Assessing Storm Tide Hazard for the North-West Coast of Australia using an Integrated High-Resolution Model System

Jim Churchill[1], David Taylor[1], Dr Joanna M. Burston[1] and Jarrod Dent[1]
[1] Baird Australia, AUSTRALIA.
email: jchurchill@baird.com

Abstract

Australia's north-west coast extends across an active tropical cyclone region with a dynamic coastal zone which includes several regional towns as well as major infrastructure associated with Australia's resources industry. The threat posed by tropical cyclone induced storm surge and associated storm tide is a significant concern for local communities and infrastructure owners in the region.

A series of studies to define the storm tide hazard along Australia's north-west coastline has delivered an integrated 10,000-year event dataset that defines wind and storm tide at high-resolution across the whole region. Storm surge and tide has been modelled with a hydrodynamic model extending across 2,000km of coast, developed using Delft-Flow Flexible Mesh (D-Flow FM). The model delivers high shoreline resolution with efficient model run times and can be deployed to a cloud computing environment.

Validation of the hydrodynamic model to predicted and measured astronomical tide at standard port locations across the north-west region of Australia shows excellent agreement to tidal constants in both amplitude and phase. For storm surge simulations, cyclonic wind and pressure fields associated with historical cyclones were modelled with Baird's in-house *Cycwind* program which combines a Holland et al. (2010) vortex model blended into Climate Forecast System Reanalysis (CFSR) regional scale atmospheric fields. The storm surge model was validated for 18 historical events with modelled peak storm surge showing very good agreement to measured data.

The calibrated wind, tide and storm surge models have been combined with Baird's Monte-Carlo cyclone track model for over 28,000 synthetic cyclone tracks impacting the north-west of Australia. The resulting high-resolution storm tide outputs (≈ 1 km resolution) have been applied to an inundation mapping algorithm to determine storm surge and tide inundation hazard across the region at high-resolution (≈ 20 m) for use in applications such as coastal planning and infrastructure risk assessment.

Keywords: tropical cyclone, storm surge, coastal hazard.

1. Introduction

The northwest coast of Australia is a sparsely populated region of Western Australia, home to several small regional towns, as well as significant coastal infrastructure and port facilities associated with the oil and gas and resources industries (Figure 1). The coastal zone is composed of a wide variety of coastal types, from tidal flats and mangrove areas to sandy and rocky shorelines with a tide ranging from meso-tidal to macro tidal. An active tropical cyclone region, the cyclone season extends between November and April each year, and on average there are 5 tropical cyclone events annually (between 105°E and 125°E), with 2 making landfall of which one is generally severe [1].

Tropical cyclones have the potential to generate extreme winds, waves and water levels that can lead to both erosion and inundation of the shoreline areas. The threat posed by tropical cyclone induced storm surge and associated storm tide is a real concern for local communities and infrastructure owners and planning and infrastructure design in the region has recognised the need to factor extreme water levels into design, coupled with appropriate allowances for projected sea level rise in future planning periods. For local planning in Western Australia, new development must be set above the storm tide level equivalent to the 500-year annual recurrence interval (ARI500), an event with a 1 in 500 (0.02%) chance of being exceeded. For oil and gas operators, design levels as high as 10,000-years ARI (ARI10,000) can be required, recognising the critical value of the infrastructure and safety of personnel involved, as well as the uncertainty associated with making long term climate predictions.

2. Methods

There is an inherent challenge in developing reliable long term estimates of storm surge from the relatively short historical measured data record available. Measured water level data sets across the northwest Australian region are available from standard ports (Figure 1) dating back approximately 30 years, which can provide a reasonable basis for estimate up to approximately the 50-year annual recurrence interval (ARI50). However, due to the large tide range across northwest Australia the uncertainty in estimating 50-year annual recurrence interval storm tide conditions can be large.

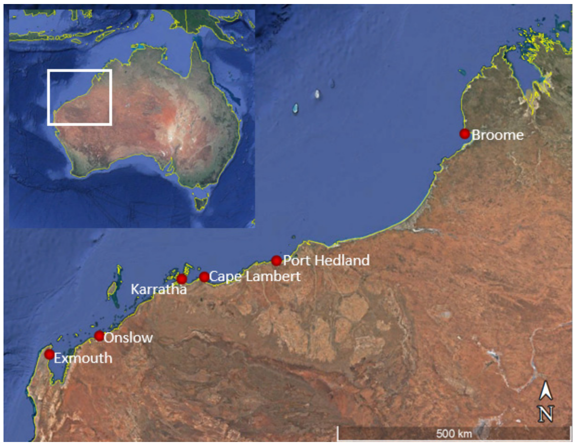

Figure 1 Northwest Coast of Australia with Standard Port Locations Shown (Google Earth).

Extreme water levels are the result of tropical cyclone events, which similarly only have reliable measured data going back approximately 30 years in the region. To deliver a robust assessment of long term water level at the 100yr ARI and beyond, the historical cyclone record is used as the basis for developing an extended event set of synthetic cyclone tracks, through a Monte Carlo based modelling approach.

Baird Australia have developed a cyclone track database of over 28,000 synthetic cyclones for the north-west coast of Australia, through a stochastic modelling approach as reported in [2] and [3]. The synthetic data set approximates to a 10,000-year period, with validation of the synthetic cyclone tracks and landfall rates against the historical climatology for the northwest coast of Australia showing very good agreement.

The synthetic cyclone tracks have been applied in a hydrodynamic model of the northwest coast of Australia, developed by Baird using the Delft-Flow Flexible Mesh (D-Flow FM) model presented in Section 3. The D-Flow FM model accurately reproduces the astronomical tide at coastal sites across the region, and was adopted as the platform for evaluating storm surge in extreme events. The cyclonic wind and pressure fields for historical cyclones were developed using Baird's in-house *Cycwind* program, with validation of the wind field and modelled storm surge from key cyclone events in Section 4.

The calibrated wind, tide and storm surge models were combined with Baird's Monte-Carlo cyclone track model to assess over 28,000 synthetic cyclone tracks impacting the northwest of Australia. A brief overview of the combined model system is provided in Section 5, with a discussion of model sensitivities in Section 6.

3. Hydrodynamic Model

Baird's hydrodynamic model was established using the Delft3D Flexible Mesh Suite (Delft3D FM 2017, 1.2.2.36603), which is designed for the simulation of complex hydrodynamic processes and flows from tidal and meteorological forcing including storm surges, cyclones, waves and water levels and the interactions between these processes [4]. The model was developed in 2D on a triangular unstructured mesh of approximately 90,000 elements with increasing resolution from the offshore to nearshore areas. The model extends across 2000 km of the northwest coast of Australia and offshore up to 800 km. The offshore areas are defined at approximately 20 km resolution, whilst nearshore the element size reduces to a maximum of 1 km, although are typically 200 m at the coastline. The overall model extent is shown in Figure 2 along with two key infrastructure locations, to demonstrate the nearshore grid detail.

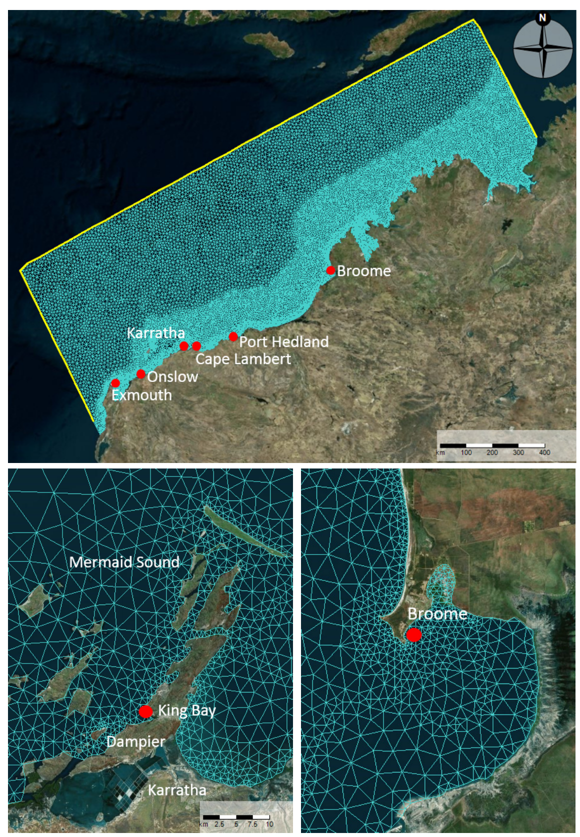

Figure 2 Delft FM model grid extent (upper), nearshore areas for Karratha / Dampier (Mermaid Sound) (lower left) and Broome (lower right).

Model depth is assigned at mean sea level (MSL) across the domain using survey, LiDAR and hydrographic chart data where available. An accurate model bathymetry is an important component in accurately modelling tides across northwest Australia. The offshore boundary of the model is forced by 14 key TOPEX-8 [5] tidal constituents (A0, M2, S2, N2, K2, K1, O1, P1, Q1, M4, MS4, MN4, MM and MF). Approximately 4,000 reporting locations were assigned in the model at 1 km intervals along the 10 m depth contour (MSL).

The validation of the hydrodynamic model to predicted and measured astronomical tide at six port locations across the north-west region of Australia shows very good agreement to water level amplitude and phase (Figure 3, Table 1). Comparison of the top eight constituents across the six sites shows very good validation to the predicted values (National Tidal Centre, NTC 2015), with average phase error across all sites of 0.2°.

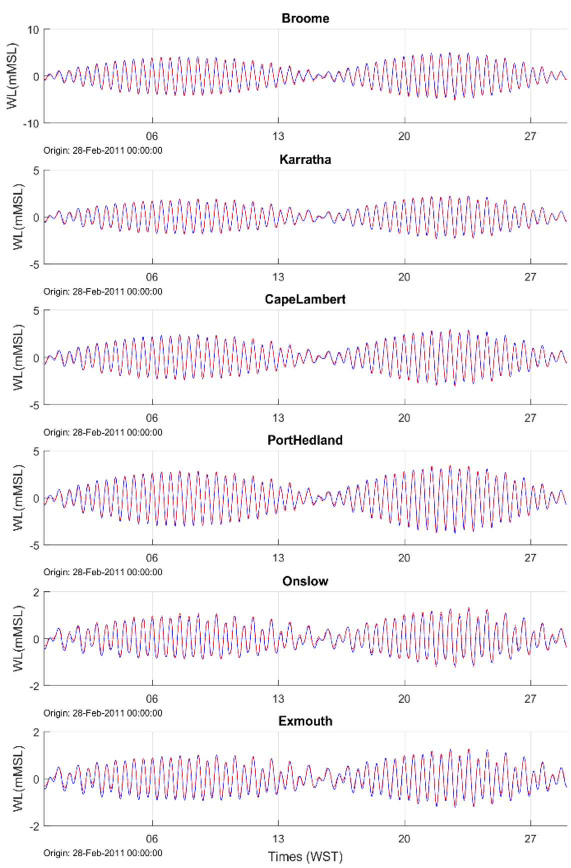

Figure 3 Validation of D-Flow FM hydrodynamic model at six port locations on the north west of Australia. Measured water level (blue), modelled water level (red).

Table 1 Comparison of measured and modelled water levels for port locations in northwest Australia.

Location	Bias (m)	Skill	RMS error (m)
Broome	-0.029	0.997	0.206
Cape Lambert	-0.008	0.998	0.119
Exmouth	0.003	0.991	0.102
Port Hedland	0.000	0.998	0.128
Onslow	0.008	0.991	0.100
King Bay Karratha	0.004	0.997	0.102

4. Historical Cyclone Validation

The validated hydrodynamic model was used as a basis for storm surge validation, with cyclonic wind and pressure fields generated for historical events through Baird Australia's *Cycwind* program. *Cycwind* combines a Holland et al. (2010) vortex model blended into Climate Forecast System Reanalysis (CFSR) regional scale atmospheric fields [6]. Wind and atmospheric pressure fields for 18 historical cyclones post 1985 were developed for the validation cases, with an example of *Cycwind* wind and pressure fields shown in Figure 4 for TC Orson (1989) at Karratha.

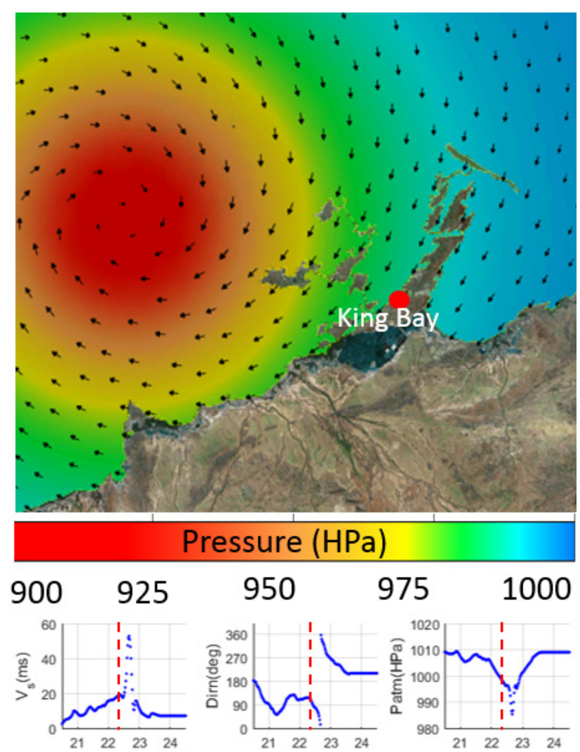

Figure 4 Spatial plot of modelled winds and pressure from *Cycwind* for TC Orson at Karratha, 22 April 1989 0930UTC. Time series modelled data from King Bay site.

The historical cyclone events were simulated in the D-Flow FM model, with the time series wind and pressure fields applied over the astronomical tide. For the event set, modelled peak storm surge is plotted against the measured peak storm surge where data was available from the port locations as shown in Figure 5. The validation shows the model is replicating measured peak tidal residuals well with a linear fit of 0.99 (R^2 = 0.92).

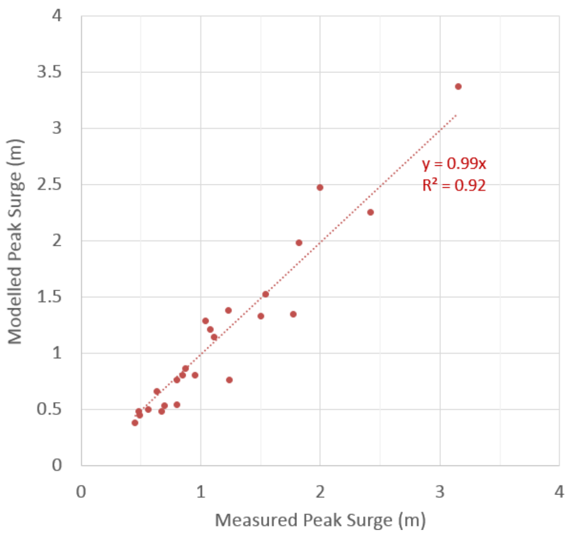

Figure 5 Measured and modelled peak surge values for key historical cyclone events impacting northwest Australia post 1985.

5. Production Run Model Cases

The calibrated wind (*Cycwind*) and hydrodynamic model (D-Flow FM) were combined with Baird's Monte-Carlo cyclone track model to assess over 28,000 synthetic cyclone tracks impacting the north-west of Australia. All model cases were run at a fixed water level of MSL to optimise model run time, with simulations performed using the Microsoft Azure™ cloud supercomputer, requiring over 25,000 hours of CPU time. Time series storm surge outputs from the completed model simulation cases were extracted from the approximately 4000 reporting locations along the coast and combined linearly with concurrent astronomical tide.

Estimates of the ARI storm tide values for the reporting locations along the coast based on extreme value analysis (EVA) of the water level outcomes from the full synthetic event set was undertaken with appropriate Peak-Over-Threshold (POT) censoring based on the methods of [7] applied in the analysis of the peak storm tide data. Not all synthetic events generated a storm surge level of inundation above Highest Astronomical Tide (HAT), due to either the cyclone being situated too far offshore, or the timing of the cyclone impact on the coast with respect to the tide level.

The resulting high-resolution storm tide outputs (≈ 1 km resolution) were applied to an inundation mapping algorithm to spatially present storm surge and tide inundation hazard for shoreline areas.

6. Modelling Sensitivity Investigations

The sensitivity of the storm tide model residual was examined against three mechanisms: wind shear stress, time varying tide level and joint wave conditions.

During extreme cyclonic events, the winds acting across the ocean surface create wind generated waves and a wind setup of the water level due to the transfer of the wind energy. In the D-Flow FM model, the force exerted by the wind on the flow field is coupled to the flow equations as a shear stress [4] with the wind shear stress controlled in the model through a wind drag coefficient term (Cd) dependant on wind speed. There are several methods that can be specified in the model, with the Smith and Banke approach [8] adopted in Baird's model setup which allows a piecewise linearly varying drag coefficient, such that as the wind speed increases the wind drag also increases.

The selection of appropriate limits for wind drag coefficients at high wind speeds is well established, following data and publications over the last 10-years (eg Donelan et al 2004 [9]). However, at the lower end of wind speed, there is nearly an order of magnitude variation in published wind drag coefficients ([10],[11]). The wind drag values (Cd) applied in the production run cases are based on [9] at the upper end (>30ms^{-1}) with the lower end based on average measured data presented in [11]. As a sensitivity test, alternative values for Cd based on the upper limit wind drag values in [11] were applied in ten cyclone cases specifically impacting the model domain in the Mermaid Sound region shown in Figure 2, with the outcomes presented on Table 2 for average (Cd1) and upper limit cases (Cd2).

Table 2 Wind drag coefficient sensitivity cases for cyclones impacting Mermaid Sound

Cyclone Name	Closest	Peak Residual (m) – King Bay		
		Measured	Cd 1	Cd 2
Orson 1989	55km W	3.15	3.37	3.48
Glenda 2006	75km NW	1.65	1.33	1.48
Clare 2006	25km NW	1.54	1.40	1.59
Vance 1999	245km W	1.25	0.65	0.86
Bobby 1985	90km W	0.95	0.80	0.96
Olwyn 2015	240km W	0.76	0.35	0.56
John 1999	80km E	0.66	0.58	0.66
Monty 2004	110km W	0.60	0.56	0.64
George 2007	250km E	0.53	0.63	0.66
Darryl 2006	120km N	0.39	0.62	0.73

The outcomes on Table 2 show that the storm surge residual for historical cyclones at the King Bay, Mermaid Sound location is in generally better agreement with measured residual where the wind drag coefficient (Cd) is based on upper limit measured data (Cd2). A cross plot of measured and modelled storm surge for the 10 cyclone cases on Figure 6 indicates the coefficient of variation (R^2) improves for the Cd2 wind drag value (R^2 = 0.94 for Cd2 vs R^2 = 0.90 for Cd1).

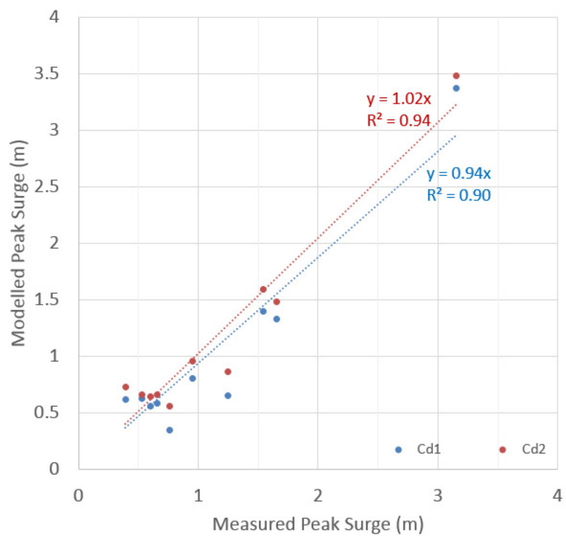

Figure 6 Measured and modelled peak surge values for 10 historical cyclone events impacting Mermaid Sound (King Bay) showing sensitivity of modelled storm surge to the adopted wind drag coefficient (Cd)

The influence of the tide level on the storm surge level was examined using the D-Flow FM model for three cyclone cases impacting Mermaid Sound – TC Orson, TC Vance and TC Olwyn. The surge comparison is shown in Figure 7 for TC Orson, for a scenario with time varying tide compared against a model scenario with tide fixed at MSL. The peak surge level between the two scenarios is generally consistent (dynamic tide peak of 3.37m compared with 3.31m with a fixed water level MSL). The total water level comparison is shown in Figure 7 for the TC Orson case, with the MSL surge case combined with astronomical tide resulting in peak water level marginally below the dynamic tide case (dynamic tide peak water level of 2.26m compared with 2.18m in the fixed MSL case). Table 3 summarises the outcomes for the three cyclone events and indicates the dynamic tide level can make a small difference to the resultant surge values and water level peak, however these are generally consistent with the constant water level (MSL) scenarios.

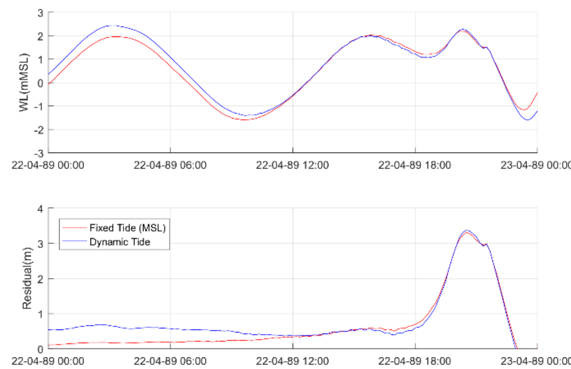

Figure 7 (upper) TC Orson modelled water level for dynamic tide and fixed tide at mean sea level (recombined with astronomical tide) and (lower) modelled storm surge.

Table 3 Modelled peak storm surge residual and storm tide level for cyclone events impacting Mermaid Sound for dynamic and fixed tide conditions.

Cyclone Name	Residual Peak		Water level Peak	
	Dynamic	Fixed	Dynamic	Fixed
Orson 1989	3.37	3.31	2.26	2.18
Vance 1999	0.66	0.74	2.78	2.58
Olwyn 2015	0.43	0.40	1.82	1.83

The impact of joint wave conditions on the modelled storm surge level was examined for the same three cyclone cases at Mermaid Sound. The production simulations do not implicitly model wave conditions, with storm surge in the simulations chiefly the result of wind stress generated setup combined with the 'inverse barometer effect' due to atmospheric pressure variations through the event. The influence of waves on the hydrodynamics can be an important factor for water level within embayment's as previous studies ([9], [10]) have demonstrated that wave radiation stress gradients generated by wave breaking at coastal entrances can result in addition water level residuals that are phase dependant on the astronomical tide.

The joint wave simulations were modelled for the three cyclones with a Delft3D model developed from the unstructured D-FM Flow hydrodynamic model. Wave and hydrodynamic conditions are coupled in the Delft3D model (FLOW-WAVE-FLOW), with the key processes affecting water level including radiation stresses updated continuously through the cyclone event. The results for the three cyclones are presented on Figure 8 showing that with joint wave conditions storm surge levels are increased through the lower ebb tide, however at the higher water level there is negligible difference in storm tide compared to the equivalent non-waves case. In conclusion for peak water level during the cyclone event the storm surge level is unaffected by the joint wave condition at the study reference area of Mermaid Sound.

Shoreline impacts and coastal inundation are however influenced by local shoreline wave setup and run-up.

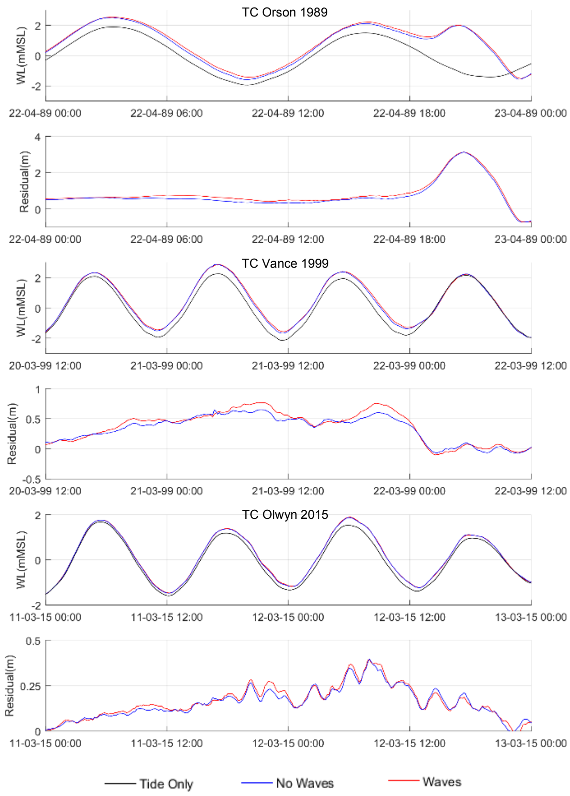

Figure 8 Modelled water level and storm surge with and without joint wave conditions for (upper) TC Orson 1989, (middle) TC Vance 1999 and (lower) TC Olwyn 2015.

7. Summary

In summary, the D-FM Flow model developed for the northwest Australia region validates well to astronomical tide and historical storm surge events, and was successfully adopted for production runs of over 28,000 synthetic cyclone cases to develop estimates of long term storm tide for the region. The resulting high-resolution storm tide outputs (≈ 1 km resolution) have been applied to an inundation mapping algorithm to determine storm surge and tide inundation risk across the region for use in applications such as coastal planning and infrastructure hazard assessment.

Investigations of model sensitivities show the surge levels in the model are sensitive to the wind shear stress, and varying the wind drag coefficient value in the model (Cd) is a useful parameter in model calibration, particularly for lower wind speeds where low intensity cyclones in combination with large astronomical tides may cause coastal inundation. Modelling of three significant cyclone cases at Mermaid Sound showed that time varying tide levels could lead to minor differences in overall storm tide level compared with a fixed tide level of MSL. Modelling of joint occurrence wave conditions with the storm tide at the Mermaid Sound location for three historical cyclone cases showed that higher water level residuals were generated that were phase dependant on the astronomical tide, peaking at lower water ebb and thus not impacting the peak water levels through the events.

8. References

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