Estimating Extreme Water Levels in Torres Strait

B. A. Harper[1], L. B. Mason[2], D. J. Hanslow[3] and J. Rainbird[4]
[1] Systems Engineering Australia Pty Ltd and GHD Pty Ltd, Brisbane, Australia; bruce.harper@ghd.com
[2] University of Tasmania, Australian Maritime College, Launceston
[3] University of Sydney and NSW Office of Environment and Heritage, Newcastle, Australia
[4] Torres Strait Regional Authority, Thursday Island, Australia.

Abstract
The Torres Strait, located between Queensland and Papua New Guinea, is a remote region having significant complexity and diversity of geophysical parameters, low levels of reliable insitu information and with a widespread community vulnerable to the impacts of the sea. There have been many individual studies over time into various aspects of the geomorphology, oceanography, tides and meteorology of the region, but none have previously addressed the quantification of the extreme ocean water levels that can possibly occur. This paper describes a recent study that has provided this essential information, which can now be used to perform detailed community vulnerability mapping and risk assessments as well as forming a rational basis for adaptation planning for climate change and for assisting in the design of emergency services. The study has also significantly improved knowledge of the land-sea elevation datum across the various island communities and provides estimates of the community risks from extreme winds.

Keywords: storm surge, tides, hydrodynamic modelling, tropical cyclones, statistical analysis.

1. Introduction

The Torres Strait is home to 20 separate communities, many of which are located on small low lying islands that already experience undesirable erosion and occasional inundation episodes in extreme weather events. As part of planning for a sustainable future and expected increases in sea level associated with climate change, better understanding of the interaction of causes and threats of ocean inundation are required. Here we provide an outline of the methodology, models and processes used to construct a statistical model of the Torres Strait ocean water levels and associated wave conditions [1]. The complex astronomical tides were combined with the broadscale seasonal (monsoon and trade winds) and inter-decadal sea level variability, verified against statistically-resampled long term tidal residual records. In addition the local effects of tropical cyclones were considered and the combined results compared with anecdotal community experiences of the frequency of inundation episodes.

2. Regional Meteorology

The study considered the broadscale wind and pressure forcing that influences water levels in Torres Strait by examining long-term records at specific locations and available numerically hindcast wind and pressure fields [2]. Tropical cyclone aspects were separately treated. The long-term site-specific wind data recorded by the Bureau of Meteorology (BoM) was analysed to determine the regional variability of extreme conditions so that the later veracity of the developed statistical wind models (both broadscale and tropical cyclone related) could be assessed. The suitability of the available hindcast modelled surface wind and pressure datasets were then assessed relative to the site specific data. Such data were also used for deterministic checks of some historical events.

2.1 Seasonal Synoptics

The large scale meteorology of the Torres Strait region is dominated by the influence of:

- The summer NW Monsoon, and
- The winter SE Trade Winds.

The seasonality, strength and persistence of these two major influences dictate the mean oceanic response. Tropical cyclones (TCs) are then capable of intermittently influencing and interacting with these larger scale influences during summer. On the larger scale, inter-annual influences due to the El Niño/Southern Oscillation (ENSO) [3] and potential inter-decadal influences such as the Interdecadal Pacific Oscillation (IPO) [4] act to adjust the background conditions.

2.2 Extreme Wind Analyses

BoM recorded wind data from 10 regional sites across Cape York and the Gulf of Carpentaria were considered for Extreme Value Analysis. After adjustments for station exposure, the peak 10-min mean and peak daily gusts were analysed to estimate long term Return Periods (or Average Recurrence Intervals ARI). The Thursday Island site, although the longest record in the region at 42 years, was found to be significantly influenced by topographic effects. This required correlation with other shorter term records in order to establish a consistent description of the broadscale wind variability, while periods of tropical cyclone influence were separately analysed. These analyses helped inform a decision to upwardly adjust the NCEP modelled winds by around 40% to better match the local groundtruth. This is justified by the relatively coarse NCEP 2° spatial resolution, which is similar to the scale of the Torres Strait itself. These adjusted winds were then used to estimate local broadscale (non-cyclonic) wave conditions.

3. Astronomical Tides

The Torres Strait is situated essentially at the junction of two oceans – the Coral Sea to the east and the Arafura Sea to the west - each with significantly different tidal regimes as a result of the continental separation formed by Australia, Papua New Guinea and the so-called Maritime Continent of SE Asia. This commonly leads to situations where the astronomical tide is approaching high water on one side of the Strait while the other side is near low water, resulting in the generation of steep water level gradients and strong tidal currents. The strait is also shallow and partially blocked by a number of reefs and islands, such that the high water level gradient generated by the tide is focused along the chain of islands and reefs directly north of Cape York.

3.1 Analysis of Regional Tide Gauge Data

The measured tidal data in the region is the primary source of information regarding storm tide events from both broadscale and tropical cyclone origins. It was therefore necessary to separate, as much as possible, the periodic astronomical signal from the raw signal to obtain estimates of both the tidal constituents and the residual non-tidal water levels. This was done by tidal harmonic analysis. Long term tidal data was available for Thursday Island (the Standard Port for the region) plus five Australian Maritime Safety Authority gauges servicing the navigational needs across the area (up to 39 y record). Other recent shorter-term tide data [5] measured at a number of the island communities was also made available.

3.2 Bathymetry of the Torres Strait

The bathymetry of the region is generally shallow and particularly complex, with morphological changes at a local level on a seasonal basis as a result of tidal, non-tidal and wave influences. The available sounding data was only recently composited [6], providing a resolution of about 100 m horizontally. Figure 1 shows the major bathymetric features as:

- The eastern Coral Sea deepwater boundary and Great Barrier Reef region consisting of numerous reefs, shoals and some isolated islands in intermediate depth of 20 to 50 m;
- A middle shallowing region typically below 20 m depth, comprising coral cays and shoals;
- The central island chain extending north beyond Cape York comprising mainland islands with large banks and shoals, often with depths below 15 m. Further to the north, the island chain reduces to extensive areas of banks and shallows below 10 m, culminating in the muddy coast of Papua New Guinea;
- The western extent comprising generally open water gradually deepening westward to the Arafura Sea, with a horizontal extent similar to the middle region on the eastern side.

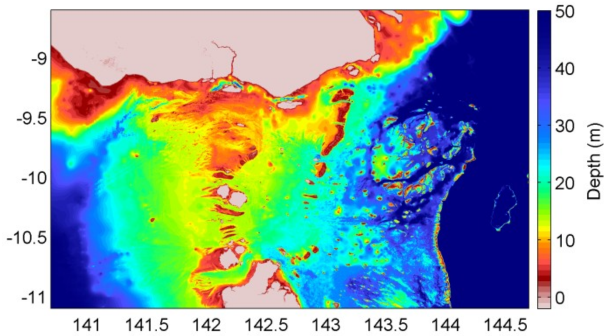

Figure 1 Bathymetry of the Torres Strait.

3.3 Numerical Hydrodynamic Modelling of the Regional Astronomical Tide

A numerical model was constructed [7] that encompasses the entire Torres Strait at a resolution of 1' (one minute of arc or 1.85 km) and the model was driven by tidal signals along its eastern and western boundaries. The model's ability to incorporate internal sub-grid scale boundary conditions provided for enhanced resolution of reefs, banks and shoals. The tidal model was calibrated using 36 major and minor tidal constituents and evaluated at the individual constituent level, with the 5 major tidal constituents O_1, K_1, N_2, M_2 and S_2 being satisfactorily reproduced. Figure 2 shows the modelled amplitude of the major semi-diurnal constituent (M_2) across the region as a series of height contours and the propagation phase angle as a colour-coded background.

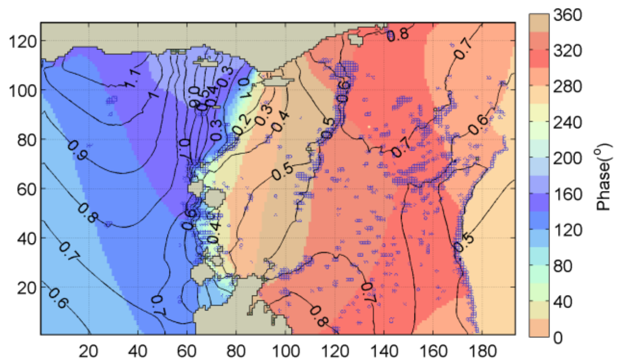

Figure 2 Modelled M_2 component tidal pattern.

The islands and reefs are also shown and can be seen to play a principal role in the propagation pattern of this major tide harmonic in the region, which contributes to the twice-daily high and low tides. In particular, the tidal phase colour-coding shows the significant phase separation between east and west and the contours show the concentration of amplitude variation along the separation line, which follows the central line of islands, shoals and reefs. Combinations of harmonics, plus shallow water sub-harmonics generated by the tidal flow interaction with the bathymetry, are responsible for giving the tide its special and complex character throughout the region.

4. Modelling the Broadscale Sea Level Variability

To obtain a reliable estimate of the extremes of the sea level across the region it is also necessary to model the non-tidal water level gradients and associated currents passing through the Torres Strait. The mean oceanic levels (i.e. ignoring the tide) on either side of the strait are influenced by seasonal changes in oceanic water level in the Coral and Arafura seas. Meanwhile, the sea level in the nearby shallow Gulf of Carpentaria is strongly influenced by both seasonal changes in synoptic wind patterns and other intense synoptic scale weather systems such as the monsoon and tropical cyclones. The approach to modelling these various elements was to separately address the principal scales of forcing.

4.1 The Broadscale Hydrodynamic Model

A relatively coarse outer model domain (10 km resolution) was added to the inner tidal model, covering both the Gulf of Carpentaria and the western Coral Sea, as shown in Figure 3. This captures the response to regional synoptic weather systems, as represented by the hindcast NCEP surface wind and pressure data. This forcing produces the annual water variations that were excluded in the tidal analyses -and also inter-annual effects. The NCEP 2° resolution is not capable of adequately representing the presence of tropical cyclones, unless they are very large in scale, and this suits our purposes because the effect of intense tropical cyclone forcing is separately treated as a “local” or small scale forcing within the region. However, as part of the deterministic validation, the very large but relatively weak *TC Charlotte* event in 2009 provided a suitable data check of the model.

4.2 Broadscale Model Boundaries

The model open boundaries represent the slowly varying oceanic water levels that are further separated from the immediate synoptic scale. Two open boundary components were considered:

- The annual average water level signal, based on tide stations across the region comprising very long datasets; and the
- Inter-annual mean water level variation that represents effects that may last for a year or more, derived from the modulation of the SOI climate sequence (1876 – 2009), calibrated through least squares fit (r^2=0.7) to the Darwin tide gauge (1984 – 2009).

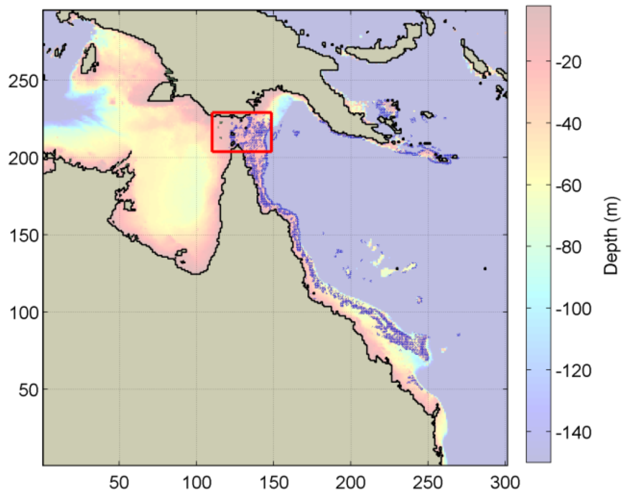

Figure 3 Broadscale model domain with inset of the finer scale tidal model.

4.3 Statistical Broadscale Modelling and Validation

The broadscale model was then used to simulate the 60 y period of available NCEP-NCAR surface wind and pressure data (since 1948), with the open boundaries forced by the annual water level signal (derived from tide gauges) and the inter-annual (SOI) signals discussed previously. No astronomical tides were included in this simulation, such that the resulting modelled water elevations can be considered as “residuals” relative to the background tide. Then the inner tidal model was run for the same 60 y period, but with its open boundaries forced by the combination of the broadscale model signal and the astronomical tide. These results were then compared with the actual residual water levels at available tidal stations and found to be reasonable. Next, in order to account for the tidal variability influencing these comparisons, the raw data tidal residuals were combined with 20 alternate tide sequences (annually locked) to create a re-sampled record approximately equivalent to a 700 y sample. A similar process was applied to extend the modelled statistics, given that there are only 60y of NCEP wind and pressure available. Here the models were re-run a further 20 times, with each instance of the outer model SOI-derived inter-annual boundary water levels offset by 3 years from each other. The TS models were then run with differing tides, giving a total synthetic broadscale water level record of 21 × 60 = 1260 y.

The comparison between the re-sampled data and model statistics was quite compelling at all gauge sites, with return period curves having similar slopes and biases of the order of 0.05 m. Figure 4 presents the comparison for Goods Island, which is located to the NE of Thursday Island. Modelled return period curves for broadscale water levels were then produced for each point in the tidal model domain, allowing mapping of the 100 y return period surface as shown in Figure 5, which is clearly strongly modulated by the background semi-diurnal tidal amplification pattern.

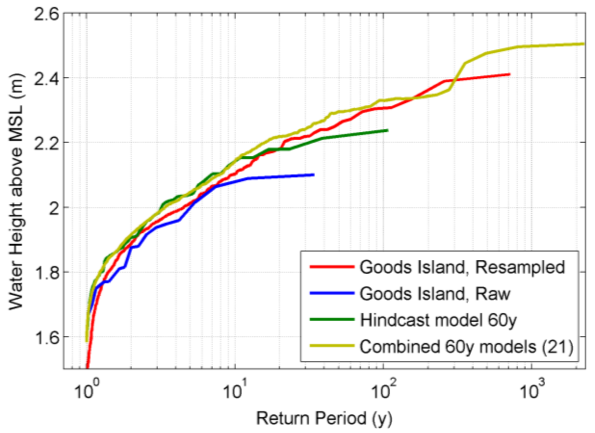

Figure 4 Comparison between measured and modelled water level at Goods Island (blue is raw data, red is raw extended to 700 y; green is 60 y modelled, yellow is 1760 y modelled).

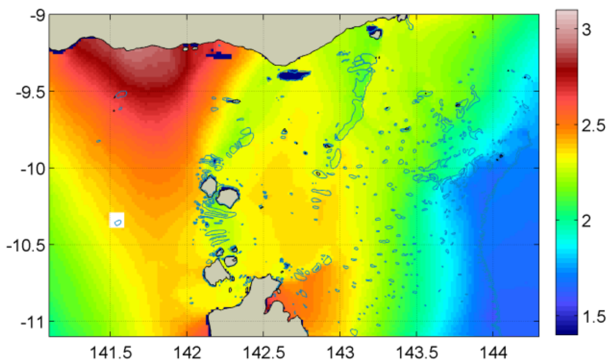

Figure 5 100 y Return Period simulated broadscale water levels.

4.4 Informing of Regional Land Datums

A principal source of uncertainty in the study was the relative sea-land elevations. Accurate land elevation is critical for assessing the impacts of storm tide events on the various communities and to enable detailed inundation mapping for assisting in future planning decisions, especially in regard to projected sea level rise. Historically there has been difficulty in establishing vertical datums due to the complex tidal regime and the paucity of long term sea level measurements. This has led to a variety of methods being used for the different communities over time, many on an ad-hoc basis, resulting in anomalous estimates of MSL and tidal planes being used for infrastructure projects, and contributing to their sometimes poor performance.

While the recent short term tide measurements [5] were valuable, the long term mean sea level available from the hydrodynamic models has enabled a survey quality assessment of the MSL for the very first time. This resulted in datum shifts at several islands of more than 2 m being assigned by the Queensland Department of Environment and Resources, in association with adoption of the AUSGeoid09.

5. Tropical Cyclones

TCs are the most energetic of the regional weather systems and represent the more significant source of life-threatening inundation episodes if passing close to a community. However, existing historical data suggest that the regional TC threat is relatively low and has even markedly decreased during the past 50 years. Notwithstanding this, it is known that the historical record of TC intensity is subject to a variety of limitations [8] and a selective review of the intensity and scale of TCs affecting the area, directly or indirectly, was undertaken by team member Mr Jeff Callaghan (BoM retired). This resulted in 10 storms over the period 1952 to 1995 being assigned markedly increased intensity estimates, although none of these were especially close to the Torres Strait area.

5.1 TC Climatology

The corrected BoM dataset from 1959/60 to 2008/09 was used, yielding a 78 storm sample within a 500 km radius of the study region, averaging 1.56 storms per season. However, the spatial distribution varies markedly within that radius, and three basic track classes were assigned - easterly moving (18%), westerly moving (32%) and southerly moving (50%). TC central pressure estimates for each track class were subjected to Extreme Value Analysis, with allowance for Maximum Potential Intensity limits of 880 hPa and storm size (lacking from the BoM dataset) was estimated from validated US-based hurricane datasets that are deemed representative [9]. A "Holland" analytical wind and pressure model was then adopted to produce surface forcing [10] , with the B parameter set to support the generally accepted concept that intense northern Australian cyclones tend to be relatively small in size and have highly peaked wind fields (e.g. *Kathy, Ingrid and Monica*). All of the above statistical estimates of tropical cyclone behaviour and strength were then assembled for use by a Monte Carlo statistical [11] model to generate thousands of synthetic TC storm events.

5.2 TC Storm Surge Modelling

The MMUSURGE model was used, developed as part of the Queensland Climate Change Study [12] and verified against several historical storms. It has since been used extensively for storm surge studies across Queensland and the Northern Territory. The model utilised the same inner and outer model domains as the broadscale modelling but was conducted at mean sea level. Checks were done at a finer 0.2 nmile resolution in some areas to ensure that sub-grid boundaries were adequate in representing the many small passages between islands.

An example of the storm surge generated by an idealised "Category 4" storm moving W-E directly through the strait in Figure 6 shows that peak surges for many mid-strait island communities will typically be limited to about 1.5 m. However these could be doubled at some coastal communities for a (very rare but possible) storm crossing of the Papua New Guinea coast.

The model performance in the region could not be formally validated due to a lack of data, but a demonstration of the possible impacts from the infamous TC “Douglas Mawson” in March 1923 compared favourably with anecdotal evidence from several island communities.

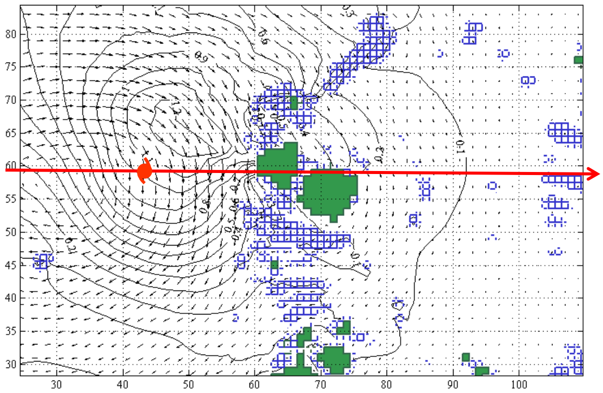

Figure 6 Example “Category 4” storm surge pattern moving W-E ; peak surge magnitude is 1.4 m, contours are 0.1 m interval.

6. Wave Modelling

Estimates of extreme wave heights and periods in association with storm surge events was needed to provide wave setup and runup components at each community [12]. The large number of TC events to be modelled, plus the intervening periods of broadscale modelling, required a very efficient approach to wave modelling. A series of trials and validation studies were conducted between a 2nd generation spectral model (ADFA1), a simple directional steady-state model and an unsteady fetch-limited model. As there is no recorded wave data in the region, recourse was made to satellite altimetry data [13] and cross-correlation with the local wind data to provide confidence in the various wave height and period estimates. As a result of these tests, an unsteady fetch-limited model similar to [14] was developed, reliant on the following principal assumptions:

- Waves are mostly locally generated due to the bordering Great Barrier Reef to the east and the extensive western shoals;
- Refraction effects are small due to reasonably constant depth;
- Diffraction effects are negligible;
- Bed friction effects are small;
- Wave breaking effects can be neglected;
- Current modification is small.

Due to the small spatial scale of the majority of island communities, some were able to be treated as single points, avoiding the need to spatially model wave conditions across the whole region.

7. Statistical Storm Tide Simulation Modelling

The regional water levels were then statistically modelled using a specially-developed variant of the SEA numerical model SATSIM (Surge And Tide SIMulation). This is a discrete Monte-Carlo event sampling model that, operating at a 0.5 h timestep, accumulates exceedance statistics of winds, tide+surge, wave height, breaking wave setup and runup at all of the Torres Strait community sites for a continuous period of 50,000 y. This provided 50 values to form the basis of the average 1000 y return period water level. Importantly, the modelling methodology retains all seasonally-locked information, such as the astronomical tide, the annual broadscale forcing and the summer-only tropical cyclone influences. A total of 33,816 individual TC model simulations were required to satisfy the 2010, 2050 and 2100 climate conditions.

The modelled wind climate compared favourably at the more reliable of the regional measurement sites. The modelled water levels also compared well to anecdotal experience of the frequency of inundation of some communities. Figure 7 summarises the combined result for both the broadscale and TC effects, with the broadscale influences tending to dominate until at least the 100 y return period. The communities exposed to the greatest storm tide hazard are typically those located against the mainland, while the lowest hazard is at isolated small islands in open, deep water. However, the vulnerability varies greatly from one community to another, with Saibai, Boigu, Poruma, Warraber, Iama and Masig being the top six communities at risk from potentially chronic levels of inundation.

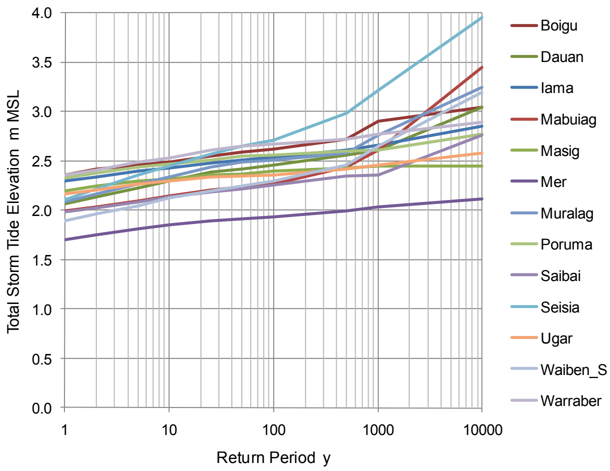

Figure 7 Selected simulated total storm tide levels (tide+surge+setup) for combined broadscale and tropical cyclone for the 2010 climate.

8. Potential Future Climate Change

For the broadscale environment, this was limited to consideration of future changes in MSL only, implicitly assuming that tidal characteristics will not alter significantly by the year 2100. Nominal values of maximum expected sea level rise were +0.30 m by 2050 and +0.80 m by 2100, these being values adopted by the Queensland Government, relative to sea level in 1990. The available advice on potential changes in regional mean wind speed and direction, ENSO and other broadscale forcing was considered either of minor significance compared with the modelling assumptions here or too qualitative to usefully incorporate.

The sensitivity of the regional risk of TC storm tide under potential future climate conditions was assessed through the adoption of scenarios that may modify the Maximum Potential Intensity of TCs (MPI) and their frequency of occurrence by the year 2050 and 2100. The preferred reference [15] is the latest review and consensus expert statement summarising the status of current research in this area. This has been assumed to be reasonably represented by a 10% increase in MPI pressure deficit by 2050 and 20% by 2100. Likewise, the consensus is that the global frequency of tropical cyclones will either decrease or remain essentially unchanged and there is low confidence in model estimates of changed areas of genesis or tracks. Accordingly no changes are adopted here for the year 2050, but a nominal precautionary allowance for a +10% change in frequency of occurrence is assumed by the year 2100. Notwithstanding these allowances, the projected future climate change impacts are dominated by the assumed increases in MSL.

9. Summary

This investigation has shown that ocean water levels in the Torres Strait region are dominated by the highly variable astronomical tide but that extreme water levels are caused by subtle combinations of relatively small inter-annual changes in the regional ocean level, strong seasonal variability due to the prevailing winds and occasional high energy weather events (monsoon surges and tropical cyclones). The interplay of these components on a range of time and space scales likely leads to periods of both enhanced and reduced ocean impacts on the various communities. It is concluded that extreme water levels are controlled by generally broadscale processes up until around the 100 y return period, after which close-approach tropical cyclones may increasingly begin to influence and impact wind, wave and water levels at some communities.

10. Acknowledgements

The study described here was commissioned by the Torres Strait Regional Authority though its Land and Sea Management Unit. The Torres Strait Regional Authority (TSRA) is a Commonwealth statutory authority responsible for coordinating the delivery of policies and programs that benefit Torres Strait Islander and Aboriginal people living in the Torres Strait region. Permission to publish this paper is gratefully acknowledged.

11. References

[1] SEA (2011) Torres Strait extreme water level study - final report. Prep by *Systems Engineering Australia Pty Ltd* for the Torres Strait Regional Authority, draft.

[2] Kistler R., Kalnay E., Collins W., Saha S., White G., Woollen J., Chelliah M., Ebisuzaki W., Kanamitsu M., Kousky V., van den Dool H., Jenne R. and Fiorino M. (2001) The NCEP–NCAR 50–Year Reanalysis: Monthly Means CD–ROM and Documentation. *Bulletin of the American Meteorological Society*, 82, 2, Feb, 247–267.

[3] Nicholls N. (1992) Historical El Niño/Southern Oscillation variability in the Australian region. In: Nicholls, N., 1992: Recent performance of a method for forecasting Australian seasonal tropical cyclone activity. *Aust. Meteor. Mag*., 40, 105 110.

[4] Power S., Casey T., Folland C., Colman A. and Mehta V. (1999) Inter-decadal modulation of the impact of ENSO on Australia. *Climate Dynamics*, 15, 319-324.

[5] Lemckert C.J., Zier J. and Gustafson J. (2009). Tides in Torres Strait. *Journal of Coastal Research*, SI 56: 524-528.

[6] Daniell J., (2008) The development of a bathymetric grid for the Gulf of Papua and adjacent areas—a note describing its development. *Journal of Geophysical Research,* 113, F01S15, doi:10.1029/2006JF000673.

[7] Bode, L. and Mason, L.B. (1994) Application of an implicit hydrodynamic model over a range of spatial scales, Computational Techniques and Applications: CTAC93, D. Stewart, H. Gardner and D. Singleton, Eds., *World Scientific Press*, 112--121

[8] Harper B.A., Stroud S.A., McCormack M. and West S. (2008) A review of historical tropical cyclone intensity in north-western Australia and implications for climate change trend analysis. *Australian Meteorological Magazine*, Vol. 57, No. 2, June, 121-141.

[9] Vickery P.J., Skerlj P.F. and Twisdale L.A., (2000) Simulation of hurricane risk in the U.S. using empirical track model. *J. Structural Engineering*, ASCE, 126,10, Oct, 1222-1237.

[10] Harper, B.A. and Holland, G.J. (1999) An updated parametric model of the tropical cyclone. Proc. 23rd Conf. Hurricanes and Tropical Meteorology, *American Meteorological Society*, Dallas, Texas, 10-15 Jan, 1999.

[11] Harper B.A (1999) Numerical modelling of extreme tropical cyclone winds APSWE Special Edition, *Journal of Wind Engineering and Industrial Aerodynamics*, 83, 35 - 47.

[12] Harper B.A. (ed) (2001) Queensland climate change and community vulnerability to tropical cyclones - ocean hazards assessment - Stage 1, Report prep by Systems Engineering Australia Pty Ltd in association with James Cook University Marine Modelling Unit, *Queensland Government*, March, 375pp.

[13] Young, I.R. (2010) personal communication.

[14] Walker D.J. (1989) An efficient wave hindcasting model. Proc 9th Australasian Conf Coastal and Ocean Engin., *IEAust*, Adelaide, 4-8 Dec, 117-121.

[15] Knutson T.R., McBride J.L., Chan J., Emanuel K., Holland G., Landsea C., Held I., Kossin J.P., Srivastava A.K. and Sugi M., 2010: Tropical cyclones and climate change. *Nature Geoscience*, 3, 15 –163.