Nat Hazards
DOI 10.1007/s11069-009-9382-3

ORIGINAL PAPER

Developments in storm tide modelling and risk assessment in the Australian region

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Received: 22 July 2008 / Accepted: 4 March 2009

Abstract An overview is provided of some of the significant storm tide modelling and risk assessment studies undertaken over the past few years within Australia and the nearby oceanic regions for government and industry. Emphasis is placed on the need for integrated planning and forecasting approaches for storm tide risk assessment. The importance of the meteorological forcing and the appropriate modelling of each of the storm tide components, namely, astronomical tide, storm surge, breaking wave setup and coastal inundation is discussed. The critical role of tropical cyclone "best track" datasets for risk assessment studies and the potential impacts on design criteria and risk assessment studies is highlighted, together with the challenge of developing credible enhanced-greenhouse climate change scenarios. It is concluded that storm tide modelling needs to be undertaken in a holistic framework that considers the relative uncertainties in each of the various elements—atmospheric, hydrodynamic and data, as well as addressing operational forecasting, design and planning needs.

Keywords Storm tide · Hydrodynamic modelling · Simulation · Climate · Risk

1 Introduction

Australia has an extensive tropical coastline that is regularly impacted by severe tropical cyclones (TCs) and, in spite of its sparsely settled population, has recorded significant storm tide impacts dating from the late 1800s. Accordingly, there has been a history of

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development of storm surge modelling, risk assessment and associated atmospheric modelling capabilities since the availability of significant computational power in the 1970s. This work has focused on the east coast of Queensland (Harper 1999), where TCs occur along a settled and rapidly developing coastal margin, much of which is bounded by the Great Barrier Reef (GBR). The most intense TCs in Australia are observed in the north west of Western Australia, although the population there is relatively sparse and storm tide studies have been typically limited to specific towns or industrial facilities.

Australian research efforts into TC storm tide essentially began following Tropical Cyclone *Althea* in 1971, which generated a 3 m storm surge at the North Queensland coastal city of Townsville. Thankfully the peak surge occurred close to low water and the local 4 m tide range limited the impact to one of only relatively minor inundation of some beachside areas. During the 1980s considerable research and investigation was undertaken, mostly at James Cook University in Townsville, and this resulted in a significant increase in knowledge of the storm tide generating processes (Bode and Hardy 1997) and their impacts (Harper 1999). Following the UN-declared International Decade for Natural Disaster Reduction (IDNDR) of the 1990s and the increasing concerns over enhanced-greenhouse climate change, a renewed interest in storm tide investigations began in the new millennium. This article outlines aspects of several studies with which the authors have been involved.

2 Queensland climate change study

This refers to a number of investigations[1] undertaken over the period 2000–2004 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. 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 TCs. Importantly, a holistic approach (Fig. 1) 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.

Subsequent studies conducted principally by JCU-MMU provided updated TC-induced surge plus tide updates for selected east coast sites (Hardy et al. 2004a, b) all with and without allowance for predicted enhanced-greenhouse effects by 2050. This work was done using the JCU-MMU storm surge, wave and TC wind field models that had been extensively calibrated over many years (Bode and Mason 1994; Hardy et al. 2001; James and Mason 2005). 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.

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[1] All Queensland Climate Change study reports are available from the following URL as at January 2009: http://www.longpaddock.qld.gov.au/AboutUs/Publications/ByType/Reports/ClimateChange/VulnerabilityToTropicalCyclones/index.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.

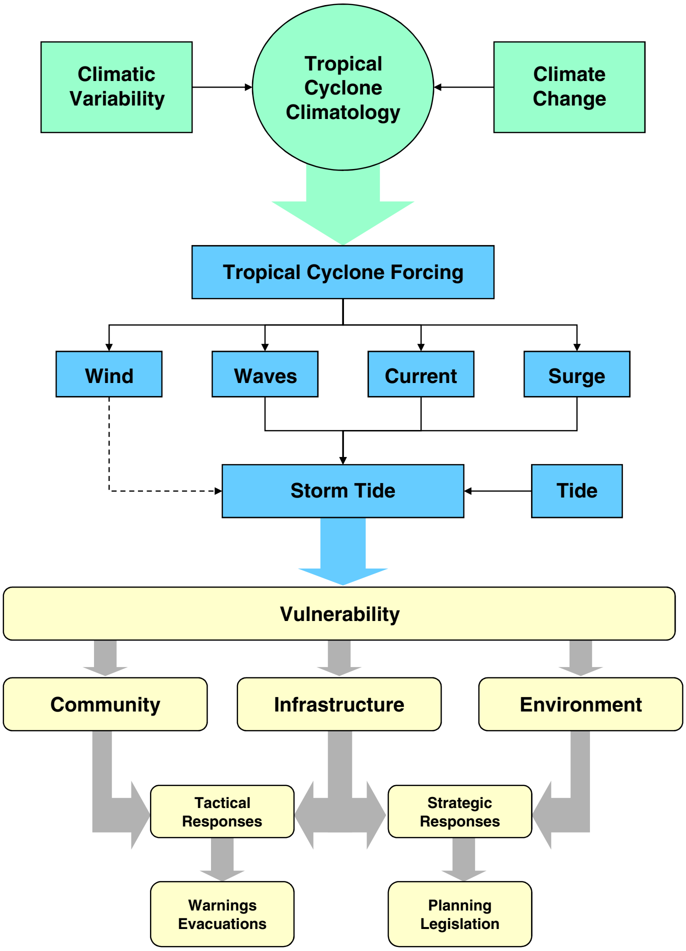

Fig. 1 Tropical cyclone storm tide hazard assessment process (after Harper 2001)

The numerical ocean modelling of the 3,600 km coastline utilised a three-stage nested regular grid in alignable 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 Fig. 2), with nearshore ‘C’ grid resolution 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. These resolutions and extents were based on recommendations arising from Harper (2001), as summarised in Table 1, where Δs is the model domain spatial resolution (minutes-of-arc or km); Δt is the timestep resolution (s); R is the radius to maximum winds (km); V_{fm} is the maximum forward motion speed (m s^{-1}) and d is the depth (m). Desirable bathymetry accuracy is also indicated and the table identifies the principal environmental scales (ocean, coastal, bay and beach) and, with regard to a selection of relevant scale parameters and conflicts, suggests appropriate criteria for each situation. With the increasing uptake of variable-mesh models, these criteria should of course be more easily achievable.

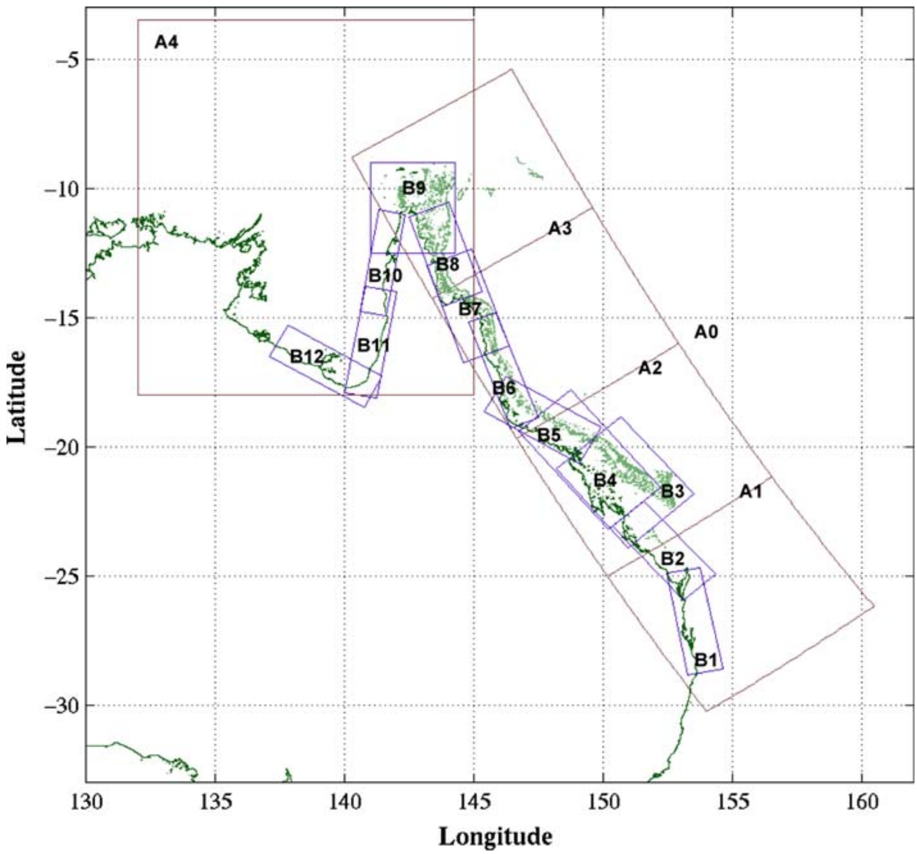

Fig. 2 Queensland climate change 'A' and 'B' numerical domains (after Harper 2001)

Table 1 Model scale considerations (after Harper 2001)

Scale consideration	Suggested criterion for each environment			
	Ocean	Coastal	Bay	Beach
Coastal features resolution (nominal) Δs	$\Delta s < 15$ km	$\Delta s < 5$ km	$\Delta s < 1$ km	$\Delta s < 0.2$ km
Windfield resolution $\Delta s \leq R/4$	$\Delta s \leq R/3$	$\Delta s \leq R/4$	$\Delta s \leq R/5$	$\Delta s \leq R/5$
Wavelength resolution $\Delta s \leq 4R/20$	$\Delta s < 0.4\ R$	$\Delta s < 0.2\ R$	$\Delta s < 0.1\ R$	n/a
Waveperiod resolution $\Delta t \leq 4R/(20\ V_{\mathrm{fm}})$	$\Delta t < 0.8\ R/V_{\mathrm{fm}}$	$\Delta t < 0.4\ R/V_{\mathrm{fm}}$	$\Delta t < 0.2\ R/V_{\mathrm{fm}}$	n/a
Along-shore spatial response (nominal) Y	50 R	(10–15) R	2 R	n/a
Cross-shore spatial response (nominal) X	10 R	5 R	1 R	n/a
Deepwater boundary (nominal)	$d > 500$ m	$d > 50$ m	$d > 20$ m	$d > 10$ m
Bathymetry accuracy (nominal)	$d < 10$ m	$d < 5$ m	$d < 2$ m	$d < 1$ m

A principal feature of the predictive aspects of the study (Hardy et al. 2004a, b) was that a simulated TC track climatology (James and Mason 2005) was utilised, which represented a significant departure away from the schematised control-volume approach typically adopted for 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 JCU-MMU studies considered TC data from 1969 onwards only when constructing the synthetic TC track climatology so as to partly avoid the well known pre-satellite data quality issues (Harper and Callaghan 2006). 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 (Hardy et al. 2001), which added significant computational burden, could not be undertaken for all selected east coast sites and was therefore limited to the high priority areas of Hervey Bay and the Sunshine Coast (Hardy et al. 2004a) 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 the contemporary expert advice (Henderson-Sellers et al. 1998; Walsh and Katzfey 2000; Harper 2004b). This 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 3a presents a summary of the predictions for the east coast sites for present climate (Hardy et al. 2004b) and shows the 100, 500 and 1,000 y Average Recurrence Interval (ARI) tide plus surge level variation with latitude (no wave setup) relative to the Highest Astronomical Tide (HAT).[3] Figure 3b shows the differences[4] 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 hydrodynamic response.[5] The results indicate the wide range of variability possible between sites on this complex coastline, much of which is affected by the GBR and the varying continental shelf extent. Because of this, the storm tide response in the region of peak TC occurrence (18°–22°S) is attenuated by the nearshore GBR and the narrow shelf. Meanwhile, south of 22°S 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 allowance for MSL rise must be added to Fig. 3b, the predicted changes at the 500 y ARI are typically less than the 0.3 m static sea level rise,

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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] Note that in this case the highest ARI may not necessarily show the greatest difference because of regional sensitivities.

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

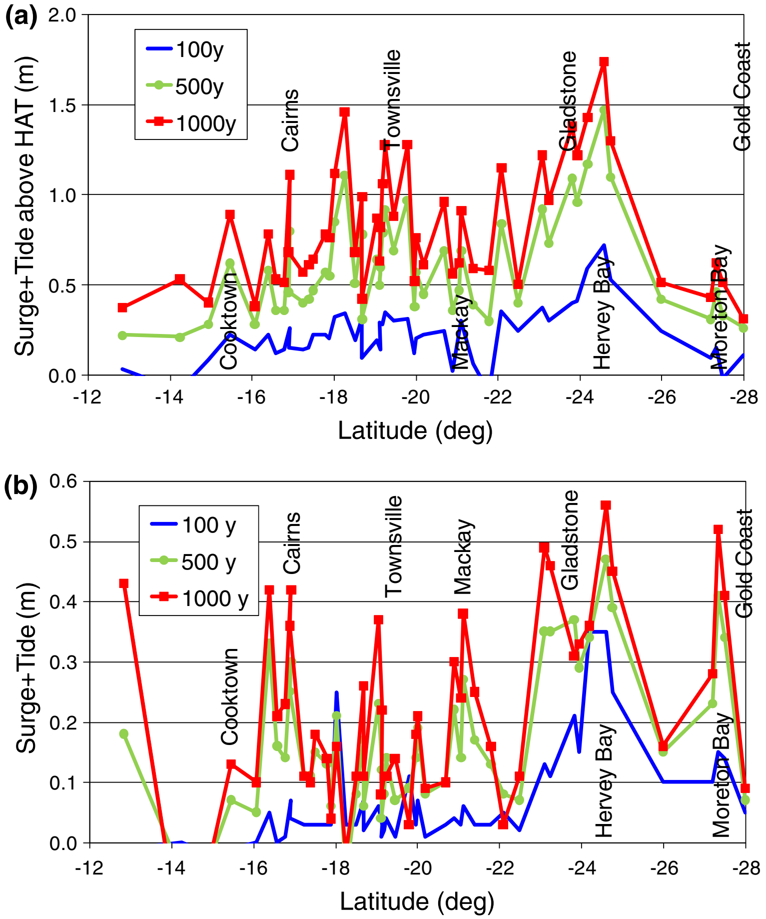


Fig. 3 Summary of east coast tide plus surge predictions for present and 2050 climate scenario for tropical cyclone only. **a** Present climate, **b** differences for 2050 climate and nil MSL rise

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 sometimes considerable effect of breaking wave setup on an open coast is illustrated by the results in Fig. 4 for an exposed narrow continental shelf site on the Sunshine Coast (near 26°S). Here, the additional quasi-steady increase in water levels is estimated to be about 1 m above the tide plus surge levels for both present and future climate (Hardy et al. 2004a). The predicted 2050 climate increase in storm tide level over and above the static 0.3 m MSL rise is however only of the order of 0.15 m.

3 Local coastal inundation studies

In addition to the state-wide study described above, coastal local government regions in Queensland have been active in assessing storm tide risks for the purposes of updating circa 1985 local planning levels and for emergency response. Federal and state financial

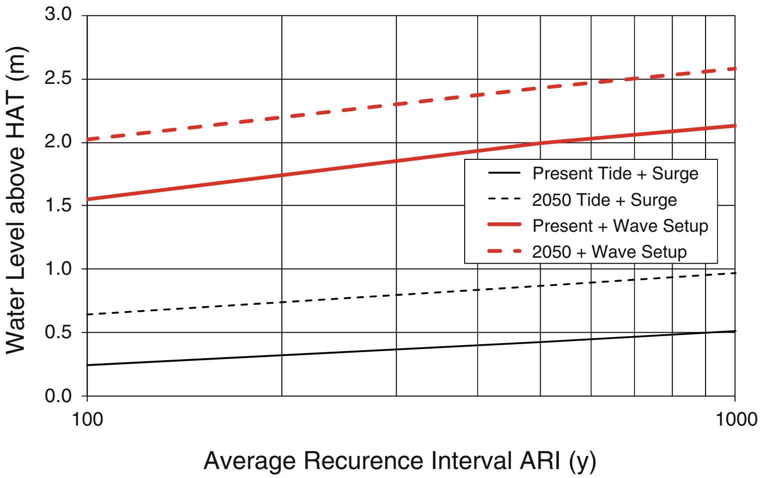


Fig. 4 Example predictions for Sunshine Coast site with wave setup effects for present and 2050 climate scenario for tropical cyclones only (includes 0.3 m MSL increase)

assistance has been available for the past decade under the Natural Disaster Risk Management Studies Program (NDRMSP) and the Natural Disaster Mitigation Program (NDMP). Approximately, 10 localised storm tide studies have been completed during this time on the basis of commercial tenders open to consulting engineering companies. As a result, a variety of methodologies have been adopted, which in some situations have led to inconsistencies in predictions at the coastal jurisdictional boundaries. Several of these studies overlap or predate the Queensland Climate Change investigations previously described. There are now State Government efforts to ensure a more unified product for future studies (EPA 2006). While the various commercial consultants have utilised conventional and reputable deterministic hydrodynamic models—often at high resolution (50 m or less)—differences in the atmospheric modelling assumptions, the climatological and statistical approaches and limited opportunities for calibration and verification can lead to significant differences in conclusions.

SEA and GHD have jointly undertaken two local inundation studies in Queensland—the Whitsunday coast and islands (Fryar et al. 2004) and the Townsville–Thuringowa region. The methodology employed in each of these follows the “hybrid” approach recommended in Harper (2001), namely the use of fully consistent predictive models for the planning and warning contexts. To achieve this, a parametric storm tide model (surge and wave) was developed based on comprehensive hydrodynamic model parameter response mapping of the study region. The parametric model then provides an economical kernel for Monte Carlo simulation and a flexible test bed for sensitivity testing of a range of model assumptions, El Niño Southern Oscillation (ENSO) or climate change influences, as well as being capable of forming the basis of a dynamic forecasting and warning system (refer later). Figure 5 shows the Whitsunday study area and the methodology flowchart, where potential for inundation was relatively limited due to the steep coastal topography, but the considerable tidal variability across the region required special consideration. For Townsville–Thuringowa, the emphasis was on inundation across low-lying coastal margins and the potential influence of wave setup. In this latter case, a series of scenarios were hydrodynamically modelled at 55-m resolution to represent the impacts of a range of statistically derived ARI levels and detailed water surface mapping was produced. Water

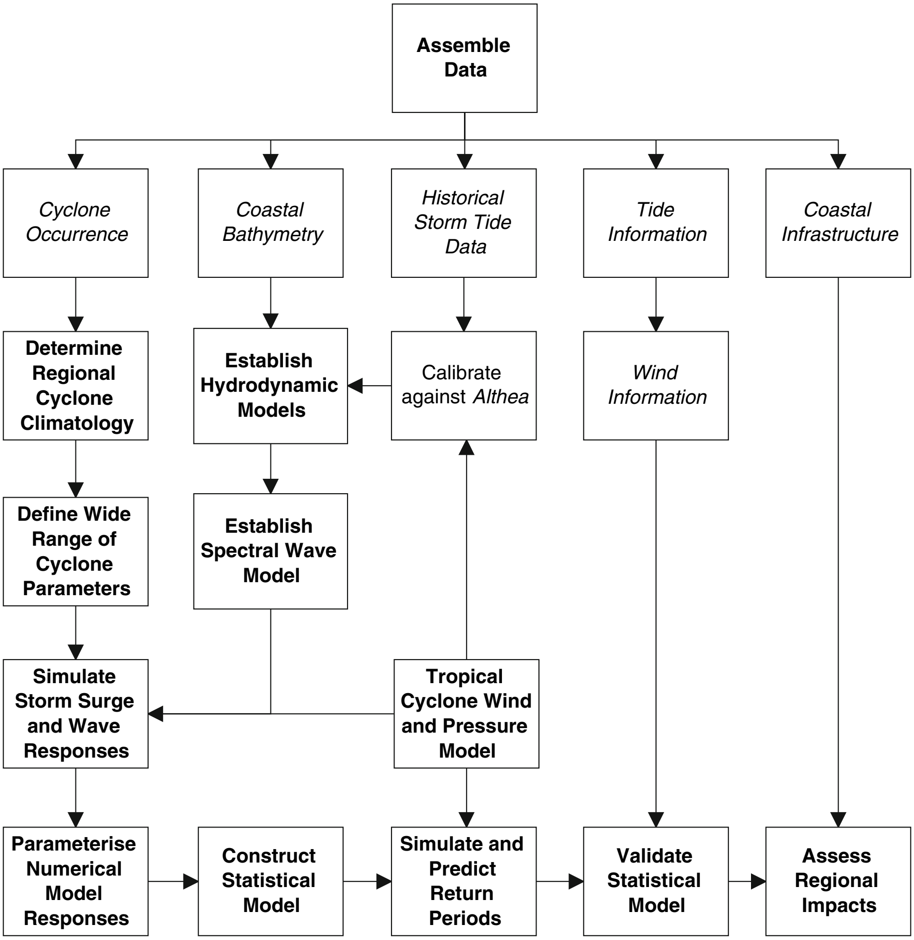


Fig. 5 Whitsunday coasts and islands storm tide study methodology (after Fryar et al. 2004)

level persistence and joint probabilities of surge, tide, wave height and period are also available from these studies as a result of the adopted methodology.

4 Coral atoll and reef environments

Coral atoll and fringing reef environments can present significantly different vulnerabilities from the typical continental margin environments described previously and require consideration of concurrent non-linear tide, surge and wave interactions. SEA and GHD have jointly undertaken studies for the Cocos (Keeling) Islands in the South West Indian Ocean (Harper et al. 2001) and Rarotonga in the South West Pacific that have illustrated these difficulties. The principal threat of inundation in such low lying environments is due to extreme water levels on the outer reefs (Fig. 6) due to the combined effects of the pressure deficit component of a storm surge acting coincidentally with a high tidal level and high wave setup, caused by wave breaking on the outer reefs and reef entrances. Breaking wave

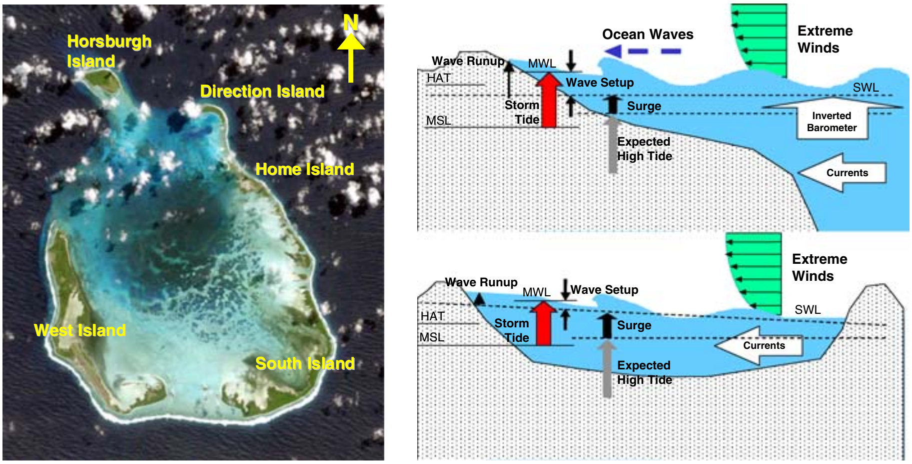


Fig. 6 Storm tide processes modelled at Cocos (Keeling) Island (*left*) to represent outer reef (*top right*) and inner lagoon (*bottom right*) sites (after Harper et al. 2001)

setup can be expected to be the dominant water level controller with magnitudes as high as several metres. Wind-stress induced storm surge setup is small because of the surrounding deep ocean environment, but potentially more significant in some parts of shallow lagoons.

Because of the complex non-linear interactions of storm surge, tide and breaking wave setup, a statistical simulation methodology is again necessary and a combination of parametric surge, wave and wave setup models have been used successfully within a Monte Carlo driven TC climatology. The method has been validated against historical events and delivers sequences of time-varying water level components that would be generated during a severe TC event, with breaking wave setup on the outer reef flats and local wind stress influencing the shallow lagoon regions. Both these effects are critically modulated in a non-linear fashion by the stage of the tide.

5 Storm tide warning systems

One of the aims of the Queensland Climate Change 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. The proposed "hybrid" approach, a combination of detailed deterministic hydrodynamic modelling and derived parametric models, satisfies these criteria by providing a self-consistent framework for long-term climatology modelling and short-term warning needs. This method differs from the static Maximum Envelope of Waters (MEOW) approach in that it provides a rapid response tool that can incorporate tidal variation and storm parameter uncertainty.

Based on these recommendations, the Bureau of Meteorology (BoM) in Queensland subsequently 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. 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 TC forecast centres around the world that do not have aerial reconnaissance capability, where the Dvorak satellite image interpretation method (Harper 2004a) is the primary intensity forecast tool. Even with the rapid development of advanced atmospheric models this situation is unlikely to change significantly within the next few decades.

The Northern Territory BoM 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 7 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. Approximately, 25,000 individual TCs were modelled as part of this development and storm tide predictions are available for over 1,000 named localities. However, the resulting parametric prediction model SEAtide can generate around 100 probabilistic storm tide forecasts within 1 min on a typical desktop computer. A snapshot of its operation is given in Fig. 8 for the Townsville regionm, where the Local Government Authorities commissioned a similar system as part of the SEA-GHD storm tide risk assessment and planning study.

6 Accuracy of historical tropical cyclone datasets

In parallel with the significant storm tide modelling efforts in Australia 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,

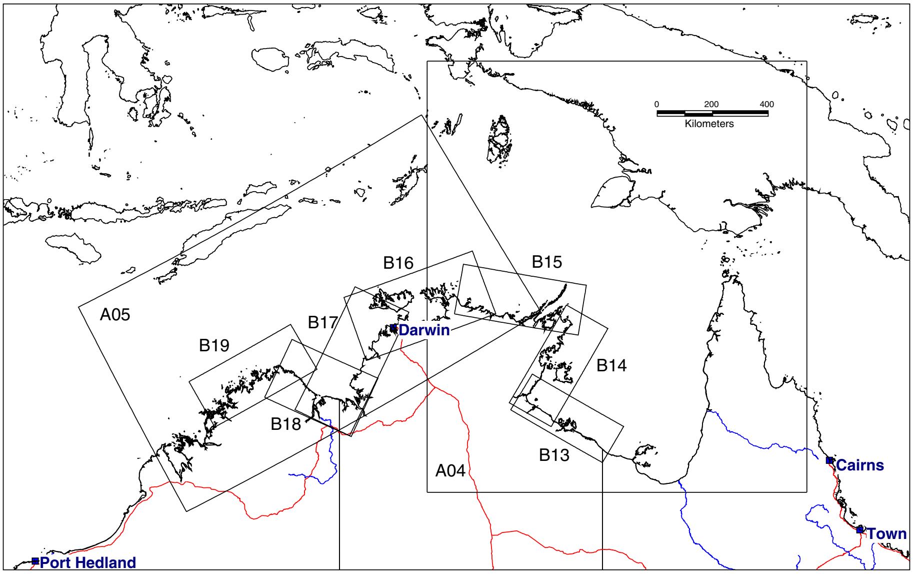
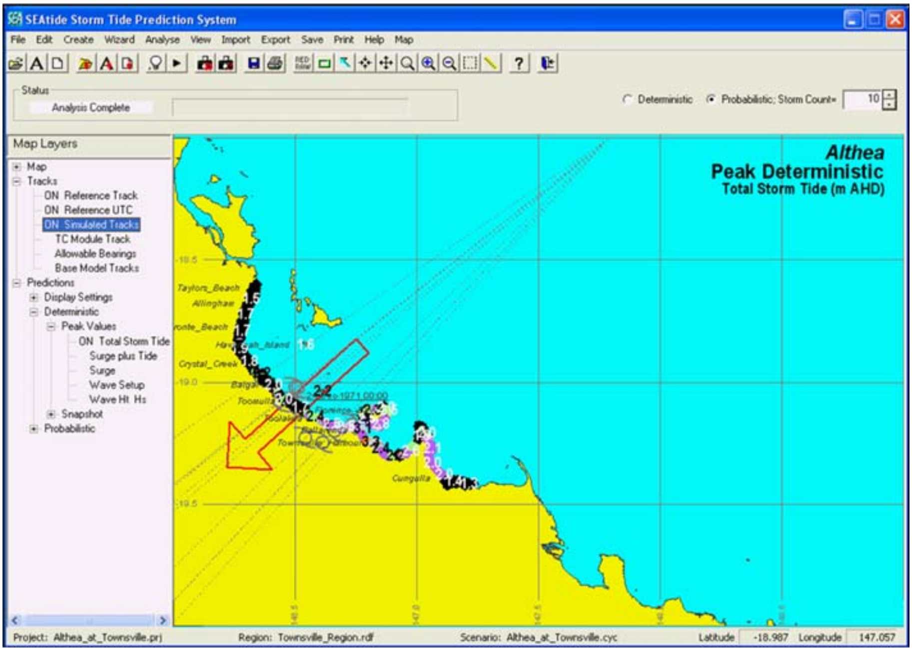


Fig. 7 Extent of the Northern Territory storm tide warning modelling system



Analysis Complete

○ Deterministic ● Probabilistic; Storm Count= 10

Project: Althea_at_Townsville.prj Region: Townsville_Region.rdf Scenario: Althea_at_Townsville.cyc Latitude -18.987 Longitude 147.057

Fig. 8 Example SEAtide prediction model interface for the Townsville–Thuringowa region in North Queensland

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. Without a mandated central coordinating authority, original global datasets have remained largely unadjusted, except for example, occasional typographical corrections and consistency checks.

The US-NOAA reanalysis project is the only known example of a thorough organizational review of the original meteorology. One reason for this situation is that there has been little imperative on behalf of most agencies originally contributing to the best track datasets to undertake reviews of their historical data while these techniques have advanced. Likewise, researchers 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 industry and BoM-backed program of review was initiated in 2001/2002 (Harper 2002; Harper and Callaghan 2006; Harper et al. 2008) in an attempt to rectify the BoM best track intensities since 1968/1969. The result of that limited but consistent review, illustrated in Fig. 9, uncovered a very wide range of differences from the original BoM dataset, well into the 1990s. A clear bias of intensity underestimation of 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 Fig. 9 highlights the times when specific satellite and other technique improvements were

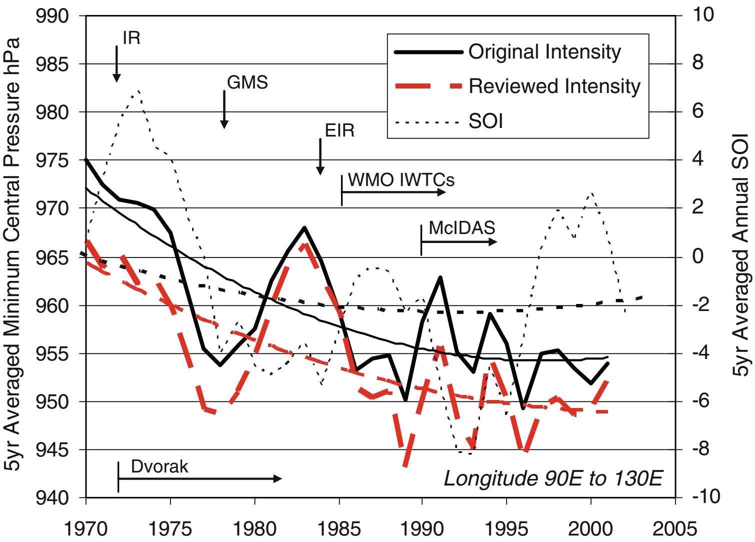


Fig. 9 Results of a recent review of historical tropical cyclone intensity in North Western Australia (after Harper and Callaghan 2006). The *light-dashed lines* are the SOI average plus quadratic trend. The *solid lines* are the original intensity data plus quadratic trend. The *heavy dashed lines* are the revised data and quadratic trend

introduced, as well as the Southern Oscillation Index (SOI) variability). Contrary to recent highly publicised claims regarding enhanced-greenhouse influences on global TC 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 (Landsea et al. 2006; Kossin et al. 2007). Notwithstanding this, there is a critical need for storm tide risk assessments to consider the potential influences of enhanced-greenhouse climate change (Harper 2004b).

7 Conclusions

Storm tide research and development in Australia has increased in the new millennium in response to increased availability of Government funding, much of which has been justified on the basis of concerns over enhanced-greenhouse climate change. A principal driver in updating the assessments that were originally completed in the 1980s has been the greater awareness of increasing community risks due to rapidly rising coastal populations along the tropical coastline. This renewed investment has enabled improvements to be made in the representation of the meteorological processes, the hydrodynamic modelling precision and the representation of the climatology of storms. This has provided a firm basis for realistically representing existing climate and provided a springboard for investigating potential enhanced-greenhouse impacts. Importantly though, fitness-for-purpose is an important aspect of the design of any storm tide risk assessment study, whereby the methodology must adequately address the relative levels of uncertainty in the many interconnected aspects of the phenomena.

Deterministic numerical hydrodynamic model precision alone is but one of many essential components of the problem and recalibration may be necessary following recent critical measurements (Powell et al. 2003). 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 concepts.

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