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Report

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Surge Plus Tide Statistics for Selected Open Coast Locations along the Queensland East Coast

In association with:

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Marine Modelling Unit

Queensland Climate Change and Community Vulnerability to Tropical Cyclones: Ocean Hazards Assessment
Stage 3

The Frequency of Surge Plus Tide During Tropical Cyclones for Selected Open Coast Locations Along the Queensland East Coast

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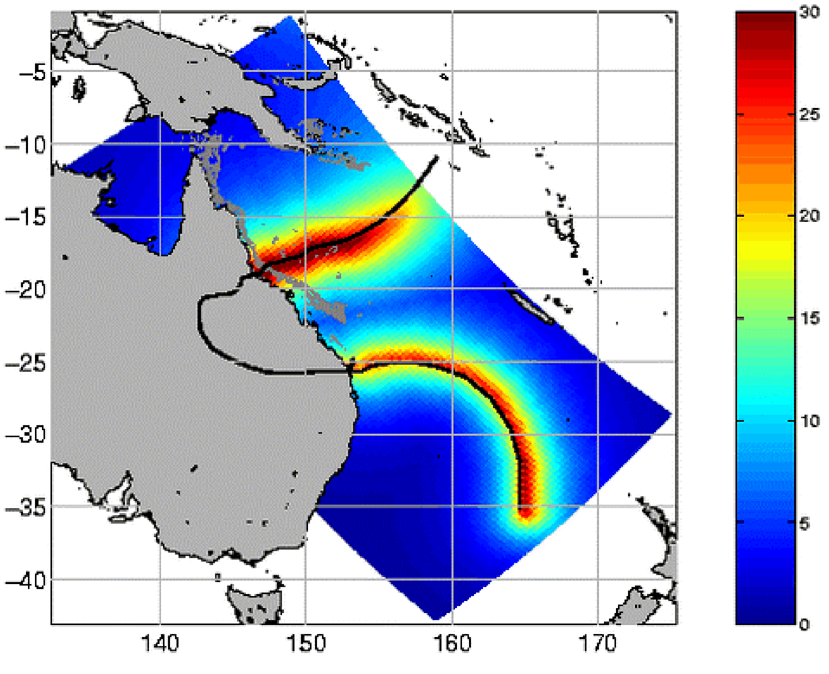

JAMES COOK UNIVERSITY

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Executive Summary

The frequency of storm surge plus tide during tropical cyclones was determined for 50 open coast locations along the east coast of Queensland, Australia (Figure 1). The goal was to produce return period curves for storm surge plus astronomical tide for return periods between 10 and 1000 years.

A series of sophisticated models was employed. First a tropical cyclone track and pressure model produced a synthetic dataset consisting of the time series of position and pressure for almost 10,000 storms. This represents 3000 years of data for the western Coral Sea. Numerical models with three nested grids with increasing spatial resolution for storm surge were established for the study areas. The storm surge model was validated in Phase 1 of this overall study (Harper *et al.,* 2001).

It was computationally impossible to model all 10,000 storms to the needed resolution; therefore, a system was developed to determine which storms would contribute to return periods above 10 years. To do this all storms were modelled on the less computationally expensive coarse grid. The most severe results on these coarse simulations were used to cull the number of storms to be modelled on the finer resolution grids from 10,000 to about 500 for each of the 20 fine resolution *C*-grids.

An astronomical tidal signal was created using tidal analyses. Each storm surge time series from a single storm was linearly added to 500 separate tidal time series. The tide series were randomly chosen (with a weighting to reflect the monthly change in cyclone frequency) from a long tidal record. The maximum storm surge plus tide water level during each storm-tide event was determined and these values were ranked by magnitude and return period curves were created.

Establishing a datum and a tidal range at the project output points caused considerable difficulty. Most of the output points were not at established tidal measurement stations. Hence the datum at a location was often transferred from the nearest tide station and these official values (that were provided to us) did not always provide the best tidal information at that location. Considerable time and energy was expended to check and recheck values of MSL, AHD and HAT. Some official values were updated during the project in consultation with Maritime Safety Queensland. In the end, the decision was reached to model storm surge relative to the official MSL and use the official transfer from MSL to AHD.

The effect of greenhouse-induced climate change was investigated. Three separate scenarios were tested. These were (A) combined effect of an increase in maximum intensity (MPI) by 10% and a poleward shift in tracks of 1.3°. (B) increase in frequency of tropical cyclones of 10%. (C) mean sea level rise of 300 mm. In general the mean sea level rise is the most important effect especially at lower return periods. The 10% increase in tropical cyclone frequency is insignificant. The combined increase in intensity and poleward shift in tracks becomes increasingly significant with larger return periods. Both the magnitude and probability of greenhouse-induced mean sea level rise are more certain than greenhouse-induced changes in tropical cyclone frequency, central pressure, or track.

For all project reporting locations, the occurrence of a tropical cyclone was defined as any that occurred in the western Coral Sea regardless of its distance from the location. This has the property of merging the return period curve for tropical cyclone-induced storm tide into the return period curve for astronomical tide at the lower end of the curves. A more selective definition of tropical cyclone occurrence would have caused the return period curve of storm tide to decrease rapidly (sometimes below HAT) at the lower end of the curve. The adopted definition was used to avoid any misinterpretation of the frequency of water levels at return periods that may be dominated by non-cyclonic events.

There are several influences that affect water levels that are not considered in this study.

- **Wave setup, runup and overtopping were not considered. These could have a significant impact on water levels in locations under direct wave attack. However, it is important to note that water levels created by wave setup will not translate far inland after overtopping frontal dunes, flowing overland over low lying areas, or proceeding through inlets. Once flow starts wave setup reduces markedly; therefore, storm tide curves that include wave setup would apply only to areas with direct wave attack.**
- **Over land flooding was not considered. For areas more than a couple hundred metres landward of the shoreline during the storm, an overland flooding study might be necessary to provide definitive results for inland locations, especially if the inland floodable area is large.**
- **The results in this study are for tropical cyclone-induced water levels. For return periods below about 100 years, non-cyclonic events will be increasingly important; therefore, the combined curve of tropical and extra-tropical storm tides will be higher than the cyclone-induced storm surge plus tide curves shown in this report. The increase due to non-cyclonic events is expected to be about 0.2 m at 10 years reducing to 0.0 m at about the 200 year return period.**

The largest storm surges in the synthetic ensemble, although severe, are not the largest possible. The probable maximum water level at a given location would be caused by a tropical cyclone and tide with the following characteristics. (1) very severe central pressure, (2) large radius to maximum winds, (3) landfall point at a distance equal to the radius of maximum winds to the north, (4) forward speed of the eye equal to the short wave speed offshore and the shallow water wave speed over the shelf, and (5) most importantly for the Queensland region with its large tidal ranges, an astronomical tide level, at the time of maximum surge that is close to HAT. The combination of these characteristics would be very rare, but not impossible.

If an estimate of the probable maximum level were calculated by adding the largest storm surge from the 3000 years of simulations to the HAT level, then this would result in a total water level relative to AHD of about 5.3 m at *Cairns*, 6.8 m at *Townsville* and 6.8 m at *Mackay Town Beach*. These are approximately 2.4, 3.5 and 2.5 m, respectively above the 1000 year water levels. It must be emphasised that these probable maximums are not accurate estimates. As discussed in Section 5, the maximum *Townsville* surge appears to be an outlier, and this highlights the random and infrequent nature of very severe tropical cyclones.

A caution is necessary on the possibility of water levels much higher than the 1000 year levels that are presented in this report. The occurrence of the probable maximum water level could have devastating consequences for a nearby community. Although the probability of occurrence is very rare, a calculation of the risk (probability times consequences) is an important component of both disaster and longer term land use planning.

1.0 INTRODUCTION

The Australian Bureau of Meteorology (*BoM*) in conjunction with the Queensland Environmental Protection Agency (*EPA*) commissioned this study with the financial support from the Greenhouse Special Treasury Initiative. The *Marine Modelling Unit* (*MMU*) of the School of Engineering at James Cook University working through the *Cooperative Research Centre for the Great Barrier Reef World Heritage Area* (*CRC Reef*) was commissioned to provide storm tide statistics during tropical cyclones for the east coast of Queensland. The impact of possible greenhouse climate change was to be assessed.

This study is the third in a series of studies under the heading the *Queensland Climate Change and Community Vulnerability to Tropical Cyclones* project. The first two studies are reported in Harper *et al.*, 2001 and Hardy *et al,* 2004.

The frequency of surge plus tide levels during tropical cyclones has been determined for 50 locations along the east coast of Queensland. These locations are shown in Figure 1. Similar information is available in the Stage 2 report (Hardy *et al,* 2004) for the Hervey Bay and Sunshine Coast regions that also includes the contribution from wave setup.

1.1 Scope

The scope of the project is as follows:

Storm Tide Simulations

1. A very large ensemble of synthetic tropical cyclones was created using the *MMU* track and pressure model (James and Mason, 1999, in press). This ensemble represents 3000 years of storms. The goal was to accurately define the 1000 year return periods.
2. This ensemble was simulated by *MMUSURGE*.
3. The storm surge time series was linearly combined with a large number of possible astronomical tides to create a very large set of storm tide events for each study area.
4. Wave setup was not included.
5. The final results are statistics (return period) of total water level at open coast locations (i.e. overland flooding was not be considered). Statistics for at most 50 open coast locations were generated.

Greenhouse Effects

6. The effect of greenhouse-induced sea level rise, and tropical cyclone frequency and intensity changes was incorporated by either post-processing the simulation results or re-simulation (at most one) of the ensemble.

2.0 FREQUENCY OF TROPICAL CYCLONE STORM TIDE

Our goal is to provide a good estimate of the 500-year return period and a reasonable estimate of the 1000-year level, so an ensemble representing 3000 years was modelled. The results can be thought of as 1, 3 and 6 samples of the infinite number of possible 3000, 1000 and 500 year lengths of record, respectively. Since lower return periods are increasingly dominated by non-cyclonic events, the goal is to determine which tropical cyclones will contribute storm tides greater than the 10-year level and to simulate only those storms.

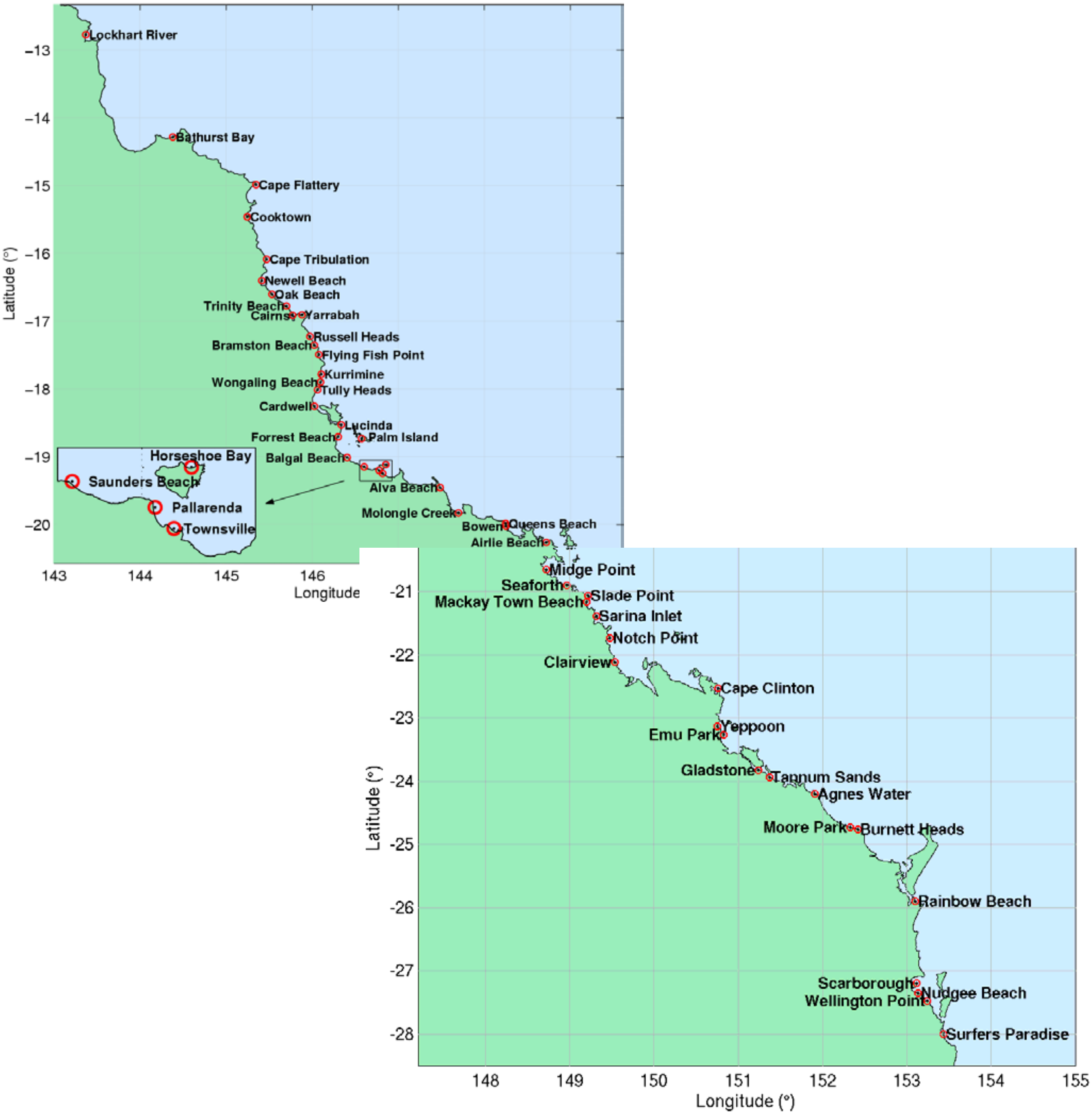

Figure 1. Locations of return period curves of surge plus tide during tropical cyclones

The results of this modelling will be presented in terms of return period curves for the maximum storm surge plus tide that occurs during a tropical cyclone. The return periods, R_η, of the *maximum* water level that occurs during a single storm are given as the inverse of the rate of occurrence, λ_η, of water levels that are *equal to or greater than* that given magnitude (η), or

$$R_\eta = \frac{1}{\lambda_\eta} . \tag{1}$$

The rate of occurrence, λ_η, is determined by ranking the values of water level from largest to smallest over a known period of time and then dividing by the length of that time period. This is given by

$$\lambda_\eta = \frac{m_\eta}{n} , \tag{2}$$

where m_η is the rank of the maximum water level during the storm and n is the number of years of record. For example, if a simulated cyclone has a maximum water level of 3.2 m and this is the 6th largest in 3000 years of simulated record then the frequency of occurrence and return period of a water level equal to 3.2 m would be

$$\begin{aligned} \lambda_{\eta=3.2} &= \frac{6}{3000} = 0.002 \\ R_{\eta=3.2} &= \frac{1}{0.002} = 500 \text{ years} \end{aligned} . \tag{3}$$

3.0 PRESENTATION OF THE MODELLING SYSTEM

3.1 Synthetic Tropical Cyclone Track and Pressure Model – *CycSyn*

The availability of data for Coral Sea tropical cyclones is discussed in the Stage 1 report (Harper et al., 2001) and by Holland (1981). Although some satellite data is available from 1960, the record is not complete until 1969 when increased satellite coverage and improved analysis techniques began to provide a complete record of track position and central pressure. The creation of the synthetic database used in this project requires a complete data set. A complete and reliable set of historical data on the tracks and intensities of tropical cyclones affecting the western Coral Sea is limited to the relatively small number (approximately 108 which have occurred (1969-2001). The data are available from the BoM web site, ftp://ftp.bom.gov.au .

If just these tropical cyclones were modelled, this sample would give only one of an infinite number of possible renditions of 33 years of water levels during tropical cyclones. This short record is much too small to define the 500 year or even the 100 year return period values. To overcome this lack of data, a model (*CycSyn*) capable of simulating synthetic time histories of tracks and central pressures of tropical cyclones in the Coral Sea was developed. Full details of the model are contained in James and Mason (1999 and submitted). A very brief description of the model is as follows.

Cyclone position and central pressure are determined by an autoregressive 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 regression of 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. Historical starting values could be used to generate a large number of synthetic tracks, but the small number of historical starting positions could bias these tracks. Therefore initial values were randomly selected from a six-dimensional data space based on the data set of historical initial values of each of the six parameters.

The box in Figure 2 indicates the boundary of data zone for both initial values and model coefficients. This region was selected, as opposed to the whole of the Coral Sea, since we desired the population of tropical cyclones that threatens the east coast of Queensland and storms that do not cross into this region pose little threat.

Radius of maximum winds is an important parameter for since larger radii increase both the available wind energy and the area over which the winds act. Almost no radius to maximum winds data are available for Coral Sea tropical cyclones and time series data are rare in other regions; therefore, an autoregressive model such as that described above for position and central pressure cannot be developed and an alternative procedure was necessary (Hardy *et al.* 2003).

The time histories of position (latitude, ϕ and longitude, λ), central pressure, p_o, and radius to maximum winds, R_m, were created for a 3000 year long record of cyclones or 9911 synthetic tropical cyclones. The statistics of this synthetic ensemble compares well with those of the measured data as is shown in Figures 3-8. In these figures the historical data fall within the 90% confidence limits about the model results obtained by applying a bootstrap technique (Efron, 1979) to the synthetic data.

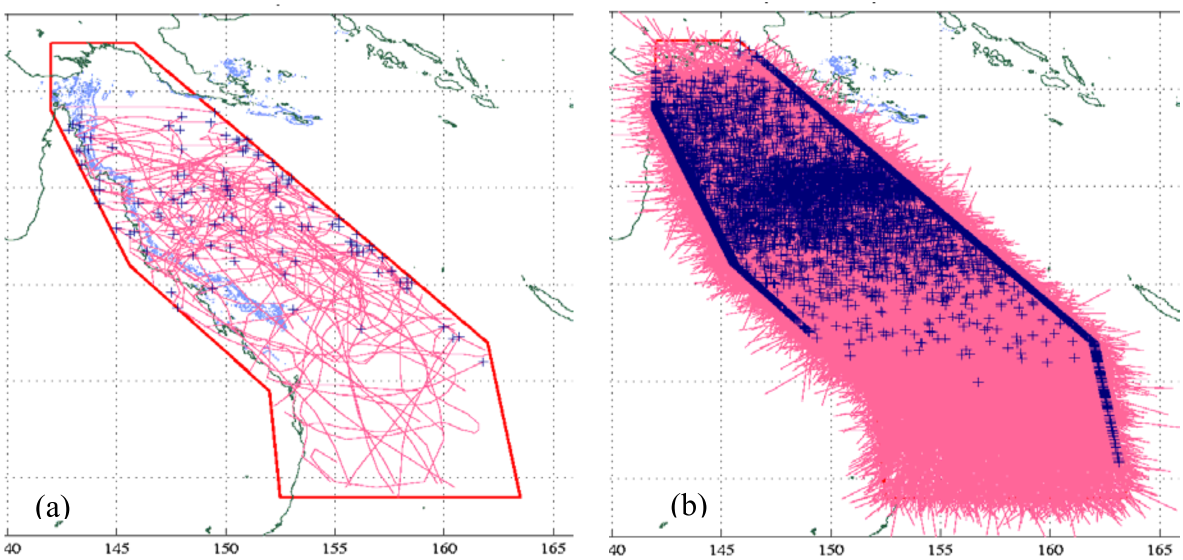

Figure 2. 3000 years of synthetic tropical cyclones tracks. (a) contains 108 historical tracks (1969-2002). (b) contains 9911 tracks (3000 year simulation). Dark blue crosses indicate starting positions. Light blue area in (a) is the Great Barrier Reef.

The track histories of position, pressure and radius to maximum winds were created for a 3000 year long record of cyclones or 9911 synthetic tropical cyclones. The statistics of this synthetic ensemble compares well with those of the measured data as is shown in Figures 3 to 8. In these figures, synthetic and measured data are compared for minimum central pressure, forward speed of the "eye" of the storm and direction of storm movement. Six different regions are considered covering the whole of the eastern Queensland coast. The historical data fall within the 90% confidence limits about the synthetic data that is obtained by applying a bootstrap technique (Efron, 1979) with 5000 replications.

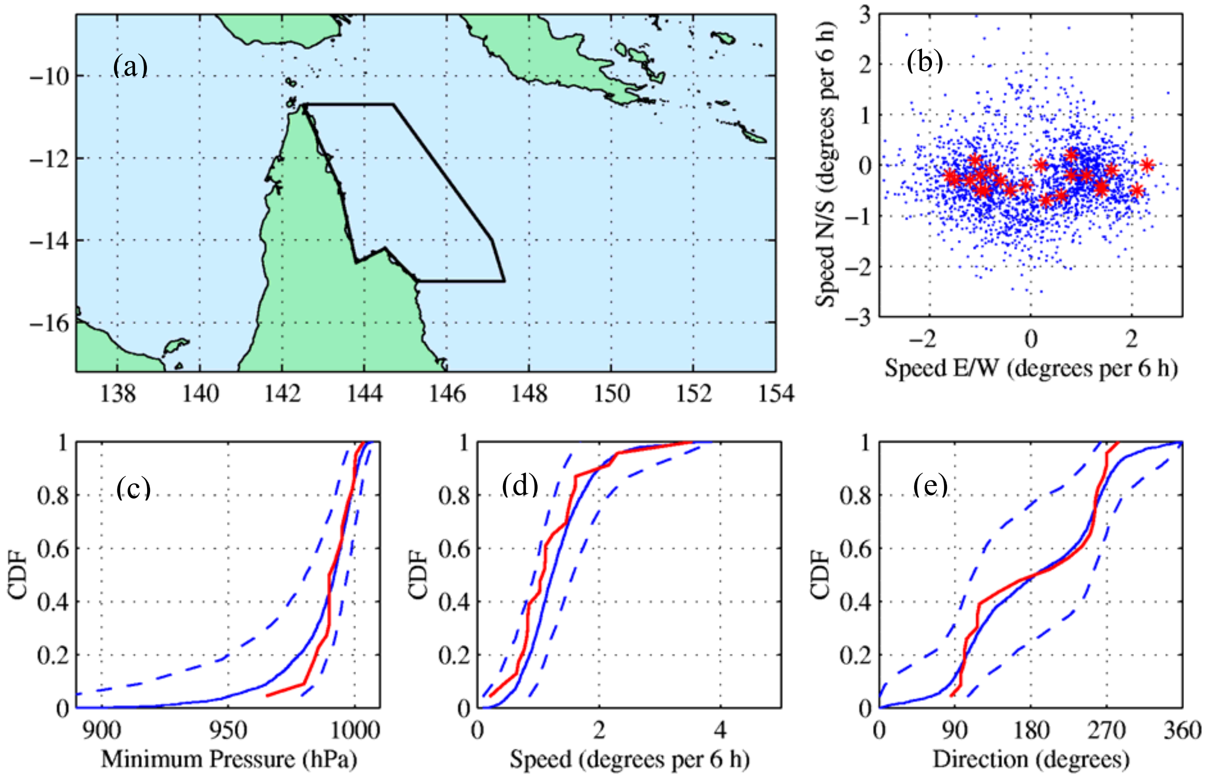

Figure 3. Statistical comparison between synthetic and measured data inside box in (a). Measurements are shown by * and numerical data by • in (b). The lines in (c), (d) and (e) are ▬ historical data; ▬ synthetic data; and – – 90% confidence limits about synthetic data.

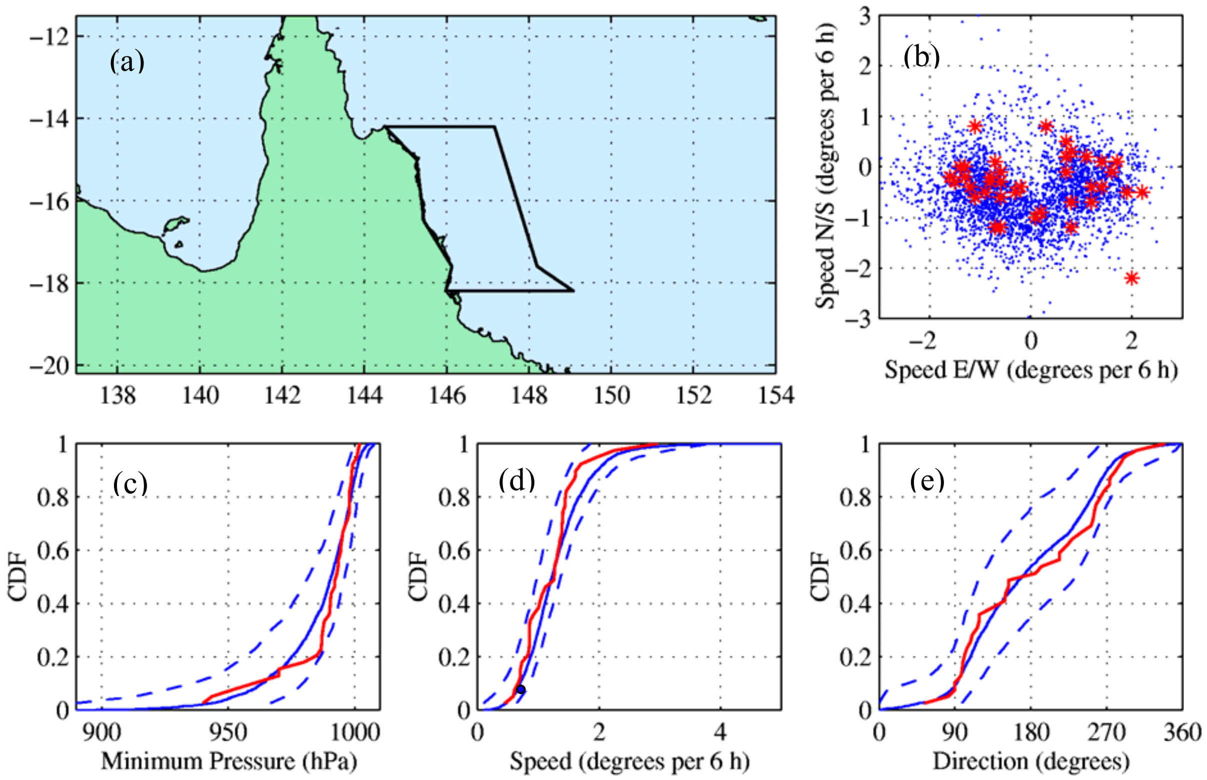

Figure 4. Statistical comparison between synthetic and measured data inside box in (a). Measurements are shown by * and numerical data by • in (b). The lines in (c), (d) and (e) are ▬ historical data; ▬ synthetic data; and – – 90% confidence limits about synthetic data.

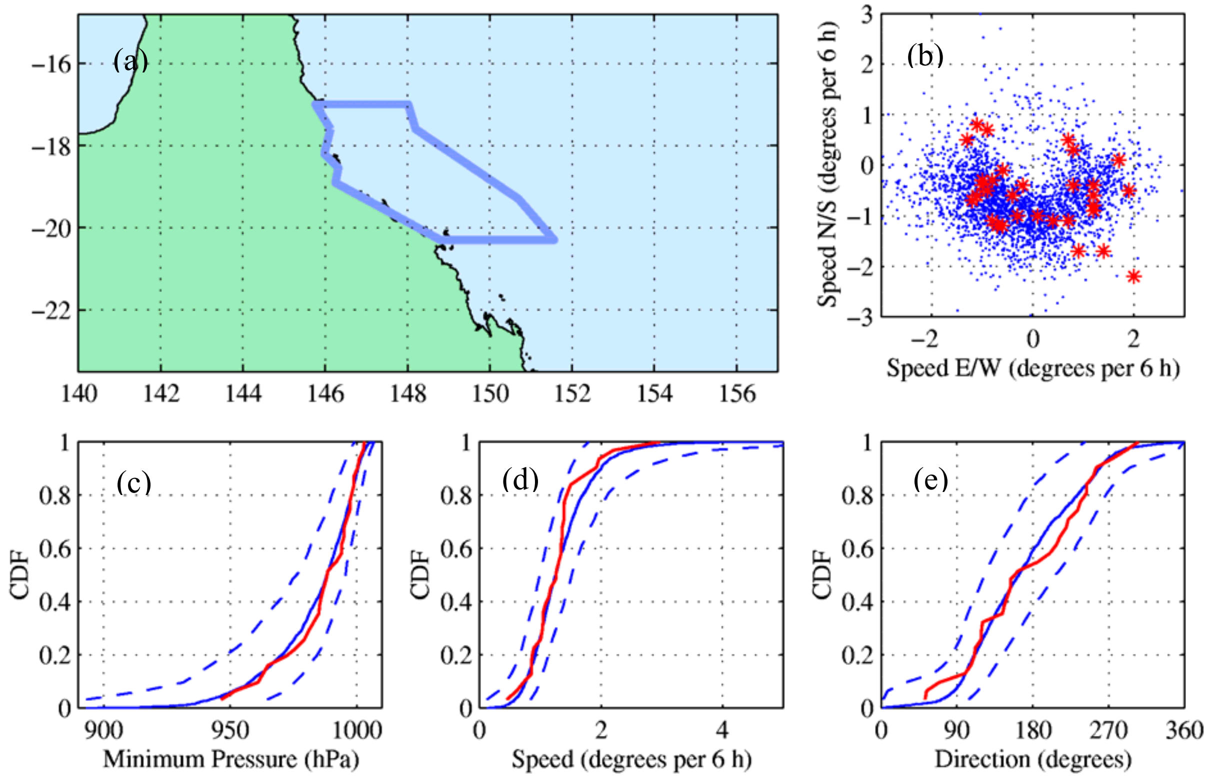

Figure 5. Statistical comparison between synthetic and measured data inside box in (a). Measurements are shown by * and numerical data by • in (b). The lines in (c), (d) and (e) are historical data; synthetic data; and 90% confidence limits about synthetic data.

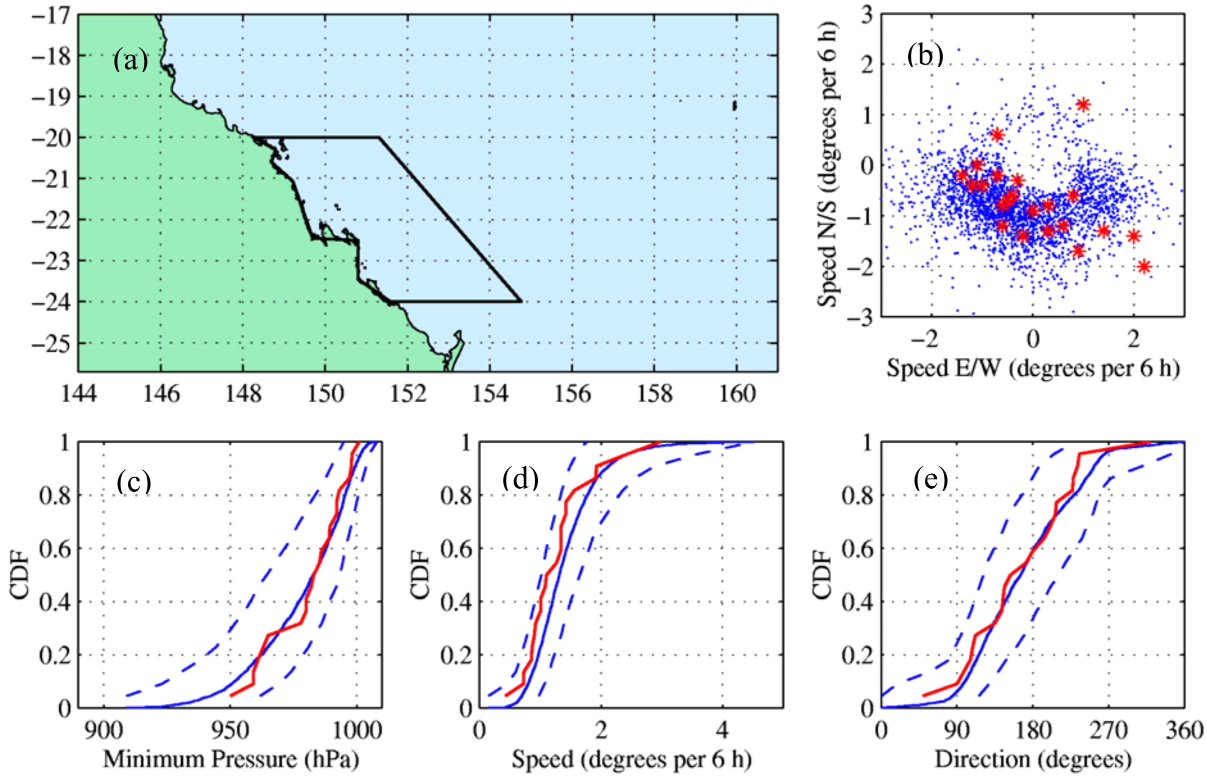

Figure 6. Statistical comparison between synthetic and measured data inside box in (a). Measurements are shown by * and numerical data by • in (b). The lines in (c), (d) and (e) are historical data; synthetic data; and 90% confidence limits about synthetic data.

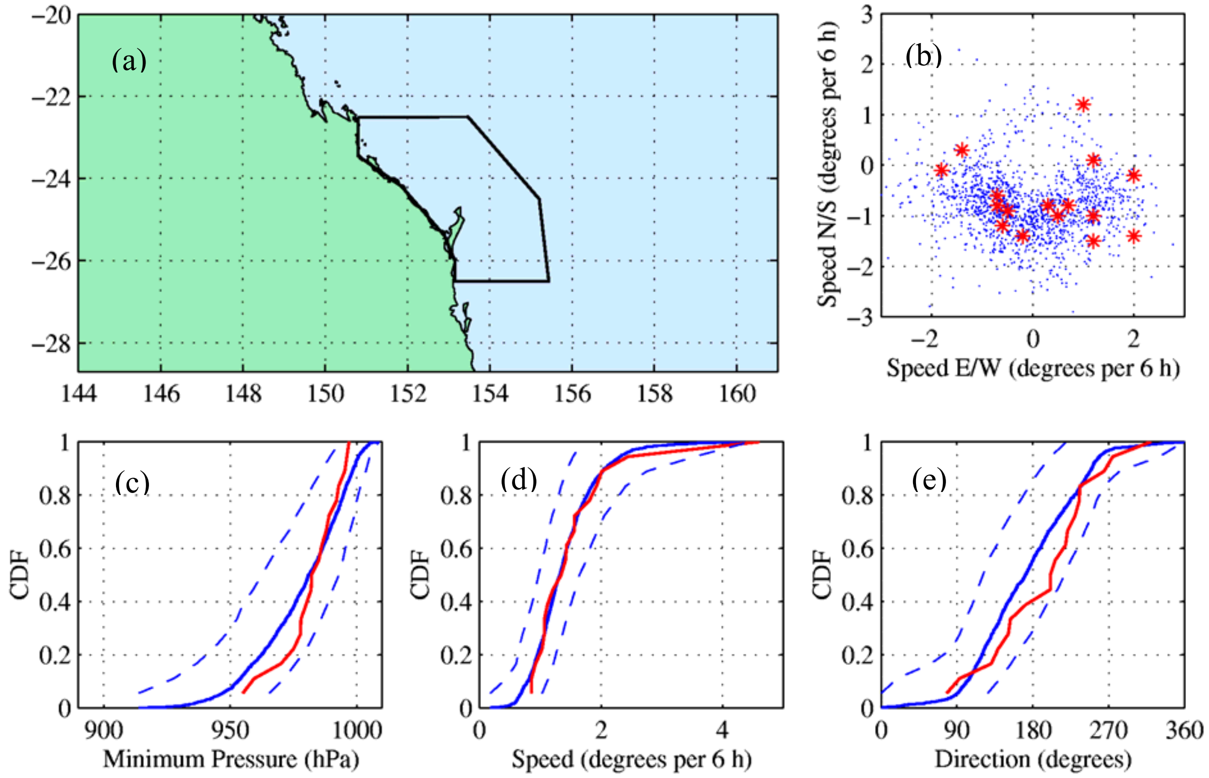

Figure 7. Statistical comparison between synthetic and measured data inside box in (a). Measurements are shown by * and numerical data by • in (b). The lines in (c), (d) and (e) are ▬ historical data; ▬ synthetic data; and ▬ ▬ 90% confidence limits about synthetic data.

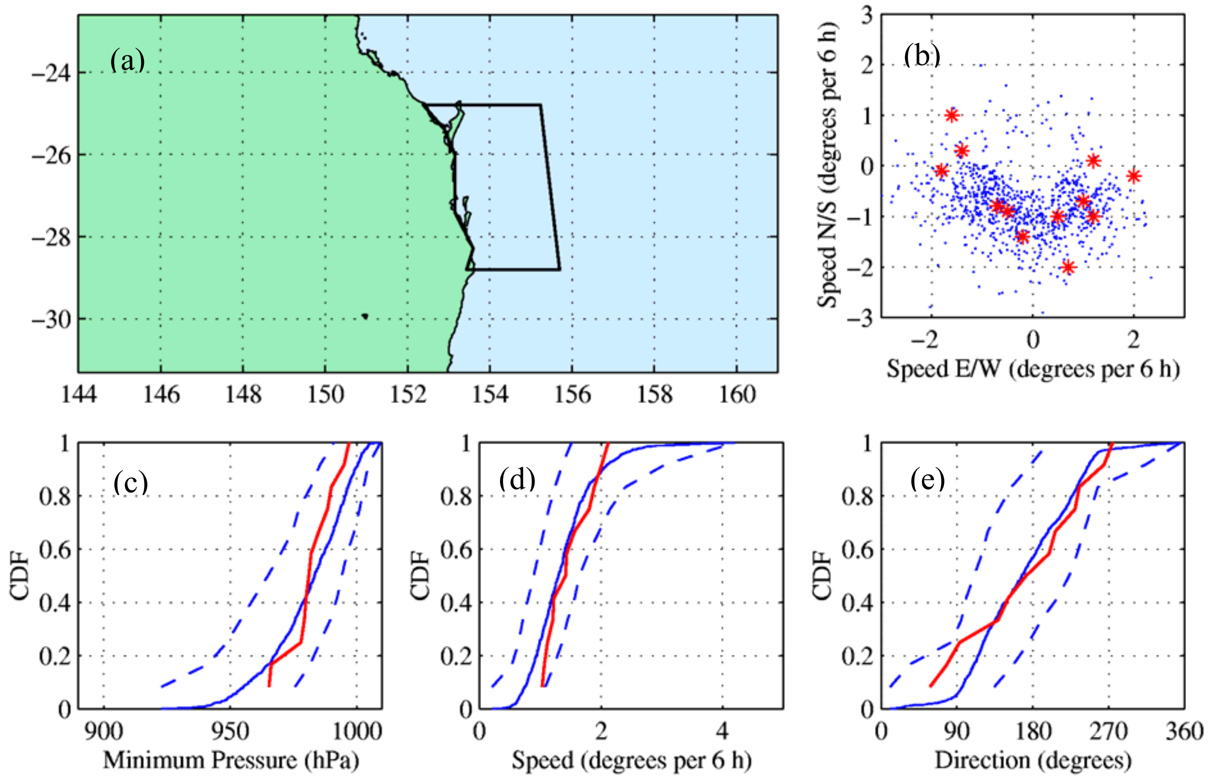

Figure 8. Statistical comparison between synthetic and measured data inside box in (a). Measurements are shown by * and numerical data by • in (b). The lines in (c), (d) and (e) are ▬ historical data; ▬ synthetic data; and ▬ ▬ 90% confidence limits about synthetic data.

3.2 Tropical Cyclone Windfield Model for the Coral Sea - *CycWind*

The *MMU* has developed a parametric model of the wind fields during tropical cyclones in the Coral Sea region. This model named *CycWind* is fully described in McConochie *et al.* (1999, in press). *CycWind* is based on the parametric model introduced by Holland (1980).

A secondary vortex is included in *CycWind*, following the work of Thompson and Cardone (1996). Willoughby *et al*. (1982) discussed the occurrence of multiple concentric eyewalls in tropical storms, typhoons and super typhoons for the western Pacific region. They found that the presence of two concentric eyewalls was a common occurrence in intense symmetric storms. The secondary eyewall has also been found in Coral Sea tropical cyclones such as *Justin*, (Callaghan, personal communication) and *Althea* (Callaghan, 1996). Although a second eyewall does not always occur in Coral Sea cyclones, tropical cyclones in this region are almost always embedded in the monsoon trough. Hence use of a secondary eyewall formulation, which creates an outer extended region of lower pressure, can also be used to represent the effect of the trough. The effect of the second eyewall is to reduce the wind speed in the vicinity of the primary eyewall and to increase it at distances greater than about three times the radius to maximum winds.

Full description of the wind field model is beyond the scope of this report and can be obtained from McConochie *et al.* (1999, in press). In brief, the wind field (speed and direction as a function of time and space) is determined as a function of nine parameters

$$\{\Delta p_1, \Delta p_2, R_{m1}, R_{m2}, B_1, B_2, K_m, U_s, \theta_s\}$$

for which the subscripts 1 and 2 indicate the primary and secondary vortices, respectively; Δp_i is the portion of the pressure deficit assigned to the vortex, R_{mi} is the radius to maximum winds of the vortex, B_i is a peakedness parameter that affects the shape of a special cross section of the wind profile, K_m converts the gradient winds to a 10 m elevation, U_s and θ_s are the speed and direction of the synoptic winds (see below).

For this study

$$\Delta p = p_\infty - p_o = \Delta p_1 + \Delta p_2 , \quad (4)$$

where p_o, the central pressure of the storm, is obtained from *CycSyn*, $p_\infty = 1010$ hPa is the ambient pressure.

Extensive testing (McConochie *et al.,* 1999, in press) has found that Coral Sea tropical cyclones are well represented by values of pressure deficit and radius for the secondary vortex of

$$\Delta p_2 = 8 + \frac{1}{20}(\Delta p - 8) \text{ hPa}, \quad (5)$$

$$R_{m2} = 250 \text{ km}. \quad (6)$$

Finally, the peakedness parameters were given values of

$$B_1 = 7.3 - \frac{p_o}{160}$$
$$B_2 = 7.2 - \frac{p_o}{160} \quad . \tag{7}$$

For example, if p_0 = 950 hPa (representative of the severest storm in the measurements in this region), then Δp = 60 hPa, Δp_2 = 10.6 hPa, B_1 = 1.3625 and B_2 = 1.2625.

The extended pressure field as described by Cardone et al. (1994) is calculated using

$$p = p_0 + \sum_{i=1}^{2} \Delta p_i \, e^{-(R_{mi}/r)^{B_i}}$$
$$\sum_{i=1}^{2} \Delta p_i = p_\infty - p_0 \quad , \tag{8}$$

where p is the pressure at radial distance r.

The gradient wind speed, V_{gc}, due to the cyclone, which is a balance between the pressure gradient force, the Coriolis force , f, and the centrifugal force, is calculated using

$$V_g = \sqrt{\sum_{i=1}^{2} V_{ci}^2 + \left(\frac{rf}{2}\right)^2} - \frac{r|f|}{2} \quad , \tag{9}$$

where, the cyclostrophic wind speed is given as

$$V_{ci} = \sqrt{\left(\frac{R_{mi}}{r}\right)^{B_i} \frac{B_i \Delta p_i}{\rho_a} e^{-\left(\frac{R_{mi}}{r}\right)^{B_i}}} \quad . \tag{10}$$

In order to obtain the surface winds, a boundary layer wind speed and direction (inflow) correction is applied to the gradient wind. The surface wind speed at a 10 m elevation is calculated using:

$$V_{10} = K_m V_g \quad . \tag{11}$$

The formulation adopted for the calculation of the parameter K_m is based on work reported in the Stage 1 study, Harper et al. (2001), in which

$$\begin{array}{lll} K_m = 0.81 & & V_g < 6 \text{ m/s} \\ K_m = 0.81 - 2.96\times10^{-3}\left(V_g - 6\right) & 6 \leq & V_g < 19.5 \text{ m/s} \\ K_m = 0.77 - 4.31\times10^{-3}\left(V_g - 19.5\right) & 19.5 \leq & V_g < 45 \text{ m/s} \\ K_m = 0.66 & 45 \leq & V_g \text{ m/s} \end{array} \quad . \tag{12}$$

The inflow angle correction is applied to represent the cross-isobaric flow caused by surface friction and based on the work of Sobey et al (1977) is given as,

$$
\begin{aligned}
\beta &= 10\frac{r}{R_{m1}} & r &< R_{m1} \\
\beta &= 75\frac{r}{R_{m1}} - 65 & R_{m1} \leq\ r &< 1.2R_{m1} \\
\beta &= 25 & 1.2R_{m1} &\leq r
\end{aligned}
\qquad (13)
$$

This wind profile is used to simulate not only concentric eye-wall cyclones (as in Cardone et al., 1994), but also to improve the fit of the model wind speeds to those measured more than $3R_{m1}$ from the centre of the cyclone. The adoption of the Cardone pressure profile formulation was motivated primarily by the existence of monsoon troughs in which cyclones in the Coral Sea are often embedded. The formulation has worked very well in enabling better fits in a wide range of tropical cyclones in both the Coral Sea and Australian Indian Ocean (McConochie et al., 2001, in press).

A representation of winds generated outside the cyclone vortex, herein called s*ynoptic* winds has been included in the wind model used in this project. During Coral Sea cyclones, large pressure gradients often occur between the cyclone and the mid-latitude high pressure cell, which can induce wind speeds up to 40 knots (Callaghan, 1996). Since waves generated by these winds can add considerable energy to the region during cyclones, a wind field based solely on a vortex model will under-estimate wave energy, especially more than about $8R_m$ to the south of the storm centre where the diminished effect of the main cyclone vortex makes synoptic winds relatively more important.

For each synthetic simulation a speed and direction for the synoptic component were randomly selected from historic data during tropical cyclones at weather stations in the south Coral Sea. These values are held constant throughout the simulation. Holding the synoptic winds constant will give a conservative result, since changes would invoke both duration and fetch limitations.

3.3 Tropical Cyclone Storm Surge Model – *MMUSURGE*

MMUSURGE is a computer model that calculates water velocities (actually transports) and water surface elevation on a discrete grid by numerically solving the conservation of momentum and mass equations using finite difference techniques. *MMUSURGE* was used in Stage 1 of this project (Harper *et al.*, 2001) for modelling storm surge along the Queensland coast. It is a 2-D version of the 3-D model *MMUHYDRO*, which has been under continuous development and use by the *MMU* over the last two decades.

The horizontal transports *U* and *V* are specified on a spatially staggered finite difference grid (the Arakawa *C* scheme). The governing equations are solved by a fully implicit splitting procedure, based originally on work by Wilders *et al.* (1988). Changes from this scheme of Wilders *et al.* are described in more detail in Bode & Mason (1994) and include the use of transport rather than velocity components as prognostic variables, implicit bottom friction, and an implicit method for treating the Coriolis terms on a staggered grid. Changes have also been made to the treatment of advective terms. A pre-conditioned version of the conjugate gradient squared method is used to invert the sparse matrices generated by the difference scheme. Further modifications to the difference scheme have been implemented to accommodate the reef parameterisation algorithms.

Storm surge grid system

The main rationale behind the use of the nested grid system used in *MMUSURGE* is the need to overcome open boundary condition problems, which are commonly encountered in limited area, fine-scale modelling. By means of nesting, the finest-scale grid, which surrounds the area of interest, is linked to the dynamics of the continental shelf, so that open boundary problems are largely transferred further afield, where: (i) The extensive range of tidal data from the shelf region can be utilised for boundary conditions. (ii) Any inaccuracies in the specification of boundary conditions will have negligible influence on the evolution of model solutions in the region of interest. (iii) The essentially unknown boundary conditions associated with wind forcing are assumed to be zero.

Three nested grids are used for computational efficiency, so that accurate wind driven and tidal boundary conditions can be supplied to the finest grid. A standard 5:1 increase in resolution between successive grids was used to obtain an approximately 550 m resolution in the study area. The *A*-grid (Figure 9) has a 7.5′ resolution. (Note that 1.0′ of latitude (1.0 minute of arc) is equal to 1.0 nautical mile which is equal to 1852 m). The eight *B* grids (Figure 9) have resolutions of 1.5′ (2800 m). The twenty *C* grids (Figure 9) increase the resolution to about 550 m. The varying oblique orientations of the grids are achieved by using transformed spherical coordinate systems. The primary source of information for model bathymetry were navigational charts. This was supplemented by bathymetric surveys supplied by *EPA*.

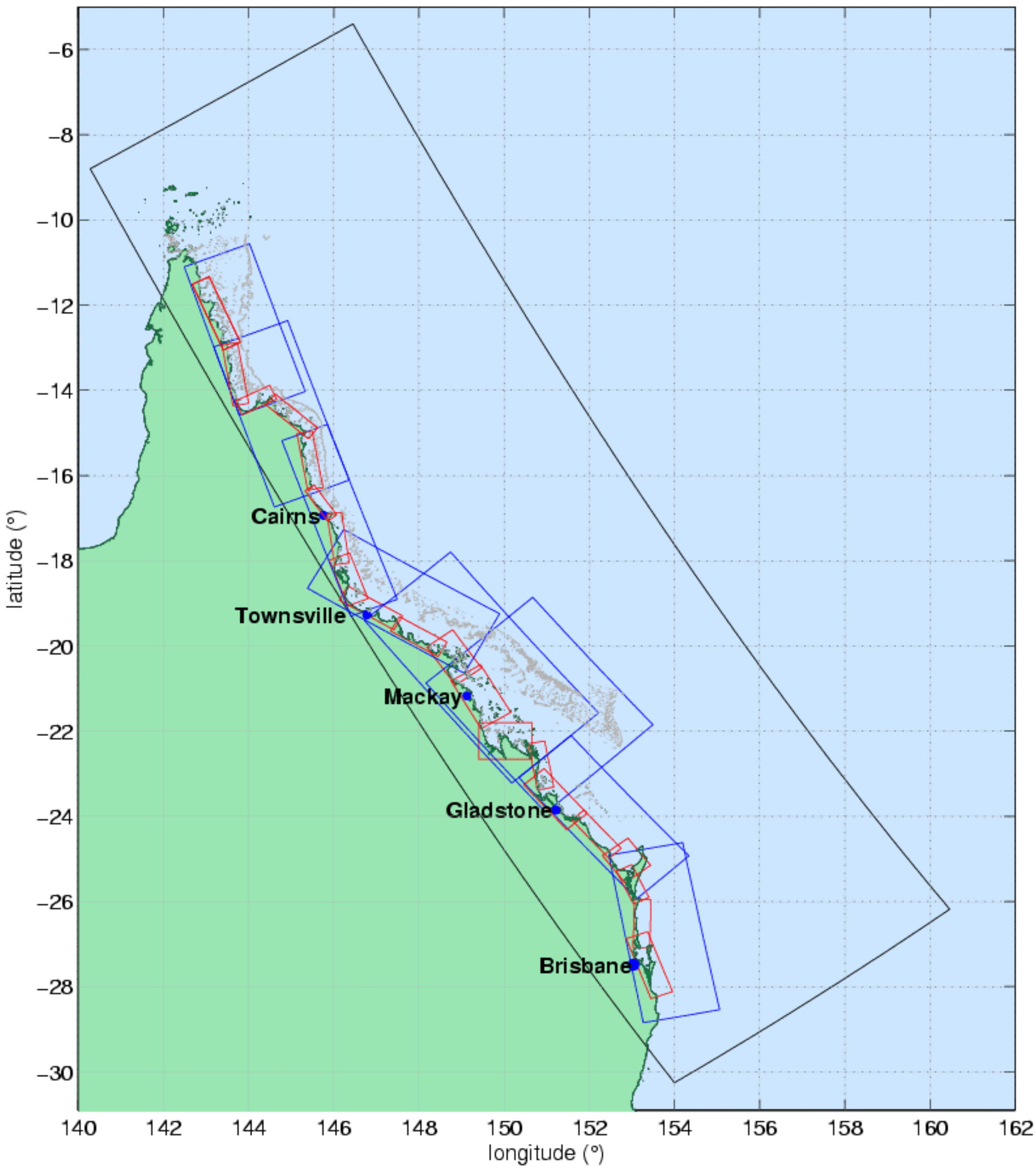

Figure 9. Nested grid system. One *A* grid: (black) resolution 7.5′. Eight *B* grids (blue) resolution 1.5′. Twenty *C* grids (red) resolution 550 m.

Validation of MMUSURGE

Extensive validation results for *MMUSURGE* were presented in the Stage 1 report (Harper *et al.*, 2001). This implementation of the model did not require changing the values of any calibration parameters.

4.0 MODELLING STORM TIDE OF THE TROPICAL CYCLONE POPULATION

4.1 Synthetic Ensemble of Tropical Cyclones for the East Coast of Queensland

The tropical cyclone database (http://www.bom.gov.au/climate/how/ and Harper *et al,* 2001) provides data on Coral Sea tropical cyclones after 1969 – the advent of analysis from weather satellites. These data were analysed to separate the tropical cyclones that threatened the eastern Queensland coast (defined as entering the area delineated by the box in Figure 2). Thus a rate of cyclone occurrence of λ_C = 3.3030 tropical cyclones per year (109 tropical cyclones in 33 years: 1969 to 2001) was determined from this data. We chose to conduct a Monte-Carlo simulation of 3000 years of tropical cyclones, so that an estimate of the 1000 year return period would be reasonably accurate. To achieve this target, 9911 tropical cyclones (3000 years) × (3.3030 T.C. per year) were modelled.

The first step in this process was to create the time series of position, pressure and radius to maximum winds for 9911 tropical cyclones using *CycSyn*. The model was calibrated using historical tropical cyclones that started or passed through the area shown by the box in Figure 2. These tropical cyclones represent the population of tropical cyclones that threaten the eastern coastline of Queensland, so not all of these will cause a severe impact in the study areas of this project. Statistics from this synthetic ensemble are compared to the historical data in Figures 3 to 8.

4.2 Selecting the Tropical Cyclones to be Modelled by *MMUSURGE*

Recall that the final results of this study are return period curves of surge plus tide. Surge and astronomical tide are nonlinearly related, as they both affect and are affected by changes in water level. As will be seen in the following presentation, developing the frequency relationships will require a large number of simulations and this makes it infeasible to model these in a coupled, nonlinear fashion. Therefore storm surge and astronomical tide will be independently modelled and the storm tide will be determined by a linear superposition of the resulting time series.

The procedure to determine the ensemble of storms that defined return periods above 10 years is as follows: First, all 9911 storms (3000 years) were simulated by *MMUSURGE* on the *A* grid. Simulations on the coarse grid are much less computationally expensive than on *B* or *C* grids. Computational points from the *A* grid, which are inside the area of a *C* grid were used to represent each study area. These representative *A*-grid points were chosen to be the first two rows of points along the coastline in each of the study area grids. For example, this is shown in Figure 10 for Cairns, Townsville and Mackay.

For each storm in the ensemble, the maximum surge that occurred at each representative *A*-grid point was identified. After the whole storm ensemble was simulated, these maxima were ranked by size at each point. These ranks are the values of m_η in eqn. 2. After substituting eqn. 2 into eqn. 1, the value of the rank at R = 10 years becomes

$$m_\eta = \frac{n}{R} = \frac{3000}{10} = 300 \qquad (14)$$

Thus storm surges greater than or equal to the 10 year level are determined by the storms with the 300 largest values of maximum storm surge. Thus only the 300 severest storms (at each point) need to be simulated in order to define the return period curve above 10 years for the study area. Thus, each location would require simulation of only a very small subset of the ensemble of 9911 storms.

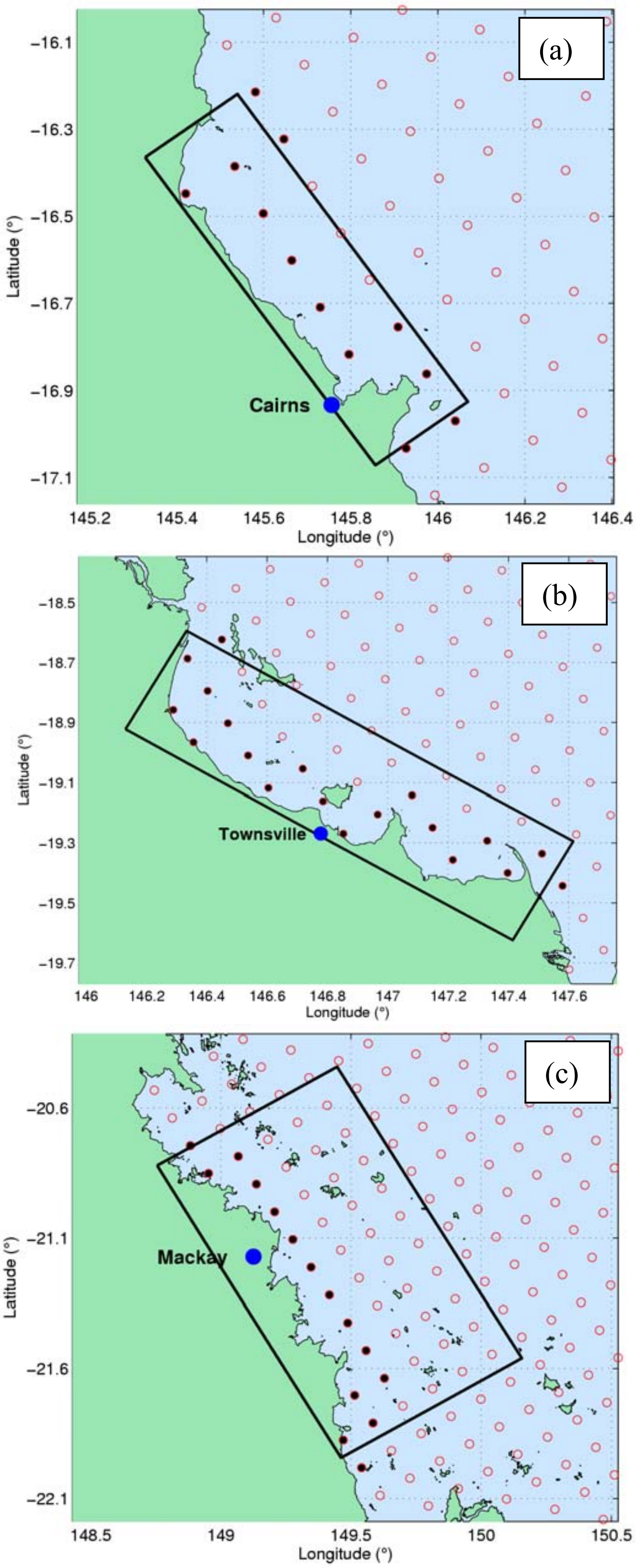

Figure 10. *A*-grid output points (solid circles) chosen to select storms, using *A*-grid simulations, that cause storm surge greater than the 10 year return period at (a) Cairns, (b) Townsville and (c) Mackay. Boundaries of the storm surge *C*-grids are shown.

Of course, each representative *A*-grid point could have a unique set of the most severe 300 storms. Although the variation of these lists inside the relatively small geographical region of a single *C* grid would be limited, it is unlikely that the largest storm surges at *all* locations in the area covered by the *C* grid would come from the same 300 tropical cyclones.

To account for the variation inside a C-grid, we decided to simulate all tropical cyclones that caused the largest 300 values in storm surge at *any* of the representative points. These tropical cyclones were simulated by *MMUSURGE*. The number of tropical cyclones simulated for a single *C* grid varied from 421 to 619. For the results shown below for Cairns, Townsville and Mackay, 525, 585 and 541 storms were simulated on the respective *C* grids. In total for the whole east coast of Queensland, 3622 individual storms were simulated and there were 10,854 *C*-grid simulations.

Since over 500 of the severest storms are simulated instead of only the 300 most severe that are needed to define the 10 year return period, it is instructive to see how much lower this defines the return period curve. An analysis showed that approximately 370 out of the largest 400 (R = 7.5 years) were simulated. This means that tropical cyclones that produce surges with magnitudes larger than that of the 7.5 year return period are well represented.

The final outputs of this study are return period curves of *storm surge plus tide*. The storm events that contribute *water levels* above the 10-year level do not include solely those storms with *storm surges* above the 10 year level. A storm with surge smaller than the 10 year level could contribute to the storm surge plus tide curve above 10 years, if the maximum surge during the storm combines with higher tides. Therefore simulating only the largest 300 storm surges may slightly underestimate the level of the return period curve between 10 and, say, 100 years. This problem would disappear if the whole ensemble were simulated. However it is infeasible to model all 9911 storms on the fine resolution grids. Even it were feasible, a problem arises with the definition of when a tropical cyclone occurs.

The purpose of this project is to produce results *during tropical cyclones*. At the lower end of the return period curve a definition of *tropical cyclone* is necessary. Recall that the storm ensemble represents the western Coral Sea (Figure 2), so that surges with lower rank (perhaps the bottom 90%), at any one location, occur during storms that do not pass close to that location. For many of these storms, the storm surge may well be lower than those that occur during more frequent non-cyclonic events. For example, should a tropical cyclone that is located in the far northern Coral Sea be considered a tropical cyclone occurrence for the southern coast of Queensland, which might be more than 1500 km distant?

The storm tide during such a storm is largely determined by the maximum tide that occurs during the duration of the storm. Is this truly a “storm tide” and should it be included in the set of storm tides “during tropical cyclones”? Certainly the magnitude of storm surge during remote tropical cyclones would occur much more commonly during the much more frequent non-cyclonic events.

Various definitions of what constitutes a tropical cyclone for a given location have been used. These definitions have included an approach with a set distance of the study area, say within 500 km; or the occurrence of strong winds, say above 40 knots; or the occurrence of storm surge above a set level, say 0.3 m. Many other similar definitions are possible, but any such definition is arbitrary. The first attempt at a definition for this project was the occurrence of storm surge above the 10 year return period (nominally the 7.5 year return period as discussed above). This definition is defendable as this project was to produce statistics of severe water levels, and surges at and below the 10-year level are increasingly dominated by events other than tropical cyclones. However, at lower return periods the resulting return period curve dips below highest tide levels and thus below the curve that would result from combining tropical cyclone-induced water levels with non-cyclonic water levels. This result may be misinterpreted by inexperienced users.

After additional consideration, a definition of tropical cyclone has been adopted that includes the whole ensemble of tropical cyclones in the western Coral Sea, regardless of the proximity or effect at a project output location. The inclusion of all storms, the vast majority of which cause very small values of storm surge, creates storm surge plus tide return period curves that will asymptote at lower return periods to a return period curve of tidal height. Since it was infeasible to model the whole ensemble down to *C*-grid resolution, a method was developed to model a small number of representative storms.

The value of tropical cyclone storm surge with a return period of 10-years is about 0.5 m (300^{th} largest out of almost 10,000 storms in 3000 years of simulation) for most of the 50 project output locations. The vast majority of storms in the whole ensemble (more than 9600) have maximum surges that are less than that, i.e. the maximum surges with ranks 1000, 5000 and 9000 are less than about 0.5 m at most locations and in the narrow range between 0.5 and 0.0m.

An *A*-grid point was chosen to represent each output location. At each of the 50 project output locations weaker storms were selected with ranks of 9500, 8500, 7500, 6500 and 5500. Recall that a rank of 1 is most severe and a rank of 9911 the least severe. These 5 extra storms ensured that each output point was represented by a range of very weak storm surges. These additional 250 storms (50 output points × 5 storms) were simulated on all C grids, so that each output point had an additional 250 storm surge time series. Thus each output point had more than 750 storms (the 500+ needed to represent R > 10 years at all points in the grid plus the 250 weak extras) that were each combined with multiple tidal signals to create the surge plus tide return period curves at each location.

4.3 Astronomical Tides

A twenty-one year tidal prediction at a 15 minute interval was produced at each of the project output locations using the best available set of tidal constituents obtained from the analysis of a time series of tide gauge measurements. Few of the output locations are co-located with tidal measurement stations; therefore, a subjective judgement of the best nearby stations was necessary. Table 1 shows the information on the official station and datum (provided by EPA) and the station and data record length used to produce the project tidal signal. The acronyms HAT, LAT, MSL and AHD mean Highest Astronomical Tide, Lowest Astronomical Tide, Mean Sea Level and Australian Height Datum, respectively. The official and project tidal stations differ for several reasons. In some cases neither measurement time series nor tidal constituents were available at the official stations for the determination of tidal constituents needed to produce the time series of tidal heights. In some cases data were available at locations better representative of the output location. At most of the project tide stations, the length of the data time series was longer than one year. For those stations with records shorter than 1 year, semi-annual and annual constituents, from the nearest, long term analysis, were added to those obtained from tidal analysis.

The project tide and storm surge time series were assumed to oscillate about the official values of MSL and then the official difference between AHD and MSL (Table 1) were used to adjust the storm tide signal from a MSL to an AHD datum.

Where tidal analyses were available based on long term tide gauge data, the amplitudes and phases of tidal constituents based on measurements were used to produce the tidal signal.

For a few of the locations (signified by *M* in Table 1) a previously established hydrodynamic tidal model with a resolution of one nautical mile that covers most of the Queensland coast was used to produce tide time series for the storm tide output points that were not best served by moving data from the closest official tidal gauge. The hydrodynamic model used boundary conditions formed by 22 tidal constituents available from a global tidal model based on satellite altimetry (Eanes, 1994).

These boundary conditions were adjusted by calibrations through comparisons of model with measurement stations from the whole GBR region. Over 30 stations were used in this calibration including standard coastal ports (e.g. Townsville, Mackay, Gladstone, etc) and reef based stations (e.g. Gannet Cay, Myrmidon Reef, Raine Island, etc).

These 22 constituents calibrated from the global tidal model input were supplemented by the inclusion of long period constituents from the tidal analysis at the official tidal gauge (Australian National Tide Tables, 1998) and also shallow water constituents that account for the nonlinear interaction of the main constituents that occur as the numerical model carries the tidal signal into coastal areas. Thus the tidal signal was composed of a total 32 constituents. The end result of the modelling is a set of amplitudes and phases for the tidal constituents in the project location. Figure 11 shows comparisons between probability density functions of water elevation during twenty year tidal signals generated by measured and modelled constituents at Cooktown, Mackay and Town of 1770 (close to Agnes Waters).

Figure 11 shows that the tide model does an excellent job of creating the tidal signal.

4.4 Combining Surge and Astronomical Tide to Produce Storm Surge Plus Tide Time Series.

The storm surge was simulated on a constant "tide" of MSL. Since the *timing* of a tropical cyclone is not dependant on the tidal signal (i.e., the cyclone can hit the coast at any phase of the tide), each of the surge time series was linearly added to multiple separate tidal time series to create a very large number of surge plus tide time series for each of the simulated synthetic tropical cyclones. The starting point in the tidal time series was randomly selected using a weighting that favoured months with more cyclonic activity (e.g. February) over months with fewer storms (e.g. November). The weights are shown in Figure 12.

Each of the 300 storm surges at each output point (chosen so that return periods above 10 years were represented) was combined with 500 tidal time series. Recall that just over 500 storms were simulated on any one *C* grid since not all points have the same set of the 300 largest maximum storm surges. These additional 200+ tropical cyclones, as well as the 250 extra "weak" storms were handled differently. For each *A*-grid point that represented an output location, the maximum storm surge of each of these storms was placed in the ranking of the 9911 storms. Thus, these 450+ storms were spread throughout the 9611 storms with maximum storms surges less than the 10 year level. Each was deemed to represent the storms in its region of the distribution from half way from its nearest neighbour below to half way to its nearest neighbour above. If k is the number of storms represented by one of these 450+ storms, then the number of tidal signals with which the storm surge time series would be combined was calculated as $500k$. For example, if the 450 extra storms were evenly distributed between ranks of 300 and 9911, then k would be approximately 21.

This process of representing the population of storm surge plus tide events by combining the 3000 years of simulated storm surge time series with 500 tides can be thought of as repeating a 3000 year ensemble of storm surge plus tide 500 times, approximating a 1,500,000 year record. As will be noted below this long record will be used to predict only up to the 1000 year return period level.

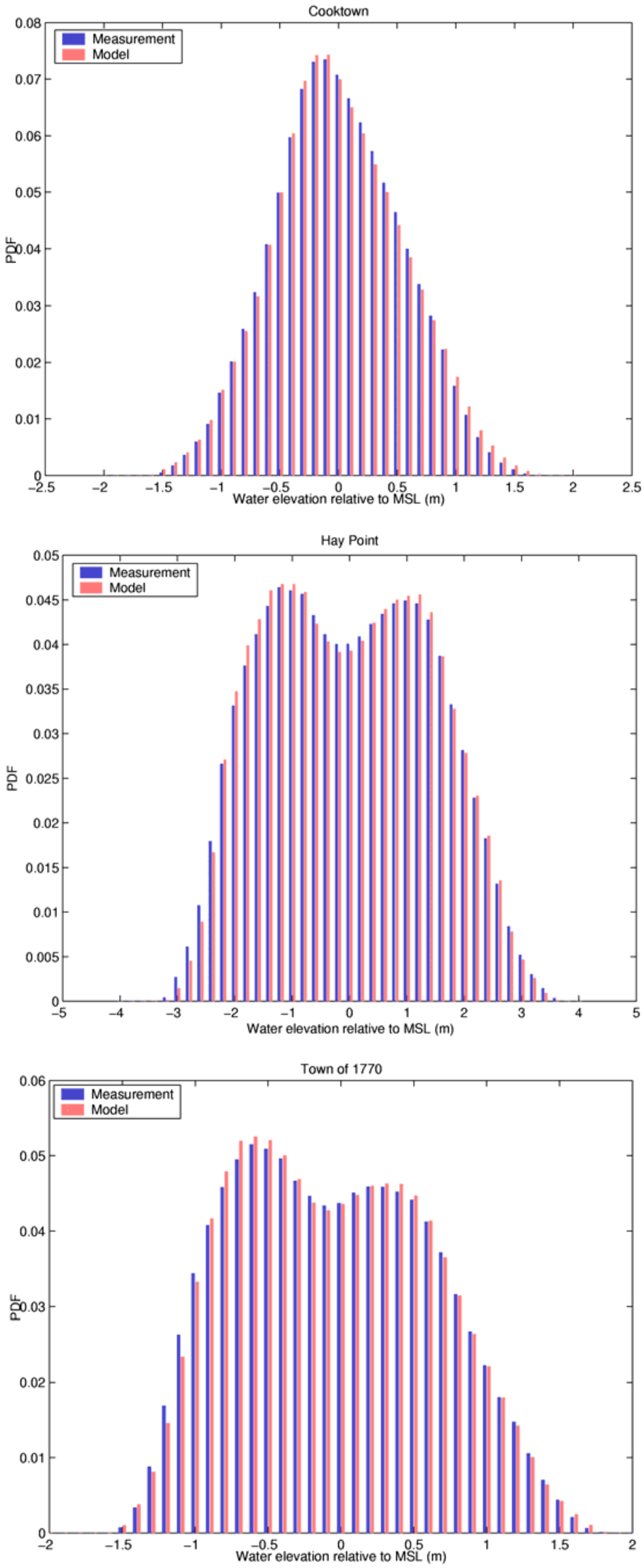

Figure 11. Probability density function comparison of tidal elevation created by tidal constituents determined from measurements (▌) and modelling (▌) for (a) Cooktown, (b) Hay Point and (c) Town of 1770.

Table 1. Tidal Information: Official Data was supplied by Maritime Safety Queensland. Project tides are the location and record length of the tidal measurements used to produce the tidal constituents. An *M* in the last column denotes tidal constituents were produced by model.

	Official Data (m, LAT)					Project Tides	
Location (Fig. 1)	**Tide Station**	**HAT**	**MSL**	**AHD**	**MSL-AHD**	**Tide Station**	**Series Length**
Lockhart R.	Portland Roads	3.42	1.63	1.63*	0.000	Lockhart River	*M*
Bathurst Bay	Normanby R.	3.4	1.39	1.39*	0.000	Bathurst Bay	*M*
Cape Flattery	Stn 067001A	3.01	1.479	1.479*	-0.001	Cape Flattery	39 days
Cooktown	Stn 066003A	3.13	1.530	1.480	0.050	Cooktown	11.7 yrs
Cape Tribulation	Low islet	3.18	1.55	1.55*	0.000	Mossman River	14.3 yrs
Newell Beach	Stn 041014A	3.18	N/a	1.55	0.000	Mossman River	14.3 yrs
Oak Beach	Cairns	3.42	1.683	1.643	0.040	Port Douglas	12.7 yrs
Trinity Beach	Cairns	3.42	1.683	1.643	0.040	Cairns	15.67 yrs
Cairns	Stn 056012A	3.42	1.683	1.643	0.040	Cairns	15.67 yrs
Yarrabah	Cairns	3.42	1.683	1.643	0.040	Cairns	15.67 yrs
Russell Heads	Flying Fish Point	3.35	1.692	1.627	0.065	High Island	57 days
Bramston Beach	Flying Fish Point	3.35	1.692	1.627	0.065	High Island	57 days
Flying Fish Point	Stn 036007A	3.35	1.692	1.627	0.065	Mourilyan	15.68 yrs
Kurrimine Beach	Clump Point	3.59	1.737	1.678	0.059	Clump Point	14.7 yrs
Wongaling Beach	Clump Point	3.59	1.737	1.678	0.059	Clump Point	14.7 yrs
Tully Heads	Dunk Island	3.6	1.79	1.79*	0.000	Clump Point	14.7 yrs
Cardwell	Stn 035012A	4.06	1.946	1.863	0.083	Cardwell	14.7 yrs
Lucinda	Stn 062006A	3.89	1.872	1.844	0.028	Lucinda	15.24 yrs
Forrest Beach	Lucinda	3.89	1.872	1.844	0.028	Lucinda	15.24 yrs
Palm Island	Townsville	4.01	1.931	1.856	0.075	Lucinda	15.24 yrs
Balgal Beach	Jaloonda	4.26	2.01	1.96	0.075	Jaloonda	36 days
Saunders Beach	Jaloonda	4.26	2.01	1.96	0.075	Jaloonda	36 days
Horseshoe Bay Magnetic Is.	Magnetic Is Arcadia	3.88	1.91	1.84	0.075	Townsville Fairway Beacon	3.75 yrs
Pallarenda	Stn 055006A	4.00	N/a	1.880	0.000	Townsville	44.49 yrs
Townsville	Townsville	4.01	1.931	1.856	0.075	Townsville	44.49 yrs
Alva Beach	Cape Ferguson	3.73	1.76	1.69	0.070	Cape Ferguson	5 yrs
Molongle Creek	Abbott Point	3.6	1.67	1.626	0.044	Abbott Bay	36 days
Queens Beach	Bowen	3.73	1.744	1.776	-0.032	Bowen	13.78 yrs
Bowen	Bowen	3.73	1.744	1.776	-0.032	Bowen	13.78 yrs
Airlie Beach	Stn 030016A	3.94	1.795	1.748	0.047	Airlie Beach	*M*
Midge Point	Laguna Quays	6.13	2.781	2.806	-0.025	Laguna Quays	8.6 yrs
Seaforth	Halliday Bay	5.98	2.65	2.635	0.015	Seaforth	*M*

Table 1. Continued.

	Official Data (m, LAT)					Project Tides	
Location (Fig. 1)	**Tide Station**	**HAT**	**MSL**	**AHD**	**MSL-AHD**	**Tide Station**	**Series Length**
Slade Point	Mackay	6.41	2.996	2.941	0.055	Mackay	12.82 yrs
Mackay Town Beach	Mackay	6.41	2.996	2.941	0.055	Mackay	12.82 yrs
Sarina Beach	Hay Point	7.14	3.34	3.34	0.000	Hay Point	14.02 yrs
Notch Point	Flock Pigeon Island	8.5	4.08	4.08*	0.000	Notch Point	*M*
Clairview	Flock Pigeon Island	8.5	4.08	4.08*	0.000	Clairview	*M*
Cape Clinton	Port Clinton	5.2	2.45	2.45*	0.000	Port Clinton	29 days
Yeppoon	Rosslyn Bay	4.93	2.372	2.360	0.012	Rosslyn Bay	3.79 yrs
Emu Park	Rosslyn Bay	4.93	2.372	2.360	0.012	Rosslyn Bay	3.79 yrs
Gladstone	Auckland Point	4.69	2.322	2.268	0.054	Auckland Point	17.67 yrs
Tannum Sands	Gatcombe Head	4.17	2.08	2.08*	0.000	Golding Channel	1.05 yrs
Agnes Waters	Agnes Waters	3.48	1.600	1.610	-0.010	Town of 1770	47 days
Moore Park	Bundaberg	3.58	1.708	1.693	0.015	Burnett Heads	17.52 yrs
Burnett Heads	Bundaberg	3.58	1.708	1.693	0.015	Burnett Heads	17.52 yrs
Rainbow Beach	Noosa Head	*2.18*	*1.06*	*1.123*	-0.063	Noosa Head	2089 yrs
Scarborough	Stn 048002A	2.41	1.111	1.170	-0.059	Tangalooma	5.29 yrs
Nudgee Beach	Cabbage Tree Creek	*2.6*	*1.19*	*1.310*	-0.120	Brisbane Bar	37.4 yrs
Wellington Point	Stn 007204A	2.82	1.263	1.331	-0.068	Brisbane Bar	37.4 yrs
Surfers Paradise	Snapper Rocks	*2.09*	*0.970*	*0.980*	-0.010	Gold Coast Seaway	18.87 yrs

Values in red are inferred values taken from nearest applicable tide location.
(*) AHD values are assumed to be equal to MSL.

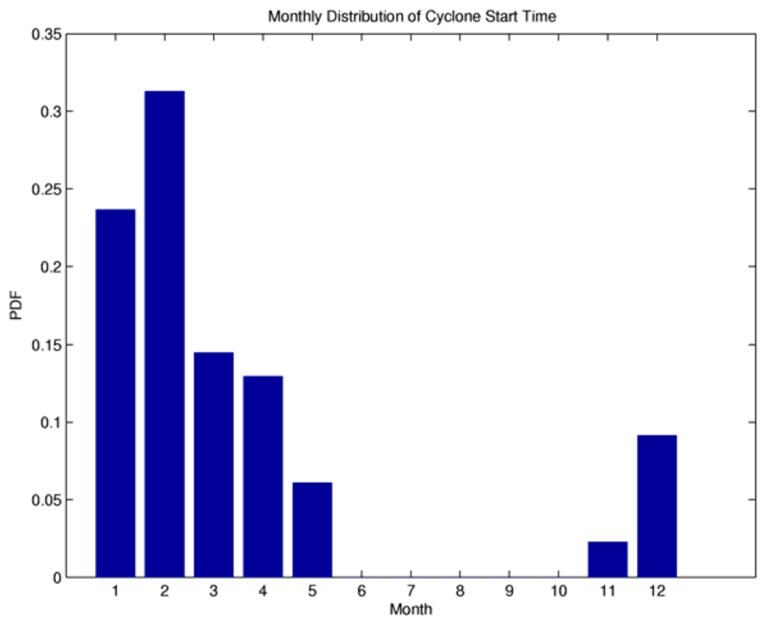

Figure 12 Probability distribution used to weight selection of tidal time series.

5.0 RETURN PERIOD CURVES OF STORM SURGE PLUS TIDE

5.1 Creating Return Period Curves of Storm Surge plus Tide

The synthetic tropical cyclones that were modelled on the fine resolution *C* grids were chosen to represent the cyclones that caused storm surges greater than the 10 year return period. However, since the ensemble of storms needed to satisfy this criterion at all locations of the grid, more storms were modelled than the 300 that were necessary at each point. The result is that return periods less than 10 years are represented and this improves the characteristics of the lower portion of the return period curves for storm surge. However the final product of this study is not the return period of storm surge but rather the return period of surge plus tide.

Substituting eqn. 2 into eqn. 1 gives the formula for return period, which for this project becomes

$$R_\eta = \frac{n}{m_\eta} = \frac{1,500,000}{m_\eta}. \tag{15}$$

The record length for the storm tide is n = (3000 years)(500) = 1,500,000 years since the 3000 year synthetic storm record is repeated 500 times (each storm is repeated with 500 separate tide time series). The largest storm tide was assigned the rank, $m_\eta = 1$, and this water level is nominally the 1,500,000 year return period value (eqn. 1). The magnitude of the 150,000th largest storm tide (m_η = 150,000) indicates the 10 year return period. Note that the curve above the 1000 year level will not be reported. The 3000 year synthetic storm ensemble, in effect, gives three renditions of 1000 years, which gives a reasonably robust estimate at 1000 years. Determination of return periods above 3000 years would require the modelling of an increased number of synthetic tropical cyclones.

5.2 Results: Storm Surge plus Tide During Tropical Cyclones

The return period curves are formed by plotting points with (x, y) coordinate values of (return period, magnitude). Example storm surge plus tide return period curves are shown in Figures 13 (*Cairns*), 14 (*Townsville*) and 15 (*Mackay Town Beach*). The datum for water levels is Australian Height Datum (AHD), which is approximately equal to mean sea level at most locations (see Table 1). The two water level components (storm surge and astronomical tide) of each point of the return period curve are also plotted in Figures 13a, 14a and 15a. The separate return period curves for storm surge plus tide and storm surge only are plotted in Figures 13b, 14b and 15b.

Between the 10 and 1000 year return periods, 148,500 storm-tide events make up the storm surge plus tide curve. The density of the events increases rapidly toward lower return periods. For example only 1500 events make up the higher end of the curve (not plotted here) between the 1000 and 1,500,000 year return periods; 13500 events are between 100 and 1000 years, and 135,000 are between 10 and 100 years. In Figures 13a, 14a and 15a only one in 10 of these storm tide events is plotted, in order to more clearly see patterns in the combination of surge plus tide.

Several characteristics of surge plus tide combinations are evident in Figure 13a, the results for *Cairns*. Note the bands in both storm surge and tide. The surge bands are horizontal and are more evident at higher levels. These bands are multiple contributions from the *maximum* surge during a single storm. Each has been matched with a different tide level in the combination of 500 tidal signals with the surge time series of that single storm. Note that the maximum surge during a storm does not always contribute to the maximum surge plus tide level during the event, but it is more common for this to be the case for higher surge plus tide water levels.

The tide bands in Figure 13a are diagonal and parallel to the surge plus tide curve. The lowest band consisting of three points contains the tide levels that combined with the surges of the three points of the uppermost surge band. Note that these three tide contributions are negative (i.e. tide was less than mean sea level at the time of highest water level during the storm-tide event); therefore, if this 3.5 m surge combines with a high tide, those surge plus tide combinations all occur at return periods well above 1000 years.

At lower return periods in Figures 13a, 14a and 15a a few of the points on the return period curve have surge components that are negative. The maximum water level during these events occurred at high tide when the storm surge was negative (e.g. wind was blowing offshore). This does not mean that all events at the lower portion of the curve had negative storm surges at time of maximum water level. In fact most did not. Remember that a dense array of events exists at lower levels most of which have varying positive values of storm surge as can be seen in the figures.

Note the anomalous largest surge recorded at *Townsville* (≈ 4.6 m) that appears in Figure 14a at about the 900 year return period. This is about 1.6 m larger than the next largest maximum surge at Townsville. It was created by a storm that had a very low central pressure (898 hPa) and a fast forward speed in the hours just before landfall. The tides that combined with this maximum at the 900 to 1000 year levels are below –1.0 m (AHD) (the bottom of the graph). This storm is closer to the maximum possible surge than are the modelled maxima for *Cairns* and *Mackay Town Beach*. Although this storm produced the largest storm surge at *Townsville* during the 3000 year simulation, it most likely has a return period much longer than 3000 years. This highlights the random and infrequent nature of tropical cyclone storm surge.

The largest storm surges in the synthetic ensemble, although severe, are not the largest possible. The probable maximum water level at a given location would be caused by a tropical cyclone and tide with the following characteristics. (1) very severe central pressure, (2) large radius to maximum winds, (3) landfall point at a distance equal to the radius of maximum winds to the north, (4) forward speed of the eye equal to the short wave speed offshore and the shallow water wave speed over the shelf, and (5) most importantly for the Queensland region with its large tidal ranges, an astronomical tide level, at the time of maximum surge that is close to HAT. The combination of these characteristics would be very rare, but not impossible.

If an estimate of the probable maximum level were calculated by adding the largest storm surge from the 3000 years of simulations to the HAT level, then this would result in a total water level relative to AHD of about 5.3 m at *Cairns*, 6.8 m at *Townsville* and 6.8 m at *Mackay Town Beach*. These are approximately 2.4, 3.5 and 2.5 m, respectively above the 1000 year water levels. It must be emphasised that these probable maximums are not accurate estimates. As discussed above the *Townsville* surge appears to be an outlier. The point to be made here is that the probable maximum water level during a tropical cyclone is much larger than the 1000 year level for the east coast of Queensland.

The return periods curves presented in this report are for water levels *during tropical cyclones*. A return period curve which included non-cyclonic events would be higher than the curves in this report at the lower return periods and would merge with the cyclonic curves at levels between 100 and 200 years at most locations. An example of the differences between cyclonic and non-cyclonic water level return period curves is given for *Townsville* in Figure

16. In this figure the curve labelled *Tropical cyclone-induced storm surge plus tide* (*modelled*) is the final product of this study. The curve labelled *Water level* (*measured*) is created using approximately 44 years of data from the Townsville tide gauge including both cyclonic and non-cyclonic influences. Note that the maximum recorded water level during the last 44 years occurred during *Tropical Cyclone Althea* even though the peak surge and maximum water level occurred just after low tide. The curve labelled *Residual non-cyclonic water level* (*measured*) *plus tide* was created by the following process: (i) Periods of tropical cyclone activity were deleted from the tide gauge record. (ii) The residual water level time series was created by subtracting the predicted tide. (iii) Each year of this non-cyclonic residual signal was combined with 200 separate year-long tidal signals that were randomly chosen from the 250 year modelled tide. This allows the residual signal to combine with a multiple number of possible tidal signals. (iv) The return period of this *residual non-cyclonic water level (measured) plus tide* was calculated and plotted. Finally the curve labelled *Combined cyclonic and non-cyclonic water level* is created by adding the probabilities of the cyclonic and non-cyclonic curves at a given water level.

In Figure 16 the non-cyclonic and cyclonic curves cross at about a 90 year return period with the non-cyclonic curve higher at lower return periods. The combined curve is higher than both the non-cyclonic and cyclonic curves at lower return periods and merges with the cyclonic curve at about the 200 year level. At 10 and 100 year return periods, the combined curve is higher than the cyclonic curve by less than 0.2 and 0.1 m, respectively. We believe that this contribution at *Townsville* from non-cyclonic events is indicative of results from central and north Queensland. Thus differences between the final product of this study and the combined curves above a 10 year return period are relatively small.

Return Period curves for surge plus tide for the 50 locations shown in Figure 1 are displayed in Appendix A and also in the *Atlas of Physical Processes in the Great Barrier Reef World Heritage Area* which is located on the *MMU* web site (http://mmu.jcu.edu.au). Table 2 contains a summary of this results with surge plus tide levels for both 2003 and greenhouse at return periods of 100, 500 and 1000 years for each of the 50 locations.

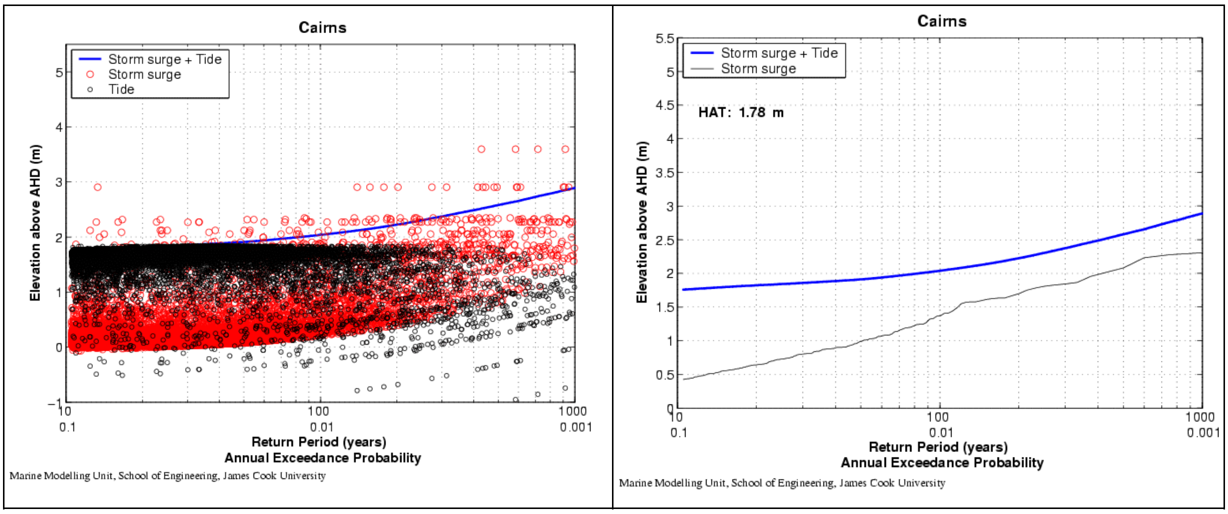

Figure 13. Components of the storm surge plus tide return period curve at *Cairns*

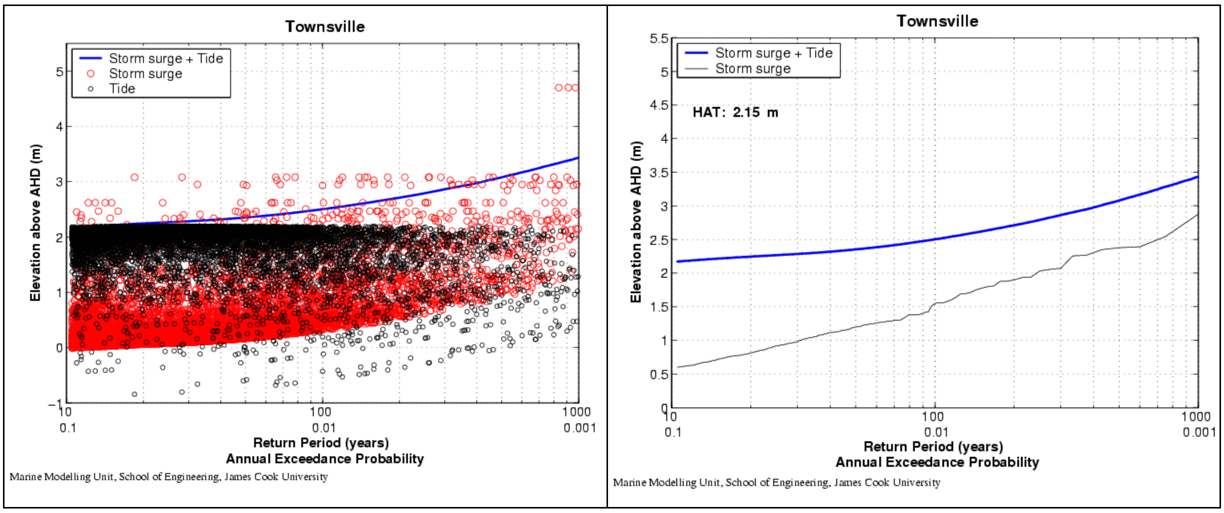

Figure 14. Components of the surge plus tide return period curve at *Townsville*

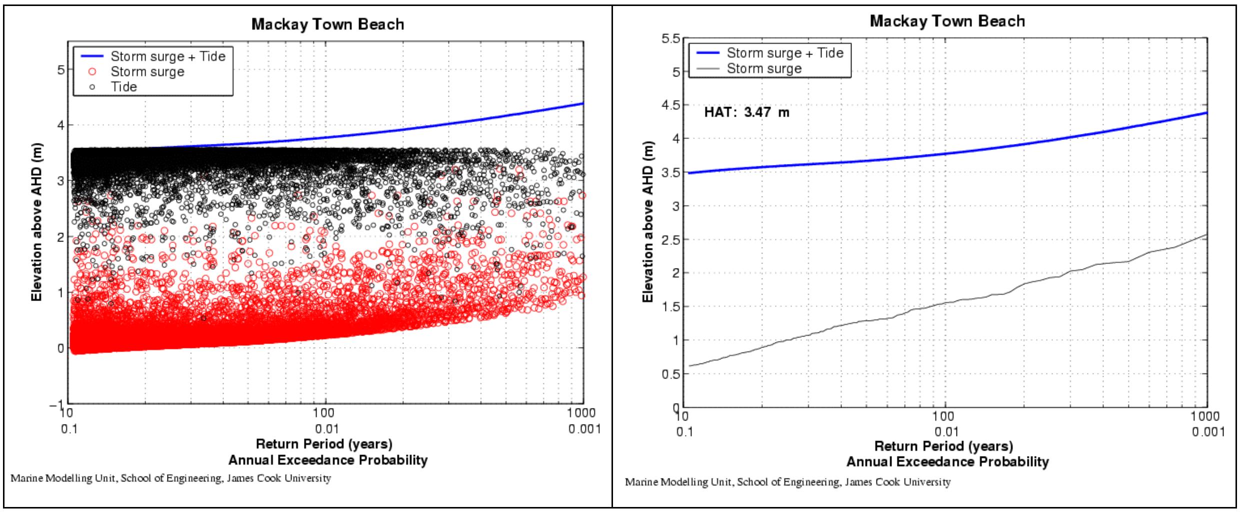

Figure 15. Components of the surge plus tide return period curve at *Mackay Town Beach*

Table 2. Storm surge plus tide at given return periods for 2003 and combined greenhouse scenarios

Location	Storm Surge + Tide (m, AHD) for three return periods:					
	100 year		500 year		1000 year	
	2003	Green house	2003	Green house	2003	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	2.46	2.66	2.95	2.93	3.20
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 Mag. 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	4.51
Tannum Sands	2.50	2.95	3.05	3.64	3.31	3.94
Agnes Waters	2.46	3.01	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

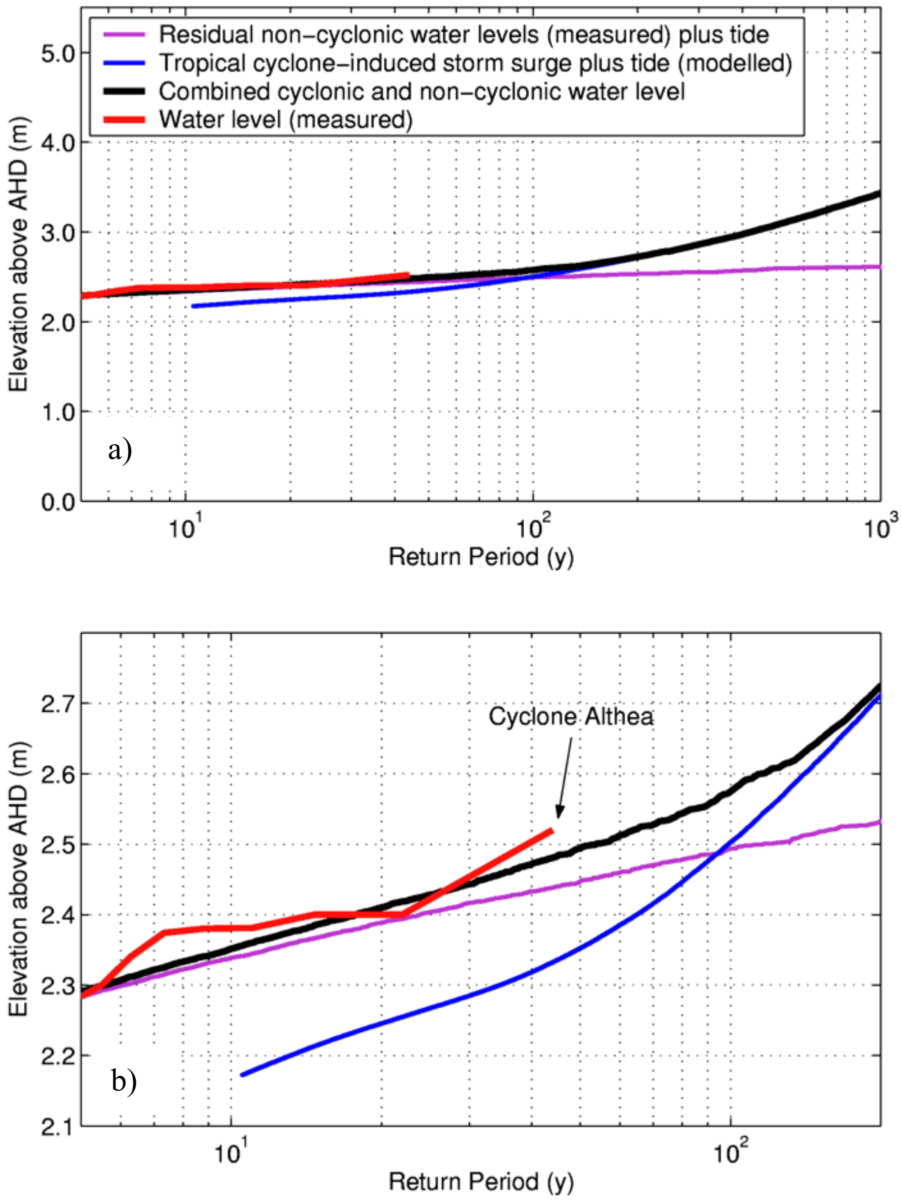

Figure 16. Comparison of return period curves created from tropical cyclone-induced (modelled) and non-cyclonic (measured), gauge data and predicted tide at *Townsville*. a) full curves; b) blow up of lower end of curves.

6.0 GREENHOUSE SCENARIOS

It is well established that changes in atmospheric concentrations of the so-called greenhouse gasses will change climate patterns. Both magnitude and frequency storm tides may be significantly affected by any changes in climate; therefore, one of the tasks of this study is to simulate changes storm surge statistics for a few specified greenhouse scenarios. These are

1. Combined effect of an increase in Maximum Potential Intensity (MPI) of 10% and a poleward shift in tracks of 1.3°.
2. Increase in frequency of tropical cyclones of 10%.
3. Mean Sea Level rise of 300 mm.

It is very important to emphasise here that we are *not* endorsing these chosen values, although care has been taken to propose reasonable values. Rather the intention is to demonstrate the sensitivity of the storm surge plus tide frequency curves to these climate change scenarios.

6.1 Increase in Intensity and Poleward Shift of Tracks: Scenario A

Unlike a change in MSL or a change in frequency of tropical cyclones, changes in either intensity or track imply changes in the ensemble of storms; therefore, these changes require the re-simulation of the ensemble. Since re-simulation of almost 10,000 storms for the whole east coast of Queensland is an expensive exercise, these two Greenhouse enhancements were combined and simulated together.

An increase of 10% in the Maximum Potential Intensity (MPI) was chosen for simulation following the advice from the IWTC-V (International Workshop on Tropical Cyclones, Cairns December 2002) (B. Harper, personal communication). As with the changes in frequency of tropical cyclones, an increase in intensity of tropical cyclones is uncertain. Although theoretical models (Emanuel, 1988; and Holland, 1997) indicate intensification with a warmer climate, other considerations (e.g. vertical shear) may temper the magnitude of any intensification (Walsh and Ryan, 2000). The 10% value is considered an upper estimate for the western Coral Sea.

This assumed increase in MPI was simplified to a generalised 10% increase of intensity for our tests by the following formulas, which alter the central pressure of the synthetic tropical cyclones. The greenhouse-induced central pressures (indicated by an $*$) became

$$p_{0*} = p_\infty - \Delta p_* , \tag{16}$$

where

$$\Delta p_* = 1.10\left(p_\infty - p_0\right). \tag{17}$$

This transformation was applied at each time step of the time series of central pressures of the synthetic tropical cyclone ensemble.

Walsh and Katzfey (2000) used a regional climate model to simulate the response of the tropical cyclone formation and movement under a doubling of the CO_2 concentration. They found a slight poleward shift in genesis points and a slight poleward shift in forward motion and these could be approximated with a 1.3° poleward shift in track. This was accomplished by translating the tracks of the storms in the synthetic ensemble 1.3° to the south as suggested by Walsh and Katzfey.

After the application of eqn. (17) and the 1.3° poleward shift in track the ensemble was re-simulated using the process described above in Section 4.

6.2 Increase in Frequency of Tropical Cyclones: Scenario B

A Greenhouse-induced increase in the frequency of tropical cyclones was assumed to be 10% based on discussions at the recent International Workshop on Tropical Cyclones (IWTC-V) held in December 2002 in Cairns (B. Harper, personal communication). Of the four Greenhouse enhancements tested, the change in frequency has the least certainty. As with the change in MSL, the effects of changes in the frequency of tropical cyclones can be posted-processed, i.e. there is no need to re-simulate storm surge. The Greenhouse enhanced frequency of tropical cyclones, given a 10% increase is

$$\begin{aligned}\lambda_{c+} &= 1.10\lambda_c \\ &= (1.10)(3.3030\ ) \\ &= 3.63 \text{ T. C. per year}\end{aligned} \tag{18}$$

This higher frequency translates into a period (n_+) shorter than 3000 years in which the M = 9911 tropical cyclones occur. The new record length becomes

$$\begin{aligned}n_+ &= \frac{M}{\lambda_{c+}} \\ &= \frac{9911}{3.6} = 2753 \text{ years}\end{aligned} \tag{19}$$

Thus for a given magnitude of water level, the rank (value of m) does not change, but the return period of that magnitude does change. The Greenhouse enhanced return period is given as (for the example of water level, η)

$$\begin{aligned}R_{\eta+} &= \frac{1}{\lambda_{\eta+}} \\ &= \frac{1}{m/n_+} = \frac{1}{m/2753}\end{aligned} \tag{20}$$

The frequency and return period under the Greenhouse enhanced tropical cyclone frequency of 10%, as a function of existing frequency and return period, become

$$\begin{aligned}\lambda_{\eta+} &= 1.10\lambda_\eta \\ R_{\eta+} &= 0.909R_\eta\end{aligned} \tag{21}$$

Therefore, at a given water level, the return period curve for enhanced Greenhouse conditions is shifted towards lower return periods.

6.3 Mean Sea Level Rise: Scenario C.

A MSL rise of 300 mm is assumed. This is predicted to be the upper envelope of the rise in MSL by 2050 (IPCC, 2001). For this level of mean sea level rise, the effect on magnitudes of storm tide at the coast will be approximated as a linear addition to the return period curve that has been developed for present conditions. In other words the water level, at all return periods, increases by an amount equal to the chosen value of sea level rise. Other MSL rise scenarios can be easily adopted by the linear addition of the chosen value.

Of course, changes in MSL will have some nonlinear affects on storm tide levels. Holding all other thing constant, deeper water reduces storm surge, since the slope of the water surface caused by wind stress is inversely proportional to the water depth. Nevertheless these nonlinear effects are assumed to be much smaller than the linear effect of a sea level rise. The likely significant changes in beach slope and shoreline position (recession) that would result from a rise in sea level were not considered.

6.4 Greenhouse Storm Surge plus Tide Results

Examples of return period curves for storm surge plus tide for Greenhouse scenarios are given in Figures 17, 18 and 19 for *Cairns, Townsville* and *Mackay Town Beach*. The full set of results of the greenhouse simulations of storm tide are shown in *Appendix B* and in the *Atlas of Physical Processes in the Great Barrier Reef World Heritage Area* which is located on the *MMU* web site (http://mmu.jcu.edu.au). Greenhouse induced water levels for 100, 500 and 1000 year return periods are included in Table 2.

The 10% increase in the frequency of tropical cyclones (Scenario *B*) elevates the curve only an inconsequential amount at all locations. At low to medium return periods, mean sea level rise (Scenario *C*) has the most significant effect of the three scenarios at all locations. The southerly 1.3° shift and 10 % increase in MPI (Scenario A) becomes increasingly important at higher return periods.

In general, the greenhouse curves formed from the combinations of all three scenarios increase the storm surge plus tide curve about 0.3 – 0.4 m at R = 10 years to about 0.6 – 0.7 m at R = 1000 years. There is some random variation in this results. The largest random variation is caused by the 1.3° southerly shift in tropical cyclone tracks. This moves more storms into the far southern regions and reduces the number of storms at far northern locations. This tends to increase water levels for Scenario A in the south and sometimes reduces the water level in the north. Also the shift can cause a severe storm to either hit or miss a location if compared with the 2003 ensemble of storms.

For example at *Townsville* (Figure 18) the combined 10% increase in MPI and 1.3° southern shift has a much smaller effect than at many other stations including *Cairns* (Figure 17) and *Mackay Town Beach* (Figure 19). This is caused by the presence of the extreme 4.6 m storm surge in the *Townsville* ensemble. This storm raises the 2003 curve at the 1000 year level perhaps 0.3 to 0.4 m more than if the ensemble had not included this outlier. When the storm ensemble is shifted 1.3° to the south, this storm no longer causes a large surge at *Townsville*. Thus, in this case at *Townsville*, the shift of 1.3° reduces the impact of the 10% increase in MPI and the combination raises the water level at the 1000 year level by only about 0.1 m. The 1000 year greenhouse increases at *Cairns* and *Mackay Town Beach* are about four times as much. This, once again, highlights the random nature of the occurrences of severe water levels during tropical cyclones. If a different 3000 year ensemble were simulated, the results could vary again. Thus any differences in trends in the Scenario *A* greenhouse curves between nearby locations have no significance other than demonstrating the random nature of direct hits by severe storms.

The 100 year greenhouse water levels corresponds to the 400, 300 and 400 year water levels for 2003 conditions at *Cairns*, *Townsville* and *Mackay Town Beach*, respectively. Although this indicates that higher water levels will become much more frequent, increases of greenhouse water levels above the 2003 water levels at the 100 year return period are only 0.37, 0.34 and 0.36 m for *Cairns*, *Townsville* and *Mackay Town Beach*, respectively. This relatively small amount indicates that the increases will impact much more on property losses rather than on threats to human life.

Again it must be emphasised that these greenhouse tests are not meant to be a prediction of what is expected, but rather to provide some insight to the relative magnitudes of the most commonly cited greenhouse induced water level changes.

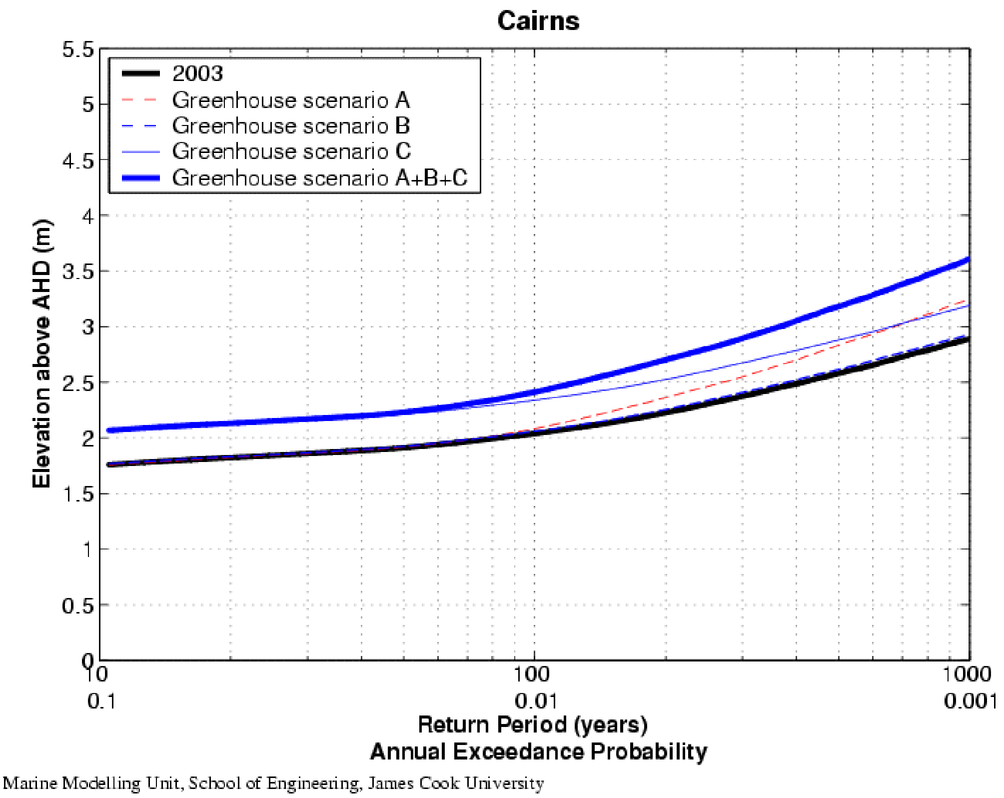

Figure 17. Storm surge plus tide for greenhouse scenarios – *Cairns*. A) Combined effect of an increase in Maximum Potential Intensity (MPI) of 10% and a poleward shift in tracks of 1.3°. (B) Increase in frequency of tropical cyclones of 10%. (C) Mean Sea Level rise of 300 mm.

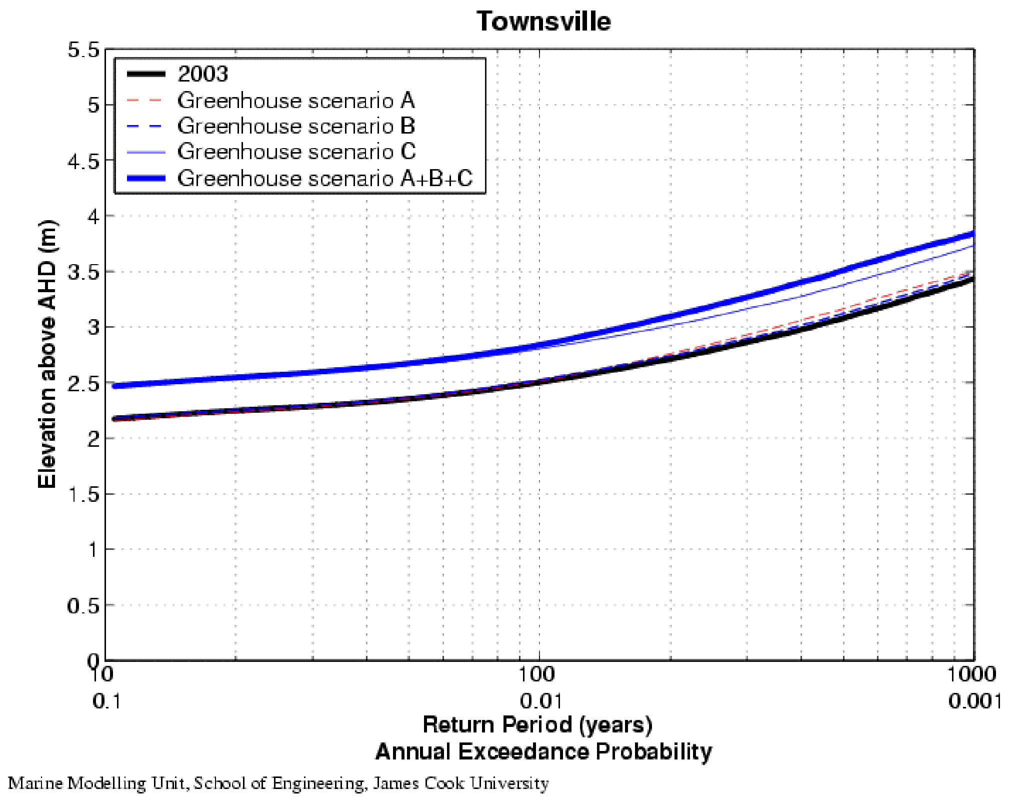

Figure 18. Storm surge plus tide for greenhouse scenarios – *Townsville*. A) Combined effect of an increase in Maximum Potential Intensity (MPI) of 10% and a poleward shift in tracks of 1.3°. (B) Increase in frequency of tropical cyclones of 10%. (C) Mean Sea Level rise of 300 mm.

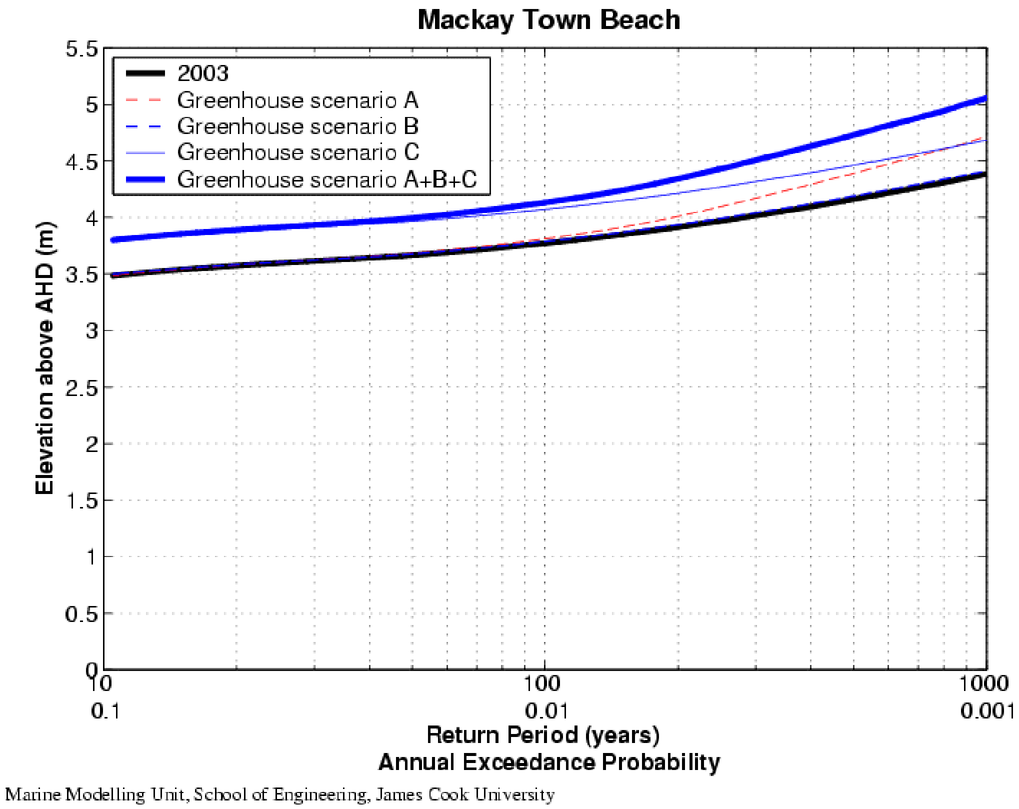

Figure 19. Storm surge plus tide for greenhouse scenarios – *Mackay Town Beach*. A) Combined effect of an increase in Maximum Potential Intensity (MPI) of 10% and a poleward shift in tracks of 1.3°. (B) Increase in frequency of tropical cyclones of 10%. (C) Mean Sea Level rise of 300 mm.

7.0 CONCLUSION AND DISCUSSION

The frequency of storm surge plus tide during tropical cyclones was determined for 50 open coast locations along the east coast of Queensland, Australia (Figure 1). The goal was to produce return period curves for storm surge plus astronomical tide for return periods between 10 and 1000 years.

A series of sophisticated models was employed. First a tropical cyclone track and pressure model produced a synthetic dataset consisting of the time series of position and pressure for almost 10,000 storms. This represents 3000 years of data for the western Coral Sea. Numerical models with three nested grids with increasing spatial resolution for storm surge were established for the study areas. The storm surge model was validated in Phase 1 of this overall study (Harper *et al.,* 2001).

It was computationally impossible to model all 10,000 storms to the needed resolution; therefore, a system was developed to determine which storms would contribute to return periods above 10 years. To do this all storms were modelled on the less computationally expensive coarse grid. The most severe results on these coarse simulations were used to cull the number of storms to be modelled on the finer resolution grids from 10,000 to about 500 for each of the 20 fine resolution *C*-grids.

An astronomical tidal signal was created using tidal analyses. Each storm surge time series from a single storm was linearly added to 500 separate tidal time series. The tide series were randomly chosen (with a weighting to reflect the monthly change in cyclone frequency) from a long tidal record. The maximum storm surge plus tide water level during each storm-tide event was determined and these values were ranked by magnitude and return period curves were created.

Establishing a datum and a tidal range at the project output points caused considerable difficulty. Most of the output points were not at established tidal measurement stations. Hence the datum at a location was often transferred from the nearest tide station and these official values (that were provided to us) did not always provide the best tidal information at that location. Considerable time and energy was expended to check and recheck values of MSL, AHD and HAT. Some official values were updated during the project in consultation with Maritime Safety Queensland. In the end, the decision was reached to model storm surge relative to the official MSL and use the official transfer from MSL to AHD.

The effect of greenhouse-induced climate change was investigated. Three separate scenarios were tested. These were (A) combined effect of an increase in maximum intensity (MPI) by 10% and a poleward shift in tracks of 1.3°. (B) increase in frequency of tropical cyclones of 10%. (C) mean sea level rise of 300 mm. In general the mean sea level rise is the most important effect especially at lower return periods. The 10% increase in tropical cyclone frequency is insignificant. The combined increase in intensity and poleward shift in tracks becomes increasingly significant with larger return periods. Both the magnitude and probability of greenhouse-induced mean sea level rise are more certain than greenhouse-induced changes in tropical cyclone frequency, central pressure, or track.

For all project reporting locations, the occurrence of a tropical cyclone was defined as any that occurred in the western Coral Sea regardless of its distance from the location. This has the property of merging the return period curve for tropical cyclone-induced storm tide into the return period curve for astronomical tide at the lower end of the curves. A more selective definition of tropical cyclone occurrence would have caused the return period curve of storm tide to decrease rapidly (sometimes below HAT) at the lower end of the curve. The adopted definition was used to avoid any misinterpretation of the frequency of water levels at return periods that may be dominated by non-cyclonic events.

There are several influences that affect water levels that are not considered in this study.

- **Wave setup, runup and overtopping were not considered. These could have a significant impact on water levels in locations under direct wave attack. However, it is important to note that water levels created by wave setup will not translate far inland after overtopping frontal dunes, flowing overland over low lying areas, or proceeding through inlets. Once flow starts wave setup reduces markedly; therefore, storm tide curves that include wave setup would apply only to areas with direct wave attack.**
- **Over land flooding was not considered. For areas more than a couple hundred metres landward of the shoreline during the storm, an overland flooding study might be necessary to provide definitive results for inland locations, especially if the inland floodable area is large.**
- **The results in this study are for tropical cyclone-induced water levels. For return periods below about 100 years, non-cyclonic events will be increasingly important; therefore, the combined curve of tropical and extra-tropical storm tides will be higher than the cyclone-induced storm surge plus tide curves shown in this report. The increase due to non-cyclonic events is expected to be about 0.2 m at 10 years reducing to 0.0 m at about the 200 year return period.**

The largest storm surges in the synthetic ensemble, although severe, are not the largest possible. The probable maximum water level at a given location would be caused by a tropical cyclone and tide with the following characteristics. (1) very severe central pressure, (2) large radius to maximum winds, (3) landfall point at a distance equal to the radius of maximum winds to the north, (4) forward speed of the eye equal to the short wave speed offshore and the shallow water wave speed over the shelf, and (5) most importantly for the Queensland region with its large tidal ranges, an astronomical tide level, at the time of maximum surge that is close to HAT. The combination of these characteristics would be very rare, but not impossible.

If an estimate of the probable maximum level were calculated by adding the largest storm surge from the 3000 years of simulations to the HAT level, then this would result in a total water level relative to AHD of about 5.3 m at *Cairns*, 6.8 m at *Townsville* and 6.8 m at *Mackay Town Beach*. These are approximately 2.4, 3.5 and 2.5 m, respectively above the 1000 year water levels. It must be emphasised that these probable maximums are not accurate estimates. As discussed in Section 5, the maximum *Townsville* surge appears to be an outlier, and this highlights the random and infrequent nature of very severe tropical cyclones.

A caution is necessary on the possibility of water levels much higher than the 1000 year levels that are presented in this report. The occurrence of the probable maximum water level could have devastating consequences for a nearby community. Although the probability of occurrence is very rare, a calculation of the risk (probability times consequences) is an important component of both disaster and longer term land use planning.

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APPENDIX A

STORM SURGE PLUS TIDE RETURN PERIOD CURVES: QUEENSLAND EAST COAST: *2003*

Return Period curves for storm surge plus tide are presented for 50 output points along the east coast of Queensland (Figure A1). These same curves are also displayed in the *Atlas of Physical Processes in the Great Barrier Reef World Heritage Area* which is located on the *MMU* web site (http://mmu.jcu.edu.au).

These curves are valid for water levels produced during tropical cyclones. Extra-topical storms and other meteorological and oceanic causes of water level change (not modelled here) will contribute to the return period of water levels at lower return periods.

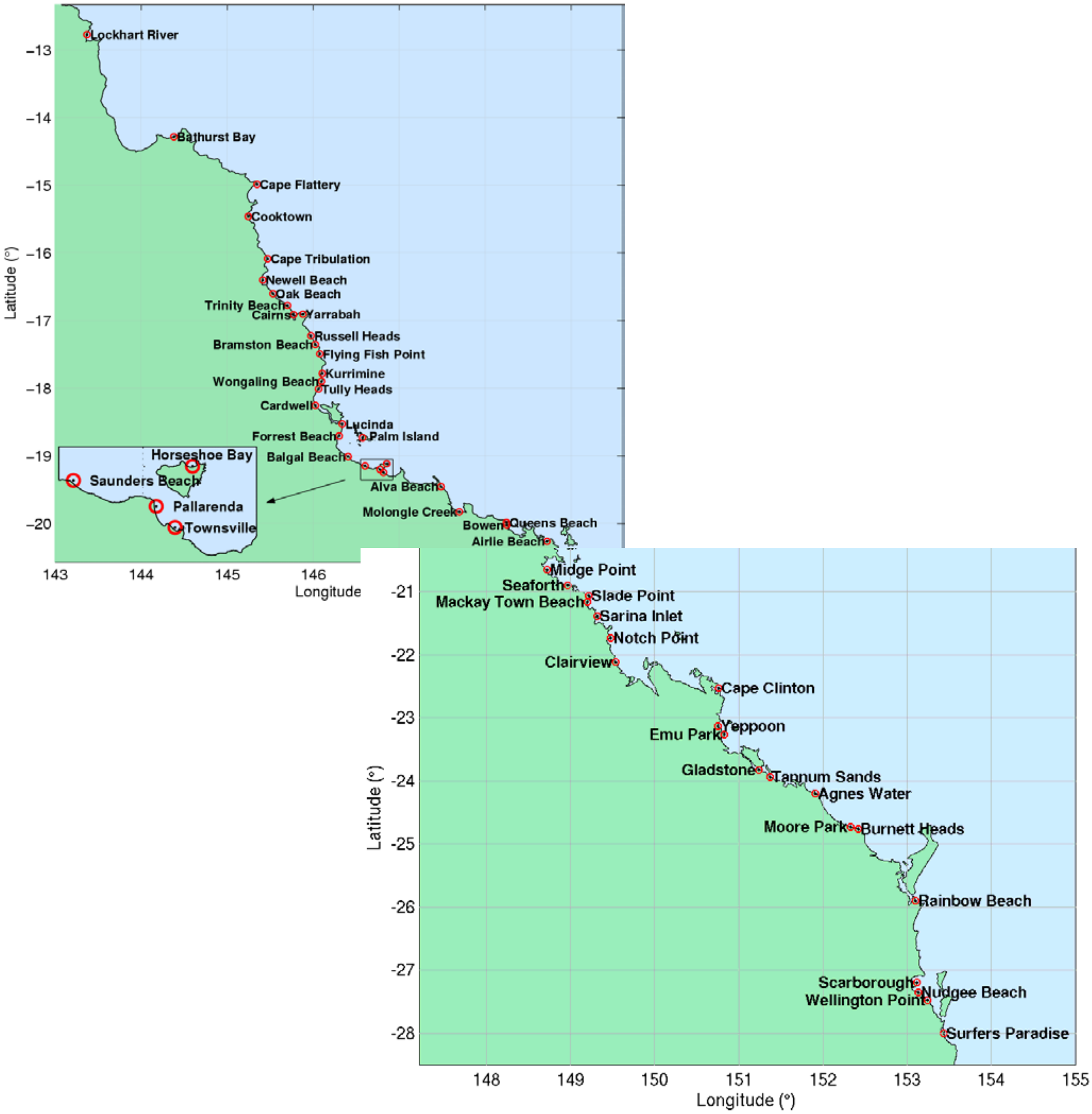

Figure A1. East Coast Queensland reporting locations

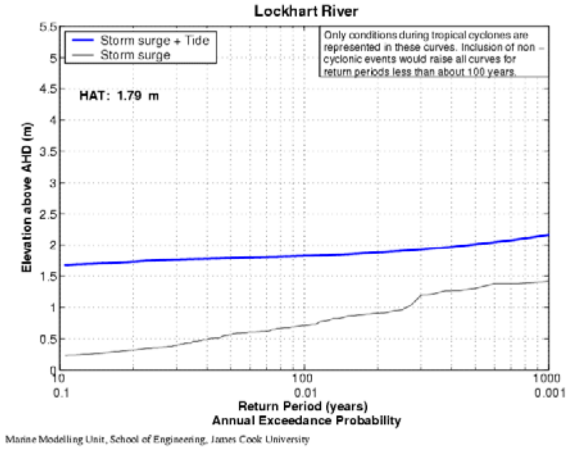

Figure A2. Water level frequency: *Lockhart River*

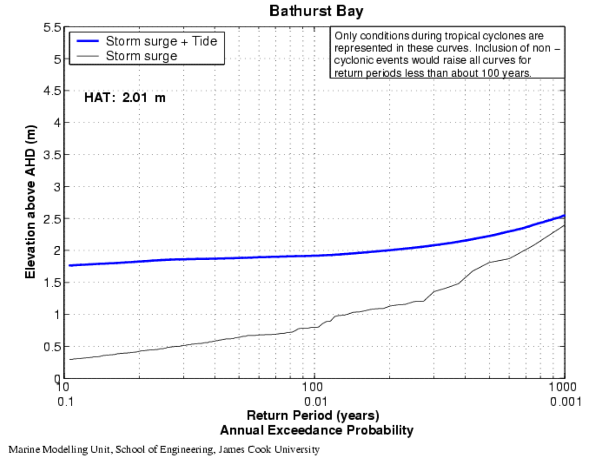

Figure A3. Water level frequency: *Bathurst Bay*

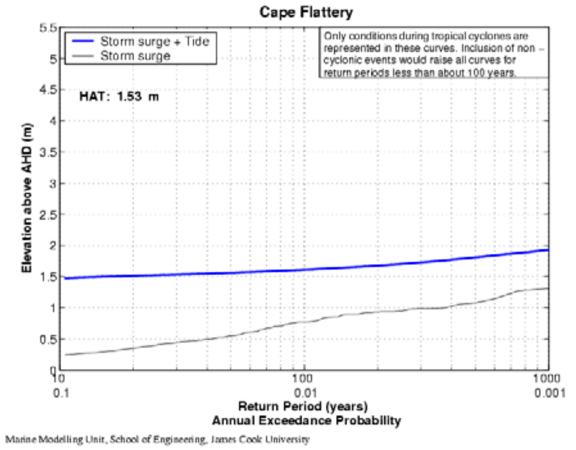

Figure A4. Water level frequency: *Cape Flattery*

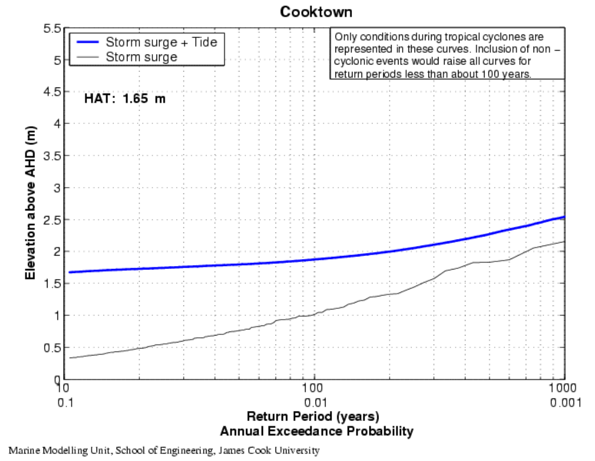

Figure A5. Water level frequency: *Cooktown*

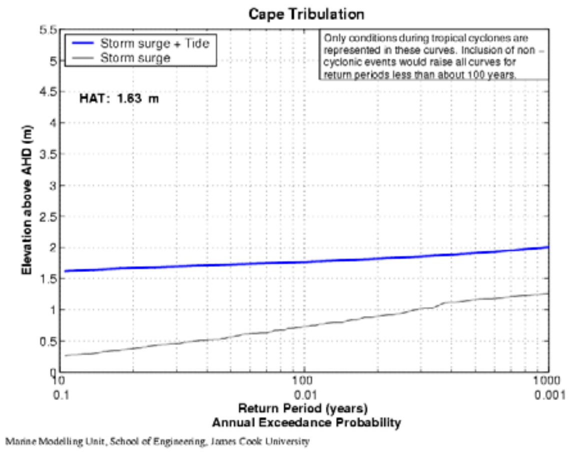

Figure A6. Water level frequency: *Cape Tribulation*

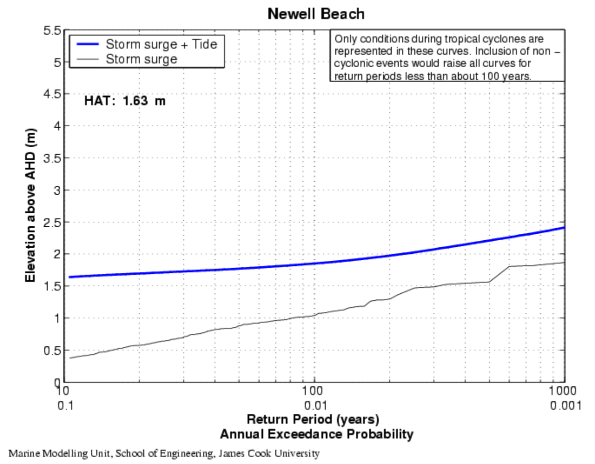

Figure A7. Water level frequency: *Newell Beach*

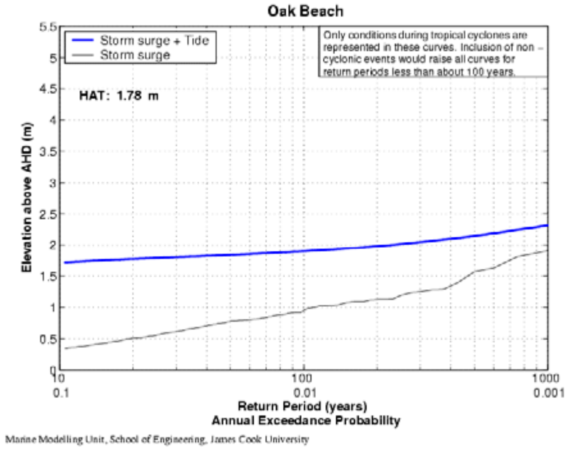

Figure A8. Water level frequency: *Oak Beach*

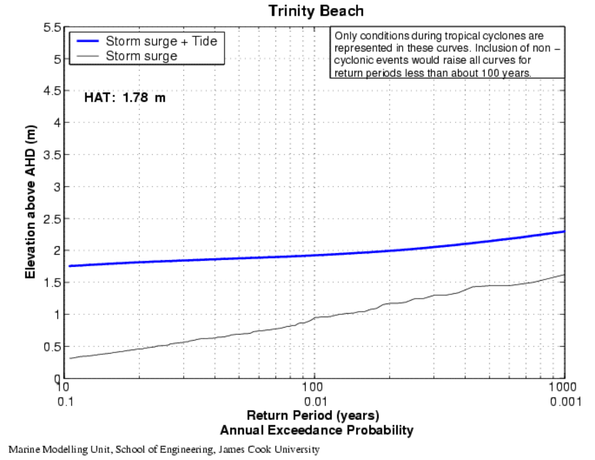

Figure A9. Water level frequency: *Trinity Beach*

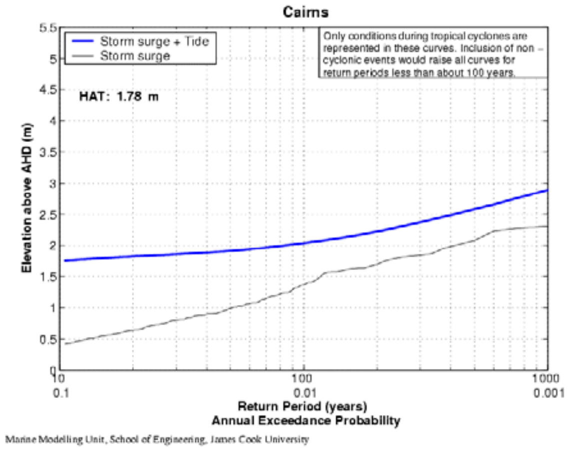

Figure A10. Water level frequency: *Cairns*

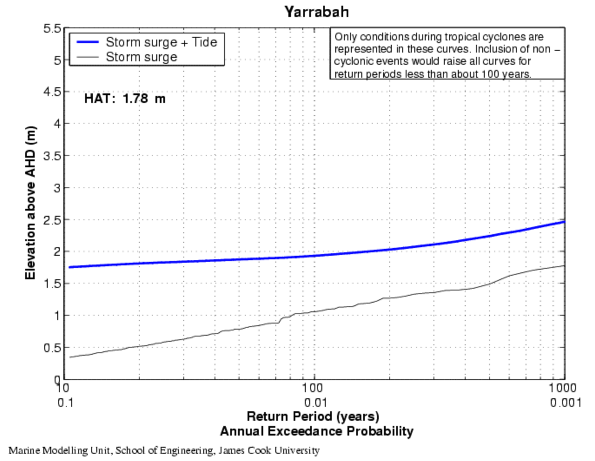

Figure A11. Water level frequency: *Yarrabah*

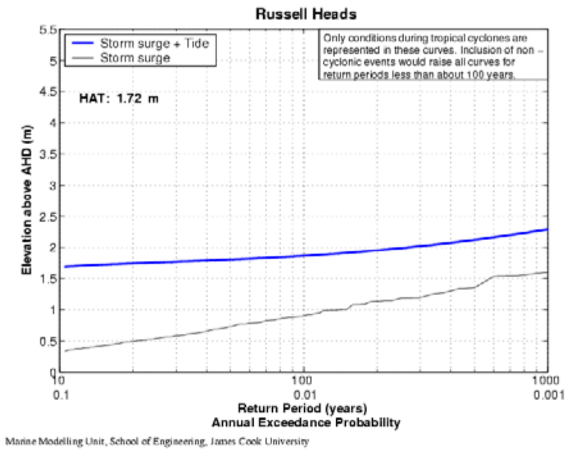

Figure A12. Water level frequency: *Russell Heads*

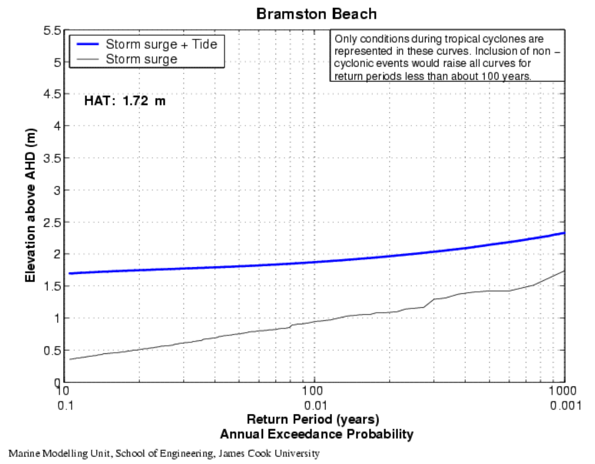

Figure A13. Water level frequency: *Bramston Beach*

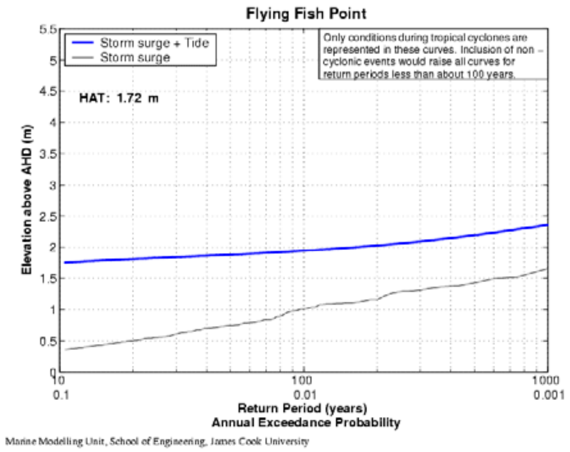

Figure A14. Water level frequency: *Flying Fish Point*

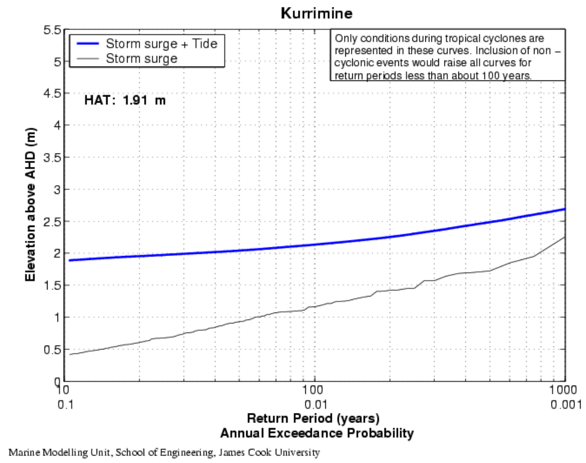

Figure A15. Water level frequency: *Kurrimine Beach*

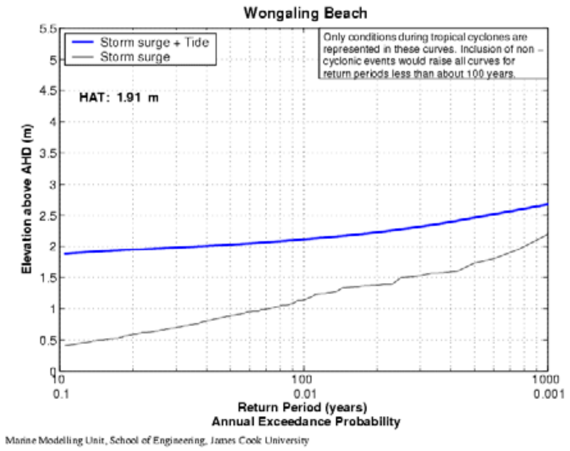

Figure A16. Water level frequency: *Wongaling Beach*

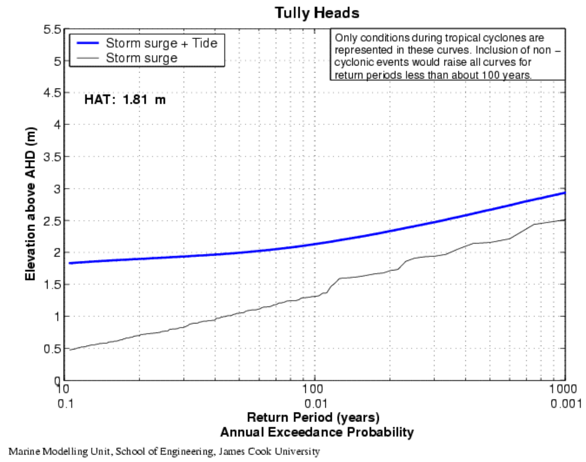

Figure A17. Water level frequency: *Tully Heads*

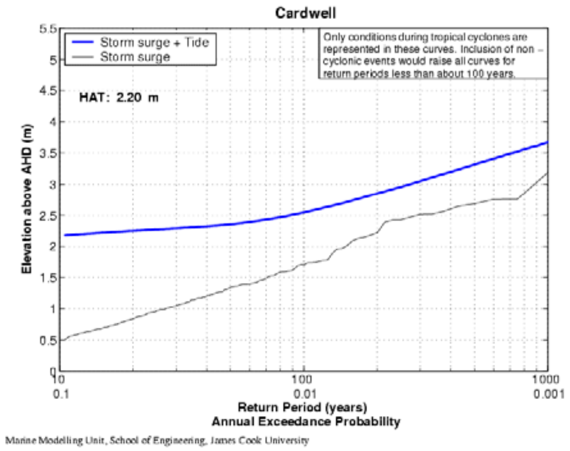

Figure A18. Water level frequency: *Cardwell*

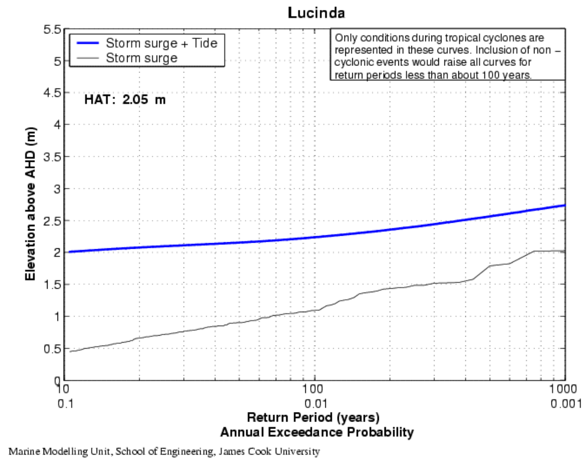

Figure A19. Water level frequency: *Lucinda*

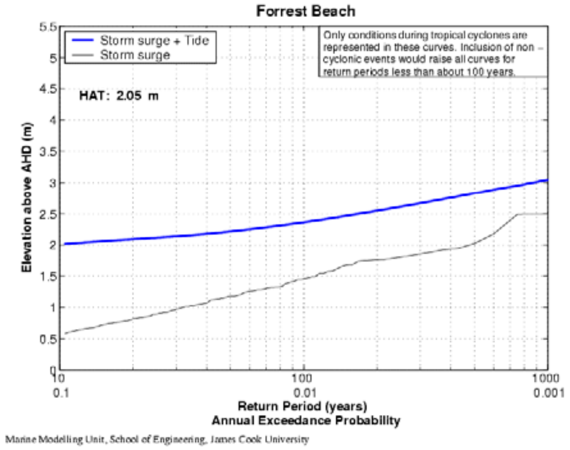

Figure A20. Water level frequency: *Forrest Beach*

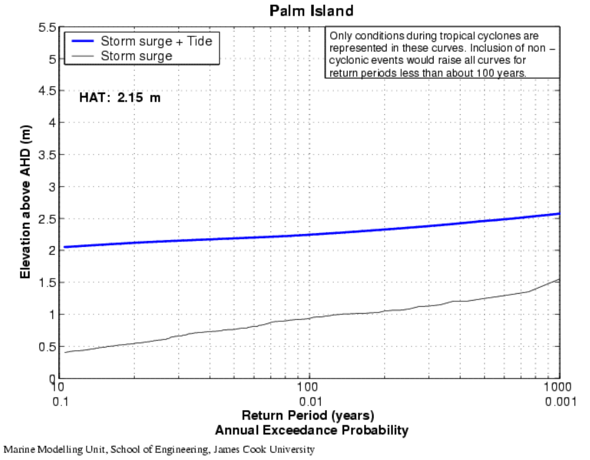

Figure A21. Water level frequency: *Palm Island*

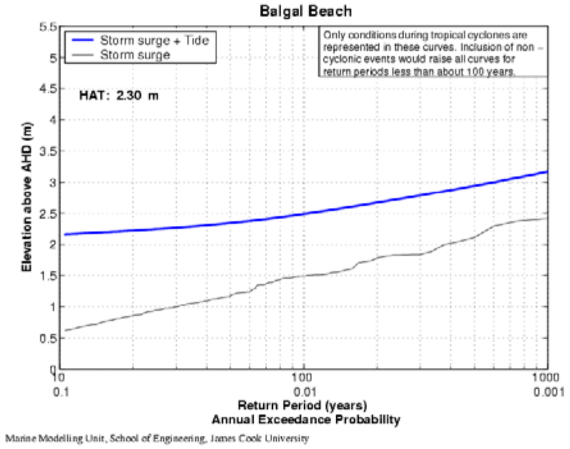

Figure A22. Water level frequency: *Balgal Beach*

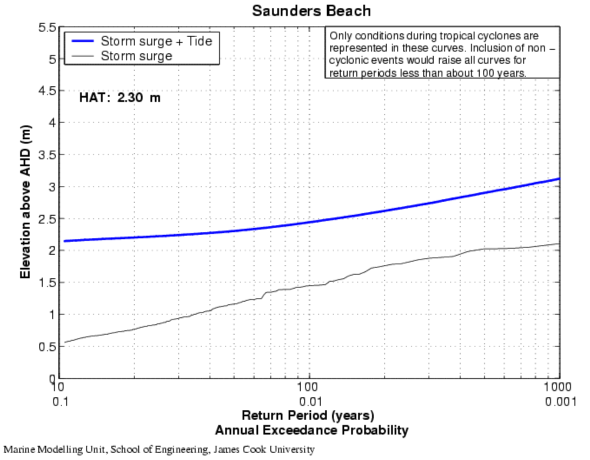

Figure A23. Water level frequency: *Saunders Beach*

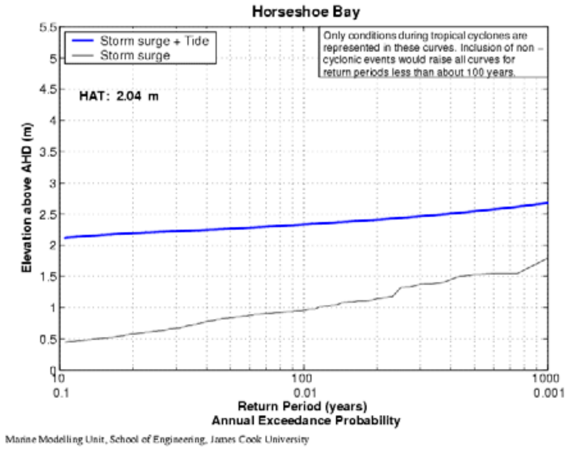

Figure A24. Water level frequency: *Horseshoe Bay*

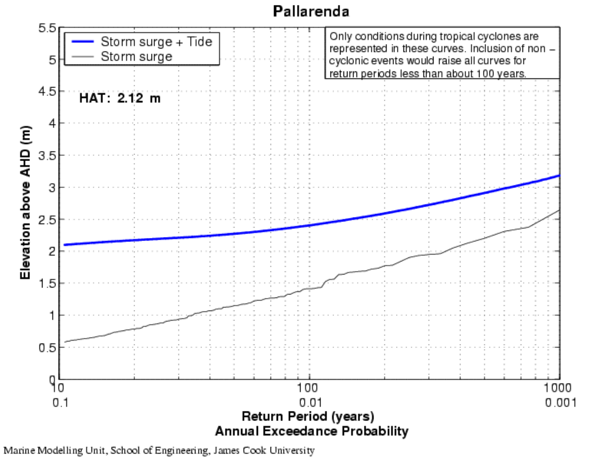

Figure A25. Water level frequency: *Pallarenda*

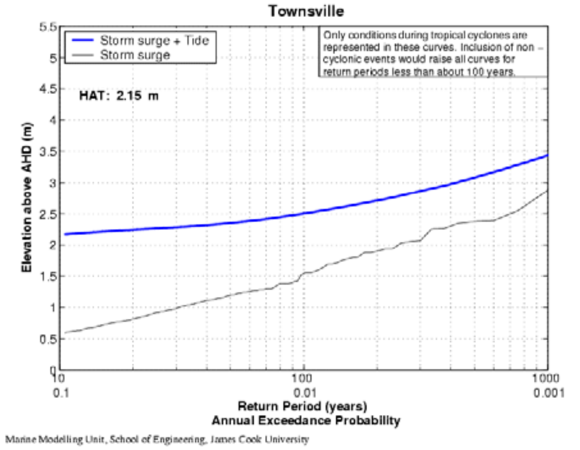

Figure A26. Water level frequency: *Townsville*

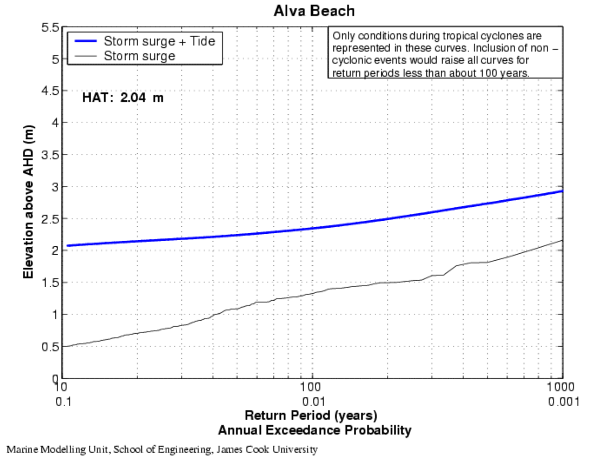

Figure A27. Water level frequency: *Alva Beach*

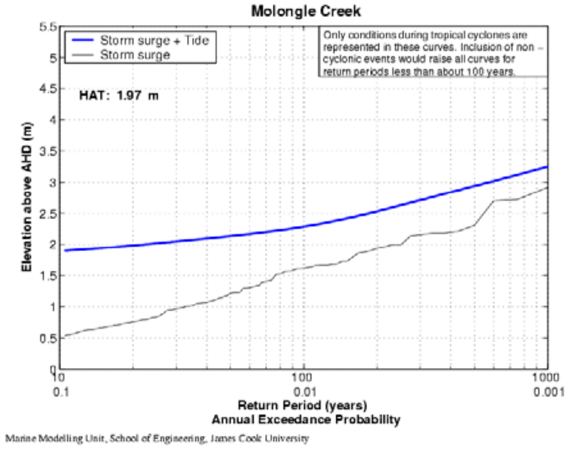

Figure A28. Water level frequency: *Molongle Creek*

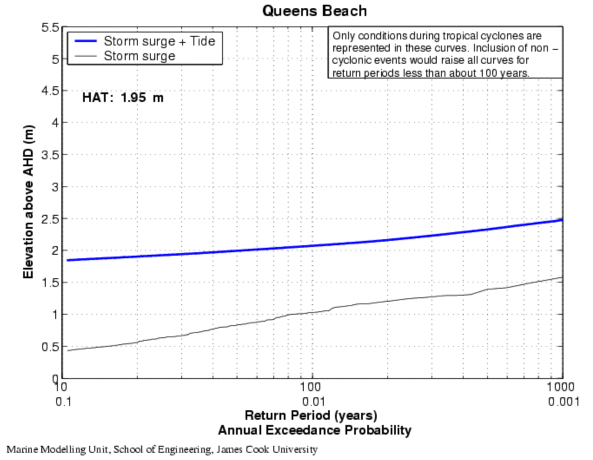

Figure A29. Water level frequency: *Queens Beach*

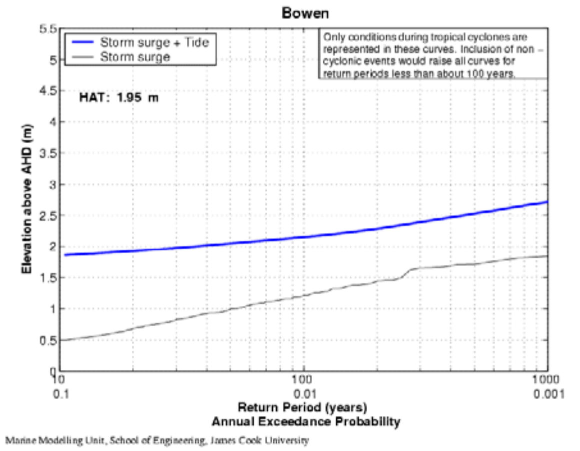

Figure A30. Water level frequency: *Bowen*

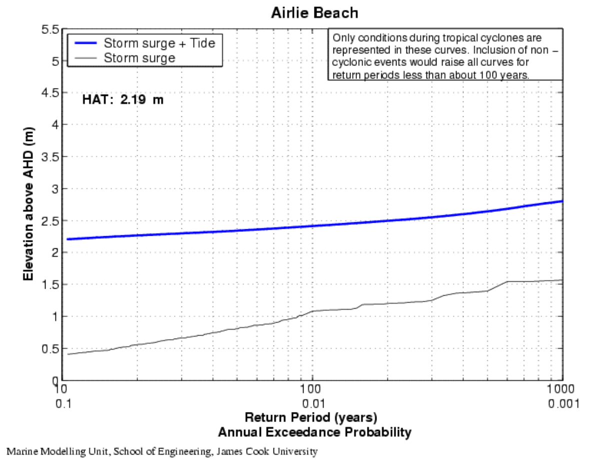

Figure A31. Water level frequency: *Airlie Beach*

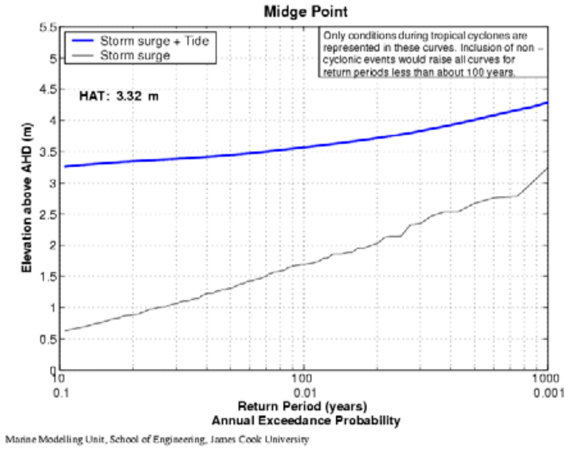

Figure A32. Water level frequency: *Midge Point*

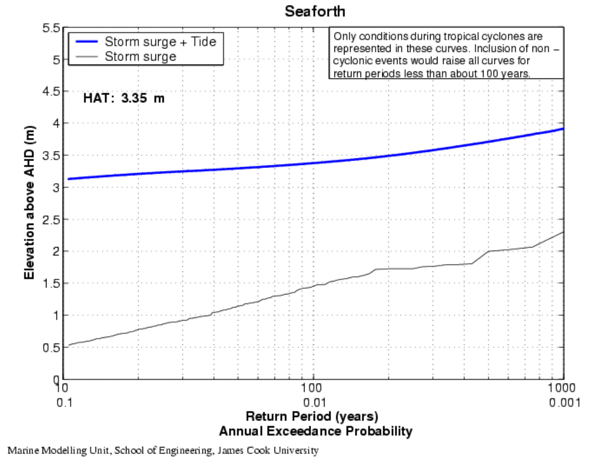

Figure A33. Water level frequency: *Seaforth*

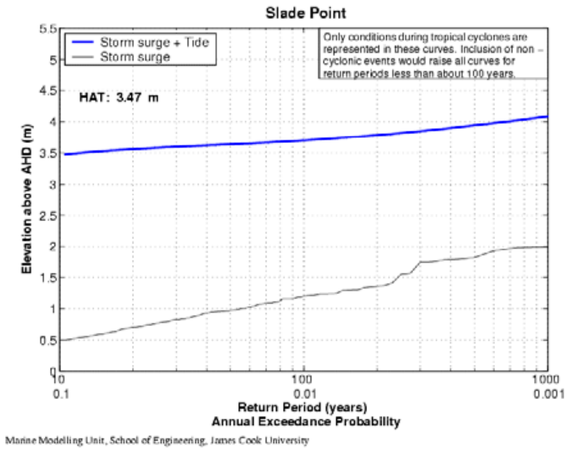

Figure A34. Water level frequency: *Slade Point*

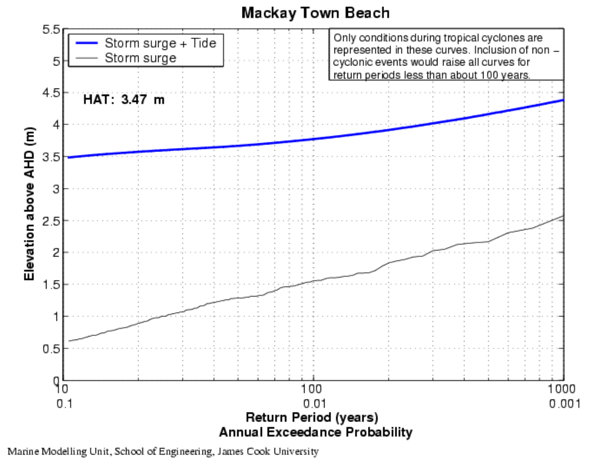

Figure A35. Water level frequency: *Mackay Town Beach*

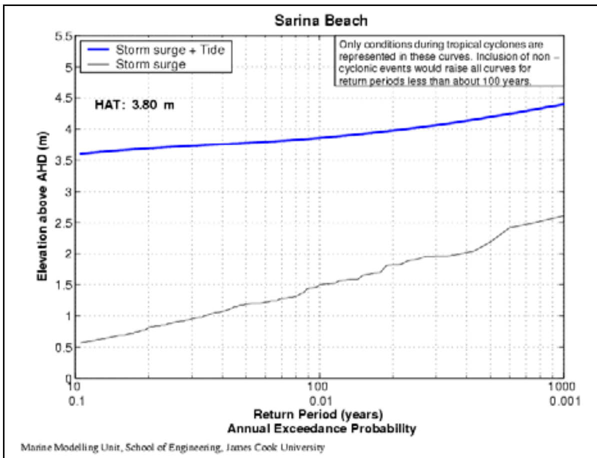

Figure A36. Water level frequency: *Sarina Beach*

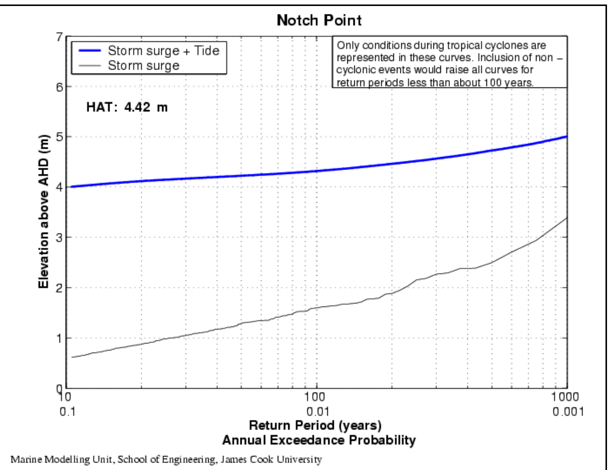

Figure A37. Water level frequency: *Notch Point*

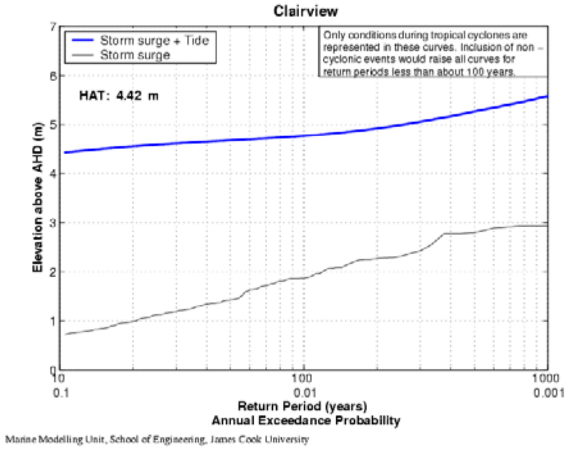

Figure A38. Water level frequency: *Clairview*

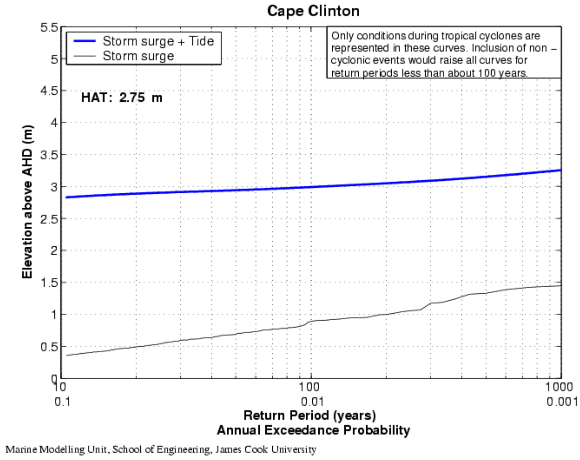

Figure A39. Water level frequency: *Cape Clinton*

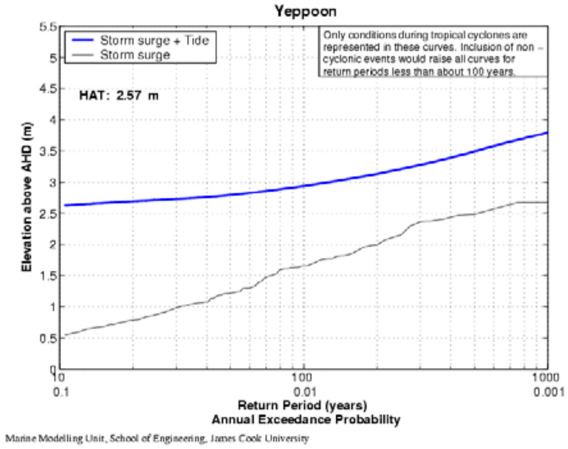

Figure A40. Water level frequency: *Yeppoon*

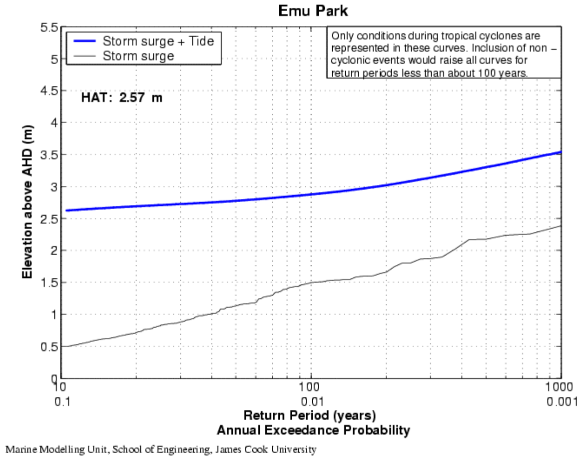

Figure A41. Water level frequency: *Emu Park*

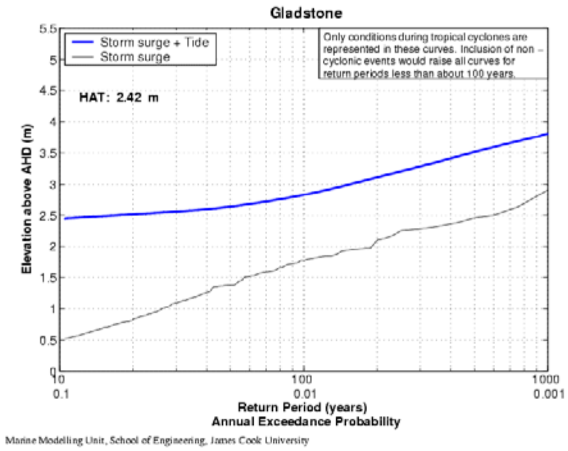

Figure A42. Water level frequency: *Gladstone*

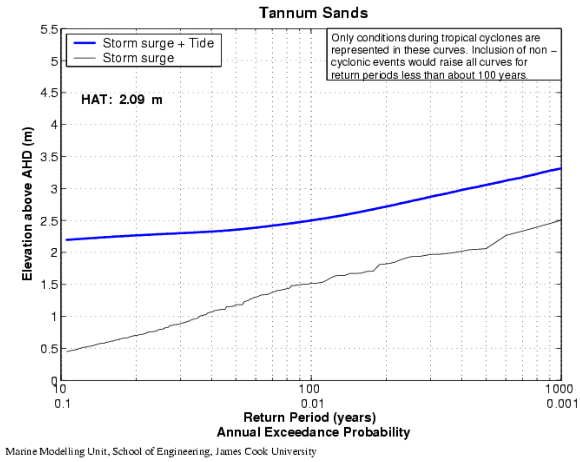

Figure A43. Water level frequency: *Tannum Sands*

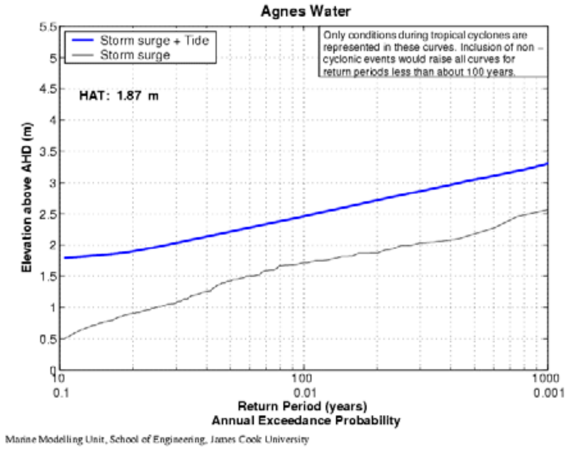

Figure A44. Water level frequency: *Agnes Waters*

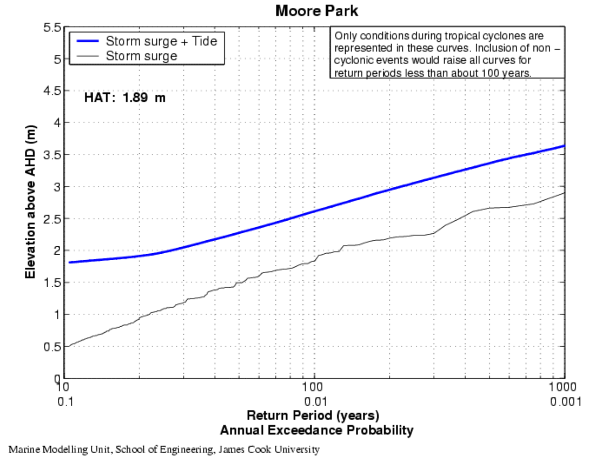

Figure A45. Water level frequency: *Moore Park*

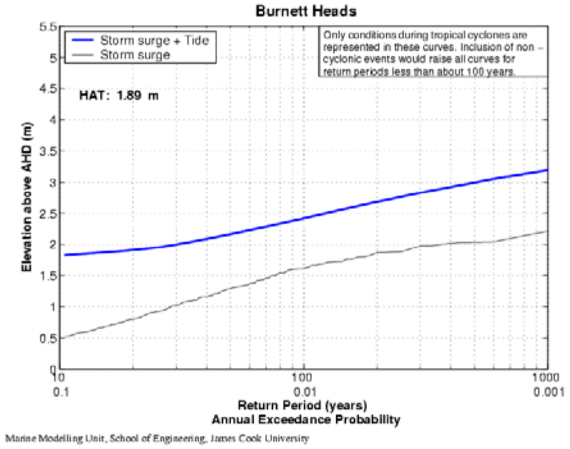

Figure A46. Water level frequency: *Burnett Heads*

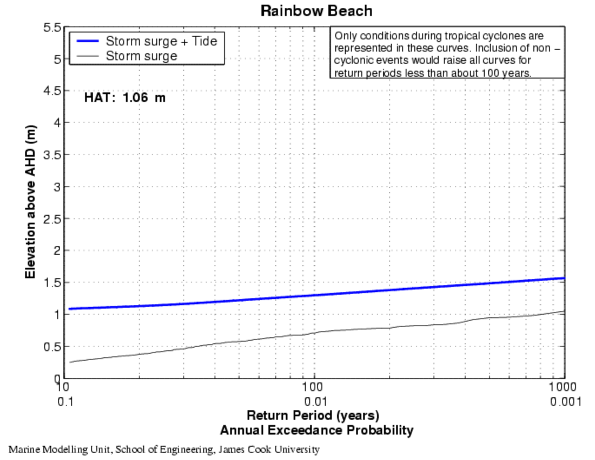

Figure A47. Water level frequency: *Rainbow Beach*

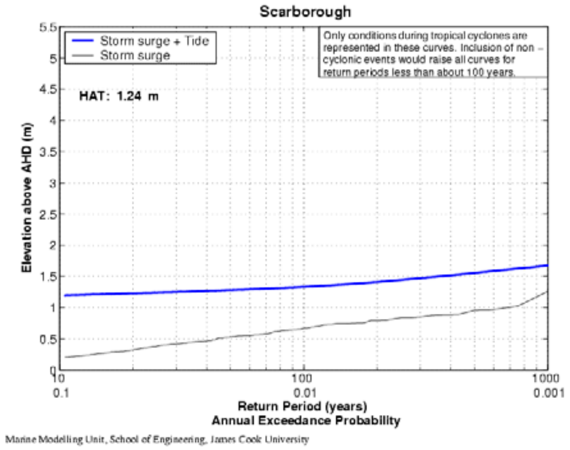

Figure A48. Water level frequency: *Scarborough*

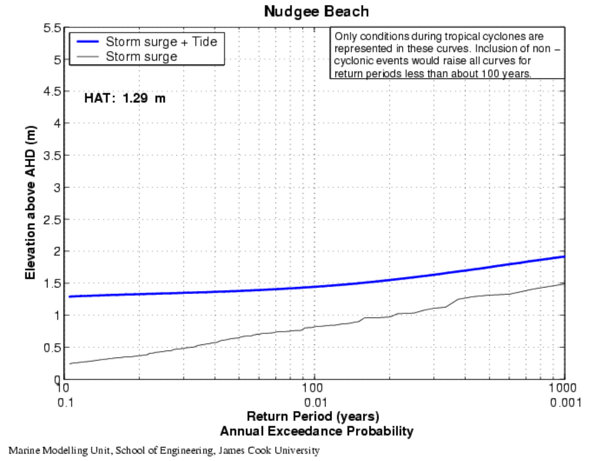

Figure A49. Water level frequency: *Nudgee Beach*

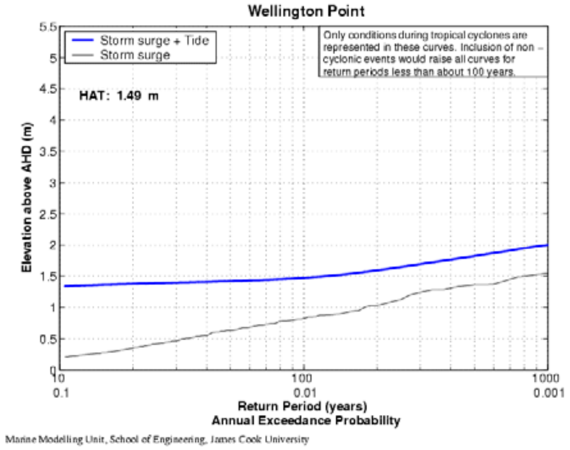

Figure A50. Water level frequency: *Wellington Point*

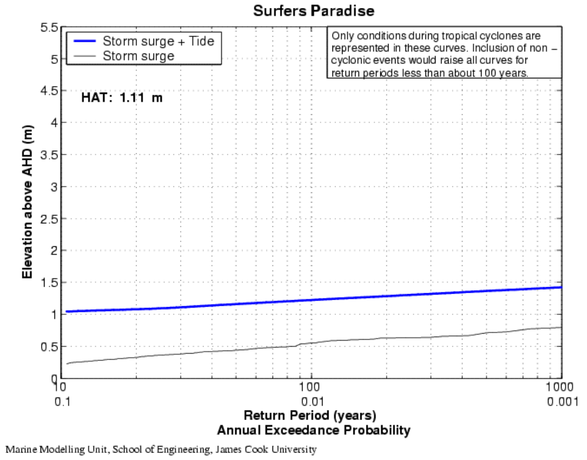

Figure A51. Water level frequency: *Surfers Paradise*

APPENDIX B

STORM SURGE PLUS TIDE RETURN PERIOD CURVES

QUEENSLAND EAST COAST: *GREENHOUSE*

Return Period curves for storm surge plus tide considering greenhouse effects are presented for 50 output points along the east coast of Queensland (Figure B1). These same curves are also displayed in the *Atlas of Physical Processes in the Great Barrier Reef World Heritage Area* which is located on the *MMU* web site (http://mmu.jcu.edu.au).

These curves are valid for water levels produced during tropical cyclones. Extra-topical storms and other meteorological and oceanic causes of water level change (not modelled here) will contribute to the return period of water levels at lower return periods.

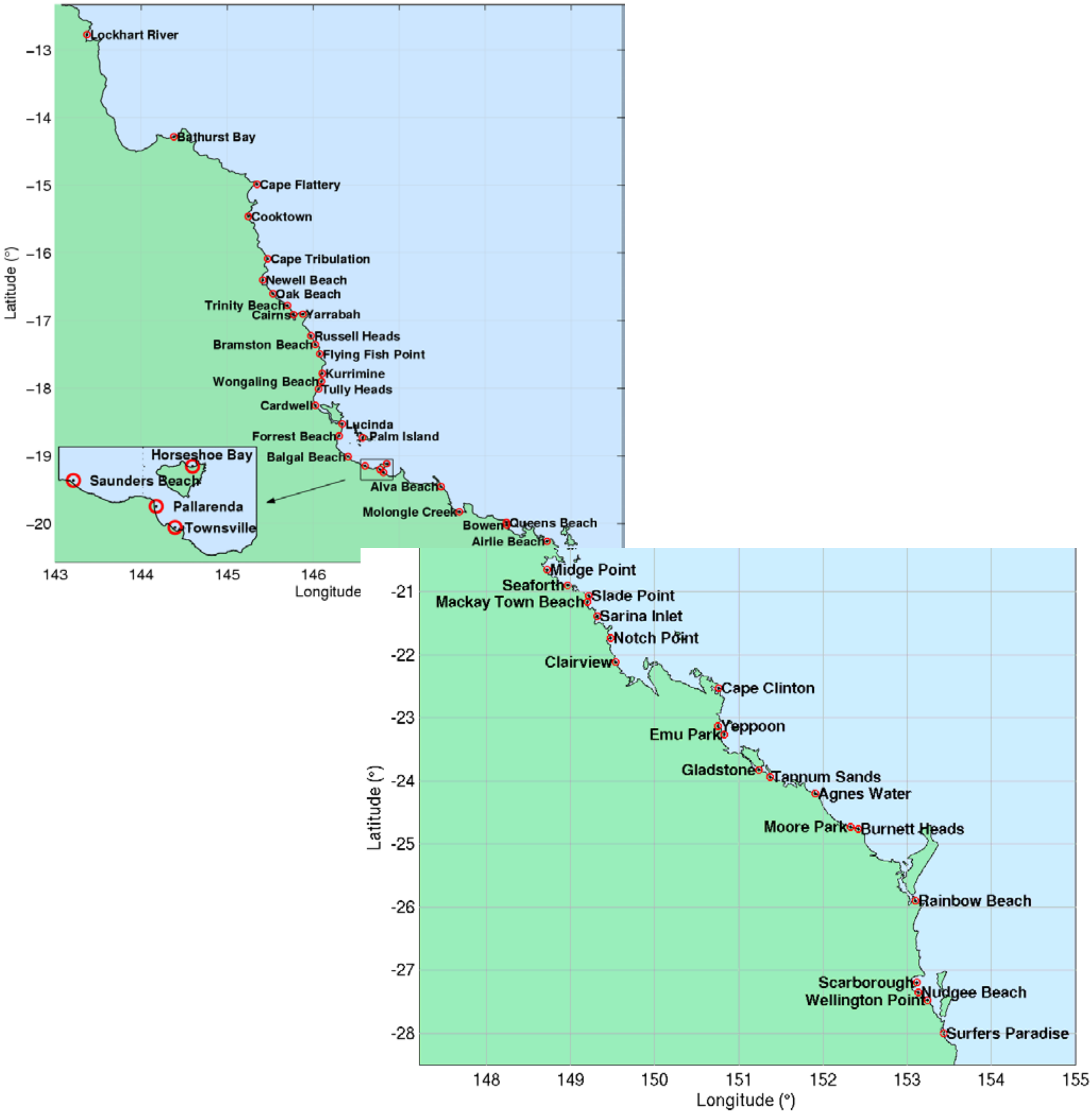

Figure B1. East Coast Queensland reporting locations

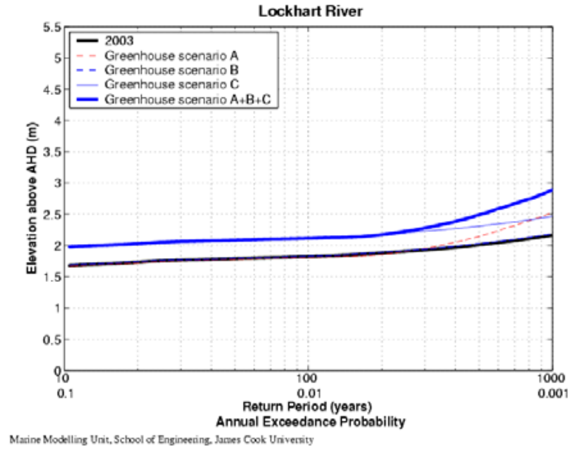

Figure B2. Water level frequency - *Greenhouse*: *Lockhart River*

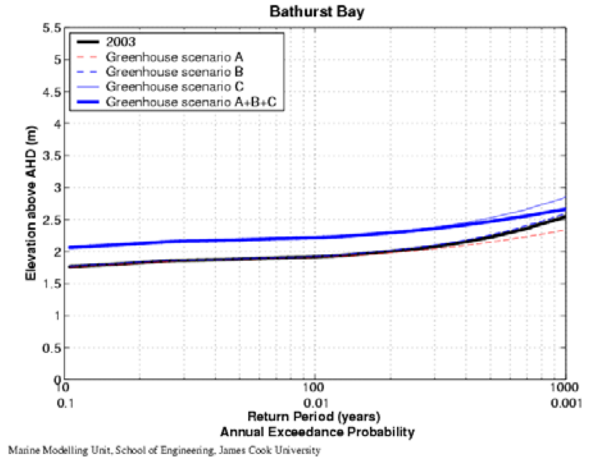

Figure B3. Water level frequency - *Greenhouse*: *Bathurst Bay*

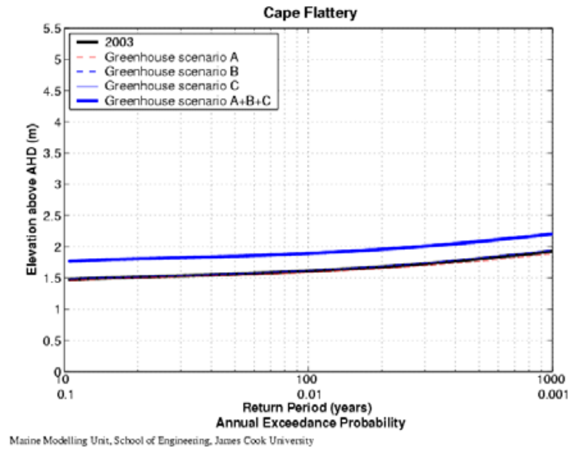

Figure B4. Water level frequency - *Greenhouse*: *Cape Flattery*

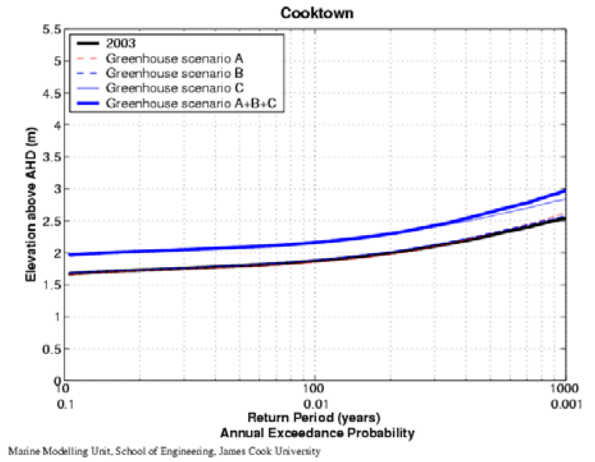

Figure B5. Water level frequency - *Greenhouse*: *Cooktown*

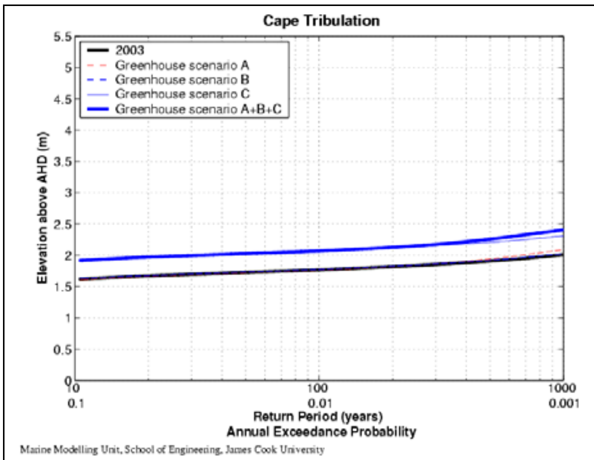

Figure B6. Water level frequency - *Greenhouse*: *Cape Tribulation*

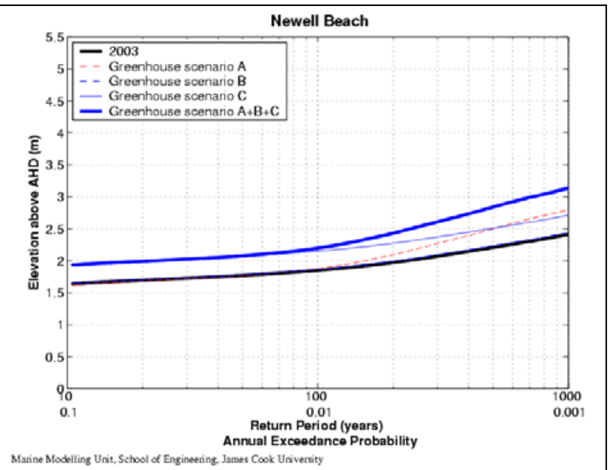

Figure B7. Water level frequency - *Greenhouse*: *Newell Beach*

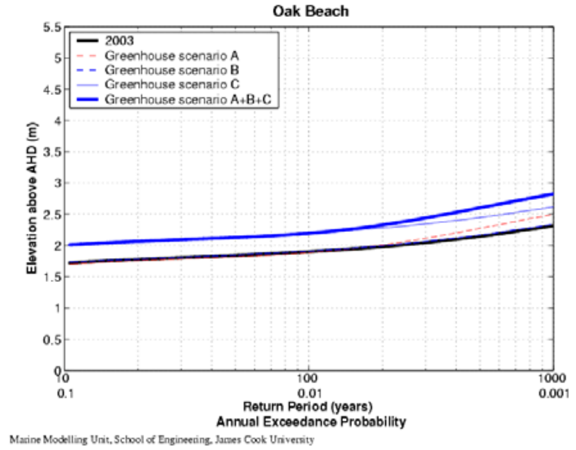

Figure B8. Water level frequency - *Greenhouse*: *Oak Beach*

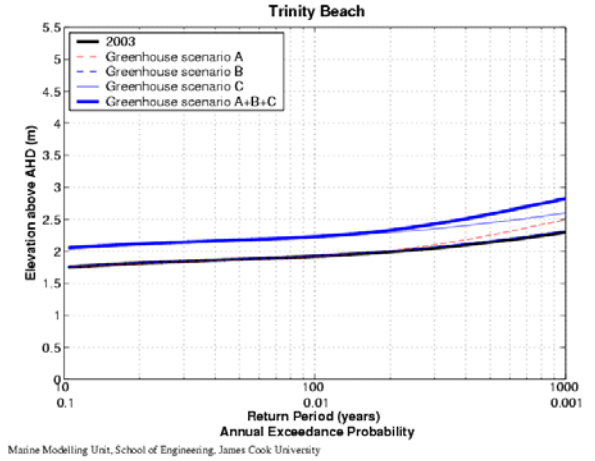

Figure B9. Water level frequency - *Greenhouse*: *Trinity Beach*

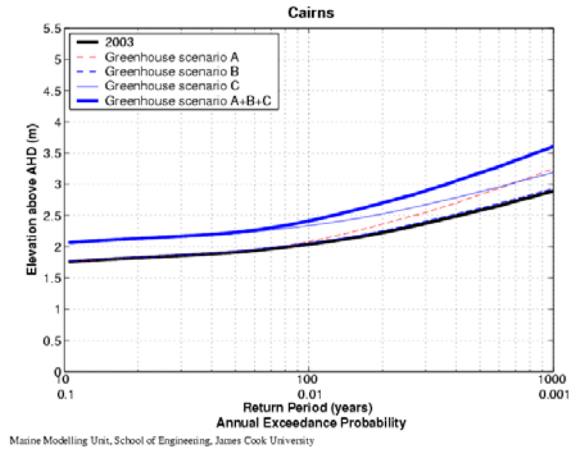

Figure B10. Water level frequency - *Greenhouse*: *Cairns*

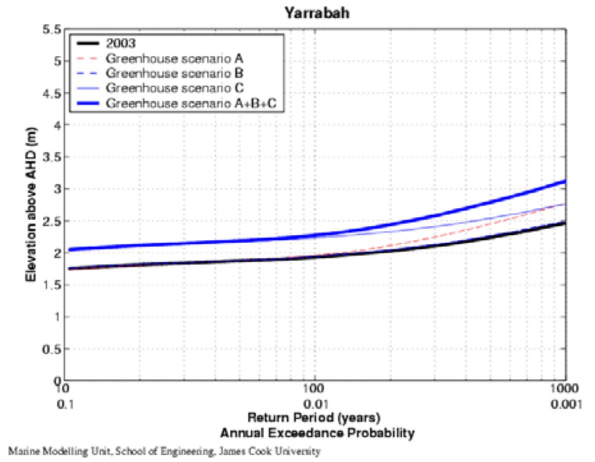

Figure B11. Water level frequency - *Greenhouse*: *Yarrabah*

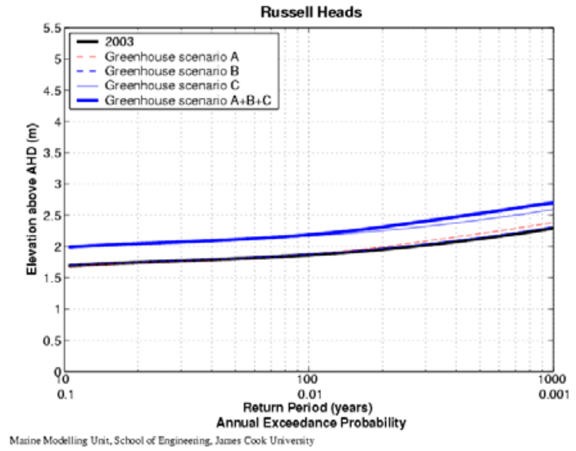

Figure B12. Water level frequency - *Greenhouse*: *Russell Heads*

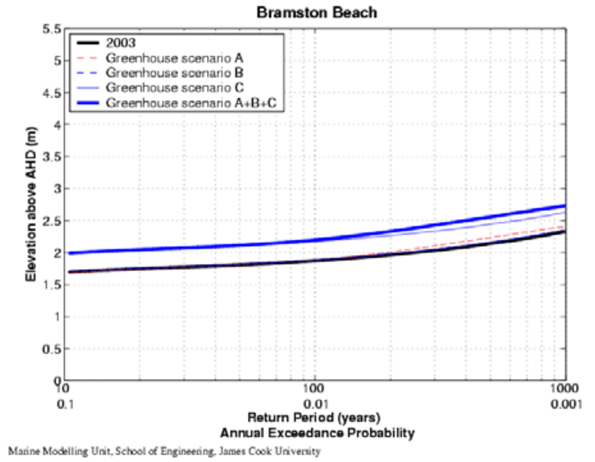

Figure B13. Water level frequency - *Greenhouse*: *Bramston Beach*

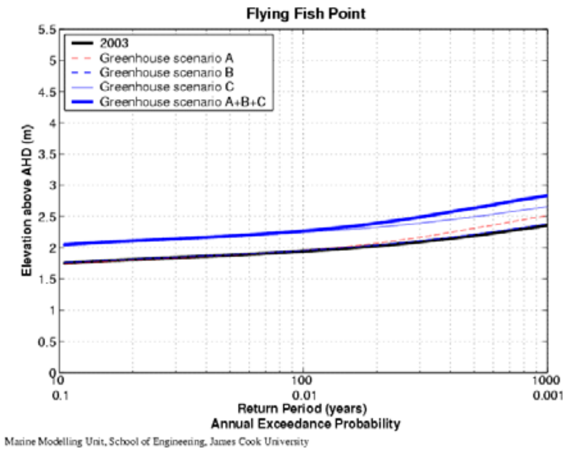

Figure B14. Water level frequency - *Greenhouse*: *Flying Fish Point*

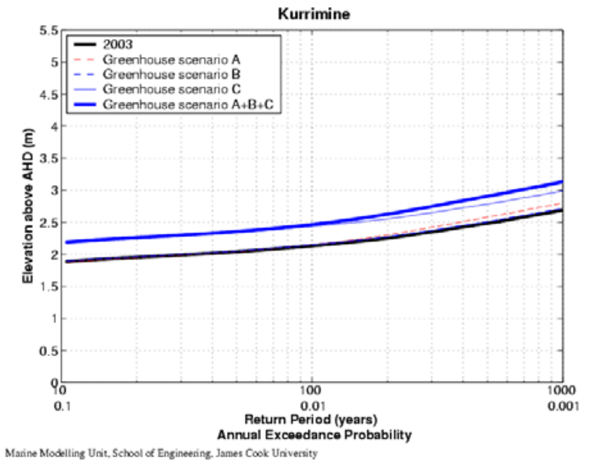

Figure B15. Water level frequency - *Greenhouse*: *Kurrimine Beach*

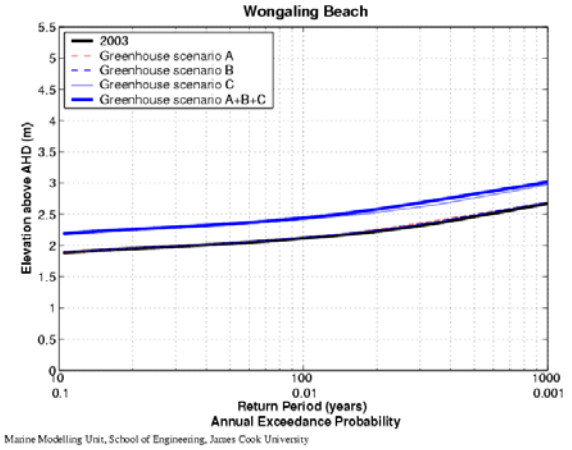

Figure B16. Water level frequency - *Greenhouse*: *Wongaling Beach*

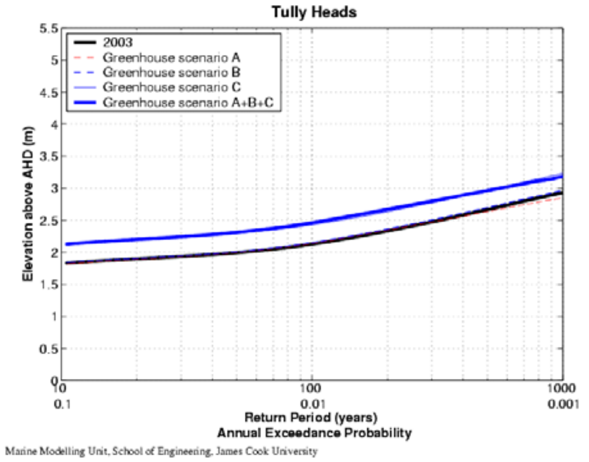

Figure B17. Water level frequency - *Greenhouse*: *Tully Heads*

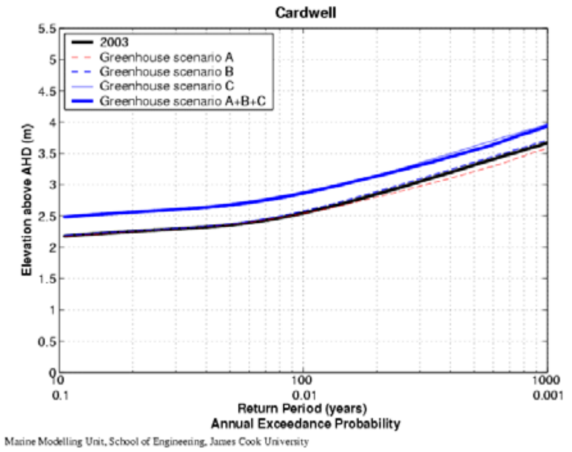

Figure B18. Water level frequency - *Greenhouse*: *Cardwell*

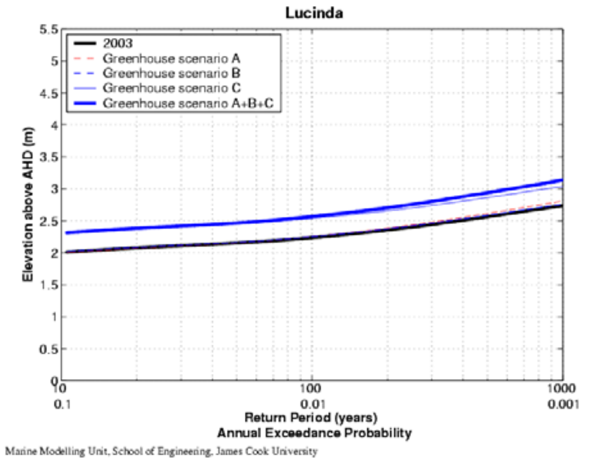

Figure B19. Water level frequency - *Greenhouse*: *Lucinda*

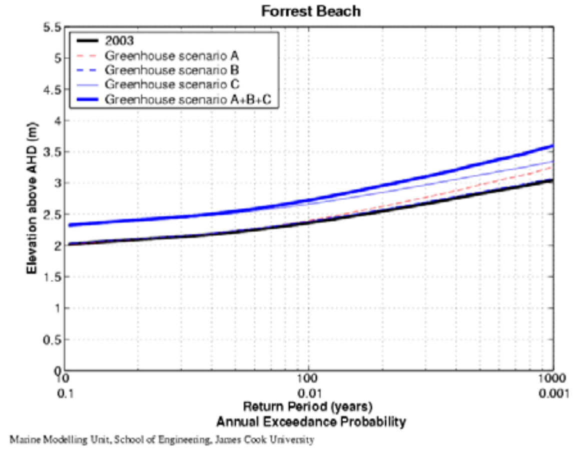

Figure B20. Water level frequency - *Greenhouse*: *Forrest Beach*

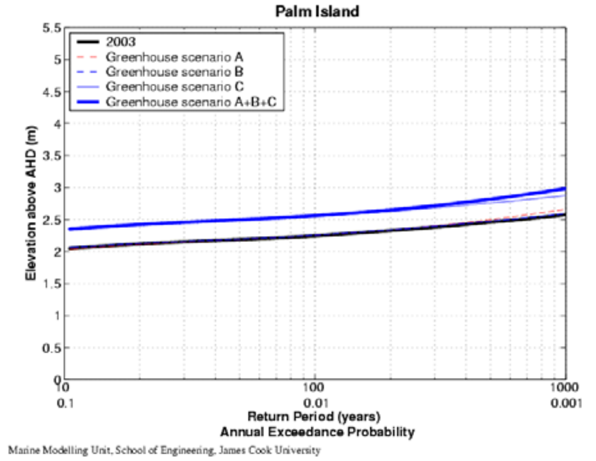

Figure B21. Water level frequency - *Greenhouse*: *Palm Island*

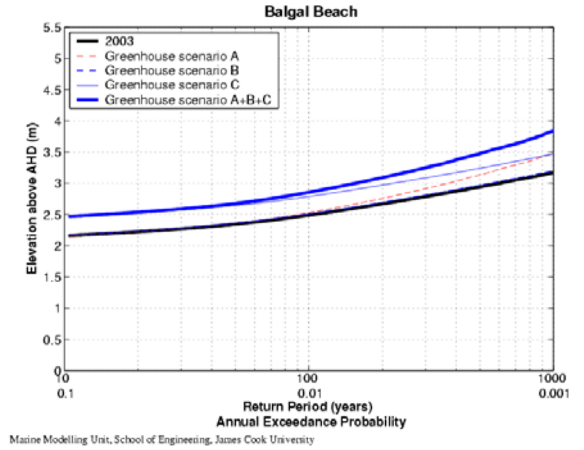

Figure B22. Water level frequency - *Greenhouse*: *Balgal Beach*

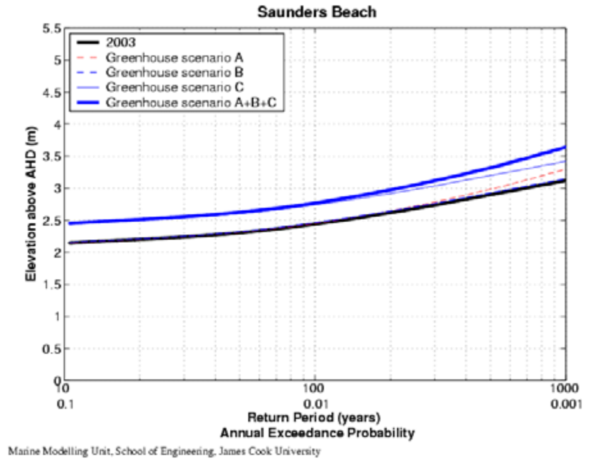

Figure B23. Water level frequency - *Greenhouse*: *Saunders Beach*

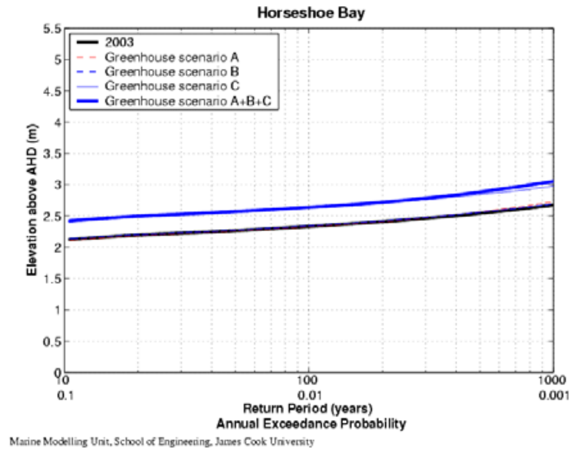

Figure B24. Water level frequency - *Greenhouse*: *Horseshoe Bay*

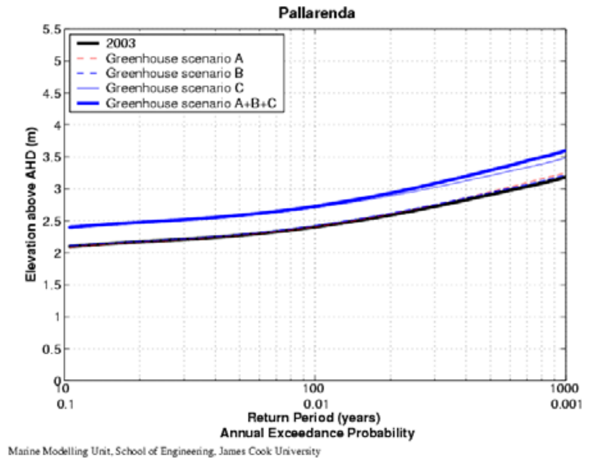

Figure B25. Water level frequency - *Greenhouse*: *Pallarenda*

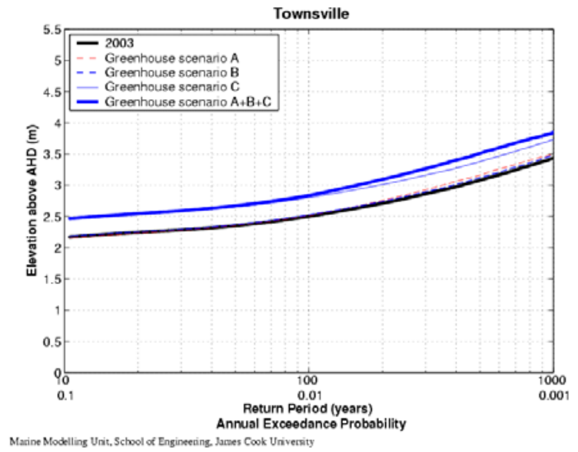

Figure B26. Water level frequency - *Greenhouse*: *Townsville*

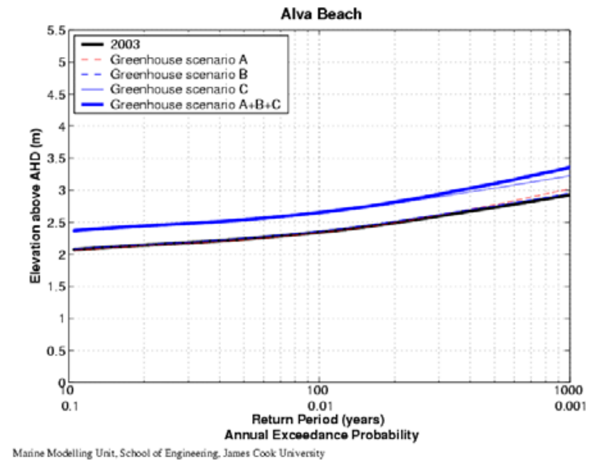

Figure B27. Water level frequency - *Greenhouse*: *Alva Beach*

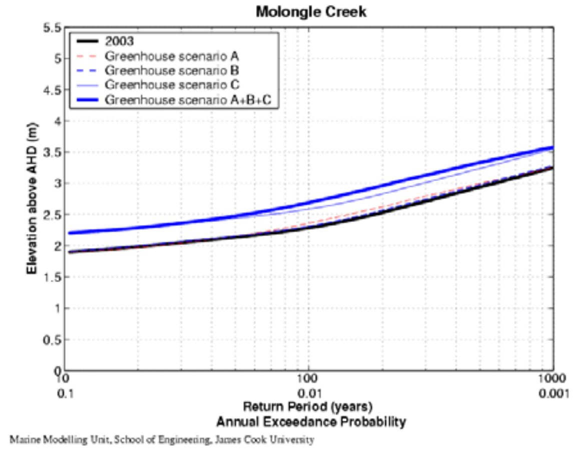

Figure B28. Water level frequency - *Greenhouse*: *Molongle Creek*

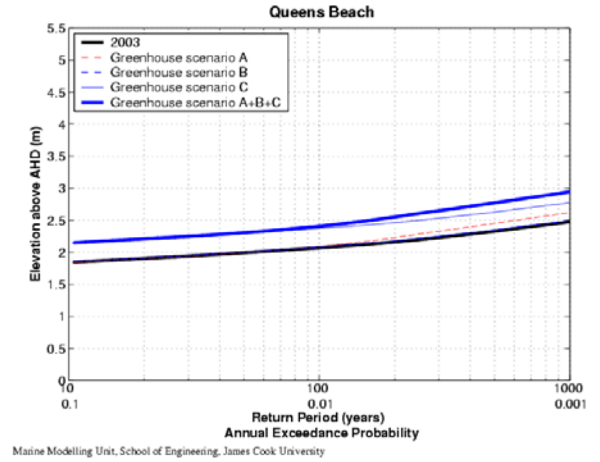

Figure B29. Water level frequency - *Greenhouse*: *Queens Beach*

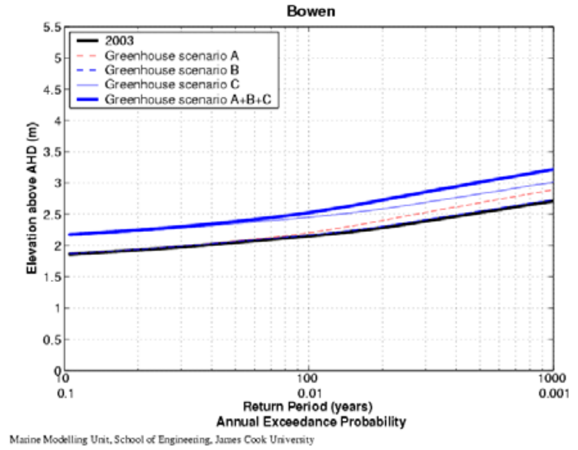

Figure B30. Water level frequency - *Greenhouse*: *Bowen*

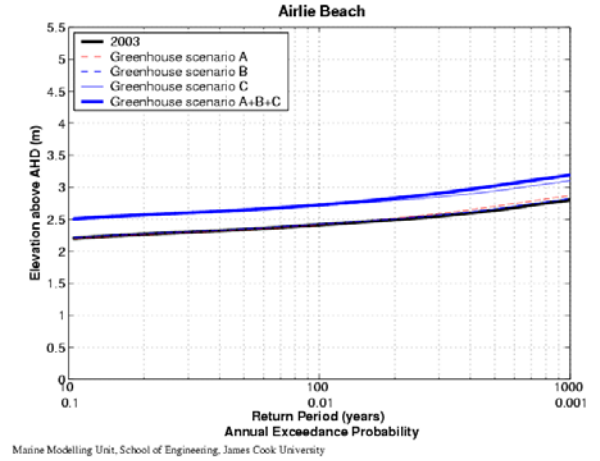

Figure B31. Water level frequency - *Greenhouse*: *Airlie Beach*

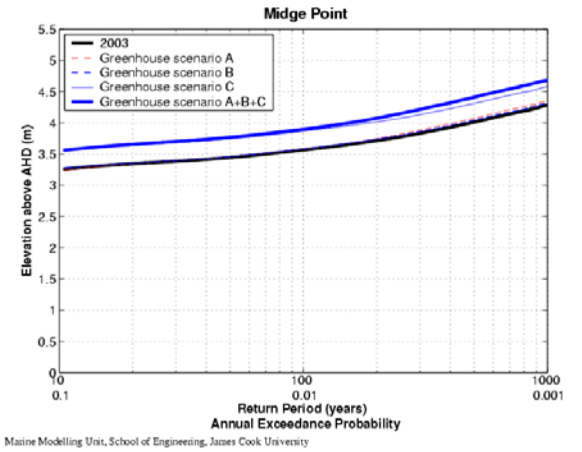

Figure B32. Water level frequency - *Greenhouse*: *Midge Point*

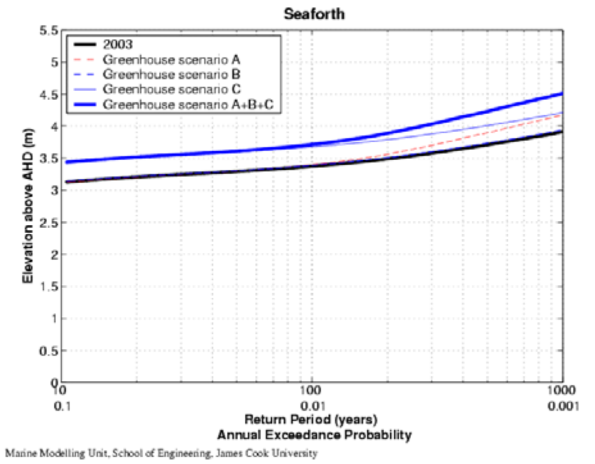

Figure B33. Water level frequency - *Greenhouse*: *Seaforth*

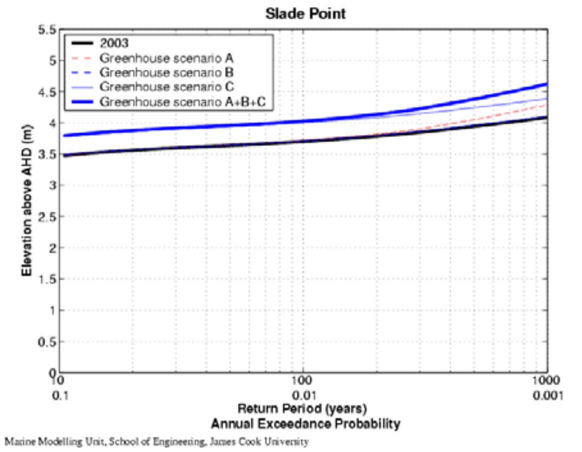

Figure B34. Water level frequency - *Greenhouse*: *Slade Point*

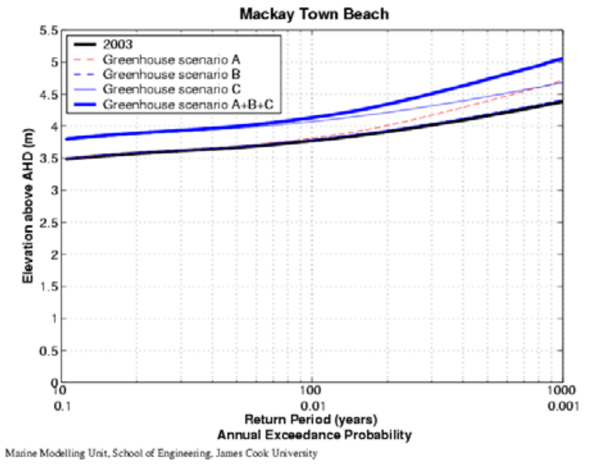

Figure B35. Water level frequency - *Greenhouse*: *Mackay Town Beach*

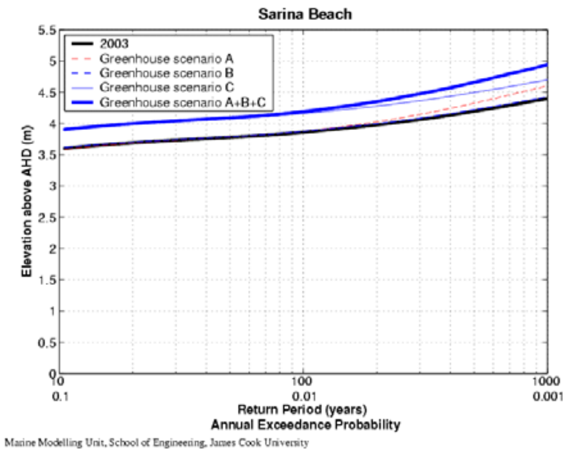

Figure B36. Water level frequency - *Greenhouse*: *Sarina Beach*

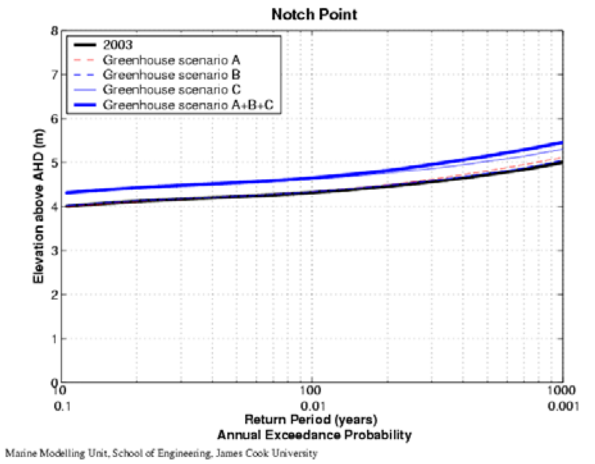

Figure B37. Water level frequency - *Greenhouse*: *Notch Point*

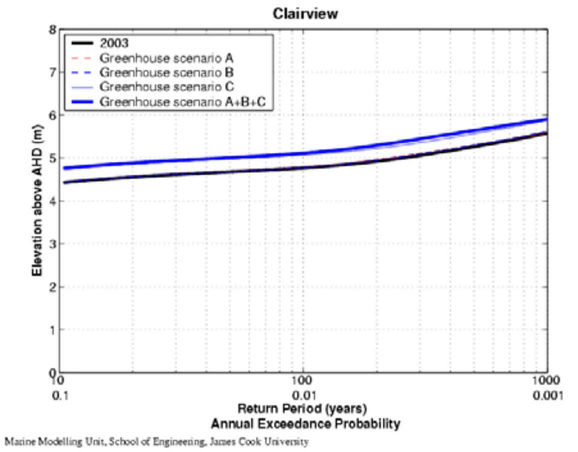

Figure B38. Water level frequency - *Greenhouse*: *Clairview*

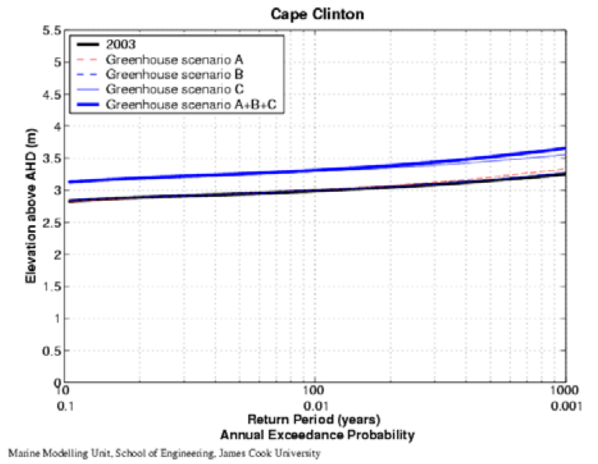

Figure B39. Water level frequency - *Greenhouse*: *Cape Clinton*

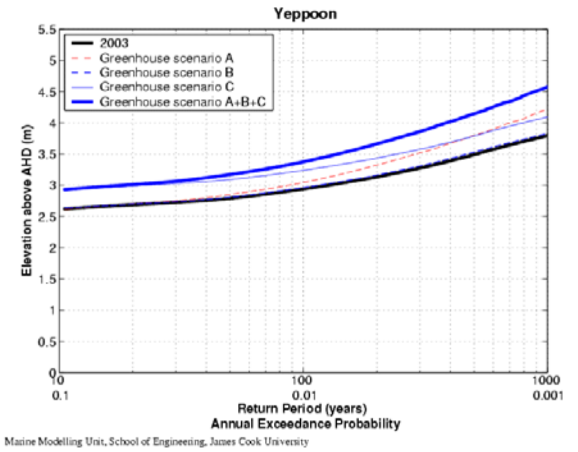

Figure B40. Water level frequency - *Greenhouse*: *Yeppoon*

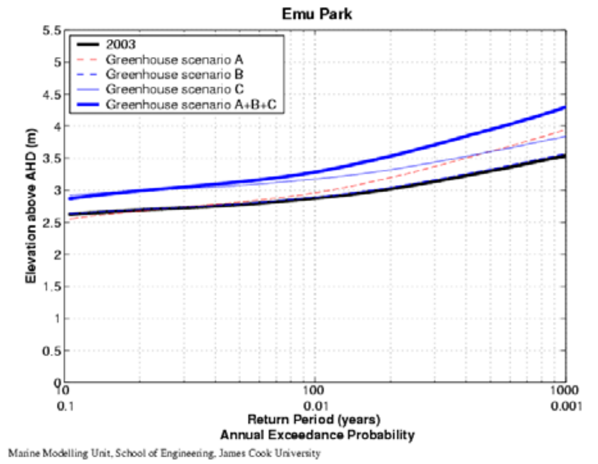

Figure B41. Water level frequency - *Greenhouse*: *Emu Park*

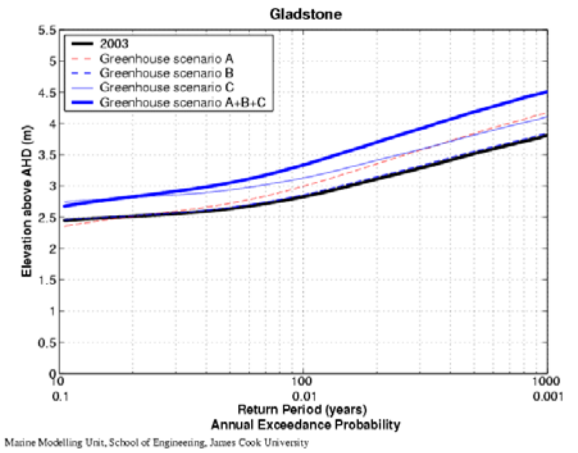

Figure B42. Water level frequency - *Greenhouse*: *Gladstone*

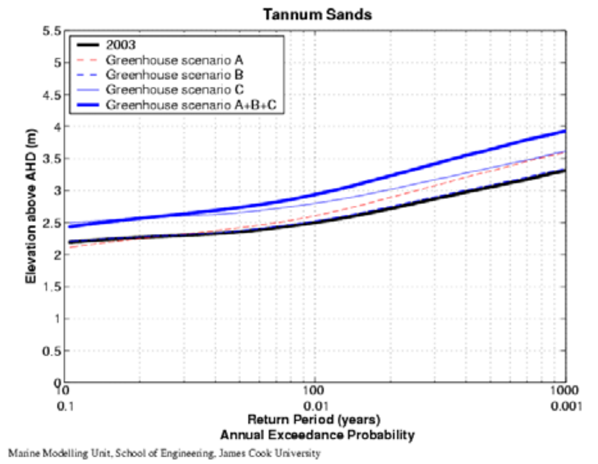

Figure B43. Water level frequency - *Greenhouse*: *Tannum Sands*

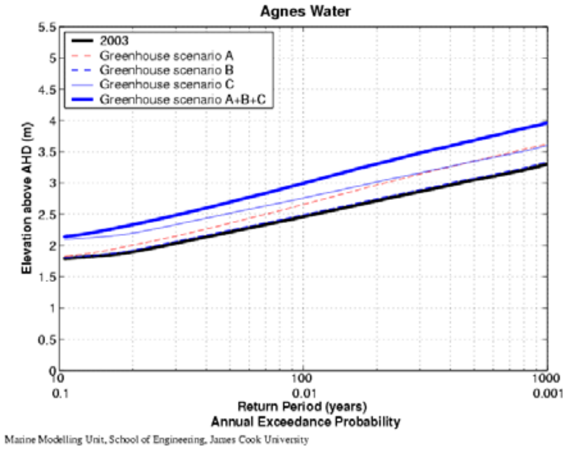

Figure B44. Water level frequency - *Greenhouse*: *Agnes Waters*

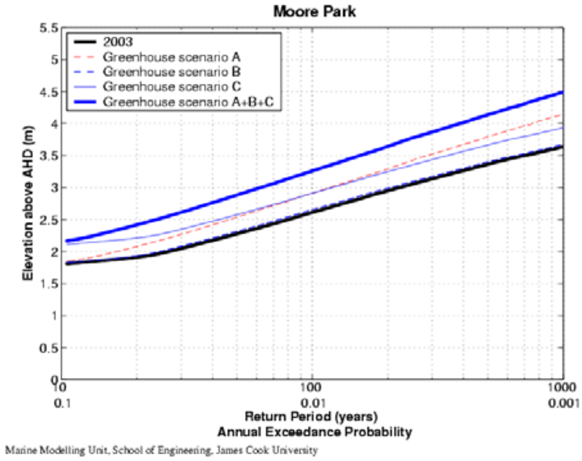

Figure B45. Water level frequency - *Greenhouse*: *Moore Park*

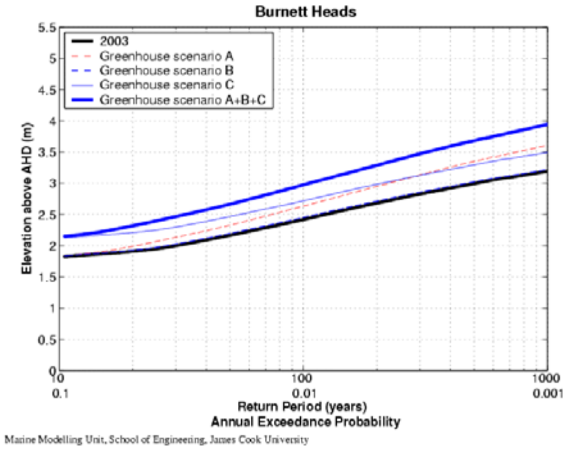

Figure B46. Water level frequency - *Greenhouse*: *Burnett Heads*

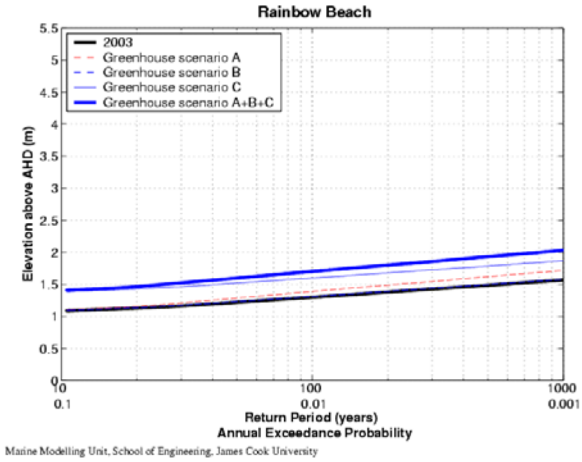

Figure B47. Water level frequency - *Greenhouse*: *Rainbow Beach*

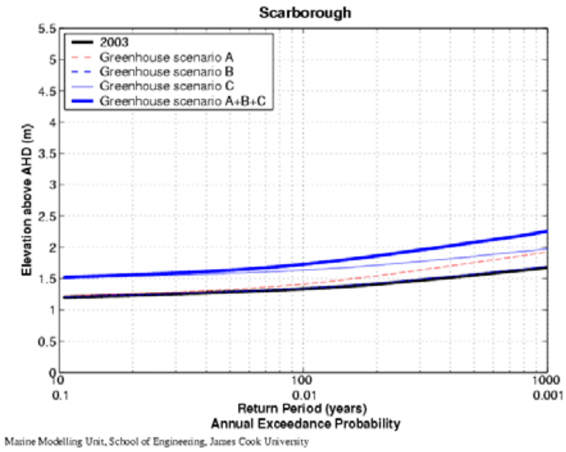

Figure B48. Water level frequency - *Greenhouse*: *Scarborough*

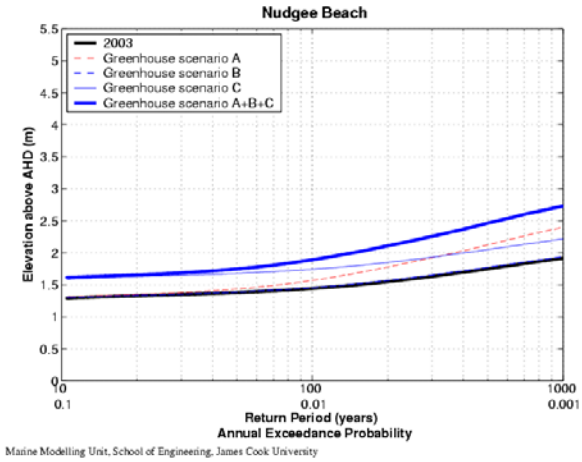

Figure B49. Water level frequency - *Greenhouse*: *Nudgee Beach*

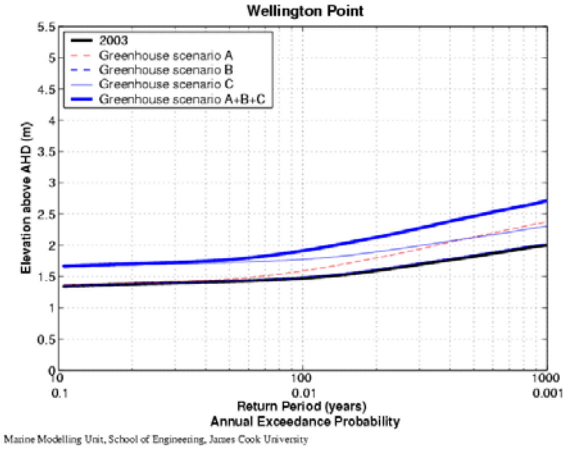

Figure B50. Water level frequency - *Greenhouse*: *Wellington Point*

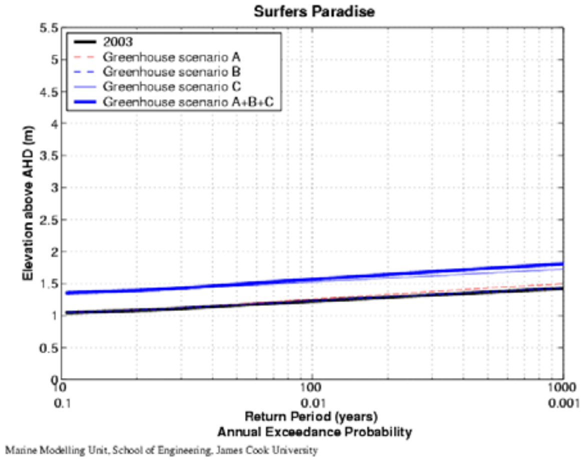

Figure B51. Water level frequency - *Greenhouse*: *Surfers Paradise*