Queensland Government
Department of Natural Resources and Mines
Department of Emergency Services
Environmental Protection Agency

Queensland Climate Change and Community Vulnerability to Tropical Cyclones

OCEAN HAZARDS ASSESSMENT

Synthesis Report

August 2004

An Overview and Discussion of Results from Project Stages 2,3 and 4

SEA Systems Engineering Australia Pty Ltd
Numerical Modelling and Risk Assessment

Australian Government
Bureau of Meteorology

In association with:
JCU James Cook University
Marine Modelling Unit

Queensland Government

Department of Natural Resources and Mines
Department of Emergency Services
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Executive Summary

This *Synthesis Report* provides an overview and current summary of progress on the *Queensland Climate Change and Community Vulnerability to Tropical Cyclones* project. The project was instigated in 1999/2000 through the combined efforts of the Bureau of Meteorology in Queensland and the Queensland Departments of Emergency Services, Natural Resources and Mines and the Environmental Protection Agency. Financial support to date has been principally through the State *Greenhouse Special Treasury Initiative* (GSTI) but with increasing support from the Commonwealth/State *Natural Disasters Risk Management Studies Program* (NDRMSP).

The project has sought to assess:

the magnitude of the present and future *ocean* threat from tropical cyclones in Queensland, and

the *vulnerability* of coastal communities to extreme winds.

Part A of the project has updated and extended understanding of the threat of storm tide inundation in Queensland on a state-wide scale, including the effects of extreme wave conditions in selected areas, and estimates of potential enhanced Greenhouse climate impacts. Part A represents the first major update of State-wide storm tide hazard estimates since the mid-1980s and has proceeded within the context of a Stage A.1 technical blueprint setting out the essential methodologies and data requirements for a state-of-the-art assessment of the ocean hazards from tropical cyclones. Subsequent stages of the study have focused firstly on improving real-time forecasting capabilities for the Bureau of Meteorology and then on updating and extending present estimates of storm tide statistics for long-term planning and emergency response purposes and in developing near-shore extreme wave statistics for coastal management and design needs. Importantly, the potential impact of future climate change through the enhanced Greenhouse effect has also been able to be assessed within the full context of the naturally complex climatic variability of tropical cyclones. A number of the detailed recommendations from the Stage A.1 blueprint have been able to be addressed, at least in part, although all components of the work have been limited by the available funding.

The project has been able to progress mainly through the application of existing numerical and statistical models having the recommended capabilities. Compared with earlier studies, the Stage A.2 and A.3 results indicate a reduction of estimated *storm surge plus tide* levels for many parts of the Queensland coast, especially North Queensland. This is consistent with the expectations of undertaking numerical modelling to a higher resolution and accuracy than achieved previously. However, the more detailed Stage A.2 estimates for Hervey Bay and the Sunshine coast, which include allowance for *wave setup*, suggest that previously nominal allowances for this component may have been widely underestimated, thus increasing the potential impact on coastal erosion and the likelihood of inundation of some nearshore housing communities. The project has identified a critical need for further research into wave setup and that significant effort would be needed to explore this effect State-wide. The enhanced Greenhouse scenarios that have been adopted by the project are predicted to increase present climate storm tide levels by about 0.5 m on average (approximately a 19% increase), with a standard deviation of 0.13 m. The standard deviation indicates that there are regional variations and South East Queensland typically experiences higher than average predicted increases.

Within a limited budget, much progress has been made in advancing the knowledge of ocean hazards in Queensland caused by tropical cyclones, but much still remains to be done. Although sophisticated numerical and statistical models have been utilised, the data requirements are significant, much of the work is still highly labour intensive, attention to detail is critical and the coastline is extensive. The significant roadblocks to further quantification of the risks include: (i) the need to review and revise the historical database of tropical cyclone tracks, intensities and scale parameters; and (ii) obtaining high resolution land elevations to enable accurate overland flooding calculations. The project has also highlighted potential shortcomings in the present understanding of wave setup within complex topography and under extreme conditions that might only be addressed through long-term monitoring and targeted research. Finally, the relative contribution of non-cyclonic or more remote cyclonic events to medium-term return period water levels (e.g. up to 100 y) is yet to be investigated, but may be more significant than previously thought. If so, these effects may amplify enhanced Greenhouse MSL rise impacts much more than currently anticipated.

Under Part B of the project, an advanced numerical model of housing vulnerability under extreme winds has been developed for the Cairns, Townsville and Mackay regions. The model presently provides community-wide estimation of wind damage caused by specific cyclone scenarios and the results indicate that Cairns has a higher resilience against building damage than either of the other cities. This resilience is linked to the spatial distribution of housing age, style and the local topography. The model is also capable of being extended to other regions and enhanced to incorporate probabilistic aspects such as those resulting from the Part A outcomes. This would allow a rigorous assessment of (i) economic and societal impacts of climate change, (ii) highlight sensitivity to building styles and practices in different climatic regions, (iii) permit comparison of estimated community vulnerability with the target design resilience assumed by current building regulations, and (iv) assist in developing optimized building practices and effective long-term community insurance products. It is also identified that, in conjunction with the Part A outcomes, a similar approach could be developed to address vulnerability of housing to storm tide impacts. This issue, which is already comprehensively addressed in the USA, will increasingly be of concern for coastal communities and the tourism industry under the threat of possible sea level rise.

A number of individuals from government, consulting and academia have participated in this project over the past 4 years and their contributions are gratefully acknowledged in Appendix A.

1 Introduction

The *Queensland Climate Change and Community Vulnerability to Tropical Cyclones* project was instigated in 1999/2000 through the combined efforts of the Bureau of Meteorology in Queensland, and the Queensland Departments of Emergency Services, Natural Resources and Mines and the Environmental Protection Agency. Financial support from the State Greenhouse Special Treasury Initiative (GSTI) was used to establish the project, and to assess:

the magnitude of the present and future *ocean* threat from tropical cyclones in Queensland, and

the *vulnerability* of coastal communities to extreme winds.

The ocean hazards assessment project (Part A) was intended to update and extend the present understanding of the threat of storm tide inundation in Queensland on a state-wide scale, including the effects of extreme wave conditions in selected areas, and estimates of potential enhanced Greenhouse climate impacts. Later phases of this project (refer Table 1.1) received additional funding through the Commonwealth/State *Natural Disasters Risk Management Studies Program* (NDRMSP). Although technically outside of the present project, a fully NDRMSP-funded extension to consider the whole of the Gulf of Carpentaria, also involving the Northern Territory Department of Infrastructure Planning and Environment, is mentioned here for completeness.

Part A of the project represents the first major update of State-wide storm tide hazard estimates since the early numerical model development and deterministic studies done in the late 1970s sponsored by the Queensland Beach Protection Authority (Sobey *et al.* 1977, Harper 1977) and the subsequent statistical modelling in the 1980s (Harper and McMonagle 1985, Harper 1985). As highlighted by Harper (1999a), there remained compelling reasons for a re-working of these estimates to take advantage of improved modelling capabilities, increased computational resources, longer data series and to provide essential coverage of the many parts of the Queensland coast that had witnessed significant development and population increases since the 1980s. In addition, the potential for climate change as a result of enhanced Greenhouse conditions added a further significant uncertainty that had never previously been considered. Part A has provided a technical blueprint for the overall study, provided updated storm tide estimates for over 50 east coast sites and assisted the Bureau of Meteorology in developing an improved storm tide forecasting system.

The coastal community vulnerability study (Part B) built on earlier funding through the Tropical Cyclone Coastal Impacts Project (TCCIP) in 1998/99, which had resulted in establishing databases of representative housing characteristics for Cairns, Townsville and Mackay. These data were combined with the knowledge base of the James Cook University Cyclone Testing Station (CTS) in Townsville, which has been actively involved in the design, testing and performance of housing to resist cyclonic winds for over 30 years (e.g. Reardon *et al.* 1981, 1986, 1996, 1998; Henderson *et al.* 1999, 2003). Part B of the project represents possibly the most significant advance in knowledge of domestic housing resistance to strong winds since the late-1970s, following the devastating impacts of cyclones *Althea* and *Tracy* (e.g. JCU 1972; Leicester *et al.* 1975, 1976, 1978; Walker 1975). Part B has resulted in the formulation of various housing damage models applicable to a range of identified Queensland construction classes. In association with Systems Engineering Australia Pty Ltd, these damage models have been imbedded into an existing deterministic wind field model of tropical cyclones, allowing estimation of community-wide damage for specific scenarios. Future developments are expected to (i) extend the model to include additional communities and (ii) enhance the model capabilities to include probabilistic estimates and test regional sensitivity to climate change scenarios.

Parts A and B of the project have progressed essentially in parallel. This overview report aims to provide a summary of the various project components to date, both past and ongoing, their inter-relationships, outcomes and recommendations.

Table 1.1 Summary of project activities.

Stage	Timeline	Activity Title	Funding	Principal Consultant / Developer
A.1(a)	May 2000 to March 2001	Review of Project Technical Requirements	GSTI[1]	Systems Engineering Australia Pty Ltd
A.1(b)		Establishment of a Storm Surge Modelling System	GSTI	Systems Engineering Australia Pty Ltd
A.1(c)	April 2001 to March 2002	Development of Parametric Storm Surge Modelling Capabilities	GSTI	Systems Engineering Australia Pty Ltd
A.1(d)	April 2002 to June 2004	Production Storm Surge Modelling and Implementation of a Parametric Storm Tide Prediction System	GSTI BoM[2]	Bureau of Meteorology - Queensland
A.2	May 2002 to June 2004	Water Levels and Waves: Hervey Bay and Sunshine Coast plus Web-Based Data Centre	GSTI 33% NDRMSP[3] 67%	James Cook University Marine Modelling Unit / Systems Engineering Australia Pty Ltd
A.3	May 2003 to June 2004	Frequency of Surge plus Tide for Selected Open Coast Locations along the Queensland East Coast	GSTI	James Cook University Marine Modelling Unit
A.4	2004	Tropical Cyclone Surge and Wave Impacts: Gulf of Carpentaria	NDRMSP	N/A
B.1	1999 to 2002	Tropical Cyclone Impact on Coastal Communities' Vulnerability: Housing Damage Model Development	GSTI	James Cook University Cyclone Testing Station
B.2	2003	Tropical Cyclone Impact on Coastal Communities' Vulnerability: Housing Wind Risk Assessment Model Development	GSTI	James Cook University Cyclone Testing Station / Systems Engineering Australia Pty Ltd

Although the project was largely funded by GSTI and NDRMSP, significant financial support was also provided by the Australian Bureau of Meteorology, the Environmental Protection Agency and the Queensland Department of Emergency Services.

[1] Queensland State Government Greenhouse Special Treasury Initiative (GSTI).
[2] Australian Bureau of Meteorology.
[3] Commonwealth/State Natural Disasters Risk Management Studies Program (NDRMSP).

2 An Overview of Tropical Cyclone Hazards

Following Harper (2001), Figure 2.1 provides a schematic overview of the inter-relationships between the tropical cyclone hazard and its impacts, firstly in terms of directly-induced hazards on the land and in the ocean environment and secondly in terms of indirect impacts on community, infrastructure and the environment. The knowledge elements required for assessment of this hazard include:

- *Tropical Cyclone Climatology*
  Essential knowledge of the incidence and behaviour of tropical cyclones affecting the Queensland region, which is intrinsically related to climatic variability and possible climate change.
- *Tropical Cyclone Forcing*
  The ability to estimate the impacts on the land and in the ocean environment, including extreme winds, waves, currents and storm surge.
- *Tropical Cyclone Storm Tide*
  The ability to predict the combined impacts of wave, current and storm surge together with the natural tide variability along the coastline and develop long-term probability descriptions of the threat.
- *Vulnerability*
  Essential knowledge of community, infrastructure and environmental vulnerability to the wind and ocean hazards and the ability to address avoidance and mitigation options.

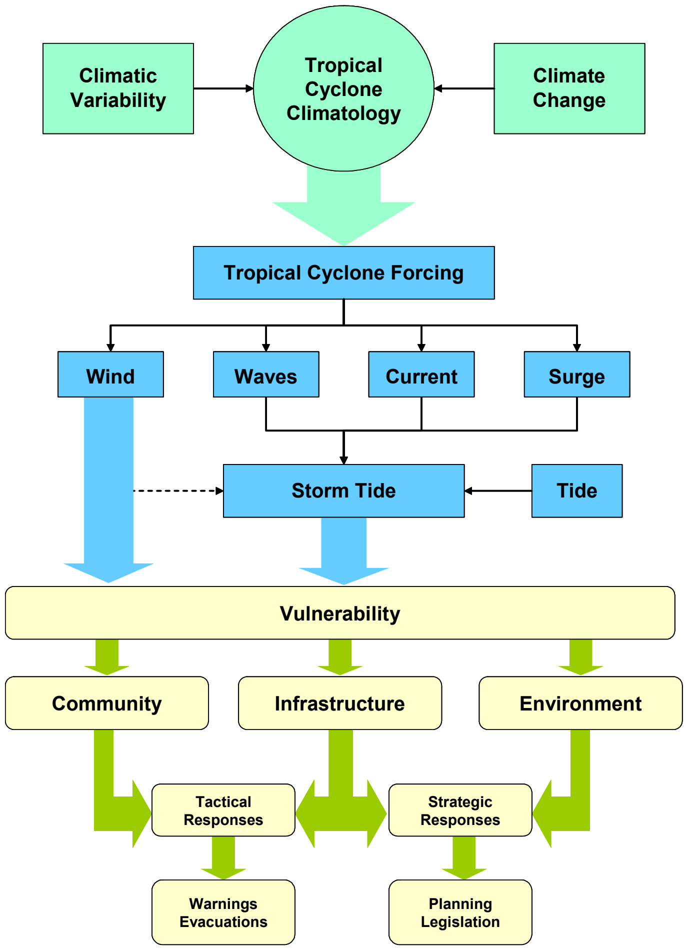

Figure 2.1 The tropical cyclone hazard assessment process.

2.1 Tropical Cyclones

Tropical cyclones are large scale and potentially very severe low pressure weather systems that affect the Queensland region typically between November and April, with an average incidence of around 5 storms per year since the 1960s.

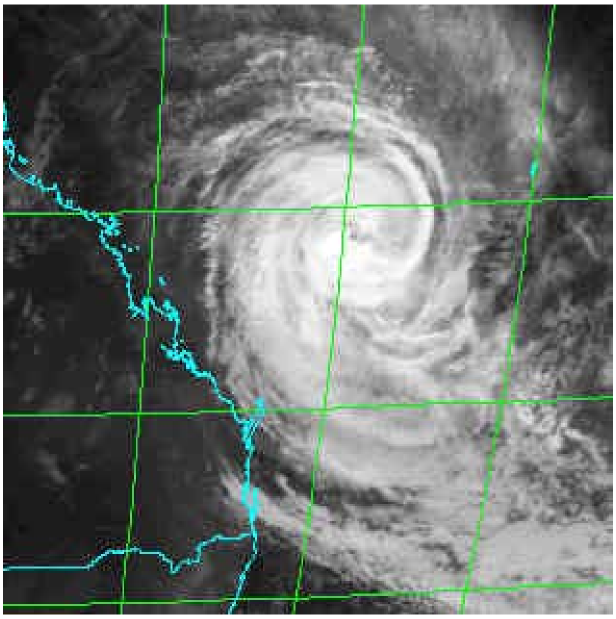

Figure 2.2 Tropical cyclone *Fran* approaching the Queensland coast in March 1992.

There are three components of a tropical cyclone that combine to make up the total cyclone hazard - strong winds, intense rainfall and induced ocean effects including extreme waves, currents, storm surge and resulting storm tide. The main structural features of a severe tropical cyclone at the earth's surface are the eye, the eye wall and the spiral rainbands (refer satellite image in Figure 2.2). The eye is the area at the centre of the cyclone at which the surface atmospheric pressure is lowest. It is typically 20 to 50 km in diameter, skies are often clear and winds are light. The eye wall is an area of cumulonimbus clouds, which swirls around the eye. The rain bands spiral inwards towards the eye and can extend over 1000 km or more in diameter. The heaviest rainfall and the strongest winds, however, are usually associated with the eye wall. Given specifically favourable conditions, tropical cyclones can continue to intensify until they are efficiently utilising all of the available energy from the immediate atmospheric and oceanic sources. Thankfully, it is rare for any cyclone to reach its maximum potential intensity because environmental conditions often act to limit this in the Queensland region.

2.2 Extreme Winds

The destructive force of cyclones over land is usually expressed in terms of the strongest wind gusts experienced. Maximum wind gust is related to the central pressure and structure of the storm system, combined with local terrain and topography effects, while extreme waves and storm surge are linked more closely to the combination of the mean surface winds over the sea, central pressure and regional bathymetry. The Bureau of Meteorology (BoM 1999) uses the five-category system shown in Table 2.1 for classifying tropical cyclone intensity in Australia where s*evere* cyclones are those rated at Category 3 and above. The destructive wind *gusts* are often 50 per cent or more higher than the *mean* winds.

For any given intensity, the spatial size of individual tropical cyclones can vary enormously. Generally, smaller cyclones occur at lower latitudes (nearer the equator) and larger cyclones at higher latitudes but there are many exceptions. Size is typically described by the radius to the maximum winds or the radius to gales. Cyclonic winds circulate clockwise in the Southern Hemisphere. The wind field within a moving cyclone, however, is generally asymmetric so that, in the Southern Hemisphere, winds are typically stronger to the left of the direction of motion of the system (the 'track'). This is because on the left-hand side the direction of cyclone movement and circulation tends to act together; on the right-hand side, they are opposed. During a coast crossing in the Southern Hemisphere, the cyclonic wind direction is onshore to the left of the eye (seen from the cyclone) and offshore to the right. Figure 2.3 presents a modelled wind field of the category 3 Cyclone *Althea* approaching Townsville in 1971, showing the wind field asymmetry and the Radius to Maximum Winds.

Table 2.1 Australian tropical cyclone category scale.

Cyclone Category	Maximum Wind Gust		Potential Damage
	$m\ s^{-1}$	$km\ h^{-1}$	
1	<35	<125	minor
2	35-47	125-170	moderate
3	47-63	170-225	major
4	63-78	225-280	devastating
5	>78	>280	extreme

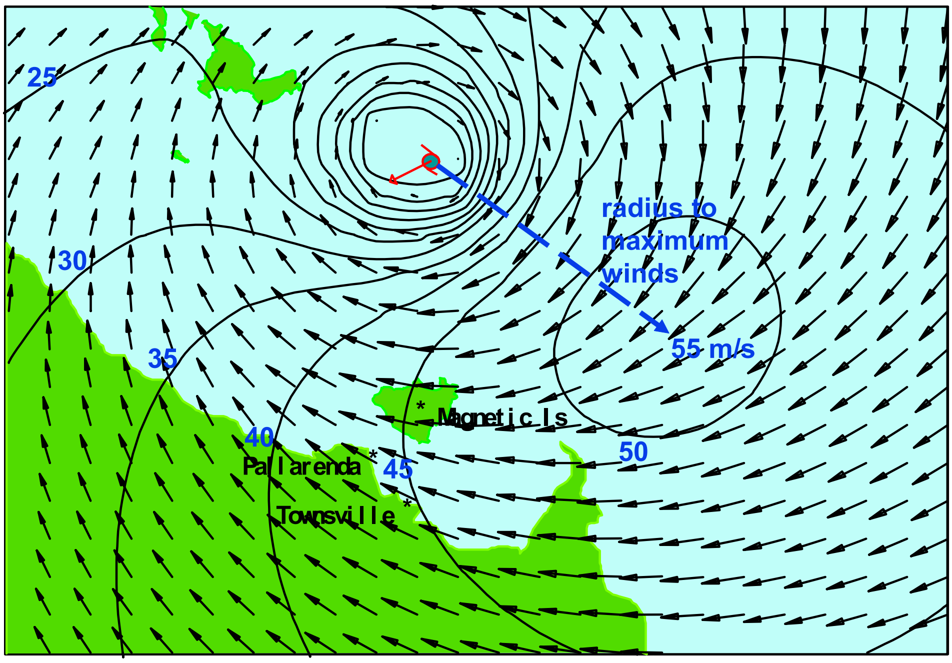

Figure 2.3 The modelled wind field of Cyclone *Althea. (after Harper 1999b)*

2.3 Extreme Waves

Ocean waves are generated as a result of the transfer of energy from the wind to the sea, causing complex seastates, which subsequently impact the coastline. In the nearshore environment, the local coastal topography limits the available *fetch* (or distance acted on by the wind) to generate waves from various directions. For many parts of the eastern coast of Queensland north of Mackay, wave growth is essentially limited by the presence of the Great Barrier Reef, various island chains and large sand shoals. South from Mackay the influence of the reef decreases as the available fetch increases. In the Gulf of Carpentaria, the region is essentially land-bounded but the available fetch under tropical cyclone conditions can be quite large and extreme waves can result.

As waves enter increasingly shallow water they will eventually reach a point of gravitational instability and wave breaking will occur. However, some of the wave energy is transferred into forward momentum within the surf zone and this can result in an increase of the local beach water level above the still water level that would otherwise occur in the absence of any waves. This phenomenon is termed *wave setup* and affects any beach subject to wave breaking.

In addition to wave setup, any residual kinetic energy of waves will result in a vertical *runup* of the upper beach face. This allows some wave energy to attack at higher levels than just implied through the setup level alone. Since setup and runup are essentially part of the same energy dissipation process, it follows that their influences are typically complementary. For example, very flat beaches will experience the majority of the energy dissipation as *setup* while very steep beaches experience higher levels of *runup*. The absolute vertical level of runup though will typically exceed that of setup and allow erosion of the upper beach or possible dune overtopping to occur. The time for which the sensitive portion of the beach is exposed to severe runup is therefore critical in determining the degree of damage that might result.

2.4 Storm Surge

All tropical cyclones on or near the coast are capable of producing a *storm surge*, which can increase coastal water levels for periods of several hours and significantly affect over 100 km of coastline. An individual storm surge is measured relative to the tide level at the time and is caused by the combined action of the severe surface winds circulating around the storm centre, which generates ocean currents, and the decreased atmospheric pressure, causing a local rise in sea level. When a severe tropical cyclone crosses the coast, the strong currents impinging against the land are normally responsible for the greater proportion of the surge, while complex coastal bathymetry can significantly interact with the storm surge, affecting both its generation and propagation in a region. The storm surge arrives as a prolonged and generally gradual increase in coastal water levels, followed by a similar decline after the event has passed. The region of peak and potentially destructive surge levels is associated with the region of maximum wind speeds of the tropical cyclone, which is of the order of 50 to 100 km in diameter.

Flat, shallow continental shelf regions are much more effective in assisting the generation of large storm surges than are narrow, steep shelf regions. Storm surge magnitude can often be regarded as directly proportional to the cyclone intensity for a given coastal site, over the range of intensities likely to be experienced at that site. It can also be highly site specific due to local factors.

2.5 Storm Tide

When the *storm surge* is combined with the normal *astronomical tide* variation and the *wave setup* contribution at the coast, the absolute combined *mean water level (MWL)* reached is called the *storm tide* level. Because it includes the tide, the *storm tide* level can be referenced to a specific ground contour and is given as an absolute level such as *Australian Height Datum (AHD)*. It is the *storm tide* level which must be accurately predicted and conveyed to emergency managers to enable timely evacuation of low lying areas prior to storm landfall. Loss of life through drowning is the principal community threat caused by the extreme storm tide.

Figure 2.4 summarises the various components which work together to produce an extreme storm tide. Firstly, the *storm surge*, mainly caused by the interaction of the extreme wind-driven currents and the coastline, raises coastal water levels above the normally expected tide at the time - producing the so-called *stillwater level (SWL)*. Meanwhile, extreme wind-generated ocean waves, which are combinations of swell and local sea, are also driven before the strong winds upon the raised *SWL*. As part of the process of wave breaking, a portion of the wave energy is transferred to vertical *wave setup*, yielding a slightly higher *mean water level (MWL)*. Additionally, individual waves will *run-up* sloping beaches to finally expend their forward energy and, when combined with the elevated *SWL*, this allows waves to attack foredunes or nearshore structures, causing considerable erosion or destruction of property.

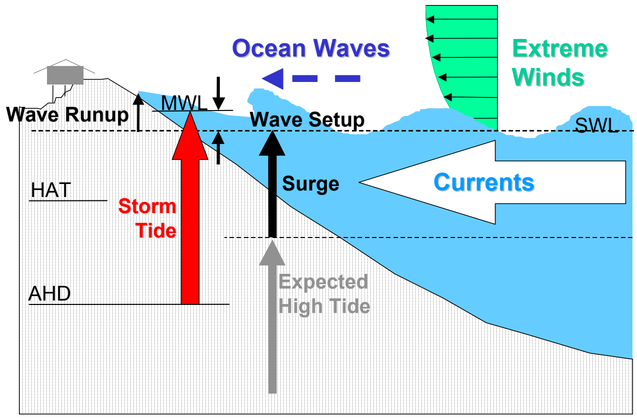

Figure 2.4 Water level components of a storm tide.

The principal role of the astronomical tide is then in providing a background modulation in coastal water levels. The relative phasing of the arrival of the storm surge and associated wave setup relative to the tide determines the actual variation in storm tide levels, as illustrated in Figure 2.5. The example shown is similar to the storm tide response during cyclone *Althea* in Townsville in 1971, where the peak surge arrived fortunately close to the time of low tide (Harper *et al.* 2002).

The first critical phase of a storm tide is when the MWL commences to exceed the local *Highest Astronomical Tide (HAT)*, which represents the normal landward extent of the sea at any coastal location. By this time, depending on the coastal features, it is likely that extensive beach and dune erosion will have occurred due to wave runup effects alone. If the water level rises further, inundation of normally dry land will commence and the storm tide will be capable of causing loss of life through drowning and significant destruction of nearshore buildings and facilities if large ocean swell penetrate the foreshore regions.

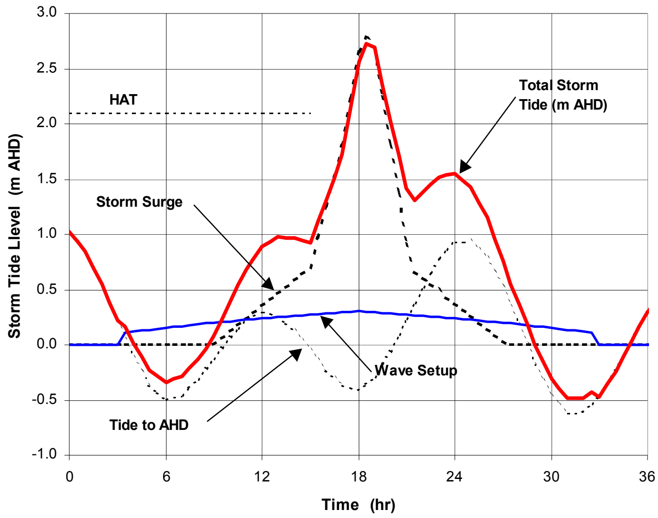

Figure 2.5 Combined effect of tide, storm surge and wave setup phasing on storm tide level.

3 Specific Project Aims, Activities and Outcomes

3.1 Stage A.1(a) - Review of Project Technical Requirements

Stage A.1 of the project was awarded on the basis of competitive tender and carried out by Systems Engineering Australia Pty Ltd (SEA) in association with the James Cook University Marine Modelling unit (MMU) within the School of Engineering. Additional external specialists from the University of Queensland and the University of Adelaide were also sub-contracted by SEA (refer Appendix A). The work items specifically identified by the Project Management Committee under Stage A.1(a) were:

- An assessment of enhanced Greenhouse climate change and sea level rise;
- A review of the technical requirements for the numerical modelling of cyclone storm surge;
- A review of the technical requirements for the numerical modelling of cyclone wind waves;
- The conceptual design of a software system/database for the prediction of storm tide levels based on the *Maximum Envelope of Waters* (MEOW) technique;
- A review of the technical requirements for an operational forecast system;
- Consideration of how to disseminate information on ocean hazards.

The outcome from this phase of work was a comprehensive 380 page technical report (Harper 2001) which provided:

- An introduction and overview of the concepts and definitions relevant to the assessment of ocean hazards from tropical cyclones in Queensland within the context of both existing climate and the potential for enhanced Greenhouse climate change;
- A summary of the known climatology of tropical cyclones and inter-seasonal factors such as ENSO (El Niño Southern Oscillation), as well as addressing issues of data quality and applicability for ocean hazard assessment (e.g. Figure 3.1);
- An assessment of the current state of knowledge of enhanced Greenhouse climate change and sea level rise with special consideration of the *Maximum Potential Intensities* (MPIs) of tropical cyclones;
- An overview of the development and current science of analytical models of the tropical cyclone wind and pressure field environment relevant to the generation of cyclone storm surge and extreme waves;
- A comprehensive technical review of the state-of-the-art of numerical hydrodynamic modelling of tropical cyclone storm surge;
- Design and provision of four large-scale (*A*) numerical storm surge computational domains and 12 finer scale (*B*) domains covering the entire Queensland coast (Figure 3.2);
- An extensive investigation into the meteorology and ocean response of a number of significant historical tropical cyclone events in Queensland, proving the capabilities of the proposed modelling systems (*Althea:* Figure 3.3, Figure 3.4; *Ted:* Figure 3.5);
- An overview of techniques for developing storm tide statistics and the various advantages and disadvantages of a number of methods;
- A comprehensive overview of the status of numerical modelling of tropical cyclone wind waves;
- An introduction to the physics of nearshore wave behaviour in respect of wave setup and runup characteristics;
- Consideration of system design issues in regard to the need to provide both a storm tide warning capability and to create long-term planning tools, including an assessment of present US practice;

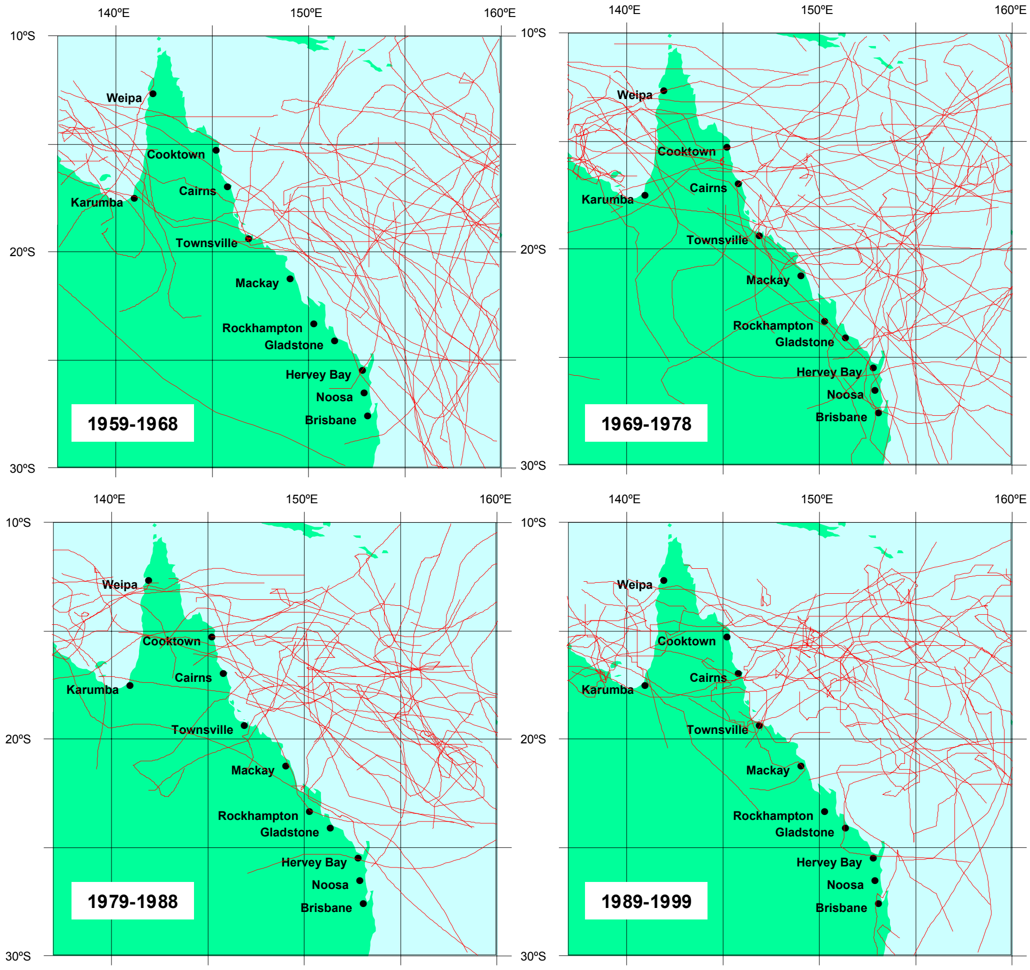

Figure 3.1 Decadal tropical cyclone track variability post-1959.

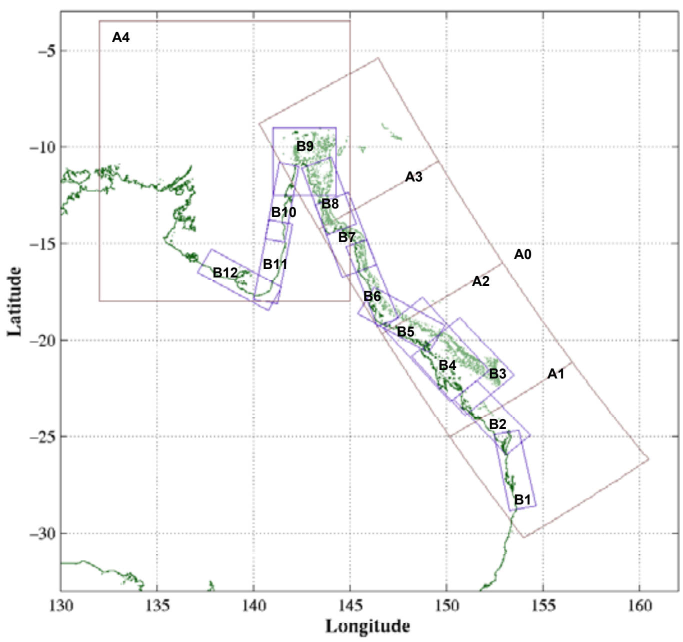

Figure 3.2 Storm surge model A and B domains designed for the Queensland coast.

- Identification of the wide range of potential stakeholders that need knowledge of storm tide hazards and a range of potential information products that could be targeted towards different types of community needs.

A total of 10 detailed recommendations were offered by the Stage A.1(a) review:

1. A comprehensive climatology study be undertaken to provide a statistical description of tropical cyclone variability across Queensland, including synoptic scale interactions, decay after landfall, re-curvature and re-generation issues. The climatology would underpin studies for long-term estimates of storm tide, other community impacts and also to provide guidance for real-time forecasting;

2. The assessment of long-term storm tide risks should include allowance for the current estimates of enhanced Greenhouse sea level rise, a 10% to 20% potential increase in the MPI of tropical cyclones and a 10% increase in frequency of occurrence;

3. Further sensitivity testing of the impact of the latest tropical cyclone boundary layer research be undertaken by selective hindcasting and comparison with existing Australian wind data before committing to an extensive storm tide modelling project;

4. Improved land elevation and tidal data be obtained to allow the MMU numerical storm surge model to be further calibrated for estimating inundation effects in the high-risk Gulf of Carpentaria region;

5. The *Monte Carlo Method* be adopted as the most suitable technique for establishing storm tide statistics, assuming a parametric storm tide model is developed;

6. A 3rd generation spectral wave model be adopted for numerical modelling of tropical cyclone generated wind waves in support of coastal storm tide prediction and planning requirements, and to be conducted in parallel with storm surge modelling, utilising the same model domains and resolutions where possible and that nearshore extreme wave estimates be included in any statistical estimates of coastal storm tide;

7. Analytical wave setup methods be used for the estimation of breaking wave setup using nearshore spectral wave model output parameters obtained from fine scale resolution grids (500m) and that further research be initiated into the nearshore physics of extreme inundation episodes so as to provide better guidance for the likely significant community impacts;

8. The optimum long-term storm tide forecast and warning systems should be based on real-time application of numerical storm surge and spectral wave models integrated into Bureau of Meteorology forecasting systems but that shorter-term use of parametric models would provide much enhanced capabilities and the same parametric models could be applied in storm tide statistics analyses (refer Figure 3.6: Step 1 *planning*, Step 2 *forecasting*);

9. A detailed storm tide forecast system design specification be prepared that would preserve tidal phase and surge relationships, include extreme waves and wave setup, incorporate probabilistic parameter estimates and allow a selection of data source modules (i.e. parametric or real-time);

10. Ocean hazard information products be jointly developed and designed by physical and social scientists, and cover a variety of media and formats targeted to a range of important government, industry, occupational, educational and public sector groups.

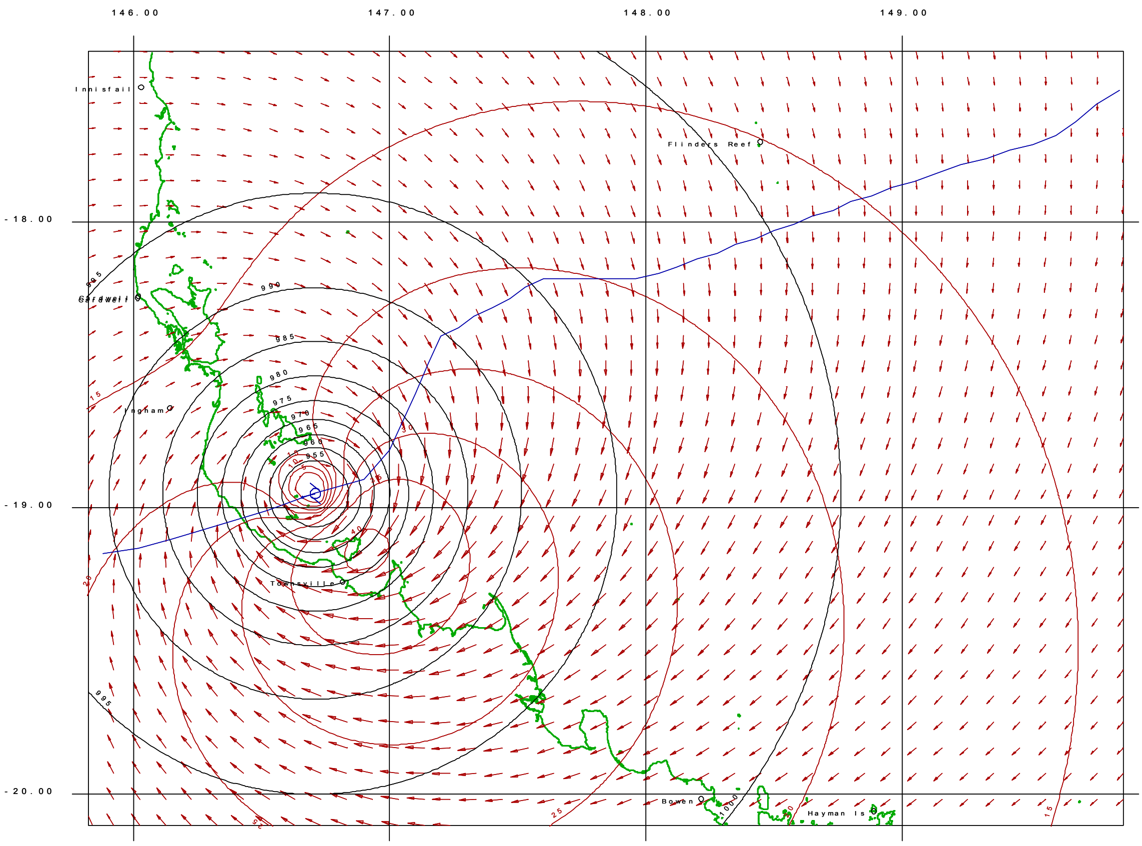

Figure 3.3 Reconstructed cyclone track and wind and pressure fields near landfall for *Althea.*

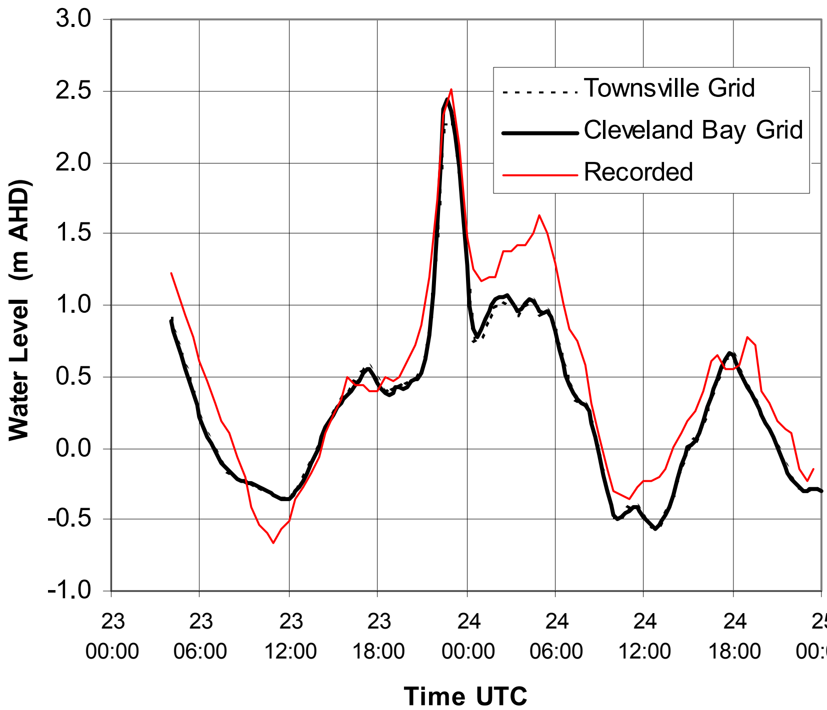

Figure 3.4 Measured and modelled storm tide at Townsville Harbour during *Althea*.

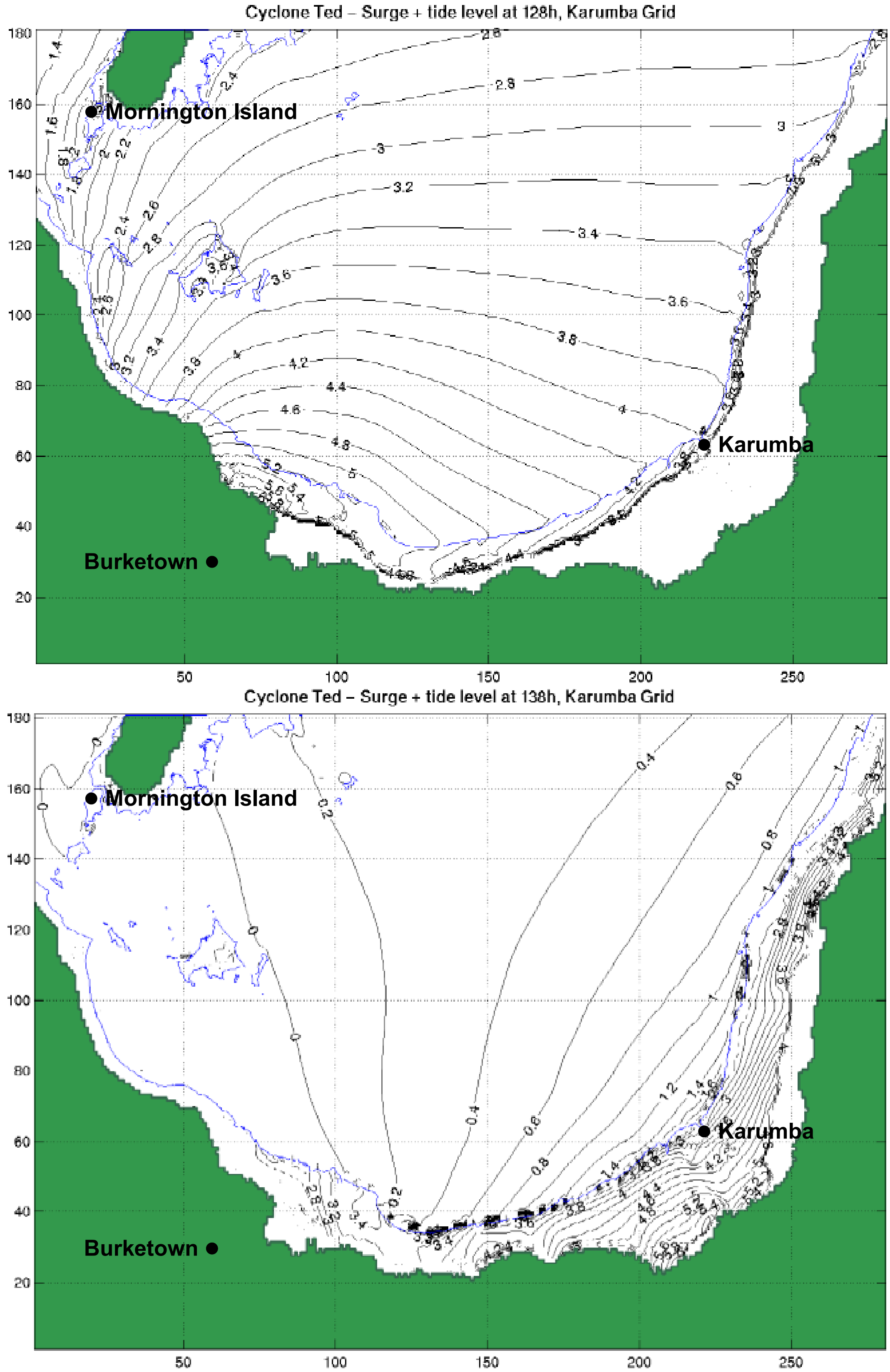

Figure 3.5 Example of modelling of overland flooding for Cyclone *Ted*.

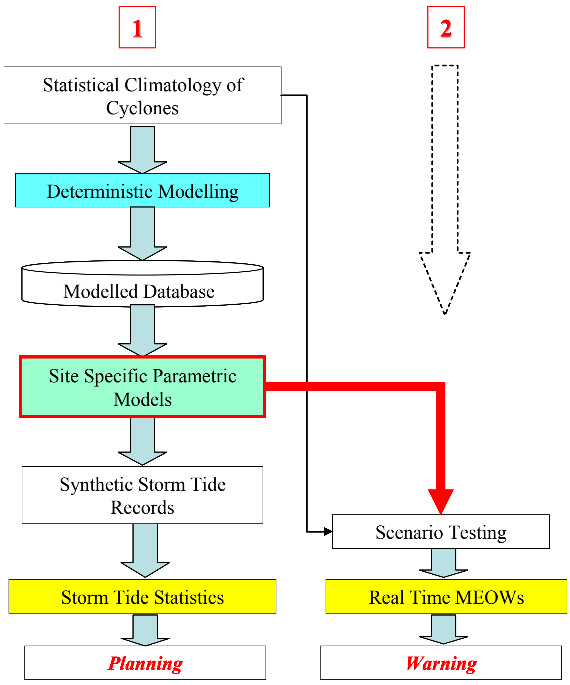

Figure 3.6 Suggested hybrid approach to the storm tide prediction problem.

3.2 *Stage A.1(b) - Establishment of a Storm Surge Modelling System*

This phase of the Stage A.1 work required establishing the MMU storm surge modelling system on the Bureau of Meteorology computer system at the Queensland Regional Office and the design of a suitable database structure. The numerical model MMUSURGE is the result of 30 years of development of storm surge modelling capabilities at the School of Engineering of James Cook University in Townsville, which was prompted by the experiences from Cyclone *Althea* in 1971 (Sobey *et al.* 1977). Under the terms of the Stage A.1 contract, the MMUSURGE model was made available free of charges to the Bureau for public interest studies. Other project participants may also access the model by arrangement.

The outcome of this work was the installation and testing of the MMUSURGE model by SEA in the Bureau Brisbane office, the assembling of the associated comprehensive numerical model grids developed for the Queensland coast under Stage A.1 and basic training of Bureau personnel. A user guide was also provided for future Bureau use (Mason and McConochie 2001) that provided a basic real-time storm surge modelling capability.

3.3 *Stage A.1(c) - Development of Parametric Storm Surge Modelling Capabilities*

This phase of work followed acceptance of recommendation #8 from Stage A.1(a), whereby the development and use of parametric storm tide models was seen as a highly desirable capability for enhancing storm tide forecasting within the Queensland Regional Office of the Bureau of Meteorology.

The specification and development of the necessary in-house Bureau software systems was awarded to SEA, working directly with Bureau staff and systems. The work involved capacity building of Bureau systems to provide the necessary system tools for the analysis of the MMUSURGE model output, specification of the analyses leading to parametric representations of storm surge, design of data handling and processing requirements and a preliminary climatological analysis. Coding of the analysis procedures was undertaken by Bureau staff. No wave or wave setup modelling was undertaken within this scope.

The outcome of the Stage A.1(c) work was an automated system for the large-scale production of MMUSURGE storm surge scenarios for the entire Queensland coast and a post-analysis system that efficiently processed the model data into parametric descriptions. A series of finer scale C grids were also defined to ensure that the modelled boundary values would be retained for possible future analyses. The work done was documented as SEA (2001), which details the modelling systems, procedures and the climatological assessment used to specify the range of tropical cyclone parameters to be modelled. Figure 3.7 is an example of the automatic track generation facility developed and the identification of all coastal settlements that was undertaken.

Figure 3.7 Example generated storm tracks for Townsville from Stage A.1(c).

3.4 Stage A.1(d) – Production Storm Surge Modelling and Implementation of a Parametric Storm Tide Prediction System

This phase of work was a continuation of Stage A.1(c), whereby the significant MMUSURGE numerical modelling effort that was required to build regional storm surge parametric models and provide coverage of the entire Queensland coast, was to be undertaken by the Bureau using in-house staff and resources. This work is currently well-advanced and expected to be fully completed by end 2004, providing a parametric coast-crossing storm surge prediction capability for the entire coast. The less severe case of near-parallel coastal cyclones has yet to be considered.

Additional work to extend the storm surge capability to a full storm tide forecast system (i.e. towards Stage A.1(a) recommendation #9) requires incorporation of regional tidal effects and possibly allowance for cyclone forecast error. This work is expected to be completed prior to the 2004/2005 cyclone season but without the capability to predict wave setup effects.

Figure 3.8 illustrates the conceptual basis of a parametric storm surge model, which uses simplified cyclone descriptors to generate a series of MMUSURGE predictions that are then transformed and condensed into a storm-relative response function to enable rapid scenario testing.

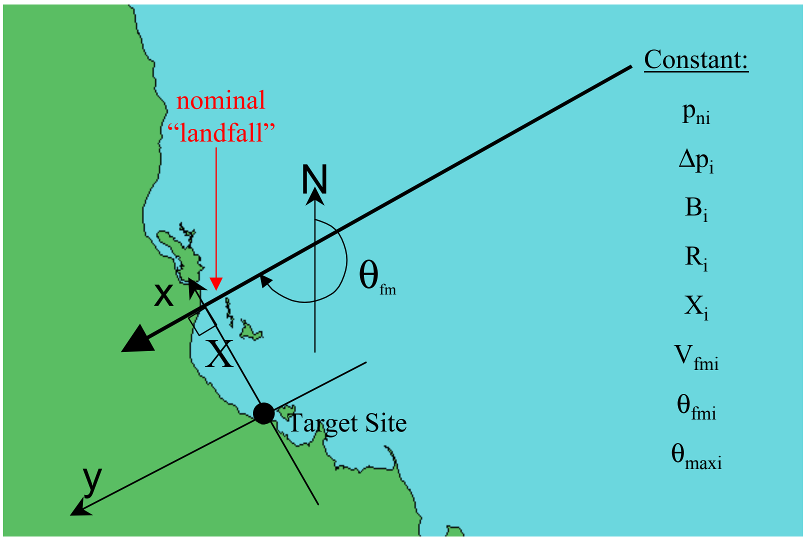

Figure 3.8 Parametric storm surge model track definitions.

3.5 Stage A.2 - Water Levels and Waves : Hervey Bay and Sunshine Coast

This stage of work was designed as a *test case* targeted at addressing and progressing aspects of Stage A.1(a) recommendations #1, 2, 5, 6 and 7 but limited to two selected coastal regions of interest. The work was awarded to the James Cook University Marine Modelling Unit as principal contractor with SEA sub-contracted to develop a parametric wave model for comparison purposes. The goal was to produce return period curves for *storm tide* (storm surge plus wave setup plus astronomical tide) and for *significant wave height* for return periods between 10 and 1000 years. In addition to the continued use of the MMUSURGE numerical storm surge model, the spectral wave model WAMGBR (e.g. Hardy *et al.* 2000) was also adopted. The Stage A.2 study is described in detail in Hardy *et al.* (2004a) and the results are additionally summarised on a web-based data archive and presentation system.

As a result of discussions between MMU and the Project Management Team during 2002, a deviation from the originally recommended Stage A.1(a) modelling philosophy for *planning* purposes (Figure 3.6, step 1) was agreed. This was based on replacing the use of parametric models of surge and waves with full primitive equation models but necessarily limiting the number of actual storms being considered. The rationale for this change was that recent increases in computing capacity available to MMU had enabled more efficient primitive equation modelling. It was then judged preferable, in the storm tide statistics context, to adopt a rationally selected subset of storms for direct detailed modelling rather than develop potentially less accurate parametric models based on the primitive equation models. The adopted methodology is summarised in Figure 3.9, which can be seen to differ from the original approach through the omission of the *parametric model* step, basically representing a change from the *Monte Carlo Method* (MCM) to the *Empirical Simulation Technique* (EST) (refer Stage A.1(a) report by Harper *et al.* 2001). It was noted that the Bureau of Meteorology was independently developing storm surge parametric models to enable an efficient *forecasting* system for the whole Queensland coast. The MMU scope however retained a sub-contracted activity for SEA to develop parametric wave models for Hervey Bay and the Sunshine Coast as a demonstration of the ability to include wave setup capabilities in future Bureau forecast systems. Although full primitive equation models for storm surge and waves were used, each water level component was independently simulated and then linearly superimposed on a sampled astronomical tide to obtain the combined storm tide level.

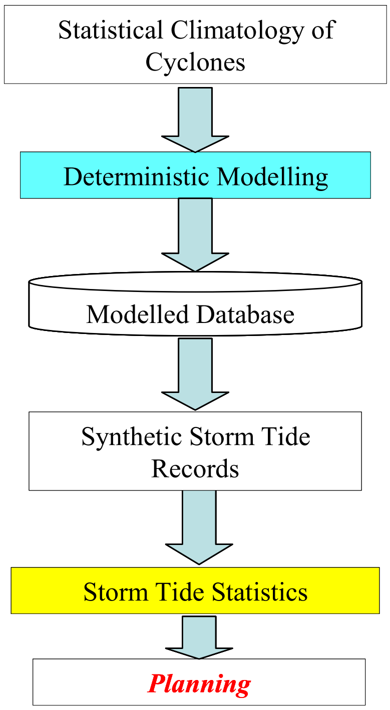

Figure 3.9 Adopted approach for developing storm tide statistics in Stage A.2.

Following Stage A.1(a) recommendation #1, a revised climatological description of tropical cyclones was developed based on the previously identified MMU research (e.g. James and Mason 1999, Hardy *et al.* 2003). While this did not fulfill the Stage A.1(a) recommendation for a comprehensive review of the base climatology, it addressed other important issues in regard to having a consistent and complete description upon which to base statistical storm tide models. The adopted method generates 3000 years of synthetic cyclone position and central pressure data using an autoregressive *Monte Carlo* model that determines the change of longitude, latitude and central pressure based on the changes at the preceding time step. The model coefficients are estimated by multiple linear regressions of the historical cyclone data for a chosen sub-region of the Coral Sea. Each simulation of a synthetic cyclone required initial values of position and pressure which, rather than being based on the limited number of historical starting values, were randomly selected from an n-dimensional data space that was based on the data set of historical initial values of each of the parameters required (refer Figure 3.10). The statistics of this synthetic ensemble was found to compare well with those of the measured data, falling within the expected 90% confidence limits of randomly selected samples.

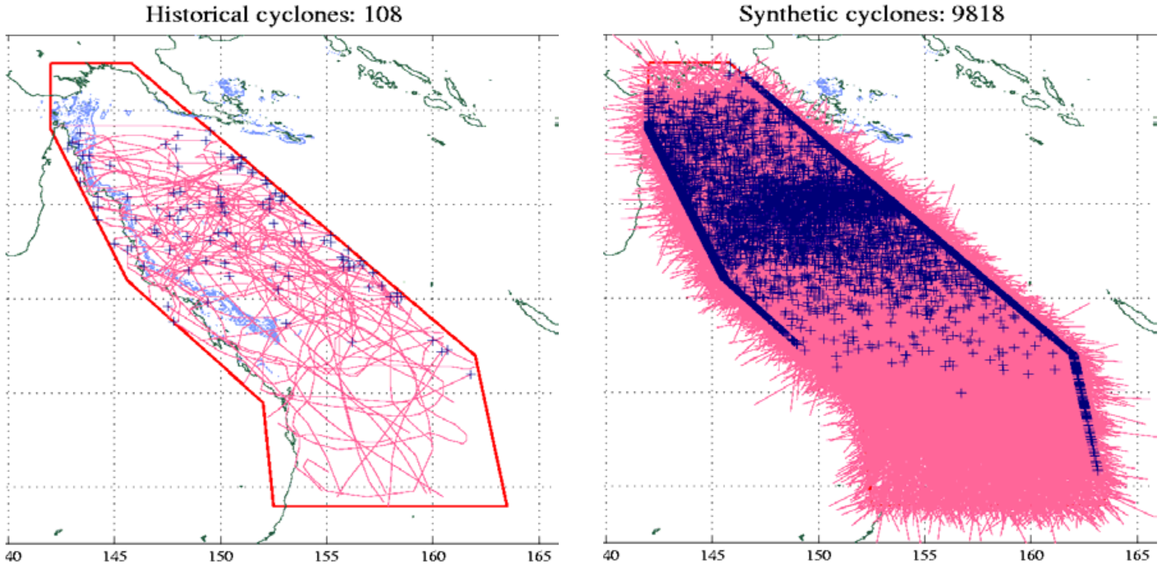

Figure 3.10 Comparison of 108 historical tropical cyclone tracks with 9818 simulated tracks[4].

Due to the impracticality of modelling 3000 years of simulated cyclones using primitive equation models within fine scale coastal grids, a reduced set was derived by firstly simulating all storms on a coarse *A* grid to determine a relative ranking within each coastal region of interest. The final storm set selected for fine scale modelling was then reduced by including only those storms whose *A* grid impact (storm surge *or* wave height) would have exceeded the 10 year return period condition. This is equivalent to choosing the "top 300" storms from the total of 3000 storms. However, because the surge and wave impacts are not identically correlated, this resulted in 540 storms being chosen for detailed modelling at Hervey Bay and 506 at the Sunshine Coast. The Stage A.1(a) numerical *B* grids designed for storm surge modelling (Figure 3.2) were extended slightly but with lower resolution to include larger fetch generation areas needed for modelling tropical cyclone waves and local *C* grids were defined with a final resolution of 550 m for surge and 1500 m for waves. The detailed study regions considered in Stage A.3 are shown in Figure 3.11, covering the Hervey Bay coast from Woodgate in the north down to River Heads and the Sunshine Coast from Teewah south to Woorim.

Consistent with the Stage A.1(a) MMUSURGE storm surge model calibration for 4 historical storms, the WAMGBR spectral wave model accuracy was demonstrated against tropical cyclone *Simon*, which affected the Hervey Bay region in February 1980. Although the storm surge from *Simon* was small, a significant WAVERIDER data record was available from the EPA for comparison with the model at Burnett Heads. The windfield of *Simon* was first determined in an analogous manner to the Stage A.1(a) approaches by using all available wind and pressure data from coastal and island locations, combined with the Bureau of Meteorology best track parameters. The resulting comparison between the modelled and measured significant wave height at the Burnett Heads site is shown in Figure 3.12, showing a very good agreement near the peak of the storm and further demonstrating the capabilities of the WAMGBR model.

[4] This figure illustrates the generation of 3000 years of synthetic tropical cyclones tracks. On the left contains 108 historical tracks (1969-2002); on the right contains 9818 tracks (3000 year simulation). Dark blue crosses indicate starting positions. Light blue area in (a) is the Great Barrier Reef.

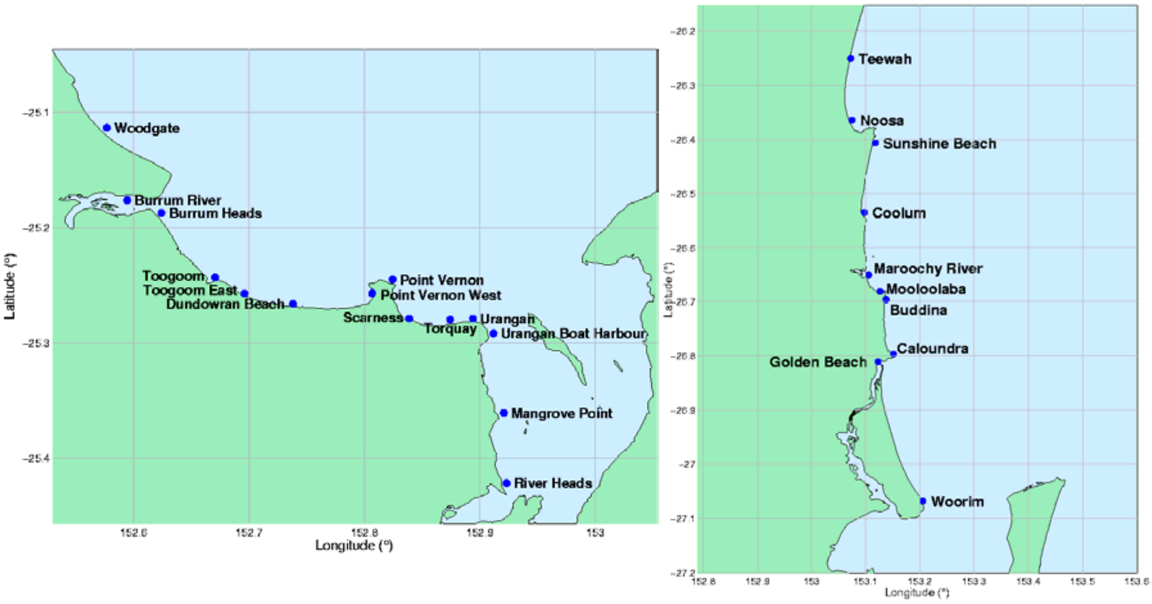

Figure 3.11 The Stage A.2 study output locations.

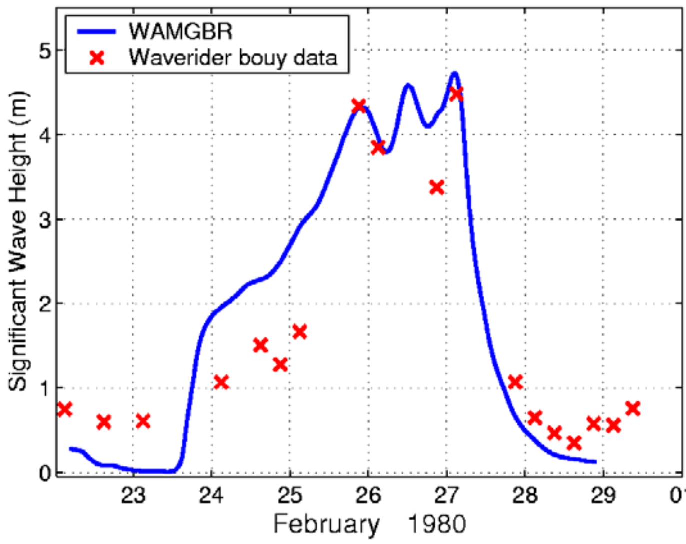

Figure 3.12 Comparison of WAMGBR with measured wave data during cyclone *Simon.*

During Stage A.2, additional investigations were also undertaken into methods for estimating breaking wave setup magnitudes at the shoreline. This resulted in a potentially wide range of estimates, with some being strongly depth-limited. However, the Stage A.1(a) recommendation (Hanslow and Nielsen, 1993) was again adopted as the preferred approach even though it provided by far the highest estimate, as it was deemed to be based on the most extensive set of field measurements.

An important outcome from the Stage A.2 work was the identification of potentially significant differences between the components of storm tide hazard between different coastal regions that are not widely separated. Accordingly, Figure 3.13 provides an interesting comparison of the predicted storm tide levels at Torquay (Hervey Bay) and Buddina (Sunshine Coast). In this case, the higher storm tide levels are predicted for Torquay, which is situated at the base of Hervey Bay where tidal and storm surge amplification is significant due to the shallow confined waters but wave effects are likewise relatively low due to attenuation. Buddina by contrast is located on an open deepwater coast with a narrow continental shelf where tidal range and storm surge is lower but where wave impacts are severe. These differences are clearly evident in the storm tide components where, considering the 1000 year return period, Torquay is expecting a 2.5 m surge contribution compared with Buddina's 0.75 m but only a 1.1 m wave setup compared with 1.9 m at Buddina. The tidal plane is also about 1 m higher at Torquay, which is reflected in the left hand side of the graphs. As a result of all these differences combined, the storm tide level at a return period of 1000 years is about 1 m higher at Torquay than at Buddina.

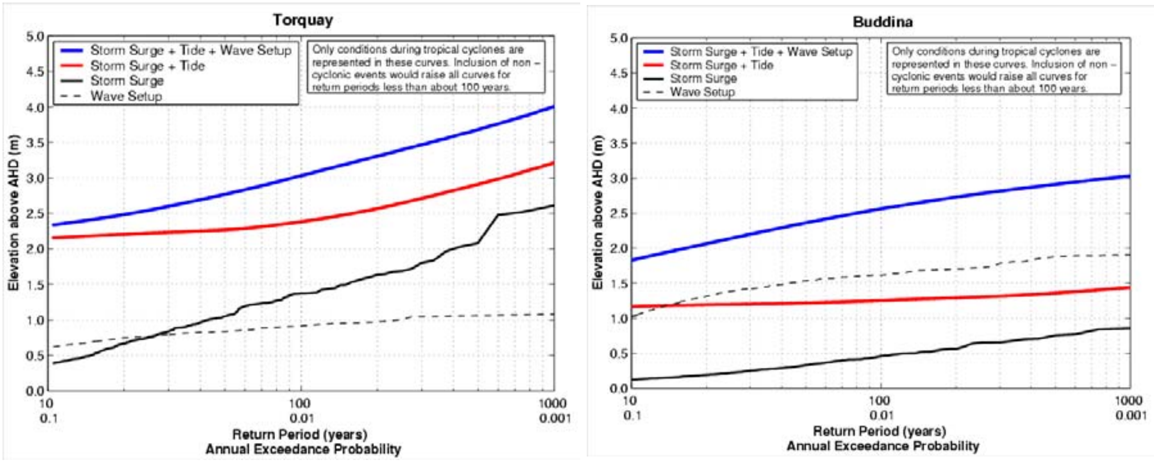

Figure 3.13 Comparison of estimated storm tide levels at Torquay and Buddina for present climate conditions.

Stage A.2 also provided detailed information on extreme wave conditions (height, period and direction) at a number of nominated locations. An example of this output is presented in Figure 3.14, which shows a selection of return period and directional wave information for a site in about 15 m depth 20 km north of Torquay.

Finally, Stage A.2 addressed the important issue of potential changes to storm tide hazard as a result of future enhanced Greenhouse climate change. Following the Stage A.1(a) recommendations, three scenarios were tested, *viz*:

A) A Mean Sea Level (MSL) rise of 300 mm by the year 2050 (IPCC 2001);

B) An increase in frequency of occurrence of tropical cyclones of 10%, which was deemed prudent in the Stage A.1(a) report (Harper 2001);

C) Combined effect of an increase in maximum intensity (MPI) of 10% and a poleward shift in tracks of 1.3° (following Henderson-Sellers *et al.* 1998 and Walsh and Katzfey 2000).

Scenario A was achieved adequately and simply by adjusting the MSL, while Scenario B was shown to result in a very small shift in the probability axis and with results largely indistinguishable from the 2003 climate base case. However, Scenario C required re-computing the synthetic track data and re-modelling the full storm set with a 10% increase in intensity for all timesteps and with poleward-biased tracks.

The results of the enhanced Greenhouse scenarios can be seen in Figure 3.15, again comparing Torquay and Buddina. In general, the enhanced Greenhouse curves formed from the combinations of all three scenarios increase the total water level curve at Hervey Bay from about 0.5 m at 10 years to 0.75 m at 1000 years. For the Sunshine coast, Greenhouse and 2003 curves are more parallel with an enhanced Greenhouse increase of about 0.5 m at all return periods. Appendix B presents a summary table of the predicted storm tide levels for all the study sites.

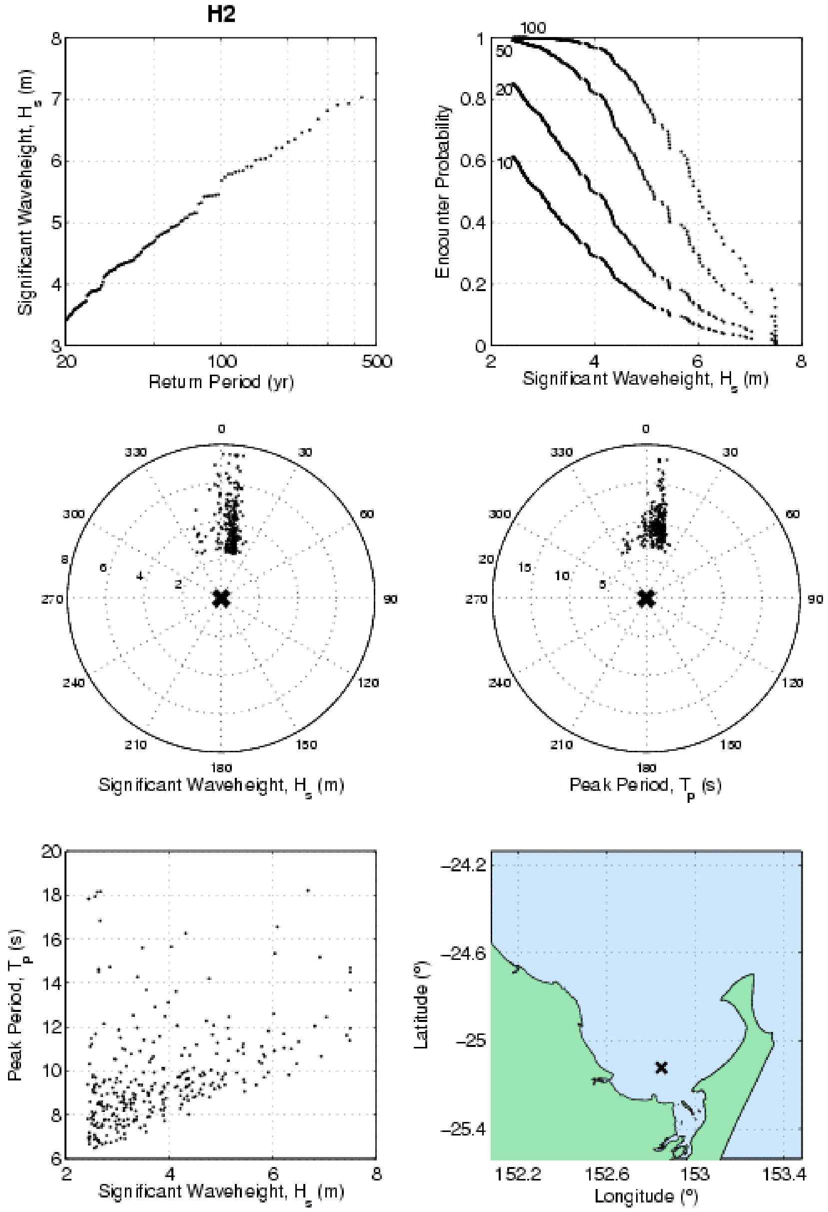

Figure 3.14 An example of detailed wave statistics derived for Hervey Bay.

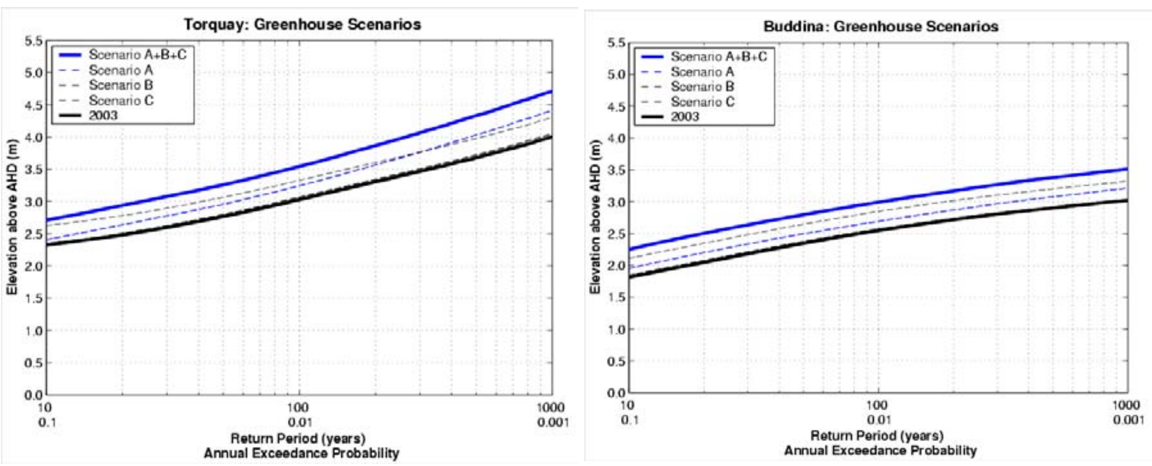

Figure 3.15 Comparison of estimated storm tide levels at Torquay and Buddina for future enhanced Greenhouse scenarios.

3.6 Stage A.3 - Frequency of Surge plus Tide for Selected Open Coast Locations along the Queensland East Coast

The Stage A.3 work (Hardy *et al.* 2004b) follows the same surge plus tide methodology as used in Stage A.2 but does not consider the effects of waves or wave setup. As shown on Figure 3.16, a total of 50 locations were nominated for estimating the surge plus tide risks on the basis of present climate and the previously identified enhanced Greenhouse climate scenarios. To achieve this, the Stage A.1(a) *A* and *B* grids were augmented by the creation of a further 20 storm surge modelling *C* grids to cover the selected locations at a resolution of 550 m (refer Figure 3.17).

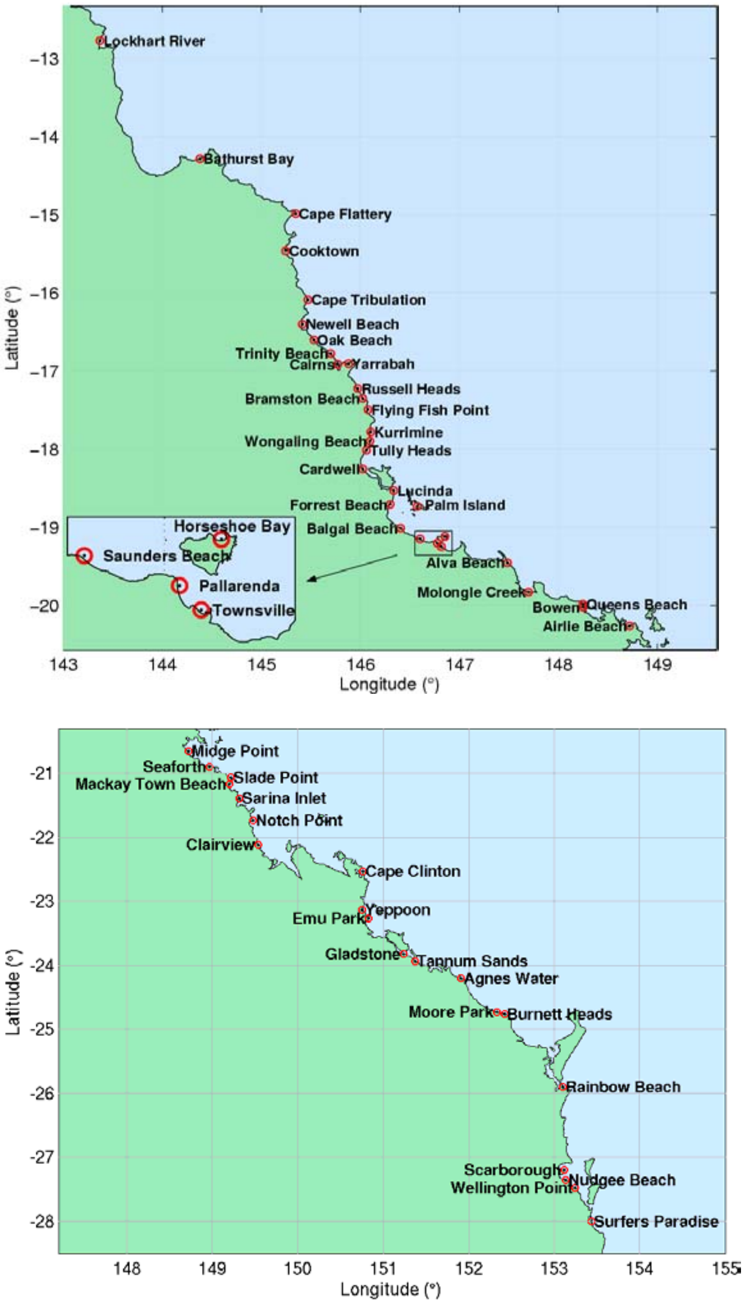

Figure 3.16 The Stage A.3 study output locations.

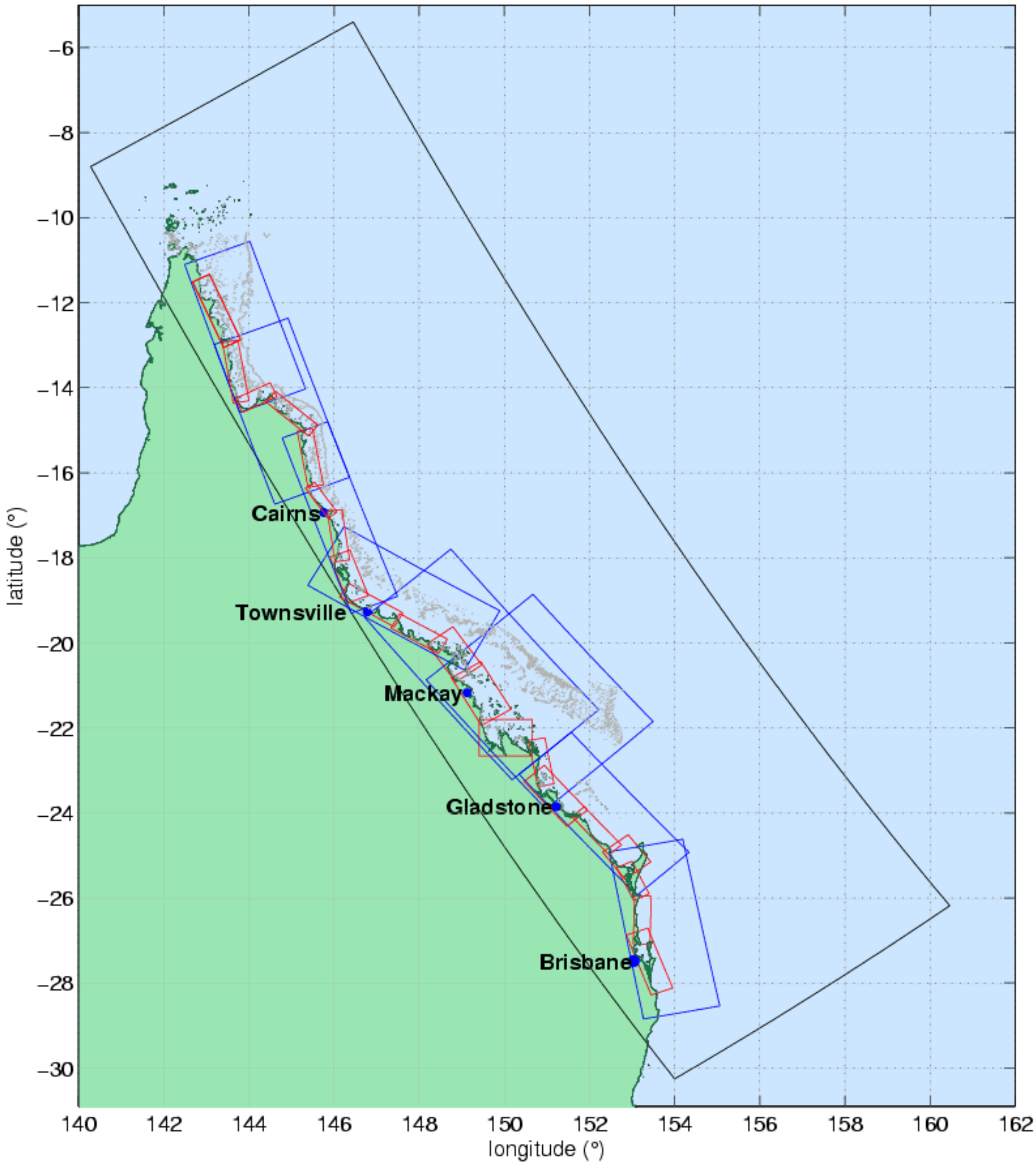

Figure 3.17 The Stage A.3 numerical domains showing A, B and C grids.

Examples of the resulting storm tide elevation return period curves are included as Figure 3.18 for Cairns, Townsville and Mackay. The differences in surge plus tide levels between these three regions is also affected by differences in the tidal plain (increasing towards Mackay) and the combined effects of the changing storm climatology and the coastal features, such as the width of the continental shelf. The predicted sensitivity to enhanced Greenhouse conditions is seen to be similar at Cairns and Mackay (0.7 m at 1000 y) but slightly less at Townsville (0.4 m at 1000 y). Appendix C presents a summary table of the predicted storm tide levels for all the Stage A.3 study sites. Although individual sites vary, the mean increase in predicted storm tide levels due to enhanced Greenhouse is of the order of 0.5 m.

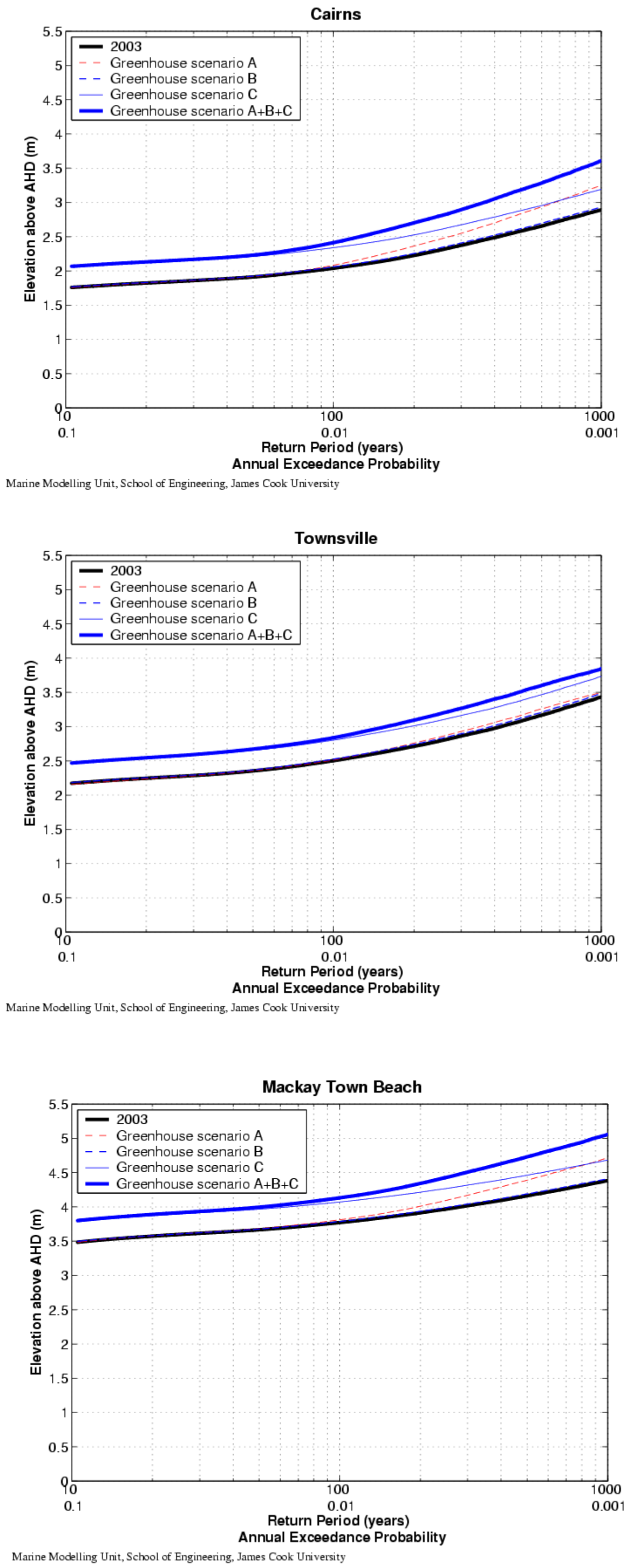

Figure 3.18 Example surge plus tide estimates (no wave setup) for selected Stage 3 sites under present climate and future enhanced Greenhouse climate scenarios.

3.7 Stage A.4 – Tropical Cyclone Surge and Wave Impacts: Gulf of Carpentaria

This is the first phase of Part A to be fully funded under the NDRMS program and, consistent with Stage A.1(a) recommendation #4, is targeted at improving the accuracy of total storm tide level estimates for the Gulf of Carpentaria region. Because of the complexity of the Gulf region's tidal response, its shallow waters and sensitivity to wind forcing, the entire Gulf of Carpentaria needs to be modelled. This has lead to a natural extension of the study along the Northern Territory coastline and has gained the support of the NT Department of Infrastructure, Planning and Environment. A total of 15 Queensland and 7 Northern territory locations between Weipa and Gove have been identified (refer Figure 3.19).

The project will follow the Stage A.2 philosophy, providing total storm tide (tide plus surge plus wave setup) and consideration of overland flooding. Extreme wave statistics will also be developed for selected locations together with joint probability statistics of extreme waves and water levels. This latter information is deemed critical for the design of coastal protection structures, development of coastal management plans and emergency response activities and will form a basis for planning for potential enhanced Greenhouse climate change and sea level rise. The proposed study will need to rely upon presently published digitally-based land elevation data, although the accuracy of such data is known to be poor.

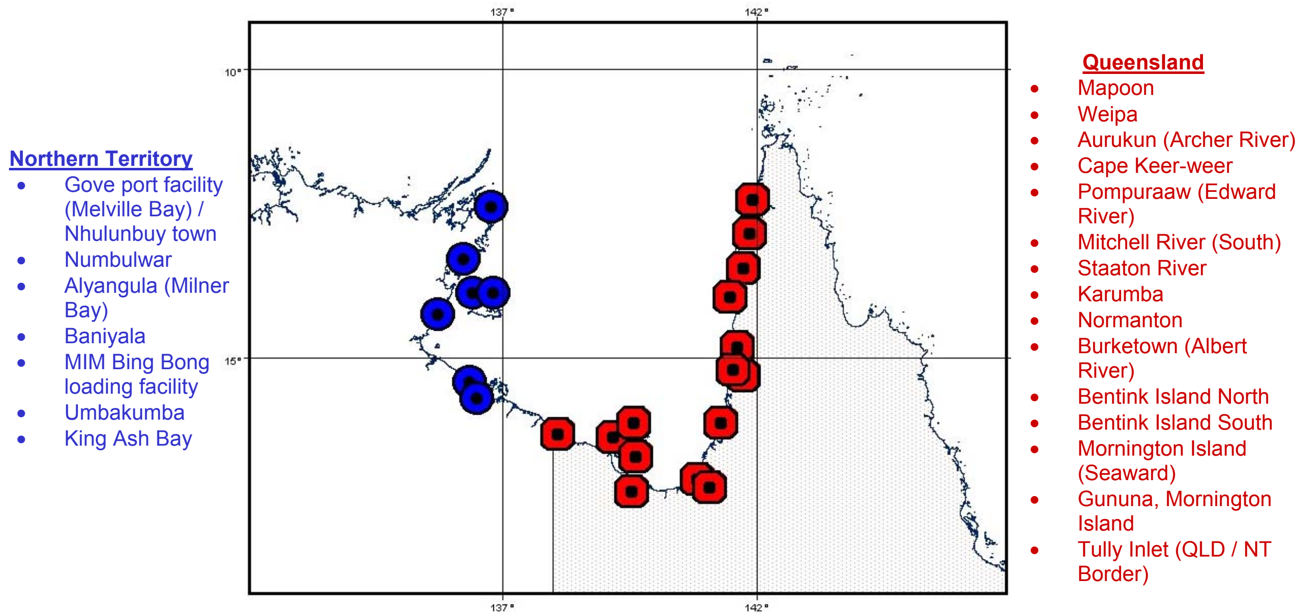

Figure 3.19 Proposed Stage A.4 storm tide study locations.

3.8 Stage B.1 – Development of Community Vulnerability Housing Damage Models

This aspect of the project was undertaken by the James Cook University Cyclone Testing Station (CTS) in Townsville, building on an earlier project supported under the Tropical Cyclone Coastal Impacts Program (TCCIP) and the Dept of Emergency Services in the late 1990s.

Any city or town comprises a wide range of house types, with differences in size, shape, window size, external cladding material, roof shape, age, and methods of construction. Each of these features can have an effect on the resilience of a house to resist wind forces. Houses also have varying degrees of exposure to wind forces, with those dwellings located in a suburban environment gaining shelter from surrounding structures as opposed to houses near the sea or open terrain. Topographical features such as hills can concentrate or divert the wind flow. The wind speeds from a tropical cyclone impacting on a community will vary according to its intensity, size and distance from the community. Therefore an assessment of the wind resistance of housing requires knowledge of house types and their distribution throughout the community. All of these factors have made it difficult to accurately predict the likely damage to a community's housing from cyclonic winds.

Domestic construction (i.e. houses and flats) also act as shelter during cyclone events. For this reason, knowledge of housing performance (resilience) is crucial for agencies involved in disaster mitigation and response. The methodology developed during Part B.1 has been designed to assess the amount of damage likely to occur in the Queensland coastal cities of Townsville, Cairns and Mackay, and to obtain a distribution of that damage over each community for a cyclone of any given intensity and path. The study did not attempt to assess the performance of individual houses or even small groups of houses but to provide a general estimation or indication of potential community-wide damage from particular cyclone events.

Under the banner of the TCCIP, comprehensive data surveys of the external features of housing samples had been conducted over several years for Cairns, Townsville and Mackay with the assistance of Commonwealth and Local Government agencies. The CTS also conducted a physical attribute housing survey for Townsville along with detailed structural inspections of 100 houses. From knowledge of the development of the cities forming this study, a review of current and superseded building regulations, detailed internal house inspections, and an overall survey of the housing stock, the multitude of house styles were generalized into six classes, covering houses from the 1860's through to present day forms, based on overall geometry and construction techniques.

A house frame is a very complex structure and does not lend itself to a straightforward structural analysis, as there are multiple building elements providing load-sharing and in some cases full redundancy. The CTS-developed housing wind resistance models are not targeted at determining the most efficient joint or member size, but for an assessment of the likely failure mode and failure load for a representative proportion of houses. Findings from full-scale house testing, and individual component joint strength tests, have also been incorporated in the estimation of the failure capacities.

The CTS housing wind resistance models developed in Part B.1 focus on the chain of connections starting from the roof cladding fixings and extending through to the wall tie-down onto the base of the structure or the ground. Findings from damage surveys and full-scale house testing results all conclude that the predominant mode of wind-induced failure is associated with the load capacity of the joints in the house structure. Five probabilistic failure modes (*Failure at cladding, Failure at cladding to batten connection, Failure at batten to truss/rafter connection, Failure at truss/rafter to wall connection, and Failure of wall tie down connection*) were developed for each of six identified house groups for longitudinal and lateral wind directions for both full (C_{pi}=0.7) and partial (C_{pi}=0.2) internal pressure conditions (Figure 3.20).

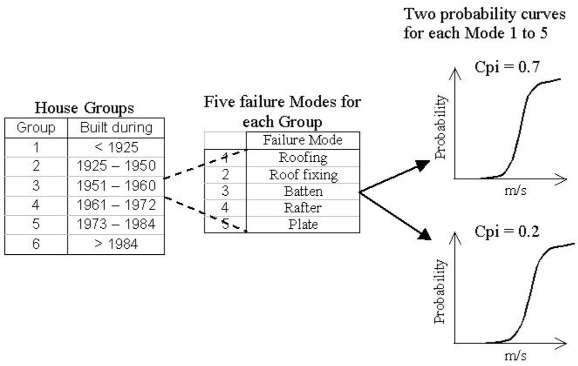

Figure 3.20 House group and failure mode model.

Sudden full internal pressurisation of a house occurs when there is a breach in the outer building envelope caused by wind-driven debris breaking a window or blowing-in a door and this can dramatically increase the internal wall load and upward load on the roof structure. Failures of house elements also add to the debris field impacting on downwind houses, which increase their risk of failure, leading to higher probabilities of further failures downwind (e.g. a "snowball" effect). Accordingly, the CTS developed a module to estimate the numbers of houses likely to be subjected to full internal pressure as a result of the windborne debris.

3.9 Stage B.2 – Development of the Housing Wind Risk Assessment Model

In Stage B.2 of the project, the wind damage relationships from B.1 were formalized into the CTS wind housing resistance model (CTSWhrap) and combined with the existing SEA proprietary deterministic wind field model SEACATd to provide a user-friendly software interface for estimating the number of houses suffering wind-induced damage from a cyclone of given parameters (track, intensity, radius etc). The combined study is detailed in CTS (2003).

SEACATd uses an analytical wind model of tropical cyclones based on Harper and Holland (1999) combined with regional descriptions of the variation in the surface wind boundary layer, as depicted schematically in Figure 3.21. Here the vertical profile of the near-surface winds is shown, whereby the incident wind speed on houses can be seen to be typically decreasing away from the coastline due to surface frictional increases, but localized effects from hills can sometimes result in acceleration and increased speeds.

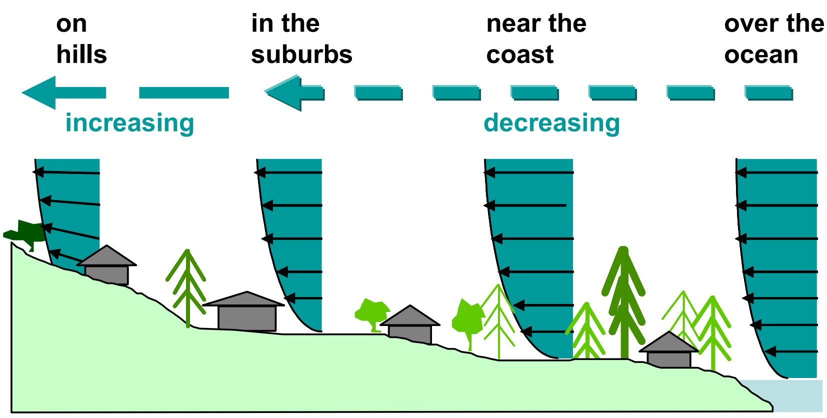

Figure 3.21 Surface boundary layer effects on housing.

Within the SEA model framework, topographic *factors* in accordance with the boundary layer coefficients detailed in the Australian Wind Load Standard (Standards Australia 1989) are assigned to account for ground slope, surrounding terrain roughness and the influence of neighbouring structures. The complex variability of these features is based on a LANDSAT satellite thematic analysis of vegetation classes, overlaid with a digital elevation model (Harper 1999b), which is then collated into a series of slope and terrain classes and assigned on a postcode basis. Figure 3.22 shows an example of the SEA terrain and topography mapping process applied to Townsville, with the left-hand image being a false-colour LANDSAT image and, after processing, each colour in the right-hand image represents a specific surface wind factor. The proportion of "colours" in each postcode is then used to assign wind speeds to the aggregated housing, combined with the proportion of each house strength group based on the housing surveys. The total damage is then aggregated on the basis of the local wind speed, house group and the applicable CTS housing damage models.

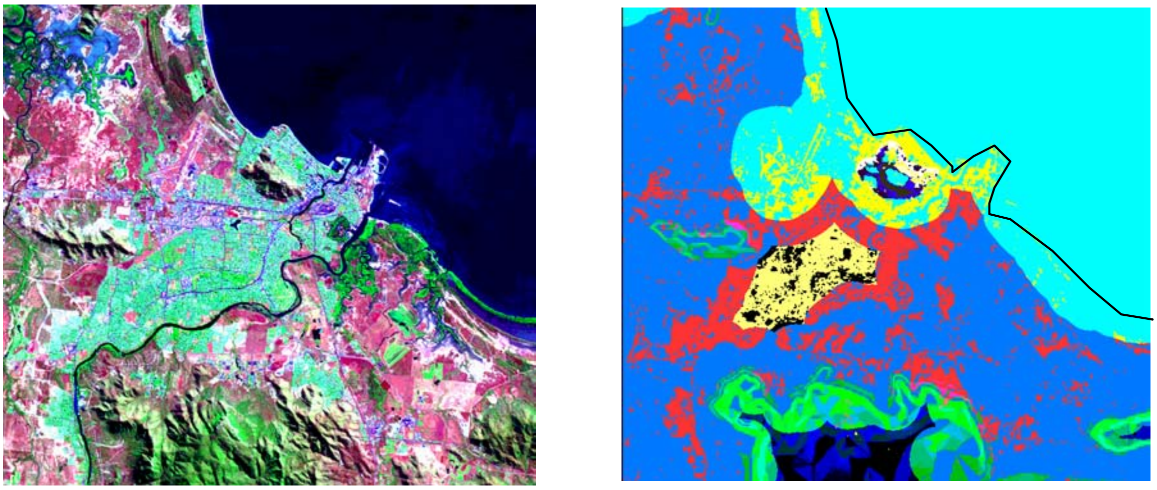

Figure 3.22 Example terrain and topography modelling of Townsville (*after Harper 1999b*).

As a verification check, the combined CTS/SEA model has been tested against real damage data from Tropical Cyclone *Althea*, which impacted Townsville in 1971. Overall city-wide damage levels from this category 3 event (JCU 1972) were 16% but reached a high of 68% for one exposed coastal suburb, while the model predicts 15% and 71% respectively, comparing very favourably with the reported damage. Output from the predictive model provides the estimated number of houses damaged within each defined district and for each house group as well as the types of structural failures occurring and highlights the relative vulnerability of certain housing types caused by their terrain and topographic exposure.

The value of the model lies then in its expected ability to predict likely damage from other cyclone scenarios or to assess the likely benefits of adopting more stringent building regulations

Figure **3.23**, for example, maps the predicted distribution of housing damage for a recurrence of cyclone *Althea*, whereby the damage is estimated to be considerably lower than the 1971 event because of the expected improved performance of housing built since post-1984 building regulations came into effect. After comparing the three modelled regions, the study has shown that Cairns is estimated to have a lower relative vulnerability of its housing stock to wind loads than the Townsville and Mackay regions, mainly because it has a greater proportion of post-1984 housing.

The project has demonstrated a practical yet advanced methodology for estimating the community impact from tropical cyclones or other extreme wind events that is superior to more simplified models in common use. While there is much opportunity to improve the present model, it does represent an advanced assessment of house performance for high winds undertaken in Australia. A full probabilistic version of the model is now being considered that will estimate return periods of losses and provide the necessary basis for assessing the possible impacts of enhanced Greenhouse climate change.

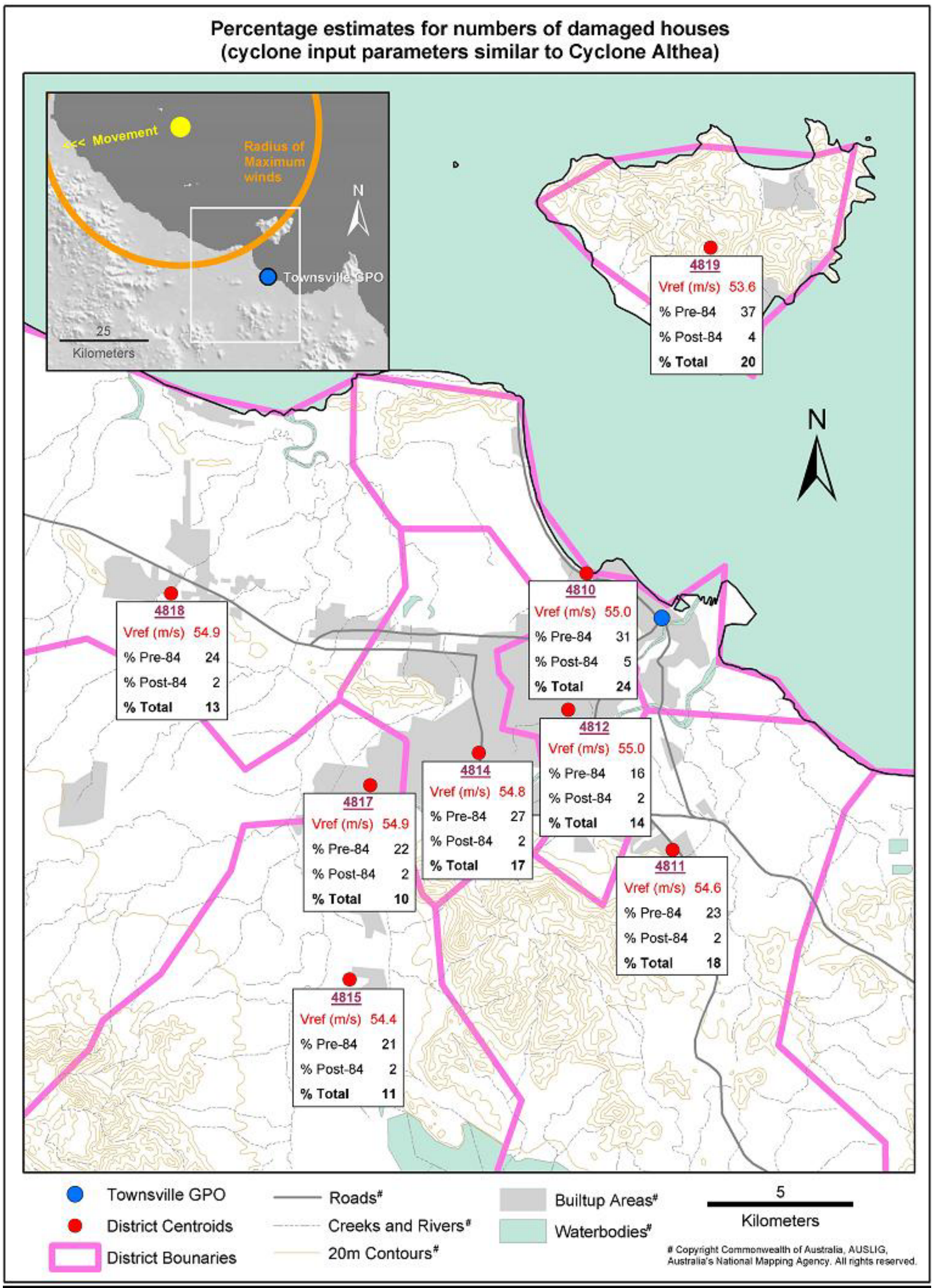

Figure 3.23 Model estimates of housing damage in Townsville due to a possible recurrence of Cyclone *Althea*.

4 Overall Progress and Identified Issues for Future Work

The foregoing sections have highlighted the individual methodologies and outcomes from each phase of the project to date. Here, a view of the incremental progress within the broader context of the complete tropical cyclone hazard is presented, identifying aspects and issues for future work.

4.1 Part A – Ocean Hazards Assessment

A number of the detailed recommendations from the Stage A.1(a) investigation have been able to be addressed, at least in part, although all components of the work have been limited by the available funding. Importantly, the project has been able to progress through the application of existing numerical models having the recommended capabilities (e.g. MMUSURGE, WAMGBR), coupled with proven analytical wind and pressure models of the tropical cyclone forcing and improved statistical climatology models. Other than the BoM parametric storm surge model, no new techniques, models or data sets have yet been developed or applied as part of the project.

It is important to remember that any probabilistic interpretations of the ocean hazard presently being made are dependent upon the accuracy and completeness of the underlying historical tropical cyclone database. While certain inadequacies in this dataset have been recognised for some time (e.g. a critical lack of scale information etc) more recent studies have highlighted potentially more significant biases that could relate to the evolution of the knowledge and application of the *Dvorak* technique for estimating cyclone intensity from satellite images (e.g. Harper 2002). The Stage A.1(a) recommendation #1 for a comprehensive climatology review is therefore now even more compelling and will remain as a significant roadblock to refining the probabilistic accuracy of storm tide statistics, especially those involving joint probability. This is both an Australia-wide and international issue that affects the accuracy of historical meteorological databases. In addition, there remains a need to address the broader aspects of tropical cyclone behaviour such as better identifying the role of synoptic scale interactions, decay after landfall, re-curvature and re-generation issues. Many of these aspects are likely to influence the lower-magnitude shorter-term return period regime, where non-cyclonic influences also play an as-yet unquantified role, but where initial impacts of a rising MSL through enhanced Greenhouse will be most readily felt.

The existing hydrodynamic models use relatively simple descriptions of the tropical cyclone wind and pressure fields that have been essentially calibrated through experience over many years to reproduce measured events. The extent to which such models can be reliably extrapolated to the most severe conditions is presently somewhat unknown. For example, Stage A.1(a) model calibrations highlighted the potential for dynamic structure changes and conflict between measured data and model results based on commonly accepted beliefs about the asymmetry of the wind field. Meanwhile, research into the role of the tropical cyclone boundary layer is progressing and should yield valuable insights that could in turn be applied to the existing models. However, there is no formal project addressing this transfer of technology or actively working for liaison between the various technical parties.

In terms of the deterministic prediction capacity of the hydrodynamic surge and wave models, these are probably accurate enough, given the level of the other unknowns. However, the present models are being independently applied, without interaction in terms of the impact of changing water levels from either tide or storm surge or the effect of currents on wave refraction and the like. While these effects are generally able to be regarded as small, there will be some regions where such feedback may be more significant and over time these situations should be identified and addressed to provide increased assurance against “freak” conditions. In this regard, the development of new fully-coupled hydrodynamic models is also highly desirable to provide greater confidence in the application of analytical wave setup formula. There is a critical lack of knowledge about these processes in extreme conditions that will require a concentrated research and monitoring effort.

Finally, the accurate modelling of wave runup, overland inundation and flooding is severely limited by an almost universal lack of detailed land elevation and beach slope data. While there is no technical barrier to obtaining such data, it remains a very considerable financial hurdle, with costs for accurately mapping (say 0.5 m contours) even modest portions of a single local government region likely to well exceed the allocated budget of this present State-wide project.

4.2 Part B - Community Housing Vulnerability

The outcome of Stage B.2 is a deterministic model of housing damage to strong winds that embodies a wide range of experience both in the structural strength of housing and its manner of construction in Queensland. Coupled with community databases, cyclone wind models and terrain and topography models, it forms a powerful basis for an objective State-wide impact assessment that could address both economic and societal issues. One of the first steps towards such a capability would be to develop a probabilistic version of the model that utilizes the climatology advances already developed for the ocean hazards assessment and the ability that follows to determine sensitivity to climate change. With such a tool, the risks from tropical cyclones to housing and its occupants will be much more accurately assessed and be able to be compared against the nominal benchmark reliability targeted by the Australian Building Codes Board, through the Building Code of Australia (BCA 2002). Ideally, any shortfall in an acceptable level of community risks could then be considered in the context of retro-fitting and strengthening (e.g. Stewart 2002) or more targeted insurance products, possibly with Government backing. Use of the model in this way will serve to find the optimum balance between regulation/inspection, with its inherent economic costs, and the subsequent risk to occupants and their potential economic loss.

A natural extension of the housing vulnerability project would then be to consider combining the Part A and Part B outcomes to consider the effects of storm tide on domestic construction – an aspect yet to be fully considered in the Australian context but which, exacerbated by sea level rise, will increasingly impact coastal communities and the tourism industry. In this regard, much can be learned from the experience of the US National Flood Insurance Program (e.g. FEMA 1998, 2000) in identifying coastal inundation risks and long-term mitigation strategies involving local government planning regulations and insurance.

4.3 A Summary of Future Needs

Accurately estimating the impacts of tropical cyclones on the community and the environment is a challenging task requiring contributions from many different scientific disciplines. Developing and implementing the necessary practical warning, planning and mitigation measures needed to ensure an acceptable level of protection is an equally difficult activity. It is generally expected that all attempts will be made to minimise the future risk of tropical cyclone hazards. Accordingly an ongoing commitment to continuous improvement is required to assist in the planning and management of safer communities.

At the present level of understanding there are a number of complex issues that demand greater attention. While many of these have been described in some detail in the context of work done to date, others are worth noting within the wider context of ongoing refinement and future needs. The following is an indicative list of future needs:

Tropical cyclone climatology:

- Improving the accuracy and consistency of the historical cyclone dataset
- Systematic classification of severe weather systems in general
- Representing synoptic scale interactions
- Utilising paleoclimate indicators in a quantitative manner
- Continuing investigation of possible Enhanced Greenhouse effects on severe weather

- Refinement of statistical track modelling approaches.

Tropical cyclone numerical wind and pressure modelling:

- Tropical cyclone structure and dynamics
- Atmospheric boundary layer representations
- Parametric model improvements
- Terrain and topography representations
- Increasing the quality and aereal density of wind and pressure validation data.

Hydrodynamic modelling:

- Coupled tide, storm surge, wave, wave setup, river and flood models
- Improved tidal data for model boundaries
- Improved bathymetry and land elevation data
- Increasing the quality and aereal density of hydrodynamic validation data, in particular wave setup and runup.

Inundation modelling:

- Wave overtopping processes
- Dune breaching mechanisms
- Overland storm tide flow characteristics, including interactions with housing and infrastructure, debris etc.
- Local wind setup.

Statistical modelling:

- Continued Enhanced Greenhouse scenario testing
- Joint probability of river flood and storm tide (i.e. incorporating rainfall and runoff modelling)
- Probabilistic modelling of housing and infrastructure damage
- Extending to very low probability assessments (e.g. 10^{-4} p.a.)
- Scenarios to support planning for evacuation, traffic management and shelter needs
- Insurance requirements
- Assessing the overall level of community resilience.

Best practice guidelines:

- Risk assessments, including quantifying “acceptable” risk
- Planning and operational measures
- Building design, construction, inspection and maintenance standards for tropical cyclone wind loadings and storm tide impacts.

Improving administrative arrangements:

- dissemination of high quality information on tropical cyclone / storm tide impacts to operational end-users.

5 Conclusions

The *Queensland Climate Change and Community Vulnerability to Tropical Cyclones* project represents a detailed review and consideration of the potential hazards posed by these extreme events to the State-wide coastal community. It encompasses both the inherent natural variability of such events and additionally provides a basis for assessing the additional impacts of possible climate change through enhanced Greenhouse.

Under Part A of the project, the storm tide threat along the Queensland east coast has been reviewed. The project has proceeded within the context of an initial technical blueprint that set out the essential methodologies and data requirements. Subsequent stages of the study have focused firstly on improving real-time forecasting capabilities for the Bureau of Meteorology and then on updating and extending present estimates of storm tide statistics for long-term planning and emergency response purposes and in developing near-shore extreme wave statistics for coastal management and design needs. Importantly, the potential impact of future climate change through the enhanced Greenhouse effect has also been able to be assessed within the full context of the naturally complex climatic variability of tropical cyclones.

Consistent with the expectations of undertaking finer scale wind and storm surge modelling to a higher accuracy than achieved previously, the Stage A.2 and A.3 studies indicate a reduction of estimated *storm surge plus tide* levels for many parts of the Queensland coast compared with earlier studies (e.g. Harper 1999a). However, the Stage A.2 estimates for Hervey Bay and the Sunshine coast, which include allowance for *wave setup*, suggest that previous nominal allowances for this component may have been widely underestimated. Enhanced Greenhouse is predicted to increase present climate storm tide levels by about 0.5 m on average (0.13 m S.D.), or approximately 19%.

Within a limited budget, much progress has been made in advancing the knowledge of ocean hazards in Queensland, but much still remains to be done. Although sophisticated numerical and statistical models have been utilised, the data requirements are significant, much of the work is still highly labour intensive, attention to detail is critical and the coastline is extensive. The significant roadblocks to further quantification of the risks include the need to review and revise the historical database of tropical cyclone tracks, intensities and scale parameters and to obtain high resolution land elevations to enable accurate overland flooding calculations.

In some specific locations, more sophisticated coupled numerical modelling may also prove to be necessary to address specific communities at high risk. The project has also highlighted potential shortcomings in the present understanding of wave setup within complex topography and under extreme conditions that might only be addressed through long-term monitoring and targeted research. Finally, the relative contribution of non-cyclonic or more remote cyclonic events to medium-term return period water levels (e.g. up to 100 y) is yet to be investigated, but may be more significant than previously thought. If so, this effect may amplify enhanced Greenhouse MSL rise impacts much more than currently anticipated.

Under Part B of the project, an advanced model of housing vulnerability under extreme winds has been developed and combined with previously collected housing statistics for the Cairns, Townsville and Mackay regions. The resulting housing wind resistance models have been verified against an historical event and coupled with a deterministic wind field model and terrain and topography descriptions to enable community-wide estimation of wind damage caused by specific cyclone scenarios. Further development would enable the model to be extended to other regions and enhanced to incorporate probabilistic aspects such as those resulting from the Part A outcomes. This would allow assessment of (i) climate change impacts, (ii) highlight sensitivity to building styles and practices, (iii) permit comparison of estimated community vulnerability with the target design resilience assumed by current building regulations, and (iv) assist in developing effective insurance products. A similar approach could be developed to address vulnerability to storm tide impacts.

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Appendix A Project Participants and Acknowledgements

Mr Rex Falls, former Regional Director of the Bureau of Meteorology in Queensland, was instrumental in establishing Part A of the project as one of the many initiatives under the Tropical Cyclone Coastal Impacts Project (TCCIP). He also served as Chair of the Project Management Committee until 2001.

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Appendix B Surge plus Tide plus Wave Setup Levels from Stage A.2

Tables below are from Hardy *et al.* (2004a)

Return periods of storm: both 2004 and combined greenhouse scenarios: Hervey Bay

	Return Period: Storm Tide (m, AHD)					
	100 year		500 year		1000 year	
Location	2004	Green house	2004	Green house	2004	Green house
Burrum Heads	2.79	3.29	3.46	4.17	3.73	4.55
Burrum River *	2.24*	2.82*	2.87*	3.62*	3.16*	4.01*
Dundowran Beach	2.96	3.54	3.69	4.45	4.03	4.85
Mangrove Point *	2.54*	2.91*	3.12*	3.65*	3.36*	4.02*
Point Vernon West	2.98	3.55	3.66	4.39	4.00	4.81
Point Vernon	3.02	3.56	3.68	4.36	3.99	4.73
River Heads *	2.62*	3.08*	3.30*	3.93*	3.58*	4.32*
Scarness	3.11	3.68	3.82	4.55	4.15	4.95
Toogoom East	3.00	3.57	3.75	4.50	4.07	4.90
Toogoom	2.88	3.59	3.58	4.52	3.88	4.89
Torquay	3.03	3.59	3.68	4.38	4.01	4.77
Urangan Boat Hr.	2.93	3.46	3.51	4.18	3.75	4.52
Urangan	2.98	3.50	3.58	4.23	3.83	4.57
Woodgate	2.95	3.45	3.55	4.22	3.79	4.56

*Storm surge levels only. Wave setup not included

Return periods of storm tide: 2004 and combined greenhouse scenarios: Sunshine Coast

	Return Period: Storm Tide (m, AHD)					
	100 year		500 year		1000 year	
Location	2004	Green house	2004	Green house	2004	Green house
Buddina	2.55	3.02	2.90	3.40	3.02	3.53
Caloundra	2.55	3.07	2.98	3.52	3.10	3.66
Coolum	2.44	2.88	2.76	3.21	2.88	3.33
Golden Beach *	1.05*	1.50*	1.29*	1.88*	1.41*	2.03*
Maroochy River	2.50	2.96	2.86	3.33	2.98	3.47
Mooloolaba	2.37	2.80	2.63	3.11	2.74	3.23
Noosa	2.29	2.71	2.61	3.03	2.68	3.16
Sunshine Beach	2.61	3.09	3.01	3.49	3.15	3.62
Teewah	2.61	3.08	3.05	3.49	3.19	3.64
Woorim	2.29	2.78	2.61	3.18	2.75	3.34

*Storm surge levels only. Wave setup not included

Appendix C Surge plus Tide Levels from Stage A.3

Table below is from Hardy *et al.* (2004b)

Return periods of storm tide (no wave setup): 2004 and combined greenhouse scenarios.

	Return Period: Storm Tide (m, AHD)					
	100 year		500 year		1000 year	
Location	**2004**	**Green house**	**2004**	**Green house**	**2004**	**Green house**
Lockhart R.	1.82	2.11	2.01	2.49	2.16	2.89
Bathurst Bay	1.92	2.22	2.22	2.47	2.54	2.66
Cape Flattery	1.61	1.89	1.81	2.08	1.93	2.20
Cooktown	1.87	2.16	2.27	2.64	2.54	2.97
Cape Tribulation	1.77	2.07	1.91	2.26	2.01	2.41
Newell Beach	1.85	2.20	2.21	2.84	2.41	3.13
Oak Beach	1.90	2.20	2.14	2.60	2.31	2.82
Trinity Beach	1.92	2.23	2.14	2.58	2.29	2.82
Cairns	2.04	2.41	2.58	3.18	2.89	3.61
Yarrabah	1.93	2.27	2.24	2.79	2.46	3.12
Russell Heads	1.86	2.19	2.12	2.53	2.29	2.70
Bramston Beach	1.87	2.20	2.14	2.55	2.33	2.73
Flying Fish Point	1.94	2.27	2.19	2.64	2.36	2.84
Kurrimine Beach	2.13	2.46	2.48	2.91	2.69	3.13
Wongaling Beach	2.11	2.44	2.46	2.82	2.67	3.01
Tully Heads	2.13	2.68	2.66	3.17	2.93	3.39
Cardwell	2.54	2.87	3.31	3.55	3.66	3.94
Lucinda	2.24	2.57	2.56	2.94	2.73	3.14
Forrest Beach	2.36	2.73	2.83	3.30	3.04	3.60
Palm Island	2.24	2.56	2.46	2.82	2.57	2.98
Balgal Beach	2.49	2.85	2.94	3.47	3.17	3.84
Saunders Beach	2.44	2.77	2.90	3.32	3.12	3.64
Horseshoe Bay Magnetic Is.	2.33	2.64	2.54	2.88	2.67	3.05
Pallarenda	2.40	2.72	2.91	3.29	3.18	3.59
Townsville	2.50	2.84	3.07	3.51	3.43	3.84
Alva Beach	2.34	2.65	2.73	3.10	2.92	3.36
Molongle Creek	2.28	2.69	2.94	3.33	3.25	3.58
Queens Beach	2.07	2.40	2.33	2.77	2.47	2.95
Bowen	2.15	2.52	2.52	3.01	2.71	3.22
Airlie Beach	2.41	2.72	2.64	3.02	2.80	3.19
Midge Point	3.56	3.89	4.01	4.41	4.28	4.68
Seaforth	3.37	3.71	3.71	4.23	3.91	4.51
Slade Point	3.70	4.03	3.94	4.38	4.09	4.63
Mackay Town Beach	3.77	4.13	4.16	4.73	4.38	5.06
Sarina Beach	3.86	4.19	4.19	4.66	4.39	4.94
Notch Point	4.32	4.65	4.72	5.15	5.00	5.46
Clairview	4.77	5.12	5.26	5.64	5.57	5.90
Cape Clinton	2.99	3.31	3.15	3.52	3.25	3.66
Yeppoon	2.94	3.37	3.49	4.14	3.79	4.58
Emu Park	2.87	3.28	3.30	3.95	3.54	4.30
Gladstone	2.82	3.33	3.51	4.18	3.80	4.41
Tannum Sands	2.50	2.95	3.05	3.64	3.31	3.94
Agnes Waters	2.46	3.11	3.04	3.68	3.30	3.96
Moore Park	2.61	3.26	3.36	4.13	3.63	4.49
Burnett Heads	2.42	2.97	2.99	3.68	3.19	3.94
Rainbow Beach	1.30	1.70	1.48	1.93	1.57	2.03
Scarborough	1.33	1.73	1.55	2.08	1.67	2.25
Nudgee Beach	1.44	1.89	1.75	2.46	1.91	2.73
Wellington Point	1.47	1.91	1.82	2.46	2.00	2.71
Surfers Paradise	1.22	1.57	1.37	1.74	1.42	1.81