Options for real-time forecasting of storm tide inundation for emergency management in Queensland, Australia

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Whilst evacuation arrangements for the large storm tide experienced during Tropical Cyclone (TC) Yasi in North Queensland, Australia, in 2011 were successful with no deaths from this hazard, post-event assessment of the current storm tide warning system suggested that improvements are possible. Workshopping with emergency managers identified the translation of storm tide warning levels into onshore estimates of inundation, refinement of the timing of the peak surge with regards to high tide and also understanding the underlying uncertainties currently unexpressed by the deterministic forecast as potential areas for development. Here, the potential for probabilistic real-time storm tide inundation forecasting is explored via an options analysis for each component of the storm tide forecasting process: TC tracks, wind fields, hydrodynamic modeling and post-processing of outputs for use in risk assessment. We identify the high degree of uncertainty in the forecast TC track as the key factor governing the development of a probabilistic system. This uncertainty requires simulation of a large ensemble, necessitating run-time optimization of the wind field and hydrodynamic modeling processes. Taking into account the results of the options analysis, we propose a feasible real-time storm tide forecasting system. A case study demonstrating this system based on TC Yasi (2011) is presented.

Keywords: storm surge; tropical cyclones; numerical modelling; high-performance computing; emergency management.

I. Introduction

Storm tide presents the greatest hazard to life in tropical cyclone (TC) events with the potential for water levels exceeding the height of single-story buildings. The Queensland coastline of tropical to subtropical eastern Australia has particular vulnerability to this hazard due to its exposure to frequent tropical cyclone events, wide continental shelf particularly within the Great Barrier Reef (GBR), growing coastal population centers and low-lying developments. Griffith has initiated a research project in partnership with Emergency Management Queensland (EMQ), the Queensland Cyber Infrastructure Foundation (QCIF) and DHI Australia investigating the potential for real-time forecasting of storm tide inundation during TC events using numerical modeling.

The current emergency management response to an impending storm tide hazard in Queensland is evacuation to higher ground. The lead time for effective evacuation is 24 to 48 hours prior to the predicted onset of gale force winds, depending on the local setting. Decisions on the necessity of evacuations are made by emergency managers based on storm tide warnings issued by the Australian Bureau of Meteorology (BOM). The current forecast system for storm tide in Queensland is deterministic in nature, matching the forecast cyclone track and intensity parameters to a set of pre-run scenarios, and outputting estimated storm tide levels at discrete offshore locations along the coastline. Upgrading the current system towards probabilistic output with higher spatial resolution, inundation mapping and reduced conservatism by improving the calculation of the timing of the storm surge event with the astronomical tide have all been highlighted as areas for potential improvement that would enable more targeted deployment of emergency resources in a TC event.

The aim of this pilot project is to explore the options for real-time probabilistic storm tide forecasting that would add value to emergency planning and to frame a feasible system framework. Firstly, we establish the system requirements and assess the existing system. We then explore options with regards to TC tracks, TC wind fields, hydrodynamic modeling and output presentation. The structure of a feasible system capable of generating real-time probabilistic storm tide forecasts based on this options analysis and using the real-time information available to Australian forecasters is presented. It consists of: (1) an approach to create a probabilistic ensemble of TC tracks and parameters at the present time in the TC forecast suitable for simulating storm tide; (2) an extension of existing parametric wind field generation techniques making use of available TC parameter information; (3) a calibrated and validated finite volume hydrodynamic storm tide model that has been optimized for real-time simulation; and (4) a probabilistic inundation mapping technique enabling delivery of inundation forecasts to emergency managers. Each of these components is discussed in further detail. A case study demonstrating the feasibility of the proposed system based on TC Yasi (2011) is presented.

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II. System Requirements

A. Basic System Framework

A storm tide forecasting system consists of the following key components:

a. Forecast TC track
b. Generation of cyclonic wind and pressure field
c. Hydrodynamic modeling of storm surge
d. Post-processing of storm tide magnitudes
e. Risk assessment methodology

This system framework can then be extended into ensemble mode by supplying an ensemble of TC track inputs and iterating through the above steps. If probabilities are associated with each of the input tracks, the output storm tide magnitudes can be mapped as probabilistic outcomes. There are several possible options for each component of the system and here we assess the current system and explore the possibilities for a new system based on the trade-offs between run-time and added accuracy.

B. Assessing the Current Storm Tide Forecasting System

The current storm tide forecasting system for Queensland operated by BOM and delivering storm tide warnings to EMQ is deterministic in nature and implements the following options for each of the key components:

a. Forecast TC track: A consensus TC track derived from the forecaster's best assessment of predicted TC behavior from outputs of several atmospheric model and other guiding information such as available wind and pressure measurements and modeled sea surface temperatures is used in the storm tide forecast system. The selection of this consensus track is presently a manual process.
b. Wind field: The consensus TC track is matched to the closest track from a pre-run library of scenarios for landfalling TCs [5]. The wind/pressure field used in these pre-run scenarios is based on the parametric profile of Holland (1980) [6].
c. Hydrodynamic model: The pre-run library of storm surge scenarios was made by using the input wind/pressure field to force the finite difference 2D hydrodynamic model MMU-SURGE [5]. It has three levels of nesting with the spatial resolution of the finest grid being 0.3 arcseconds (0.56 km). While this model is custom-built for its application and computationally very efficient, some of its limitations include no wetting and drying, and spatially constant bottom friction, both of which prevent more detailed modelling of overland flow. The model is run with a static initial water level and no tidal forcing.
d. Post-processing: Storm surge magnitudes are estimated at discrete locations along the Queensland coast at an offshore contour. The output storm surge height is then added to the highest tide of the day until ~12-24 hours prior to landfall (when there is more certainty in landfall time and location), when the appropriate predicted tide magnitude is used. Potential wave set-up levels are considered by applying offshore forecast wave height and period estimates to the empirical equations of Hanslow and Nielsen (1993) [4] (pers. comm.. B. Gunn, BOM, 2013). The resultant storm tide warnings delivered to emergency management agencies.
e. Risk assessment methodology: The storm tide warning magnitudes are used by EMQ officers to create surfaces in GIS that are intersected with the terrestrial Digital Elevation Model (DEM) in a bath-tub inundation approach to identify pre-defined evacuation zones in 0.5 m increments above highest astronomical tide (HAT) on a region-wide basis.

C. Identifying the Ideal Storm Tide Forecasting System

A survey of Queensland local councils and workshopping with EMQ identified the desired output and requirements of an improved storm tide forecast system. Some key requirements are outlined below:

- Spatial resolution of output: While refined spatial resolution is highly desirable, evacuation mapping would be performed on a 'block-by-block' basis, meaning that output mapped at a spatial resolution finer than approximately 100 m would likely be redundant.
- Timely output: Output is required with a 1-hour turn-around from the time of TC track updates (every six hours).
- Accuracy: Storm tide risk is currently identified in 0.5 m increments above HAT, meaning that storm tide estimates at finer vertical resolution will be rounded up. Accuracy of storm tide magnitude to 0.1-0.2 m is sufficient.
- Acceptable conservatism: While conservatism in hazard warnings seems prudent, arguments made by disaster managers against over-cautiousness include limited availability of emergency personnel for deployment requiring targeted response to potential risk, the effect of false warnings on the public's behavior and the risks posed to the public during evacuations making overly cautious evacuations undesirable.
- Understanding uncertainty: At a minimum, real-time emergency management decision-making would benefit from an understanding of the 'worst-case' and 'most-likely' scenarios, especially with regard to timing of storm surge with high tide. However, each possible TC landfall has the potential to generate the 'worst-case' storm surge in some location along the coastline, making an ensemble approach more appropriate. Emergency managers identified the probabilistic inundation mapping of storm surge produced by NOAA for events such as Hurricane Sandy as useful (Fig. 1), although are not clear on how such a view of inundation probabilities would be used in a real-time event.

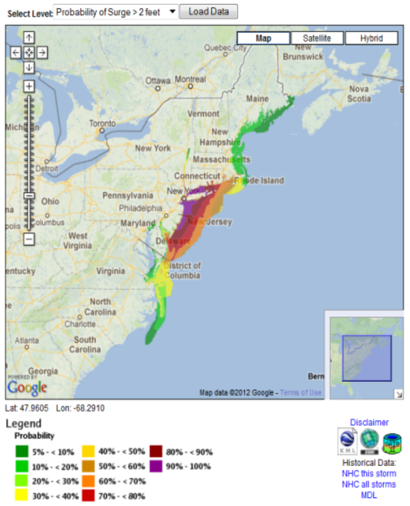

Fig. 1. Example of a probabilistic storm surge forecast map for Hurricane Sandy, 29th October 2012 (NOAA: www.nhc.noaa.gov/aboutpsurge5.shtml).

While emergency managers would find ideal a system that provides highly accurate predicted water levels incorporating all physical processes including waves and the freshwater contribution to water levels in estuaries at fine spatial resolution with sufficient lead time for effective evacuation, some trade-offs are of course required. The key factor governing the development of a storm tide system is the high uncertainty contained within the TC track forecast at the timeframe when evacuation decisions are made. The current deterministic system can provide a false level of comfort, because although the storm tide magnitudes are conservative given their combination with the highest expected tide, the full range of landfall locations and hence spatial risk is not realized nor is the potential for rapid TC intensification.

An updated storm-tide system would also have the advantages of integrating the latest available bathymetric and topographic data. Whilst availability of high-resolution bathymetry along the Queensland coastline is limited, 1-m resolution LiDAR DEM data covering most of the Queensland coastline have been available by the Queensland State Government, enabling extension towards inundation modelling.

III. Options Analysis

A range of possible approaches for addressing the system requirements for storm tide forecasting based on the framework presented in II.A. are discussed in this section.

A. Options for Tropical Cyclone Ensemble

Probabilistic storm tide estimation is only possible by running simulations with probabilistic TC wind and pressure field forcing inputs. The size of the TC ensemble necessary to capture the range of storm surge possibilities at a given point in a forecast informs subsequent development of the wind field and hydrodynamic modelling framework by providing guidance on the model run-time and computational resources necessary to complete such simulations within the desired turn-around time. At the evacuation timeframe of 48 hours from landfall, the potential area of landfall and hence peak surge magnitude may be hundreds of kilometers wide as illustrated in Fig. 1. This uncertainty together with the high sensitivity of storm surge magnitude to the TC track supports an ensemble approach with a large number of members.

In terms of available probabilistic TC information in forecast mode, options for generation of an ensemble of forecast TC tracks may include: (1) Multi-model ensemble of tracks; (2) Single-model ensemble of tracks generated by perturbing the model initial conditions and model settings; and (3) Stochastic ensemble of tracks. Multi-model tracks are not currently available operationally at BOM and are also difficult to associate with probabilities. A single-model ensemble output for a tropical cyclone-specific atmospheric model (e.g., ACCESS-TC) is also unavailable operationally at present. BoM operationally generate a 1000-member stochastic set of TC tracks for the purposes of generating wind hazard probability maps (pers. comm.., Dr M. Foley 2013). This set of tracks is based on the consensus forecast track, and created using the method of DeMaria et al. (2009) [3] by sampling the errors in TC parameters from distributions computed from the errors between the consensus and ultimate best track at different forecast periods for TC events in the Australian region over a 5-year period. The TC parameters considered include: track location (calculated in along-track and cross-track components), intensity (Maximum Sustained Winds (MSW)) and scale (given as Radius of Maximum Winds (RMW) and radius to 34, 48, and 64 knot winds (R34, R48, R64) for four quadrants). A sample of this ensemble for TC Yasi at 48 hours from landfall is shown in Fig. 2.

There are several disadvantages of this stochastic track ensemble for direct use in storm surge simulation given that it was not developed for this purpose, including:

- The error distributions are climatological and there is no account for current physical processes that may constrain the range of track possibilities, e.g., sea surface temperature (SST) and upper level steering;

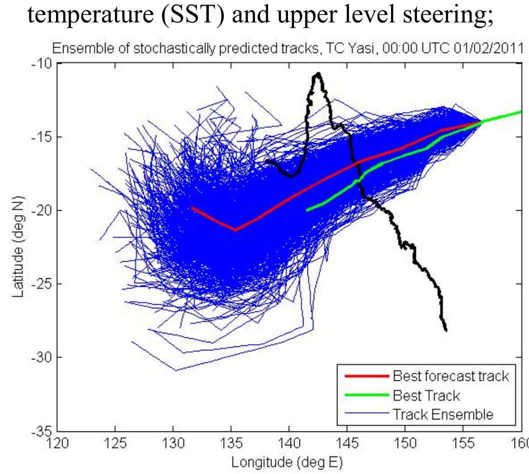

Fig. 2. Example of the DeMaria 1000-member TC track ensemble for TC Yasi at 48 hours from landfall, showing considerable spatial spread in potential landfall locations along the Queensland coast (black) (courtesy M. Foley, CAWCR).

- The independence of the along-track/cross-track error in forecast cyclone position means that a change in direction in the forecast TC track leads to unrealistic changes in the translation speed and some unphysical deviations in track. While having little influence on wind probability calculations, these characteristics would prove problematic for storm surge simulation;
- The size of the ensemble, while found sufficient to ensure convergence of the Monte Carlo approach for wind probability estimation [3], is likely insufficient to generate convergence of probability estimates for the parameters of interest in storm surge simulation, given the sensitivity to intensity, landfall location and timing.

B. Options for Tropical Cyclone Wind Fields

Hydrodynamic modelling of storm surge is forced by input wind and pressure fields. Firstly, we demonstrate that existing operational wind/pressure field products are unsuitable for storm surge modelling. Despite its status as a state-of-the-art cyclone model, BOM's current operational tropical cyclone atmospheric model, ACCESS-TC, is not suitable for use as forcing for storm surge modeling for the following reasons: (1) its 0.11 degree spatial resolution is inadequate to capture the peak intensity of the system, (2) in forecast mode, the TC intensity and track are not adequately predicted for accurate storm surge modeling. For example, despite the good model performance for TC Yasi, the peak modeled storm surge magnitude using ACCESS-TC wind fields is 2.23 m at the key impact site of Cardwell, North Queensland, compared to the measured peak of 5.3 m. This difference is attributable to an error in landfall location of approximately 35 km to the north along with a minimum central pressure 15 hPa above the measured minimum (Fig. 3).

In the absence of dynamical atmospheric model output, an alternative for generation of cyclonic wind fields offering more flexibility in ensemble mode and specification of intensity is a parametric approach, as implemented in the current system [5]. A parametric radial wind/pressure profile such as that of Holland (1980) [6] is extended into the azimuth and time dimensions with adjustments for asymmetry, translation speed and inflow angle. Validation exercises conducted in this project found the Holland et al. (2010) [7] wind/pressure profile an improvement in matching modelled to measured winds over the currently used Holland (1980) profile, with its flexibility to adjust wind speeds in the tails of the wind profile for either estimates of scale parameters such as radius to gales (R34) by quadrant or observations (Fig. 4). Insufficient TC forecast or measurement information is available in real-time to justify use of a double vortex model such as that suggested by [7] or more sophisticated variants. The disadvantages of this parametric approach include the difficulty in replicating synoptic-scale features and more complex cyclonic structures that may add to the peak storm surge magnitude.

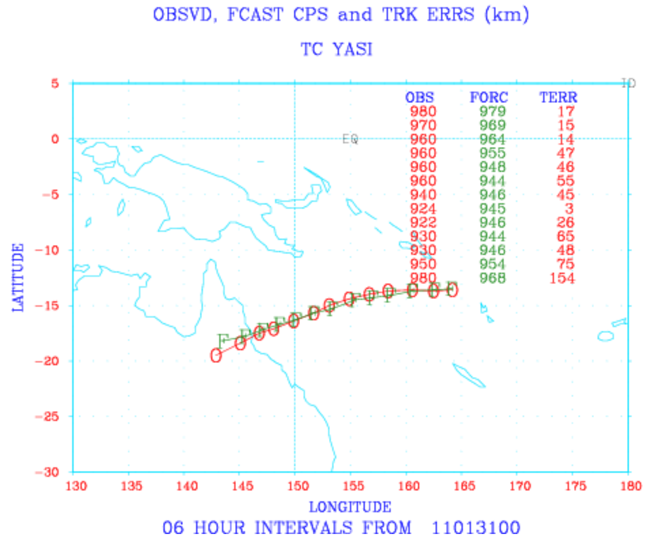

Fig. 3. Comparison of the ACCESS-TC forecast (green) and observed (red) tracks for TC Yasi (courtesy Noel Davidson, BOM), also giving the observed and forecast central pressures (hPa) and track errors (km).

C. Options for Hydrodynamic Modelling

A thorough options analysis of the numerical modelling requirements of accurate and efficient storm surge modelling was conducted prior to implementation of the current storm tide forecasting system [6]. Although available computational processing power has since increased, the TC ensemble approach developed above still requires fast run-times of each ensemble member and precludes the inclusion of additional processes in the simulations that might have value if simulation of one or a limited range of TC tracks is required. Such additional processes may include dynamic tides, forcing by wave radiation stresses, three-dimensional processes, and overland flow. The improvement in computational processing also makes possible the use of dynamic simulations over pre-run scenarios, which enables greater variety in the path of TC tracks that can be considered.

We focus on advances in hydrodynamic modelling in the period since the development of the existing system. In this time, finite volume hydrodynamic models such as ADCIRC, MIKE21 and Delft-Flow-FM have become more widely applied. The advantage of the finite volume over the finite difference method lies in the capability for more accurate description of complex coastal boundary conditions. While finite volume models can be less computationally efficient than finite difference, the simulation time can be contained by focusing areas of higher resolution elements over complex bathymetry such as nearshore channels and entrances, the Great Barrier Reef and island groups without requiring multiple levels of nesting and reducing the number of elements in areas with simple bathymetry.

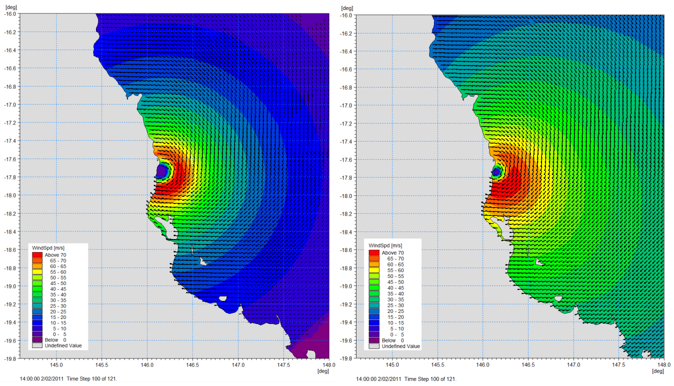

Fig. 4. Samples of best calibrated wind fields for TC Yasi (2011) based on (a) Holland (1980) and (b) Holland et al. (2010).

D. Options for Post-Processing and Output Display

Alternatives for generating probabilistic storm tide inundation maps improving upon the current region-wide bath-tub inundation mapping were identified as using the output of a coarser 'nearshore' model with faster run-time combined with a bath-tub inundation approach, and high resolution 'inundation' model which dynamically maps overland flow due to storm tide. The trade-off between these two approaches is between accuracy of the output water level and run-time.

The coarser 'nearshore' approach involves offline combination of simulated storm surge water levels at output points at 1 – 2 km spacing along the coastline with tidal water levels drawn from empirical distributions built from the range of timing of TC landfall across the ensemble. Probabilistic storm tide heights at each model output point are calculated using the probabilities associated with each TC ensemble member. These probabilities can be expressed either as the probability of storm tide greater than *X* m, or storm tide magnitude (m) that is exceeded by *Y* % of ensemble members (as for NOAA's p-surge model; [8]). Both display methods were identified as useful for disaster managers. The resultant storm tide surfaces are then mapped onto the terrestrial DEM to produce inundation depths and extents. While similar to the current approach, this method has finer spatial resolution of output and avoids discontinuities in the storm tide surface. It has disadvantages in that the local wind set-up resulting in elevated water levels between the output point and the ultimate vertical extent of storm tide penetration is neglected.

The possibility for detailed inundation modelling enabling high resolution simulation of overland flow is explored through a case study validation of measured overland flow experienced during TC Yasi (2011). Mesh elements with a spatial resolution of 80 to 100 m were found to be required to replicate the storm surge inundation over land observed due to this event. The inundation model at this resolution covering coastal townships in the Cassowary Local Government area in North Queensland contains 99535 elements, more than the greater Coral Sea model. The simulation time per ensemble member is 4912 seconds per core, which is 38 times slower than the coarser model. This run-time would be expected to be higher for more populated risk areas where the inundation model would contain more mesh elements. We conclude from this case study that the inundation modelling approach currently has prohibitive simulation times for use in ensemble mode for currently available computational resources.

IV. A Feasible Storm Tide Forecasting System Design

Based on the options analysis above, we now present the structure of a feasible system capable of generating real-time probabilistic storm tide forecasts using the real-time information available to Australian forecasters. It consists of: (A) an approach to create a probabilistic ensemble of TC tracks and parameters at the present time in the TC forecast suitable for simulating storm tide; (B) an extension of existing parametric wind field generation techniques making use of available TC parameter information; (C) a calibrated and validated hydrodynamic storm tide model that has been optimized for real-time forecasting; and (D) a probabilistic inundation mapping technique enabling delivery of inundation forecasts to emergency managers.

A. TC Ensemble

Despite the disadvantages of the DeMaria stochastic track ensemble identified in II.A., this product was the most suitable for application to this project given that development of more sophisticated techniques is not likely in the time frame of this project. Using the DeMaria ensemble, we have developed a method to reconstitute a set of representative tracks from the probability distributions of the parameters important for storm surge with associated probabilities of occurrence for use in real-time probabilistic storm surge simulation as follows:

a. For each ensemble member in the forecast period, the track is intersected with the coastline and the scale (RMW) and the time and position of landfall (crossing time and position) are calculated.

b. The proportion of tracks making landfall in each coastal segment spanning 0.5° of latitude along the eastern Queensland coastline from 15°S to 29°S is calculated. This length of coastal segment was chosen as a balance between the extensive length of the coastline and the typical RMW.

c. For each coastal segment, the empirical probability distributions of crossing time and RMW are determined.

d. To make the new TC track ensemble for storm surge simulation, a set of tracks comprising those representing the range of variability present in the forecast is assembled. The size of the resulting ensemble, n, is:

$$n = n_{cl} \text{ x } n_i \text{ x } n_{RMW}, \qquad (1)$$

where n_{cl}, n_i, and n_{RMW} are the number of realizations necessary to appropriately represent the empirical probability distribution of crossing location (*cl*), intensity (*i*), and scale (*RMW*), respectively. Crossing time (*ct*) is considered offline via linear addition with the estimated tide. The ensemble tracks are recomputed every forecast output period. As the TC progresses closer to the coastline and the range of landfall locations narrows, the spatial resolution of the coastal segments is decreased.

Ascertaining the size and composition of this TC ensemble requires an understanding of the sensitivities of the predicted storm surge to the various input parameters defining the TC wind fields. As part of this study, an extensive set of sensitivity analyses will be tested using the TC wind field and hydrodynamic models described in the following sections in order to identify the values of Δi and ΔRMW necessary to capture the range of possible storm surge heights for each coastal segment. The robustness of the proposed ensemble selection for probabilistic storm surge forecasting would be best tested through comparison of the resulting probability storm surge surface with that generated using a very large (~1 million) set of simulations based on an expanded DeMaria set. Approaches for ensemble selection for more complicated cases, including non-landfalling TCs, TCs crossing from the land out to sea and offshore islands, are under development.

B. Wind/Pressure Field Model

A wind/pressure field model based on Holland et al. (2010) [7] which uses the information available in the DeMaria TC track ensemble for RMW, R34 by quadrant, and MSW is applied. This model was found to be superior to the Holland (1980) [6] model in replicating historical storm surge events in validation exercises [2].

C. Hydrodynamic Model

Given the advantages of finite volume modelling indicated above, a calibrated and validated hydrodynamic model of Queensland's 3000 km long east coast including the complexity of the Great Barrier Reef was constructed using MIKE21 by DHI using an unstructured mesh. The model is implemented on HPC facilities and has been optimized for real-time forecasting of storm surge due to tropical cyclones by reducing the number of elements without compromising the calibration and validation, improving run time by 35 % over the initial form of the model. The model domain is the Coral Sea (Fig. 5), calibrated for the astronomical tide for 13 measurement sites from the Gold Coast Seaway (27.95 °S) to Cooktown (15.45 °S). The most recent bathymetry was sourced from multiple local, state, federal agencies and industry, and adjusted to AHD.

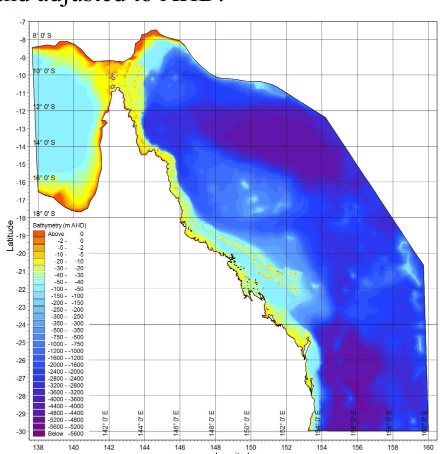

Fig. 5. Extent of the Coral Sea hydrodynamic model and bathymetry.

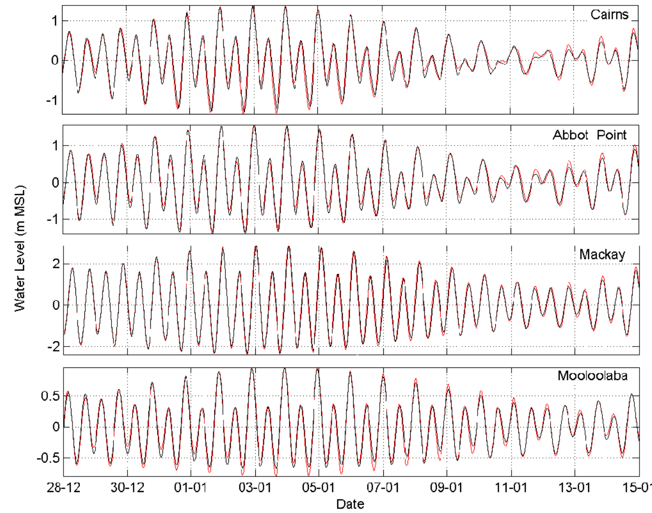

Fig. 6. Modelled (black) and predicted (red) water levels at four calibration sites in the Coral Sea hydrodynamic model for Dec 2010 to Jan 2011.

The model consists of ~87 000 elements with arc lengths varying between 150 m and 50 km. Sample tidal calibration plots are shown in Fig. 6 (additional calibration data provided in [2]). A comparison of modelled to measured tidal constituents shows good agreement in both amplitude and phasing (sample in Table 1). The model has been validated against several historical storm tide events [2] and shown to be suitable for modelling storm surge magnitudes (Fig. 7). Model run-time is substantially reduced by selecting an appropriate domain extent. A pre-defined library of model domains has been created and a tool developed to select the appropriate domain based on the area of influence of the TC ensemble member to be simulated. An example of such a model domain for the best track of TC Yasi contains 6742 elements (Fig. 8).

TABLE I. SAMPLE COMPARISON OF MODELLED AND MEASURED TIDAL CONSTITUENT AMPLITUDE AND PHASE FOR THE CORAL SEA MODEL (EXTRACTED FROM [1]).

Tidal Const	**Location**					
	Cairns			***Mackay***		
	Mod	***Meas***	***Diff***	***Mod***	***Meas***	***Diff***
	Amplitude (m)					
Q_1	0.02	0.03	0.00	0.03	0.04	-0.01
O_1	0.13	0.15	-0.02	0.17	0.20	-0.02
P_1	0.09	0.09	0.00	0.11	0.12	0.00
K_1	0.28	0.31	-0.03	0.36	0.39	-0.03
N_2	0.20	0.19	0.01	0.40	0.41	-0.02
M_2	0.64	0.58	0.06	1.63	1.67	-0.04
S_2	0.33	0.34	-0.01	0.57	0.61	-0.04
K_2	0.10	0.09	0.01	0.10	0.09	0.02
	Phase (°)					
Q_1	132	130	2	131	124	7
O_1	150	154	-3	146	147	-2
P_1	190	187	3	184	183	1
K_1	190	191	-1	184	187	-2
N_2	260	256	4	304	305	-1
M_2	280	276	3	322	322	0
S_2	258	248	11	327	321	6
K_2	254	245	9	323	319	4

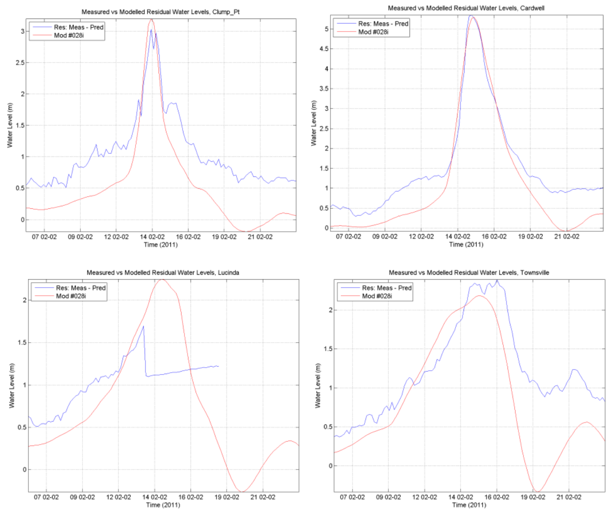

Fig. 7. Measured tidal residual (blue) vs modelled storm surge (red) (Holland et al. 2010 winds) for (a) Clump Point, (b) Cardwell, (c) Lucinda, and (d) Townsville for TC Yasi. Time in UTC.

D. Inundation Mapping

Based on the options analysis in III.D., the 'nearshore' inundation mapping technique is suggested for the storm tide forecasting system. Hydrodynamic simulations are made without a tide given the uncertainty in forecast TC track timing, and a set tidal water levels are subsequently added onto the each member of the simulated set of storm surge water levels. This makes the assumption that storm surge and tide are linearly additive, which is conservative at high tide but not so at low tide as storm surge development is greater in shallow water. Using the calibrated Coral Sea tidal model, a predicted tide time series for each of the model output points is generated. For each member of the DeMaria ensemble, the TC crossing time is used to select the corresponding tidal water level at each output point.

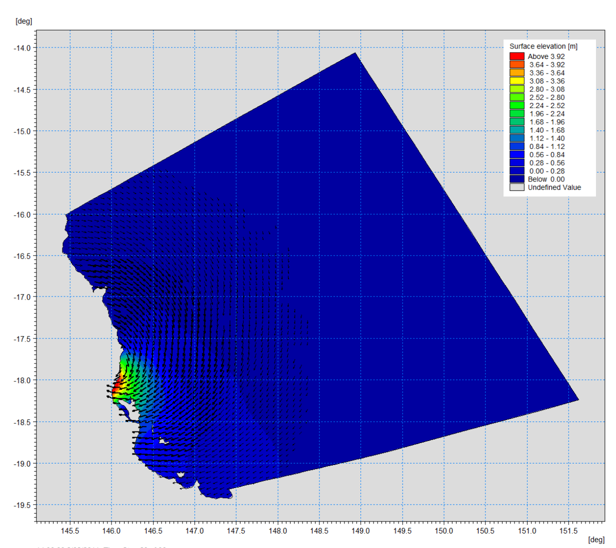

Fig. 8. Sample model domain for TC Yasi from Townsville to Cairns showing the storm surge water level at landfall using Holland et al. (2010) wind/pressure field.

The empirical probability distribution of the tidal water level at each output point is then calculated from which a set of realizations are drawn and combined with the storm surge ensemble results. Probabilistic storm tide surfaces are then computed as for NOAA's p-surge model [8]. However, EMQ wish to consider the total ocean water level including wave set-up where applicable. While modeling of wave set-up is outside the scope of this study, functionality to include a wave set-up estimate is included in the mapping technique, which could be used in a predefined open coast zone.

The resultant total ocean water level heights would then be delivered to EMQ to map inundation using a bath-tub approach in GIS software as previously described. The resultant probabilistic inundation depth extents and surfaces can then be intersected with pre-defined evacuation zone maps by EMQ and local emergency managers to identify areas requiring evacuation orders.

V. Example: TC Yasi

As an example, the resulting TC ensemble for TC Yasi selected using the method outlined in VI.D. with the DeMaria stochastic ensemble 48 hours prior to landfall as input contains 282 members assuming Δi=10 m/s and ΔRMW=5 km. In terms of operational run-time, each simulation would be required to run in (X*45*60)/n seconds per core for X computing cores (e.g., 282 simulations on 32 cores of computing resources = 306 sec per run per core) to achieve a one-hour turn-around from each TC track forecast update assuming 45 min for simulation and 15 min for pre- and post-processing. Such an example is achievable with the hydrodynamic model established for this study combined with the domain selection tool (see Table 2).

The model run-time required to accurately simulate the peak storm surge magnitude for one TC track is 130 sec/core (Table 2), which is sufficient to meet the required system turn-around time for the 282-member ensemble using only 16 computational cores. This encourages expansion of the ensemble set towards finer spatial resolution in landfall locations.

TABLE II. Example model run-time in seconds (speed-up factor) for MIKE 21HD FM on Griffith University's HPC facilities.

Domain	**Run Length**	**No. Cores**					
		1	***2***	***4***	***8***	***16***	***32***
Coral Sea	28 days	81717 (1)	26468 (3.1)	13827 (5.9)	7468 (10.9)	3660 (22.3)	2018 (40.5)
TC Yasi	24 hrs	130 (1)	68 (1.91)	40 (3.25)	24 (5.42)	16 (8.13)	18 (7.22)

VI. SUMMARY

This paper has outlined a workable system for probabilistic real-time forecasting of storm tide heights and mapping of inundation for Queensland based on assessment of system requirements with stakeholders and an options analysis. An approach for building a TC ensemble suitable for storm surge simulation based on available forecast information is introduced, as are a wind/pressure model, a finite volume hydrodynamic modelling system comprised of multiple domains and a probabilistic inundation mapping technique. The optimized hydrodynamic model has been established on high performance computing and yields run-times for TC events suitable for an ensemble modeling approach. Through case study modelling of TC Yasi, we have concluded that extension into high resolution storm surge inundation modelling is not currently permissible in real-time given the computational expense. However, such fine scale output may be possible for pre-run scenarios.

Such a probabilistic system will enable disaster managers to have an understanding of the likelihoods of possible outcomes from an impending event. While the high uncertainty in current TC forecasts may not lead to a decrease in the conservative nature of storm tide predictions (for instance, by refining the TC crossing time with the phase of the tide), an improved understanding of the spatial variability in landfall locations is useful. Any improvements to TC forecasting can refine the output of this storm tide modelling system.

The uncertainty present in the accuracy of TC forecasts would not warrant efforts to refine the storm surge modelling for other uncertainties or neglected processes such as storm surge and tide dynamics, the influence of wave-induced radiation stress or wave-dependent variations in wind drag coefficients etc. Extension of the inundation mapping to include the wave setup component also remains for future work.

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