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DEVELOPING BETTER PREDICTIONS FOR EXTREME WATER LEVELS

Annual project report 2014-2015

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Cover: The Office of Environment and Heritage NSW assessing erosion at Jimmy's Beach after damage from an east coast low in April 2015.

Photo: The Office of Environment and Heritage NSW.

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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 exceedanceexceedance 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.

After the initial delays in personnel recruitment the project has made quite good progress with the progress made in all different components of the project. When the project proposal was written we did not expect that we will be able to run a model which incorporated surface gravity waves. We now have developed and tested a coupled wave and storm surge model which yield very good results. Additional work needs to be done but we are very excited to have this tool which will be first time a such a coupled model has been used in Australia. We have successful simulated continental shelf waves and TC Alby with the hydrodynamic models with which are in agreement with the measurements. This gives us confidence to extend the model to other parts of Australia. Perhaps the most impact has been made in the area of meteotsunamis. As the only research group undertaking such research in Australia (and only a few globally) the ship accident in Fremantle highlighted the importance of meteotsunamis as a natural coastal hazard. This resulted in a lot of interest locally as well as in the national press and also leading to publications.

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 [4]. 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.

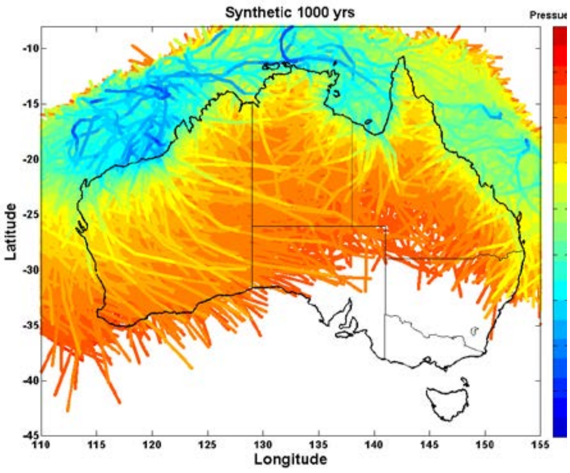


Figure 1 – Paths of synthetic tropical cyclones predicted over a period of 1000 years (Haigh et al. 2012)

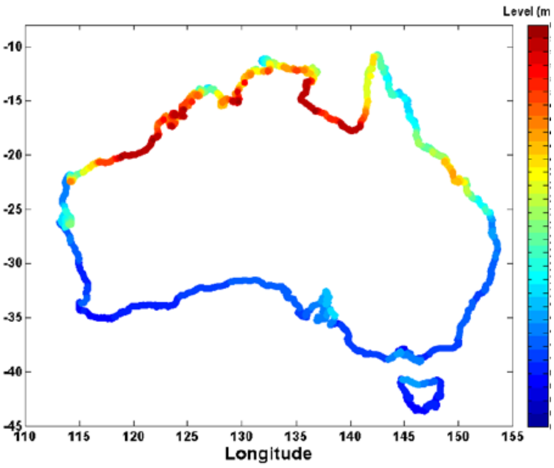


Figure 2 – 1:1000 annual recurrence interval extreme water levels for Australia (Haigh et al. 2012)

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 proposal.

(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^{o} 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 (Eliot and Pattiaratchi, [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 [3] 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 [5]. 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. [5]). 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 however, there were delays in recruitment of personnel. Two post-doctoral researchers were recruited with Dr Yasha Hetzel staring in August 2014 and Dr Ivica Janekovic starting in April 2015. We also recruited a postgraduate student, Alireza Saheli who started in September 2014. After a relatively slow start due to the delays in recruitment, the project has made quick progress and a summary of the work undertaken with respect to different sections of the project are detailed below. Significant progress has been made with initial simulation undertaken with the use of an unstructured grid for the Australian region (Figure 1).

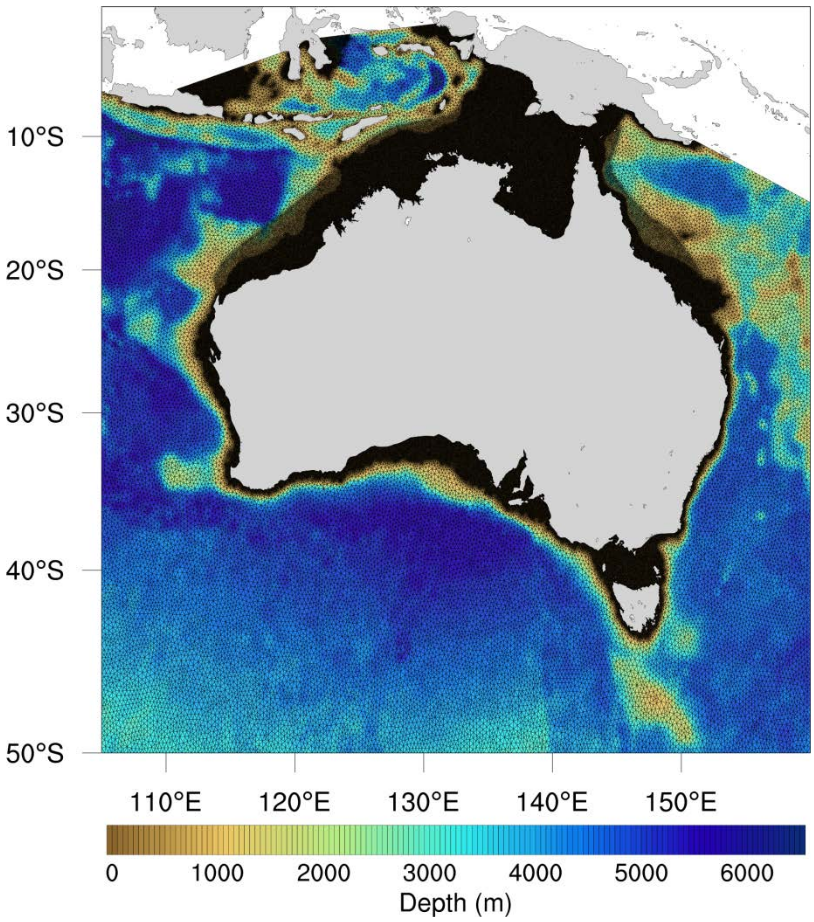


Figure 1. Australia-wide mesh grid showing the large domain and varying resolution, from tens of kilometres in the open ocean to approximately 2 km at the coastline.

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. In the original project proposal it was 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.

SELFE 3D is a finite element (unstructured grid) hydrodynamic modelling system that has successfully been applied to simulate circulation and storm surges in a broad range of coastal environments. The model uses a semi-implicit finite element Eulerian-Lagrangian algorithm to solve the Navier-Stokes momentum equations and naturally incorporates wetting and drying of tidal flats. The numerical algorithm is stable, computationally efficient and does not suffer from numerical stability constraints (e.g. the Courant-Friedrich-Lewy (CFL) condition) that restrict the maximum allowable timestep as is an issue in many other ocean modelling codes (e.g ROMS, POM, ADCIRC).

Wave dynamics were modelled using The Wind Wave Model III (WWM-III) wave spectral model, based on the original code by Hsu et al. but since significantly updated by Roland et al. []. The WWM-III incorporates the framework of residual distribution schemes] within a hybrid fractional splitting method using a third order Ultimate Quickest schemes in spectral space, similar to the WAVEWATCH III (WWIII) model]. The numerical schemes for wave advection in WWM-III have also been successfully implemented into the WWIII model. The WWM-III model has been shown to successfully simulate ocean wave conditions across a range of locations and scales including the Adriatic Sea, the Gulf of Mexico and the South China Sea. The SELFE—WWMIII modelling system is capable of two-way exchanging information between the hydrodynamic model and wave model providing feedback into the hydrodynamic model and wave model at each time step during the whole simulation. The two-way coupled system accounts for the wave induced momentum flux from waves to currents, based on the radiation stress formulations according to, the Wave Boundary Layer (WBL) according to the theory of, surface mixing following, and the current induced Doppler shift for waves.

Initial results indicated the importance of including waves into storm surge simulations, adding an additional ~15% on a top of only storm surge sea levels for the regions with the highest values (Bunbury and Busselton). From the physical point of view coupled model systems provided better representation of the dynamics by allowing exchange of information between two models at each time step and improving each of them. In the case of the wave model it received surface currents, and sea level of the ocean, while the hydrodynamic core received better formulated wind stress, effects of the waves on the currents, wave boundary layer and surface mixing.

Validation and analyses focused on Bunbury and Busselton in the SW of Western Australia where most damaging surges occurred. Tide gauge data were available for the simulated storm period at Fremantle and Bunbury with analysis showing Bunbury to be located in the region of maximum surge (Figure 2). Due to the damage inflicted by Cyclone Alby the Bureau of Meteorology compiled a detailed report of the meteorological characteristics and effects along the coast. This report was a useful reference for validating the timing and magnitude of the simulated surge as well as offshore wave heights (ship observations), and wind speeds within the JRA-55 data.

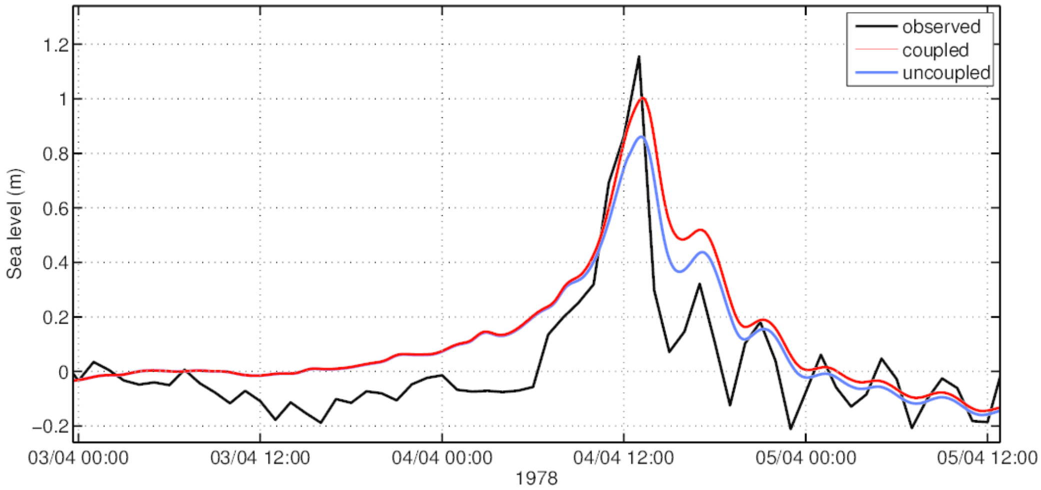


Figure 2. Bunbury observed residual low pass filtered sea level data (black), 2-way coupled model (red), and uncoupled model (blue) results for the same location.

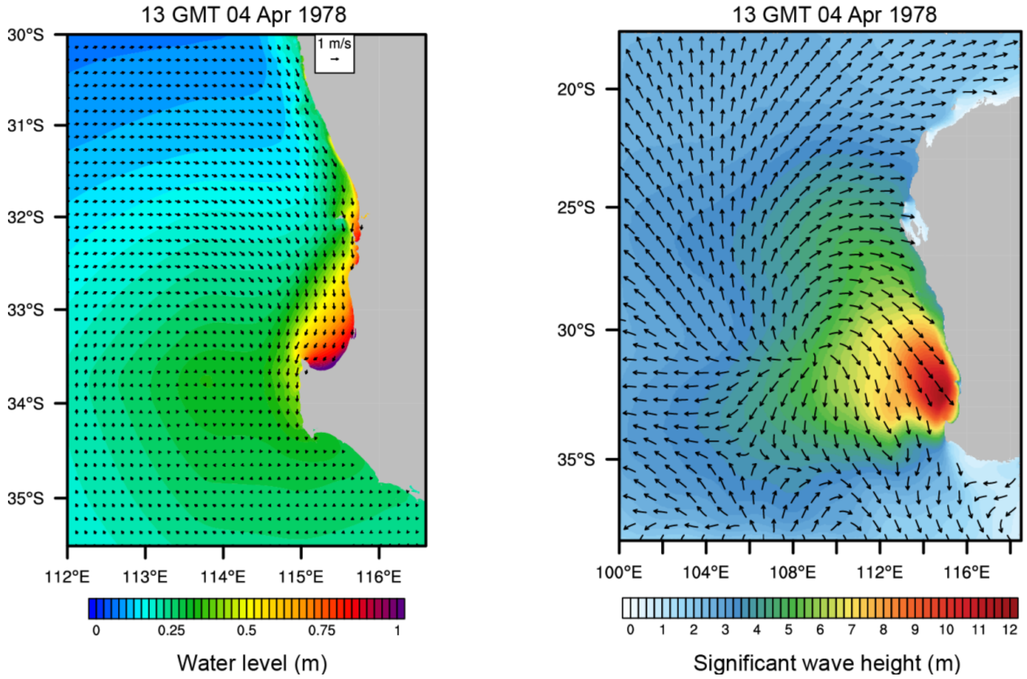


Figure 3: Storm surge sea level (left) and significant wave height (right) for the 2-way coupled simulation

The maximum storm surge for Cyclone Alby was approximately 1.15 m on the evening of 4th of April 1978 (approx. 1pm GMT or 9pm local time) at Bunbury and this compared well with the coupled model results which indicated a surge of ~ 1 m at the same location (Figures 3). However, the tide gauge data were only given at hourly intervals and could therefore have missed the peak of the storm surge. The duration and timing of the surge matched well with the observations.

Spatially, the coupled model clearly showed that the most extreme surge occurred along the north facing coast of Geographe Bay from Bunbury to Cape Naturaliste (Figure 3, left), which was consistent with reports. Simulated wave heights (Figure 3, right) were also comparable to ship reports and exceeded 10 m offshore.

Leading up to 30 March, 1978 Alby moved west along the coast in the northwest of WA, causing shore parallel winds that set up water levels to the east of the NW Cape with amplitudes of approximately 0.2 m with maximum levels in Exmouth Gulf. Alby then moved offshore during 2-3 April and the surge coincided with the central low pressure centre due to the inverse barometric effect with peak amplitudes nearing 0.5 m. During 2-4 April, surface gravity waves created by the storm exceeded 10 m offshore (Figure 4, right). As the storm moved southward and neared the coast passing Shark Bay (latitude 25 ^{o}S), the northerly winds caused a setup of water levels of up to a metre in the enclosed inner regions of the bay.

During 4th of April, Alby interacted with an approaching cold front and underwent extratropical transition, tripling its translational speed (from approximately 10 m/s to 30 m/s) and becoming highly asymmetric. The strong northerly winds set up water levels from Shark Bay south all the way to the southwest capes ranging from 0.2 m to ~ 1 m in Geographe Bay between Bunbury and Busselton (Figure 3 and 4 left). Wave heights also reached a maximum during this time with heights up to ~12 m (Figure 4, right) which was consistent with ship reports away from the storm centre. After the storm passed the southwest corner of the state water levels returned to normal following 5 April.

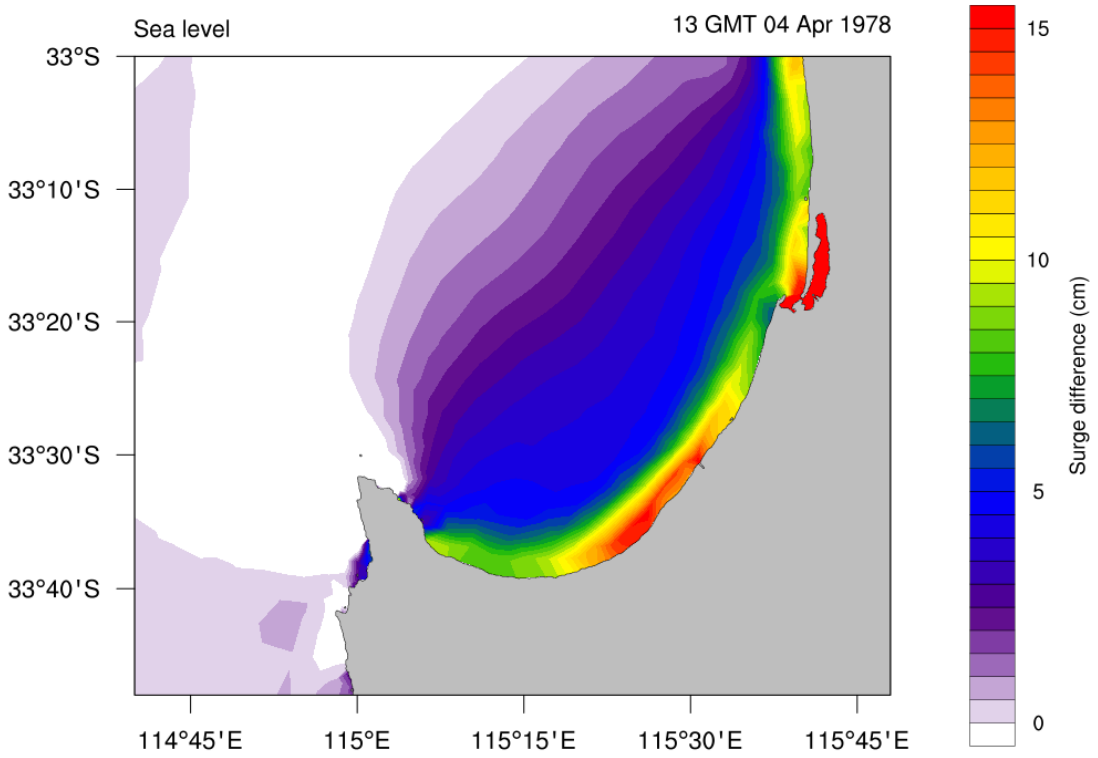


Figure 4. The wave-induced storm surge component estimated using the differences in the predicted storm surge heights in south-west Australia with and without the inclusion of waves in the coupled model.

Using uncoupled storm surge models, i.e. not exchanging information between them and not including wave effects in the storm surge part, resulted in significant differences in the peak amplitude of the simulated surge. In the case of the most affected regions: (a) Bunbury — the uncoupled maximum value was 0.86 m while for the coupled system the surge was 1m, an increase of 17%; (b) Busselton — uncoupled 0.99 m, coupled 1.08 m with an increase of 9%; (c) Perth city — uncoupled 0.47 m, coupled 0.74 m, with an increase of 58%; (d) Fremantle — uncoupled 0.5 m, coupled 0.72 cm, increase of 45%.

The difference in surge height related to coupling with waves (i.e. for the most flooded regions ~15%) could be crucial when simulating inundation at high resolution. For Perth, the most populated city in Western Australia, the wave coupled difference resulted in almost doubled values, however this location did not experience the full impact of Alby due to its position offshore.

TRANSITION FROM TROPICAL TO EXTRA-TROPICAL CYCLONES

Highly damaging storms along coastlines can occur when tropical cyclones (TCs) collide with winter weather systems. For example, in 2012 on the east coast of the United States tropical cyclone Sandy merged with a winter weather system just prior to landfall causing widespread devastation affecting 65 million people and destroying 570,000 buildings.

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. 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.

Many residents do not recognize the danger and risks that can happen when a tropical cyclone reaches colder water and undergoes extratropical transition. Often, predictions of ET by numerical forecast models do not accurately depict the characteristics of ET and the subsequent evolution of the resulting extratropical cyclone, compounding the risks to coastal communities.

ET occurs in nearly every ocean basin that experiences tropical cyclones. Australia experiences both tropical and extratropical cyclones and thus the potential threat from tropical cyclones undergoing extratropical transition warrants investigation.

The main difference between tropical cyclones and extratropical cyclones (cyclones out of the tropics) is the energy source—tropical cyclones are compact storms that extract heat from warm ocean waters and release it in the storm centre (warm-cored systems) whilst extratropical storms are fueled by temperature differences in the atmosphere and cover a much larger area.

As a tropical cyclone moves poleward it experiences changes that may include increased baroclinity (temperature/density gradients) and vertical shear, meridional humidity gradients, decreased sea surface temperature (SST) or strong SST gradients, and an increased Coriolis parameter. The structural changes of that occur during ET can be seen as a transformation from a symmetric warm-core TC to an asymmetric cold-core cyclone.

Extratropical Transitions around Australia

A preliminary review of literature and tropical cyclone tracks indicates that the southwest of Western Australia is more at risk from ET compared to the East Coast. However, few studies have investigated these events, and Australia remains the least studied region affected by ET compared to other ocean basins.

Australia is impacted by both tropical cyclones from the north (Figure 5) and mid latitude low pressure systems (extratropical cyclones) originating in the southern ocean. Tropical cyclones occur along both the Pacific and Indian Ocean coasts of Australia and generally move east to west and poleward before recurving toward the east. Tropical cyclone activity affecting Australia is strongly modulated by the El Niño Southern Oscillation (ENSO) with more cyclones generally crossing the coast during La Niña years. On a multi-decadal timescale there is evidence for decreasing numbers of TCs, but increasing intensity around Australia.

Southwest Pacific (Eastern Australia)

A general climatology for the Southwest Pacific of cyclones moving into the midlatitudes was developed by Sinclair [6]. However, they did not look specifically at those storms affecting the Australian coast. Jones et al. [7] indicated that the threat of ET events for the east coast of Australia was underestimated. In the Southwest Pacific tropical cyclone season is from November to May with highest numbers of tropical cyclones in February. Nearly one-third of TC's in this region make it into the midlatitudes (south of 35 deg. S).

In the Southwest Pacific the onset of ET occurs between 20-25 deg. S which is closer to the equator than in any other basin. Most storms undergoing ET develop extratropical characteristics by the time they reach 25 deg S as compared to 40 deg in the Northern Hemisphere. Sinclair [6] demonstrated that the existence of relaxed or enhanced pressure gradients south of the storms determined whether the storms would weaken or intensify. The approach of a midlatitude trough from the west triggered extratopical transition in this region.

Storms making it south of 35 deg S to the west of the dateline are more likely during La Niña years and late in the season (March and after). The general eastward component of movement of tropical cyclones as they go south alleviates some of the threat of ET impacting the East Coast of Australia since few storms have historically passed near to the coast south of 24 deg S (Figure 6).

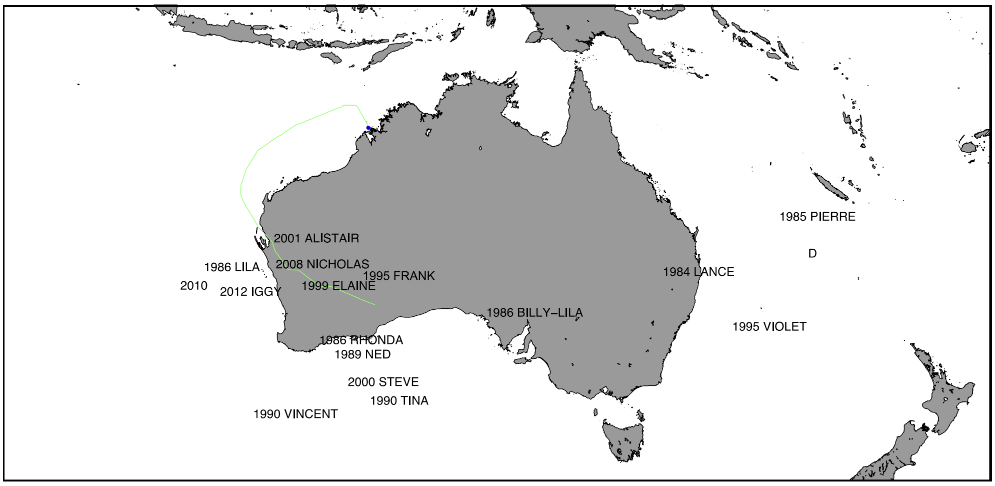


Figure 5. Plot of all tropical cyclone tracks around australia 1950-2013.

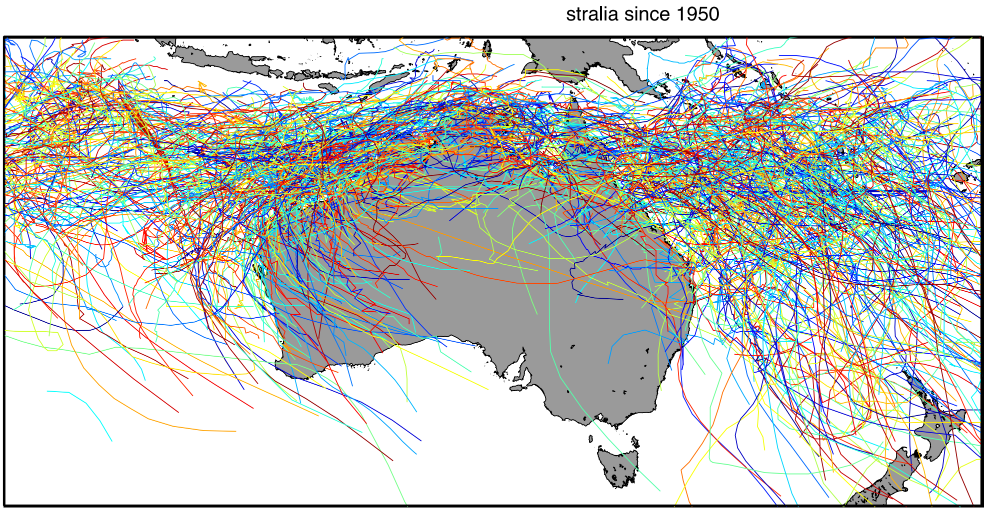


Figure 6. Cyclones with potential to impact the australian coast whilst undergoing et from 1970-2013. Potential ET cyclones were defined as storms passing within 100km of the coast below 24 degrees S. Blue dots indicate the first recorded position and green dots mark the last recorded location of the low pressure centre.

Southeast Indian Ocean (Western Australia)

Over the southeast Indian Ocean relatively few tropical cyclones undergo ET [7,8]. However, these storms are perhaps more likely to impact the coast due to their tracks (Figure 5).

Foley and Hanstrum [8] completed the most comprehensive study of Extratropical Transistion in Australia and compiled a climatology of tropical cyclones affecting the subtropical west coast of Australia. They found that twice as many cyclones affect the northern part of the state with around twenty percent moving into the midlatitudes maintaining some intensity.

Tropical cyclones were classified into two categories based on synoptic weather patterns:

(1) “Cradled” by easterly flow to the south

- All of these passed near NW Cape, moved southward parallel to coast with little acceleration and an average speed 6.5 m/s.
- Cradled cyclones were most likely to occur during January-April

(2) “Captured” by prefrontal westerly flow from midlatitudes due to an approaching low and cold front. These systems were considered to be undergoing extratropical transition.

- These storms accelerated and moved generally southeastward ~12.5 m/s (24 hours before affecting the coast).

- Acceleration occurred when fronts arrived within an average distance of 1660 km +/- 220 km.
- 100% of tropical cyclones causing damage at Perth were captured while only 20% captured damaged Carnarvon in the NW.
- These events were most likely March-April.
- Structural changes resulted in most rain poleward with dry conditions and strongest winds equatorward.

Summary of review findings

- As tropical cyclones move toward the poles they can interact with midlatitude weather systems causing the storms to lose tropical characteristics and become more extratropical in nature, often intensifying and accelerating-- this is known as Extratropical Transition (ET).
- Storms that undergo ET pose a serious threat to life and property by extending tropical cyclone–like conditions over a larger area in latitudes that do not normally experience such events.
- The conditions associated with ET are favourable for the generation of large damaging waves and storm surges.
- ET occurs in nearly every ocean basin that experiences tropical cyclones and numerical model predictions of these storms are typically inaccurate.
- The Australian region remains the least studied in terms of ET with only one study specifically focusing on the threat of ET to the Australian coast.
- Cyclone track records suggest that the southwest of Western Australia is the region most at risk, late in the season, when intense tropical cyclones are most likely to interact with approaching cold fronts.
- Storms making it south of 35 deg S to the west of the dateline are more likely during La Niña years and late in the season (March and after).
- The general eastward component of movement of tropical cyclones in the South Pacific alleviates some of the threat of ET for the East Coast of Australia as many of the storms curve away from the coast as they move south.
- Global reanalysis models provide useful tools to study ET events. However, these models typically underestimate the intensity of tropical storms and are limited by resolution.
- Improving the accuracy of storm surge models of ET events will require careful selection of forcing data, sensitivity studies, and special parameterisations due to the complex dynamics of these rapidly changing systems.

Prescribing wind fields for transitioning cyclones

Storm surge models rely on wind and pressure fields and simulated water levels are highly sensitive to these inputs. Global reanalysis models (e.g. NCEP, ECMWF ERA-I, JRA55) typically do not have the resolution required to accurately simulate the intense winds in tropical cyclones and as a result underestimate wind intensity in the cyclone core [9]).

A common alternative method for modelling landfalling tropical cyclones is to derive wind fields using a simple parametric wind model that uses only cyclone track data such as location, central pressure, radius of maximum wind, etc. For tropical cyclones, these simple models are surprisingly accurate and are broadly applied for emergency planning, risk assessment, and storm surge modelling (Vickery et al., 2009).

However, when tropical cyclones move into higher latitudes and undergo extratropical transition (ET) their dynamics change dramatically and the assumptions in these parametric wind models become invalid (Jones et al., 2003). In Australia this fact has commonly been ignored in storm surge modelling studies due to a lack of practical alternatives and/or the lack of information regarding the dynamics of ET.

The aim of this study was to determine whether parametric wind models or reanalysis models better reproduce the wind field of the most damaging ET event to affect Australia, Cyclone Alby (1978), for forcing a storm surge model.

The recently released Japanese Reanalysis JRA-55 reanalysis atmospheric model provided wind and MSL pressure fields on 1.25 degree resolution at 6 hourly intervals for TC Alby (Figure 7). This dataset has been shown to successfully capture the structure of storms transitioning from tropical to extratropical (Murakami, 2014). An advantage of the dataset is its vortex relocation algorithm that uses cyclone track data to ensure that the simulated storm follows an accurate trajectory. It appeared that the JRA55 data represented the structure of the transitioning storm as it approached the SW of Western Australia. Cyclone reports indicated the storm became highly asymmetrical at this time with strong northerly winds along the coast and this feature was evident in the model data (e.g. Figure 7e).

Since the magnitude of the simulated storm surge relies primarily on the wind field used to force the model it is critical to provide the best available data. For this application we found the JRA-55 reanalysis 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.

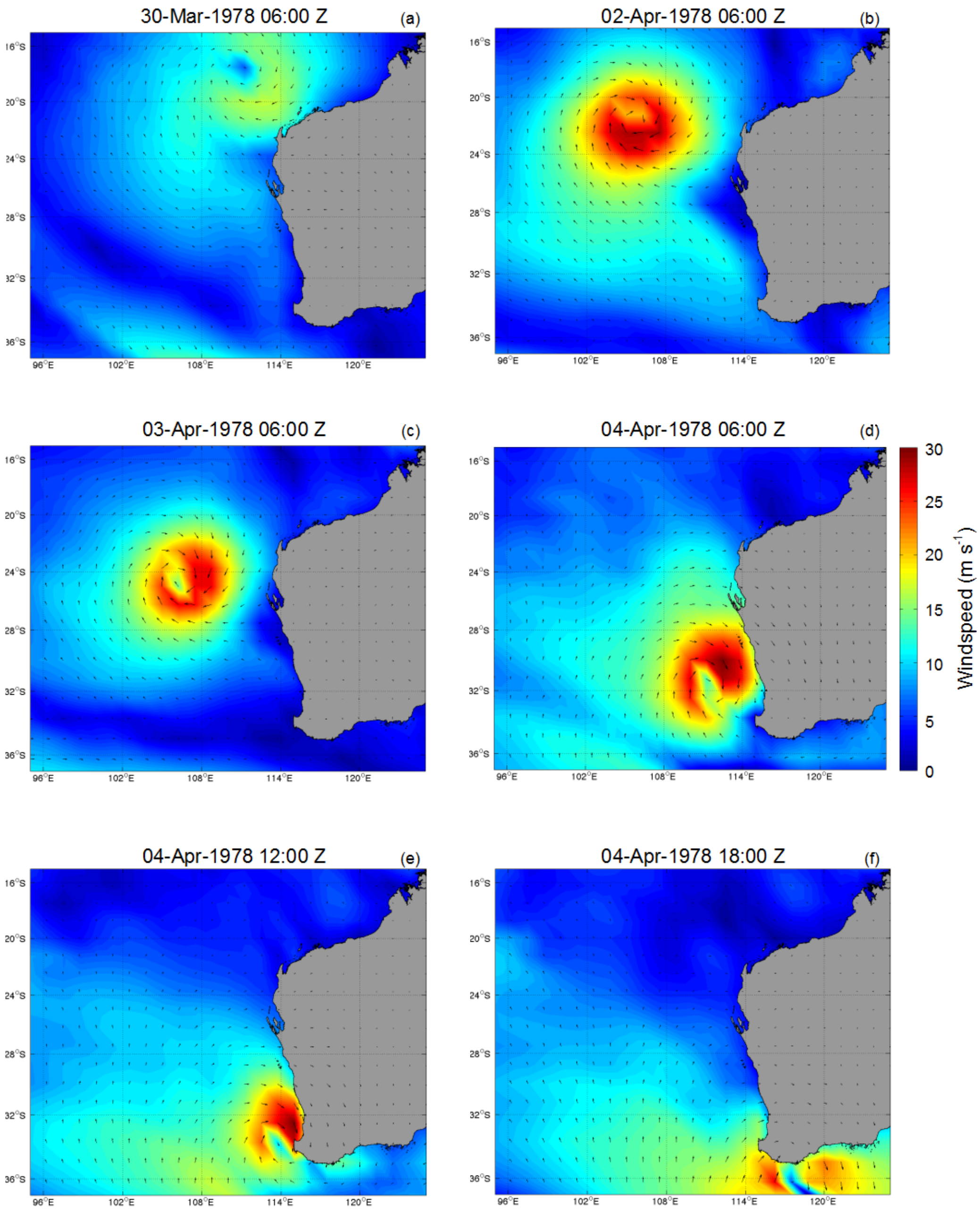


Figure 7. JRA-55 model wind speeds for cyclone Alby from 30 Mar 1978 to 4 April 1978 used to force the hydrodynamic/surge model. Intense winds over a broad area created extreme surges along the SW Australian coastline. Dates and times are given in GMT (local time is GMT+08 hours). Maximum winds and water levels occurred in Bunbury and Busselton around 04 April 12Z (8pm local time).

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 which 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}.

Along the west Australian coastline, the continental shelf waves are generated through the passage of mid-latitude low-pressure systems and tropical cyclones. The continental shelf waves can be identified from the sea level records by low-pass filtering (i.e. removal of the tidal component). An example is shown on Figure 8 for tidal records from Port Hedland, Geraldton, Fremantle and Albany due to tropical cyclones Isobel and Jacob can be identified. The propagation time of the CSW between Geraldton and Fremantle was 23 hours, and between Fremantle and Albany it was 17 hours, yielding a mean propagation speed of ~500 km day^{-1} (~6 ms^{-1}). The period of the continental shelf wave range between 3-10 days and corresponds to the passage of synoptic systems from west to east across the west Australian coastline.

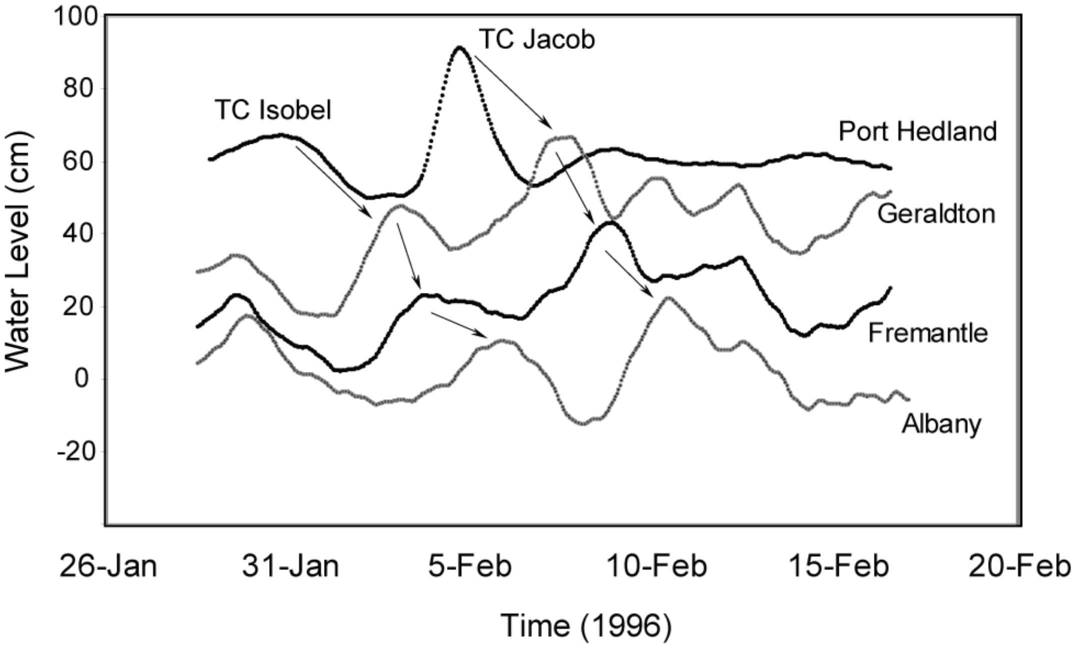


Figure 8 – Water level observations along Western Australia following TC Isobel amd TC Jacob – February 1996.

Tropical cyclones are intense low pressure systems which form over warm ocean waters at low latitudes and are associated with strong winds, torrential rain and storm surges (in coastal areas). They may cause extensive damage as a result of strong winds and flooding (caused by either heavy rainfall and/or coastal storm surges). The impacts of tropical cyclones on the North-West region of Australia are well known with several severe cyclones impacting this region over the past few years. The most noticeable impacts of these cyclones are normally restricted to the region of impact of the cyclone, and hence the direct effect of cyclones on south-western Australia is rare. Fandry et al. [10] identified 1 to 2 m amplitude peaks in sea level propagating southwards with speeds ranging between 400-600 km day^{-1}. These were associated with tropical cyclones travelling southward and were attributed to a resonance phenomenon when speeds of the southward component of the cyclone speeds were close to the southward propagating continental shelf wave.

Ongoing development and testing of a numerical model for the purposes of simulating storm surges and CSWs along the Australian coast has been undertaken. It should be noted that simulating continental shelf waves is not a trivial matter and requires advanced numerical models. Previous storm surge models for Australia [2] were unable to simulate CSWs thus providing motivation for this investigation. Encouraging results have been obtained using the numerical model ROMS (Figure 9).

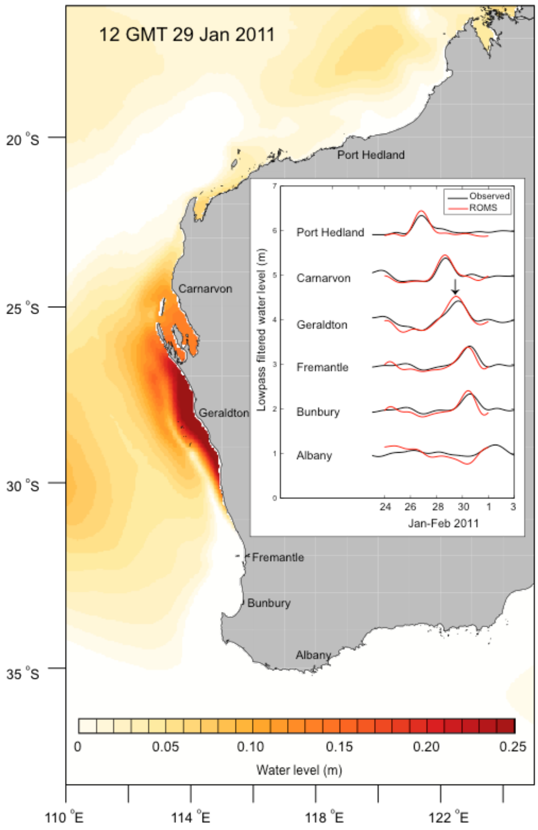


Figure 9. Simulated water levels from the ROMS model run for Bianca (2011). Colour represents the water level (no tides) with arrows showing water transport direction. The inset shows time series of the surge at the stations indicated on the map.

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 which 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 the project, the occurrence of meteotsunamis along the south-west coast of Western Australia (WA) was investigated. Tide gauge records were used to examine water level oscillations with periods < 6 hours, which were then related to local atmospheric data. A meteotsunami which occurred on 14 August 2014 is examined in detail as it resulted in a ship breaking moorings in Fremantle port and impacting on a railway bridge.

Methodology

Water level time series records from tide gauge stations, Geraldton, Jurien Bay, Hillarys, Fremantle, Bunbury and Busselton were obtained from the Department of Transport (WA). The analysis is focussed on the records obtained in recent years when high-frequency data (sampling periods between 1 and 5 minutes) were available. The annual time series record for Hillarys Boat Harbour, with a sampling interval of 1 minute, collected in 2014 were analysed for this study. In addition water level data from Two Rocks, Fremantle Inner Harbour, Fremantle Boat Harbour and current meter data from inside and outside Fremantle harbour for August 2014 were analysed.

The water level time series records were subjected to several filtering methods to isolate the meteotsunami signal as follows: (a) The observed water level record was subjected to harmonic analysis using the T-Tide MATLAB toolbox to remove the tidal components from the sea level records, resulting in the residual time series.; (b) the residual time series was subjected to a low-pass filter to remove the periods < 36 hours, resulting in a time series that included the storm surge and weather band frequencies; (c) the storm surge and weather band frequencies were subtracted from the residual time series to provide a time series that contained periods < ~six hours, which included seiches and tsunami waves (both seismic and meteo).

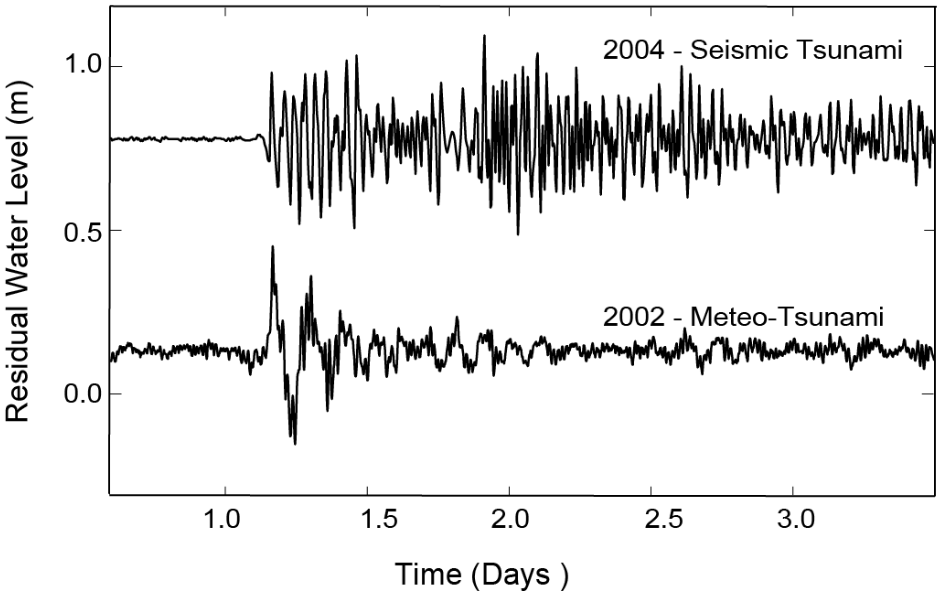
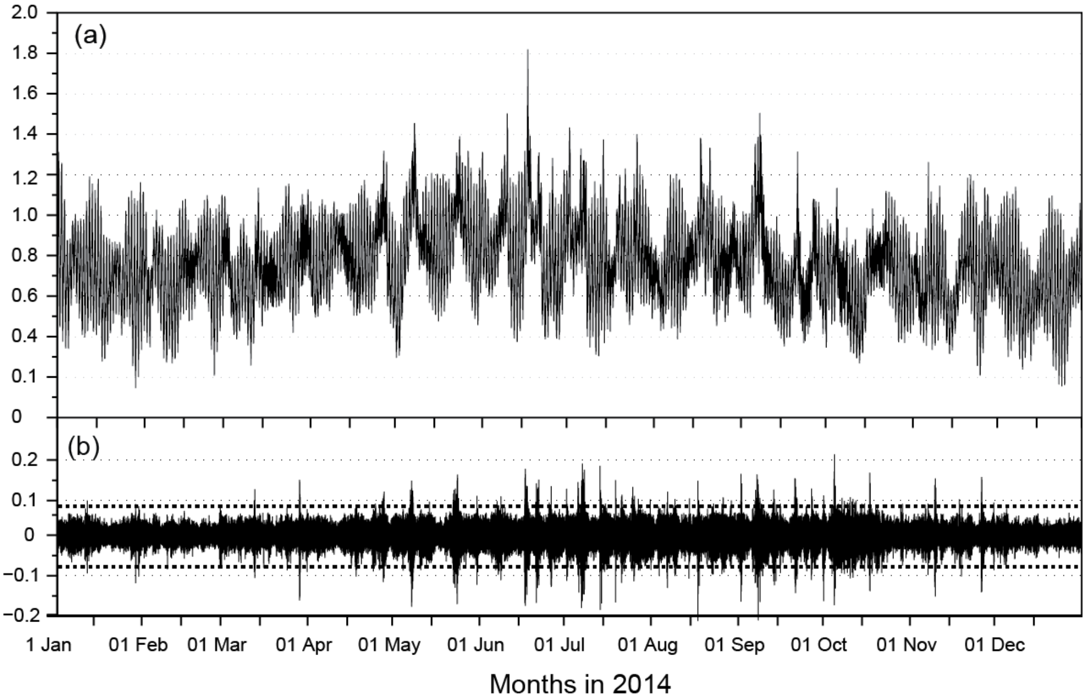


Figure 10: Time series of residual water level (filtered to include periods < 6 hours) recorded at Fremantle Boat Harbour during the 2004 Indian Ocean Tsunami and a meteotsunami recorded in 2002.

Meteotsunamis: Hillarys Boast Harbour 2014

The annual sea level record for Hillarys in 2014 exhibit typical sea level characteristics as reported in the literature (Figure 11): there is a fortnightly cycle of tropic and equatorial tides with storm surge and continental shelf wave signals superimposed. The mean sea level is a maximum during austral winter due to oceanic processes. The maximum water level was 1.82 m during the passage of the cold front in mid-June (Figure 11a). The sea level record from Hillarys, with a sampling interval of 1 minute was subject to the sequence of filtering (see above) to extract the time series with periods < 6 hours (Figure 11b). Using the threshold criterion suggested by Monserrat et al. (2006) to classify a meteotsunami as a wave amplitude which exceed 4*σ, in 2014, there were > 30 events recorded in the time series with the majority in terms of magnitude and number occurring in during the winter months. The maximum recorded wave height was 0.4 m on 5 October. The event on 17 August had a maximum wave height of 0.35 m. The occurrence of higher number of events during the winter months is mainly due to the passage of mid-latitude depressions and associated frontal systems. Other frequencies at 2.7 hours and 15 minutes are due to local seiches. The spectral energy at the 2.7 hour oscillation is present almost all the time and has been attributed to the continental shelf seiche (with the continental shelf width being ~ 50km. A feature of these two oscillations (and perhaps another minor one at ~ 1 hour) is that there is energy at the both of these frequencies almost continuously throughout the year. These represent the background oscillations in the filtered time series record which fall into the category < 4*σ and thus not classified as a meteotsunami (Figure 11b). However, there are periods when the energy is enhanced coinciding with the meteotsunamis: it appears that during the passage of a frontal system, the whole spectrum is energised as shown in the higher energy bands across all frequencies which corresponds to the meteotsunami events (cf Figures 11b and 11c). This increase in energy across all the frequencies and enhancing the existing frequencies were reported for meteotsunamis at other locations along Western Australia.

Figure 11 Time series of the Hillarys sea level record for 2014; (b) Filtered water



level (< 6 hour period) showing the meteotsunamis. The dashed line shows the 4*σ value.

Meteotsunami: 10 June 2012

The meteotsunami recorded on 10 June 2012 occurred during winter and was generated by the passage of a low pressure system across south-west Australia. The low pressure system was initiated as a tropical low off WA's north-west coast, and moved almost parallel to the coast, with the centre of the low crossing the coast to the south of Perth. The system caused maximum (gust) wind speeds > 30 ms^{-1} and a rapid change in wind direction from shore-parallel (northerly) to onshore (westerly). The system was extreme, with a drop in sea surface pressure of 30 hPa over 36 hours and a minimum of 983 hPa. Sea surface pressure values < 1000 hPa are rare in these subtropical systems. The meteotsunami generated from the low pressure system produced the highest water level ever recorded at Fremantle, which has a continuous record spanning over 110 years and is the longest sea level record in the southern hemisphere. The meteotsunami wave height was 0.61 m.

The Fremantle tide record has several components that contribute to sea level variability: tides, storm surges, and annual and inter-annual variability due to large-scale oceanic changes. The meteotsunami occurred at high tide (Figure 12) and coincided with the local storm surge; it was also a La Niña year, so the meteotsunami also coincided with a strong Leeuwin current. These factors all contributed to producing the highest water level recorded at Fremantle. In contrast, the corresponding meteotsunamis at Bunbury (wave height of 1.03 m) and Busselton (wave height of 1.10 m) had the highest wave heights recorded at these stations and were equivalent to the maximum storm surges recorded at these stations during tropical cyclone Alby in 1978.

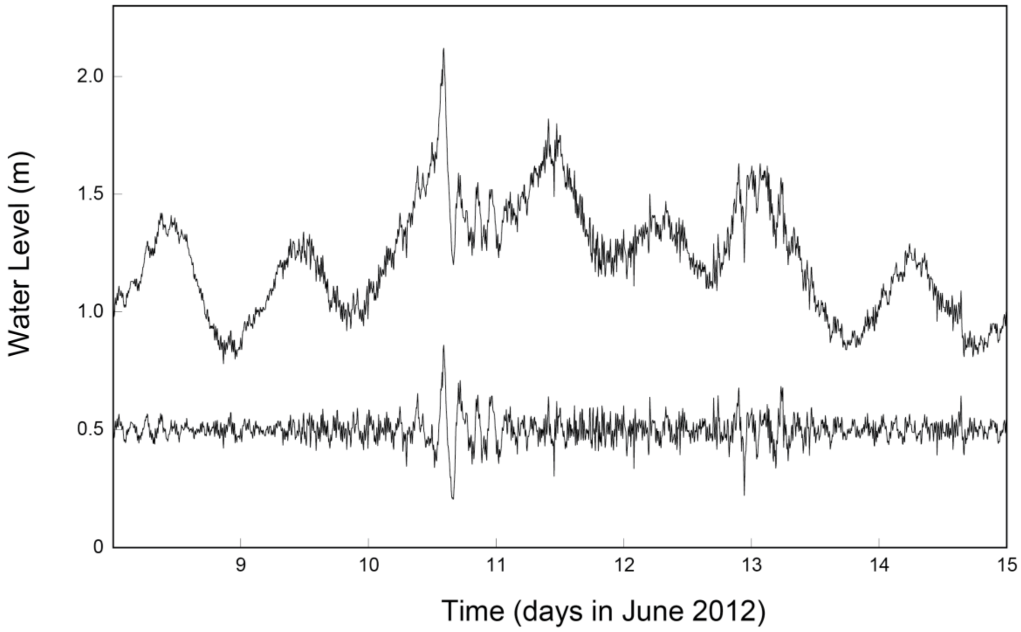


Figure 12 Time series of (a) observed and (b) filtered (< 6 hour period) water level records at Fremantle on 8-15 June 2010.

Meteotsunami: 17 August 2014

At 2203 hours on Sunday 17 August 2014, car carrier *Grand Pioneer* and the container ship *AAL Fremantle* were moored in Fremantle Port at Berths 11 and 12, respectively. A bollard that was holding all three of the *AAL Fremantle*'s stern lines and two from the car carrier the *Grand Pioneer* ripped off the wharf causing both ships to swing away from berth.

AAL Fremantle, freed from its stern lines swung around and collided with the railway bridge, which was badly damaged and closed for two weeks, severely disrupting one of Perth's major commuter railway lines. Initially, the incident was attributed to strong winds associated with a passage of a front, but further analysis revealed that the ship's moorings were broken by strong currents within the harbour which could be attributed to a meteotsunami. At the time of the incident, widespread thunderstorms were experienced in the region. Data from a local meteorological station at Rottnest Island and coastal water level data from 4 locations were examined to determine the cause of the strong currents inside the harbour. Time series of atmospheric pressure indicated a gradual decrease, with two pressure jumps evident in the record (Figure 13b). The first pressure jump of amplitude 2.1 hPa occurred over a period of 83 minutes (between 20:20 to 21:43) and was associated with pulse of wind, to maximum speed of 17 ms^{-1} whilst the second pressure jump was more severe with a 2.4 hPa change over 14 minutes (between 21:43 to 21:57) with winds speeds up to 23 ms^{-1} and gusts up to 30 ms^{-1}. Tide gage records all indicted the presence of higher water level fluctuations coinciding with the passage of the pressure jump. The higher water level fluctuations are first observed at the northern-most station, Two Rocks, which is located 70km away from Fremantle and progressing southwards, in the direction of the pressure jump. The rainfall radar also indicated progression of the rain bands from north to south. The maximum wave heights at Hillarys and Fremantle (at both Inner and Boat Harbours, Figure 3c) were observed 8 and 20 minutes later than those observed at Two Rocks, respectively (Figure 13c). As the wave progressed in the harbour, very strong currents > 1.0 ms^{-1} (depth-mean) was measured to the north of the entrance breakwater, travelling in a south-westerly direction prior to entering the harbour. As the wave progressed inside the harbour, the constriction at the location of the bridge enhanced the currents at berths 11 and 12 resulted in moorings being broken. The location of a shallow shoal, the Wangara shoal, immediately downstream of the railway bridge was thought to prevent ships impacting on the bridge. However, the water levels were higher due to the meteotsunami and thus the *AAL Fremantle* was able to pass over the shoal. Although there was insufficient water after the impact with the bridge and a different route was used to relocate the ship at the berth.

Examining the sea level time series for 2014, the event on August 2014 was not the largest event recorded during the year (Figure 11b). It is also interesting that another event on 10 September, although not very large resulted in the breaking of mooring lines within the Port without any further damage.

This is study currently being extended to cover the whole of Australia. Preliminary analysis of the high resolution sea level over the past 5 years from stations around Australia have indicated more than 200 events which currently being analysed.

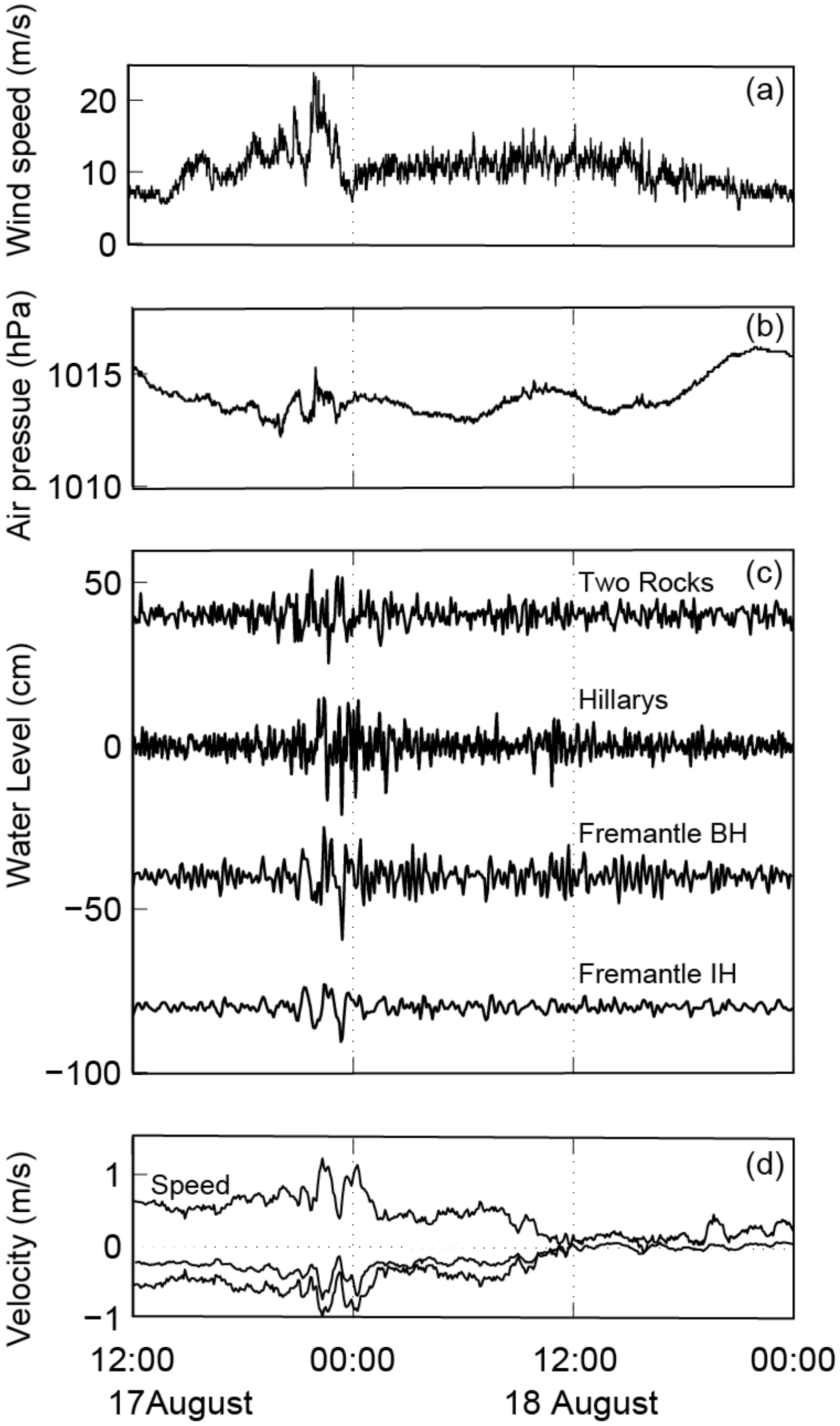


Figure 13 Time series of meteorological and oceanographic data associated with the meteotsunami in Fremantle Port on 17 August 2014. (a) & (b) Wind speed and atmospheric pressure at Rottnest Island; (c) Filtered water levels at Two Rocks, Hillarys, Fremantle Boat Harbour and Fremantle Inner Harbour; and, (d) Measured currents at AWAC station.

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Lam Wilson (The University of Western Australia)

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