Managing Sea Level Rise and Climate Change

Dr Bruce Harper

Managing Director, Systems Engineering Australia Pty Ltd., Brisbane.

Abstract

That the sea level is currently slowly rising is now beyond doubt. However, it is not sea level rise alone that is likely to impact the future management of coastal regions. The possibility of increased intensity and frequency of tropical cyclones and/or other severe low pressure systems could additionally add to the marine based threats from anthropogenic climate change through storm surge and landward penetration of extreme waves. Combined with our rapidly increasing coastal population these threats are collectively raising the risk levels in coastal communities. However, there are many well established tools for estimating coastal risks that can be applied to this problem. While adaptation through effective long term planning is the ultimate defence, enhanced emergency response training is also needed in the short term.

Key Words: climate change, sea level rise, coastal risk, tropical cyclones, storm surge, vulnerability, simulation, warning.

Introduction

Notwithstanding the likelihood of enhanced-greenhouse warming (anthropogenic or otherwise) affecting coastal climates, the principal challenges still remain, namely assessing the variability of coastal threats around our vast continent, the likely physical impacts of a gradual sea level rise combined with eroding coasts, and reconciling the ongoing social and economic pressures for coastal development.

This paper provides an overview of some of the problems facing public works engineers and Local Government in general, as well as offering some guidance for best practice investigation and planning based on robust and practical methodologies. Important new developments are also summarised.

Potential Climate Change Impacts

Projected Changes in Mean Sea Level

The principal reference in this regard is IPCC (2007), also known as “Assessment Report 4” or “AR4”, together with CSIRO (2007), which repeats the AR4 projections of future global sea level increase and provides some comment on Australian sea levels in particular. Because the AR4 only addresses the projected range of global sea level rise averaged over the period 2090 to 2099 (centred on 2095), it is necessary to merge this with earlier IPCC assessments in order to construct an updated estimate of rising sea levels from present onwards, as constructed here in Figure 1.

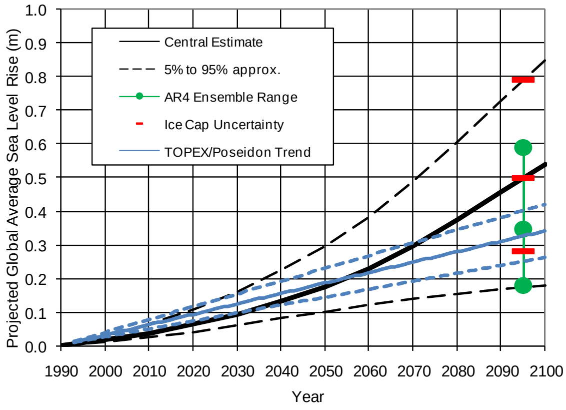

Figure 1 – Projected global average sea level rise derived from IPCC (2007) figures.

Features of this projection relative to the earlier IPCC estimates for 2100 include a rise in the nominal lower 5% non-exceedance limit of about 0.1 m, largely underpinned by the measured sea level rise of 3.1 ± 0.7 mm yr^{-1} from 10 years of TOPEX/Poseidon satellite altimetry data since 1993.

The central estimate at 2100 has also risen slightly, mainly due to the considerable uncertainty over ice cap melting, which is used here to form a nominal +95% non-exceedance upper limit at 2100. At 2050, the central estimate is close to the altimeter trend of approximately 0.2m, the upper limit remains near 0.3m, largely unchanged from earlier assessments, and the lower limit has risen to about 0.10 m.

Regional sea levels will likely vary slightly due to small changes in the principal ocean current systems (e.g. East Australian Current) and are subject to ongoing studies by CSIRO.

Changes in Storminess

Although always a pillar of potential climate change concerns, this aspect of the science remains particularly uncertain, with little or no quantitative advice being available from the IPCC and associated regional studies that is of value to coastal engineers, who are principally interested in extreme conditions.

For example, East Coast Lows (ECL), which are the principal drivers of temperate east coast wind and wave climates, are still relatively poorly understood in a climatological context but exhibit large inter-annual and decadal variability, likely linked to ENSO. Their behaviour in future climate scenarios remains unknown and sensitivity analysis remains the principal investigation tool. The behaviour of other broad-scale cold-cored weather systems such as southerly fronts and intense lows also remains highly uncertain, but with the most likely futures predicting decreased intensity near the mainland.

Likewise, tropical cyclones (TC) also exhibit very high inter-annual and decadal variability, clearly linked to ENSO in the Australian region. Once conjectured by the IPCC process to be perhaps principal and dramatic indicators of climate change, the threat of a significantly changed future tropical cyclone climate has generally receded over the years. In particular, the IPCC has never been the principal reference on this matter and the latest advice summarising current research in this area (WMO 2006) largely supports the tropical cyclone research community’s first statement in 1998. It is concluded that there is likely to be an increase in the Maximum Potential Intensity of tropical cyclones as the mean global temperature rises, of 3 to 5% per degree Celsius. Assuming a 2 to 4 degree range is possible, this may lead to an upper level increase of as much as 20% by (say) 2100 for those few tropical cyclones that are able to reach their Maximum Potential Intensity. This has variously been interpreted as a likely increase in the occurrence of “Category 4 and 5” tropical cyclones relative to the weaker systems. Concurrently though, there is strong evidence for an overall reduction in global tropical cyclone numbers as a result of increased atmospheric shear. The extent of tropical cyclone influence is not expected to greatly change. A later section discusses aspects of data quality relating to premature claims of enhanced storm activity during 2005.

Tools and Methodologies

Due to the lack of certainty about the many aspects of potential climate change, the engineering professional needs to exercise a duty of care, to be prepared to examine the full range of potential consequences and apply good judgement. The following tools and methodologies should assist in this regard.

Engineers Australia Guidelines

The Engineers Australia National Committee on Coastal and Ocean Engineering (NCCOE) first published its “Guidelines for Responding to the Effects of Climate Change in Coastal and Ocean Engineering” in 1991, and updated the guidelines in 2004 (Harper 2004). There are plans to provide a further update in the near future for consistency with IPCC (2007).

The guidelines provide a summary overview of climate change drivers, the state of the climate, future projections interpreted in an engineering context and a methodology for rationally including climate change influences in investigation and design activities. Additionally, they provide an historical perspective on past studies on a national and regional basis.

One of the critical concepts conveyed by the guidelines is the need for a risk-based assessment that includes the concept of design life and exposure to a specific level of risk (e.g. Figure 2).

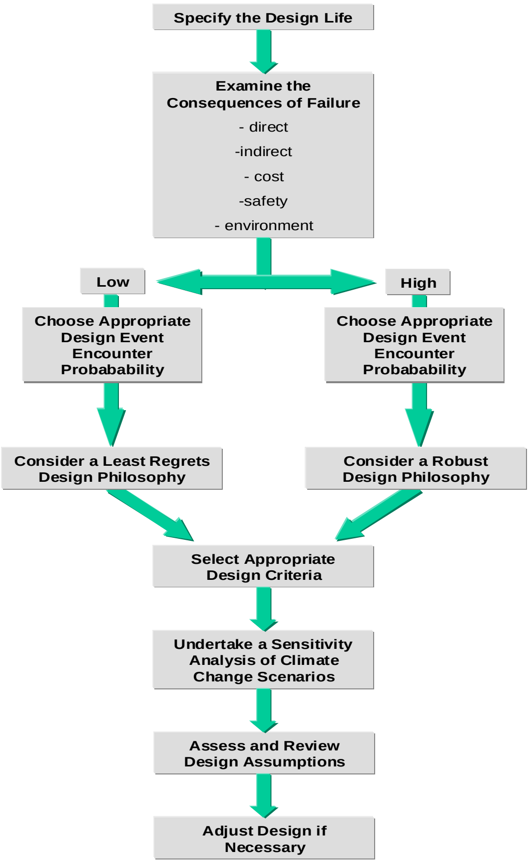

Figure 2 - Recommended engineering impact assessment procedure (after Harper 2004).

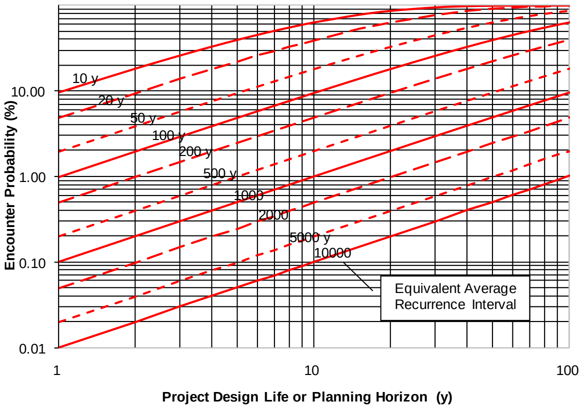

Figure 3 - Relationship between encounter probability, design life and average recurrence interval (after Harper 2004).

Associated with this methodology is the need for a correct interpretation of average return period within the context of a design life for the planning decision, structural modification or environmental design. Sea level rise, which is a trend rather than a random process, must be added into this construct.

The NCCOE methodology then provides a framework for decision making based on examining seven key environment variables related to climate change and their possible interactions with 13 secondary variables. An interaction matrix is then used to help summarise and focus the investigation and/or decision making process.

Queensland Climate Change Study QCC

This refers to a number of investigations[1] undertaken over the period 2000 to 2004 that were funded primarily through State and Commonwealth Government enhanced-greenhouse research allocations. The initial work (Harper 2001) was conducted by Systems Engineering Australia Pty Ltd (SEA) in association with the James Cook University Marine Modelling Unit[2] (JCU-MMU) and others. There remains much value in this study for local government generally.

This initial reference sets out recommended methodologies for storm tide studies that would also be capable of addressing climate change (enhanced-greenhouse) issues within the context of tropical cyclones. Importantly, storm tide is defined (Figure 4) as the combined effect of astronomical tide, storm surge and breaking wave setup, with localised wave runup also delivering intermittent impacts. A holistic approach (Figure 5) was advocated for identifying the physical forcing mechanisms, ocean responses, vulnerabilities and impacts that would lead to informed decision making and the long term mitigation of storm tide threats.

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[1] All Queensland Climate Change study reports are available from the following URL: http://www.longpaddock.qld.gov.au/ClimateChanges/pub/OceanHazardsMenu.html with access to the principal study results also available via http://mmu.jcu.edu.au/atlas/atlas.shtml.

[2] The Marine Modelling Unit now operates within the Australian Maritime College in Launceston, Tasmania.

Subsequent studies conducted principally by JCU-MMU provided updated TC-induced surge plus tide updates for selected east coast sites (Hardy et al. 2004ab) all with and without allowance for predicted enhanced-greenhouse effects by 2050.

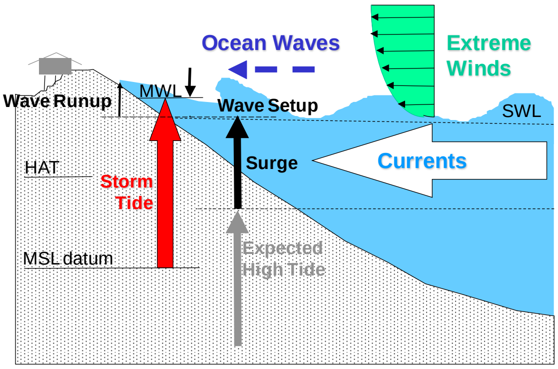


Figure 4 – Water level components of a storm tide (after Harper (2001)).

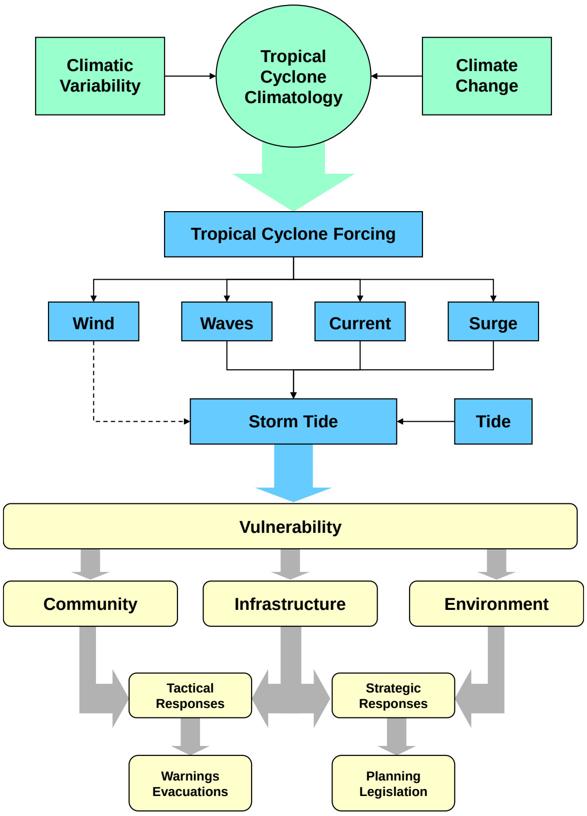


Figure 5 – Tropical cyclone storm tide hazard assessment process (after Harper (2001)).

A series of demonstration hindcasts of significant historical storms indicated that peak surge levels were likely reproducible within 5% of measured values provided that adequate meteorological and bathymetric data was available. The numerical ocean modelling of the 3,600 km coastline utilised a three-stage nested regular grid in spherical coordinates, having a broad-scale ‘A’ grid resolution of 7.5' arc or 13.9 km and an along-coast ‘B’ grid resolution of 1.5' arc or 2.8 km (refer Figure 6), with nearshore ‘C’ grid resolutions of 0.3' arc or 560 m. Although the model allowed wetting and drying, no detailed coastal inundation modelling was undertaken. Likewise, although 3D modelling was possible, a series of sensitivity tests and validation experiments justified 2D-only modelling for the full coastal area.

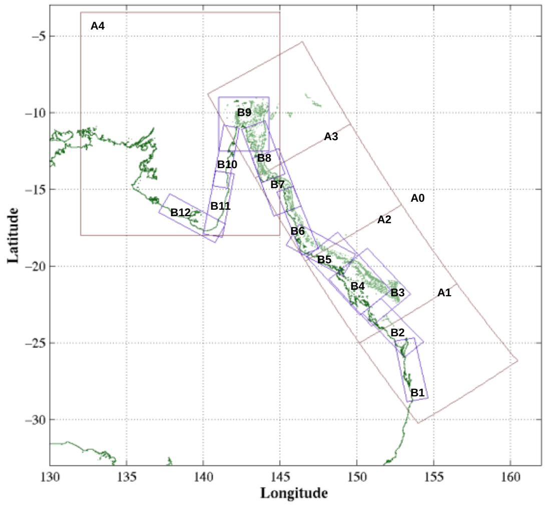
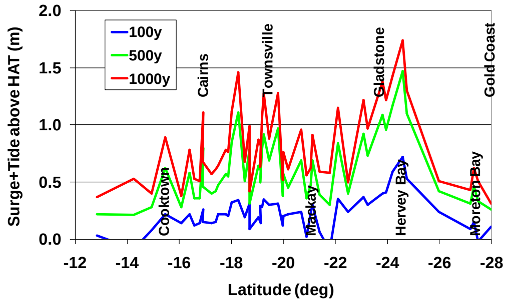


Figure 6 – Queensland climate change ‘A’ and ‘B’ numerical domains [after Harper (2001))

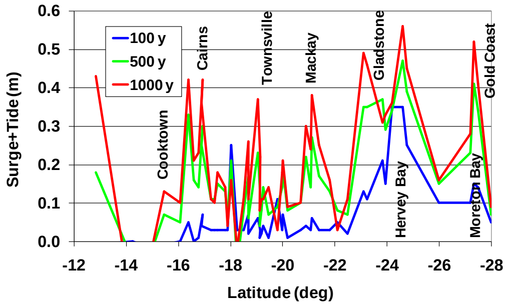
A principal feature of the predictive aspects of the study was that a simulated TC track climatology was utilised, which represented a significant departure away from previous storm tide statistics studies. The principal advantages of this were a “seamless” climatology for all areas of the coast without reliance on assumptions of fixed track, speed, direction or intensity. Other scale-like parameters such as storm size were assigned on the basis of argued intensity-dependent relationships. The modelled TC storm track set comprised 10,000 possible events affecting any part of the Queensland east coast, representing about 3,000 years of “synthetic data”. This was reduced to typically 500 storms for each of the 20 fine scale ‘C’ numerical grid domains for discrete hydrodynamic modelling to be performed. A total of 3,622 individual synthetic TC tracks were modelled for the east coast, requiring 10,854 fine scale simulations.

The astronomical tide effect was linearly added to the predicted surge in each event by randomly sampling a selected 20 year sequence of predicted tides for each site of interest and for each modelled storm. Simultaneous wave modelling using a modified WAM model, which added significant computational burden, could not be undertaken for all selected east coast sites and was therefore limited to the (client assigned) high priority areas of Hervey Bay and the Sunshine Coast in the southern portion of the State (e.g. domain B1).

Enhanced-greenhouse effects on TC climatology and Mean Sea Level (MSL) increase were considered based on contemporary expert advice, which resulted in sensitivity testing of the effects of a TC intensity increase (+10% of Maximum Potential Intensity - MPI), a potential poleward TC track biasing (-1.3°S), an increased frequency of occurrence (+10%) and an increase in MSL (+0.3 m) by 2050. Figure 7(a) presents a summary of the predictions for the east coast sites for present climate and shows the 100 y, 500 y and 1000 y Average Recurrence Interval (ARI) tide plus surge level variation with latitude (no wave setup) relative to the Highest Astronomical Tide (HAT)[3]. Figure 7(b) shows the differences from present for the 2050 future climate under the previously described (combined) enhanced-greenhouse scenario, except that the +0.3 m MSL rise is omitted to highlight the atmospheric/hydrodynamic response[4]. The results indicate the wide range of variability possible between sites on this complex coastline, much of which is affected by the Great Barrier Reef (GBR) and the varying continental shelf extent. Because of this, the storm tide response in the region of peak TC occurrence (18º to 22ºS) is attenuated by the nearshore GBR and the narrow shelf. Meanwhile, south of 22ºS the shelf is wider, more exposed and shallow, especially near Hervey Bay. At the southern margin of TC influences near the Gold Coast, the shelf is exposed but very narrow. Under the 2050 climate scenario differences the principle response is at the northern and southern margins of the region, where the changes in intensity and frequency of occurrence act to amplify the risks, while the central region is much less affected. Noting that MSL rise needs to added to Figure 7(b), the predicted changes at the 500 y ARI are typically less than the 0.3 m static sea level rise, except near Gladstone to Hervey Bay and the Gold Coast. Accordingly, the predicted MSL rise represents a significant proportion of the predicted changes under these scenarios. In addition, the study highlighted the sometimes considerable effect of breaking wave setup on open coasts south of the influence of the GBR.



(a) Present climate



(b) Differences for 2050 climate and nil MSL rise

Figure 7 – Summary of east coast tide plus surge predictions for present and 2050 climate scenarios for tropical cyclone only.

State Planning Policies

A number of States have addressed the combined threat of coastal hazards and climate change through their often very comprehensive planning policies (e.g. EPA 2006) that encourage best practice methodologies for Local Government.

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[3] The tidal range along the Queensland coast varies between 2 m (south), 8 m (central) and 4 m (north).

[4] All surge modelling was done at nominal current climate MSL; all wave modelling at MWHS.

New Developments

Uncertainties in Historical Tropical Cyclone Datasets and Detecting Trends from Variability

Notwithstanding the significant storm tide modelling effort exemplified by the QCC study there has been a growing realisation that the quality of the historical storm datasets is a principle source of uncertainty in any risk assessment study, especially when enhanced-greenhouse climate change is of interest.

The advent of routine satellite imaging circa 1965 had a profound influence on the ability of meteorologists to track and better study TCs in a global context, leading to the beginning of objective analyses in the 1970s. The march of technology, methodology, knowledge and skill has been increasing more rapidly with each decade, providing very significant advances in intensity estimation, and further improvements are expected well into the future. The impact of these changes on the accuracy of the global best track dataset storm intensities over even the past 30 years has been significantly underestimated (Landsea et al. 2006). Researchers and investigators across many disciplines have naively tended to overestimate the levels of objectivity and accuracy of best track data used to support developing theories, for underpinning numerical modelling or when estimating risks.

Faced with increasing doubts as to the accuracy and consistency of TC intensity in the North-West Australian region an oil and gas industry and Bureau of Meteorology supported program of review was initiated in 2001/2002 (Harper 2002) in an attempt to rectify the Bureau best track intensities since 1968/69. The result of that limited but consistent review, summarized in Figure 8, uncovered a very wide range of differences from the original Bureau dataset, well into the 1990s. A clear bias of intensity underestimation ranging initially from 10 hPa to about 5 hPa in central pressures was detected and a temporal trend in intensity still remained up until the mid-1980s prior to the routine use of geostationary satellites (the annotation on Figure 8 highlights the times when specific satellite and other technique improvements were introduced, as well as the Southern Oscillation Index (SOI) variability). Contrary to some highly publicised claims regarding enhanced-greenhouse influences on global tropical cyclone intensity already being evident, the review found no prima facie evidence for this specific influence in this region and supports other studies that have highlighted the role of technological and procedural changes worldwide. Notwithstanding this, there is a critical need for storm tide risk assessments to consider the potential influences of enhanced-greenhouse climate change.

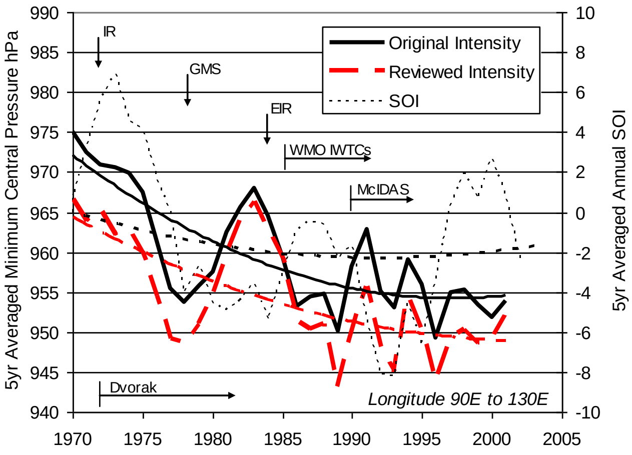


Figure 8 – Results of a recent review of historical tropical cyclone intensity in north-western Australia (after Harper and Callaghan 2006).

Tropical Cyclone Structure and Boundary Layer Interactions

Another advantage of the unprecedented ability now to observe and sample the structure of tropical cyclones is that some long established theories and knowledge are being questioned. For example, the intensive US program of GPSdropwindsonde measurements (e.g. Powell et al. 2003) continues to provide insight into the crucial role of the air-sea interface under extreme winds.

Changes to parameterisation of the surface boundary layer via the drag coefficient may have implications for calibration of many existing numerical hydrodynamic surge and wave models.

Improved Storm Tide Warning and Emergency Management Systems

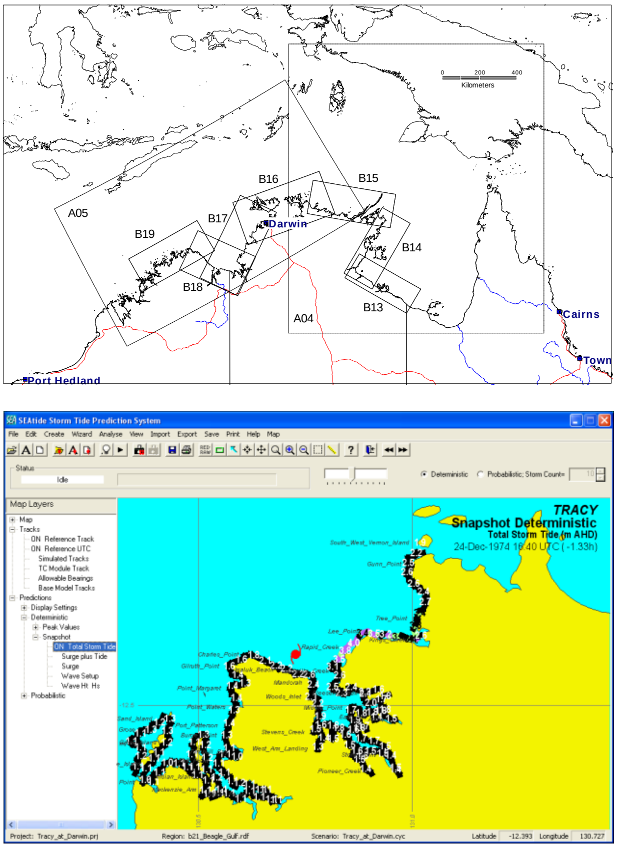
One of the aims of the QCC study (Harper 2001) was to develop self-consistent methodologies for both mitigation/planning and forecast/warning applications that could be efficiently developed and deployed to provide coverage over large sections of coastline. A proposed “hybrid” approach, being a combination of detailed deterministic hydrodynamic modelling and derived parametric models, satisfied these criteria. It forms a self-consistent framework for long term climatology modelling and short term warning needs that provides a rapid response tool that can incorporate tidal variation and storm parameter uncertainty.

The Bureau of Meteorology in Queensland adopted this approach in developing a parametric surge model for the east coast that would augment their existing access to real time hydrodynamic modelling. This provided a significant benefit in operational flexibility and also in training of forecasters, who could quickly examine and test a range of forecast scenarios.

The Northern Territory Bureau then engaged SEA in 2005 to provide a turnkey parametric storm tide forecasting system that incorporates tidal prediction, storm surge, waves and wave setup for the entire northern Australian coast from the Gulf of Carpentaria west to the Kimberley region in Western Australia. Figure 9 shows the area that was comprehensively modelled in association with JCU-MMU using seven along-coast domains, each of about 400 km extent, to provide the basis for the necessary SEA parametric models. A snapshot of the warning system operation is also shown for the Darwin region.

Approximately 25,000 individual TCs were modelled as part of the NT development and storm tide predictions are available for over 1,000 named localities. However, the resulting parametric prediction model SEAtide can generate several hundred probabilistic storm tide forecasts within one minute on a typical desktop computer.

Importantly, this approach recognises that the greatest uncertainty in the storm tide forecast relates to the variability of the forecast meteorological parameters. This is especially relevant to the vast majority of tropical cyclone forecast centres around the world that do not have aerial reconnaissance capability and rely on satellite image interpretation method as the primary intensity forecast tool. Even with the rapid development of advanced atmospheric models this situation is unlikely to change significantly within the next decade.



Project: Tracy_at_Darwin.prj Region: b21_Beagle_Gulf.rdf Scenario: Tracy_at_Darwin.cyc Latitude -12.393 Longitude 130.727

Figure 9 – Extent of the Northern Territory storm tide warning modelling system (upper) and an example of the operational system (lower).

Townsville City in North Queensland also commissioned a similar warning system as part of a recent SEA-GHD storm tide risk assessment and planning study, which provides Council with a powerful training and emergency planning tool to deal with potentially increasing storm tide threats under a changing climate.

Conclusions

There is a growing awareness of increasing community risks due to the combined effects of potential climate change and rapidly rising populations along the Australian coastline, especially in tropical regions. Modelling of climate variability remains the principal challenge, irrespective of climate trends.

Managing the potential impacts of climate change in the coastal environment requires access to the best scientific information, expert engineering interpretation and a range of methodologies and models. While deterministic modelling (tides, currents, waves, surge) has improved with the ability to increase resolution, meteorological forcing (wind, pressure) remains the principal unknown. Together with the need to practically depict present and future climate variability, the improvement of simulation methodologies remains the principal challenge and will deliver the best outcomes for coastal planners, developers and managers.

Sophisticated studies such as the QCC provide a firm basis for representing existing climate as realistically as possible, based on present knowledge, and then provide a springboard for investigating potential enhanced-greenhouse impacts. Importantly, fitness-for-purpose remains an important aspect of the design of any coastal risk assessment study, whereby the methodology must adequately address the relative levels of uncertainty in the many interconnected aspects of the phenomena.

It is concluded that the principal source of uncertainty in present day storm tide risk assessment and real-time prediction is with the meteorological parameters and the depiction of the atmospheric forcing, both historical and forecast. Historical datasets must be reviewed and revised to improve the former and predictive models for the latter must incorporate probabilistic uncertainty concepts.

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