Gulf of Carpentaria Storm Tide and Inundation Study

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Abstract
This study involved the statistical analysis of simulated ocean water levels (based on atmospheric, hydrodynamic and spectral wave modelling) throughout the entire Gulf of Carpentaria region, resulting in estimates of the probability of exceedance of extreme ocean water levels for over 2,500 km of open coast and detailed inundation mapping of specific community areas for emergency management. The study is predicated on knowledge of existing or immediately past climatic data and utilises projections of possible future climate change, including sea level rise and increased tropical cyclone intensity. A series of nested hydrodynamic models was used to simulate 50,000 years of tropical cyclone activity in conjunction with monsoonal influences, derived from a stochastic cyclone track model for both present and future climate conditions. These results were then statistically combined with the non-cyclonic only analysis. The study has shown that there is potential for storm tide inundation up to as high as 9 m AHD at the coastline and for inland penetration across the flat featureless coastal margins as much as 30 km.

The study was undertaken for the Department of Science, Information Technology, Innovation and the Arts (QLD) following receipt of a Natural Disaster Mitigation Program (NDMP) grant.

Keywords: storm tide, tropical cyclone, coastal hazards, climate change, numerical modelling.

1. Introduction

The Gulf of Carpentaria (refer Figure 1) is a partly-enclosed shallow tropical sea that experiences a range of atmospheric and ocean forcing that must be adequately described in order to represent the statistics of extreme storm tide episodes along its coastline.

While tropical cyclones (TCs) remain the principal threat to life and property, the shallow waters also react quickly to the more modest but often persistent atmospheric circulation surrounding these intense vortices, effectively extending the reach of the storm centre and likely making this area the most surge-prone in Australia. Considering the TC vortex forcing in isolation from its background environment underestimates the potential for storm tide impacts in this region. Accordingly this study has sought to retain the important linkages between these scales of forcing. Combined with the Gulf's extensive low-lying coastal regions, modest inundation of the land-sea margins above tidal levels is likely a relatively common feature of the region, and often results in "erratic" tides.

In addition to impacts posed by TCs, the Gulf also exhibits a significant seasonal variation in water level. During the summer monsoon the dominant northwesterly wind regime can result in a water level setup exceeding 0.4 m in the southern Gulf. When these strong monsoonal systems coincide with a period of high tidal amplitudes, the resulting water level can easily exceed the Highest Astronomical Tide (HAT) and result in inundation of coastal flats.

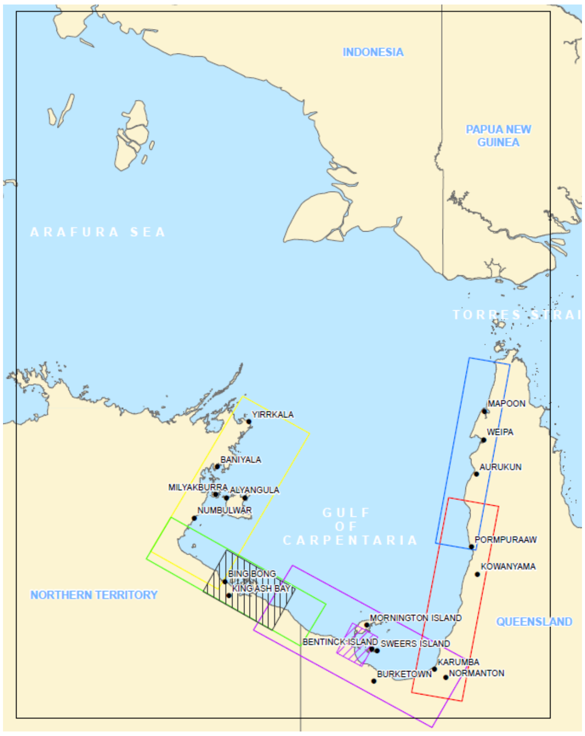

Figure 1 Study Area with hydrodynamic model extents overlayed. The A00 tidal model is represented by the outer black extent

The Gulf features prominently in the list of extreme storm tide events known to have occurred [4],in Queensland since the late 19th century.

1.1 Study Objectives

The objective of the study was to quantify the likelihood of coastal and associated waterway areas within the Gulf of Carpentaria area being inundated by storm tide caused either by severe TCs or other broadscale atmospheric influences.

With knowledge of the probability of specific water elevations being equalled or exceeded, long term planning can be adopted to mitigate against the more adverse impacts. Emergency response planning can also utilise this information to ensure adequate resources will be allocated to those areas most likely to be affected.

The study outcomes correspond to specific return period risk or ARI. These provide an essential input to long term planning whilst also allowing a relative ranking of risks for emergency response. The storm tide probability levels considered were the 50, 100, 200, 500, 1,000, 10,000 year Return Periods for 2010, 2050 and 2100 climate scenarios.

A series of parametric storm tide models for the Gulf region were also prepared that are consistent with the overall methodology and can be utilised for rapid prediction and warning purposes.

2. Regional Meteorology

The Gulf regional meteorology is dominated by the summer NW monsoon (refer Figure 2 as an example derived from Bureau of Meteorology (BoM) modelling) and the winter SE Trade circulations. The monsoon trough typically develops in late October and moves southwards during the summer, being located over the Arnhem Land region in January, and then ascends once again by April. During the monsoon trough descent and ascent periods TCs have an enhanced opportunity to form in the Arafura and Coral Sea. For the remainder of the year the region is typically under the influence of high pressure systems far to the south.

2.1 Tropical Cyclones

The study considered all available records of TCs from official BoM records (National Climate Centre) as well as recent Queensland Regional Office records in Brisbane. However, only those TCs that entered within the A00 hydrodynamic grid domain (refer Figure 1) have been included in the statistical analyses. Some editing of the official BoM datasets was undertaken to remove duplicate storm records, correct known errors and make other adjustments based on advice from Jeff Callaghan [7] following a specific review of TCs affecting the southern Gulf.

A total of 134 TCs were registered as occurring within the available 51 season record from 1959/60 to 2009/10 and within the study area, averaging 2.6 storms per season.

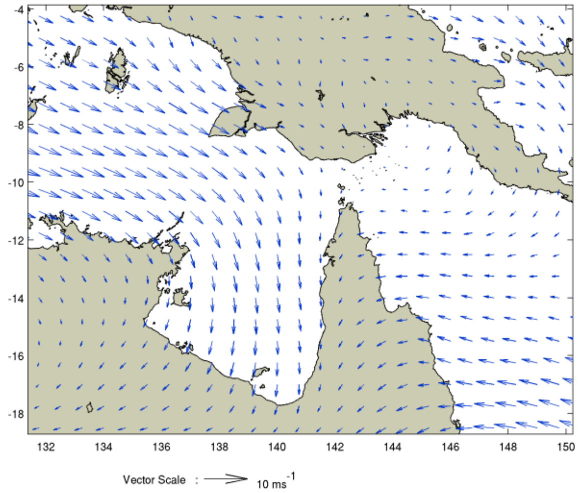

Figure 2 Mean BoM Laps modelled wind speed and direction data for January from 12 y of available data

3. Astronomical Tides

The Gulf is located at the confluence of the Pacific and Indian Oceans. On its eastern boundary Pacific waters pass into the Gulf via the Torres Strait, a region of very shallow bathymetry, reefs and islands which act to limit the flow to/from the Gulf to the Pacific. In comparison, the Arafura Sea to the west provides a largely unimpeded linkage to the Timor Sea and Indian Ocean.

Tidally, the region is complex due to the influence of these merged ocean systems, the shallow bathymetry and the degree of ocean interaction with the atmosphere.

3.1 Modelling the Astronomical Tide

A numerical model was developed bordering on the Arafura and Coral Seas encompassing the entire Gulf of Carpentaria and Torres Strait at a resolution sufficient to represent the tidal scale processes and the coastal features. The numerical tidal model used was based on MMUSURGE [1],[3], and is a rectilinear-nested two-dimensional barotropic model.

The model was calibrated using all suitable tide stations for a total of 36 major and minor tidal constituents.

The full predictive value of the output from the model is best illustrated by considering the modelled propagation of the principal tidal components in terms of their amplitude and relative phase. This is illustrated in Figure 4 which shows the modelled amplitude of the major diurnal constituent (K1) and major semi-diurnal constituent (M2) across the study region as a series of height contours and the propagation phase angle. The combinations of harmonics, plus shallow water sub-harmonics that are generated by the tidal flow interaction with the bathymetry are responsible for giving the tide its special and complex character across the region.

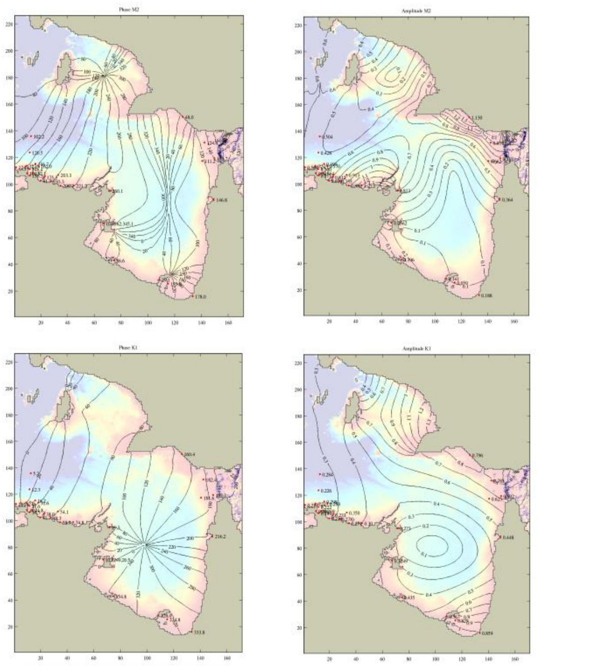

Figure 3 Calibrated tidal modelling results, M2 phase (top left), M2 amplitude (top right), K1 phase (bottom left) and K1 amplitude (bottom right) highlights the tidal complexity within the region

4. Modelling the Broadscale Sea Level Variability

The term 'broadscale' water level variability defines extreme water levels due to the combined effects of the astronomic tide plus meteorological variations not directly associated with TC vortices within the Gulf. Sometimes referred to as 'non-cyclonic' here the term 'broadscale' has been used in preference due to the at-times complicated interaction between TCs adjacent but outside the Gulf and the monsoon trough.

To reproduce observed broadscale water levels a number of local and externally driven wind, pressure datasets and oceanic water level signals were input as open boundary conditions into the calibrated hydrodynamic tidal model. These included:

- Synoptic variations acting directly on the surface of the Gulf (LAPS/NCEP hindcast surface wind and pressure)
- Average annual water level variability passing into the Gulf from both the Torres Strait and Arafura/Timor Sea (External boundary signal based on historic tidal analysis); and
- Longer term (inter annual) water level variability passing into the Gulf, such as the effect of the Southern Oscillation Index (External boundary signal based on historic tidal analysis[7]);

4.1 Broadscale Model Verification

To assess the broadscale model performance, a 60 y long hindcast was undertaken and compared with the available long term water level tide gauge records. This 60 y period coincided with the length of the available LAPS/NCEP data (1949 - 2010) and represents the longest available climate-forced record to establish the broadscale climatology.

Modelled and observed water levels were compared by extracting the annual water level maxima at each site and plotting in return period space via a ranked frequency formula

Figure 4 provides an example of the resulting performance of the broadscale model at the Groote Eylandt tide gauge comparing the observed water levels and resampled water level return periods derived from tidal analysis:

The results indicate that the broadscale model was able to highly accurately reproduce water levels derived from non – cyclonic influences.

5. Broadscale Production Modelling

To increase the available statistical record the 60 y validated hindcast record was then run within the broadscale model for 21 separate renditions with each run representing a different 20 y tidal epoch and a randomly sampled SOI signal. By varying the tidal signal the resulting broadscale water level record was extended to provide over 1,300 years.

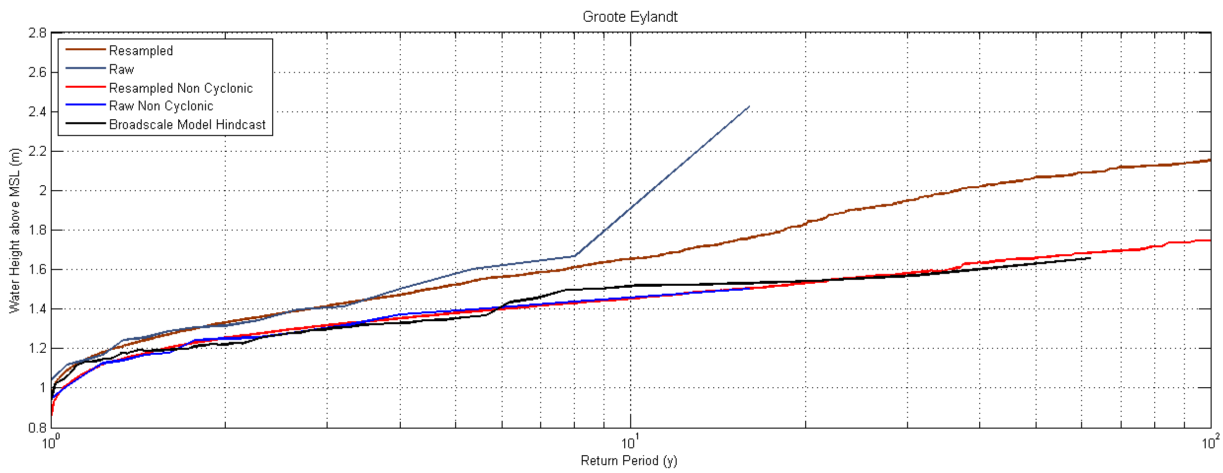

Figure 4 Broadscale verification at Groote Eylandt. Modelled broadscale levels (black) are shown to closely match the raw observed (blue) non-cyclonic levels. Tidally resampled residual observations (red) also show that beyond the available data the model is statistically accurate. Also provided are the raw observed TC data (dark blue) and statistically resampled TC residuals (brown) that typically exceed the broadscale levels by 0.1-0.3 m out to the 100 y Return Period

6. Synthetic Tropical Cyclone Modelling

The available 51 y TC track record was extended to 50,000 y using statistical modelling [5]. The technique involved the development of multiple linear regressions on the available data for key TC parameters such as heading, forward speed, central pressure and radius to maximum wind. Storms were initialised within the study area and an autoregressive model was used to determine track movement and changes to central pressure based on the preceding timestep and model coefficients. Example outputs from the synthetic cyclone model are provided in Figure 5 and 6.

6.1 Synthetic Model Verification

For each key parameter comprehensive verification was undertaken and the model compared well with the observed track data with results within 90% confidence limits using a bootstrap technique. In addition, the return periods of modelled wind speed data were compared to anemometer records at the relatively long-term stations of Weipa and Thursday Island. This showed good agreement between the modelled and measured datasets.

One example of model performance is provided for the radius of maximum wind *R, a* parameter that essentially determines the fetch length for surge and wave generation. Figure 7 provides the comparison between central pressure deficit and *R* for the full record of W&R [8] flight level data from US hurricanes, available Gulf TCs and all of the Gulf synthetically generated TCs

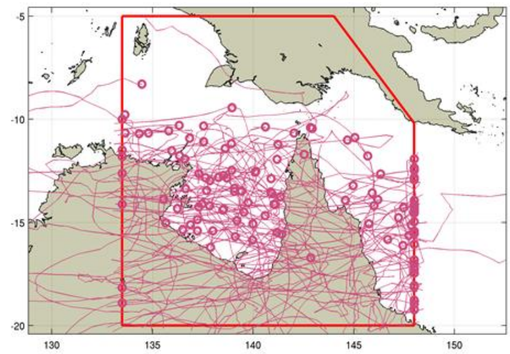

Figure 5 Sample of 5000 synthetically generated tracks

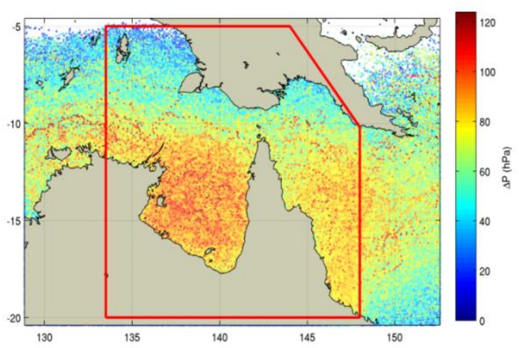

Figure 6 Modelled peak intensity of 50,000 y of TC tracks. Colours represent pressure deficit below 1010 hPa. More intense central pressures have been plotted above less intense tracks

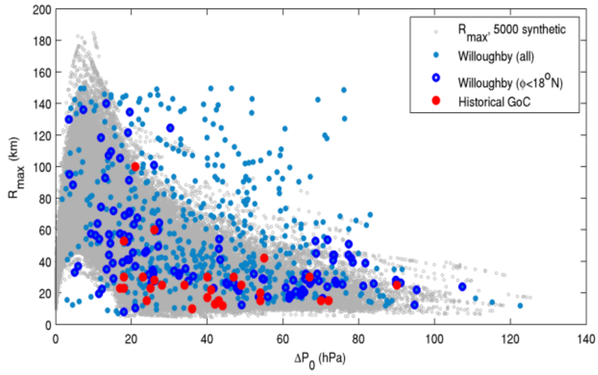

Figure 7 . Central pressure deficit (Ambient – central pressure) vs radius to maximum winds for the full record of W&R (Willoughby) flight level data from US hurricanes (light blue dots). This dataset was stratified to provide storms of similar latitude to the Gulf (bold blue dots). Observed and inferred Gulf data (red) and the background light grey shows a synthetic storms produced for this project

7. Tropical Cyclone Surge Modelling

A system of three nested transitions (refer Figure 1) comprising eight model grids was adopted for both the validation and operational stages of the numerical hydrodynamic modelling using the MMUSURGE modelling package.

The 50,000 y synthetic TC ensemble comprising over 120,000 individual tracks formed the basis for the tide plus surge modelling. During simulation of the 2010 climate over 300,000 individual model domain runs were undertaken.

To account for tidal variability, each track was nominated a randomly generated date which in turn was used to generate a tidal prediction for the duration of the storm track. Seasonal meteorological effects were included by blending the combined NCEP/LAPS data with the cyclone vortex [6].

The maximum water level for each track was stored for all gridpoints, allowing tide plus surge return periods to be provided for any location within the Gulf (refer Figure 8 and 9).

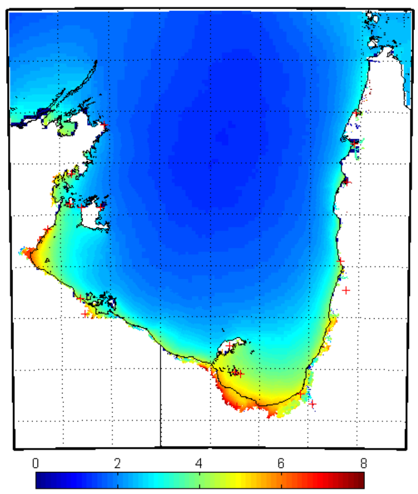

Figure 8 1000 y Return Period even tide plus surge estimates in m MSL. Regions of high surge levels include the southern and western Gulf where level can approach 8 m above MSL

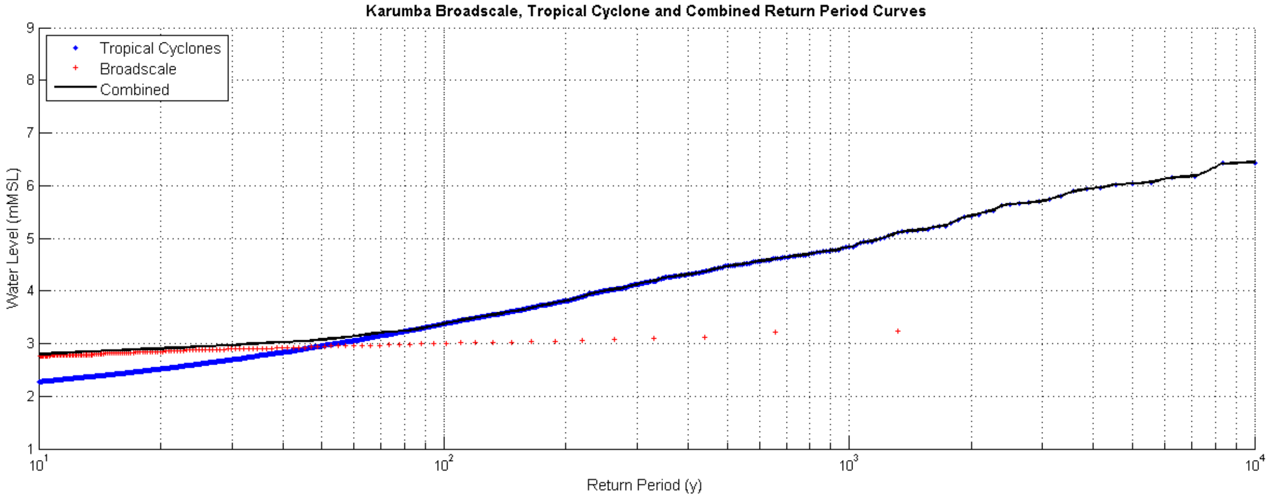

Figure 9 Broadscale (red), TC (blue) and statistically combined (black) tide plus surge Return Period curves for Karumba. Here broadscale events exceed TC level up to approximately 50 y. Note that combination (black) leads to estimated water levels that exceed either broadscale or TCs for levels with Return Periods ranging from 10 to 80 y

7.1 2050 and 2100 Surge Modelling

Production modelling for the 2050 and 2100 climates was completed in a similar manner to that undertaken for the current climate.

To make allowance for the potential effects of future climate change the synthetic track ensemble was modified by increasing all the storm central pressure deficits by 10 and 20% for the 2050 and 2100 climates respectively. Mean Sea Level (MSL) increases of 0.3 and 0.8 m were also applied.

7.2 Combining the Tropical Cyclone and Broadscale Statistics

Risk due to both broadscale and TC events was assessed by statistically combining the results from each population [2]. Figure 10 highlights the importance of considering broadscale events in the region with water levels at lower Return Period events dominated by non-cyclonic influences.

8. Calibration of Tropical Cyclone Ted and Kathy and Charlotte

To demonstrate the ability of the both the Double Holland wind and pressure model and MMUSURGE hydrodynamic models to reproduce observed events, hindcast calibrations were undertaken on *TC Ted* (1976) and *TC Kathy* (1984).

Figure 10 provides the observed and modelled wind speed (top) and MSLP (bottom) as Kathy passed over Centre Island. The figure shows the ability of both the Double (red) and Single (black) Holland models to accurately reproduce extreme events.

9. Spectral Wave Modelling

The contribution of wave setup to total water levels during TC events was assessed via the 3rd-generation numerical spectral wave model WAMGBR, [3]. A high level of calibration was achieved to *TC Charlotte,* which utilised a two tiered nested approach (refer Figure 1). Production modelling was completed for the 2010 climate utilising a sample of over 12,000 synthetic storms. Extensive investigation indicated that wave setup had a limited contribution in this specific environment due to high wave energy dissipation in the shallow nearshore waters.

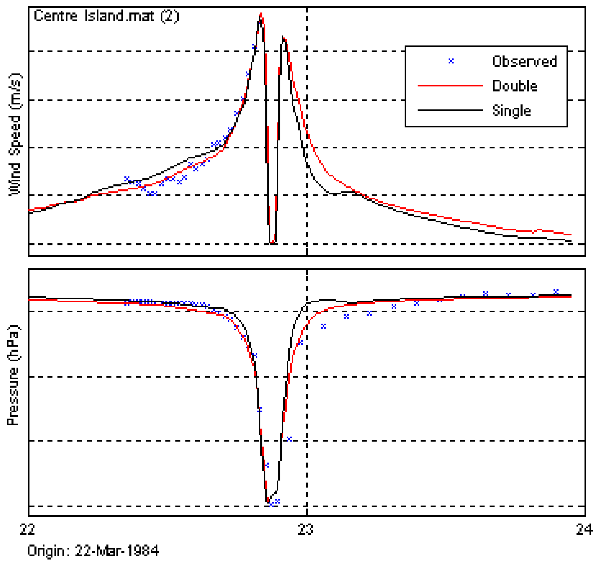

Figure 10 *TC Kathy* passage of Centre Island. Measured (blue) wind speed and MSLP. The performance of the Single (black) and Double (red) Holland models. As indicated by the MSLP fit, the Double Holland provides a better representation of the outer structure.

10. Inundation Modelling and Mapping

The extent and severity of overland flooding was assessed through the development of two high resolution Mike21 hydrodynamic models centred over the southern Gulf region and Weipa respectively. Modelled tide plus surge water surface elevations and depths were mapped, resulting in the production of key planning and emergency response datasets for the 50, 100, 200, 500, 1,000 and 10,000 y return periods over a range of climate scenarios (2010, 2050 and 2100) (refer Figure 11). These maps could then be used for emergency and landuse planning purposes.

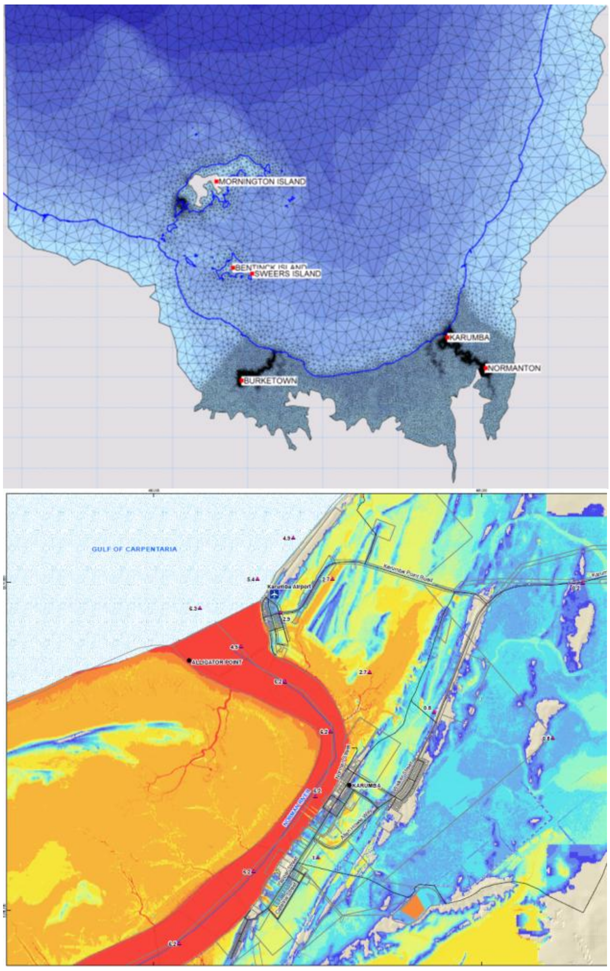

Figure 11 The southern Gulf hydrodynamic model (top) and storm tide inundation depth mapping from *TC Ted*.

11. Summary

This study has undertaken a statistical analysis of ocean water levels throughout the entire Gulf of Carpentaria region, leading to estimates of the probability of exceedance of extreme ocean water levels along the open coast and at a number of inland Gulf sites, as well as detailed inundation mapping of specific community areas. The study was predicated on knowledge of existing or immediately past climatic data and utilises projections of possible future climate change, including sea level rise.

To enable accurate estimation of extreme water levels from 50 y to 10,000 y return period and the theoretical maximum surge, both background broadscale forcing of the ocean and also the rare but extreme effects of tropical cyclones have been considered. These two influences were considered separately, because of their scale separation, and their impacts are then statistically recombined to provide the final water level estimation.

The study results show that the highest storm tide hazard risk is in the southern Gulf, predominantly the south-east corner, but also extending to the western side north of Centre Island. The communities most exposed to this hazard in Queensland are therefore Burketown, Karumba, Sweers and Bentinck Island. In the Northern Territory the highest hazard risk is indicated for Numbulwar and Bing Bong. The least affected communities are those towards the northern end of the Gulf, such as Weipa and Yirrkala. Notwithstanding this, many of the other communities have a significant storm tide hazard risk.

12. Acknowledgements

The input from other key project members is gratefully acknowledged including:

- Mr Jeff Callaghan (ex BoM Severe Weather Unit);
- Dr Kendal McGuffie (Sydney University of Technology); and
- Dr James Kossin (NOAA).

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