or submarine landslides. Time series of water level records from Fremantle (Western Australia) obtained during the seismic tsunami of 2004 and a meteotsunami in 2002 indicate similar wave heights for both events (Figure 10). The main forcing mechanism of a meteotsunami is the propagation of an abrupt change in sea surface atmospheric pressure and/or associated wind gusts. Recent work and the occurrence of several events globally in the past few years have highlighted the importance of meteotsunamis as a coastal hazard similar to that of seismic tsunamis. Although meteotsunamis are not catastrophic to the extent of major seismically induced basin-scale events, they have, nevertheless caused millions of dollars in damage to boats and harbours around the world.

Meteotsunamis are considered as a multi-resonant phenomenon where destructive events occur only when a coincidence of several crucial factors takes place at the same time. These include: (1) the local weather systems which are able to efficiently transfer energy into the ocean. For example this could include resonance conditions such as Proudman resonance where the moving speed of the atmospheric disturbance is equal to the local shallow water wave speed; (2) the continental shelf and slope topography, which controls the amount of shoaling as the wave generated by the atmospheric disturbance in deep water to the coast; and, (3) the topography and geometry of the coastline (harbours, bays, river mouths etc.) which could have a natural frequency similar to the incoming meteotsunami waves. All three of the conditions described above depend on the coastal topography and bathymetry as the speed of the shallow water waves is dependent on the water depths.

As part of the project three main tasks were completed:

(1) A review of meteotsunamis – their generation mechanisms and global occurrence has been published as a review paper:

> Pattiaratchi CB & Wijeratne EMS 2015. Are meteotsunamis an underrated hazard?. *Philosophical Transactions Royal Society of London* A. doi:10.1098/rsta.2014.0377

(2) The occurrence of meteotsunamis around the whole coast of Australia was investigated. Tide gauge records were used to examine water level oscillations with periods < 6 hours, which were then related to local atmospheric data. The analyses developed in the initial studies in south-western Australia were applied 13 tide gages around Australia which have sampling periods of 1 minute. These included: Spring Bay, Tas; Burnie, Tas; Portland, Vic; Thevenard, SA; Esperance, WA; Hillarys Harbor, WA; Cape Cuvier Wharf, WA; Broome, WA; Darwin, NT; Groote Eylandt, NT; Cape Ferguson, Qld; Rosslyn Bay, Qld; Port Kembla, NSW. At each of these sites the analysis covered a period of 5 years from December 2009 to December 2014. A total of 214 events were identified that could be classified as meteotsunami events with periods < 6 hours with amplitude > $4*\sigma$ of the residual time series. There were no events recorded in the tropical regions (Broome and Darwin), most likely due to the high tidal range and absence of travelling pressure systems. Similarly no events were recorded in Thevenard. The largest number (in terms of events and highest amplitude) occurred in Western Australia (Cape Cuvier, Hillarys and Esperance). There were also a number of events with amplitudes > 0.40 m in south-east Australia: Burnie, Portland and Port Kembla. Majority of the events coincided with the meteorological events with small changes (~2-3hPa) in atmospheric pressure and/or associated strong wind events. Some were associated with the passage of cold fronts. A large event in Cape Cuvier was attributed to the passage of atmospheric gravity waves through the region – this is the first time such an event has been described in Australia.

(2) The influence of meteotsunamis inside Ports and marinas were investigated with an emphasis on current patters. Although there are meteotsunamis events captured on water level records, measurements of currents which usually create the hazard conditions for the safety of ships and boats are rare. Time series data on water levels and currents inside Fremantle Port and Port Geographe, a small marina and canal estate in south-west Australia indicated the frequent occurrence of meteotsunamis over a 2 month record. There were up to 7 events during this period which resulted in strong currents, higher than the ambient currents that resulted in the transport of sand and seagrass wrack into the the canal estate system leading to reduction in water quality. An interesting observation is that the meteotsunami waves are not significantly attenuated within the canal system.

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CONFERENCE PRESENTATIONS

PIANC Coastal and Port Engineering in Developing Countries (COPEDEC), Rio de Janeiro, Brazil, October, 2016

Australian Coastal Ocean Modelling Conference (ACOMO) – Canberra, October 2016

56th Floodplain Management Australia Conference,17-20 May 2016, Shoalhaven Entertainment Centre, Nowra NSW

Australian Meteorological and Oceanographic Society (AMOS) Conference, Melbourne

International Symposium on the Indian Ocean (IO50), Goa

NSW State Emergency Service Tsunami Operations Capability Development Group Workshop, Sydney, 5–6 November.

Victorian Department of Environment, Land, Water and Planning Science Symposium, Melbourne, 4–6 November

Eighth Australasian Natural Hazards Management Conference, Perth

Coasts and Ports 2015, Engineers Australia, Auckland, New Zealand

Australian Meteorological and Oceanographic Society (AMOS) Conference, Brisbane

Workshop on Global and regional sea level variability and change, Mallorca, Spain.

Seventh world congress of scientific youth, Fédération Internationale des Sociétés Scientifiques, Mendoza, November 2014.

SEMINARS

Fremantle Ports, Fremantle (2)
IMarEST WA branch meeting, UWA, Perth
Bushfire and Natural Hazards CRC Research Advisory Forum, Brisbane
Coastal, Ocean and Port Engineering Panel, Engineers Australia, Perth
School of Civil, Environmental and Mining Engineering, UWA, Perth
Centre for Offshore Foundation Systems seminar, UWA, Perth
Institution of Engineers, Sri Lanka (WA Chapter), Perth
Institute of Advanced Studies, UWA, Perth
Coastal planning and oceanographic research, WAMSI, Perth
UWA Energy and Minerals Institute lunch and learn, Perth
Carnegie Wave Energy Ltd, Fremantle
Bushfire and Natural Hazards CRC Research Advisory Forum,
Melbourne Bureau of Meteorology, Perth
Conference on Coastal Engineering (ICCE), Seoul
CSIRO Marine and Atmospheric Research, Hobart
Institute of Marine and Coastal Sciences, Rutgers University
Universidad de Cantabria, Santander, Spain
Oceans Institute seminar, UWA, Perth
Environmental Protection Authority, Perth

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APPENDIX: DETAILS OF ANALYSIS UNDERTAKEN IN 2015-16

MODEL VALIDATION: TROPICAL CYCLONES

Simulations for many extreme events around Australia continue to be performed in order to further validate the model and refine the methodology for different types of events and to build an event database. A summary of findings for the events investigated is presented below.

TROPICAL CYCLONE YASI

Cyclone Yasi crossed the coast near Mission Beach in Northern Queensland on the night of 2 February 2011 as a Category 5 cyclone with estimated wind gusts up to 285 km/hr (79 m s^{-1}). Yasi was the largest and most intense storm to impact Queensland since 1913. The cyclone caused extensive damage to property and infrastructure costing $800 million over more than 500 km of coastline, however destruction would have been worse had the storm made landfall in a more populated area. Large waves combined with storm surges to erode large sections of coastline, with maximum storm surge height of 5.33 m in Cardwell.

A universal challenge in simulating historical storms with numerical models is to obtain accurate forcing and validation data. For storms like TC Alby (1978) that occurred before the satellite era (~1979-present) data are limited, whilst for more recent storms there exist many more reliable observations to force and validate storm surge models. For these reasons TC Yasi was selected as a more recent ideal modelling test case to investigate the effects of waves on storm surge levels. Using Bureau of Meteorology cyclone track data we were able to simulate wind and pressure fields using the Holland (2010) [9] parametric model for Yasi that fit well with observations. These wind and pressure fields were combined with JRA55 reanalysis data over the broader region (HJRA) and were used to force the fully couped wave-surge model.

Atmospheric forcing validation

Extreme surge and wave events around Australia are caused by both tropical and extratropical storm systems of vastly differing scales. We investigated a range of forcing options to understand how the surge and wave models respond at different time and spatial scales.

Three different atmospheric datasets were used to force the model based on the size and type of storm being simulated. These included: 1) JRA55 Japanese Reanalysis, 2) ECMWF ERA-Interim Reanalysis (ERA-I) [10], 3) A bogus vortex JRA55-Holland hybrid (HJRA). The hybrid forcing method merged wind and pressure fields from JRA55 and those calculated with the Holland [11] parametric wind model for tropical cyclones that were under represented in the reanalyses due to resolution constraints.

Global Reanalyses – Issues with TC intensity and track errors

For *large (non-tropical) storms* around Australia excluding those storms transitioning from tropical to extratropical (Extratropical transition-ET), the higher resolution (3hour, 0.125 degree) ECMWF ERA-Interim reanalysis provided highly reliable atmospheric forcing [10]. These data, however, were not accurate for other types of storms. In general, slow moving large storms were well-represented by ERA-I whilst smaller more intense storms were poorly represented. There were two reasons for this: 1) Tropical cyclone intensities were dramatically underestimated 2) Tropical cyclone tracks were often offset from reality by up to ~100 km.

For the *transitioning tropical cyclone case*, Cyclone Alby in 1978, the recently released Japanese Reanalysis JRA-55 reanalysis atmospheric model [8] was found to be superior to the ERA-I. This dataset has shown some success in capturing the structure of ET storms [12]. A vortex relocation algorithm in JRA-55 uses cyclone track data to ensure that the simulated storm follows an accurate trajectory. Although reanalysis datasets tend to underestimate the intensity of tropical cyclones [12], JRA-55 appeared to better simulate ET events compared to the common approach of using parametric wind and pressure models [e.g. 9, 13] that assume the storm is symmetric and tropical in nature when in fact this is not the case for storms undergoing ET. The JRA55 wind and pressure fields we tested included 3/6 hour 0.5/1.25 degree resolution with both performing well for the TC Alby case.

For the case of a *true tropical cyclone making landfall*, we found neither the ERA-I nor the JRA55 to be adequate as both models drastically underestimated the intensity, and the ERA-I misrepresented the cyclone track. Since storm surges are directly related to the minimum pressure and local winds it was critical to have the storm intense enough and make landfall in the correct location in order to realistically simulate water levels.

Bogus cyclone vortex/ Reanalysis hybrid

For tropical cyclone events where the ERA-I model underestimated intensity, we found that blending reanalysis model data with parametric representations of wind and pressure fields (eg. Holland, 1980, 2010) near the core of the cyclone gave the best representation of the wind and pressure fields both near the cyclone core and away from the storm. In our analysis we found that cyclone tracks in the JRA55 were much more accurate than for ERA-I, likely due to a vortex relocation algorithm implemented in the JRA55 model. In the case of Cyclone Yasi in Queensland, the ERA-I had Yasi crossing the coast~ 100 km north of Mission Beach where landfall was recorded to have occurred, whereas the track of the JRA55 agreed with observations (Figure 6). Based on this the high (model) resolution JRA55 (0.5 deg, 3 hourly) was chosen as the background wind and pressure fields into which a bogus parametric cyclone vortex [9] was inserted. JRA55 data were obtained from the NCAR Research Data Archive [14] and the Holland wind and pressure fields near the core of the cyclone were calculated using Australian Bureau of Meteorology Best Track data and digitised JRA55 track data.

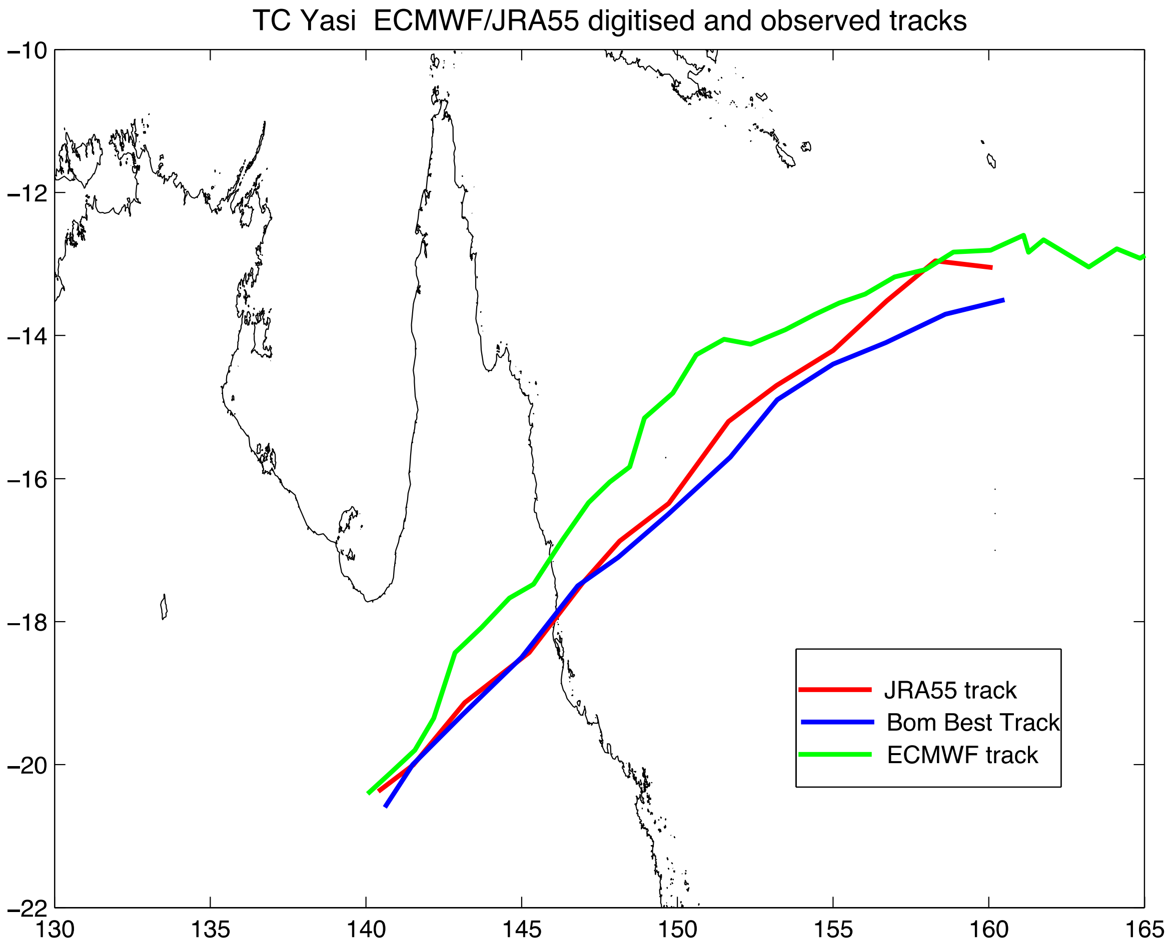

Figure 6. Digitised storms tracks for TC Yasi for JRA55 and ERA-I (ECMWF) as compared to the BOM Best Track data.

Hybrid Holland-JRA55 Reanalysis (HJRA) model description

The Holland model [13] is the most widely used parametric wind model in storm surge modelling studies [15]. This model relies on the consistency and uniformity of tropical cyclone circulations, with exponentially increasing wind speeds to a maximum near the core and a rapid drop in the eye. The Holland 1980 [13] model, hereinafter H80, approximates the pressure and wind profile with a modified rectangular hyperbola. Inputs to the model are: central pressure, environmental pressure, radius of maximum winds (rmw), and a scaling factor B that defines the peakedness of the profile. The first three inputs are commonly available from cyclone track archives and the scaling factor is generally based on historical parameters for storms in the region, and/or available observations.

The Holland model was updated in 2010 [9], hereinafter H10, to include the ability to adjust the shape of the profile based on observations at some radius from the TC centre. This modification was motivated by a consistent underestimation of wind speeds in the outer regions away from the core by the H80 model. Holland [9] recommends that H10 should be used in place of the H80 model, even if the radius of maximum winds and central pressure are the only available data. The radius of gale force winds, commonly available in archives can also be used to guide the model in the outer regions. If unavailable, these data can be estimated through analysis of more recent storms in the region, with little error [9]. The track data used for H10 calculations for cyclone Yasi were obtained from the Australian Bureau of Meteorology cyclone track database available from http://www.bom.gov.au/cyclone/history/index.shtml and supplemented with the digitised track coordinates from JRA55. The H10 parametric model resulted in a tropical cyclone that was significantly more intense than either the ERA-I or JRA55 reanalyses (Figure 7) and compared well with observations.

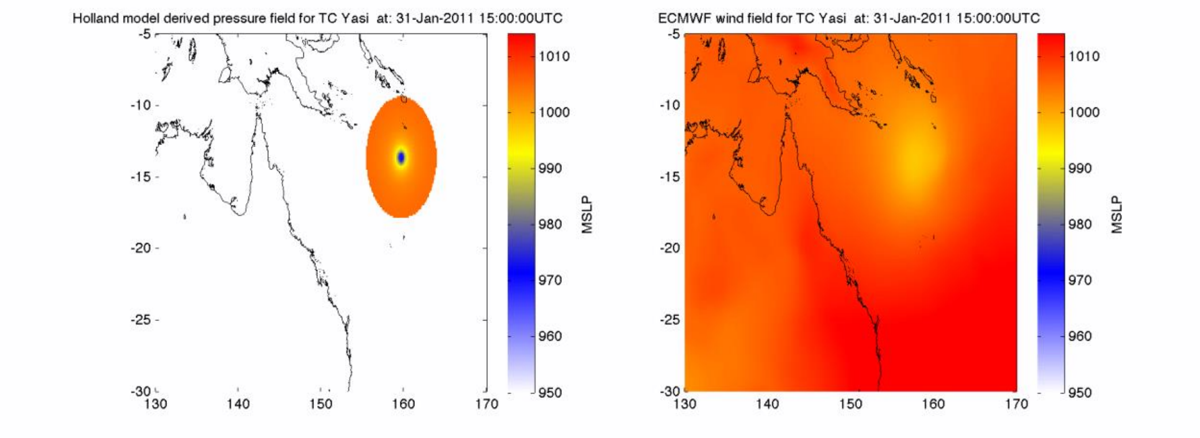

Figure 7. Mean sea level pressure comparison between the H10 parametric TC model (left) and ERA-I (right), showing the > 20 mb difference in pressure at the cyclone core.

The cyclone wind and pressure fields were calculated with H10 at the nodes on the coupled model grid and then merged with the JRA55 values away from the storm centre using a linear distance from the centre weighting method where the wind and pressure fields in the intense region of the cyclone were purely H10 and beyond the radius of the last closed isobar the values were purely JRA55. The resulting 3-hourly merged wind and pressure field used to force the coupled model is hereinafter referred to as **HJRA** (Holland-JRA55) (e.g. Figure 8). The realistic wind and pressure fields away from the core of the cyclone ensured broader trends over the region were better represented as compared to a purely Holland model (Figure 9Figure 10). The accurate cyclone track provided through the JRA55/Holland method ensured that the strong onshore winds (Figure 11) occurred in the correct area between Mission Beach and Townsville resulting in accurate water level and wave predictions.

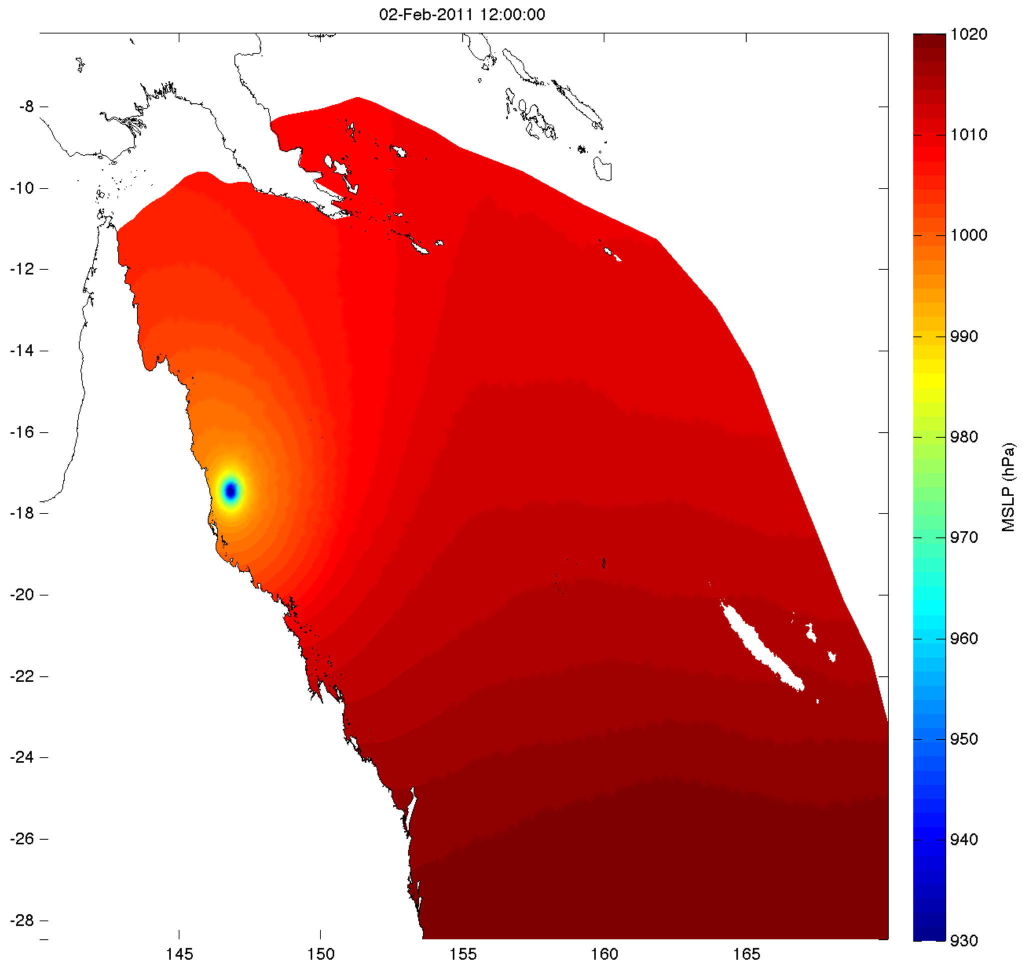

Figure 8. Hybrid bogus vortex/JRA55 mean sea level pressure field on model grid for TC Yasi two hours before landfall as a Category 5 storm.

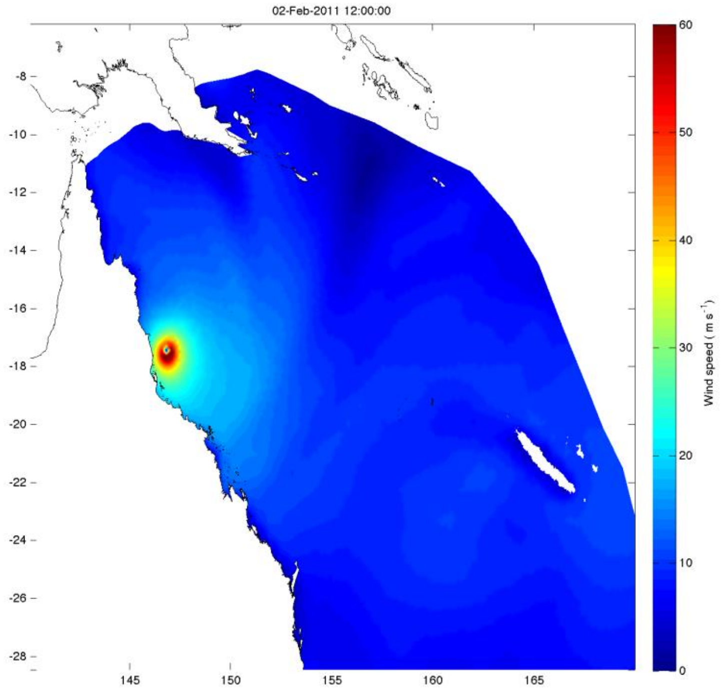

Figure 9. Example of wind field from HJRA merged Holland and JRA55 for Cyclone Yasi (2 hours before landfall) in Queensland including the bogus cyclone vortex.

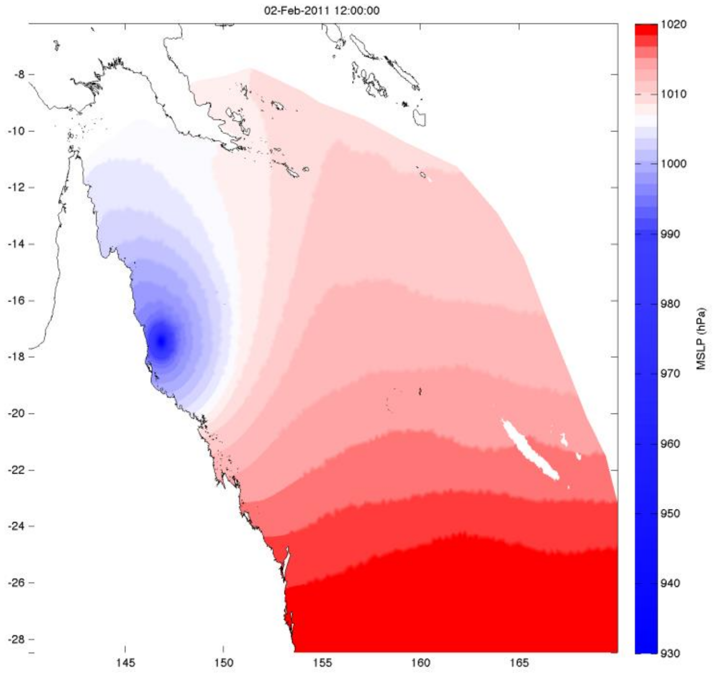

Figure 10. Hybrid bogus vortex/JRA55 means sea level pressure field on model grid for TC Yasi two hours before landfall as a Category 5 storm (same as Figure 9) with colour scale highlighting areas of lower/higher than normal pressure where water levels were raised/depressed by the inverse barometric effect.

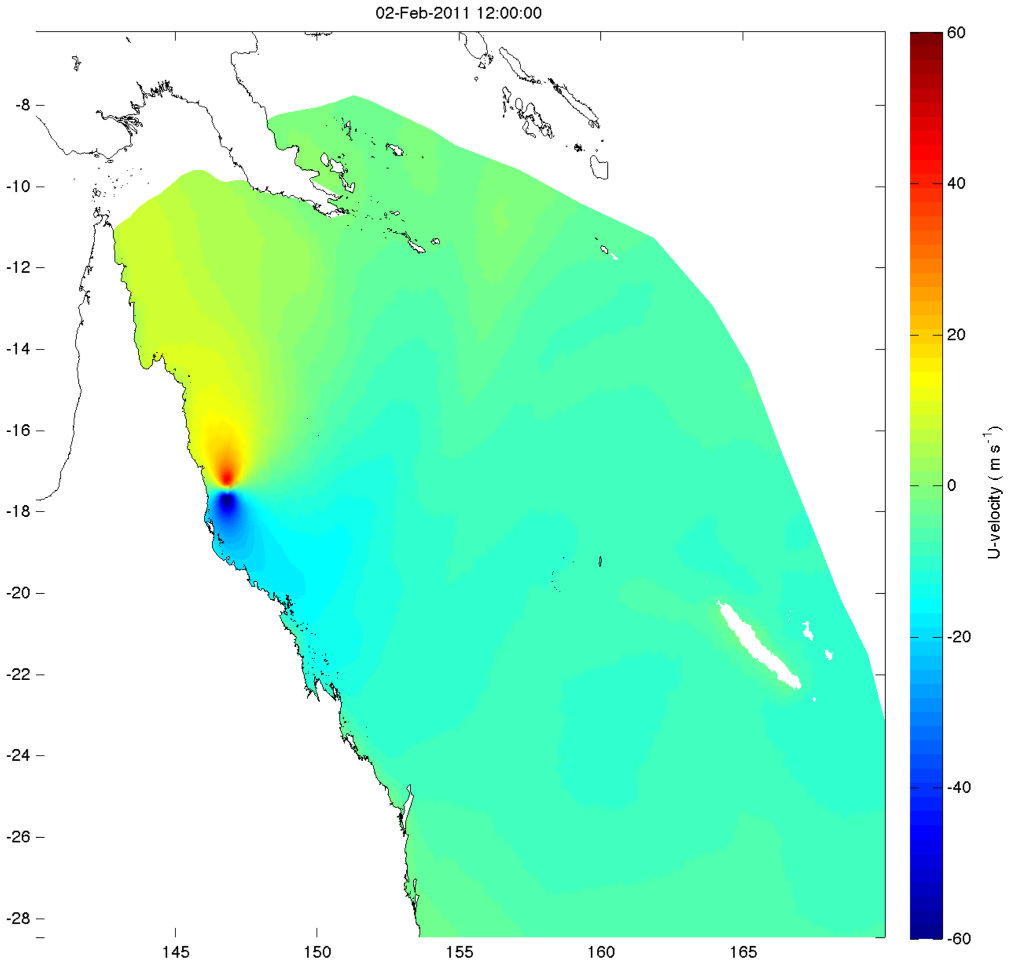

Figure 11. Hybrid bogus vortex/JRA55 East-West component of wind velocity on model grid for TC Yasi two hours before landfall as a Category 5 storm. Negative U-velocity indicates onshore (easterly) flow south of the storm centre.

HJRA wind validation

Limited observations of wind and pressure offshore were available for comparison so initial validation consisted of comparison between HJRA model wind swath of maximum winds (Figure 12) and Bureau of Meteorology equivalent maps of track and intensity (Figure 13). Estimated maximum 10-minute sustained wind speeds corresponding to Australian Cyclone Intensity scales (Table 1) allowed for an assessment of the accuracy of the wind speeds in the HJRA model. Overall, the simulated wind intensity agreed well with the observations and the horizontal structure was similar. In the absence of airborne observations that would have provided more input to the Holland model it appears that the HJRA wind fields were reliable. Higher temporal resolution would perhaps result in better water level predictions, but the lack of observational data available would mean that the wind and pressure fields would only be linear interpolates of what we have presented here. Still, a sensitivity study would be useful to determine if decreasing the timestep below 3 hours improved surge estimates. A comparison between the raw JRA55 and modified HJRA wind and pressure fields indicated that the HJRA was far superior to the raw reanalysis model which did not have the resolution to capture the dynamics of a tropical cyclone (Figure 14). This was true in both intensity and spatial structure (Figure 15,Figure 16,Figure 17).

Satellite scatterometer observations of wind speed and direction were available for two times when Yasi neared the coast. The satellite data were useful to validate that the spatial structure and intensity of the simulated winds were accurate (Figure 18), at least when the storm approached the coastline.

Table 1. Australian cyclone intensity equivalent wind speeds.

Category	Sustained wind (m s^{-1})	Strongest gust (m s^{-1})	Description
1	17-25	25-35	GALES
2	25-32	35-45	DESTRUCTIVE
3	33-43	45-62	VERY DESTRUCTIVE
4	44-54	62-77	VERY DESTRUCTIVE
5	>55	>78	VERY DESTRUCTIVE

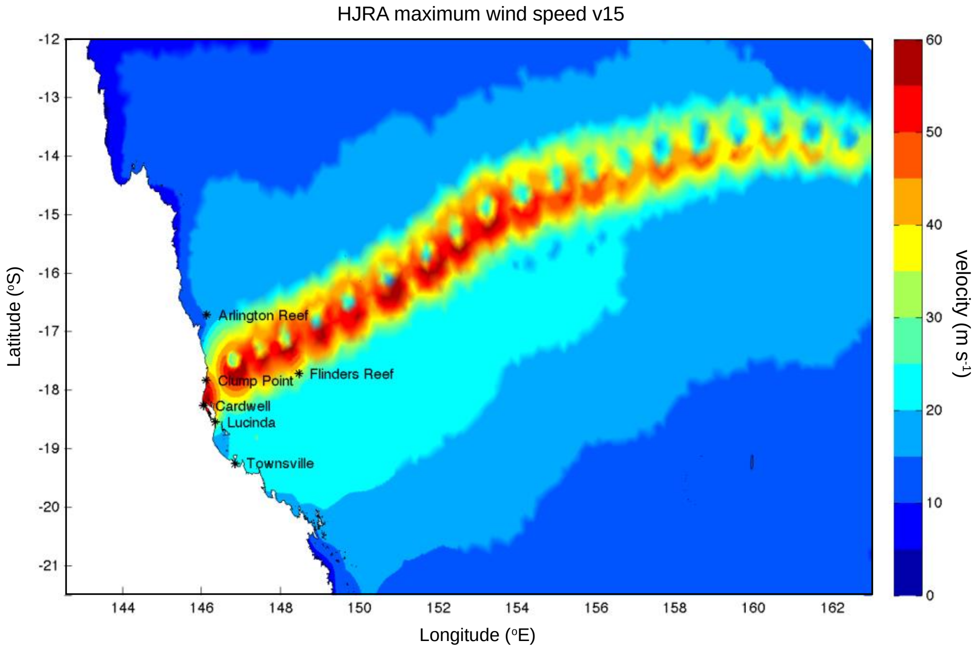

Figure 12. Wind swath map showing maximum surface winds for the HJRA model forcing that included a bogus cyclone vortex calculated with Holland (2010).

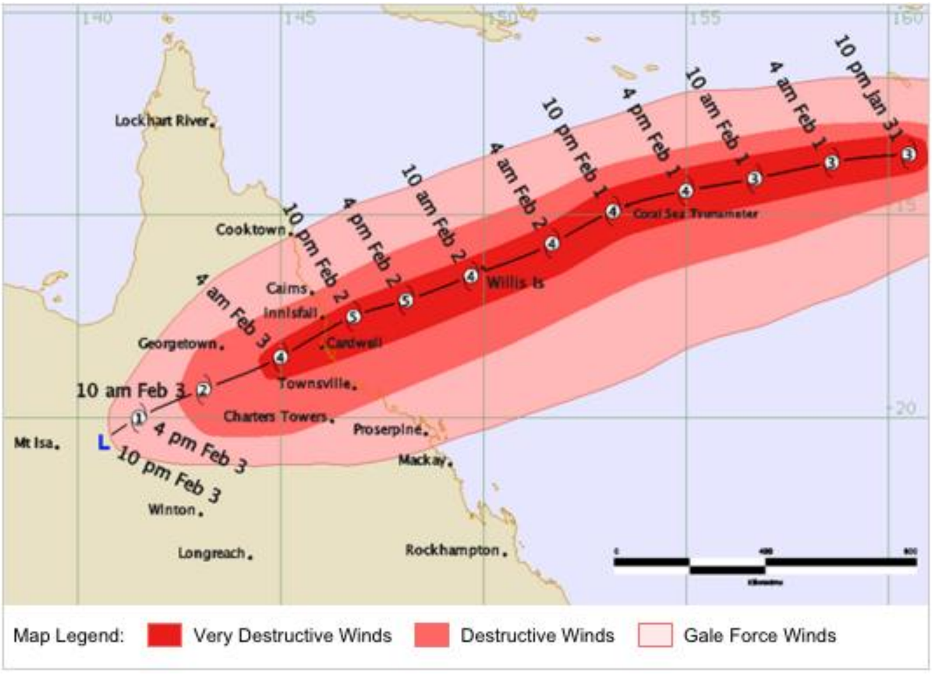

Figure 13. Track and intensity information (wind swath) for Cyclone Yasi as determined by the Australian Bureau of Meteorology.

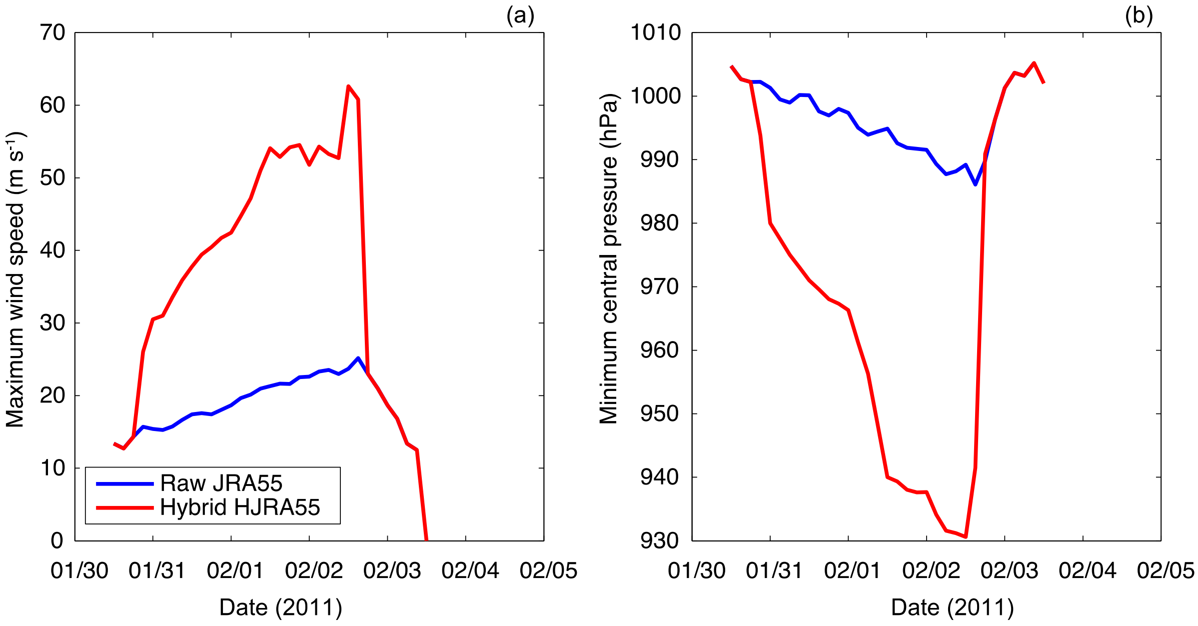

Figure 14. Comparison between raw JRA55 and hybrid Holland/JRA55 (HJRA) wind maximums and central pressure minimums.

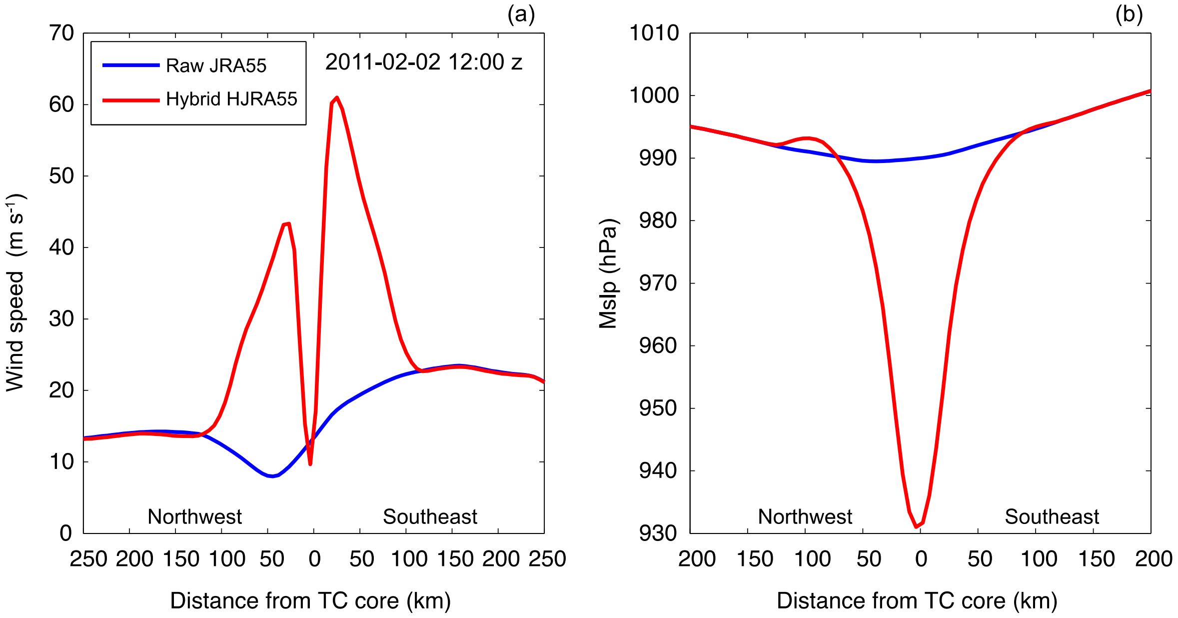

Figure 15. Simulated wind (a) and pressure (b) cross sections along a shore parallel transect across the core of TC Yasi at 12:00 (GMT) 02 February 2011 two hours before landfall comparing raw JRA55 and the bogus vortex HJRA model used to force the storm surge and wave models

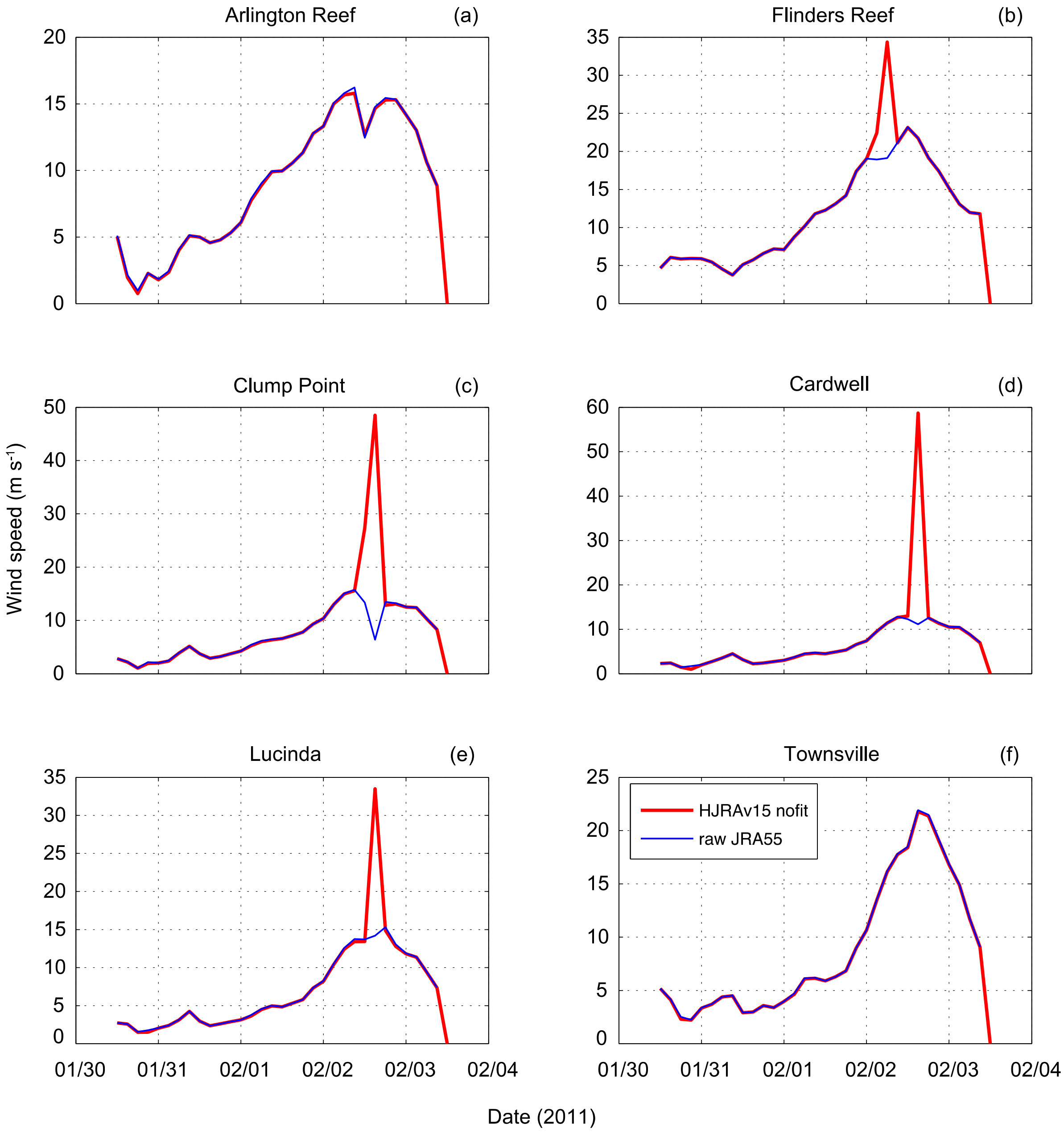

Figure 16. HJRA (red) and raw JRA55 (blue) model model winds for sites where peak observed winds were available for comparison (Observations not shown-see BOM report). Locations of sites shown in Figure 12.

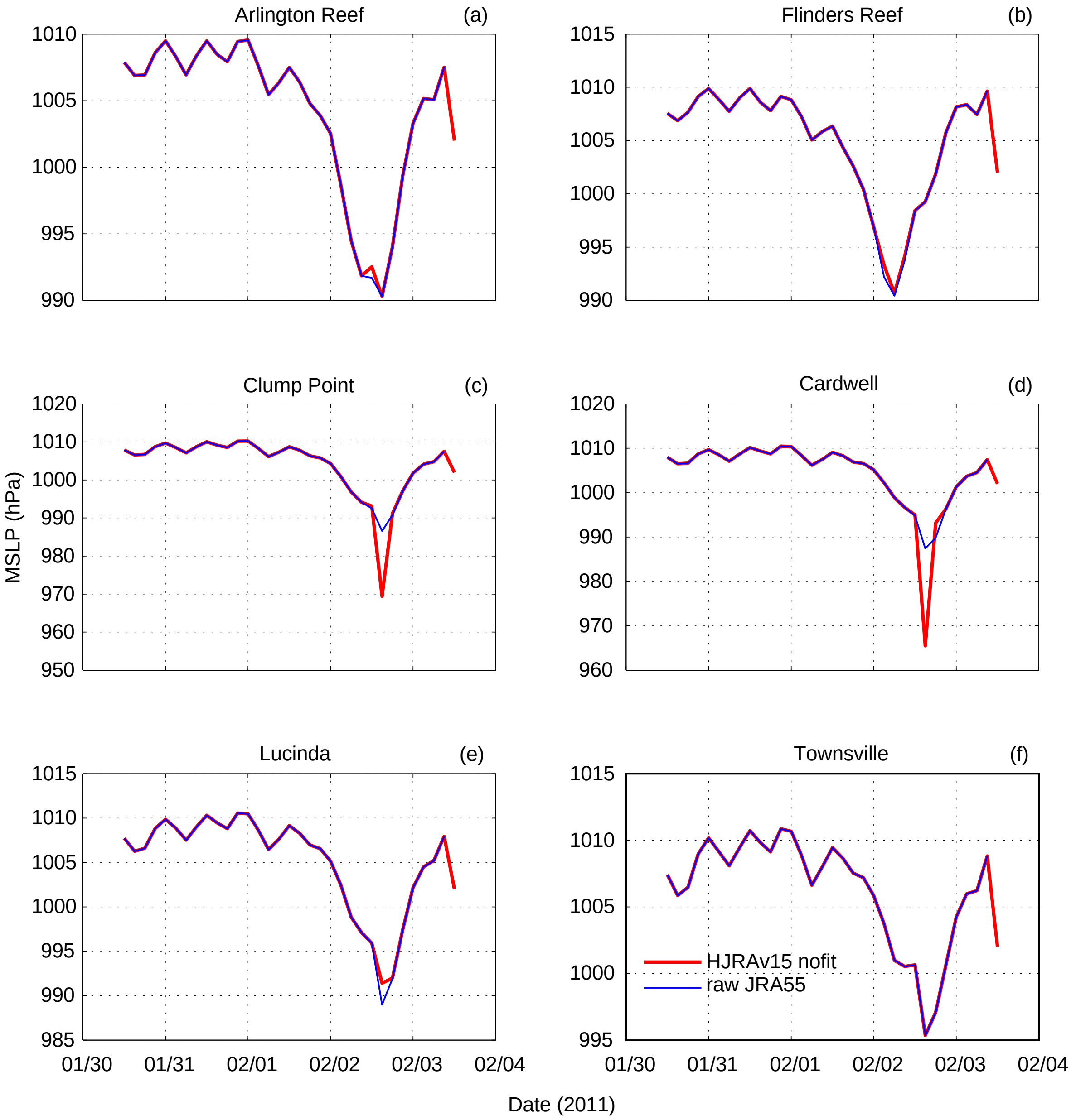

Figure 17. HJRA (red) and raw JRA55 (blue) model mean sea level pressure for sites where peak observed winds were available for comparison (Observations not shown- see BOM report). Locations of sites shown in Figure 12.

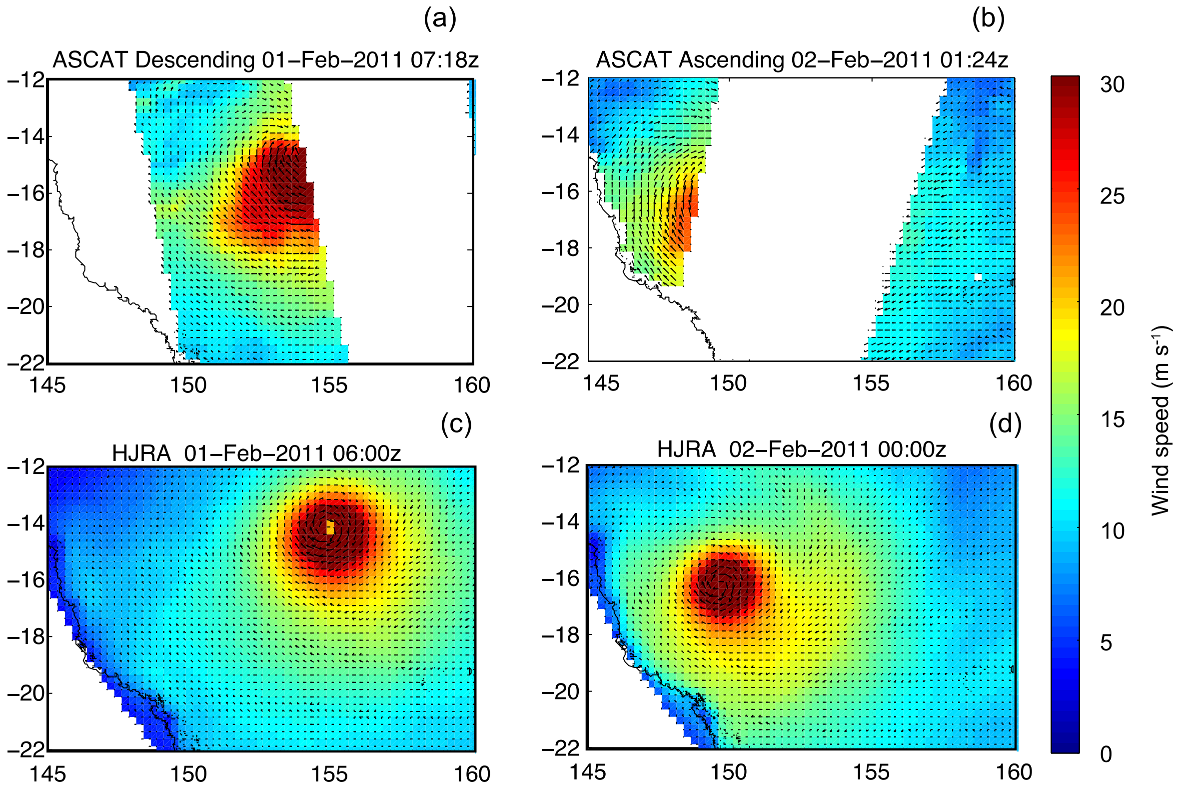

Figure 18. Comparison between ASCAT satellite scatterometer observed winds (a,b) closest in time to model forcing HJRA winds (b,c) for Cyclone Yasi. Note time and resulting storm location differences between model and observations.

Wave validation

The wave fields simulated in the WWMIII model using the HJRA wind forcing were compared against observations from a wave buoy and satellite observations of waves offshore. Accurate prediction of the wave field is therefore an indicator that the wind forcing was realistic, and gives confidence in our estimates of wave setup at the coast. The Townsville nearshore wave buoy did not capture the peak wave heights, however several overpasses of the satellite measured transects over the storm. This allowed for the verification of both the intensity and structure of the storm at approximately 12 hour intervals as the storm approached the coast (Figure 19). On 1 February at 12:00 the satellite measured wave heights of approximately 12 m near the core of the cyclone similar to the model. Equally important, the decrease of wave heights away from the cyclone core matched very well, particularly to the south of the core (Figure 19b). The model appeared to overpredict waves in the northern quadrant, however these waves were directed away from the Australian coastline and were likely related to the inability of the Holland model to capture cyclone asymmetry. Eleven hours later the south and east quadrants nearer to the coast again confirmed that the structure of the storm was close to reality (Figure 19c). Just before landfall wave heights of near 6 m were validated near the coast inshore of the Great Barrier Reef (Figure 19d).

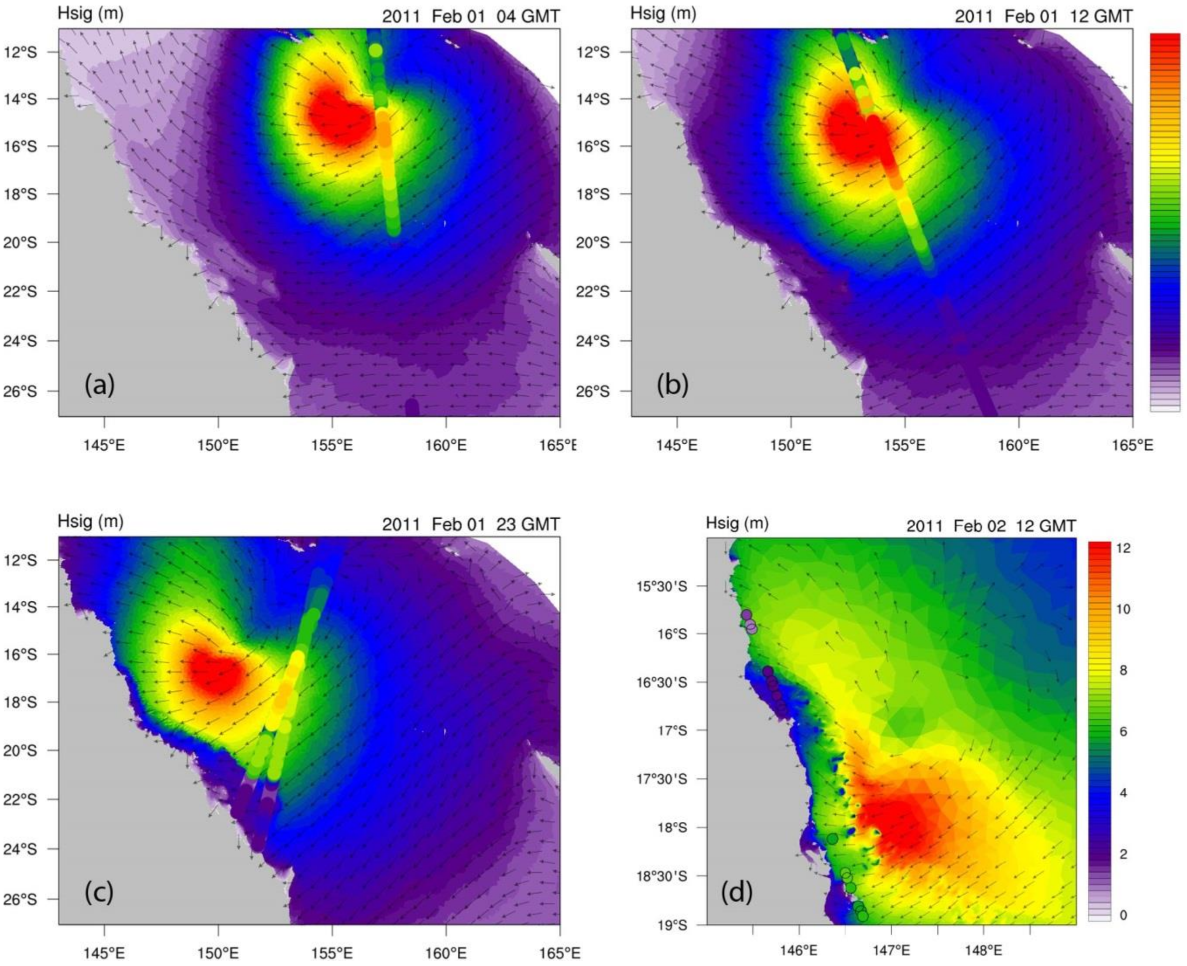

Figure 19. Modelled significant wave height (H_s) with satellite derived measurements of H_s within a two hour window plotted on top as coloured circles. A zoomed in view at 12 (GMT) on 2 February (d) shows a satellite pass over the nearshore region around Cardwell as Yasi made landfall.

Water level validation

Data from seven tide gauges near to the site where Yasi made landfall were available for validation. A tidal analysis was performed on a year of the 10-minute tide gauge data surrounding landfall of TC Yasi. The calculated constituents were then used to predict the tide for the time when the storm surge occurred. This predicted tide was then subtracted from the observed total water level and the result was the residual used for comparison against the simulated storm surge (Figure 20,Figure 21). A reasonable comparison was determined in amplitude and duration of the surge on average, with an excellent fit at Lucinda. The model somewhat overestimated the surge at Cardwell (to the south of landfall) whilst it underestimated the surge at Clump Point (to the north of landfall). These differences may be related to the local bathymetry where the tide gauge is located and/or the model bathymetry/resolution at those sites. Another possible explanation is a slight inaccuracy in the location where Yasi crossed the coast due to the 3-hourly model forcing, or inaccuracies in the model forcing.

TC Yasi sensitivity studies and final validation

Following the initial validation a series of simulations were undertaken to identify the largest sources of error for the storm surge simulations. These sensitivity tests included running the model for a range of forcing files along with correction of several bathymetric errors near validation sites. Forcing included the following scenarios for both coupled and uncoupled runs.

1. Coupled pure Holland 2010 at 1hr intervals (H101hr)
2. Coupled pure Holland 2010 at 3hr intervals (H103hr)
3. Coupled raw JRA55 (raw JRA55)
4. Un-coupled merged JRA55 - Holland 2010 at 3hr intervals (HJRA3hr)
5. Coupled merged JRA55 - Holland 2010 at 3hr intervals (HJRA3hr)
6. Coupled merged JRA55 - Holland 2010 at 3hr intervals, modified at landfall x1.1 (HJRA3hr1x1)

The dominant sources of error were due to two factors: 1) Time step resolution 2) Underestimation of intensity in the outer regions. The surge model was most sensitive to changes in the time resolution in the model, especially near the core. In general higher surges were generated by 1 hour model forcing as compared to 3 hour (Figure 20; red vs. blue) and 1 hour forcing was preferred near the cyclone core. A major limitation here was that hourly forcing required a pure Holland parametric model as hourly atmospheric reanalysis model data were not available for merging. The pure Holland approach at high temporal resolution therefore did not have realistic forcing far from the core so water levels at distant sites were underestimated and the duration of the surge was underestimated at all sites, particularly after landfall (Figure 21; blue line). Clump Point, located only several kilometres north of where Yasi made landfall showed the poorest model performance, as this site was most sensitive to: inaccuracies in track data, underestimation of intensity (both in pressure and wind speed) due to the coarse time stepping and interpolation, errors in wind direction due to both time stepping and asymmetry of the storm. In contrast, at Cardwell in the region of maximum winds, the model performed exceptionally well.

The merged HJRA forcing at 3-hourly resolution was deemed to be the best compromise for all sites, resulting in highly accurate simulated peak water levels near the core of the storm at Cardwell and also reasonably accurate water levels in the outer regions around Townsville (Figure 21). The best results were obtained with forcing that included a slight upward adjustment of winds in the eyewall by 10% to account for the coarse time resolution of the HJRA model. The model simulated the storm surge at Cardwell within 3%, only overestimating the 5.31 m surge by 14 cm. A smaller adjustment to wind speeds (~5%) would have resulted in even more accurate water levels at Cardwell, but would have decreased the model skill at Clump Point and Lucinda; therefore the (HJRA3hr1x1) forcing was deemed to be the best compromise with the model skill ranging between 0.78 and 0.97 in regions where tide gauge data were available.

In general, the coupled model performed better than the un-coupled model with higher simulated water levels due to the effects of waves (wave setup). In most cases, the coupled simulations improved model skill by 5-10%.

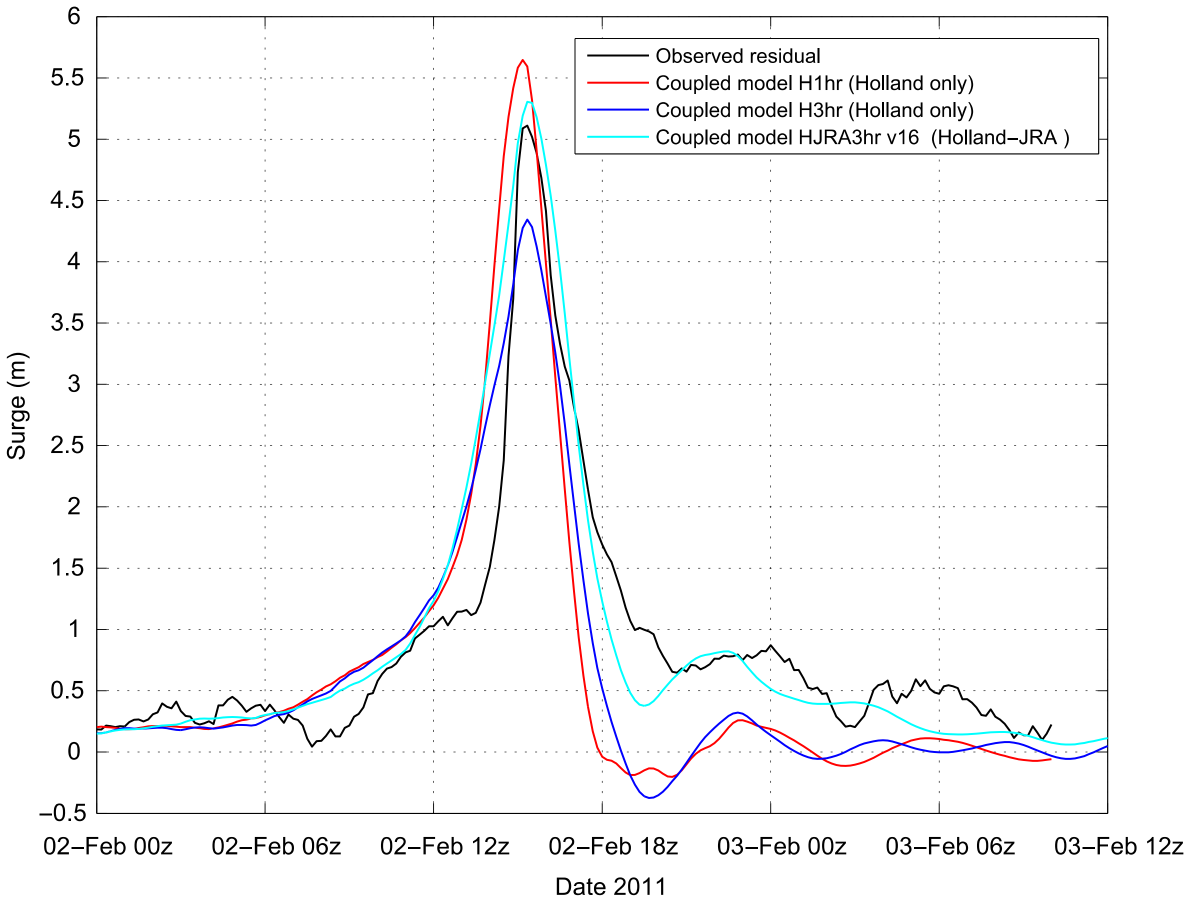

Figure 20. Simulated water levels at Cardwell for TC Yasi for three model runs plotted against the observed tidal residual.

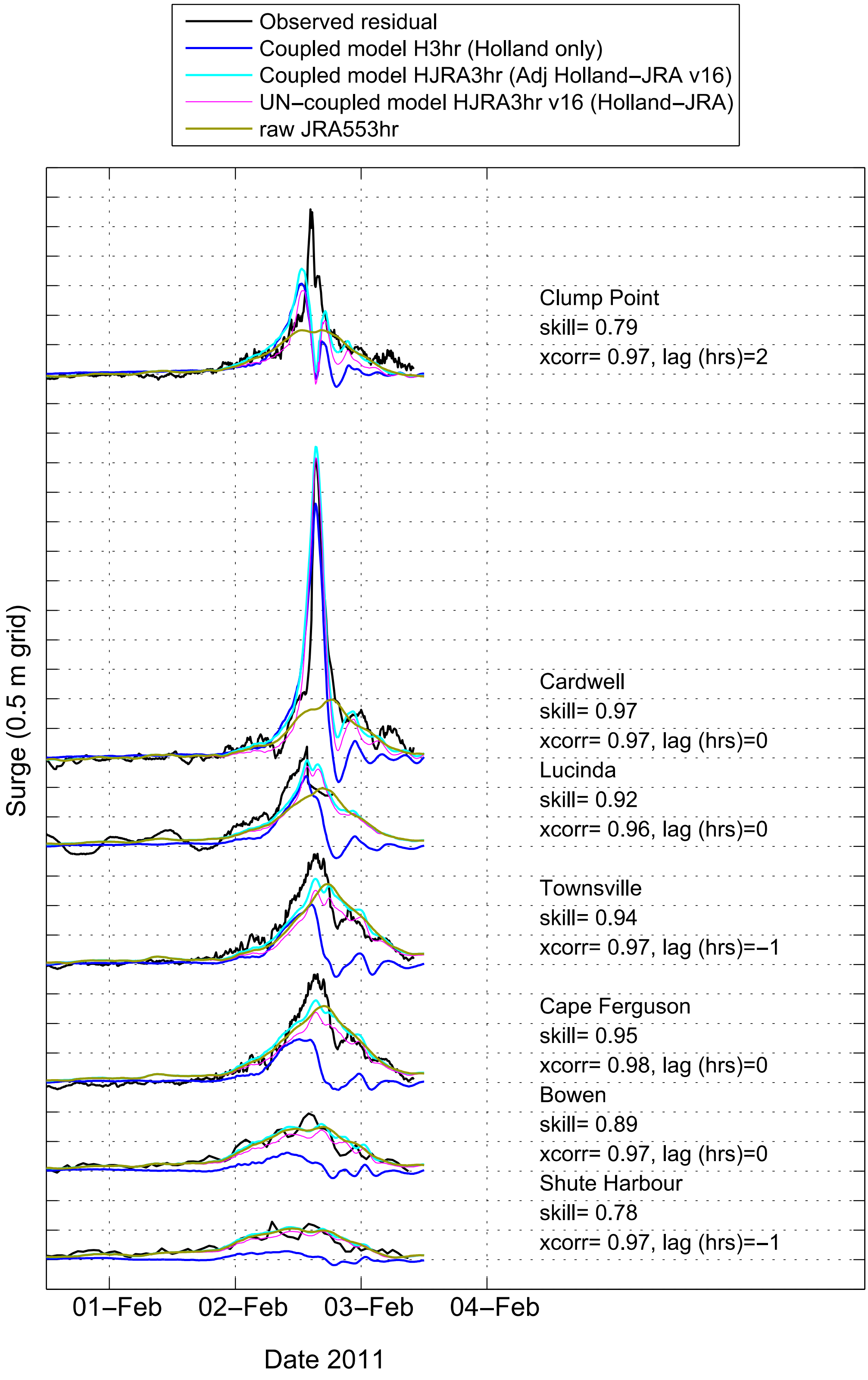

Figure 21. Simulated water levels at Queensland tide gauge sites for TC Yasi for four model runs plotted against the observed tidal residual. Willmott model skill, maximum correlation, and lag shown for the best model run (HJRAv16 coupled, cyan).

TROPICAL CYCLONE GEORGE – WESTERN AUSTRALIA, 2007

Hybrid Holland-JRA55 (HJRA) atmospheric forcing

Validation and tuning of the model for Tropical Cyclone George in Western Australia are in progress. Preliminary validation plots are shown below, and only very briefly described here. The maximum winds simulated and used to force the coupled wave-surge model matched relatively well with observations, however the simulated wind field appeared to somewhat underestimate the intensity of the storm in the outer regions (Figure 22).

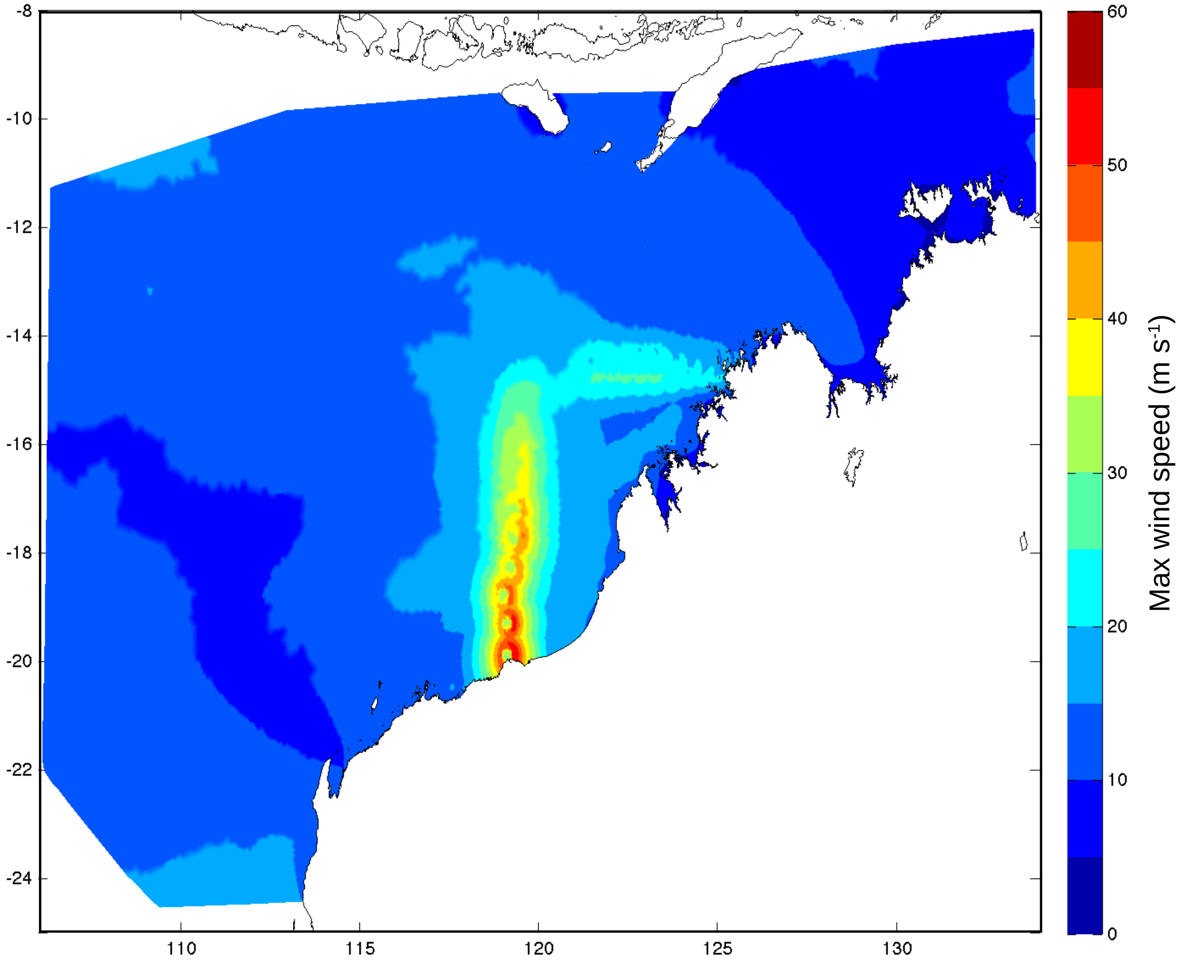

Figure 22. Simulated wind swath for TC George on the Pilbara coast of WA calculated as the maximum wind for each model timestep. The 3-hourly forcing resulted in the discontinuous appearance, particularly near the cyclone core.

As was the case with Yasi, the HJRA merged parametric wind fields were a much closer fit to reality compared with the raw JRA55, which was unable to simulate the dynamics of the tropical cyclone due to resolution constraints (Figure 23).

In 2007, the Quikscat scatterometer (1999-2009) instrument was still in operation and provided superior coverage compared to the later ASCAT instrument that was used to validate the wind fields for TC Yasi. Two days leading up to landfall for TC George had good satellite data available with both ascending and descending passes. The comparison between the simulated winds and observations showed that the simulated peak intensity was reasonable but that the medium intensity winds did not radiate far enough from the TC core where observations were available , both further offshore (Figure 24) and nearer to the coast (Figure 25). This suggests that the storm width was slightly broader than what was simulated, however this is a parameter that can be adjusted and refinements of the forcing are in progress. Nearer to where the storm made landfall the comparisons are much better with a close fit between observed maximum wind intensity and timing (Figure 26). This is more important for simulating the extreme storm surges that occur close to the eye of the storm.

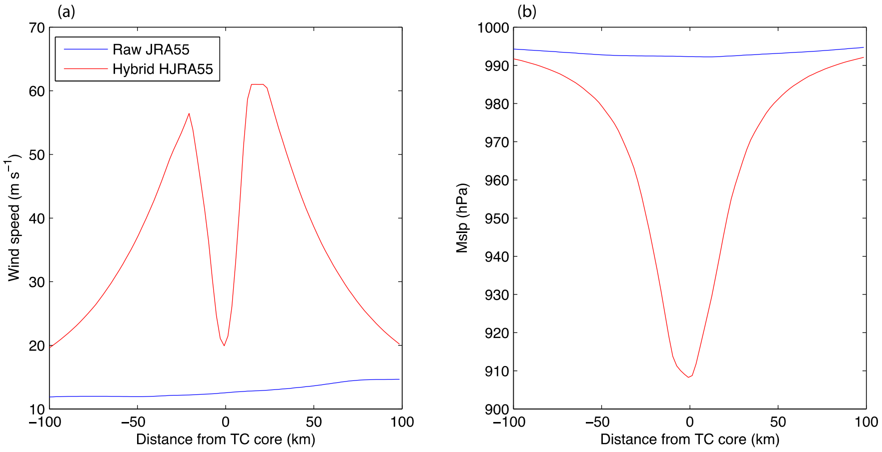

Figure 23. Shore parallel cross sections of simulated wind speed (a) and MSLP for TC George just before landfall 2007-03-08 06:00 z. The red lines represent the Holland –derived wind and pressure forcing used to force the coupled wave-surge model. The blue line is the unmodified JRA55 reanalysis model fields shown to illustrate the poor representation the tropical cyclone in the reanalysis model.

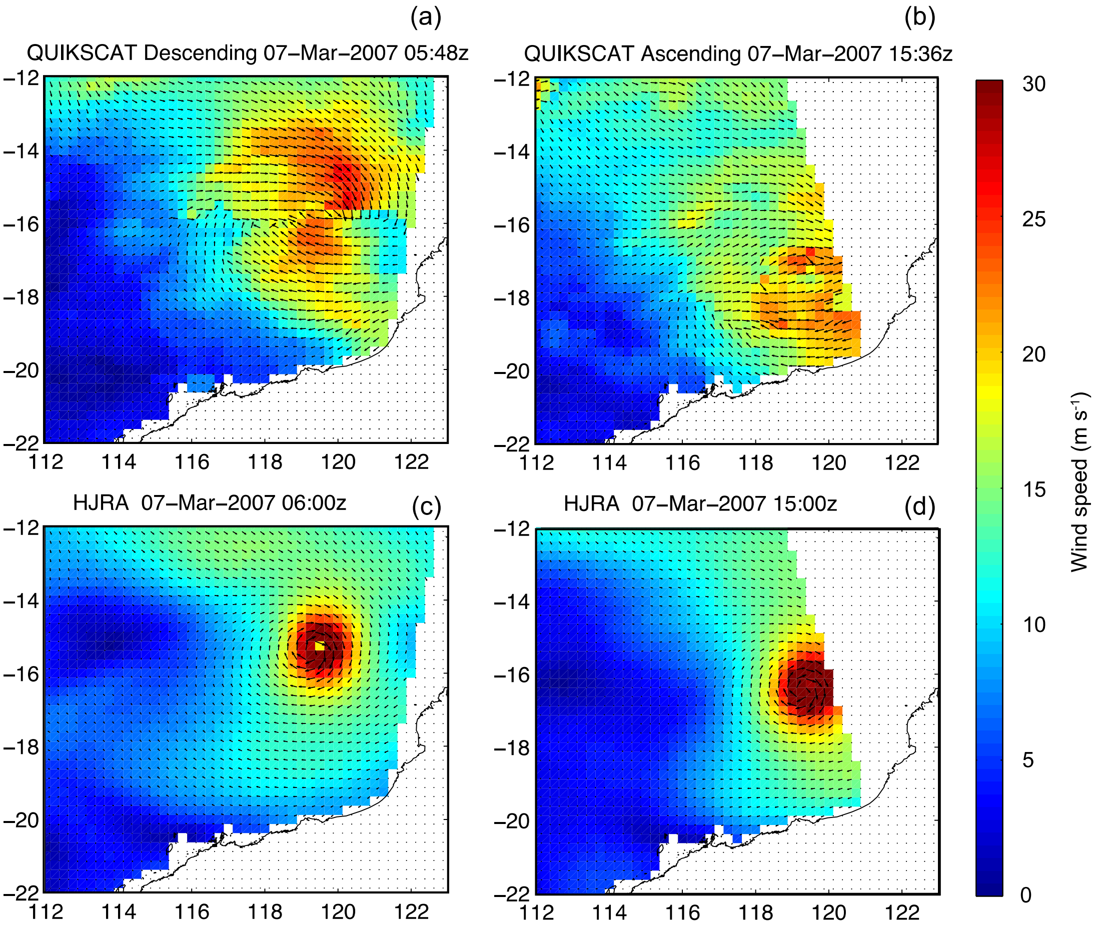

Figure 24. Comparison between QUIKSCAT satellite scatterometer observed winds (a,b) closest in time to model forcing HJRA winds (b,c) for Cyclone George on 07 March 2007 (GMT). Note time and resulting storm location differences between model and observations.

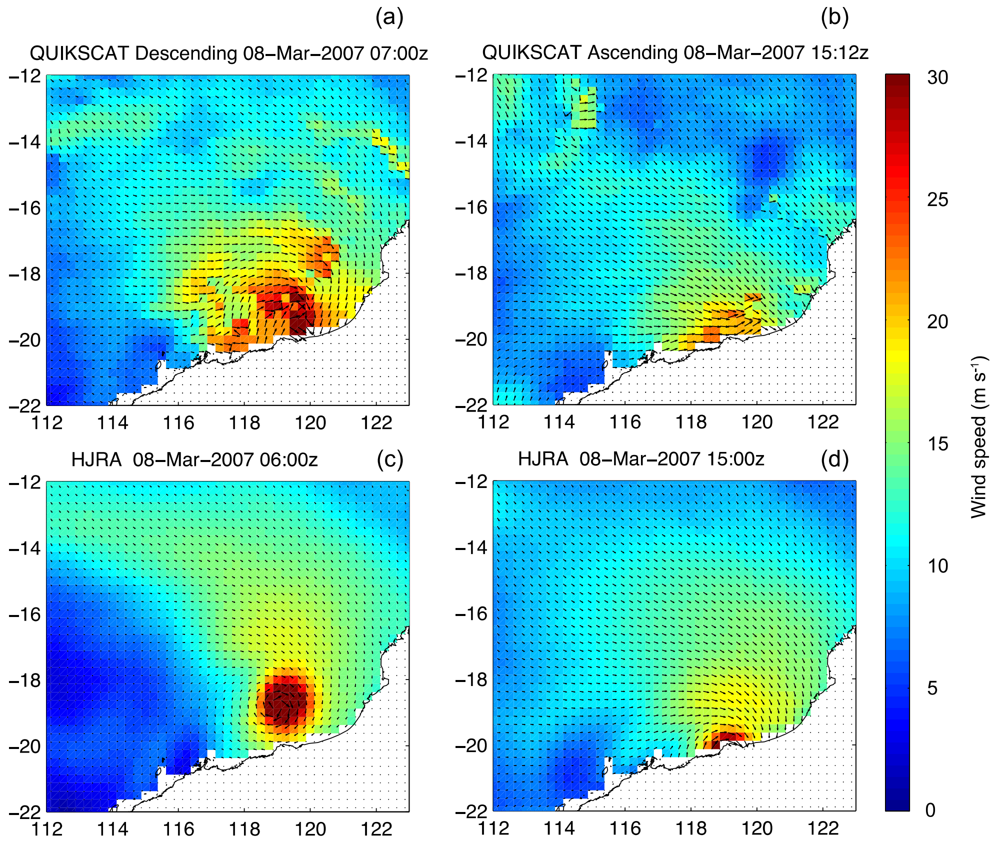

Figure 25. Comparison between QUIKSCAT satellite scatterometer observed winds (a,b) closest in time to model forcing HJRA winds (b,c) for Cyclone George on 08 March 2007 (GMT). Note time and resulting storm location differences between model and observations. Same as previous figure but for 09 March 2007.

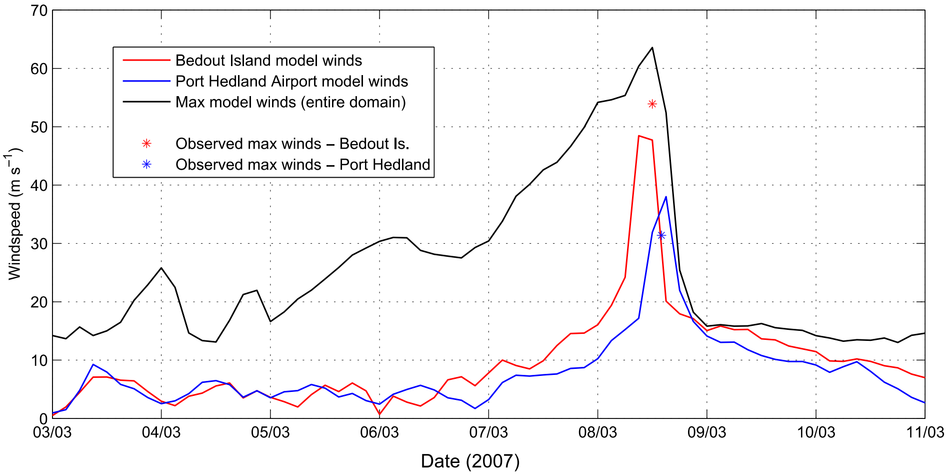

Figure 26. Time series of HJRA simulated wind at Bedout Island and Port Hedland airport for TC George shown in red and blue lines. Corresponding observed maximum wind speeds and times are shown with asterisks. Maximum model wind speed over entire domain, for each timestep are shown with a black line.

Wave validation

The wave validation for TC George is difficult due to a lack of available data. Only one satellite overpass was available and this did not pass through the core of the storm (Figure 27). Offshore, simulated wave heights exceeded 15 m (Figure 27) and at landfall the simulated waves were on the order of 10 m (Figure 28). Although wave buoy data likely exist in the region they are not publicly available as they are collected privately by the offshore oil and gas industry. For this reason, the wave validation is limited. This is not of great concern for the focus is not to exactly simulate reality but to investigate the dynamics of wave setup along this coast.

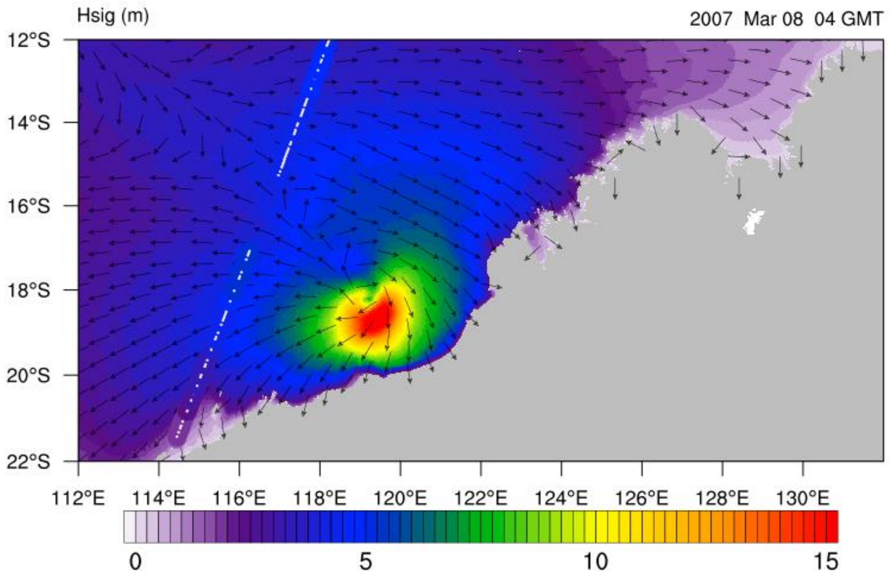

Figure 27. Simulated significant wave height for TC George with JASON satellite observed wave heights plotted as circles on top with centre points of observations shown as whit dots. Unfortunately there were no satellite overpasses that passed directly over the storm.

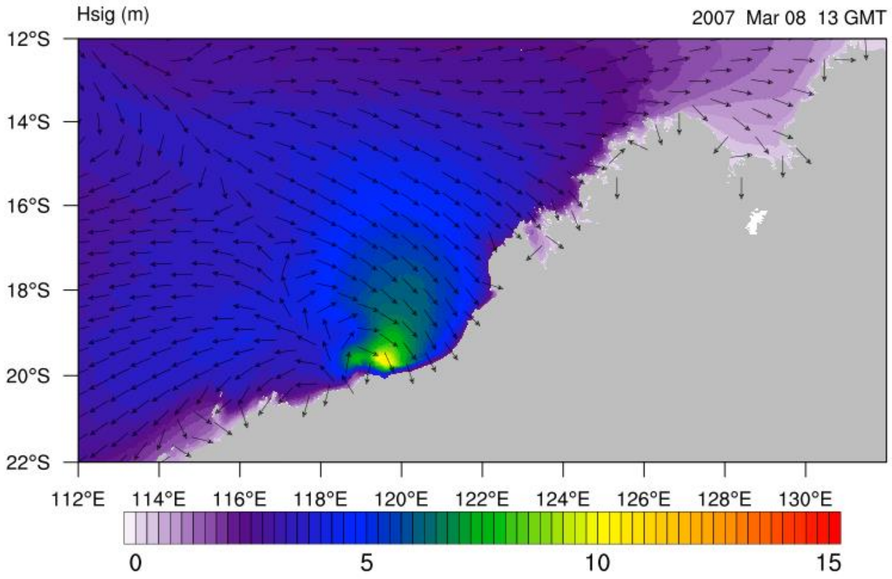

Figure 28. Simulated significant wave height for TC George at the time George made landfall. Unfortunately there were no JASON satellite data over the storm as at this time.

Water level validation

Validation of the storm surge is in progress and further validation requires more tide gauge data that have been requested. The storm surge had a range from -2 to ~4 m in the region (Figure 29,Figure 30). High water occurred to the east of the storm and low water to the west of the storm due to offshore winds as confirmed by the limited tide gauge data and model results (Figure 31). Other water level oscillations in the form of edge waves and continental shelf waves were observed in the model and tide gauge data to the east and west of Port Hedland after TC George crossed the coast (Figure 31).

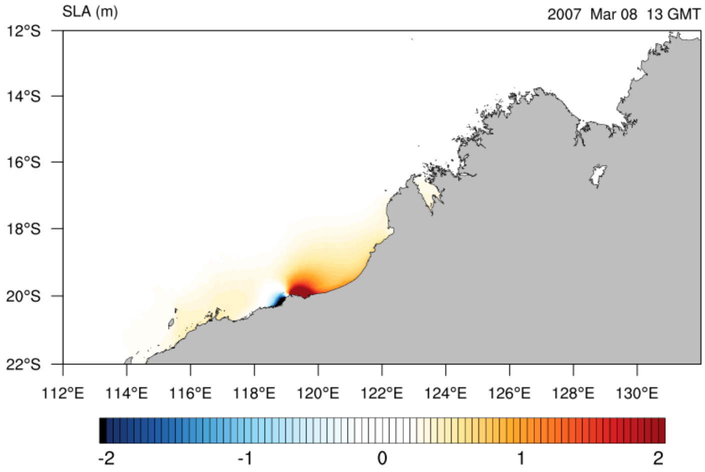

Figure 29. Simulated water levels at time of TC George crossing the coast east of Port Hedland showing high water levels (red) to the east of the storm and low (blue) water levels to the west of the storm due to strong offshore winds.

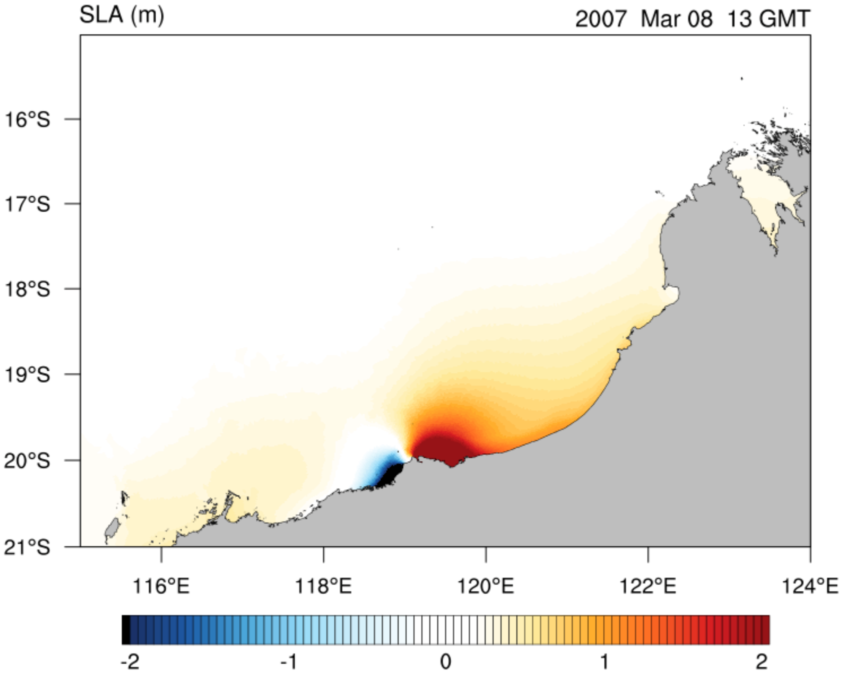

Figure 30. Same as previous figure with closer zoom. Simulated water levels at time of TC George crossing the coast east of Port Hedland showing high water levels (red) to the east of the storm and low (blue) water levels to the west of the storm due to strong offshore winds.

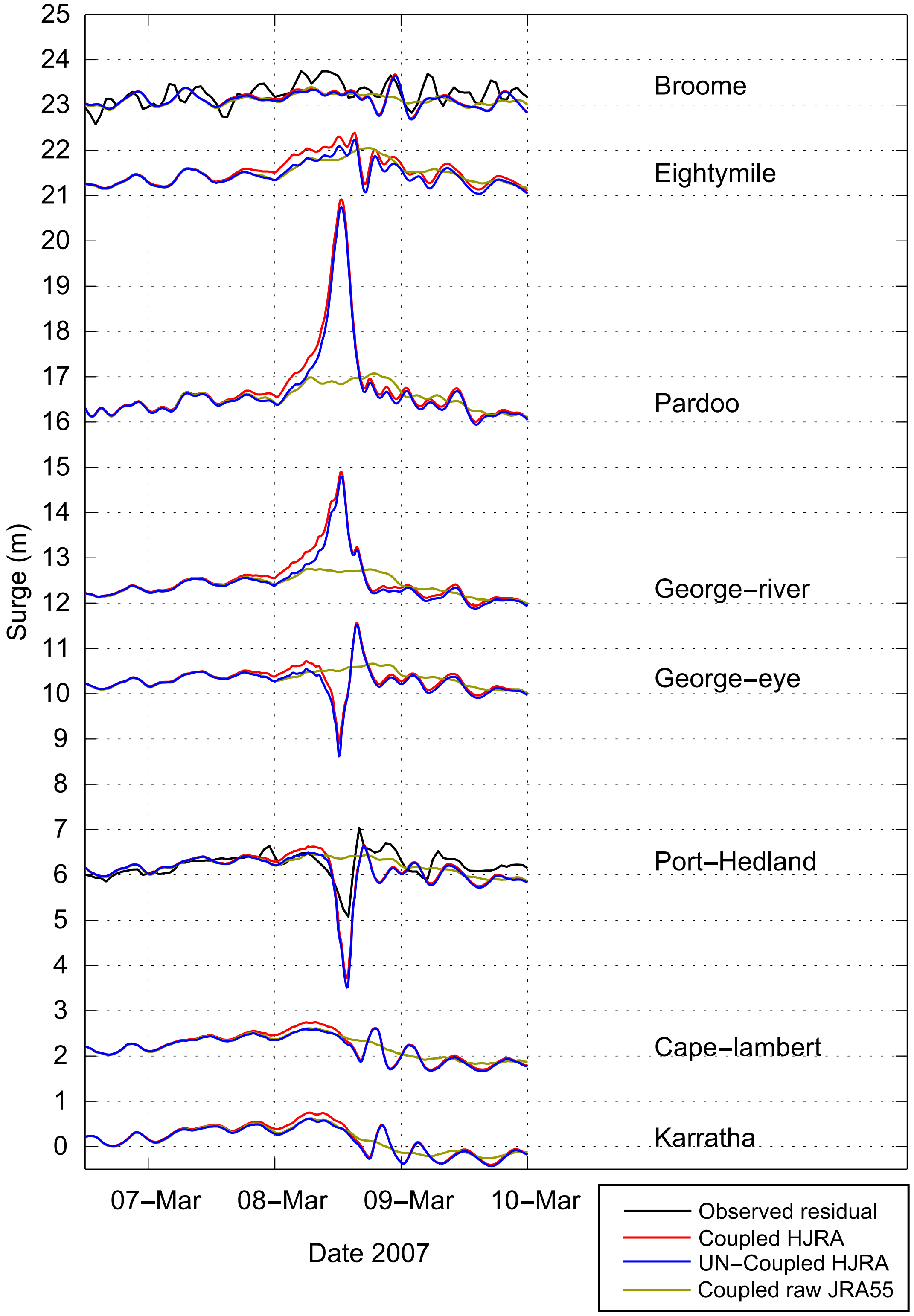

Figure 31. Observed (where available) residual vs. simulated water levels at various sites from Exmouth in the west to Broome in the east. Tide gauge residuals shown in black; uncoupled model results in blue and coupled model results in red.

CONTINENTAL SHELF WAVES

Cyclone Bianca

Cyclone Bianca developed to the west of Darwin between 21-25 January 2011 and paralleled the coast before moving offshore near Exmouth and intensifying into a Category 4 Cyclone as it recurved to the south, offshore of Carnarvon (Figure 32)[16]. Bianca was forecast to impact Perth with tropical cyclone intensity arriving at local high tide and coinciding with the passage of a continental shelf wave generated by the storm several days earlier. Hours before landfall Bianca weakened dramatically but high water levels at Perth still caused some minor flooding and large waves eroded local beaches (http://en.wikipedia.org/wiki/2010%E2%80%9311_Australian_region_cyclone_season#Severe_Tropical_Cyclone_Bianca).

The clearly defined CSW generated by Bianca (Figure 33) and availability of observations and atmospheric model data for this cyclone made it an ideal test case to investigate the ability of numerical models to simulate CSWs. The contribution from the Bianca CSW would have combined with high tides and a local storm surge to result in flooding of Perth’s underground railway if the storm had not lost strength before landfall. This highlights a benefit of simulating CSW dynamics in storm surge models.

Wind and pressure fields at from the ECMWF ERA-Interim reanalysis [10] are available from 1979-present and were used to force both hydrodynamic models. Global reanalysis models typically underestimate the strength of tropical cyclones, but the ECMWF ERA-I data are among the best available [12]. The 3-hourly and 80km resolution forcing was found to be sufficient to create a shelf wave of reasonable amplitude in the case of cyclone Bianca in Western Australia.

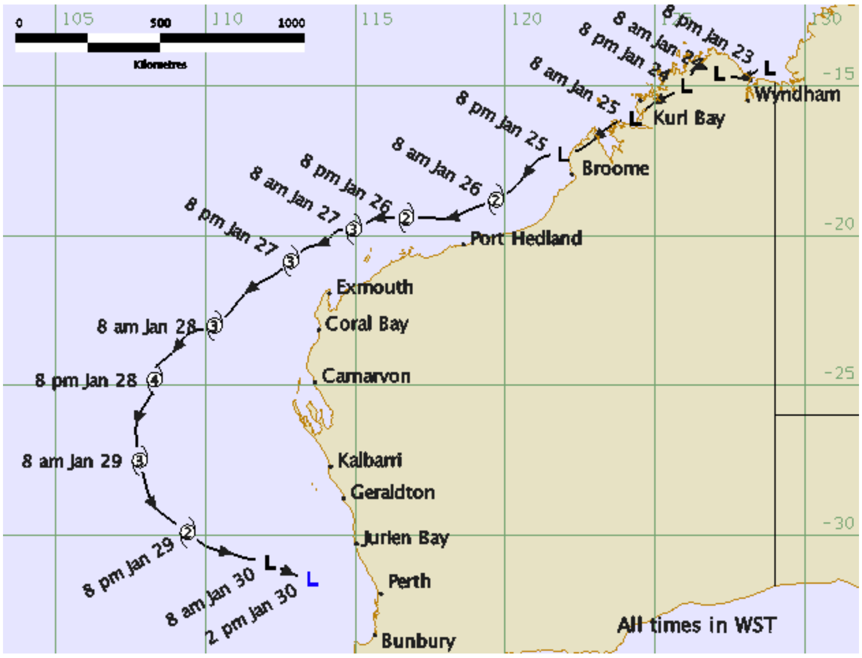

Figure 32. Track and intensity of Tropical Cyclone Bianca (2011). Data: Australian Bureau of Meteorology

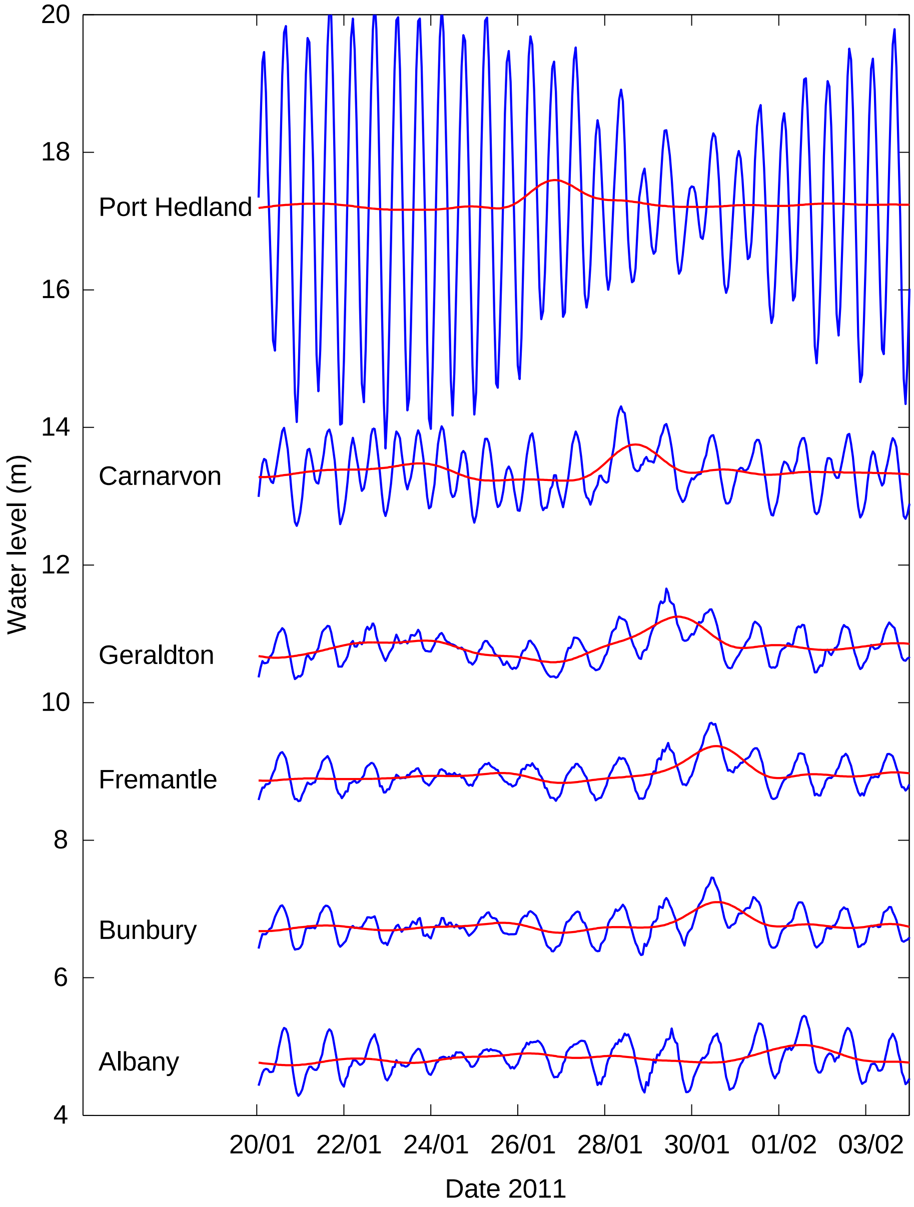

Figure 33. Observed water levels from tidal stations around Western Australia coinciding with the passage of tropical cyclone Bianca and the resultant CSW in January/February 2011. Blue lines represent hourly unfiltered water levels and red lines show water levels that have been lowpass filtered with a 38 hour Lanczos filter to remove the tides. Time given as GMT (local time is GMT+8).

SELFE/SCHISM Model results

The unstructured triangular grid allows the model to change resolution from coarse resolution in the open ocean (kilometres scale) to very fine resolution along the coast (metres scale) without the need for nesting of sub grids. This means that the SELFE model can be used to undertake long term simulations at high resolution for very large domains as is required to calculate extreme water level statistics around Australia. Multiple simulations were undertaken using two unstructured triangular mesh grids: one refined to maximise resolution near the coast (up to ~100 m) and a second that was created to 're-create' the curvilinear ROMS grid as a triangular mesh in order to directly compare grid points between the model (up to approx. 2 km resolution). In the vertical on the shelf the model contained 37 sigma layers.

The challenge investigated here is whether the SELFE model numerics and unstructured grid are able to accurately simulate the generation and propagation of continental shelf waves along the coast. Initial model runs indicated that SELFE was able to create a CSW, although the CSW dissipated quickly south of Carnarvon (Figure 34).

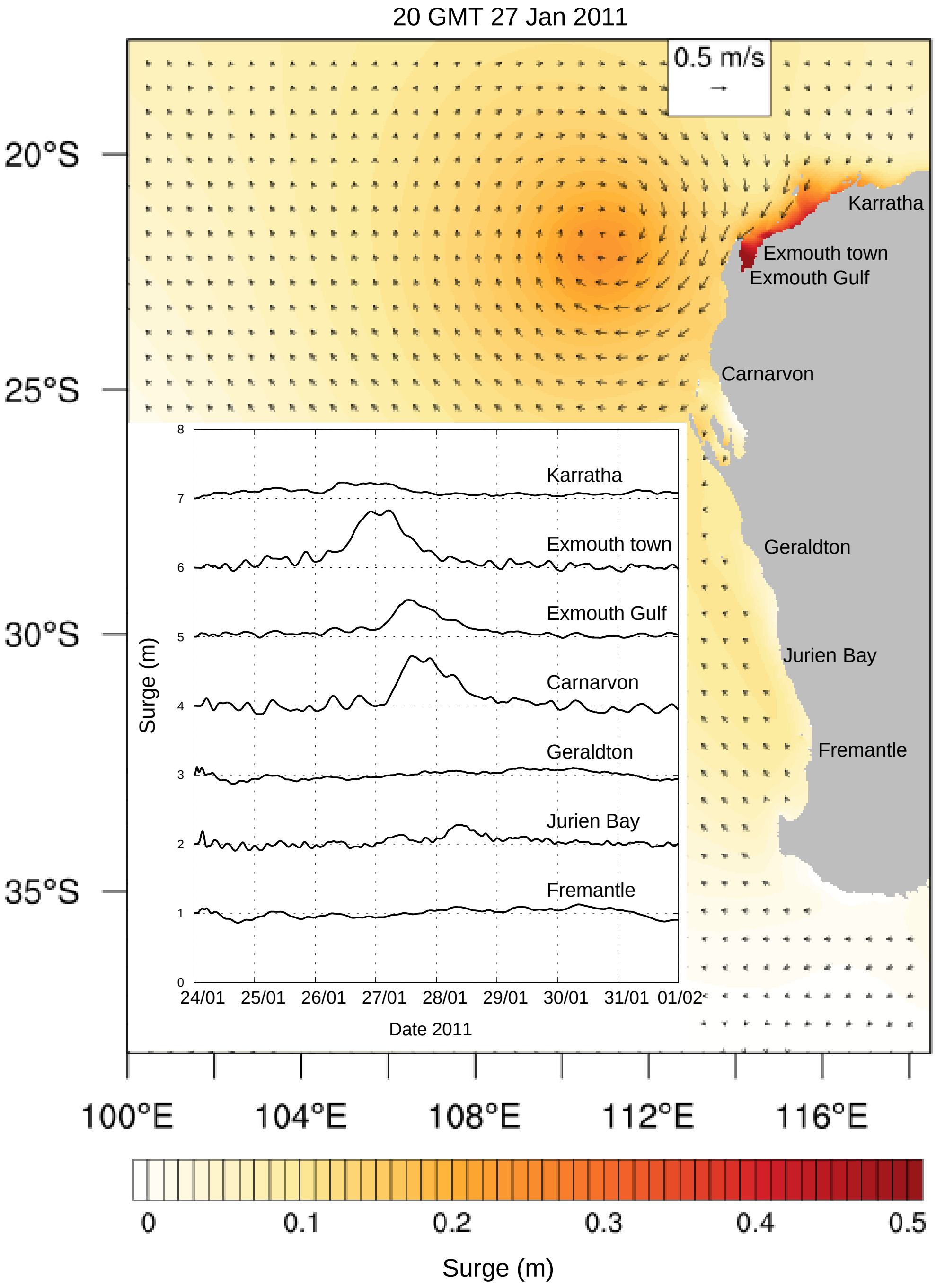

Figure 34. Simulated water levels from SELFE model run for Bianca (2011). Colour represents the water level (no tides) with arrows showing water transport direction. The inset shows time series of the surge at the stations indicated on the map.

ROMS baroclinic model results

The Regional Ocean Modeling System (ROMS) is a free-surface, hydrostatic, primitive equation ocean model (http://www.myroms.org) [17]. ROMS has been widely used in a variety of contexts to simulate the ocean environment at local to regional levels and is particularly well-suited for including density effects. The advanced numerics and sigma terrain following vertical coordinate system make ROMS an appropriate tool to simulate CSWs, and the purpose here was to compare with the SELFE/SCHISM model results.

For this application the ROMS model was also forced with ERA-interim wind and pressure fields, although the wind stress was computed from 10-m winds externally to exactly match the forcing applied to the SELFE model. The 960x960 curvilinear grid covered the entire Western Australian coast between 110 and 127 °E and -39 and -16 °S with 25 vertical sigma layers and a horizontal resolution ranging from 2.5-7 km.

Initial results indicated that ROMS also simulated the shelf wave created by Bianca (Figure 35). The CSW propagated along the coast from Port Hedland in the north to Albany in the south over a period of approximately 5 days (Figure 36) with higher amplitude, less dissipation, and further propagation compared with the SELFE simulation.

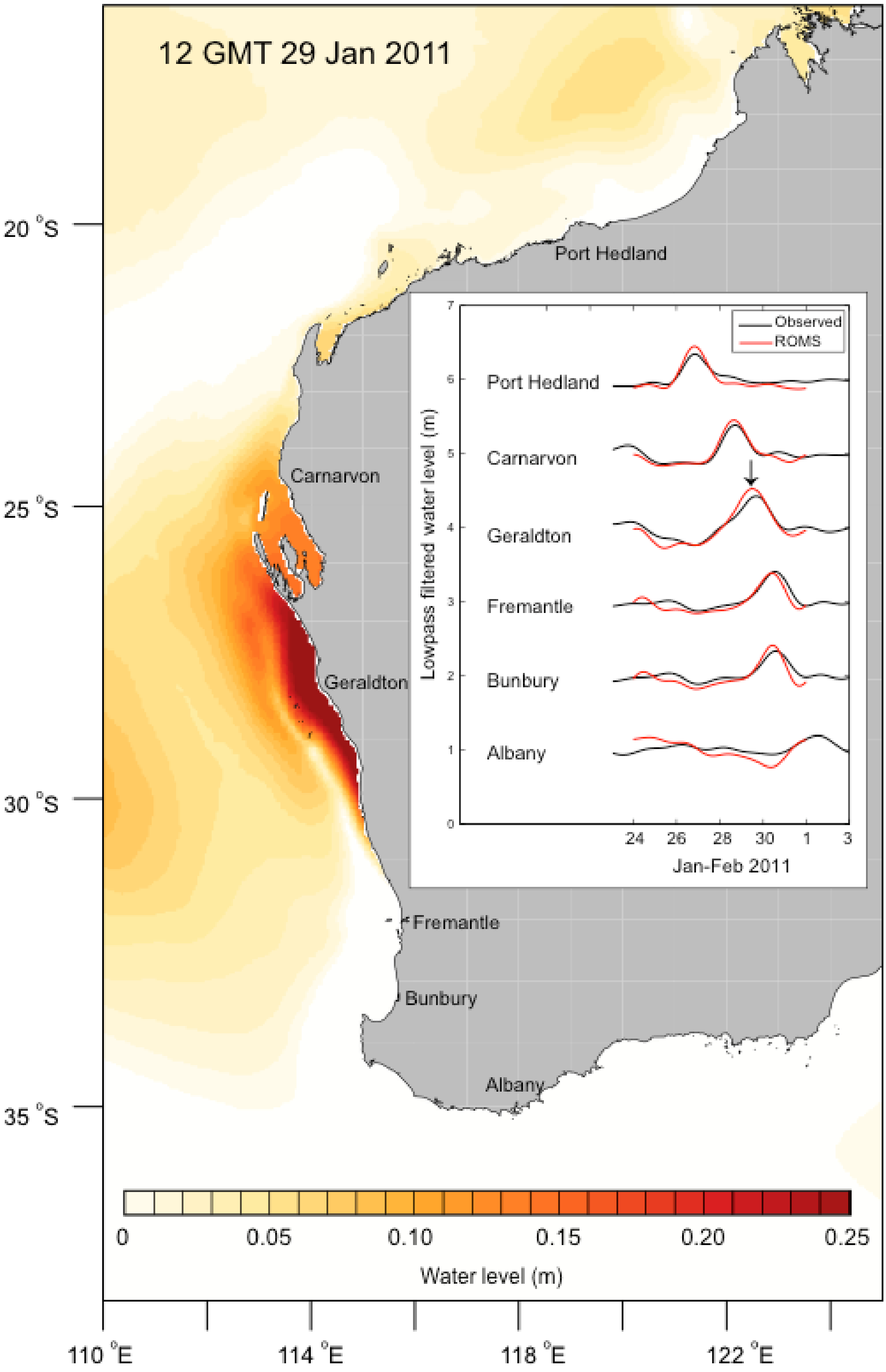

Figure 35. Simulated water levels from ROMS model run for Bianca (2011). Colour represents the water level (no tides). Inset shows time series of water levels at selected sites along the coast with the arrow marking the time and place of the water levels shown in the map.

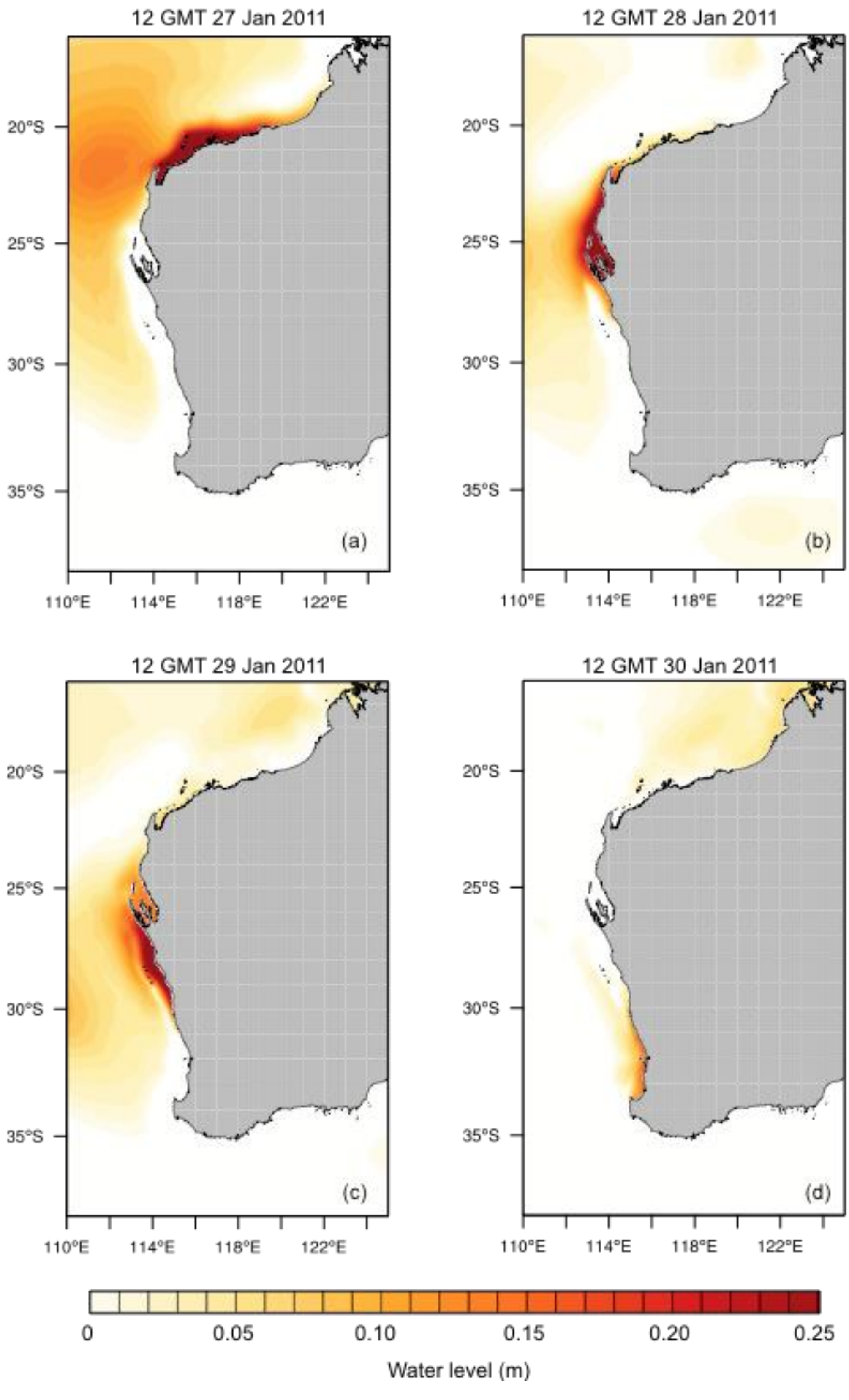

Figure 36. Simulated water levels from ROMS model run for Bianca (2011) over four days (a-d). Colour represents the water level (no tides).

While both models were able to re-create the CSW the ROMS simulation more closely matched observations, particularly as the CSW propagated south of Carnarvon/Shark Bay. This result indicated that to properly resolve shelf waves traveling around the coast it is necessary to use a full three-dimensional baroclinic model that includes density effects. It appeared that the energy of the continental shelf waves dissipated too quickly in regions of with varying bathymetry unless allowed to transform into other modes that required vertical density stratification to propagate. This result would likely repeat itself around the coastline at specific locations and these results will inform what is the best approach for modelling storm surges where shelf waves are important.

EXTRATROPICAL STORM SURGES

Initial model runs for extratropical storm surges focussed on a series of winter storms that impacted the southern margin of the continent during a six week period in June-July 2007, causing near record surges in South Australia, and very large waves. The initial validation focussed on the surge-only simulations and the sensitivity of the model to bathymetry in the Great Australian Bight where limited data are available. Further validation and model tuning are in progress.

Western and South Australia –July 2007

The two main storm systems causing the biggest surges in WA and SA occurred in the first days of July with a series of cold fronts and strong onshore winds (Figure 37). The resulting storm surges during 1-4 July 2007 were greatest along the bays of the southwest WA and South Australia coasts (Figure 38). IN WA surges reached near 0.6m and in the South Australian Gulfs water levels up to 0.9 m were simulated (Figure 38). The timing, duration, and amplitude of peak surges were reasonably close to observed residual water levels, except for several stations along the south coast where questionable bathymetric data exist and propagating continental shelf waves (CSWs) are thought to contribute significantly to surge levels (Figure 39). For this reason, adjustmenst to the bathymetry in the Bight made significant improvements to the simulated surge at Thevenard, SA (Figure 39; red vs. blue lines). Ongoing model development and validation is focussing on improving the predictions in tehse areas as well as including wave setup effects with the coupled model.

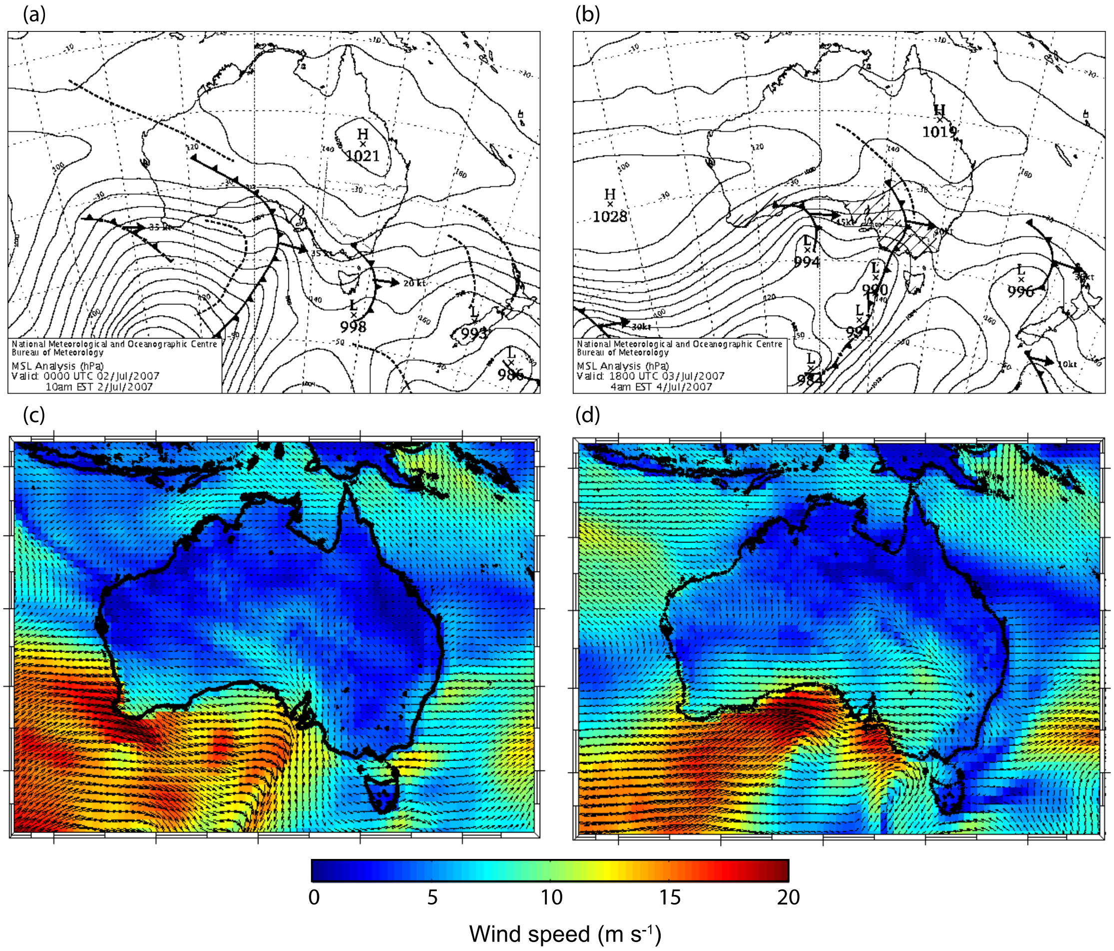

Figure 37. BOM Synoptic charts (a,b) and corresponding wind speed (c,d) from the ECMWF ERA-I model for a series of winter 2007 extratropical storms and cold fronts that were simulated in the storm surge model.

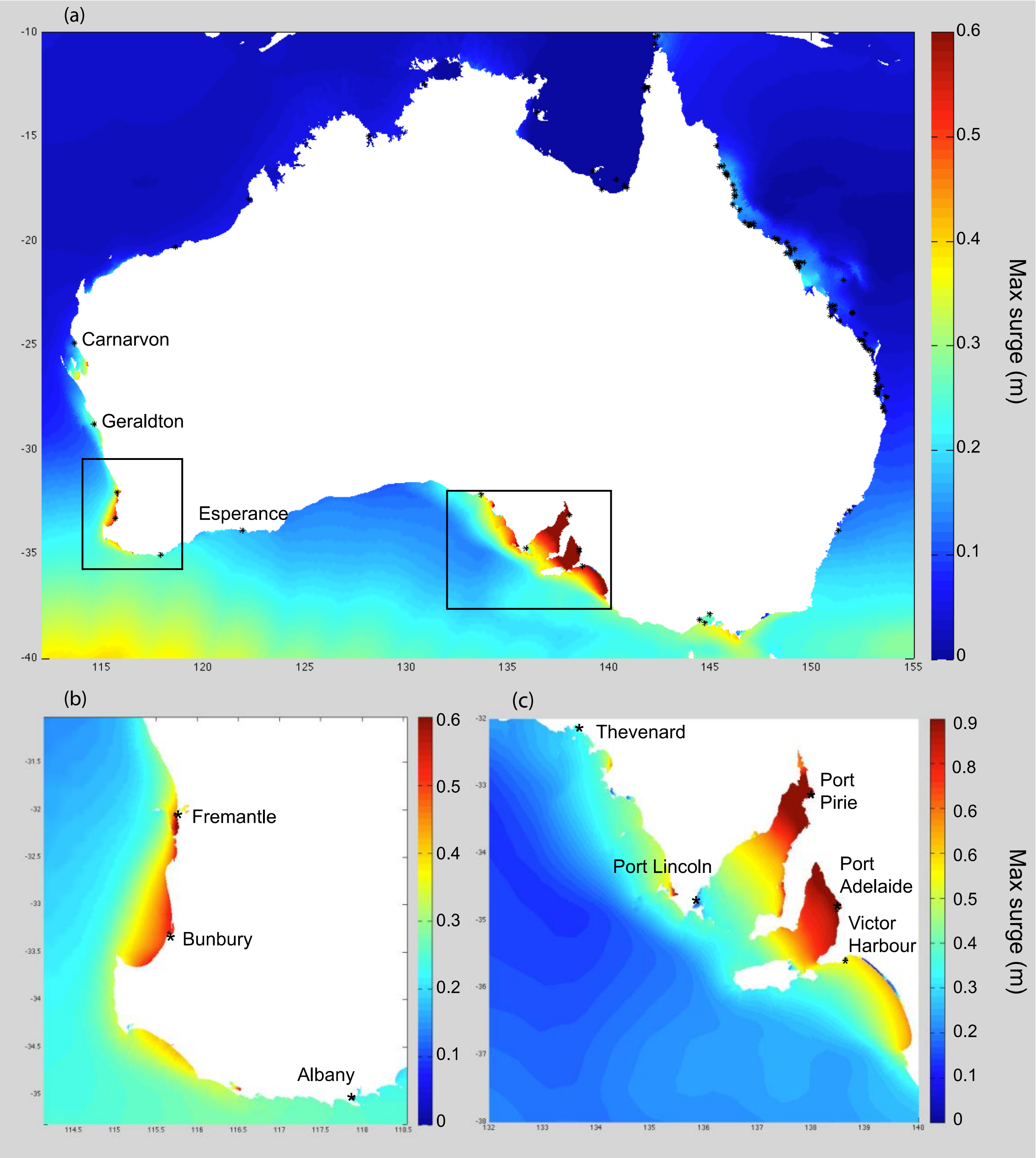

Figure 38. Maximum simulated storm surge over four days from 1-4 July 2007. Tide gauge site are shown with asterisks and timed series validation for those sites given in the following figure.

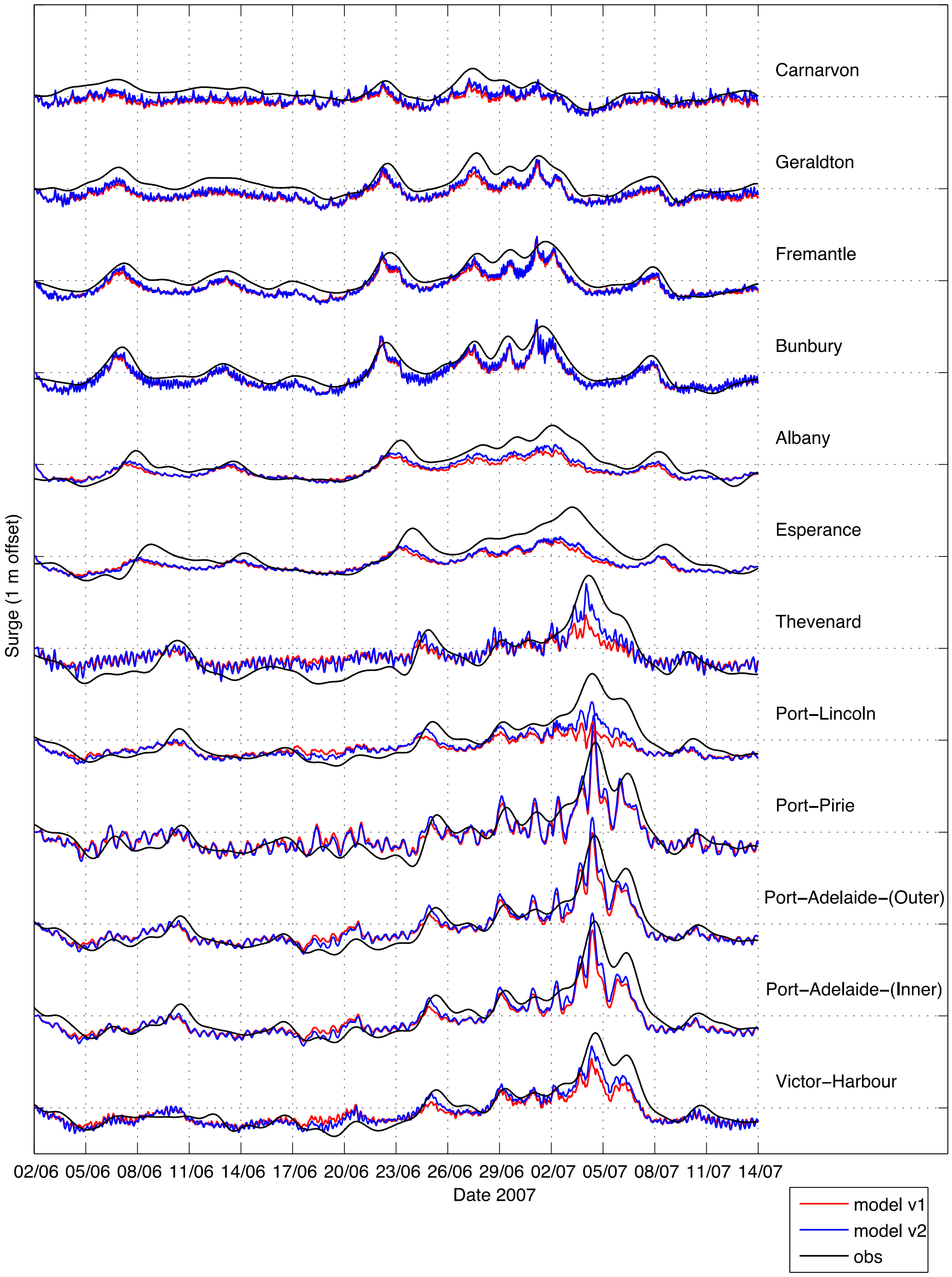

Figure 39. Observed residual water levels (black line) vs. simulated storm surge at tide gauge sites from Western and South Australia for June-July 2007. Two model runs are shown in colour with the red line indicating the model with improved bathymetry in the Great Australian Bight.