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IMPROVED PREDICTIONS OF AUSTRALIAN EXTREME SEA LEVELS THROUGH A COUPLED WAVE-SURGE MODEL

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ABSTRACT

In order to protect life and property coastal planners and emergency managers require accurate estimates of flood risk. Providing reliable predictions of extreme sea levels for this purpose represents a significant challenge due to the range of complex processes that vary from beach to beach, town to town, and state to state around the entire Australian continent. As a result, a reliable comprehensive dataset of extreme sea levels for the entire coastline does not yet exist. Recent technological advances have allowed us to develop a high-resolution numerical model capable of analysing ocean dynamics to better understand how storms will impact local beaches on an Australia-wide scale. The advanced, high-resolution (in the coastal zone ~100m) 3D finite element hydrodynamic model (SCHISM) coupled with the state-of-the art WWMIII wave model included the effects of wave breaking on top of storm surges caused by wind and pressure. Simulations of multiple extreme sea level events, ranging from Southern Ocean winter storms to destructive tropical cyclones revealed that including waves in the simulations raised surge levels between 10–50 per cent, depending on local water depths and coastline orientation. To illustrate the robustness of the coupled wave-surge model we present results from Cyclone Yasi (2011), the largest and most intense storm to impact Queensland since 1913. The cyclone caused extensive damage to property and infrastructure costing $800 million over more than 500 km of coastline. A storm surge of 5.5 m was simulated in Cardwell with waves exceeding 12 m offshore and 6 m near the coast. Wave effects raised water levels by up to 35 per cent, highlighting the benefits of a coupled wave-surge model that includes wave setup effects.

INTRODUCTION

Extreme sea levels result from the combined effects of a range of factors including astronomical tides, long-term sea-level variability, storm surges due to pressure and wind, and wave breaking processes that include wave setup and run up. Wave setup is a rise in water level near the shore due to the transfer of momentum from breaking waves to the water column resulting in a slope of the water surface (Longuet-Higgins and Stewart, 1964). 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 areas.

A majority of the Australian coastline is exposed to ocean surface waves (Short and Woodroffe, 2009) and during storm conditions waves breaking at the shoreline undoubtedly play an important role in generating extreme sea levels. This has motivated a number of recent studies aimed at better improving wave setup understanding and including the effects in storm surge numerical modelling studies (e.g. McInnes et al., 2009a; McInnes et al., 2009b; Soomere et al., 2013; O'Grady et al., 2015). Many of these studies have often been undertaken at the state or local level to inform planning and emergency management and a comprehensive Australia-wide assessment of the importance of waves for extreme sea levels still does not exist.

The approach that we have undertaken here is to utilise recent advancements to numerical models and a new Australian supercomputing facility to run a high resolution unstructured coupled wave-surge model for the whole of Australia.

METHODOLOGY

Coupled surge-wave model simulations were undertaken for historically significant storms that were recorded to cause damaging storm surges. The contribution of wave setup was then extracted from the model output by a comparison between coupled and uncoupled model runs.

Cyclone Yasi was chosen as a test case to investigate the ability of a coupled wave-surge model to simulate storm surges and wave setup effects. TC Yasi made landfall near Mission Beach in northern Queensland on the night of 2 February 2011 as a Category 5 cyclone with estimated wind gusts up to 285 km/hr (79 m s-1). Yasi was the largest and most intense storm to impact Queensland since 1913. The cyclone caused extensive damage to property and infrastructure costing $800 million over more than 500 km of coastline.

Numerical Model

The SCHISM hydrodynamic model was fully coupled with the Wind Wave Model III (WWM-III), a wave spectral model developed by Hsu et al. (2005) but since significantly updated by Roland et al. (2009). SCHISM is a full 3D finite element hydrodynamic modeling system that has successfully been applied to simulate circulation and storm surges in a broad range of coastal environments (Zhang and Baptista, 2008; Bertin et al., 2014; Bertin et al., 2015). The SCHISM-WWMIII modelling system is capable of two-way information exchange between the hydrodynamic model and wave model providing feedback into the hydrodynamic model and wave model at each time step during the whole simulation (Roland et al., 2012).

The unstructured triangular grid (containing ~800,000 nodes) allows the model to change resolution from coarse resolution in the open ocean (kilometres scale) to very fine resolution along the coast (metres scale) without the need for nesting of sub grids (Figure 1).

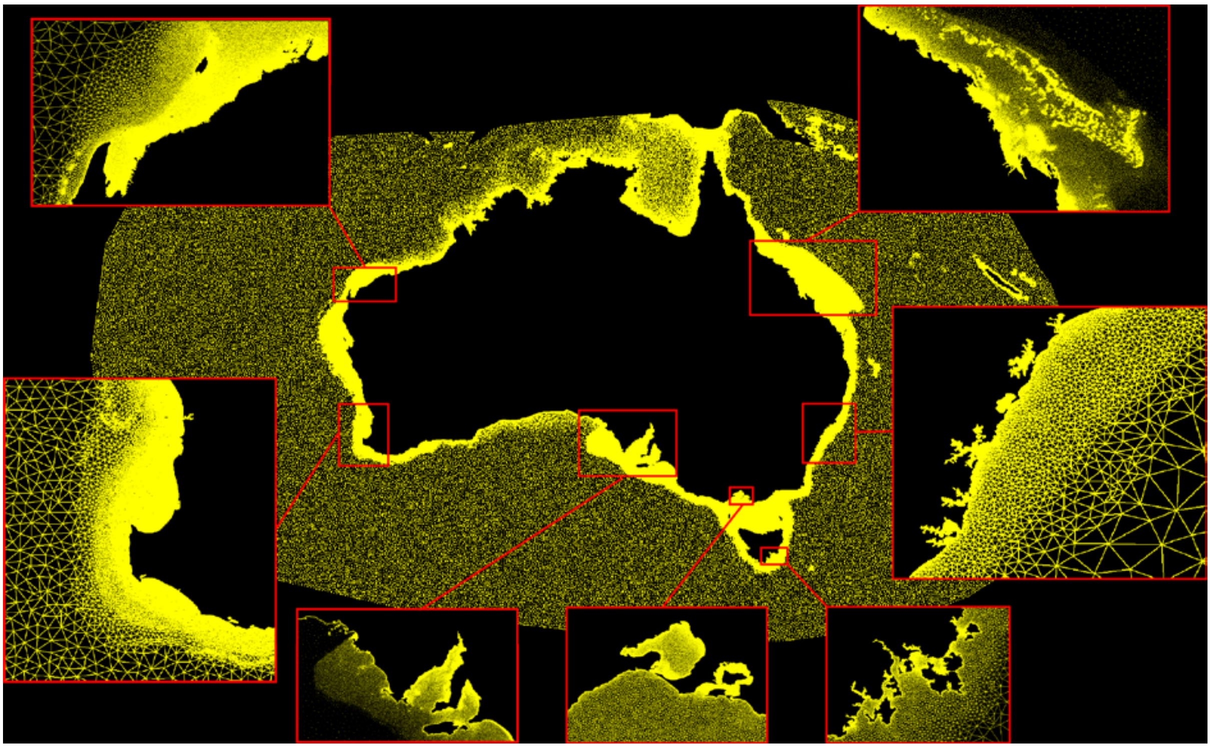

FIGURE. 1. UNSTRUCTURED MODEL GRID SHOWN FOR ENTIRE DOMAIN WITH ZOOMED IN VIEWS AT POPULATION CENTRES TO SHOW HIGHER SPATIAL RESOLUTION.

Atmospheric forcing

Atmospheric forcing for the model was derived by blending reanalysis model data (Japanese Reanalysis JRA55) (Ebita et al., 2011; Japan Meteorological Agency, 2013) with parametric representations of wind and pressure fields (eg. Holland, 1980, 2010) near the core of the cyclone.

RESULTS

Storm Surge

Storm surges occurred between Mackay and Cairns when Yasi made landfall with higher values limited to the areas between Mission Beach (2 m) and Townsville (1.6 m). To the north of Mission Beach where the storm crossed the coast, water levels were either only slightly higher than normal or even lower than normal due to strong offshore winds compensating for the inverse barometric effect (Figure 2). The shallow bay at Cardwell dramatically amplified the storm surge water level up to 5.5 m with a slightly delayed response, peaking around 16:00 on 2 February (GMT) two hours after landfall (Figure 2). In the inner regions of the bay the surge reached 6 m. This localised surge amplification highlights the critical role of bathymetry in determining maximum water levels.

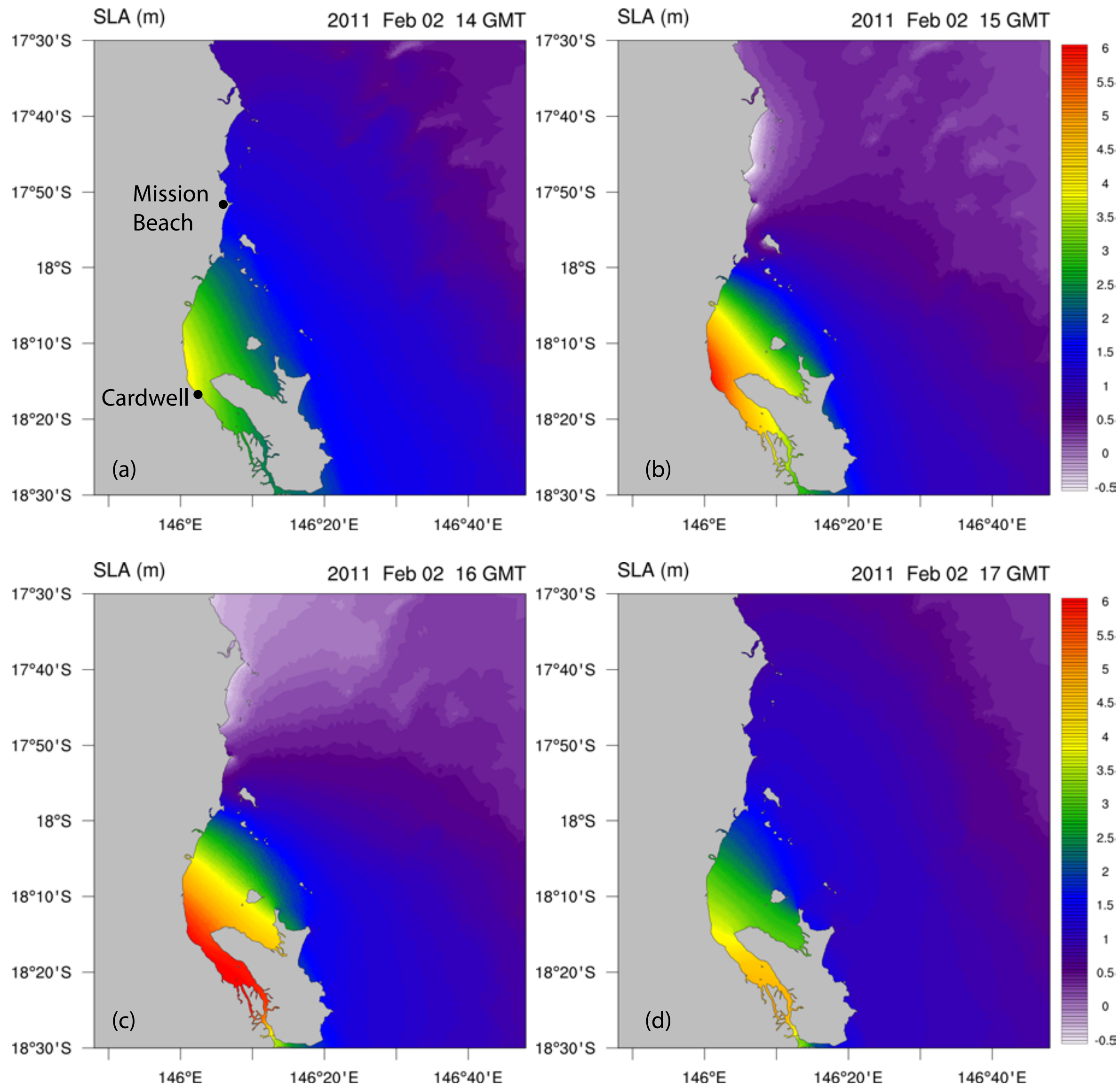

FIGURE 2. SIMULATED STORM SURGE AT CARDWELL SHOWING THE PROPAGATION OF THE SURGE INTO THE BAY FOLLOWING THE CYCLONE CROSSING THE COAST NEAR MISSION BEACH JUST AFTER 14:00 (GMT). HEIGHT COLOUR SHOWN IN METRES.

Wave setup

Cyclone Yasi caused extreme waves that reached almost 14 m on 2 February 2011 between hours 10-12 (GMT) offshore of the GBR reef system. These waves dissipated over the GBR before impacting the coast but some of the wave energy passed through the reef system and combined with locally generated waves to create significant wave heights of approximately 6 m inside of the reef. These large waves had an impact on total surge levels.

Calculating the difference between coupled and uncoupled model runs resulted in a measure of wave setup that consisted of the transfer of momentum from breaking waves into vertical change in water level. Simulations indicated that this contribution was 0.3–0.4 m over a broad area where waves impacted the coast, with peak levels around Cardwell despite the protection provided by shallow areas offshore where wave breaking occurred (Figure 3). Maximum setup levels occurred just before landfall but exceeded 0.2 m over a 10–12 hour period coinciding with large waves

(Figure 4). Two factors contributed to the amplitude of the wave setup component of the surge: wave height and the cross shelf depth profile. Along all cross shelf transects changes in wave height were inversely proportional to wave setup as expected with increased setup wherever waves transformed (or broke) and decreased in size.

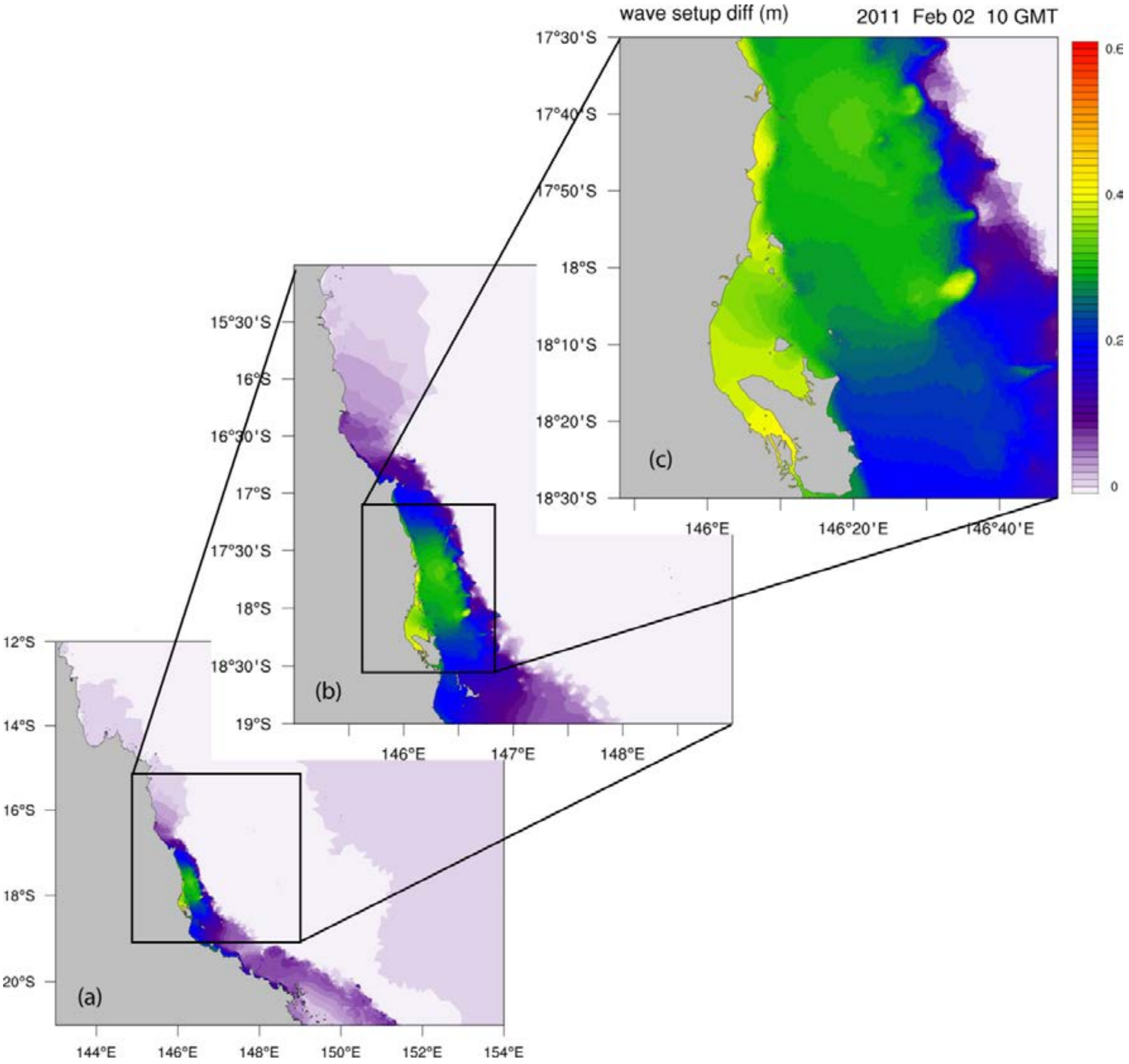

FIGURE 3. WAVE SETUP AS DEFINED BY THE DIFFERENCE BETWEEN COUPLED AND UNCOUPLED MODEL RUNS AT THREE DIFFERENT ZOOM LEVELS AROUND CARDWELL.

Maximum wave setup of 0.25–0.4 m slightly preceded maximum surges at all sites and coincided with maximum wave heights. In the hours before landfall this accounted for 30–35 per cent of the total surge (Figure 4a). Around the time of landfall the proportion of the surge related to wave setup dropped to around 20 per cent due to the increase in surge from the strong winds and decrease in pressure (Figure 4a, hour 12-14). Following landfall the wave setup component dropped below) 0.2 m but the percent contribution oscillated between 5 and 30 per cent depending on site and time owing to the persistence of waves and changes in wind direction and intensity (and thus amplitude of the storm surge).

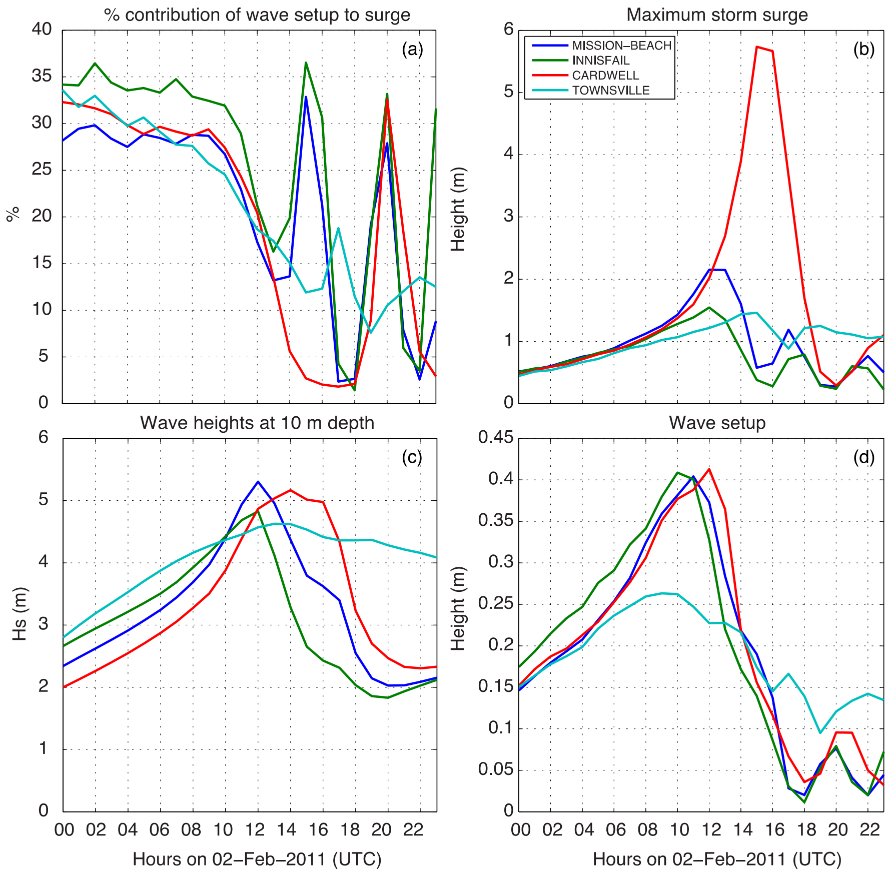

FIGURE 4. TIME SERIES OF STORM SURGE COMPARED WITH WAVE SETUP AND WAVE HEIGHTS AT 10 M DEPTH FOR ALL SITES.

DISCUSSION AND CONCLUSIONS

Recent technological advances have allowed us to develop a high-resolution numerical model capable of analysing ocean dynamics to better understand how storms will impact local beaches on an Australia-wide scale. The advanced, high resolution 3D hydrodynamic model (SCHISM) coupled with the state-of-the art WWMIII wave model included the effects of wave breaking on top of storm surges caused by wind and pressure.

This experiment indicated that wave setup for TC Yasi contributed up to 35 per cemt of total surge height and was 6-10 per cent of wave heights at 10 m depth. This supports the commonly applied engineering approach of applying a 10 per cent factor for waves in estimates of water levels, but we believe that our estimates of wave setup are conservative and in reality could be higher. Sensitivity studies indicated that increasing the resolution to better represent reality did generally result in increased wave setup and surge levels. Another important factor included the orientation of the coastline to waves and wind. Our experiments showed, for example, large variations in setup and surge over the scale of tens to hundreds of kilometres that was mostly related to the relative intensity and direction at which Cyclone Yasi impacted the coast.

The results suggest that coupling a wave and surge improves the accuracy of storm surge predictions and provides a useful tool to determine areas of the Australian coastline are more susceptible to flooding and erosion from extreme waves.

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