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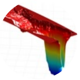

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Storm surge risk from transitioning tropical cyclones in Australia

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Abstract

When tropical cyclones come ashore strong winds can set up storm surges that devastate coastal communities through erosion and inundation of low lying areas. In Australia, storm surge risk from tropical cyclones is generally restricted to warmer northern regions whilst in the southern regions damaging storm surges tend to arise from extratropical low pressure systems. Often, tropical cyclones weaken as they move into higher latitudes passing over cooler waters and experiencing higher wind shear. However, in some cases tropical cyclones can interact with mid-latitude weather systems causing the storms to lose tropical characteristics and become 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. Here we aim to describe the storm surge risk from tropical cyclones transitioning into the higher latitudes around Australia using observations, atmospheric reanalyses, and a coupled storm surge-wave model. We highlight modelling challenges and examine two contrasting case studies: (1) the worst case scenario of Cyclone Alby (1978) that underwent ET causing large waves, flooding, erosion and $50 million in damage in southwest Australia; and, (2) a 'near miss' event from Cyclone Bianca (2011) that weakened just before making landfall in the same region. The simulated surge from Alby peaked at 1.1 m in Busselton, with approximately 10% of the height resulting from wave effects included in the model. Predicted wave heights exceeded 10 m offshore. Cyclone Bianca weakened dramatically before landfall and major damage did not occur. We propose that tropical cyclones moving into higher latitudes need to be given special consideration due to their unpredictable nature and the potential for damaging storm surges.

Keywords: sea level, cyclones, extratropical transition, continental shelf waves, storm surge.

1. Introduction

As tropical cyclones move toward the poles they can interact with the surrounding environment causing the tropical cyclone (TC) to lose tropical characteristics (deriving their energy from cloud and rain formation) and become more extratropical in nature (deriving energy from horizontal temperature gradients in the atmosphere) – this is known as Extratropical Transition, or ET. These transformed 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 [1]. They often evolve into fast-moving and occasionally rapidly intensifying extratropical cyclones that produce intense rainfall, very large waves, and tropical cyclone intensity winds [1].

Many residents do not recognize the danger and risks that can happen when a tropical cyclone reaches colder water and undergoes extratropical transition [2]. Often, predictions of ET by forecast models do not accurately depict the characteristics of ET and the evolution of the resulting extratropical cyclone, compounding the risks to coastal communities [1]. Often, storm surge models used for planning purposes treat transitioning storms as typical tropical cyclones, an assumption that is not valid and can result in under prediction of storm surges.

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 [3]. This paper describes the historical occurrence of ET around Australia based on a review of literature and archived tropical cyclone track data. Numerical storm surge simulations of two contrasting TC's (one undergoing ET and the other dissipating) in Western Australia (WA) are presented to highlight modelling challenges and the importance of treating the two storm types differently.

2. Methods

An assessment of the risk from transitioning TC's around Australia was undertaken through a review of literature and historical archive data, and through numerical hydrodynamic simulations of two storms affecting the southwest of Western Australia (WA). Cyclone Alby (27 March-6 April 1978) underwent ET and caused $50 million in damage. Cyclone Bianca (21 January- 1 February 2011) weakened just before landfall near Perth and did not undergo ET.

2.1 Observational data

Tropical cyclone track data were obtained from the IBTrACS (International Best Track Archive for Climate Stewardship [4], In the Australian region these data are derived from the Australian Bureau of Meteorology (BOM). The tropical cyclone database for the Australian region generally lacks records of whether individual TC's underwent ET. Historical references were therefore collected from published scientific papers and BOM tropical cyclone reports (http://www.bom.gov.au/cyclone/history/). Further assessments of potential coastal risk from ET relied on the TC track data.

2.2 Numerical model

2.2.1 Coupled hydrodynamic-wave model SELFE

Storm surges were simulated with the SELFE modeling system (Semi-implicit Eulerian–Lagrangian Finite Element) (http://www.stccmop.org/knowledge_transfer/software/selfe). SELFE is an open source code based on unstructured triangular grids that is specifically designed to simulate 3-D circulation and water levels across broad spatial scales, from the open ocean to shallow bays and estuaries including the ability to model inundation and wetting and drying. In this application the Wind Wave Model (WWM-II) was two-way coupled with the hydrodynamic model to better represent wind stress over the sea taking into account wave surface roughness and dynamics. The WWM-II 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 [5] and the South China Sea [6]. Multiple model runs were undertaken with coupling switched on and off to determine the effects of including waves in the simulation. Tides were not included in the simulation.

The unstructured triangular mesh grid for WA consisted of 66,893 nodes and 127,090 elements and was refined by depth with coarse resolution offshore and fine resolution near the coast (Fig. 4). The minimum element area was 700 m^2 (~40 m length scale equivalent), the maximum element area was 98 km^2 (~14 km equivalent), and the median was 36 km^2 (~8.5 km).). Bathymetry data (250 m) from Geoscience Australia [7] were merged with higher resolution data where required. The vertical grid consisted of hybrid sigma-z coordinates with 25 z levels in the deep ocean and 37 sigma levels on the continental shelf.

2.2.2 Atmospheric forcing

The recently released Japanese Reanalysis JRA-55 reanalysis atmospheric model [8] provided wind and MSL pressure fields (1.25 degree; 6 hourly resolution) were used to force the hydrodynamic model. This dataset has shown some success in capturing the structure of storms transitioning from tropical to extratropical [9]. A vortex relocation algorithm in JRA-55 uses cyclone track data to ensure that the simulated storm follows an accurate trajectory. Although reanalysis datasets tend to underestimate the intensity of tropical cyclones [9], JRA-55 appeared to better simulate ET events compared to the common approach of using parametric wind and pressure models (e.g Holland) [10] that assume the storm is symmetric and tropical in nature when in fact this is not the case for storms undergoing ET.

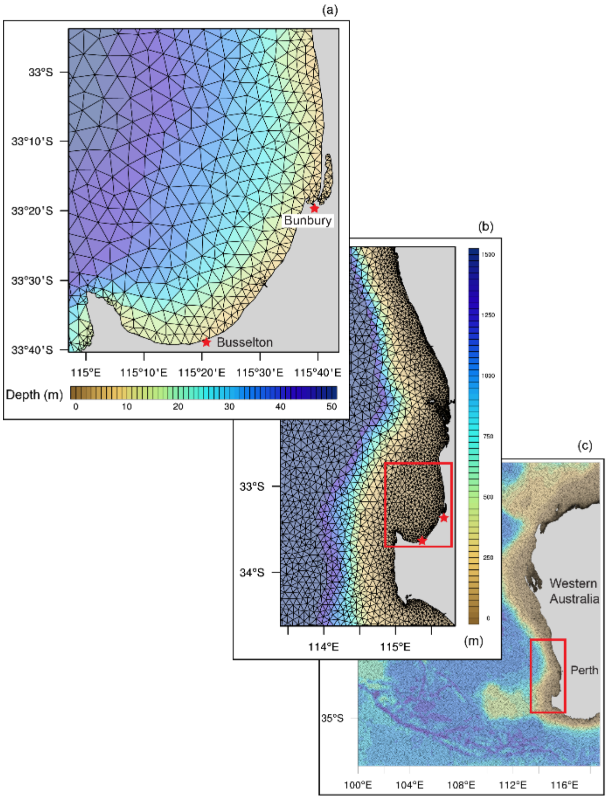

Figure 1. The model grid for western Australia showing the study site for the Cyclone Alby test case and the unstructured mesh. Resolution increased from ~2000 m offshore to as fine as ~100 m at the coastline. Sub maps (a,b) are zoomed views of the full WA grid (c) and are not separate grids.

3. Results

3.1 ET around Australia

A review of literature and tropical cyclone tracks (Fig. 2) indicated 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, such as the North Atlantic and Western North Pacific where there have been a number of field experiments dedicated to understanding extratropical transition [1].

Australia is impacted by both tropical cyclones from the north and mid latitude low pressure systems (extratropical cyclones) originating in the southern ocean [11, 12]. 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 [13].

In the Southwest Pacific nearly one-third of TC's make it into the midlatitudes (south of 35 deg. S) [13] and are more likely during La Niña years and late in the season (March and after). The onset of ET occurs here between 20-25 deg. S, which is more than 10 degrees closer to the equator than in any other basin. In general, the approach of a midlatitude trough from the west triggers ET in this region [13].

Over the southeast Indian Ocean, along the Western Australian coast, relatively few tropical cyclones undergo ET [1, 3]. However, these storms are perhaps more likely to impact Australia due to their tracks re curving back to the coast (Fig. 2). Foley and Hanstrum [3] classified tropical cyclones in this region into two categories based on synoptic weather patterns:

1) "*Cradled*" by easterly flow to the south, paralleling the coast with little acceleration and an average speed of 6.5 m/s and more 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 and were more likely to occur late in the season.

Based on this review the numerical simulations focused on the southwest of Australia, and the most intense ET event that has been recorded to impact Australia, Cyclone Alby, 1978.

3.2 Cyclone Alby 1978 – a 'worst case'

3.2.1 Background

One of the most destructive storms in Western Australia was Cyclone Alby in 1978 that caused an estimated $50 million dollars in damage and killed five people (see track Fig. 2). Large waves and extreme surges caused coastal erosion and inundation across the southwest of the state [14]. Alby was not a typical tropical cyclone. As Alby moved south out of the tropics it violently interacted with an approaching cold front and became a hybrid storm transitioning from tropical to extra tropical in nature. The storm tripled its translational speed (from 10 m/s to 30 m/s) and distorted spatially creating an extremely broad area of northerly winds along the coast, causing it to become a 'worst case scenario' for the southwest of the state due to the extreme waves and storm surge created [3].

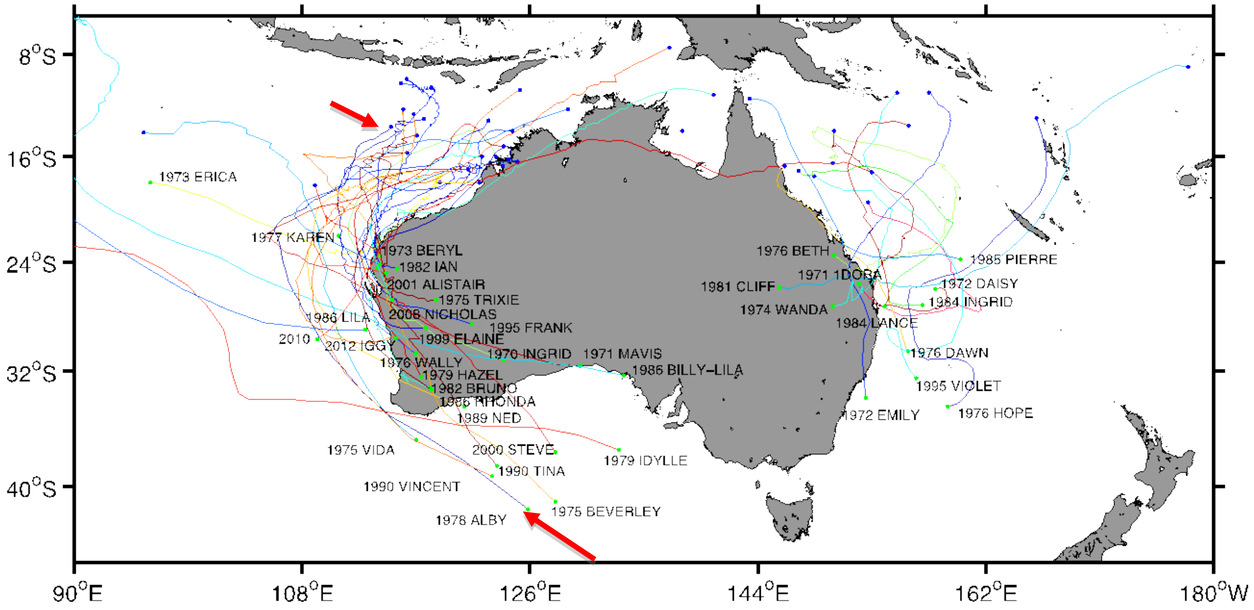

Figure 2. Cyclones with potential to impact the Australian coast while undergoing ET from 1970-2013. Potential ET cyclones were defined as storms passing within 100km of the coast below 24 degrees S (data from IBTrACS). Blue dots indicate the first recorded position and green dots mark the last recorded location of the low pressure centre. The start/end of Cyclone Alby's track are shown with red arrows.

3.2.2 Numerical model results

The maximum storm surge for Cyclone Alby was reported to be approximately 1.3 metres on the evening of 04 April 1978 (approx. 1pm GMT or 9pm local time) at Bunbury. The de-tided observed water levels peaked at ~ 1.17 m compared to the coupled model results that indicated a surge of ~ 1.02 m at the same location (Fig. 3) with similar timing and duration. Following the peak of the surge the water levels oscillated with a period around 4.5 hours due to a continental shelf seiche that commonly observed in this region. The model captured this feature but underestimated the amplitude, possibly due to model numerics or bathymetry.

During 4 April, as Alby underwent extratropical transition strong northerly winds (Fig. 4a) set up water levels from Shark Bay (~0.2 m) south all the way to ~1.1 m between Bunbury and Busselton in Geographe Bay (Fig. 4b). Wave heights also reached a maximum during this time with heights up to ~15 m offshore (not shown) 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, 1978

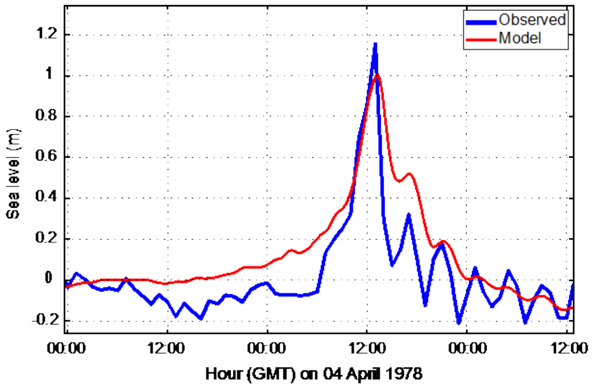

Figure 3. Simulated storm surge (5 min) plotted against hourly observed residual water levels (tide removed) at Bunbury for TC Alby on 4 April, 1978 (Time is GMT, for local time add 8 hrs). Tide gauge data for Bunbury provided courtesy of WA Department of Transport.

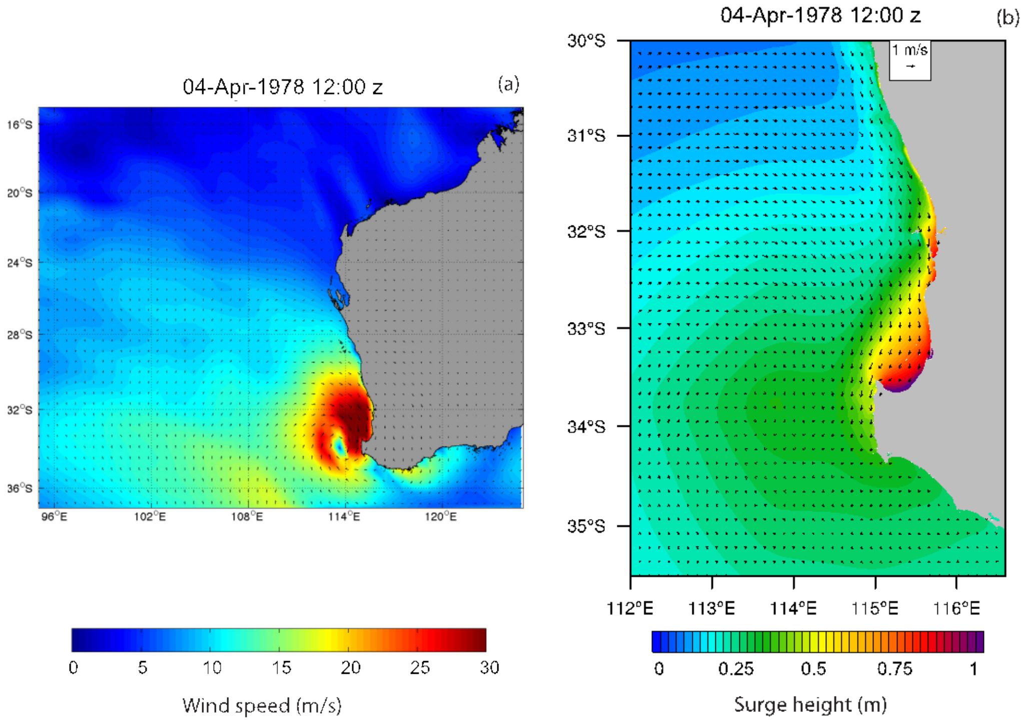

Figure 4. JRA-55 wind field (a) and simulated water level (b) at approximately the time of maximum surge observed in the SW of Western Australia caused by cyclone Alby. At this time the transitioning storm created a highly asymmetrical wind field with strong northerly winds near the coast evident in (a) which in turn caused extreme surges in the region. Vectors show wind direction and surface currents respectively. Time is given in GMT; local time is GMT +8.

Including waves in the model was found to significantly increase the amplitude of the simulated storm surge. In the fully coupled model runs the inclusion of waves resulted in storm surges at both Busselton and Perth that were 10% and 58% higher respectfully compared to the uncoupled simulations without the effects of waves (Fig. 5). Preliminary analysis show this to be mostly due to an increase in the transfer of energy from the wind to the ocean surface when waves were included, however, further investigation is needed.

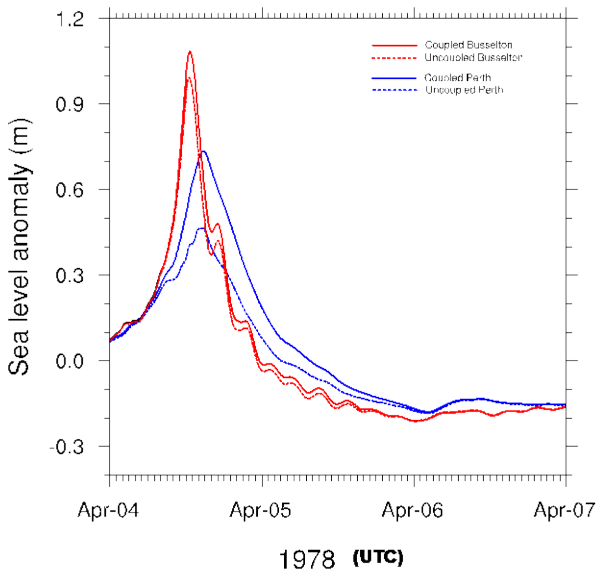

Figure 5. Simulated storm surge time series of water levels resulting from Alby in Perth and Busselton for model runs (GMT time) with/without the effects of waves included.

3.3 Cyclone Bianca 2011 – a 'near miss'

3.3.1 Background

Cyclone Bianca developed to the west of Darwin between 21-25 January 2011 and paralleled the coast before moving offshore near Exmouth and intensifying into a Category 4 Cyclone as it recurved to the south, west of Carnarvon (Fig. 6). Bianca was forecast to impact Perth with tropical cyclone intensity arriving at local high tide and coinciding with the passage of a continental shelf wave generated by the storm several days earlier. Hours before landfall Bianca weakened dramatically but high water levels at Perth still caused some minor flooding and large waves eroded local beaches (http://en.wikipedia.org/wiki/2010%E2%80%9311_Australian_region_cyclone_season#Severe_Tropical_Cyclone_Bianca).

TC Bianca did not undergo ET and is presented here to contrast the extreme surge caused by the ET of Alby in 1978.

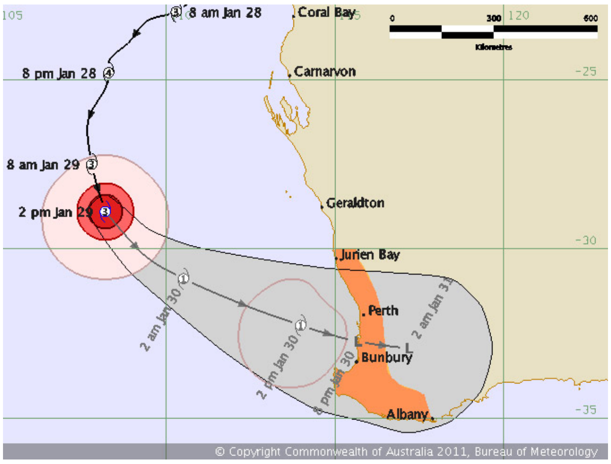

Figure 6. Forecast track for TC Bianca on 29 January 2011. If the storm had arrived as predicted damage from coastal flooding would have likely resulted. Source: Australian Bureau of Meteorology.

3.3.2 Numerical model results

The model predicted storm surges of up to 0.8 m in the northwest of the state between Karatha and Shark Bay (Fig 7) that was consistent with observations. At Karatha the surge was underestimated in the model time series of water levels, but surrounding areas showed comparable sea levels suggesting sensitivity to the grid node selected for comparison. The elevated water levels propagated down the coast as a Continental Shelf Wave (CSW). The CSW was evident in the model results as far south as Jurien Bay, although the amplitude was smaller than the actual CSW as observed in tide gauges by that latitude. In reality the shelf wave retained heights of up to 0.4 m at Fremantle and was still discernible on the south coast of WA at Albany. This highlights the challenges in modelling the many processes that contribute to extreme sea levels.

Because Bianca fully dissipated before landfall there was only a very minor local storm surge both in the model and in the observations. The wave model predicted wave heights greater 10 m offshore and under 2 m at the coast in the Southwest (not shown). Although wave heights at the coast were not large by local standards the rare northwest direction of the swells caused erosion of local beaches.

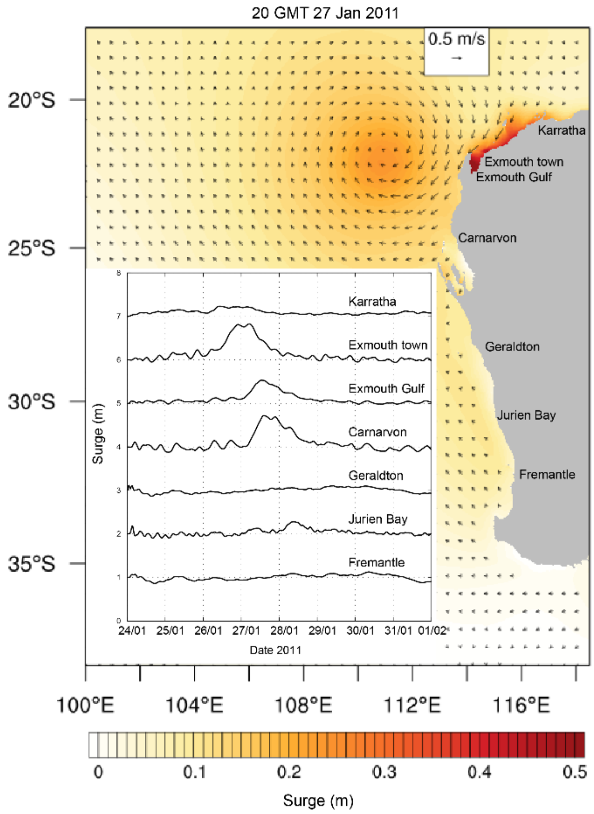

Figure 7. Simulated storm surge generated by Cyclone Bianca 24-30 January 2011 along the West Australian Coast

4. Discussion and conclusions

Although ET is not as prevalent around Australia compared to other ocean basins, there is still a substantial risk, especially for the southwest of Australia, where the most damaging storm surges were caused by a transitioning storm. The East coast of Australia is somewhat protected as most tropical cyclones recurve toward New Zealand by the time they travel far enough south to interact with midlatitude weather systems. Tropical cyclones are most likely to interact with approaching cold fronts, and undergo ET, late in the season during April and May.

Extreme water levels caused by the extratropical transition of Cyclone Alby were successfully simulated using a state of the art hydrodynamic model coupled with a wave model and forced by a reanalysis dataset. Including the coupled wave model in the simulations made a significant improvement (~20%) to prediction of water levels.

The model also predicted accurate water levels for TC Bianca in the northwest of the state and generated a shelf wave that propagated south along the coast. The simulated shelf wave dissipated somewhat prematurely before reaching Perth. In this event it was predicted that the CSW, high tide, and a local storm surge would coincide to cause extreme sea levels. Since Bianca did not undergo ET and weakened before impacting the coast the Perth region was spared major damage--a ‘near miss’.

Despite the overall underestimation of wind speeds of tropical cyclones in coarse reanalysis datasets, it is encouraging that the JRA-55 captured much of the dynamics and structural changes of the extratropical transition of Alby. It appeared that the newest reanalysis atmospheric models are becoming adequate enough to simulate a surge from an ET event.

An alternate, and more common, method for simulating storm surges from tropical cyclones is to apply a parametric wind/pressure model (such as the Holland, 1980 model) to the observed track and central pressure estimates to generate wind fields to force the hydrodynamic model. This generally works well and can be useful for deriving statistics for planning purposes [15]. However, an important question is whether this approach is valid when the storm is no longer tropical and undergoing ET.

Previous modelling studies that applied the Holland model to simulate the surge caused by Cyclone Alby found they had to artificially adjust the track of the cyclone in order to get water levels to match the observations [16]. This suggests that treating ET storms as standard tropical cyclones is not the best approach.

On the other hand for storms retaining tropical characteristics, such as Cyclone Bianca, perhaps the forcing with parametric wind models is sufficient, or better than reanalysis forcing.

Future work is planned to directly compare the surges generated using Holland wind fields against the JRA-55 reanalysis data. The goal will be to determine which of the two approaches is better for specific types of storms and/or come up with parameterisations that improve our ability to model these storms.

5. Acknowledgements

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