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1. INTRODUCTION

Storm surge can be a significant contribution to tropical cyclone insured losses, especially for particular insurance client portfolios with significant exposure along coastlines. Australia's Queensland coast is frequently impacted by strong cyclones (Fig. 1), and features several large cities near the coast with significant exposure; as such, this is a region that has potential to incur financial loss from storm surge. AIR's updated Australia cyclone model (ACM) estimates financial loss from wind, freshwater flooding and storm surge.

To simulate financial loss from storm surge, ACM utilizes a dynamical approach – the Princeton Ocean Model (POM). Due to the large number of simulations required (AIR's ACM features a 10,000 year catalog) compromises must be made between simulation resolution and computational demand.

In this study, the storm surge of Cyclone Yasi is simulated with POM on a high-resolution curvilinear domain, and the sensitivity of the results to wind field parameters and model resolution is explored. Model simulated results are compared to observations, where available, although the main comparison is between modeled results. Finally, some implications for catastrophe modeling and avenues of future research are discussed.

2. CYCLONE YASI

Yasi was first identified on January 26, 2011 as a tropical disturbance by the Fiji Meteorological Service; FMS). The cyclone gradually organized

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as it moved generally to the west and south, being classified as a tropical depression on January 27. Yasi attained severe tropical cyclone intensity with sustained winds of at least 120 km/h (75 mph) on January 31. Also on the 31st, Yasi crossed 160°E, prompting the final advisory from the FMS and the first advisory from the Australian Bureau of Meteorology (BoM) as it crossed into the Australian cyclone basin.

Yasi was upgraded to category 4 intensity on the BoM intensity scale on February 1st, and continued on a west-southwestward track towards Queensland. Yasi attained low category 5 strength on February 2nd, and maintained this intensity through landfall near Mission Beach (Fig. 4) between midnight and 1 am local time on Thursday, February 3. Yasi maintained a strong core with damaging winds and heavy rain well inland, being downgraded to a tropical low near Mount Isa late on February 3rd. The Insurance council of Australia (ICA) estimates the total financial loss from Yasi at ~1 Billion AUD.

As is typical of many cyclone landfalls in Australia, there are no verified observations of maximum wind near the cyclone center. Lucinda Point (south of the landfall location) recorded a maximum 3-s gust of 185 km/h (115 mi/h). A barograph at Tully Sugar mill recorded a minimum pressure of 929 hPa, leading the BoM to suggest that maximum wind gusts there may have reached 285 km/hr (~178 mi/hr). Post-event surveys (Ref. 6) of damage to buildings and other structures were able to provide estimates of maximum winds; surveys of windicators (i.e., failed road signs) indicate maximum wind gusts of up to 245 km/h (152 mi/h). Significant wind damage was recorded between Innisfail and Townsville where the core of the storm passed.

The maximum recorded storm surge in TC Yasi was on the order of 5.4 m at Cardwell (Fig. 5a), ~2.2 m above the highest astronomical tide (HAT). This occurred at approximately quarter tide; if the maximum storm surge had occurred at the high tide the maximum water level would have been ~4.7 m above HAT. A storm surge of 2.35 m at Townsville (Fig. 5b) was recorded, ~0.5 m lower than that recorded in Cyclone Althea (1971), which hit much closer to the city. Surveys indicate that observed surge damage from Yasi was localized in nature and highly dependent on local elevation, which is steep in this area (Fig. 7; Ref. 5).

3. SIMULATION OVERVIEW

The POM is a free-surface, three-dimensional finite-difference numerical model based on the primitive equations with Boussinesq and hydrostatic approximations. POM utilizes a bottom-following sigma coordinate system, and the horizontal grid uses an "Arakawa C" differencing scheme. POM is freely available to both the research and private industry communities for research purposes. More information is available in Mellor (2003). The addition of a wetting and drying (WAD) scheme (Oey 2005, 2006) allows water to inundate previously dry areas, enhancing the utility of the POM for inland loss calculations from surge.

In this study, several experiments utilizing a high-resolution (up to ~215-m; Fig. 7) curvilinear grid are performed in order to assess the sensitivity of the maximum surge footprint to wind profile specifications. An additional simulation with higher resolution (~85 m) is also conducted in order to test the sensitivity to model resolution. All simulations are run for 18 hours, allowing sufficient time for the storm surge to build prior to landfall. The maximum simulated footprint was found to not be sensitive to earlier model initialization. Tidal forcing is not included in these POM simulations, and therefore simulated maximum water heights will be compared to residual surge values at gauge locations.

The bathymetry and elevation grid (Fig. 8) was created using a blend of one arc minute data from the National Geophysical Data Center (NGDC) and 90 m elevation data from the Shuttle Radar Topography Mission (SRTM). Both datasets were interpolated onto the model grid and the 90 m data was utilized, where available.

4. WIND SPEED CALCULATION AND VALIDATION

POM requires a temporally varying wind field and sea-level pressure field to generate surge. AIR's parametric wind field calculation requires central pressure, radius of maximum wind (RMW), and forward speed and direction; these parameters were taken from the BoM cyclone reports. BoM estimates indicate that Yasi had a RMW of ~22 miles for the majority of its time over water. There is uncertainty associated with estimating RMW, and therefore four simulations were performed with RMW values of 16, 20, 24 or 28 miles.

Maximum wind speeds are calculated from gradient wind balance using central pressure and RMW. The AIR model's radial wind speed profile was developed based on the radial variation of wind speed described in Willoughby et al. (2006; Ref. 6). In this formulation, the radial profile is defined by three equations: one for the area inside the eyewall, one for the eyewall region, and one for the area outside of the eyewall. The radial wind profile is based on historical observations using reconnaissance data from 493 hurricanes in the Atlantic and eastern Pacific basins from 1977 to 2000. To compute winds at the surface, the AIR wind model adjusts for the storm slant and bulk reduction of the winds from flight level to 10 m.

Simulated maximum wind speeds (Fig. 9) are ~157 mi/h over water and ~147 mi/h over land. The BoM estimates maximum wind gusts of ~177 mi/h at landfall; utilizing a 0.8 conversion between 1-minute sustained and gust winds, the maximum sustained winds over land are estimated as ~142 mi/h, comparable to those simulated. Maximum 1-minute wind speed estimates based upon satellite estimates (Fig. 9; Refs. 2, 8) are ~159 mi/h (~138 knots) while Yasi was over water, comparable to the simulated maximum values over water. Additional simulations are conducted in order to test the sensitivity to uniformly increased wind

speeds; in these simulations, wind speeds are increased by 10, 20, or 30%.

5. SIMULATION RESULTS

The POM realistically simulates the qualitative distribution of storm surge, including the maximum water rise near Cardwell (Fig. 11). Simulations with up to ~215 m resolution were able to resolve the larger channels between the Australia mainland and Hitchenbrook Island, although smaller waterways are not resolved in model elevations. Although matching qualitatively, maximum storm surge values are lower than observed; the maximum simulated surge height (Table 1) is 3.7 (4.6) m in simulations with 16 (28) mile RMW, ~15% lower than the maximum observed (estimated at ~5.4 m).

Time series of surge height at Cardwell (Fig. 12a) and Townsville (Fig. 12b) are lower than those observed. POM realistically simulated the more rapid water rise and decline in Cardwell relative to Townsville. RMW specification has a large impact on simulated surge height in Townsville due to its relatively large distance from cyclone center, while in Cardwell RMW specification does not impact the maximum surge height significantly.

Given the many inherent uncertainties in calculating parametric wind speed, it is important to understand the sensitivity of modeled surge heights to simulated wind speed. Increasing wind speeds by a uniform amount leads to significant increases in surge height (Table 1, Figure 13), although it does not change the spatial distribution. A wind speed increase of 10% leads to maximum surge height increasing 12-15%, depending upon RMW.

Increasing the resolution does not lead to an increase in simulated surge height (Figure 14), and in most areas the simulation results change little. The high resolution does provide increased detail of simulated surge in areas with locally complex terrain and small channels and rivers.

6. DISCUSSION AND CONCLUSIONS

Simulation results indicate that the Princeton Ocean Model is able to realistically simulate the distribution of storm surge heights in Cyclone Yasi, although the maximum amplitudes are generally lower than those observed. Given the steep coastal bathymetry, one hypothesis is that the contribution from wave setup to the storm surge, which is not accounted for by POM, is at least partly responsible for the low bias in the model results. Another hypothesis is that simulated surge height is highly sensitive to simulated wind speed and RMW, which can be quite uncertain over water in the absence of observations and aircraft reconnaissance.

High resolution simulations still feature the low bias relative to the observations, but do allow for better detail in the simulated surge footprint in areas of complex terrain and small water features, such as near where the cyclone made landfall in the vicinity of Hitchenbrook Island. This detail could be important for exposures located in the vicinity of small-scale features. High resolution simulations would likely benefit from a higher resolution bathymetry dataset, as local bathymetric features could impact surge heights – in all simulations conducted here, the bathymetry data was on a one arc minute (~1.85 km) grid.

For stochastic simulations, the benefits of high resolution must be weighed against high computational demands. Simulating 10,000 years of cyclone landfalls in Australia requires a very large number of simulations. Stochastic simulations required ~15 minutes per simulation, while the high resolution simulation described herein required ~6.5 hours, or ~25 times longer. Further refinements to the curvilinear grid generation or a nested grid approach which produce domains that are better optimized to resolve complex coastal features may allow for higher resolution stochastic simulations.

7. FUTURE WORK

In order to more realistically simulate surge values, it may be necessary to couple POM with a near-shore wave model in order to better resolve

the effects of wave breaking and the wave setup contribution. Detailed comparison of simulated wave characteristics to observations would be required in order to assess the accuracy of any wave model. Additional experiments utilizing idealized bathymetry could be conducted in order to better understand the impact of wave breaking on simulated surge heights.

Although a curvilinear grid is beneficial for maximizing model resolution while limiting computational demand, there are instances where a nested grid approach may be more versatile. Currently, efforts are underway to add nesting capability to POM. As discussed above, additional grid generation strategies to more efficiently distribute high-resolution cells over areas of interest would also serve to maximize the benefit of increased resolution while minimizing computational demand.

8. REFERENCES

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Wind	Radius of Maximum Wind (mi)			
Speed	16	20	24	28
Control	3.7	4.1	4.5	4.6
10%	4.3 (16%)	4.7 (15%)	5.1 (12%)	5.3 (15%)
20%	4.9 (32%)	5.4 (33%)	5.8 (28%)	5.9 (28%)
30%	5.5 (48%)	6.0 (48%)	6.4 (41%)	6.5 (41%)
40%	6.2 (65%)	6.6 (62%)	6.9 (53%)	7.7 (66%)

Table 1. Maximum simulated surge height (m) in simulations with different RMW values and uniform increases in wind speed. The percentage increase in surge due to increased wind speed for each RMW specification is included (red).
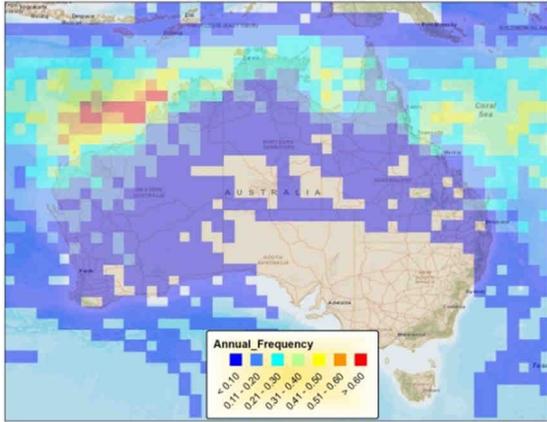
Fig. 1. Annual frequency of cyclones based on historical data (1951-2008).
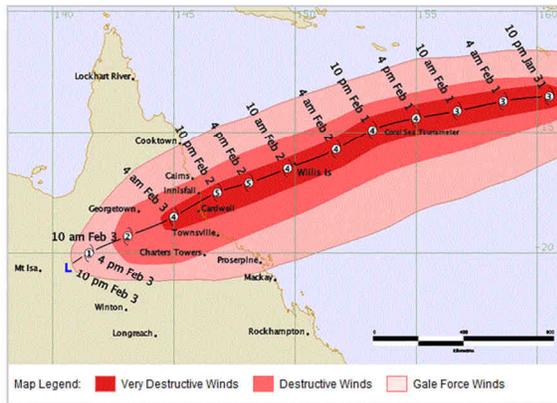
Fig. 2. Track and wind intensity for Yasi. Courtesy of the Bureau of Meteorology.
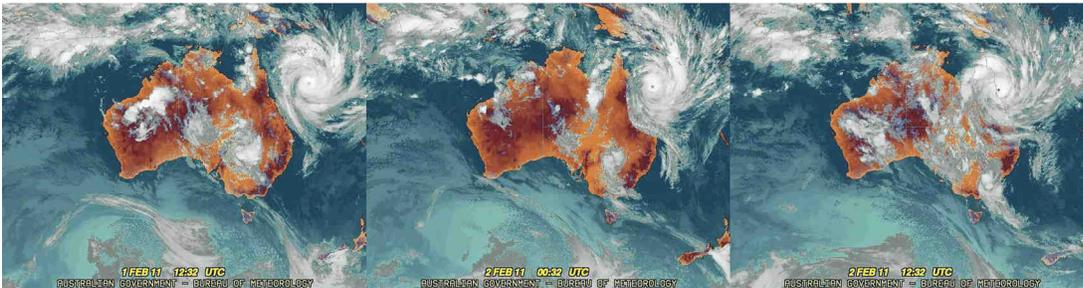
Fig. 3. Visible satellite images of hurricane Yasi as it approached Queensland. Courtesy of the BoM.
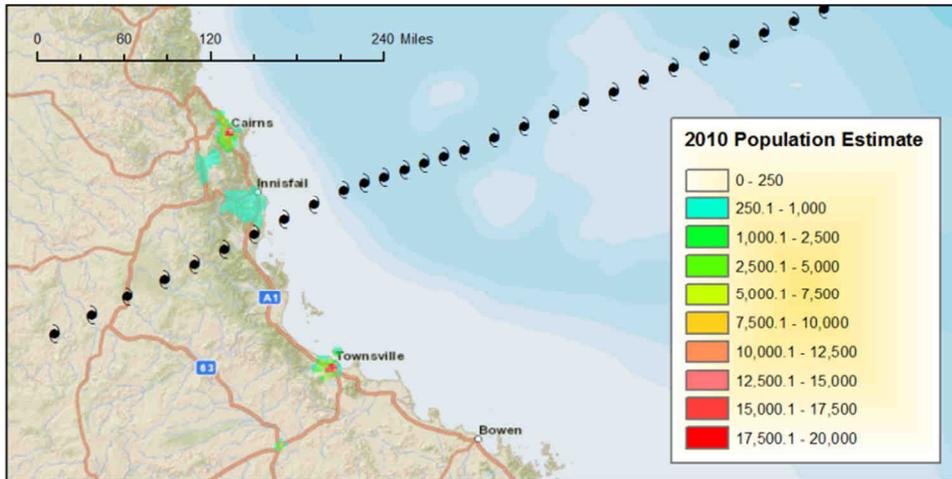
Fig. 4. Yasi track and population density near landfall location. Landfall occurred between the cities of Cairns (population ~150,000) and Townsville (population ~185,000), in a sparsely population section of coastline, reducing the amount of damage and ultimately the financial loss.
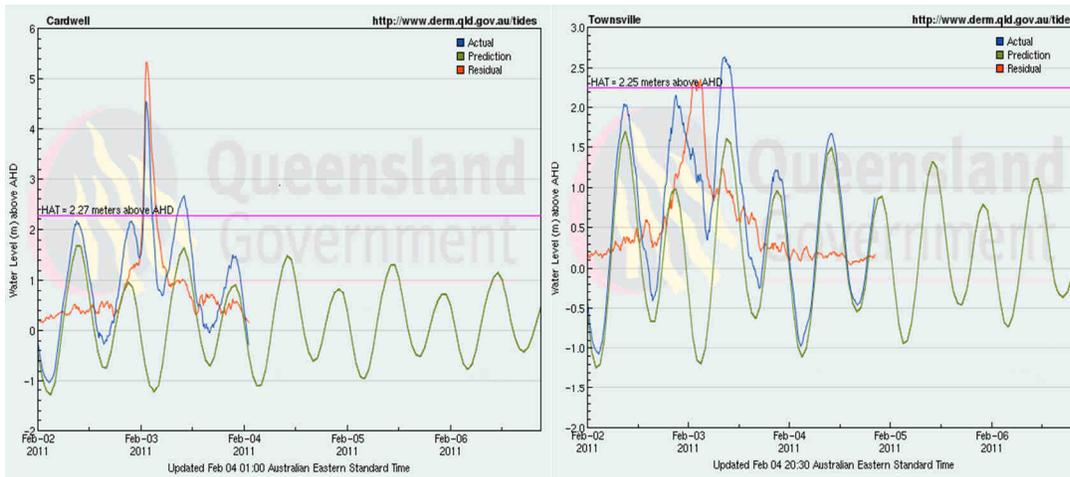
Fig. 5. Tide gauge values for Cardwell (left) and Townsville (right).
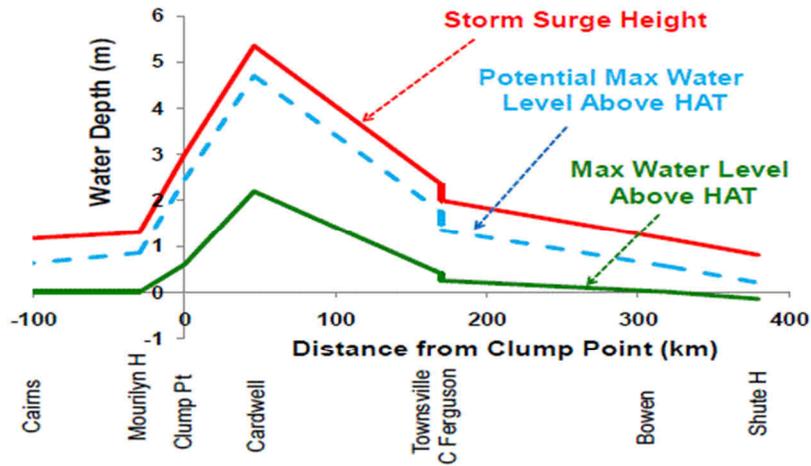
Fig. 6. Simplified storm surge profile along the coast of Queensland interpolated between tide gauges (red). Also shown is actual maximum sea level relative to HAT (green) and the potential maximum relative to HAT if the storm surge had coincided with the maximum adjacent high tide. Image from Ref.7.
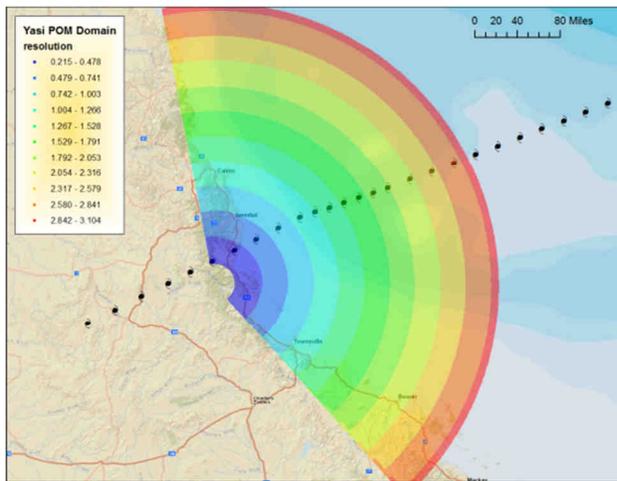
Fig. 7. Model grid spacing (m). Highest resolution is ~ 215 m.
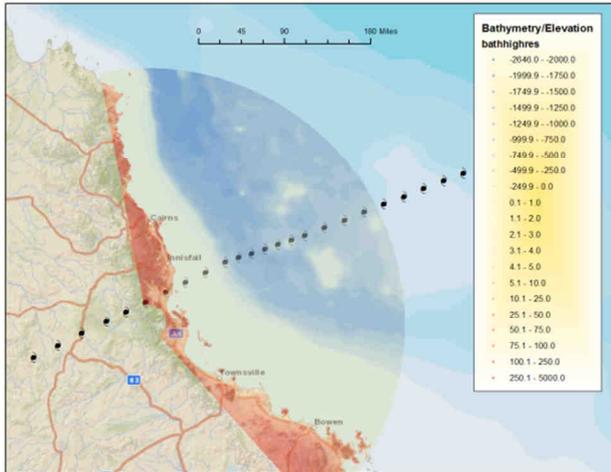
Fig. 8. Interpolated model bathymetry and elevation.
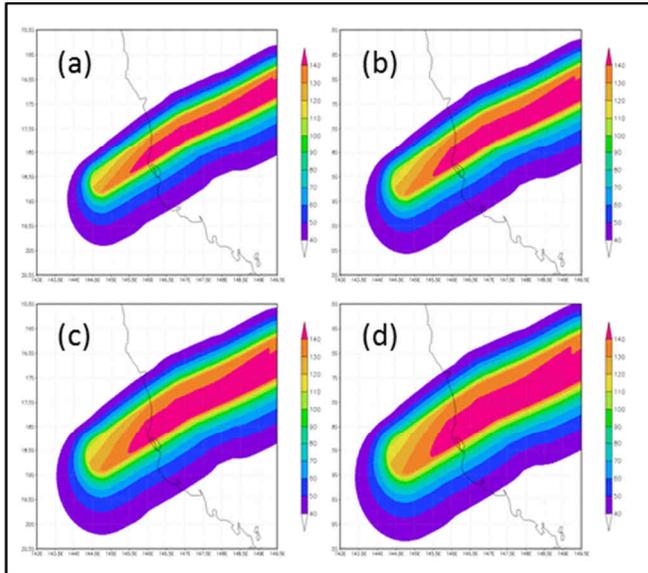
Fig. 9. Simulated maximum wind speed footprints (mph) using RMW values of 16 (a), 20 (b), 24 (c), and 28 (d).

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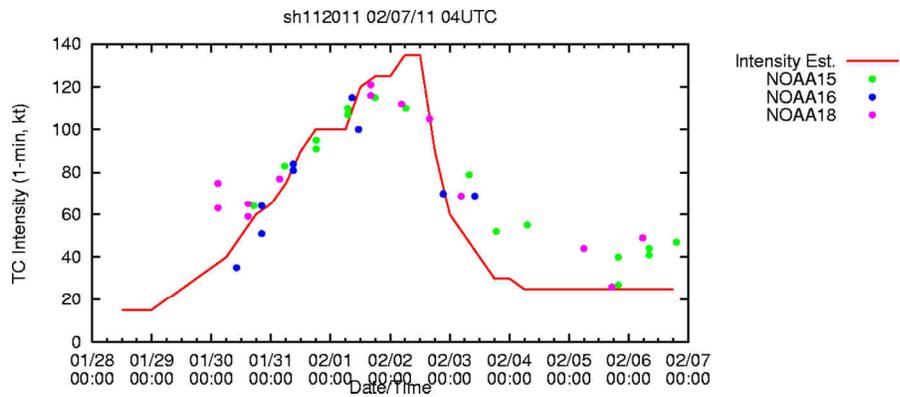
Fig.10. Advanced Microwave Sounding Unit (AMSU) based intensity estimate.
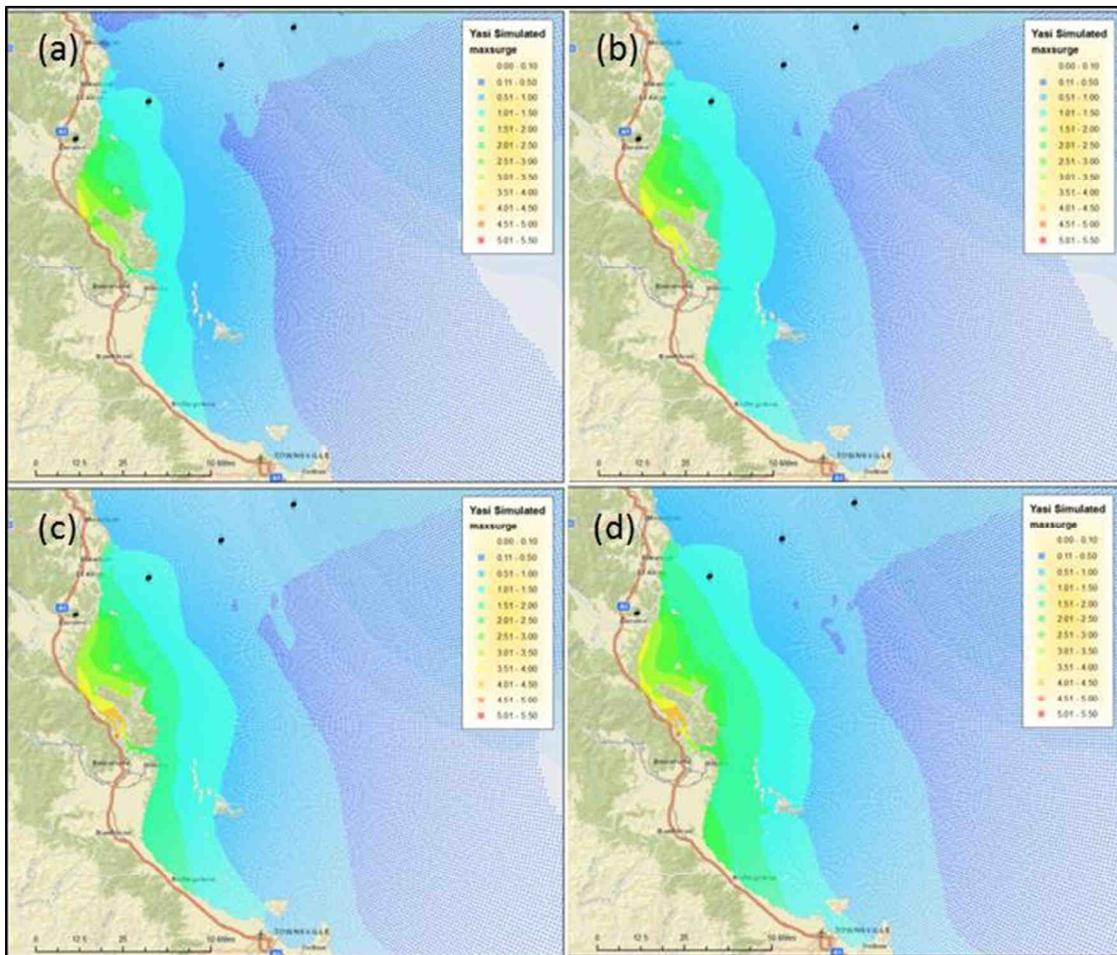
Fig.11. Simulated maximum surge footprints (m) using RMW values of 16 (a), 20 (b), 24 (c), and 28 (d) miles.
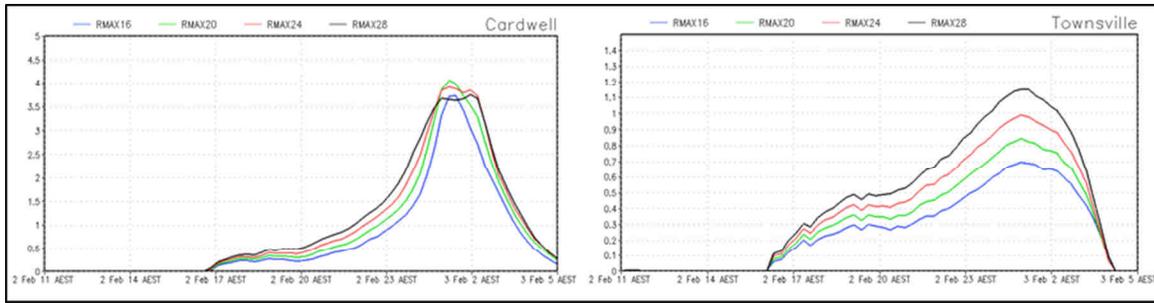
Fig.12. POM simulated surge time-series at model grid cells closest to Cardwell (a) and Townsville (b) gauges.
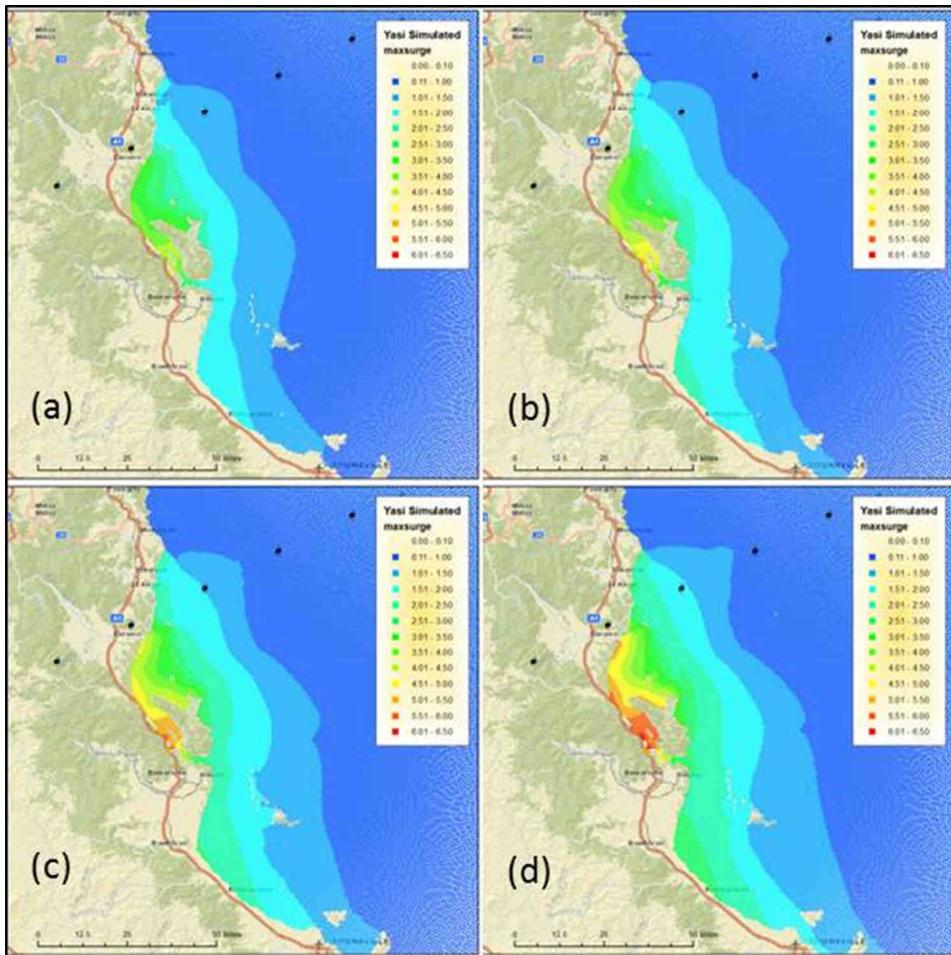
Fig.13. Simulated maximum surge footprints (m) in control simulation (a) and with uniform increases in wind speed of 10% (a), 20% (c), and 30% (d). All simulations feature 24 mile RMW.
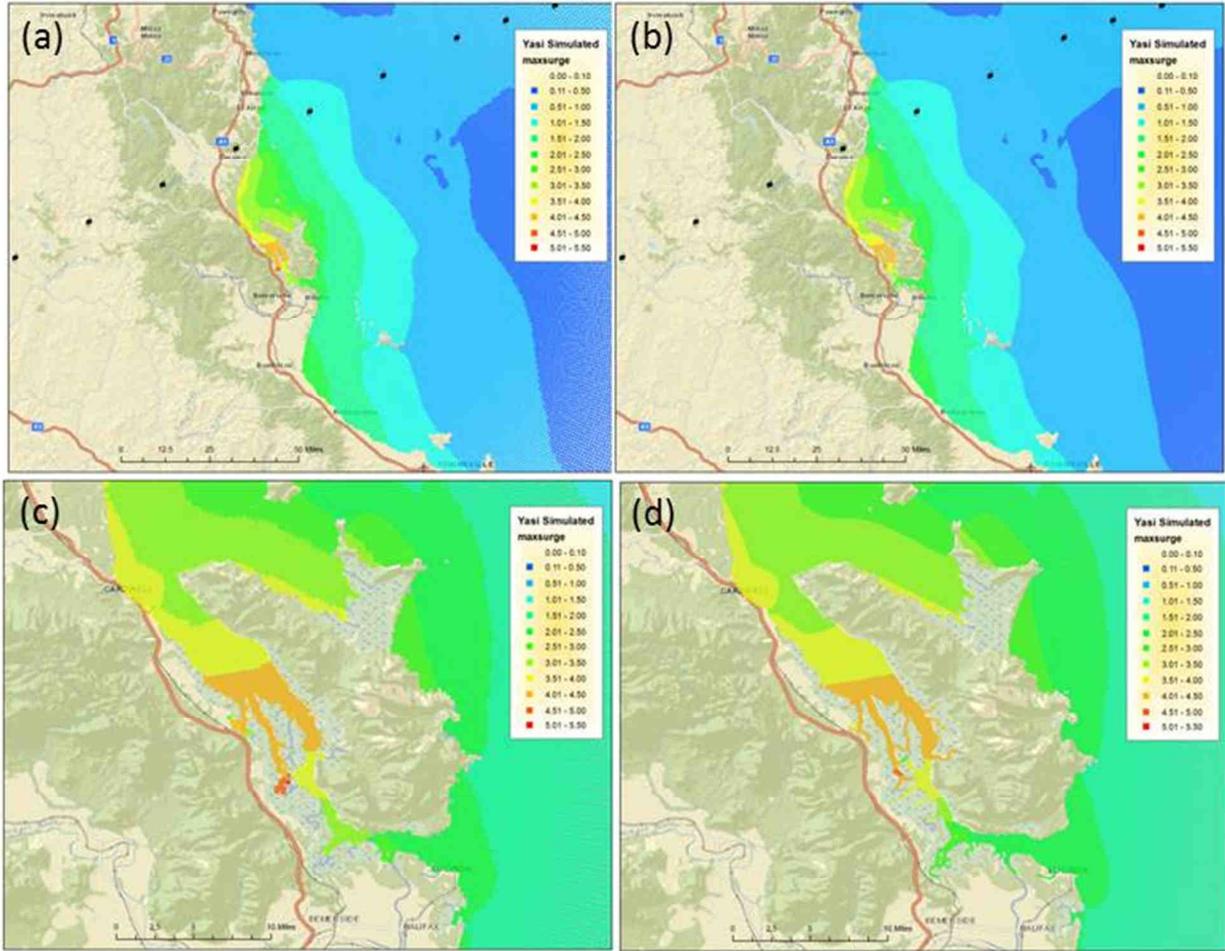
Fig. 14. Simulated maximum surge footprints (m) using RMW of 28 miles and control wind speed values in POM simulation with grid spacing as fine as ~215 m (a, c) and ~85 m (b, d).