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DEVELOPING BETTER PREDICTIONS FOR EXTREME WATER LEVELS

Annual project report 2016-2017

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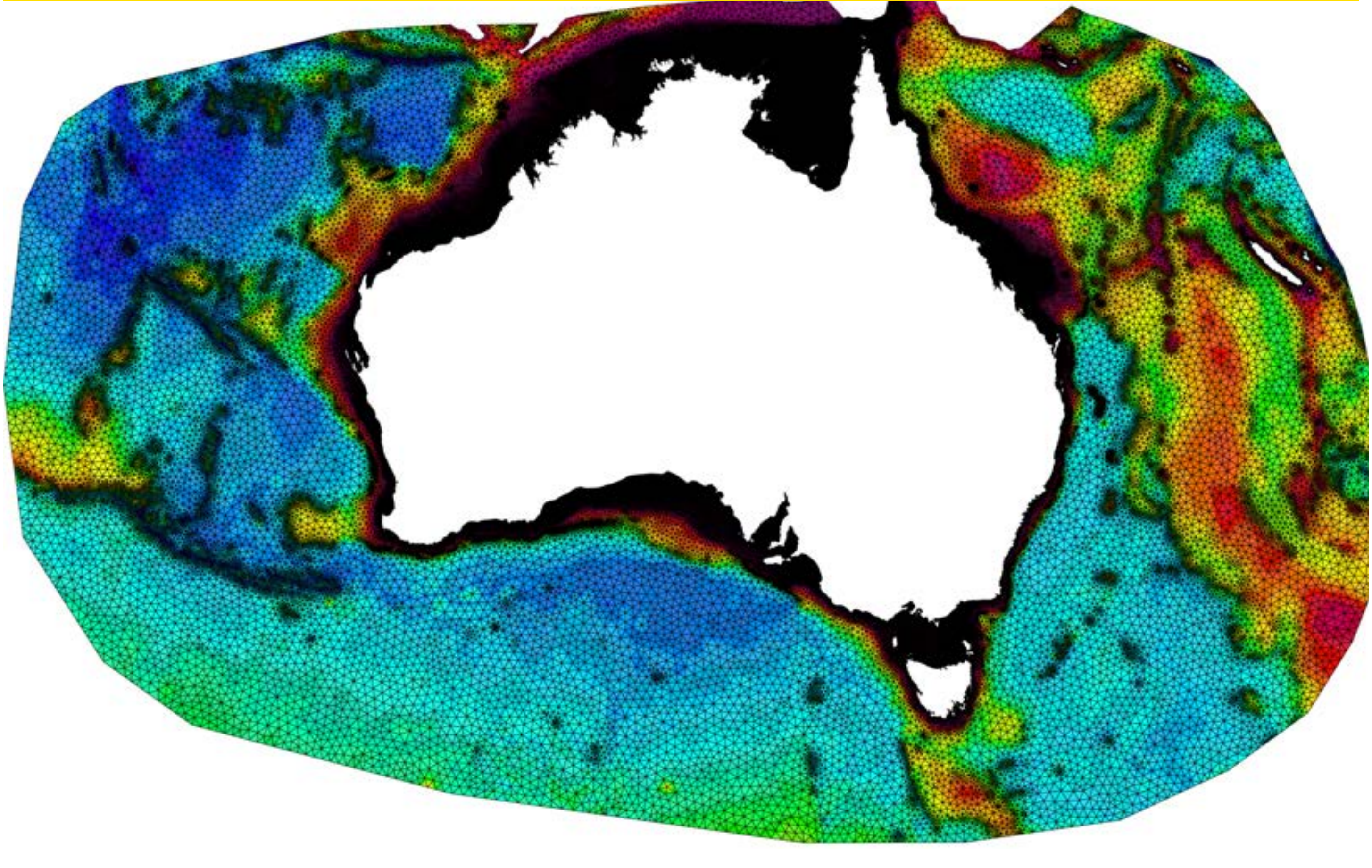
The University of Western Australia



Version	Release history	Date
1.0	Initial release of document	13/09/2017

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Publisher:
Bushfire and Natural Hazards CRC

September 2017

Citation: Pattiaratchi, C. (2017) Developing better predictions for extreme water levels: annual project report 2016-2017. Bushfire and Natural Hazards CRC, Melbourne.

Cover: Final model grid mesh showing depth, and finer mesh resolution near the coast

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EXECUTIVE SUMMARY

Major advances were achieved during 2016 and the project is on track to produce, by the end of 2017, improved predictions of extreme sea levels targeted to emergency managers and planners. This will be achieved through application of an improved high-resolution hydrodynamic model that has been developed and tested for a wide range of extreme events occurring over the past 30+ years around Australia.

Long-term model runs for the years 1959-2016 are presently nearing completion using improved meteorological forcing, higher spatial resolution at the coastline (up to 100 m), and improved bathymetic data compared to Haigh et al [1, 2] (Figure 3). The multi-decadal simulations are approximately 30% (1959-1979), complete and are expected to be finished within the upcoming month. Concurrently, work is ongoing to synthesise the results into effective communication tools for the improved sea level estimates, based on feedback from end-users.

The UWA team has worked to directly share knowledge gained through the project with the BOM storm surge model development team, as well through presentations of modeling advances at national conferences and workshops, including: AFAC (30 August 2016, Brisbane), Australian Meteorological & Oceanographic Society (AMOS, October 2016) and internationally in the UK over the past year.

Communication was initiated with end-users to develop effective data dissemination tools during a BNHCRC workshop at Geoscience Australia in Canberra during April 2017. The work has been cited as an important benchmark to give context to forecasts produced my BOM, and to give consistent estimates for planning purposes over broad regions. The project also interacted with the BNHCRC terrestrial flooding researchers from Monash University who expressed interest in using the UWA sea level predictions as ocean boundary conditions for their flood models.

Specific advances related to physical processes influencing predictions of extreme sea levels that have been achieved to date are summarised in the subsections below and explained in more detail in this report. These processes include:

- Wave setup contributions to storm surges calculated via coupled wave-surge model – this work was presented at the ACOMO workshop in Canberra in October 2016, and a journal article has been prepared for the Journal of Geophysical Research.
- Extratropical Transition – JRA55 reanalysis model has proved to be superior to atmospheric forcing previously used, and has been implemented.
- Continental Shelf Waves – modeling requirements (3D with density effects) to reproduce CSW have been defined– this work was recently presented at the Australasian Coasts and Ports Conference in Cairns, June 2017.
- Meteotsunamis – continued analysis of high frequency tide gauge data around Australia.

END USER STATEMENT

Miriam Middelmann-Fernandes, *Geoscience Australia, Canberra*

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. This project has just completed its major milestone which has delivered the 60 year model runs for the Australian coastline. End users are eagerly anticipating access to the data through a new web based tool which is being developed by the project.

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 residents 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 [3] 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 [1]. 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 [4].

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

Considerable loss of life and billions of dollars of damage to coastal infrastructure can result when sea level extremes occur along low-lying, highly populated and/or developed coastlines. 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 [5]; (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 [1]. 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 [2]. 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 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 was the 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. One advantage 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.

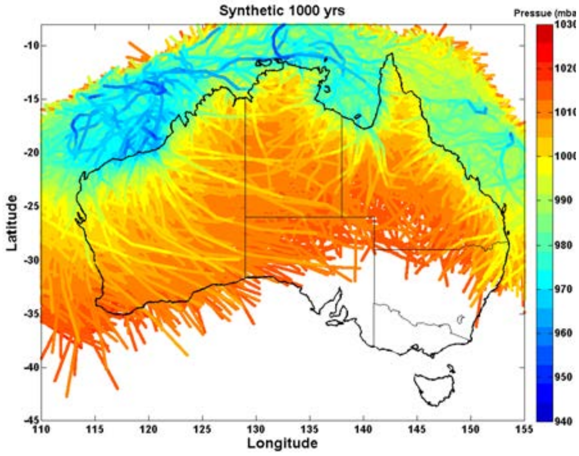

FIGURE 1. PATHS OF SYNTHETIC TROPICAL CYCLONES PREDICTED OVER A PERIOD OF 1000 YEARS (HAIGH ET AL., 2014)

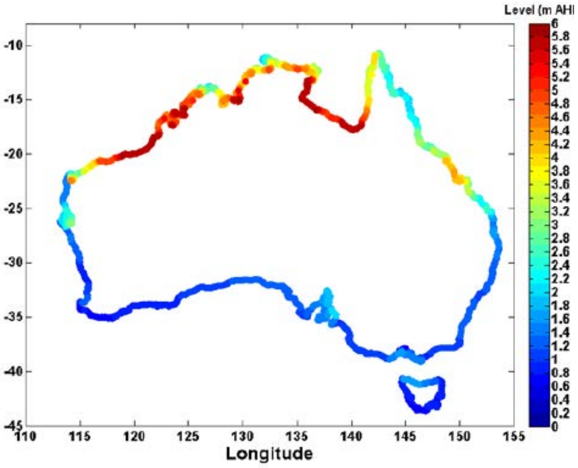

FIGURE 2: 1:100 ANNUAL RECURRENCE INTERVAL EXTREME WATER LEVELS FOR AUSTRALIA (HAIGH ET AL., 2014)

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 on the following sections with reference to their contribution to extreme water levels and work undertaken as part of this project.

WHAT THE PROJECT HAS BEEN UP TO

Over the past year the project made up for time lost through delayed personnel recruitment and is on track to produce, by the end of 2017, improved predictions of extreme sea levels targeted to emergency managers and planners. This will be achieved through application of an improved high-resolution hydrodynamic model that has been developed and tested for a wide range of extreme events occurring over the past 30+ years around Australia.

Long-term model runs are presently underway for the years 1959-2016 using improved meteorological forcing, higher spatial resolution at the coastline (up to 100 m), and improved bathymetic data compared to Haigh et al [1, 2] (Figure 3). The multi-decadal simulations are approximately 30% (1959-1979), complete and are expected to be finished within the upcoming month. The focus will then shift to synthesis of the results into effective communication tools for the improved sea level estimates.

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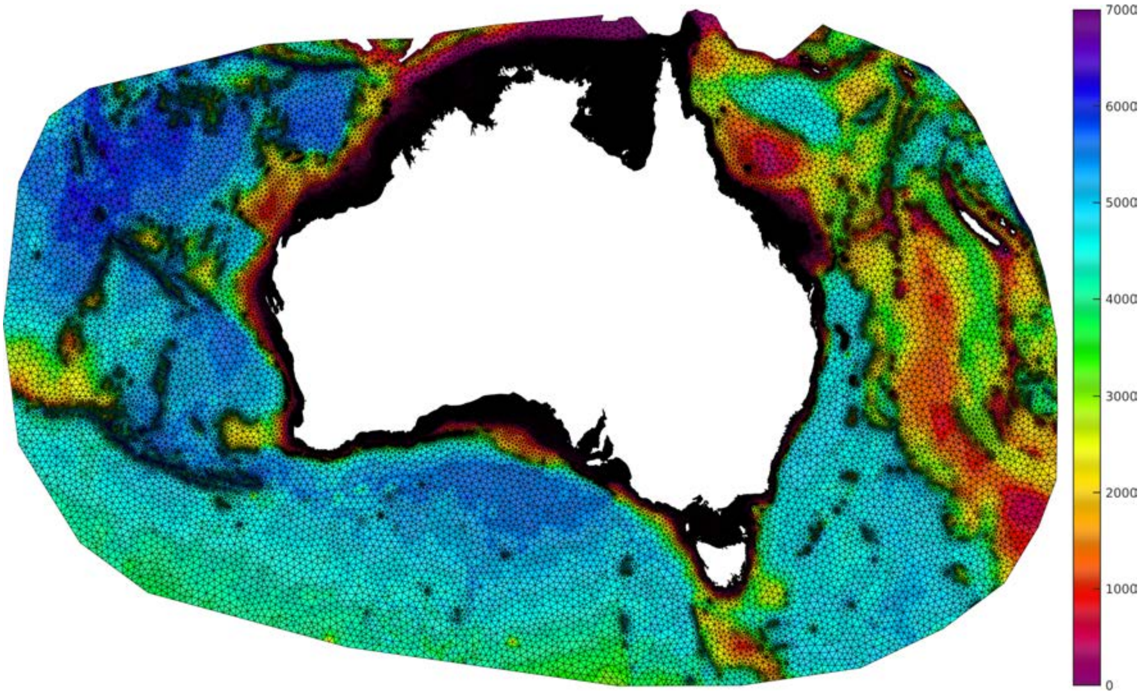

FIGURE 3. FINAL MODEL GRID MESH SHOWING DEPTH, AND FINER MESH RESOLUTION NEAR THE COAST.

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. Application of high resolution wave models for different regions were proposed as a means to identify where wave set-up was important. However, recent developments in computer models adopted by the project have allowed us to run coupled wave and storm surge models for the whole of Australia. A series of numerical experiments were undertaken for extreme events in Queensland (Tropical Cyclone Yasi), northwest Western Australia (Tropical Cyclone George), southwest Western Australia (transitioning Cyclone Alby), May 2016 extratropical low pressure system in South Australia, and a NSW East Coast Low during June 2016.

TRANSITION FROM TROPICAL TO EXTRATROPICAL 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 to 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 some reanalyses can provide superior forcing than parametric cyclone models since ET storms no longer behave as tropical cyclones. The first 20 years of the long term model runs illustrated the models ability to accurately reproduce the surge from Alby in 1978— something that was missing from the previous long term model runs described in [2]

CONTINENTAL SHELF WAVES

Extreme sea levels result from the combined effects of a range of factors including long term sea level variability, astronomical tides, storm surges due to pressure and wind, coastal trapped waves (CTWs), and wave breaking. Coastal trapped waves are longer period (~days) sea level fluctuations caused by setup of water levels at the coast due to tropical cyclones and winter cold fronts and the subsequent propagation of the surge parallel to the coast and decreasing offshore. Examples of CTWs include continental shelf waves (CSWs) that are commonly observed to propagate anti-clockwise for thousands of kilometres along the western, southern, and eastern coasts of Australia. These CTWs can be both forced and free waves and can cause important current and water level oscillations, particularly when elevated water levels from CTWs coincide with locally generated storm surges and high tides. CTWs can also impact port and shipping operations through negative surges that cause decreased channel depth when CTW troughs pass.

An extensive set of ROMS (Regional Ocean Modelling System) model sensitivity studies were undertaken for tropical cyclones Bianca (2011) and Jacob (1996) in Western Australia (WA) that generated CTWs. The detailed analyses defined requirements for simulating CTWs, the extent to which events are forced or free waves, and the influence of bathymetry and density stratification on propagation. In the case of TC Bianca the CTW was not a pure ‘free wave’ but was continuously ‘forced’ by wind and pressure along its trajectory. Results indicated that both 2D and 3D barotropic (no density effects) models were unable to reproduce freely propagating coastal trapped waves encountering changing continental shelf widths, despite the fact that these waves have been assumed to be mostly barotropic. On the other hand, the 3D model with vertical density stratification reproduced more realistic CTWs for all cases that travelled to the south coast of WA, generating current velocities greater than 0.5 m s-1 and water level anomalies up to 0.5 m more than a thousand kilometres from the source region.

These results were presented at the 2017 Australasian Coasts and Port Conference in Cairns in June 2017 and are described in more detail below.

METEO-TSUNAMIS

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. 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). At Hillarys, events meeting the criteria were identified from 2008-present (Figure 4). The individual events were analysed with annual counts indicating that 2008, 2013, and 2016 were years of high meteotsunami activity (Figure 5). There were also a number of events with amplitudes > 0.40 m in south-east Australia: Burnie, Portland and Port Kembla. During 2011 at Burnie Tasmania a meteotsunami event on 19 September (Figure 6 b) was ~30% stronger than the measured seismic tsunami originating in Japan in March (Figure 6 b). 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.

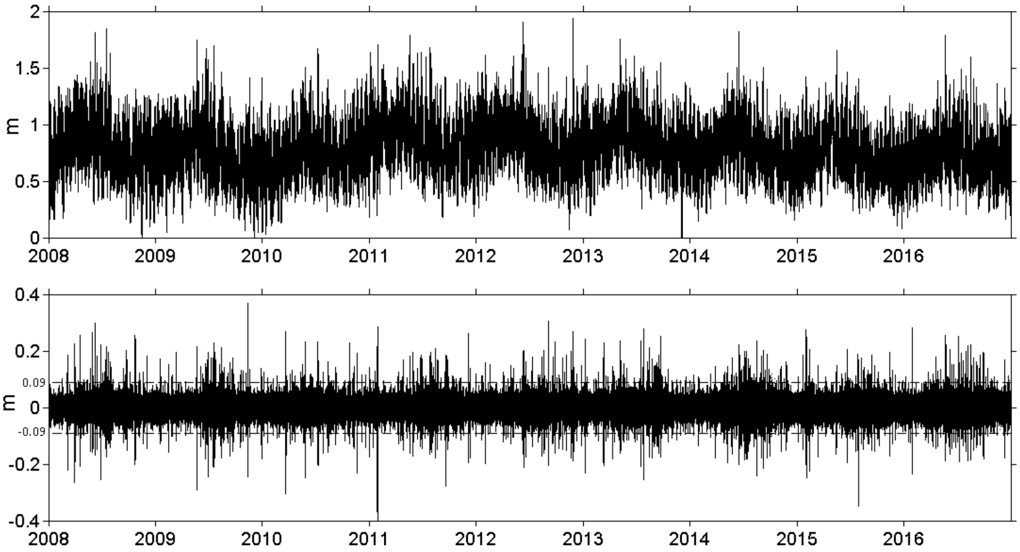

FIGURE 4. (A) 1-MINUTE TOTAL WATER LEVELS FROM THE HILARYS TIDE GAUGE (B) FILTERED TIME SERIES OF SEA LEVEL OSCILLATIONS <6 HOUR PERIODS WITH DASHED LINE INDICATING THE THRESHOLD CRITERIA FOR PORTENTIAL METEOTSUNAMI EVENTS.

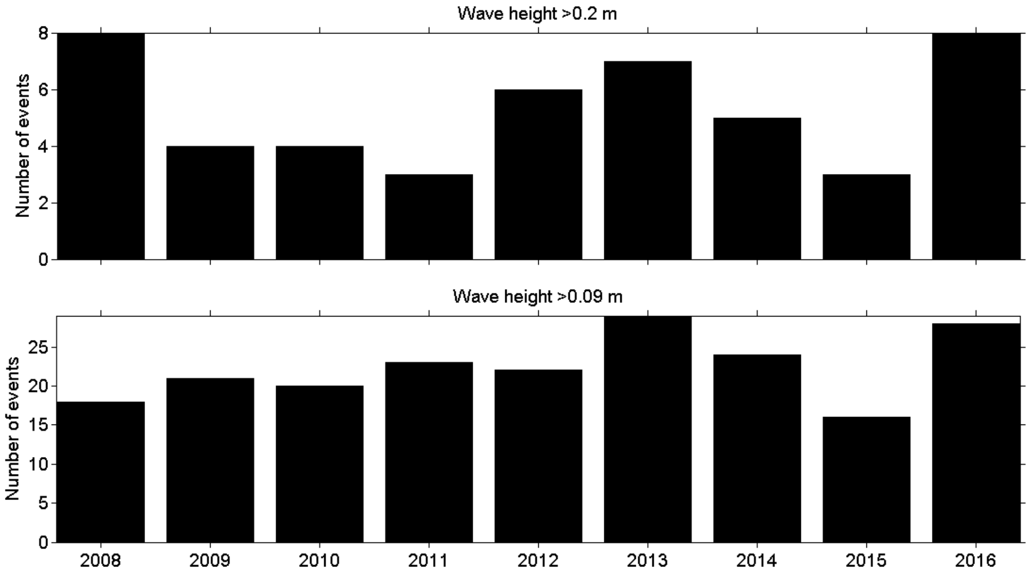

FIGURE 5. ANNUAL COUNTS OF METEOTSUNAMI EVENTS AT HILARYS BOAT HARBOUR FOR WAVE HEIGHTS >0.2 M (A), AND >0.09 M (B).

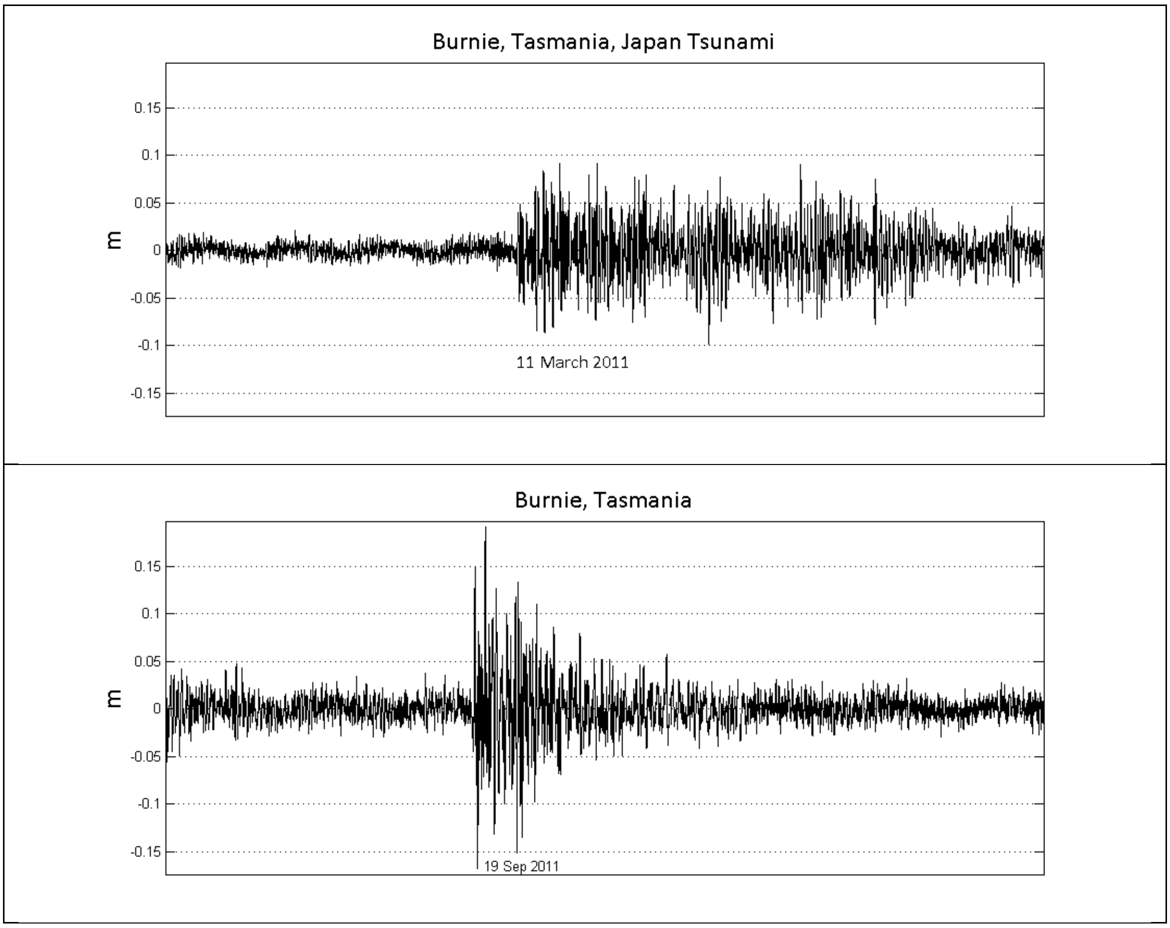

FIGURE 6 FILTERED TIDE GAUGE DATA FOR BURNIE TASMANIA FOR THE JAPANESE SEISMIC TSUNAMI EVENT DURING MARCH 2011(A) AND A METEOTSUNAMI EVENT (B) IN SEPTEMBER 2011.

(3) The influence of meteotsunamis inside Ports and marinas were investigated with an emphasis on current patterns. Although meteotsunamis events may be evident in 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.

WAVE SETUP AROUND AUSTRALIA

Most previous assessments of extreme sea levels have focused on still water levels [e.g. 1, 9, 10], but waves are a key process that can cause a substantial elevation of sea level near the shoreline through the combination of wave setup and runup [11]. Wave setup refers to the increase in mean water level at the shoreline due to the transfer of momentum from breaking waves into the water column [12, 13], whilst wave runup refers to distinct elevation maxima on the foreshore related to individual waves [11]. In certain regions wave setup and runup can account for up to 60 % of the 100 year extreme water levels [14, 15].

Directly including wave effects in numerical models is challenging and computationally expensive, however, recent advances allow for improved representation of wave-related physical processes in models, and potentially offer a way to improve extreme sea level estimates. Initial assessments such as those in the Gulf of Mexico and U.S. East Coast [16-19], and Europe [20] consistently indicated that accounting for wave effects in storm surge simulations can improve predictive skill. Local features such as bathymetry and coastline orientation with respect to storm tracks have also been shown to dramatically alter the relative importance of waves for storm surge simulations [21].

Whilst these results are encouraging, the variety of events and study sites investigated are too limited to assess whether the techniques can be reliably transferred to Australia’s diverse coastline. Therefore, in order to determine whether there are benefits to using a coupled surge-wave model over the simple approach of Haigh et al. [2014 we used a coupled wave-surge model to examine four extreme storms that impacted Australia in three different oceans, with a range of characteristics, from tropical cyclones, to a cyclone undergoing extratropical transition, to a large mid-latitude extratropical low pressure system (Figure 7).

We coupled the full 3D finite element hydrodynamic modeling system SCHISM [22, 23] with Wind Wave Model (WWM-III) spectral model, based on the original code by Hsu et al. [24] but since significantly updated by Roland et al. [25]. The two-way coupled system accounts for the wave induced momentum flux from waves to currents and water levels, based on the radiation stress formulations (S_{xx}, S_{xy}, S_{yy}) according to [26, 27]. Wind and pressure forcing was provided by JRA-55 reanalysis (0.5 deg, 3 hourly) with embedded synthetic tropical cyclone vortices [28] where required (HJRA). For each storm event we ran two configurations of the coupled model, one with radiation stress feedback into the hydrodynamic model and the other without—the difference between the two runs quantified the contribution of wave setup to total water levels.

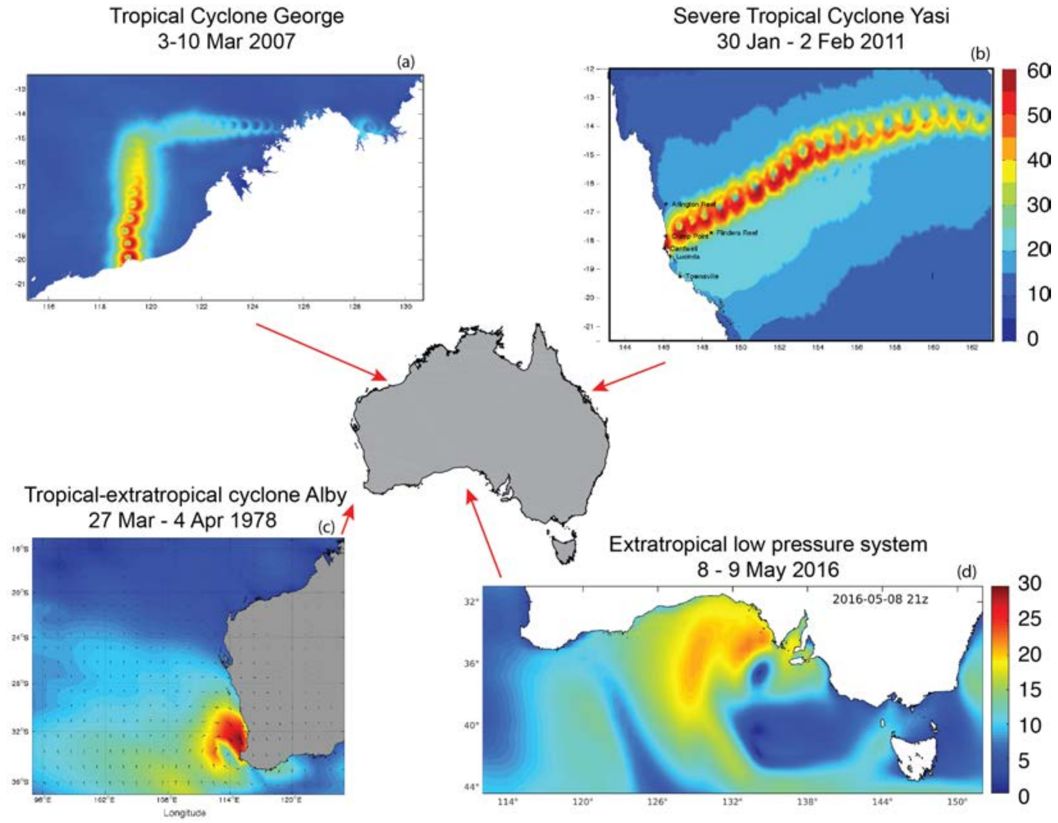

FIGURE 7 SELECTED STORM EVENTS AND MODEL WIND FORCING FOR TROPICAL CYCLONES GEORGE (A) AND YASI (B) SHOWN AS WIND SWATH (COMBINED MAXIMUM WIND SPEED FOR EACH 3 HR TIMESTEP FROM HJRA FORCING); JRA55 SNAPSHOT FOR TRANSITIONING CYCLONE ALBY ON 4 APRIL 1978 (C); AND JRA WIND SPEEDS FOR EXTRATROPICAL WINTER STORM 08 MAY 2016 IN SOUTH AUSTRALIA (D). COLOR BARS FOR A,B AND C,D ARE THE SAME, RESPECTIVELY, AND GIVEN IN M S^{-1}.

TROPICAL CYCLONE YASI (2011)

Tropical Cyclone Yasi impacted Queensland on 2 February 2011 as a category 5 system, with a 5.5 m storm surge at Cardwell (Figure 8 c). Simulated wave heights exceeded 12 m offshore of the Great Barrier Reef and 6 m inside the reef (Figure 8 b). Wave setup values of 0.1-0.45 m were predicted along the impacted coastline (Figure 8 d) and improved model skill in almost all cases, but the contribution was relatively small compared to making small changes in forcing. For example, at Cardwell a difference of 4% in peak surge level was due to including wave setup, but a 14% difference resulted from an adjustment to wind forcing at time of landfall to match observations (+ 10 %). The contribution of wave setup did make a higher relative contribution farther from the core of the cyclone (e.g. Townsville) and also acted to lengthen the duration of the surge, with maximum setup values occurring before maximum surge for Yasi. Setup along the complex coastline was also variable with highest values where high waves and shallow nearshore depths coincided. Setup also propagated into areas not directly exposed to waves. Our sensitivity studies suggested that the assumptions required in parametric cyclone models are the most important contributing factor determining storm surge accuracy, and can cause surge errors on the orders of meters, whereas the contributions of wave setup in simulations at the scale are an order of magnitude lower.

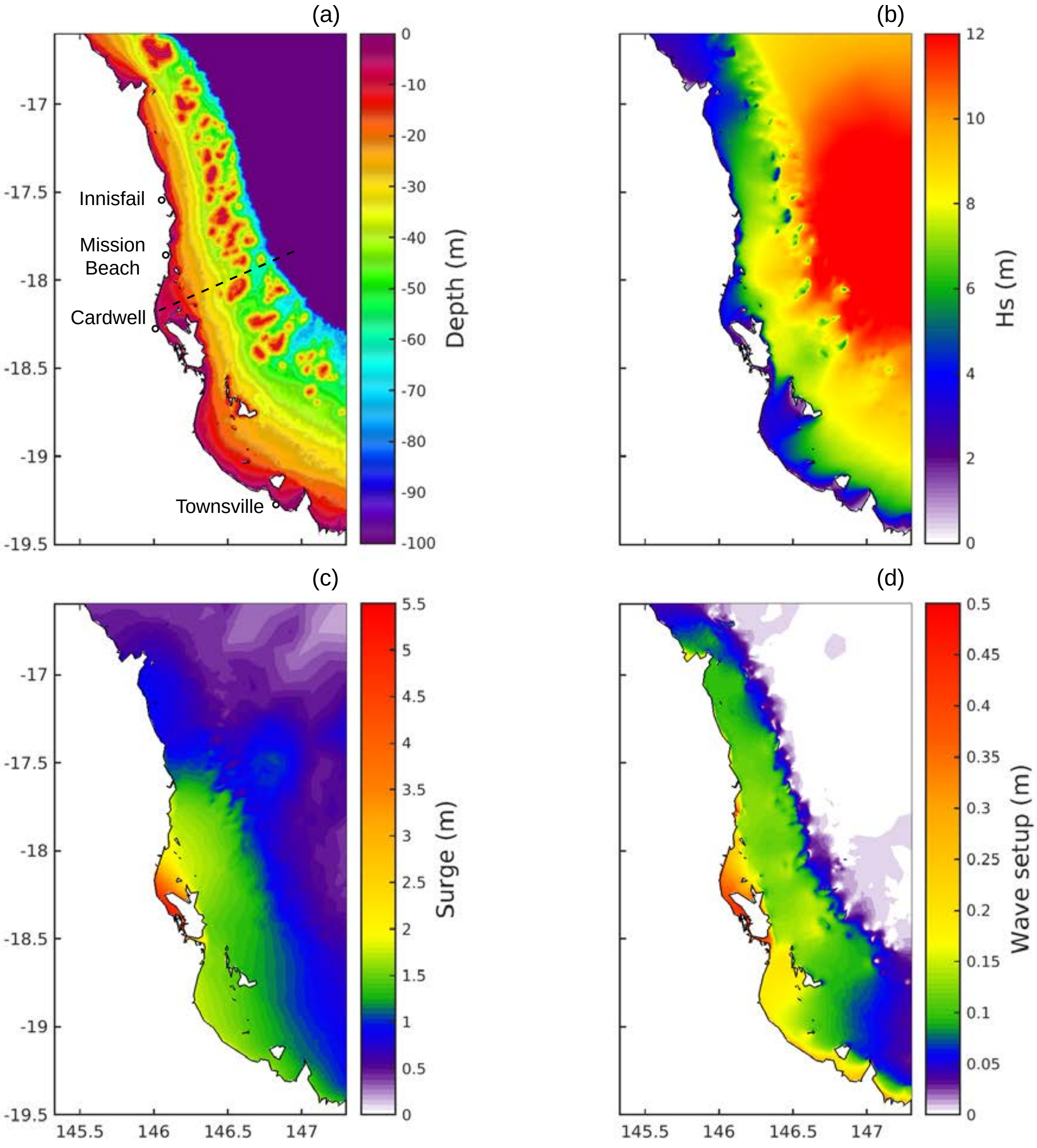

FIGURE 8. DEPTH (A) AND SIMULATED MAXIMUM HEIGHTS OVER 24 HOURS ON 02 FEBRUARY 2011 WHEN TC YASI CROSSED THE COAST FOR: SIGNIFICANT WAVE HEIGHT (HS) (B); SURGE (C); WAVE SETUP (F). LOCATIONS OF CROSS SHELF TRANSECT IN FIG. 6 AND TIME SERIES POINTS FOR FIG. 7 SHOWN IN (A)

TROPICAL CYCLONE GEORGE (2007)

Tropical Cyclone George (2007) proved to be near miss for Port Hedland with an almost 5 m surge occurred in unpopulated areas ~60 km to the northeast. The simple mildly sloping coastline provided an ideal test site that contrasted with other events and was more similar to coastlines where related modeling studies have been undertaken such as in the Gulf of Mexico. As was the case with Yasi, pure JRA55 forcing caused only a negligible surge (<1 m), whilst the synthetic vortex HJRA forcing resulted in a storm surge >5 m to the east of Port Hedland (Figure 9c).

Wave breaking occurred far offshore due to an extensive shallow river delta (< 10 m) extending up to 30 km out to sea. These specific conditions appeared to result in high wave setup values in the model over a broad area. The largest waves were experienced seaward of the delta and caused a surge up to 5.5 m over about 50 km of coastline and setup levels ~0.4 m (Figure 9 c,d). For TC George wave setup contributed up to 15-20% of the total surge on average with a reduced proportion near the landfall location where surge was higher, similar to values obtained for Yasi.

Although we consider the predicted surge to be realistic, we acknowledge that unavoidable limitations of parametric wind models result from underlying assumptions and lack of data to guide the model. In many cases this is the only option, and it is possible to accurately simulate tropical cyclone surges, however accurate cyclone track data are required, and these factors generally appeared to dominate over the wave setup contributions.

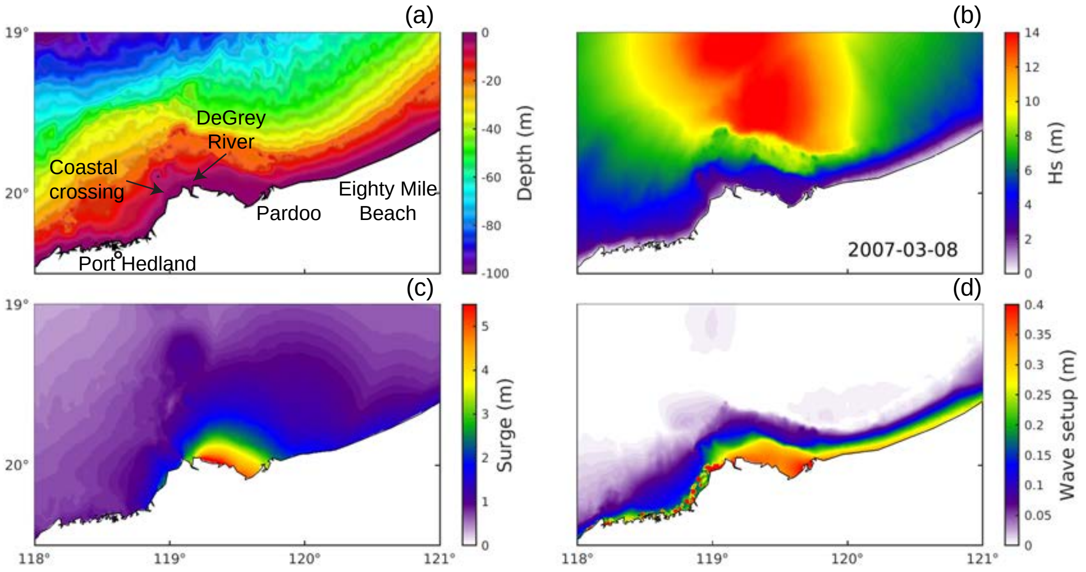

FIGURE 9. SIMULATED MAXIMUM VALUES OVER THE 24 HOUR PERIOD ON 8 MARCH 2007 WHEN TROPICAL CYCLONE GEORGE CROSSED THE COAST TO THE EAST OF PORT HEDLAND . BATHYMETRY (A); MAXIMUM SIMULATED SIGNIFICANT WAVE HEIGHT (HS) (B); MAXIMUM POSITIVE SURGE (NEGATIVE SURGE WEST OF CROSSING LOCATION NOT SHOWN) (C); MAXIMUM WAVE SETUP (D). UNEVEN VALUES NEAR THE COAST TO THE WEST IN (D) SHOULD BE CONSIDERED UNRELIABLE DUE TO UNRESOLVED PROCESSES. LOCATIONS OF INTEREST SHOWN IN (A).

For risk assessments in the tropical regions of Australia, particularly in the northwest where there are large amplitude tides, and a sparsely populated coast, the tropical cyclone trajectory and the stage of tide when it makes landfall will ultimately decide how much inundation and damage occurs. For TC George that crossed the coast at low tide, the 5.5 m surge would not have been catastrophic if it had hit Port Hedland. On the other hand, if George had crossed the coast west of Port Hedland at high tide, even a surge half as extreme could have been devastating. Correct statistical combinations of cyclone tracks and tide therefore should be the most important considerations when undertaking risk analysis in the region, with wave setup as can be resolved with a coupled model providing a secondary consideration. The coupled model, however, can still be used effectively to map out regions, such as the shallow areas around De Grey and Pardoo (Figure 9), where wave setup is likely to be important, and surges are most extreme.

TRANSITIONING TROPICAL CYCLONE ALBY (1978)

One of the most destructive storms in Western Australia was Cyclone Alby in April 1978 that caused an estimated $50 million dollars in damage and killed five people. As Alby moved south out of the tropics it violently interacted with an approaching cold front and became a hybrid storm transitioning from tropical (warm core) to extratropical (cold core) in nature as it passed the SW of the state offshore [29]. During this process of Extratropical Transition (ET) [7], the storm tripled its translational speed (from 10 m s^{-1} to 30 m s^{-1}) and distorted spatially creating an extremely broad and intense fetch of northerly winds along the coast (up to ~30 m s^{-1} recorded at Perth and Bunbury), causing it to become a ‘worst case scenario’ for the southwest of the state due to the extreme waves and storm surge [29].

The parametric wind model showed higher wind speeds in the core of the cyclone compared to the JRA55 model over the entire simulated period (not shown). However, in the outer regions, the JRA55 model contained a broad region of intense (>30 m s^{-1}) northerly winds along the coast that closely matched observed wind speeds, and thus the raw JRA55 wind and pressure fields were used to force the storm surge model.

Simulated wave heights of 12-14 m occurred offshore, similar in height to TC Yasi and TC George, with breaking wave heights around 8 m in Geographe Bay and extending for several hundred kilometers up the coast (Figure 10 b). A key difference compared to TCs Yasi and George was that Alby did not cross the coast and thus created a smaller storm surge. The model run including wave setup did a remarkable job of reproducing the surge despite the coarse atmospheric forcing with a maximum surge height of 1.19 m, only 9% below the recorded sea level of 1.3 m (Figure 10c). In contrast, the model run that did not include wave effects failed to reproduce the surge with a maximum height of only 0.9 m, an underestimation of 30%, suggesting that wave setup was the ‘missing component’. This result highlighted the benefit of using a coupled model where high-resolution bathymetry is available and adjusting the atmospheric forcing is not justified.

Unlike TCs George and Yasi, differences between model runs with and without wave setup were negligible before the peak of the storm, likely because the storm was moving so fast that waves arrived at the same time as the peak surge. Peak wave setup coincided with maximum surge around 12 UTC on 04 April, with wave setup contributing 0.28 m, or 24% of the total water level at Bunbury (Figure 10d). This wave setup contribution was a greater proportion of the peak surge compared to Yasi and George due to the timing and also to the relatively lower total storm surge. Water levels remained elevated above observations for approximately 6 hours after Alby passed the region in the setup run, whilst water levels in the no-setup run dropped off more quickly. Over the broader region maximum wave setup values varied widely between 0 to 0.35 m, indicating that the proportion of setup to surge was 0 to ~30%, with highest values where large waves encountered shallow nearshore depths and gradual slopes.

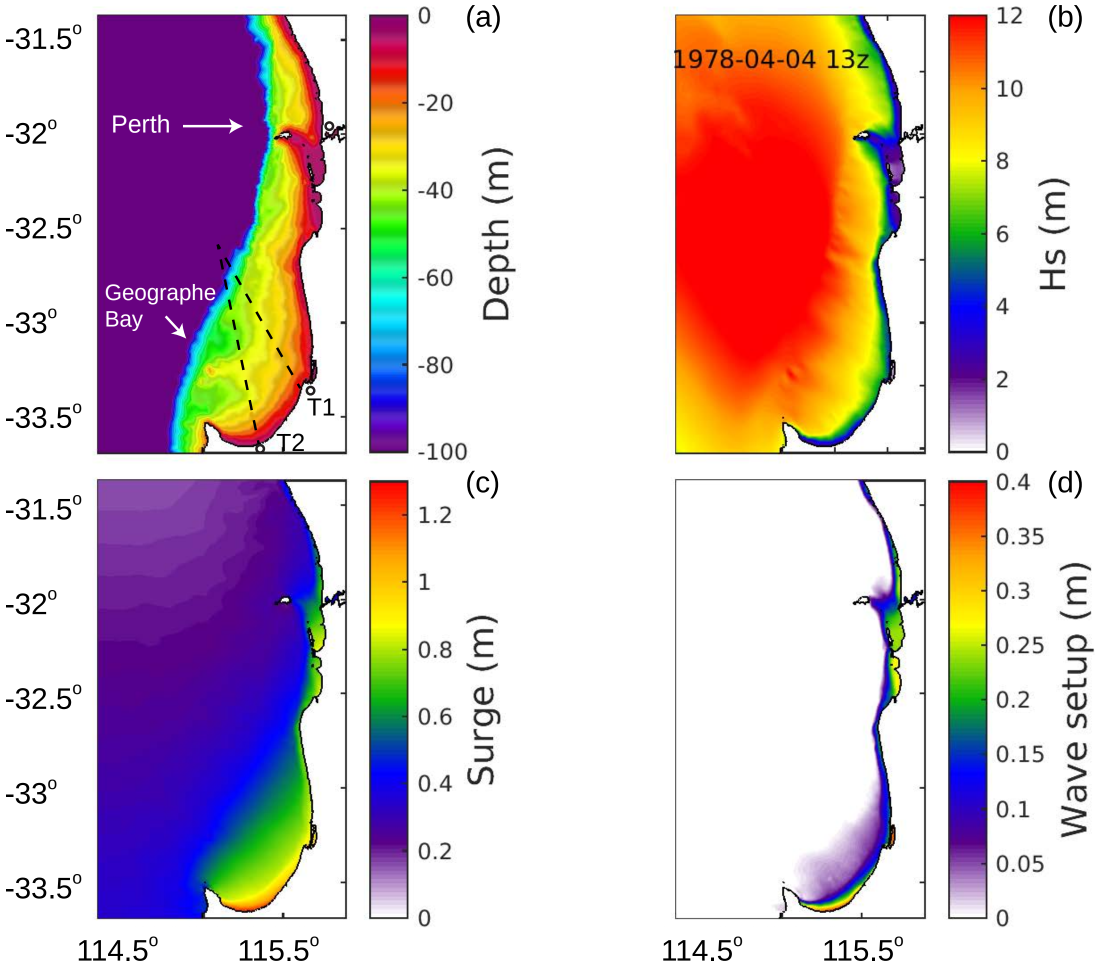

FIGURE 10. MODEL SNAPSHOT FOR 04 APRIL 1978 13:00 (UTC) AT THE TIME WHEN CYCLONE ALBY PASSED THE REGION AND MAXIMUM STORM SURGE OCCURRED. BATHYMETRY (A); SIMULATED SIGNIFICANT WAVE HEIGHT (HS) (B); SURGE (C); WAVE SETUP (D) CROSS SHELF TRANSECTS IN FIG. 12 ARE SHOWN AS DASHED LINES IN (A) WITH T1 CORRESPONDING TO BUNBURY (TIDE GAUGE LOCATION) AND T2 FOR BUSSELTON. CITY LOCATIONS INDICATED WITH BLACK CIRCLES.

EXTRATROPICAL STORM, SOUTH AUSTRALIA (MAY 2016)

The South Australian simulation contrasted with the other tropical cyclone events due to its size and the local geography. This extratropical storm was less intense, but extended over thousands of kilometers with nearshore wave heights still exceeding 7 m on exposed coasts. Maximum storm surge levels were moderate and in the range of surges that can occur each winter. However, the timing of the surge top of spring tides caused record total water levels at Outer Harbour in Adelaide [30].

Across the region, the model did a reasonable job with the timing and duration of the surge with peak simulated water levels (up to 1.2 m at Port Pirie) within 30% (~0.2-0.3 m) of the observed residuals (Figure 11 c). Given that JRA55 wind speeds and MSLP were not strongly underestimated, and that the bias was consistent across the region, a possible explanation for the bias was that the model did not resolve relevant processes, such as coastally trapped waves that are known to occur in the region with similar magnitude [31].

The storm surge from this event was mostly limited to the coastline between Thevenard and Cape Jaffa with largest surges within the Gulfs and at Coffin Bay (Figure 11). Despite the vast coast exposed to large waves, wave setup was only evident at four places around: Thevenard (0.25 m), Coffin Bay (0.2 m), western Yorke Peninsula (0.10 m), and Cape Jaffa (0.2 m). At these locations setup values were approximately ~0.5-4 % (0.5-3 %) of wave heights at 10 m (30 m) depth, markedly less than for the other Australian test cases (e.g. Figures 8-10), despite the fact that these sites had nearshore depths of 5 m or less, consistent with other simulations that showed largest setup in shallow regions. Although depths for wave setup were most favorable in the inner regions of the Gulfs limited fetch and exposure meant that waves were small in those areas and contributed to negligible setup values. Much of the coastline exposed to large waves (e.g. west coast of the Eyre Peninsula) contained nearshore depths > 5 m and as a result radiation stress gradients due to breaking waves were too small to cause significant levels of wave setup in the model despite relatively large waves (Figure 11 f). This suggested that for the areas most susceptible to large storm surges in South Australia (or similar coasts) where nearshore topography is relatively steep and/or sheltered from the open ocean, there are fewer benefits to running a coupled wave-surge model compared to low lying coasts. It is likely true that waves do have a significant impact along the exposed west coast, but the processes cannot be resolved in a model at this scale.

Maximum values of surge, wave heights and wave setup co-occurred at a majority of the sites in South Australia. This contrasted with the tropical cyclone examples for Yasi and George where large waves and corresponding increases in wave setup preceded the arrival of the storms. This suggested that wave setup effects due to large extratropical storms in the region differ to slow moving tropical cyclones, although this is likely site and storm specific.

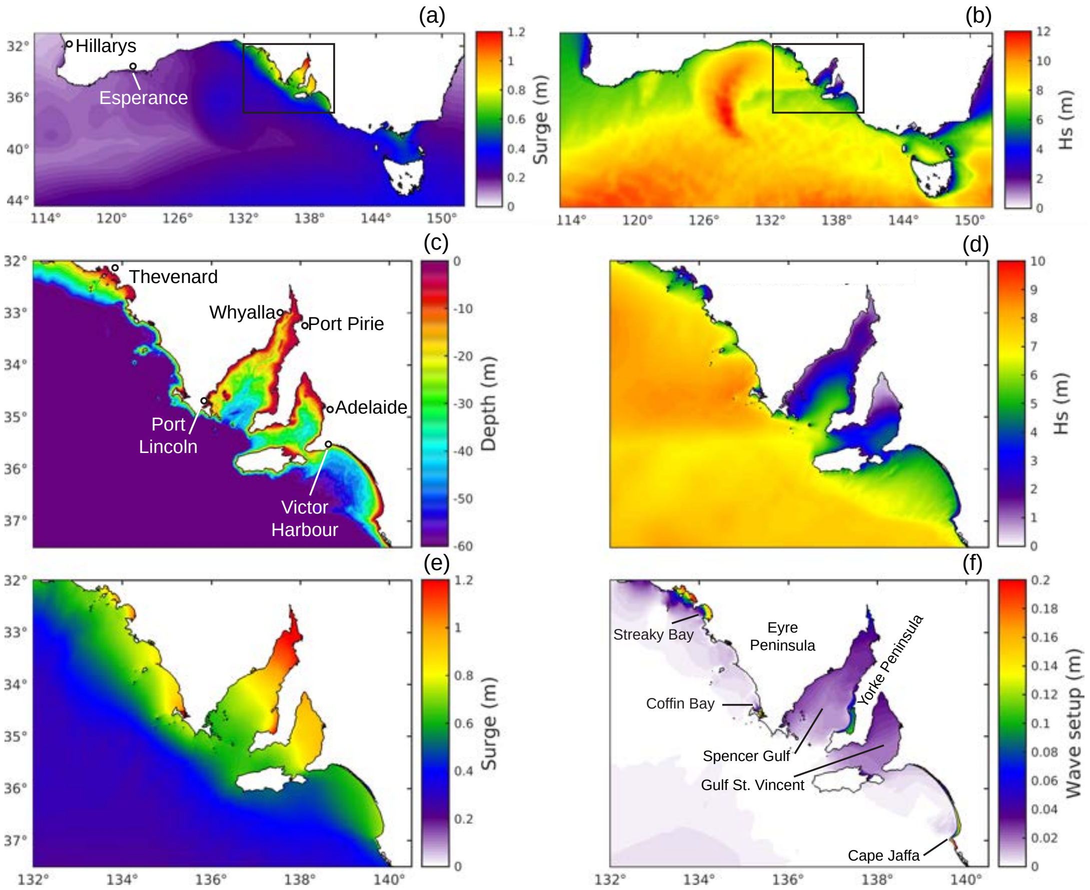

FIGURE 11. SIMULATED MAXIMUM OVER DAYS 1-9 MAY 2016 FOR: SURGE (A,E); SIGNIFICANT WAVE HEIGHT, HS (B,D); DEPTH (C); WAVE SETUP (F). LOCATIONS OF TIDE GAUGE SITES SHOWN IN (A) AND OTHER GEOGRAPHIC FEATURES (F).

CONTINENTAL SHELF WAVES

Continental shelf waves (CSWs) are a class of Coastal trapped waves that cosnsist of longer period (~days) sea level fluctuations caused by setup of water levels at the coast due to tropical cyclones and winter cold fronts, with the subsequent propagation of the surge parallel to the coast and decreasing offshore. CTWs are commonly observed to propagate anti-clockwise for thousands of kilometres along the western, southern, and eastern coasts of Australia.

Although the influence of CTWs waves in Australian waters has been well-known since the 1960’s [5, 32-37] and their dynamics investigated globally [34, 38], simulation of CTWs in hydrodynamic models has remained a challenge. As a result their effects have generally not been included in assessments of extreme sea levels derived through numerical models. For example, Haigh et al. [1, 2] used a hydrodynamic model to derive extreme sea level statistics along the entire Australian coast. They found that for the southern coasts of Australia, the return period curves calculated using the numerical model results were often underestimated compared to those calculated from tide gauge data. One of the possible contributing factors was that the 2D model did not include the effects of remotely forced coastal trapped waves.

To address whether this was the case, we applied the regional Ocean Modeling System (ROMS) model [39] to tropical cyclones Jacob (1996) and Bianca (2011)in Western Australia (Figure 12). Three different configurations included: 1) *2D barotropic* (single vertical layer and no density effects by definition); 2) *3D barotropic* (26 vertical levels, but with a constant vertical density profile throughout the domain; 3) *3D baroclinic* (26 vertical levels) with an analytical vertical density profile.

Our experiments suggested that whilst any model configuration could accurately reproduce surges forced by local wind and pressure, CTWs were quickly damped out in both 2D and 3D models that did not include vertical density stratification (Figure 13). Therefore we conclude that a 3D baroclinic model is required to allow simulated CTWs to propagate freely anticlockwise around the coast, thus supporting the suspicion that the 2D model applied by Haigh et al. [2] would have been unable to reproduce freely propagating CTWs.

In theory, coastal trapped waves such as those generated by TC Bianca and Jacob are mostly barotropic in nature and designated as mode 1 CTWs [5, 38]. These waves should then be present in barotropic models without vertically varying density, however, as indicated in the model runs presented here this seems not to be the case. This suggests that either the CTWs are not pure barotropic mode 1 waves or that other parameterisations in the model, such as how turbulence and friction are accounted for strongly influence the ability to model this process.

Along the east coast of Australia, data from a series of field experiments revealed that energy from CTWs traveling along the shelf disappeared and reappeared after encountering sharp changes in shelf width. Further numerical experiments suggested that energy scattered between the first (barotropic) mode to higher modes (dependant upon vertical stratification) when widening and narrowing shelf topographies were encountered [38]. This may explain why CTWs in the barotropic model runs were almost completely damped out at the NW Cape where the continental shelf width sharply decreases. If this is the case, even the crude vertical density stratification included through an analytical profile in the 3D baroclinic model run offers a simple solution to improve simulation of storm surges when CTWs are present.

The results from numerical experiments undertaken in this study suggested that it is necessary to include vertical density stratification if simulation of coastal trapped waves is desired. Predictions of extreme sea levels, shipping channel depths, and ecologically important currents might be improved if these processes are included in future modeling attempts.

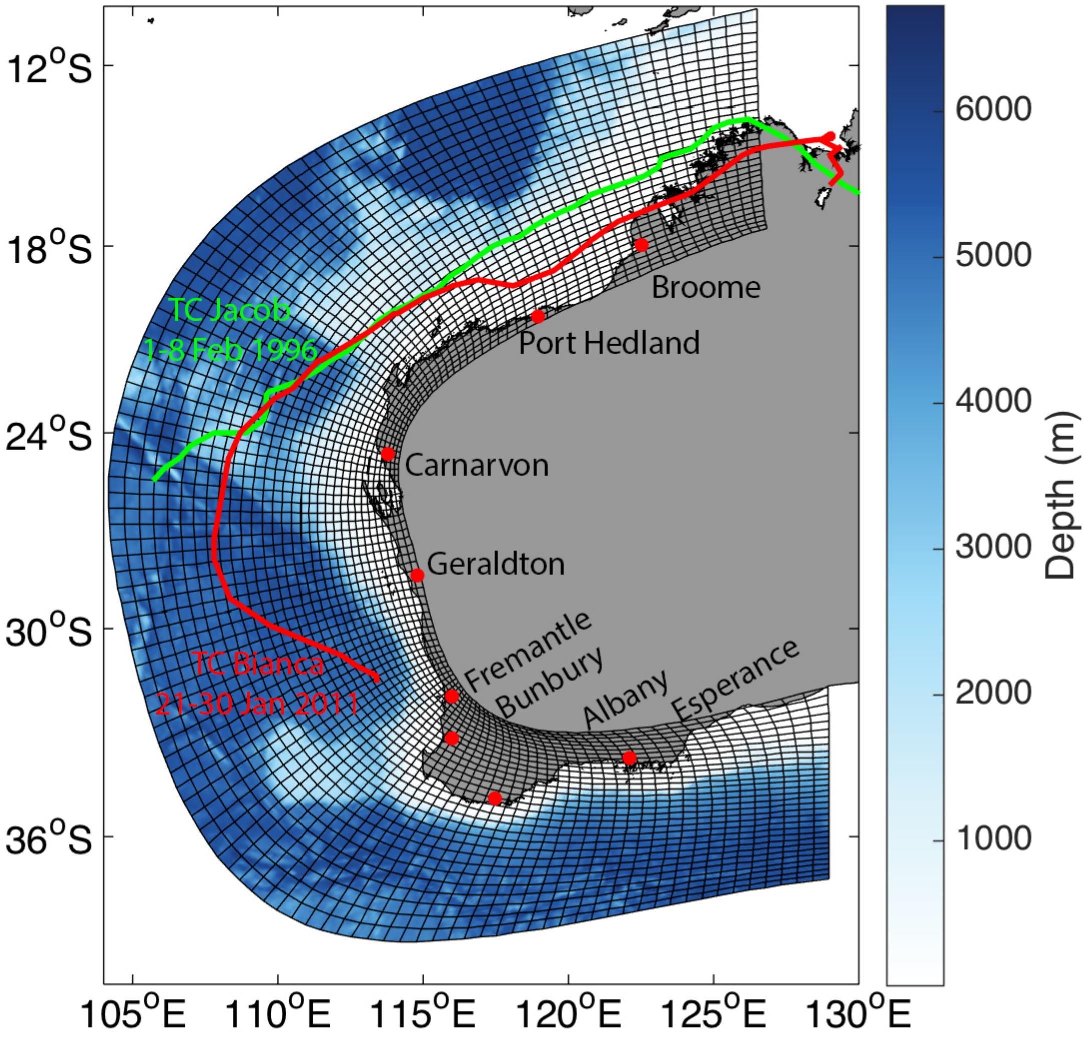

FIGURE 12. MODEL GRID, BATHYMETRY AND STORM TRACKS OF TC BIANCA (RED) AND JACOB (GREEN) IN WESTERN AUSTRALIA. TIDE GAUGE SITES ARE INDICATED AS RED DOTS.

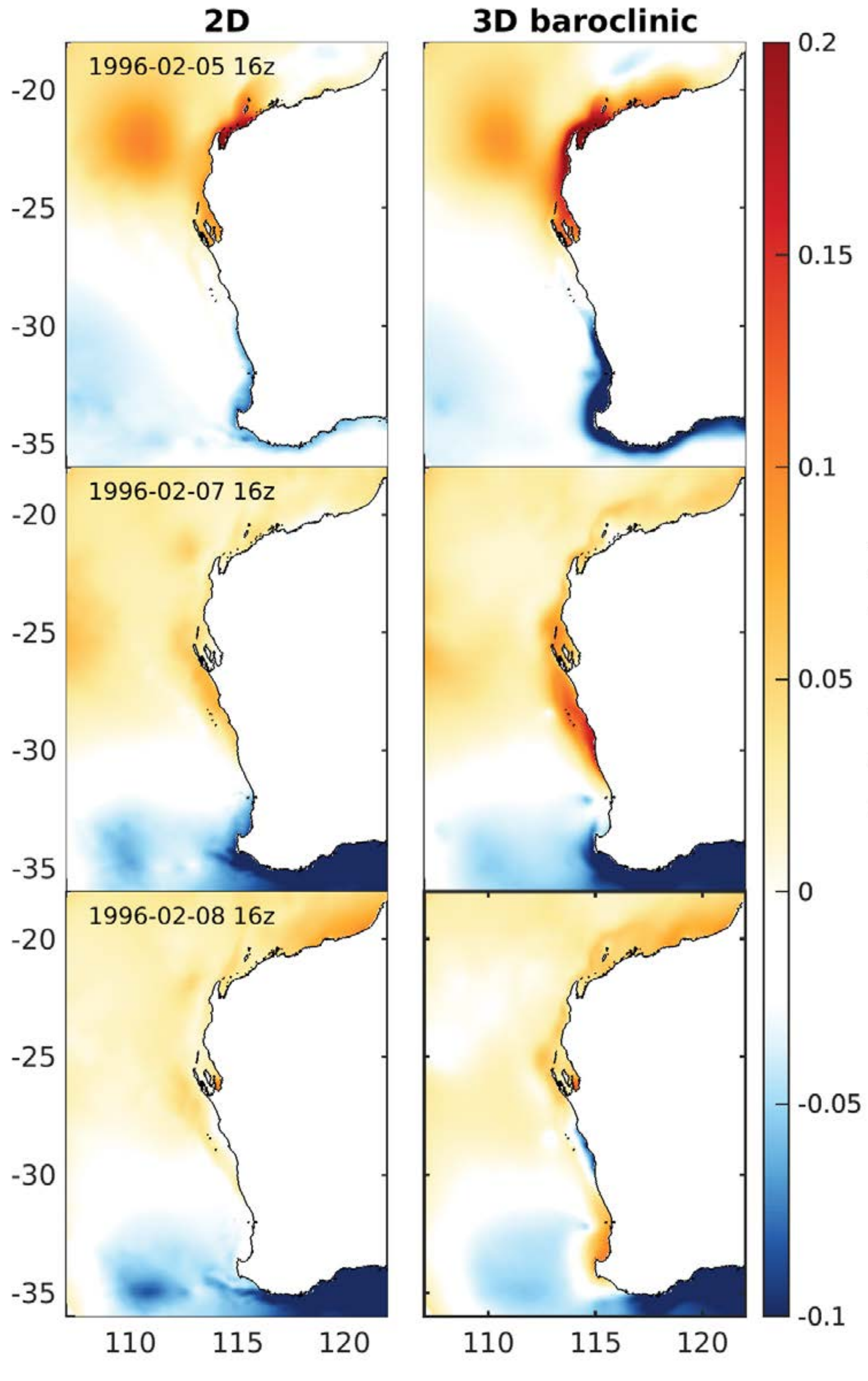

FIGURE 13. SIMULATED SEA LEVEL ANOMALY SNAPSHOTS FROM 2D BAROTROPIC (LEFT) AND 3D BAROCLINIC (RIGHT) MODEL RUNS FOR TROPICAL CYCLONE JACOB ON THE 5, 7,AND 8 FEBRUARY 1996. THE RELATIVELY HIGHER AMPLITUDE SHELF WAVE IS EVIDENT IN THE SIMULATION CONTAINING DENSITY EFFECTS (RIGHT). NOTE THE ABSENCE OF ANY POSITIVE SEA LEVEL ANOMALY IN THE 2D SIMULATION IN THE SOUTHWEST OF 08 FEB (IN FACT IT'S NEGATIVE DUE TO HIGH MSLP) AND THE POSITIVE SEA LEVEL ~0.1 M IN THE 3D BAROCLINIC RUN FOR THE SAME DAY.

60-YEAR EXTREME SEA LEVEL MODEL RUNS

SYNTHESIS OF MODEL RESULTS

The major outcome of this project is to provide improved estimates of extreme sea levels at high resolution around the entire Australian coast, in the form of return period curves. These return period curves will be based on extreme value statistical analysis of sixty-year time series (1959-2016) of water levels extracted from the numerical hydrodynamic model.

The validated hydrodynamic modelling system for Australia is at present running on the Pawsey supercomputer, with approximately 30% of the years complete. Preliminary outputs have been compiled to allow for testing of the statistical methods based on a 20-year time series at the 30 validation sites around Australia.

Extreme water levels are being calculated using the peaks over threshold (POT) method [40] where individual storm surge events are subset from the data and fit to an extreme value distribution (General Pareto Distribution, GPD) to extrapolate beyond the extent of the data (e.g. 100 or 1000 year return periods). Since the length of the total dataset and number of individual events strongly influences the return period curves, final values cannot be established before the entire 60-year simulation is complete. To illustrate the procedure and outputs, two examples are included here based on the preliminary 20-year time series at selected sites. When the long-term model runs are complete, the methodology will be applied to the complete time series at ~1 km resolution around the coast.

EXTREME VALUE ANALYSIS

Peaks over threshold (POT)

In order to effectively plan for the future at the coastal boundary and to design resilient infrastructure it is important to understand the likelihood and nature of extreme sea level events (for example the storm surge residual peaks in Figure 14 a). Design water levels and estimates of how often those levels will be exceeded are mostly based on extreme value theory, a specific statistical field that deals with rare events such as flooding [41].

During recent decades, a number of methods have been developed to estimate extreme still water levels, with each method having both benefits and limitations, and each yielding slightly different results. Recently, several comparative studies [e.g. 40] have been undertaken in order to determine which method is most robust for calculating return period curves for extreme sea levels in coastal areas. These studies suggested that the peaks over threshold (POT) method is a good choice for these analyses, provided the data are treated correctly. The POT is applied in the present study, and a brief overview of the methodology is given here.

The first step in the analysis requires the removal of long term trends from time series data such as mean sea level rise. This detrended dataset is then subsampled to include a set of sea level events deemed to be 'extreme,' which are then used to fit an extreme value distribution which allows for the extrapolation beyond the extent of the data. The statistical basis of the theory requires that the events exhibit random behaviour and therefore any trends must be removed. Here, a trend line was fitted to the annual mean sea level values and removed from the original data, based on a sensitivity study of several different methods. This method appears to work well at most stations around the world as MSL trends represent a proxy for extreme sea level trends .

[40].

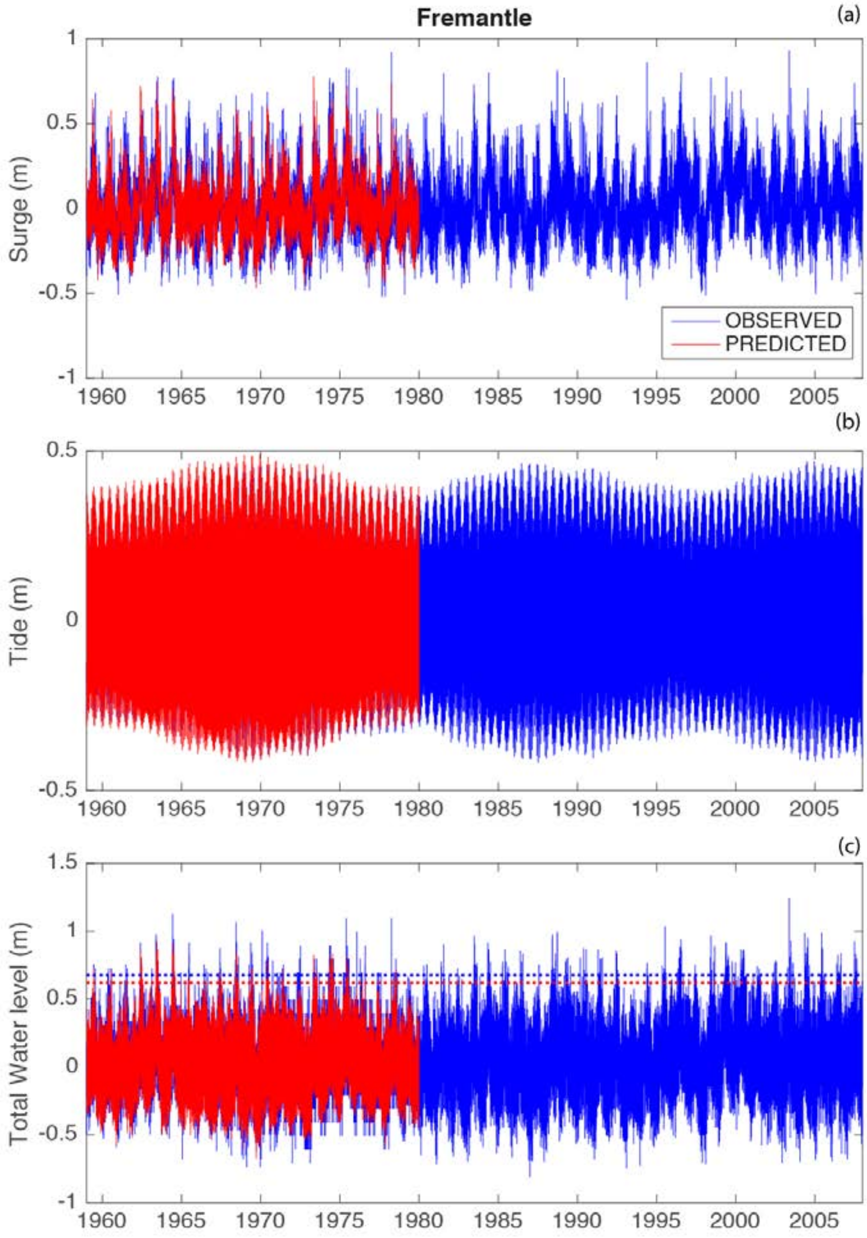

FIGURE 14. OBSERVED (BLUE) AND PREDICTED (RED) WATER LEVELS FOR: (A) STORM SURGE ONLY, (B) TIDE ONLY, AND (C) TOTAL WATER LEVELS RELATIVE TO MEAN SEA LEVEL FROM 1959-2007. DASHED LINES IN (C) INDICATE 99.7 PERCENTILE LEVELS.

Return Period Curves (first 20 years)

The POT method assumes that the generalized Pareto distribution (GPD) is a good approximation of the probability of events ocurring beyond the time span of the data. Thus the GPD was used to estimate return periods up to 1000 years (e.g. Figure 15). The resulting return period curves are sensitive to the included events and twenty years is generally too short of a time period to calculate reliable extreme values. As the model runs are completed, the difference between the curves calculated from the complete tide gauge dataset for Fremantle (black line Figure 15) and the model (red line Figure 15) should reduce. In other cases, such as in Thevenard, South Australia there is already a reasonable fit between the curves calculated from observed and predicted sea levels (Figure 16). A refinement of the methodology will be undertaken to ensure model results align with observed values once the multi-decadal model runs are complete.

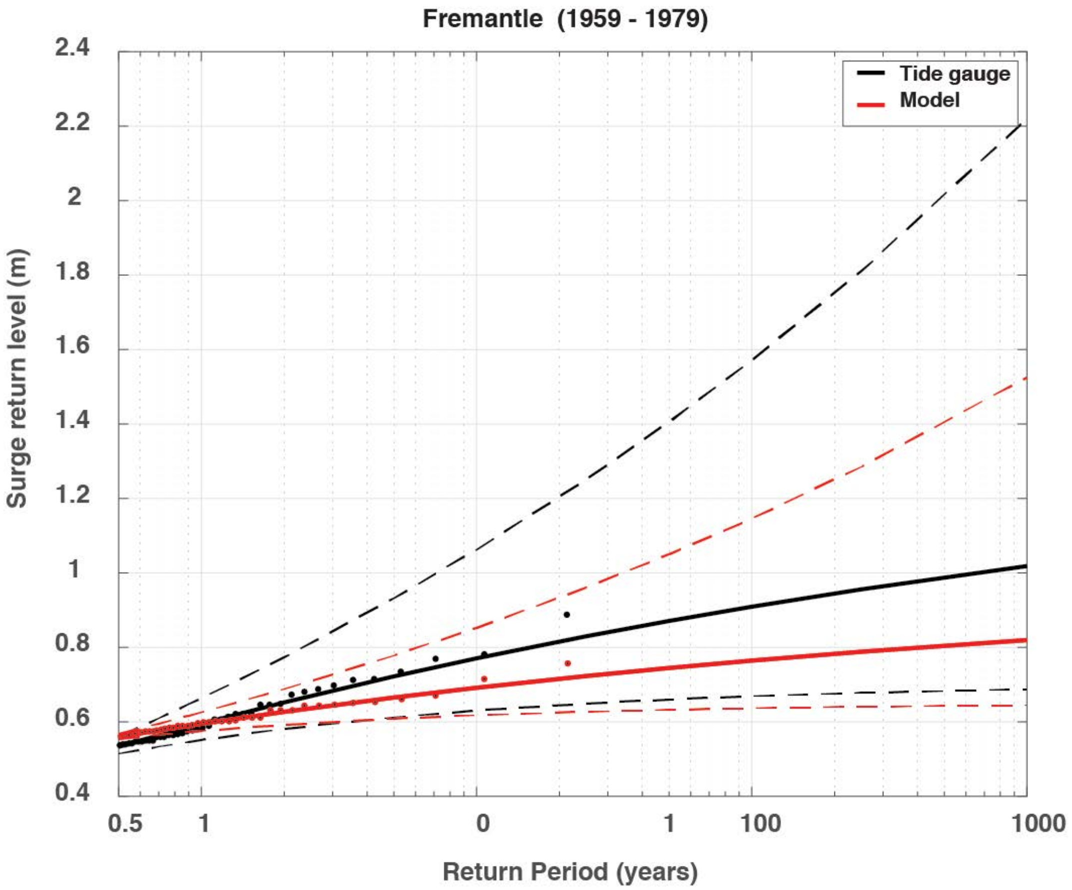

FIGURE 15. RETURN PERIOD CURVES FOR FREMANTLE STORM SURGE LEVELS (RELATIVE TO MSL) BASED ON OBSERVATIONS (1959-2007, BLACK) AND FIRST TWENTY YEARS OF THE STORM SURGE MODEL (RED).

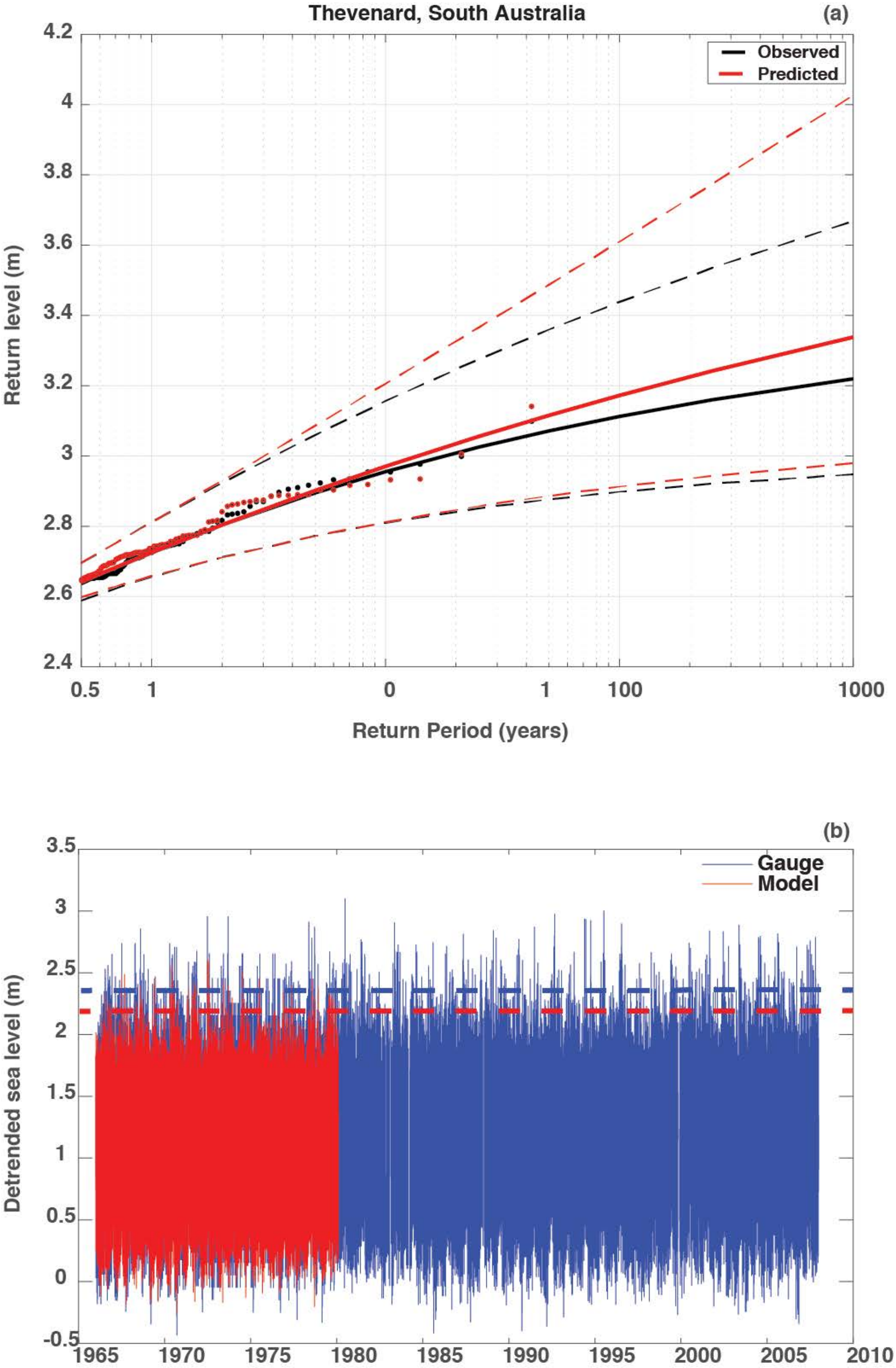

FIGURE 16. (A) RETURN PERIOD CURVES FOR THEVENARD TOTAL WATER LEVELS BASED ON OBSERVATIONS (1959-2007, BLACK) AND FIRST TWENTY YEARS OF THE STORM SURGE MODEL (RED). (B) DETRENDED TOTAL WATER LEVELS WITH 99.7 PERCENTILE THRESHOLDS SHOWN AS DASHED LINES. ALL DATA RELATIVE TO MSL.

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