Assessment of future storm surge hazard in Darwin Harbour, Australia

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Abstract
Storm surge assessment in a context of sea level rise is a major preoccupation for coastal planners and safety authorities of coastal areas. With an increasing demographic pressure in these areas, a realistic and accurate assessment of hazard is needed to ensure the development of cities and the protection of citizens. Tropical areas are subject to tropical cyclones which can produce severe storm surge induced by both wind/pressure and waves generated locally or remotely. In order to accurately assess the threat, an extensive modelling of the surge can be achieved with models which account for the hydrodynamic impacts but also the waves. Moreover, assessment of return periods for extreme events also requires a long record of events to cover the considered period. To overcome these issues, we propose here to investigate the impact of sea level rise (SLR) in Darwin Harbour, Northern Territory, Australia with the extensive modelling of 417 tropical cyclones using a synthetic database derived from historical storm tracks and which reflects the climatology of events over a 10,000 year time period. The modelling of storm surges is then performed using a coupled hydrodynamic and wave modelling system (SCHISM/WWM). Storm-surge simulations were undertaken for existing and future scenarios where SLR was based on the design reference year of 2075 with an increase of 0.6 m relative to 2020. Return periods have been calculated for surge hazard and the contribution of each parameter in the actual and future configurations are detailed. The study provides an insight into the influence of SLR in the next 50 years on waves and surge patterns in Darwin Harbour.

Keywords: tropical cyclone, storm surge, sea level rise, Northern Territory

1. Introduction

Coastal communities are becoming increasingly vulnerable to extreme water level as coastal areas become more and more populated. Under the anticipated impacts of future climate change, the projected gradual rise in sea level will increase the frequency of such events over time and their spatial and temporal distribution becomes then a key step in risk mitigation.

Extreme water level results in the combination of astronomical tide, atmospheric pressure deficit, winds driven shoreward water accumulation, wave induced setup, wave runup and over-topping. Although considered separately, these factors may not present a hazard, this is the combination in time and space that triggers extreme water levels.

For decades models have been used at global and regional scale and within a climate change perspective to quantify these extreme water level hazards [24] through the concepts of Average Recurrence Intervals (ARI) or Annual Exceedance Probabilities (AEP). These models can be probabilistic using historical records, or purely deterministic provided that enough information is available to simulate hazard and consequences.

In tropical regions the probability of extreme water level induced by Tropical Cyclones (TC) is not an easy task if we rely on tide gauge records only since historical records of TC are usually not long enough [9]. The method to overcome this issue that has been widely explored in the past decades is the generation of synthetic TC tracks [2] [6] [12]. In such an approach, TC tracks and intensities are statistically resampled and modelled from an underlying dataset, which can be either historical TC tracks or meteorological datasets from climate models. [7] used this type of method to estimate the present-day extreme water level exceedance probability around the coastline of Australia. In their study, they investigated tide surge interaction based on two cases with a small and large tidal range (1 m and 10 m). They concluded that these interactions should be considered for large tidal range and then used random tide against each event.

In the framework of a larger study and following the previous work of [20] [21] [22], an extensive study has been conducted within the Darwin Harbour area to assess extreme water level within a climate change perspective. Using a 10,000-year tropical cyclone climatology as well as a 30-year hindcast reanalysis of atmospheric conditions from which ARIs were calculated for most essential contributing factors of storm surges.

The present paper focuses on the method and a sensitivity analysis on the contribution of the different parameters implicated in the simulation of the storm surge.

2. Method

2.1 Study Site

The region of Darwin Harbour, Northern Territory, Australia, is located about 12.5 deg latitude South. The harbour is open to the Beagle Gulf and the Timor Sea to the north-east and sheltered by the Tiwi Islands to the North. Tide ranges up to 8 m with mean spring range about 6 m and mean neap range around 3 m. These macro-tides also produce strong currents that can peak at speeds of up to 2-2.5 $m.s^{-1}$. Tidal flows between Mandorah and East Point have been measured in the order of 120,000 $m^3.s^{-1}$ [25].

The latitude of Darwin Harbour makes it subject to tropical climate features such as monsoon and eventually tropical cyclones, the most destructive one being TC Tracy that devastated the city of Darwin in December 1974

2.2 Modelling approach

The method has been designed to define extreme waves, water level, currents as well as their joint probability between extreme waves and extreme water levels for Darwin Harbour, for the 2075 horizon. The population of non-TC extremes and TC extremes were separated, and two different methods applied, using a 30-year hindcast, for the non-TC extreme, and a 10,000-year database of synthetic TC events. Both approaches used deterministic process-based models to simulates events for which sensitivity analysis was conducted on the main contributing factors of the total storm surge. From these simulations, statistical analyses were applied to derive ARIs and joint probabilities. The datum chosen for the study is the Lowest Astronomic Tide (LAT), equal to 4.105 m below Australian Height Datum (AHD).

2.3 Climate change

In a similar method presented in [11] available information for the regional climate change consequences, have been assessed for each contributing factors. Projected changes in tide and monsoon have been deemed not significant and only projected changes in Sea Level Rise (SLR) and TC tracks and intensity have been considered. According to [23] and the reassessment for Australia-specific SLR presented in [17], the proposed 2075 SLR allowance is 0.6 m. Assessment of projected changes for the northern Australian region near Darwin is made according to [14] and showed that intensity change remains essentially the same as the global estimate of a +5% change by 2100.

2.4 Non-TC extreme events modelling

Ambient conditions and non-TC extremes were simulated using the spectral wave model SWAN [3]. A 30 year hindcast was run from 1990 to 2019. This simulation was only used for non-cyclonic conditions, as the global forcing does not appropriately resolve the cyclonic vortex field accurately. Thus, all cyclone signatures were carefully removed from the time series. The model was configured in non-stationary mode including all third-generation physics. Full spectral boundaries from the parent SWAN hindcast domain were prescribed from a global implementation of the WAVEWATCHIII (WW3) spectral wave model run at 0.5 deg resolution. Tide was also included in the wave model using tidal constituents forcings from the Oregon State University Tidal Inverse Solution (OTIS) [5]. Wind data included a 30 years of near-surface wind conditions from the Climate Forecast System Reanalysis CFSR and CFSv2 products [19].

2.4.1 SWAN calibration

The model was calibrated and validated against available observations including AIMS/IMOS. Comparison ware conducted against measured wave data at the IMOS ADCP (Figure 1) at the entrance of Darwin Harbour. Results show a good agreement between measured and modelled with a small bias of less than 0.1 m and Root Mean Squared Error of 0.19 m. Comparison with the shortwave record within East Arm (Figure 1) were also conducted with a corrected Bias on CFSR wind to match measured wind at this location.

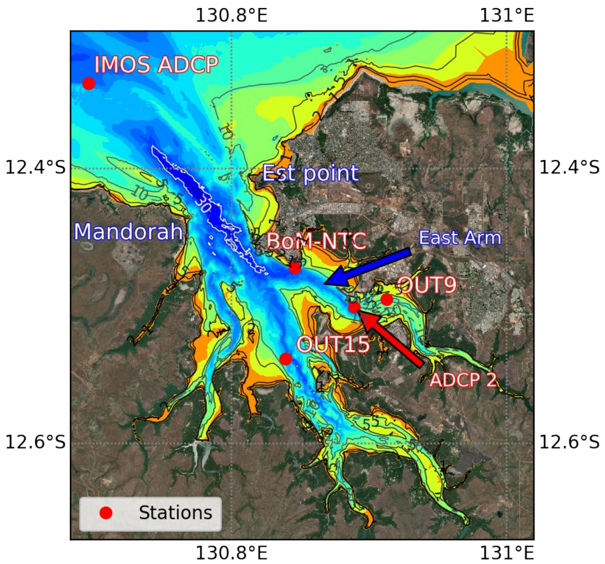

Figure 1 Study site bathymetry and station locations.

2.5 TC Extreme Events modelling

2.5.1 Wind forcing

The accuracy of the present study relies on a synthetic TC climatology forming the underlying climate reference. The synthetic statistical TC climate is founded on a "double-Holland" wind and pressure profile and has been constructed by using the historical Bureau of Meteorology Australia (BoM) TC track and intensity data together with a variety of hypothesised storm structure and scale relationships [12]. The climatology is then transformed into numerically generated ocean surface wind and pressure fields to simulate the regional response of many thousands of tropical cyclones.

To validate the synthetic TC wind climate used here, a long-term statistical analysis of the 66 years record of winds at Darwin Airport has been undertaken for when influenced by tropical cyclones within a 300 km radius. Most of the 8,600 synthetic TC events contained in the 10,000 years climatology will not produce significant impacts within the harbour. The ARI range of 2 to 1000 years, without a priori knowledge, would have required around 900 events to be modelled. A pre-selection of event became necessary to drive the high resolution toward TC selection that would impact Darwin Harbour. Once pre-estimated and ranked the impacts at this specific location, only the number required to reach a particular ARI is necessary such as presented in Table 1.

Table 1 Number of Ranked Magnitude Events Required

events	10	20	100	200	250	500	1000
ARI (year)	1000	500	100	50	40	20	10

The design TC event selection is provided by the SEAsim model, which is built upon the coupled 2D barotropic hydrodynamic model MMUSURGE [16] and the spectral wave model WAMGBR [8]. A previous version of the model has provided statistical storm tide design water levels throughout Australia and especially Darwin [20] [21] [22]. The principal role of SEAsim was to filter and reduce the 10,000-year synthetic TC event set down to a manageable number of events to facilitate the higher resolution harbour modelling.

Tide phase is also provided within the SEAsim framework since each event comes with its own time frame and thus with an associated tide phase that reflects the probability of the conjunction of tide and TC occurrence. Figure 2 provides a schematic of the methodology adopted for the tropical cyclone severe storms impact analyses, which was conducted in two stages.

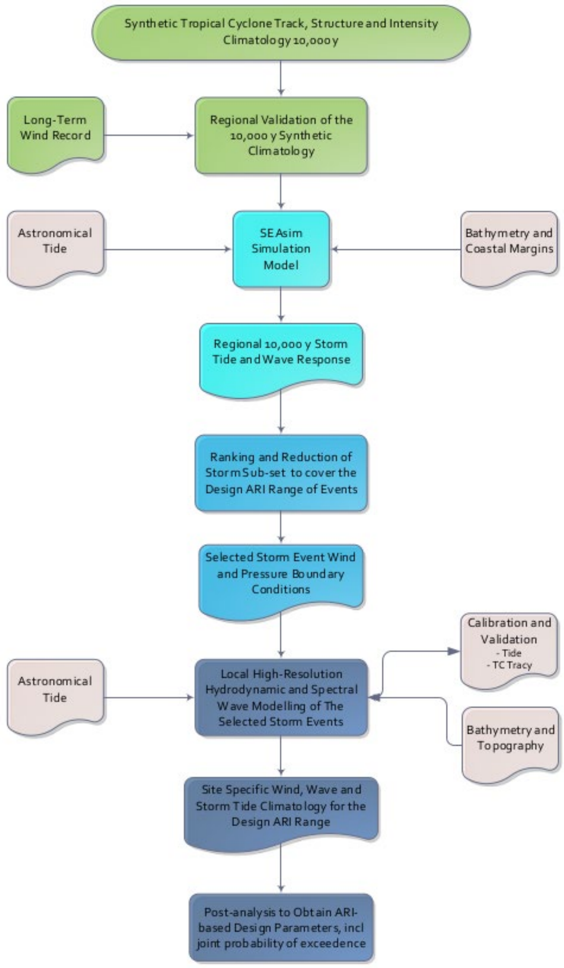

Figure 2 Outline of the TC events methodology

2.5.2 Storm surge modelling

Simulations of the 417 synthetic TC events were undertaken using the fully coupled Hydrodynamic/Wave model SCHISM/WWMIII [26], configured in 2D depth averaged, barotropic mode. An unstructured grid was covering the Timor Sea from Timor coasts to Darwin Harbour. Resolution ranged from 7 km to 25 m in Darwin Harbour. Flooding areas in low lying areas and mangroves were represented within the grid with varying drag coefficient according to mangrove and bottom substrate.

To assess the importance of some of the contributing factors, simulations have been conducted with and without some parameters. Thus, amplitude and phases of the global FES2014 [4] tidal model was applied at the boundary for a series of simulation as well as the same series without tide but a mean sea level instead. The same methods applied for waves which were turned on and off for the same number of scenarios.

Wave breaking dissipation was depth induced only, according to [1] formulation and using a breaking index of 0.73. Wave induced momentum flux from waves to currents and water levels, is based on the radiation stress formulation of [15]. Water level and wave parameters were extracted at the Peak H_s and at the Peak Storm Tide for both sensitivity analysis and extreme value analysis.

2.5.3 SCHISM/WWM calibration

Model calibration was performed against field data of water level, current and waves available both inside and outside Darwin Harbour. Water level compared at two locations (Figure 1) inside the harbour are presented in Figure 3.

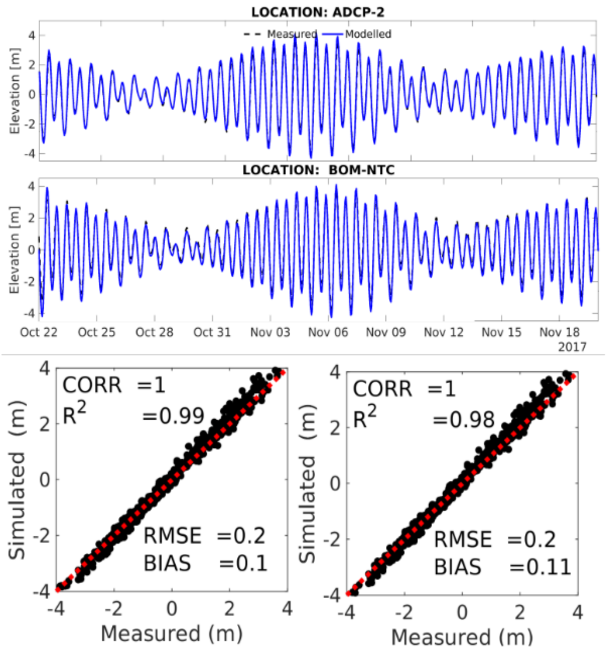

Figure 3 Comparisons between measured water levels at ADCP-2 and BoM NTC station and associated scatter plots (left and right bottom panel respectively).

Currents have also been used for calibration inside and outside the harbour at location IMOS-ADCP (Figure 1) and show good correlation of current magnitude and direction. Wave measurements inside the harbour where very limited therefore calibration was conducted using Harbour entrance data collected during the TC Carlos (2020) and satellite data also during TC Carlos for the outer domain. A correlation of R^2= 0.84 with 0.12 m bias was found, showing the ability of the model to replicate TC wave height within the computational domain. Water level during extreme events was validated with the storm surge available during the TC Tracy [10] and presented in Figure 4.

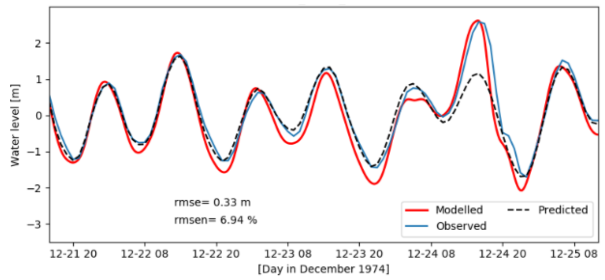

Figure 4 Comparison of measured and modelled (SCHISM) water level during TC Tracy

2.6 Statistical Analysis

A Peaks over Threshold (POT) sampling method was used for event selection, applying the 95th and 99th percentile exceedance level as the threshold for H_s and storm tide, respectively, with a minimum 24-hour window between each storm peak.

The Generalized Pareto Distribution (GPD) was used, with the Maximum Likelihood Method (MLM) applied to find the best-fit of the sampled events to the model distribution. ARI for non-TC and TC extremes were then merged. For each return period value of parameter considered, the corresponding merged ARI was obtained as follows:

$$ARI_{merged} = \left(\frac{1}{ARI_{TC}} + \frac{1}{ARI_{non-TC}} - \frac{1}{ARI_{TC} \times ARI_{non-TC}}\right)^{-1} \quad (1)$$

2.7 Sensitivity analysis

In order to assess the importance of each factor and their contribution in the total water level, simulations were conducted with specific parameters such as tide, waves or SLR turned off one by one. Maximum values of surge, Hs and mean period were then compared with simulation with all parameters turned on for different location in the harbour to assess the importance of their contribution.

3. Results

3.1 Combined Non-TC and TC Joint Probabilities

The combined TC and non-TC ARI curves for both peak Hs and peak storm tide are illustrated in Figure 5 and Figure 6, respectively in East Arm. Combined extreme significant wave height in East Arm are in the order of 0.52 m, 1.09 m, 1.26 m and 1.79 m for the 10, 50, 100 and 1000-year ARI respectively, with the TC conditions dominating the extreme at about the 25 years ARI and above.

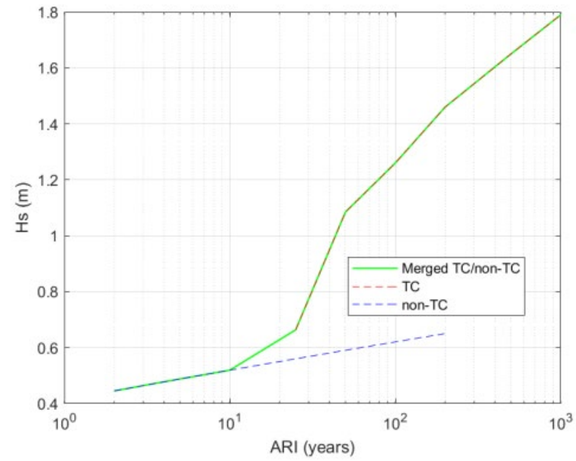

Figure 5 Combined TC and non-TC significant wave height return period values in East Arm (2075 SLR scenario)

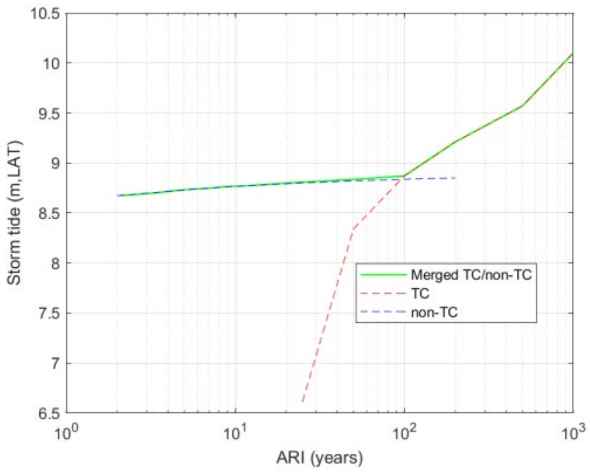

Figure 6 Combined TC and non-TC storm tide return period values in East Arm (2075 SLR scenario)

Combined extreme Storm Tide at the reference location East Arm are in the order of 8.77 m LAT, 8.84 m LAT, 8.87 m LAT and 10.10 m LAT for the 10, 50, 100 and 1000-year ARI respectively, with the TC conditions dominating the extreme from about the 100 years ARI and above.

3.2 Sensitivity analysis

Several places in the three main arms of the harbour were investigated (Figure 1). Important spatial disparities were observed, and the most important differences concerned the presence of tide and were observed in the Eat Arm of the Harbour.

3.2.1 Effect of tides

Figure 7 shows the maximum of mean wave period reached during each event when using a mean sea level (no tide) or using the tide phase provided by the SEAsim model.

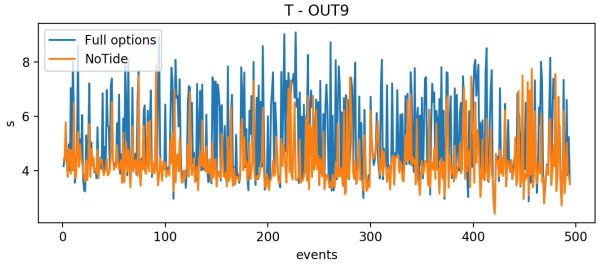

Figure 7 Maximum period for each TC event for simulation without tide (orange) and with all options (blue) at station OUT9 in the East Arm

These differences of mean period between each event have repercussion in the global distribution of events and are presented on Figure 8 showing more events within the 6-7 sec period. In this figure the ranking is made according to the maximum mean period so that events on the x axis do not represent the same event for each configuration with or without tide.

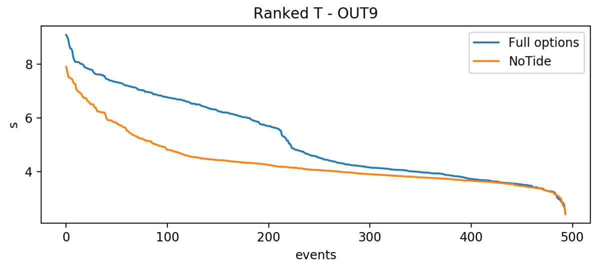

Figure 8 Maximum period for each TC event ranked. Orange are simulation without tide and blue with tide. at station OUT9 in the East Arm

To more appreciate how the mean period can vary for each event, Figure 9 shows the distribution of period difference for the same events where we can see that events simulated with random tide phase are likely to show longer mean period.

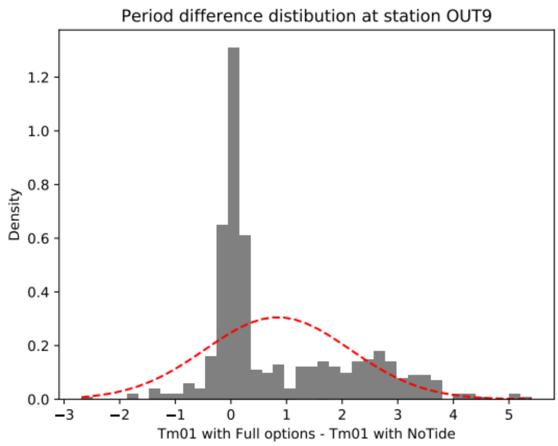

Figure 9 Density of probability of the difference in maximum period of event simulated with tide - event simulated without tide at station OUT9 in East Arm.

The distribution of total surge affected by the tide phase against mean water level in the central arm of the harbour is presented in Figure 10 for all events ranked according to the total surge and in Figure 11 where events are compared.

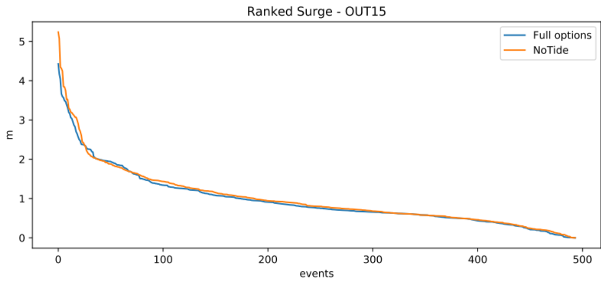

Figure 10 Ranking of maximum surge of events simulated with tide (blue) and events simulated without tide (orange) at station OUT15 in the central arm

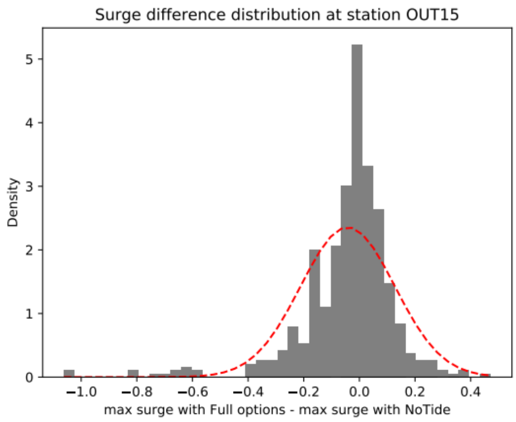

Figure 11: Density of probability of maximum surge difference between events simulated with tide and events simulated without tide at station OUT15 in the central arm

3.2.2 Effect of Waves

The effect of waves in East Arm (location OUT9) is expressed on Figure 12. The direct contribution of waves is more likely to reduce the surge, although the mean difference of –1 cm can be considered insignificant.

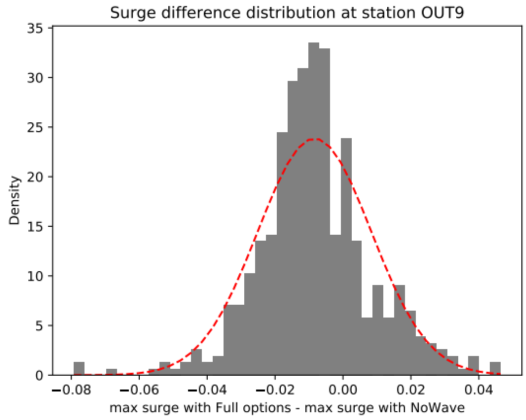

Figure 12: Density of probability of maximum surge difference between events simulated with tide and events simulated without tide at station OUT9 in East Arm.

3.2.3 Effect of SLR

The sensitivity of SLR in the storm surge (without tides) in the East Arm is in the order of 0.1 cm with a trend of reducing the surge in case of SLR (Figure 13).

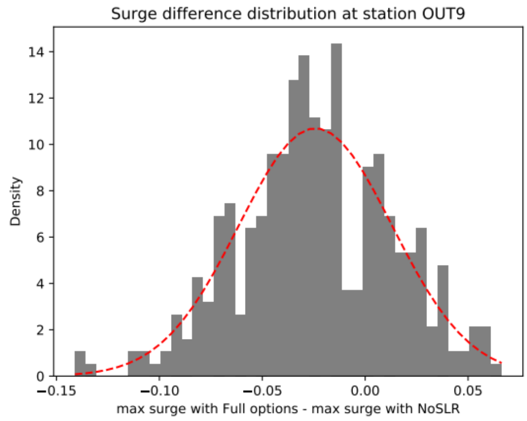

Figure 13: Density of probability of maximum surge difference between events simulated with SLR (0.6m) and events simulated at current sea level at station OUT9 in East Arm.

On the other hand, the direct effect of SLR on waves would be an increase of wave Hs of about 0.05 m in east arm and about 0.15 m in the central arm of the Harbour (Figure 14).

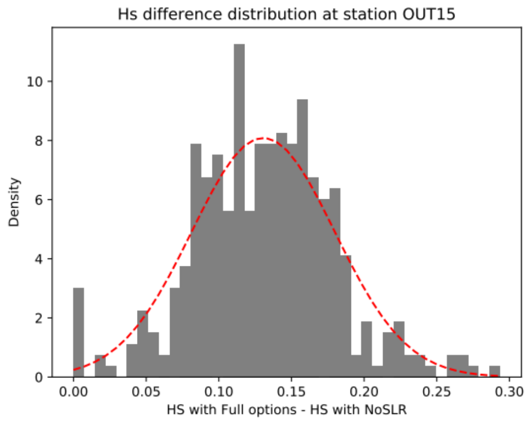

Figure 14: Density of probability of maximum Hs difference between events simulated with SLR (+0.6m) and events simulated at current sea level at station OUT15 in the central arm.

4. Discussion

The sensitivity analysis provides here some interesting information about the range of events covered by the method. The choice of the parameters included or not affects the distribution of events as for example the tide used for each event. The phase has an important impact on the distribution of the events represented. Indeed, the type of distribution presented in Figure 9 where each event is compared is of less importance than the ranked events as presented in Figure 8 and 10.

In the case of Figure 10, only the tail of the distribution will be affected with the major event having 1 m surge difference. The rest of the distribution is quite similar. Whereas on Figure 8 the whole distribution is affected where different type of events is represented.

The differences attributed to specific factors in the sensitivity analysis results from the eviction of one factor only. The relation of component between each other is not investigated. For example, the use of waves in combination with and without SLR since higher water level reduces wave breaking and hence may reduce wave induced setup component. These types of combination require more runs and should be part of future investigation. We must keep in mind that surge is not the total water level, and this analysis does not provide information whether these differences occur in conjunction of a total extreme water level

The final return period curves combining non-TC and TC simulations are providing values slightly above the available data provided by [7] and [18] model outputs available online. The sensitivity analysis indicates that the wave setup does not contribute greatly to the total storm surge. However, the tests over the contribution of waves were run independently and the combination of parameters may have more effects. Note that even with wave setup included in the total storm surge, wind and pressure forcing used for each model are also different and may remain the largest source of uncertainty.

Climate change impact was assessed through sea level elevation for each numerical simulation according to water level defined in a posteriori and a sensitivity on this impact was undertaken and showed that SLR has the more significant impact on both storm tide levels and peak wave heights. When projected changes in TC intensity and frequency are considered, these create opposing effects that attenuate their combined impacts in the harbour.

Many uncertainties remain regarding interaction between SLR and the factors contributing individually to the total water level [13]. These interactions, such as the effect of SLR on tides and waves for example, have not been considered in this study.

5. Conclusion

A database of 417 tropical cyclones representative of the past 10,000 years have been used to simulate extreme coastal hazard events in Darwin Harbour. Return period values were calculated and combined from both cyclonic and non-cyclonic extreme value analyses. A sensitivity analysis was conducted on the main contributors of extreme levels. The contribution of wave setup is minor in the total surge generated during extreme events and the contribution of the tide appears to be the dominant process in the storm surge.

6. Acknowledgements

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7. References

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