# Impact of Sea-level Rise and Storm Surges on Coastal Resorts

A report for CSIRO Tourism Research

Final Report
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**K.L. McInnes, K.J.E. Walsh and A.B. Pittock**
**CSIRO Atmospheric Research**

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## Executive Summary

This is the final report of a project that examines the impact of tropical cyclone storm surges on Cairns. Two aspects of storm surge have been investigated, return periods under current climate and the possible changes under climate change.

The storm surge, a dome of water pushed ahead of a cyclone by strong winds, is one of the most damaging aspects of tropical cyclones particularly when combined adversely with astronomical tides. Estimates of the return periods, or the average time between events, of the combination of storm surges and tides (i.e. storm tides) in the Cairns region have been made. These estimates were made by combining a statistical representation of cyclones affecting Cairns, determined through an analysis of historical cyclone records in the Cairns region, with a depth-averaged numerical model of the coastal ocean. Probability distributions of cyclone characteristics such as intensity, speed and direction provided the domain from which characteristics could be randomly sampled to construct cyclones. These statistics were used to generate 1000 artificial cyclones to simulate the full range of storms likely to affect the Cairns region. The resulting cyclone winds were randomly phased with tides and used to force a numerical storm surge model. The modelled storm tides were then ranked and their return periods calculated.

In a climate affected by global warming, two factors may act to increase the risk of storm surge:

- Sea-level rise caused mainly by thermal expansion of the oceans; and
- possible changes in cyclone characteristics, such as intensities and frequencies.

The latest scientific estimates suggest that global warming will cause modest to moderate increases in average and maximum cyclone intensities in the Australian region. A recent numerical modelling study has estimated changes in tropical cyclone intensity in the Australian region under a doubling of atmospheric $CO_2$ (corresponding approximately to the year 2050). From the results of this work, the mean cyclone central pressure in 2050 is assumed to decrease by 10 hPa (corresponding to an increase in intensity), while the standard deviation of central pressure is assumed to increase by 5 hPa. The changes in the mean and standard deviation were incorporated into the statistical representation of cyclone intensity for Cairns, an additional 1000 artificial cyclones were selected, and their associated storm tides were modelled to obtain new storm tide return periods for a warmer world.

Tropical cyclone numbers were assumed to be the same in a warmer world. Unlike intensities, little can be said at this time about the numbers of cyclones in the Australian region under $2\times CO_2$ conditions, as these are strongly associated with the El Niño/Southern Oscillation (ENSO) phenomenon, the exact nature of which in a warmer world is currently unknown. However, based on results shown here, it is unlikely that any changes in the year-to-year variability in cyclone numbers brought about by changes in ENSO will entirely negate the anticipated increase in the sea level for the given return periods.

Sea-level rise caused by thermal expansion of the oceans is then added to the changes in storm tides caused by increased in cyclone intensity. Estimates of future sea-level rise are subject to uncertainty from a range of sources. These include the uncertainty surrounding the amount of global warming predicted by various global climate models for given greenhouse gas emission scenarios and uncertainties surrounding the emissions themselves. In the present study, the mid-range estimates for sea-level rise of 20 cm by the year 2050 are added to the storm tide return periods and the upper and lower estimates of 40 and 10 cm are incorporated into the error bars.

The following table summarises the 100- and 1000-year return period estimates under present climate conditions as well as enhanced climate conditions incorporating changes to cyclone intensity and sea-level rise.

| Return Period (years) | Sea level Height (metres) | | |
|---|---|---|---|
| | Control Climate | Enhanced Greenhouse Climate (Cyclone intensity changes only) | Enhanced Greenhouse Climate (Cyclone intensity and sea level rise) |
| 1000 | 3.4 ± 0.2 | 3.9 ± 0.3 | 4.2 (+0.5/-0.4) |
| 100 | 2.3 ± 0.1 | 2.6 ± 0.1 | 2.8 (+0.3/-0.2) |

These results indicate a dramatic increase in the frequency of severe events in Cairns or alternatively, a reduction in the interval between severe events. The implications of these results for planning purposes and tourism operations is yet to be established.

## Glossary

| | |
|---|---|
| **$1\times CO_2$** | Describes a climate simulation using a global climate model under conditions of 'present-day' atmospheric concentration of carbon dioxide. The CSIRO model uses a $1\times CO_2$ carbon dioxide concentration of 330 ppm (approximate global average concentration around 1975) and its $1\times CO_2$ climate thus corresponds to about the last thirty years. |
| **$2\times CO_2$** | Defined as twice the concentration of carbon dioxide of **$1\times CO_2$**. The CSIRO model uses a $2\times CO_2$ atmospheric carbon dioxide concentration of 660 ppm. In the context of the experiments described in this report, a $2\times CO_2$ experiment refers to one in which the **slab ocean model** is used to simulate an enhanced greenhouse climate by instantaneously doubling the atmospheric concentration of carbon dioxide from the equivalent of a present-day concentration, or **$1\times CO_2$**. The atmosphere is then allowed to come to equilibrium after responding to the increase in carbon dioxide. Such simulations are often referred to as 'equilibrium' experiments. |
| **AHD** | Australian Height Datum, the datum for the Australian Map Grid. This is approximately equal to mean sea level. |
| **Bathymetry** | The varying depth of the ocean due to the shape of the ocean floor. |
| **Coupled model** | Term used to describe a global climate model that uses a full ocean model 'coupled' to an atmospheric model (cf. **slab ocean model**). A coupled model is able to represent ocean currents, the exchange of heat between surface and deep layers of the ocean, and how these processes may change under enhanced greenhouse conditions (see also **transient experiment**). |
| **DARLAM** | Division of Atmospheric Research Limited Area Model. |
| **El Niño** | Dry phase in eastern Australia of the El Niño – Southern Oscillation variability. |
| **ENSO** | El Niño – Southern Oscillation. |
| **Enhanced greenhouse** | Elevated levels of greenhouse gases as expected in the future. |
| **GCM** | Global Climate Model. |
| **HAT** | Highest Astronomical Tide. |
| **La Niña** | Wet phase in eastern Australia of the El Niño – Southern Oscillation variability. |
| **LAM** | Limited-area model. An atmospheric model run over a limited (i.e. non-global) geographical region or domain. |

| | |
|---|---|
| **RCM** | Regional climate model. A limited-area model that uses **GCM** model output as boundary conditions (i.e. is forced at its edges by the output of the **GCM**). As such, the RCM produces a finer resolution climate simulation over a region of interest. |
| **Resolution** | The spacing between grid points (horizontal resolution) or vertical levels in the atmosphere or ocean (vertical resolution). Finer resolution usually gives a better simulation. |
| **Return Period** | The average amount of time between the occurrence of events of a particular magnitude. For example, a 100-year return period **storm tide** level is expected to attained or exceeded on average once every 100 years. |
| **Slab ocean model** | Term used to describe global climate models that use a simplified ocean model in which there is no deep ocean or ocean currents (cf. **Coupled model**). |
| **SOI** | Southern Oscillation Index. A measure of the phase and strength of the ENSO phenomenon. It is defined as the Tahiti minus Darwin surface pressure and is positive during **La Niña** events and negative during **El Niño** events. |
| **Storm Surge** | Elevated sea levels resulting from extreme atmospheric winds and low pressure. |
| **Storm Tide** | The sea levels resulting from the combination of **storm surge** and astronomical tides. |
| **TCLV** | Tropical cyclone-like vortex. A low pressure system generated by a regional climate model (**RCM**) that has a number of the structural characteristics of observed **tropical cyclones**. |
| **Tropical cyclone** | In the Australian region, a storm, usually originating in the tropical oceans, with definite cyclonic (clockwise) circulation and having maximum sustained wind speeds of at least 17 m $s^{-1}$. |
| **Transient experiment** | A type of enhanced greenhouse experiment performed using a **coupled model GCM**. $CO_2$ levels are gradually increased rather than being instantaneously doubled at the start of the experiment as is done with '**slab ocean model**' GCMs. |

## Preface and Acknowledgments

In 1996, CSIRO Tourism Research funded a project investigating the impact of climate change on coastal resorts. This project addressed the possible effects of sea-level rise caused by warming and thermal expansion of the oceans, as well as possible increases in tropical cyclone intensity caused by global warming. Taken together, these factors would lead to higher storm surges in some coastal resorts. Consequently, these aspects of climate change were considered to be relevant to the coastal tourism industry. Cairns was chosen as the logical location for this work because it is low-lying, has substantial tourist infrastructure and is vulnerable to tropical cyclones and associated storm surge even in the current climate. In addition, the outputs of the project were envisaged to be useful for planning purposes, a topic of considerable interest to the tourism industry.

This report, along with its earlier companion reports (Pittock et al. 1997; McInnes et al. 1999), details the development and conclusions of this project. The authors of this report would like to thank CSIRO Tourism Research, particularly its coordinator Dick Braithwaite, for their support and encouragement during this project. We would like to thank Drs. Graeme Hubbert and Tom Beer for their expert assistance in a number of aspects of this work, as well as Noel Davidson of the Bureau of Meteorology for advice on implementation of the tropical cyclone “bogus” scheme into our regional climate model. We would also like to thank CSIRO Atmospheric Research for its financial support during the progress of the work.

# 1 Introduction

Tropical cyclones pose a major hazard to the northern regions of Australia due to their extreme winds, heavy rainfall and higher than normal sea levels. Often, the greatest destruction from a tropical cyclone is caused by coastal flooding from the *storm surge*, which is a dome of higher-than-normal sea water generated by the strong winds and low atmospheric pressure. Climate change due to the enhanced greenhouse effect has the potential to increase the risk of storm surge hazards at a given coastal location through changes to tropical cyclone characteristics and sea-level rise.

Due to the random nature of tropical cyclones, the risk of severe storm surges must be assessed in statistical terms. A return period is defined as the average time interval between events of a particular magnitude. Return periods for storm tides (the combination of the storm surge and tide) are commonly used in the design of coastal engineering projects, for the location and design of housing, and for emergency service planning, all of which are relevant to the tourism industry. While return periods can be calculated for the current climate, it is possible that in a warmer world, the characteristics of cyclones, such as their intensity and frequency, may change.

This study investigates the impact of climate change on extreme sea levels due to storm tides for Cairns on the northern Queensland coast. A methodology is employed that utilises a storm surge model to simulate a large number of randomly selected cyclones that cross the coast at randomly chosen phases of the tide. The range of possible cyclone characteristics used in the storm surge simulations is derived from an analysis of the historical cyclone record in the region. Storm tide return periods are then evaluated from the model simulations.

The possible change to the present cyclone climatology due to the enhanced greenhouse effect is also evaluated using a Regional Climate Model to simulate tropical cyclone-like lows for both the current climate and enhanced greenhouse conditions. These changes due to the enhanced greenhouse effect are then incorporated into the methodology used to generate return periods for storm tides. Finally, the impact of sea-level rise scenarios on storm tide return periods is investigated.

A number of previous studies have investigated storm surges and storm tides along the Queensland coast for design purposes. The most comprehensive of these was carried out by the Department of Civil and Systems Engineering at James Cook University for the Beach Protection Authority in the late 1970s, where storm surge modelling was undertaken at 10 locations along the Queensland coast. Subsequently, return periods for extreme sea level events were evaluated for the same locations by combining the storm surge results stochastically with tides. The modelling approach and methodology used in these studies was state-of-the-art at the time. However, the historical cyclone data record has since been improved and technological advances in computer capability now enable considerably more complex models to be run. Storm surge modelling techniques have also been improved. These developments all suggest that these original studies should be re-evaluated. The present study not only re-evaluates storm tide return periods under present conditions using a sophisticated modelling capability but also investigates the impact of climate change.

This report is organised as follows. The storm surge model and the methodology for determining storm tide return periods are described in section 2. In section 3, some examples of the model simulations are presented and discussed. In section 4, a statistical model of cyclone occurrence in the Cairns region is developed. Section 5 presents and discusses the possible changes to cyclone behaviour and mean sea level due to the enhanced greenhouse effect. In section 6, return periods are determined from the storm tide simulations under present and changed climate conditions and the uncertainty in the results is discussed. Finally, the discussions and conclusions are presented in section 7.

# 2 Methodology

## 2.1 Contributions to Coastal Sea Levels

The total water level at the coast resulting from a tropical cyclone consists primarily of contributions from the storm surge and astronomical tide (see Figure 1). The storm surge is caused by the combined action of the surface wind and pressure on the ocean surface. The maximum sea levels are generally located close to the region of maximum onshore winds as the cyclone crosses the coast. Cyclones travelling parallel to the coast will also generate elevated sea levels if sufficiently close to the coast. It should be noted that due to the non-linear interactions of bottom friction with ocean currents, sea level heights due to the combination of the positive tide and positive surge are generally lower than the sum of the individual components. For this reason, it is preferable to include tidal forcing implicitly in the model simulations, rather than adding it later. Waves also contribute to coastal sea levels during tropical cyclones. The net effect of breaking waves at the coast produces wave setup and individual breaking waves produce wave run-up. Explicit calculation of these effects is neglected due to the complexity of the models required to determine their contribution; however, an allowance is made in the final results for the likely impact of wave setup.

The magnitude of the storm surge depends on the following cyclone characteristics:

- *intensity* of the cyclone's central pressure;
- *size* (measured by the radius from the cyclone centre to the region of maximum winds); and
- *track*, including its direction of movement, forward speed and proximity to the point of interest.

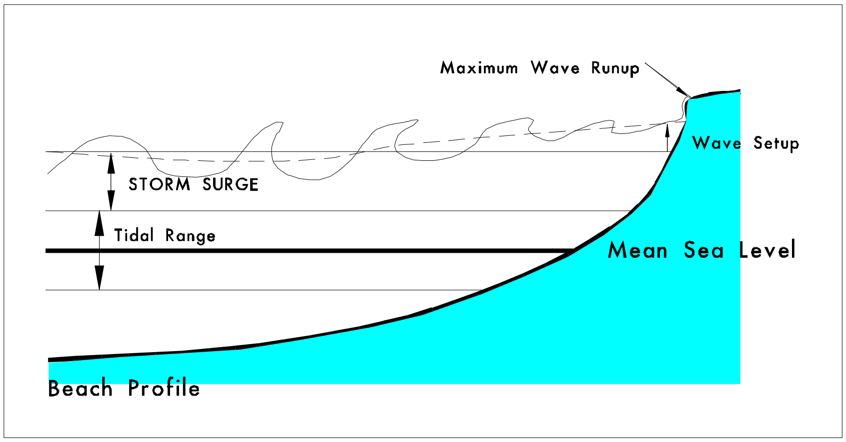


**Figure 1:** Contributions to extreme sea levels at the coast.

In addition to cyclone characteristics, the depth and shape of the ocean floor can influence the storm surge height. For example, relatively wide and shallow continental shelves tend to amplify the resulting storm surge and embayments flanked by headlands can concentrate the elevated water levels.

## 2.2 Methodology

The return period is the average amount of time between the occurrence of events of a particular magnitude. In mathematical terms, it is the inverse of the probability of the event occurring. This study is concerned with evaluating the return periods of storm tides at Cairns under present and enhanced greenhouse climate conditions. A statistical model describing the occurrence of cyclones at Cairns is developed and combined with a deterministic model for simulating the sea level heights due to storm surges and tides to generate a synthetic record of storm tide events at Cairns. The technique involves randomly selecting the various elements that determine the cyclone and tidal characteristics and conducting many storm tide simulations based on these random selections. The key factors contributing to the evaluation of the storm tide return periods are illustrated in Figure 2. The cyclone characteristics influence the storm surge height while the date and time of the cyclone determine the phasing of the tide and surge.

An estimation of the average frequency of tropical cyclone occurrence is important in converting the hundreds of random storm tide simulations into an effective time series from which the return periods can be calculated. For example, if, on average, a cyclone affects a coastal location once every five years, then each randomly performed simulation represents five years of data. The maximum storm tides resulting from all simulations performed can then be sorted and ranked against their expected recurrence interval.

Since not all cyclones impacting on a region actually make landfall, coast-parallel cyclone tracks should also be considered even though these will, in general, only contribute to the low amplitude end of the statistics. Simulations are therefore conducted for cyclones with a coast-parallel direction of movement. All other characteristics are randomly selected. A suitable ratio of the coast parallel cyclone simulations is combined with the coastal crossing cyclone simulations, depending on the observed frequency of each type recorded in the historical record.

The evaluation of return periods under enhanced greenhouse conditions involves modifying the statistical model of present day cyclone occurrence consistent with the latest understanding of changes to tropical cyclone behaviour then repeating the random storm tide simulations. The most important impacts likely under enhanced greenhouse conditions are shown in Figure 2. The modifications to the tropical cyclone characteristics are discussed in section 5. The impact of a mean sea-level rise on the results is also investigated.

## 2.3 Storm Surge Model

The storm surge model used in this study is a depth-averaged ocean current model developed to simulate currents and sea surface elevations on continental shelves (Hubbert et al., 1990, 1991; Hubbert and McInnes, 1999a,b). The model, known as GCOM2D, solves a set of mathematical equations over a grid comprised of equally spaced points in an east-west and north-south direction over the region of interest. Finer resolution grids have a greater concentration of grid points per unit area and therefore can resolve in greater detail the horizontal variation in parameters such as water depth, currents, topography and bathymetry. GCOM2D is driven by wind stresses and atmospheric pressure gradients acting on the ocean surface, sea level heights at its lateral boundaries due to tides and atmospheric conditions, and friction of the ocean floor.

GCOM2D utilises a moveable coastal boundary that simulates the flooding and draining (i.e. inundation) of the coastal terrain due to the storm tide. The inundation algorithm is described in detail in Hubbert and McInnes (1999b). It is shown that sea levels simulated at the coast are more realistic when a moveable coastal boundary is used, compared to the simpler to implement, fixed-coast storm surge models that tend to overestimate the coastal sea levels (Yeh and Chou, 1979; Hubbert and McInnes, 1999a). Nevertheless, the accuracy of the inundation algorithm is dependent on the accuracy and resolution of the data describing the low-lying coastal terrain. In general, this algorithm is only used on grid resolutions less than about 500 m.

An important feature of GCOM2D is that it can be run over successively finer regions utilising the results of the lower resolution, outer simulations as boundary conditions. This so-called "nesting" technique is an economical way of maximising grid resolution while maintaining reasonable computational overheads.

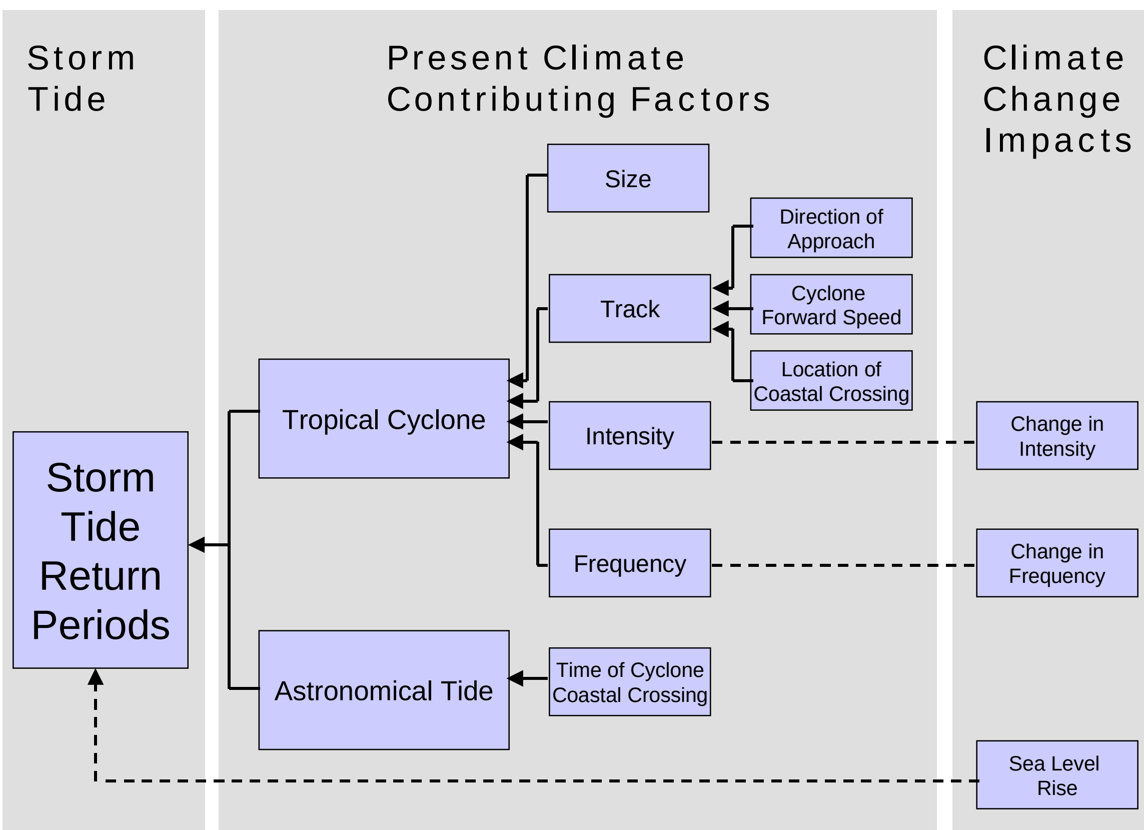


**Figure 2:** Schematic diagram illustrating the key factors likely to affect storm tide return periods under present and enhanced greenhouse climate conditions.

In this study, model simulations are carried out over two regions. The lower resolution simulations are conducted with a grid spacing of 1.6 km over the entire region shown in Figure 3. Simulations are then conducted over the smaller region centred on Cairns (Figure 3) at 200-m resolution.

Topography of the region was obtained from the AUSLIG GEODATA 9-second Digital Elevation Model (DEM) with grid spacing of nine seconds in longitude and latitude (approximately 250-m resolution); (AUSLIG, 1994). It was enhanced in the Cairns region using data from the 50-m DEM of Zerger (1996). Bathymetry in the immediate vicinity of Cairns was improved by manually digitising shipping charts of the region.

Wind speed and pressure fields required to force the storm surge model are derived using the analytical wind profile model of Holland (1980). Cyclone profiles are determined by specifying the central pressure, radius of maximum winds, speed of forward motion, direction and the wind profile shape. The surface wind is then derived following the procedure described in Hubbert et al. (1991).

While wave setup is not explicitly modelled in the present study, previous studies in northern Australia in which wave setup was explicitly modelled suggests that it is typically about 10% of the storm surge height (see, for example, Hubbert and McInnes, 1999a). In the present study, an allowance for wave setup is made by increasing the storm surge component of the total sea level by 10% (the storm surge component is determined by recalculating the tidal contribution at the point of interest and subtracting this value off).

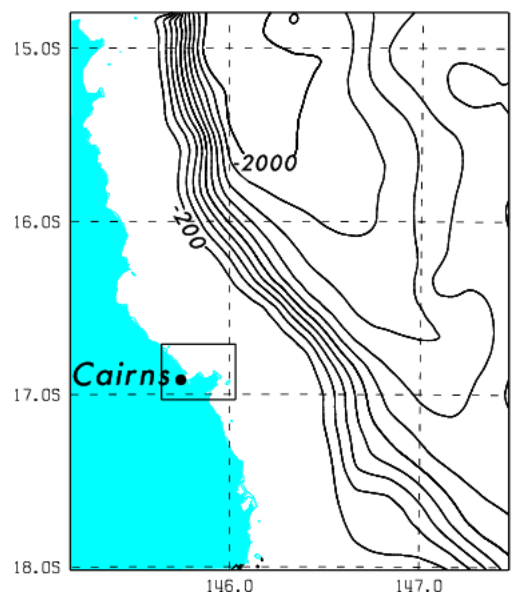


**Figure 3:** The area covered by the low resolution storm surge model on a 1.6-km grid. The small rectangle centred on Cairns is the region over which the high resolution simulations are conducted on a 200-m grid. Bathymetric contours are shown every 200 m.

## 3 Storm Surge Simulations

In this section, the nature of storm surges affecting the Cairns region is investigated using the storm surge model. In the absence of observations of severe storm tide events to use for model verification, results are compared to a previous storm surge modelling study conducted in the Cairns region. The model is also used to illustrate the effect on the storm surge of different directions of approach of the cyclone.

A set of storm surge simulations is carried out on the low resolution grid forced by four coastal crossing cyclones with central pressures and forward speeds of 945 hPa and 28 km hr$^{-1}$ respectively, as well as one coast-parallel cyclone. The directions of approach of the coastal crossing cyclones are 355º, 35º, 75º and 105º. Here, direction is defined as the bearing from which the cyclone approaches i.e. a bearing of 0º means a cyclone approaching from the north. Each cyclone is configured to make landfall just to the north of Cairns so as to place the most intense onshore winds in the vicinity of Cairns. Tidal oscillations are ignored to simplify the interpretation of the results, and sea level heights are expressed relative to the Australian Height Datum (AHD, approximately mean sea level, see glossary).

The cyclone paths are shown in Figure 4a while time series of the sea level heights at Cairns are shown in Figure 4b. Cyclones A and B produce onshore winds at all times during the approach of the cyclone and therefore produce positive sea levels in the lead up to the peak. The most pronounced surge is produced by cyclone B, which peaks at 2.5 m. The cyclone winds and pressure at the time of land fall are shown for this case in Figure 5a while the resulting storm surge is shown in Figure 5b. Elevated sea levels affect about 150 km of coastline. Clearly the headland situated to the east of Cairns assists in focussing the most severe part of the storm surge at Cairns for cyclones approaching from this general direction.

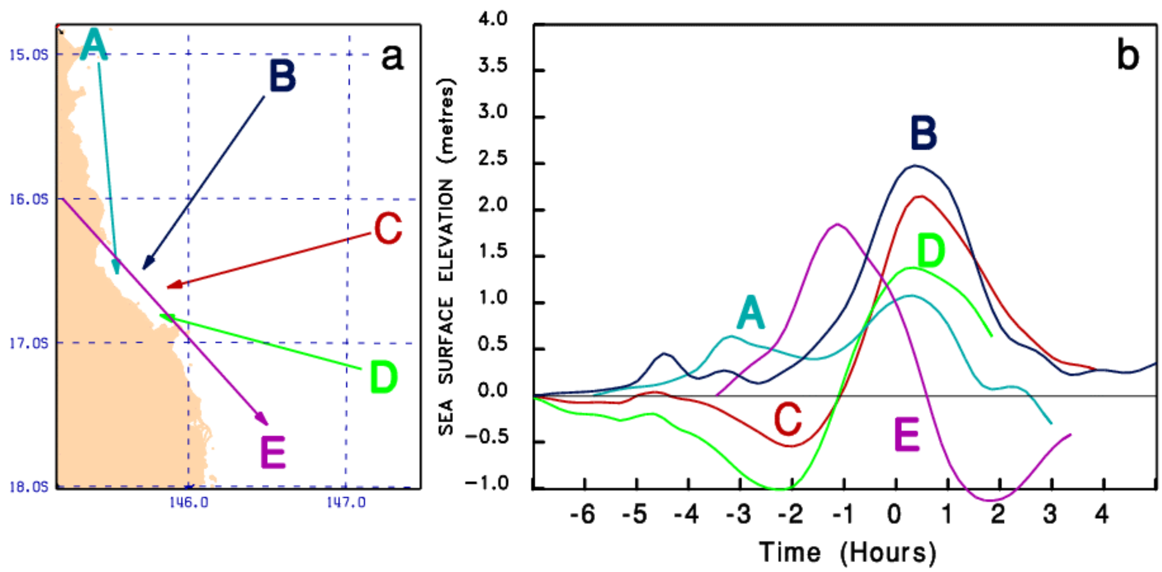


**Figure 4:** (a) Cyclone tracks for cyclones of central pressure 945 hPa and forward speed of 28 km hr$^{-1}$, and (b) the resulting simulated sea level heights. Times shown are relative to the time of coastal crossing.

Cyclones C and D produce weak negative sea surface elevations in the first half of the simulation, due to the predominantly offshore winds at the coast as the cyclone approaches. The surge peaks are also of lower magnitude and shorter duration.

Cyclones A, B and C can be compared with similar results produced by Harper et al. (1977). In the present study these cyclones produced peak storm surges of 1.0, 2.5 and 2.2 m respectively, whereas in Harper et al., the equivalent surge heights were 0.8, 2.2 and 2.0 m respectively. The differences between the maximum heights in the two studies are likely to be due to the differences in model resolution (1.6 km in the present study and 9.3 km in the Harper et al. study). Cyclone D produces a lower surge of 1.3 m due to the protection from the wind and surge offered to Cairns by Cape Grafton to the east. Cyclone E produces a positive surge until the cyclone centre passes to the south of Cairns, after which time offshore winds generate a negative surge.

These results illustrate the variation in storm surge strength and duration that occurs under different directions of cyclone approach. The most intense storm surges can be expected to occur for cyclones approaching from the northeast, assuming all other factors are constant.

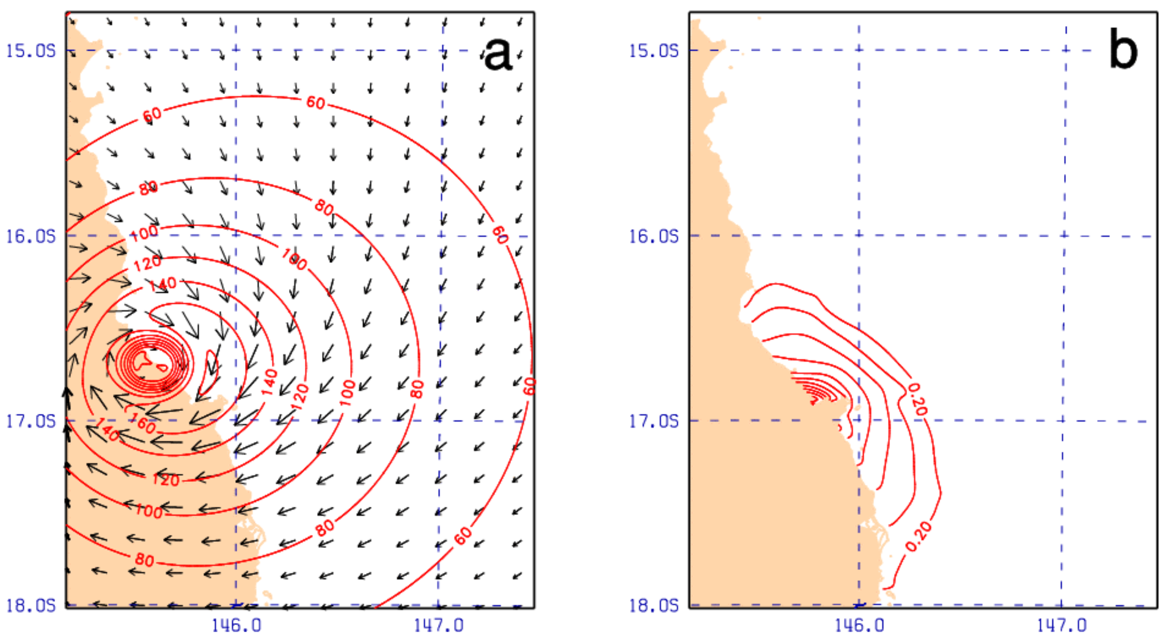


**Figure 5:** (a) Wind vectors and contours of wind speed for cyclone B as it crosses the coast, and in (b) the sea level elevations at the time of coastal crossing. Contours of wind speed are shown every 20 km $hr^{-1}$ and sea level contours are shown every 0.2 m. Sea level heights are relative to AHD.

# 4 Cyclone Climatology

In this section, probability distributions are derived for selected cyclone characteristics derived from the historical record. These provide the constraints for the random selection of cyclones in the storm tide calculations.

Cyclones occurring in the Australian region from 1907 to 1997, and documented by the Bureau of Meteorology, have been used to determine the characteristics and frequency of cyclones affecting Cairns. Since few cyclones have occurred in the immediate vicinity of Cairns in this time, a broader coastal region was considered to be representative of the Cairns area. The construction of the probability distribution functions for the various cyclone characteristics are now examined in turn.

## 4.1 Size

The size of the tropical cyclone, generally measured as the radius from the centre to the region of maximum winds, could not be categorized statistically due to an absence of data. As a consequence, following common practice, a fixed value of 30 km is assigned to this parameter in all randomly selected cyclones.

## 4.2 Track

The cyclone track is characterized by the forward speed, direction of approach and location of coastal crossing of the tropical cyclone. Coastal crossing cyclones occurring in the coastal region bounded by 14ºS - 20ºS and 145ºE - 149ºE were used to establish probability distribution parameters. This covers about 375 km of coastline with Cairns at its centre. A total of 149 cyclones were counted in this region, of which 55 crossed the coast.

Cyclone forward speeds, binned into 5 km $hr^{-1}$ classes (see Figure 6), were approximated using a normal distribution with mean and standard deviation of 15.5 km $hr^{-1}$ and 6.6 km $hr^{-1}$ respectively. The direction data, organized into 15º bins (see Figure 7), have also been approximated using a normal distribution with a mean and standard deviation of 63.8º and 27.1º respectively. Both distributions satisfy the chi-squared test of normality at the 95% confidence level.

Location of coastal crossing strongly influences the peak storm surge at the point of interest. For example, simulations presented in section 3 indicate that cyclones crossing the coast at Cairns or up to about 100 km to the north are likely to produce a storm surge effect at Cairns. Cyclones crossing to the south of this region produce offshore winds and hence negative sea surface elevations at Cairns. In the random simulations, the coastal crossing location is chosen to fall between 16ºS and 17ºS with equal likelihood. Clearly, however, the most severe storm surges will occur for cyclones crossing the coast closer to Cairns.

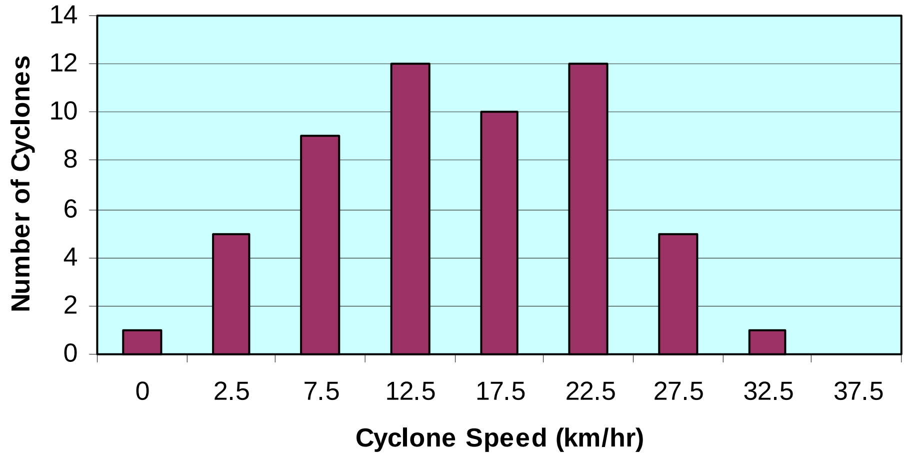


**Figure 6:** Frequency distribution for cyclone forward speeds for coastal crossing cyclones occurring between 14ºS and 20ºS.

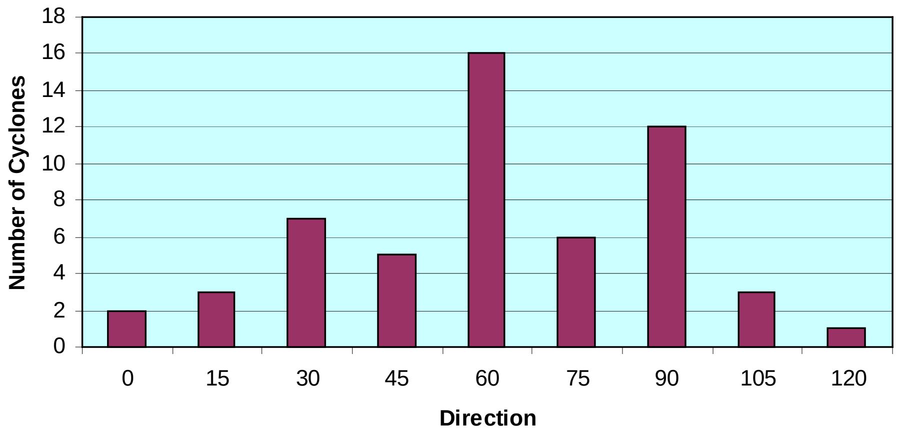


**Figure 7:** Frequency distribution for cyclone directions at the time of coastal crossing for cyclones occurring between 14ºS and 20ºS. Directions are in degrees clockwise from north.

Cyclones that travel parallel to the coast can cause storm surges if they occur within approximately 1º of the coast. Although these surges will mainly contribute to the low amplitude end of the statistics, storm tide simulations are conducted for coast parallel cyclones. The same probability distribution functions developed for coastal crossing cyclones are used for the coast-parallel cyclones except for direction, which is kept constant at 335º, and distance from coast, which can vary from 0 to 100 km from the coast with equal likelihood. The ratio of coastal crossing to coast-parallel cyclones is taken to be 85:15 based on the numbers of each category occurring historically in the search region.

## 4.3 Cyclone Intensity

The intensity of a tropical cyclone is generally characterized by its central pressure. Probabilities for cyclone intensity have been estimated using extreme value theory. All cyclones that have occurred in a 375-km radius of Cairns in the 90 years since the beginning of the record in 1907 were considered. The lowest biennial central pressures were extracted from the data with a value of 1000 hPa being used for pairs of years where no cyclone occurred. Following common practice, the Type I Extreme Value Distribution or Gumbel distribution was fitted to the data, where the probability that the central pressure P is less than some pressure $P_o$ is given by

$$\Pr(P < P_o) = e^{-e^{\frac{-(P_o - a)}{b}}} \qquad (1)$$

where $a = \overline{P} - \gamma b$ and $b = \sigma\sqrt{6}/\pi$ are the location and scale parameters respectively, with $\sigma$ being the standard deviation and $\overline{P}$ the mean pressure of the distribution. Using the method of moments, the moment estimators were found to be $a$ = 996.4 and $b$ = 11.2 respectively. Based on these values, the return period curve for central pressure is shown in Figure 8 along with the 95% data confidence limits. Selected cyclone return periods are given in Table 1. The exceedance probabilities were then converted to probabilities of occurrence for intensities within designated pressure ranges.

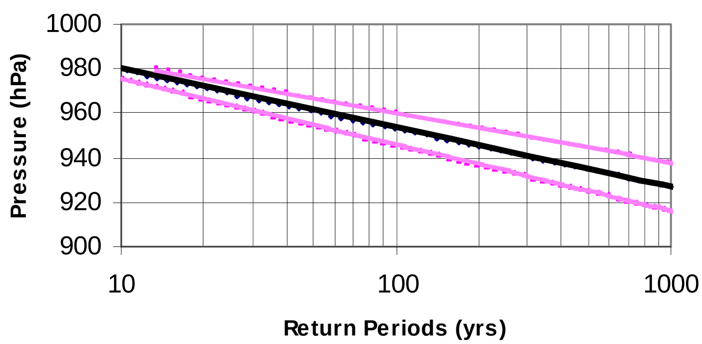


**Figure 8:** Central pressure return period curves for Cairns with 95% confidence limits.

| Return Period 14ºS-20ºS | Central Pressure (present climate) |
|---|---|
| 10 | 979 |
| 20 | 971 |
| 50 | 963 |
| 100 | 953 |
| 200 | 945 |
| 500 | 935 |
| 1000 | 927 |

**Table 1:** Return periods (yrs) for given cyclone intensities (hPa).

### 4.4 Cyclone Frequency

The average annual frequency of cyclones affecting Cairns enables a time scale to be assigned to the model generated storm tide results. Lourenz (1981) has analysed cyclones in the Australian region over the 70 years up to 1980. Based on this study, 11 cyclones have crossed the coast over the stretch of coastline 100 km to the north of Cairns, yielding a frequency of about one cyclone every six years. The frequency has not changed appreciably if one also includes cyclones that have occurred since that time. If one also includes coast parallel cyclones, this alters the frequency of cyclones to approximately one every five years.

### 4.5 Tides

The inclusion of tides in storm surge calculations is important because of the non-linear way in which tides and surges interact. The relative phasing of the tide with the storm surge is achieved by randomly selecting a time associated with the cyclone occurrence. The tides themselves vary in amplitude throughout the year. Cairns, which experiences a predominantly diurnal tidal regime, has a highest astronomical tide (HAT) of 1.8 m AHD (HAT occurs once every 18.6 years). The mean highest high water (MHHW), or in other words the average value of the highest high tide of the day, is about 1 m AHD. To take into account tidal variations throughout the year, monthly cyclone occurrence in the region was also analysed (Figure 9). This was also approximated using a normal distribution.

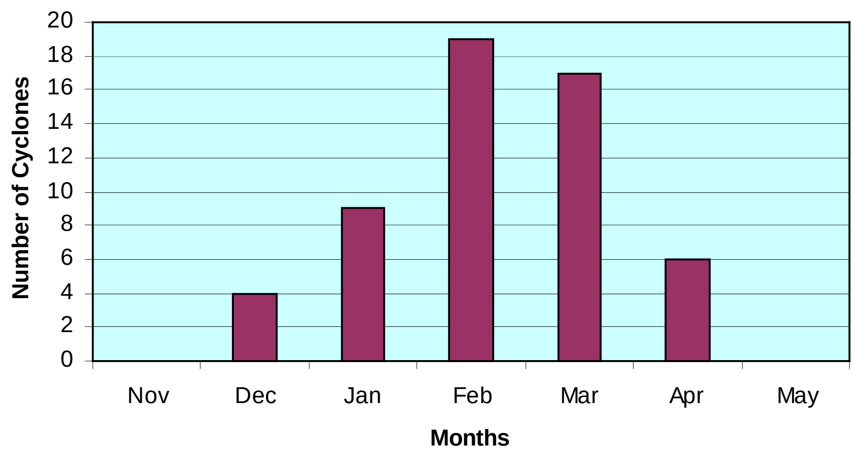


**Figure 9:** Frequency distribution for monthly cyclone occurrence in the Cairns region.

## 5 The Impact of Climate Change

In a warming climate, two factors may act to increase the risk of storm tides. These are possible changes in cyclone characteristics, such as intensities and frequencies, and mean sea-level rise.

## 5.1 Cyclone Intensity

The latest scientific estimates suggest that modest to moderate (0 - 20 %) increases in average and maximum cyclone intensities are expected in the Australian region in a warmer world. For $2\times CO_2$ conditions (about 2050), we have assumed an increase in mean cyclone intensity (decrease in central pressure) of 10 hPa and an increase in the standard deviation of 5 hPa. These figures are estimated from the results of Walsh and Ryan (2000), in which a number of artificial tropical cyclones were inserted into a limited-area model simulation of current and $2\times CO_2$ climates, and the changes in their intensities analysed. These figures are also consistent with theoretical techniques that estimate changes in maximum potential intensity (MPI) of tropical cyclones for the Australian region (e.g. Holland 1997). These theoretical techniques also suggest increases in maximum tropical cyclone intensities in the Australian region of similar magnitude, when the tail of the fitted distribution is examined. Nevertheless, these estimates remain uncertain and may be refined further in the future as better simulations become available.

The mean and standard deviation of the observed cyclone data set are modified with the changed values for the enhanced climate simulation. This yields changes to the moment estimators of the Gumbel distribution so that $a$ = 988.5 and $b$ = 14.8. The probabilities resulting from the modified distribution are evaluated and used as a basis for the randomly selected cyclone intensities for the enhanced climate storm tide simulations.

| Return Period | Central Pressure (enhanced greenhouse climate) |
|---|---|
| 10 | 966 |
| 20 | 956 |
| 50 | 941 |
| 100 | 931 |
| 200 | 920 |
| 500 | 907 |
| 1000 | 887 |

**Table 2**: Return periods (yrs) for given cyclone intensities (hPa) for enhanced greenhouse climate conditions.

## 5.2 Cyclone Frequency

Changes in numbers of cyclones in the Australian region caused by the enhanced greenhouse effect remain unknown, as cyclone numbers are strongly associated with the ENSO phenomenon, the exact nature of which in a warmer world is currently unknown. Therefore, in this study, we assume no change to cyclone frequency in the enhanced greenhouse climate scenario.

## 5.3 Sea-level Rise

Sea-level rise as a consequence of the enhanced greenhouse effect is one of the more confident results of climate change research (IPCC 1996). Global sea-level rise over the next few decades is expected from several sources. These include thermal expansion of the oceans, melting of glaciers and small ice sheets, and changes in the accumulation of snow and ice in Antarctica and Greenland. Estimates of changes to these components are made using predictions of future warming from climate models. These models are complex numerical representations of the

Earth's ocean and atmosphere and, depending on how the physical processes in the models are represented, they predict a range of different warmings for a specified increase in greenhouse gases. Furthermore, there is considerable uncertainty regarding the future emissions of greenhouse gases and associated aerosols, as the amount of these emissions depends upon the character and scale of future economic activity, which is difficult to predict. Therefore predictions of mean global sea-level rise are usually given as a range encompassing several different scenarios (see Table 3), depending upon the amount of future emissions assumed. In the present study, we use the mid-range estimate of sea-level rise for 2050 of 20 cm.

| Year | Low | Mid | High |
|---|---|---|---|
| 2020 | 5 | 10 | 20 |
| 2050 | 10 | 20 | 40 |

**Table 3**: Low, mid and high estimates of global mean sea-level rise (in cm) for the years 2020 and 2050 (IPCC 1996), relative to 1990.

# 6 Return Period Estimates

## 6.1 Control Climate

The maximum sea level heights from each of the 1000 simulations are sorted and ranked against their expected recurrence interval (e.g. assuming one cyclone every 5 years, the highest event is the 1-in-5000 year event and the fifth highest is the 1-in-1000 year event). The line of best fit is estimated using the method of least squares and is shown in Figure 10 (note that the values include an allowance for wave setup). In addition to the current and enhanced climate simulations, upper and lower bounds on each curve have also been estimated for the 95% confidence limits of cyclone central pressure. These estimates are achieved by pooling all simulations and selecting a modified set of runs that satisfies the probability distribution curves defining the confidence limits. These confidence limits are also shown in Figure 10.

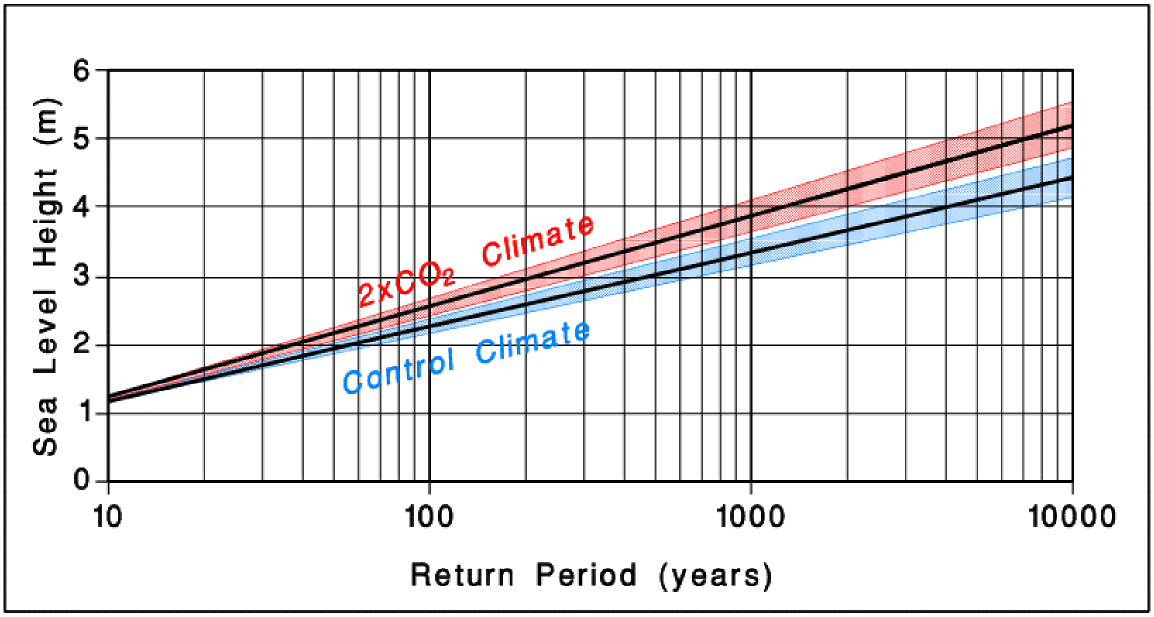


**Figure 10:** Return periods for storm tides at Cairns under present and enhanced greenhouse climate conditions. Error bars pertain to the 95% confidence limits on the cyclone intensity. The enhanced greenhouse climate curves relate to changes in cyclone intensity and not changes in mean sea level.

The results suggest that a storm tide will exceed HAT on average only once every 40 years or more. This result is not surprising considering the relatively low frequency of cyclones in Cairns as well as the many other factors that must combine adversely to produce storm tides that are higher than this value. Nevertheless, we note that the results from the present study are up to 10% lower than previous storm tide studies conducted in this region (Harper, 1999).

## 6.2 Enhanced Climate

Storm tide heights for given return periods under enhanced climate conditions are shown in Figure 10 and selected values are also presented in Table 4. These results are based on the possible increases in cyclone intensity due to the enhanced greenhouse effect. Clearly the sea levels are higher than those evaluated for current climate conditions. Such changes to the frequency of severe storm tides would cause a considerable increase in the risk to existing infrastructure and tourism industry of the Cairns region.

Enhanced greenhouse climate storm tide heights that also include sea-level rise are also shown in Table 4 and indicate an even greater risk of severe storm tide. The final column of Table 4 includes the mid-range estimate of sea-level rise by 2050 of 20 cm. However, it should be noted that sea-level rise at this time could be as high as 40 cm.

| Return Period (Years) | Sea Level Height (metres) | | |
|---|---|---|---|
| | Control Climate | Enhanced Greenhouse Climate (Cyclone intensity changes only) | Enhanced Greenhouse Climate (Cyclone intensity and sea-level rise) |
| 1000 | 3.4 ± 0.2 | 3.9 ± 0.25 | 4.2 (+0.5/-0.4) |
| 500 | 3.0 ± 0.2 | 3.5 ± 0.20 | 3.8 (+0.4/-0.3) |
| 200 | 2.6 ± 0.2 | 3.0 ± 0.2 | 3.2 (+0.4/-0.3) |
| 100 | 2.3 ± 0.1 | 2.6 ± 0.1 | 2.8 (+0.3/-0.2) |
| 50 | 2.0 ± 0.1 | 2.2 ± 0.1 | 2.4 (+0.3/-0.2) |

**Table 4:** Return periods for sea level heights under present and enhanced greenhouse climate conditions (about 2050). The fourth column includes a 20-cm sea-level rise, with error bars calculated by adding the upper or subtracting the lower sea-level rise estimates shown in Table 3.

## 6.3 Discussion

The 1-in-100 year return period of sea level heights is commonly used for planning purposes. In this study, the 1-in-100 year event in 2050 is predicted to increase by about 0.5 m. As to whether this would represent an increase sufficient to require consideration in planning or disaster management is a matter for the responsible authorities. A few general comments can be made regarding the use of these results, however. It would be unwise to rely on the central estimates of return period increase for planning purposes. This is because planning requires that conservative assumptions are made, and the central estimate of return period increase would by definition have about a 50% chance of being incorrect. An example of this issue is provided by recommendations made to the Gold Coast City Council regarding the amount of mean sea-level rise to be assumed for planning purposes (Betts, 1999). Although the central estimate of mean sea-level rise by the year 2050 is about 20 cm, Betts (1999) suggests a value of 30 cm would be more conservative and therefore more appropriate for planning purposes. Similar assumptions would need to be made about the results presented here.

The conclusions of this project are also affected by a number of sources of uncertainty in these results that are independent of the quality of the models used here. The first concerns the impact of ENSO on tropical cyclone numbers in the Australian region. The state of ENSO in a warmer world is currently unknown, although a number of recent results are suggesting a trend towards a more El Niño-like mean state (see for instance Walsh et al., 1999 for a summary of this issue). All other things being equal, this should lead to fewer cyclones crossing the Queensland coast (e.g. Basher and Zheng, 1995). Because of the generally inadequate simulation of ENSO in climate models, it is very difficult to quantify this uncertainty properly. An estimate of the influence that changes in ENSO may have on tropical cyclone numbers can be obtained by comparing the 1-in-100 year return periods in the current and enhanced greenhouse climates in Table 4. The 1-in-100 year sea level height for the current climate is estimated to be 2.3 m, while in the enhanced greenhouse climate it is 2.8 m. In the current climate, a sea level of 2.8 m corresponds roughly to a 1-in-300 year return period. Therefore, to completely negate the effect of increased cyclone intensity and sea-level rise, the number of cyclones in the enhanced greenhouse climate would have to fall by about a factor of three. This is a very large change compared to the current year-to-year variability in cyclone numbers, and as a result it is unlikely. Therefore changes in ENSO are unlikely to completely negate the anticipated increase in the 1-in-100 year return period sea level.

A number of other uncertainties arise from the modelling methodology used in this report. These include the quality of the climate model's simulations of tropical cyclone intensity, and the shortness of the observed cyclone record used to establish the distributions of observed cyclone characteristics.

The statistical distributions fitted to the available data also present a source of uncertainty in the results. An example is the choice of the Type II Extreme Value Distribution or Gumbel distribution for the cyclone intensity. One particular drawback, as noted by Holmes and Moriarty (1999), is that the values predicted by the distribution are unbounded as the return period increases. This property is not strictly compatible with cyclone intensity that is constrained by maximum potential intensity considerations. Holmes and Moriarty point out that the Generalized Pareto Distribution (GPD) has similar properties to the Type III Extreme Value Distribution (or Weibull distribution), and tends to a limiting value at high return periods and is therefore more suitable for geophysical applications. Another advantage of the GPD is that it makes use of all available data rather than just the annual (or in this case, the biennial) maximum. Whilst in the present study, the Gumbel distribution was chosen due to its relatively widespread application in similar studies (e.g. Harper et al., 1977), in future studies it is planned to examine the suitability of alternative extreme value distributions to cyclone intensity in greater detail.

# 7 Summary

In this study, a methodology for estimating return periods for extreme sea level events has been applied to Cairns. The methodology requires the running of a dynamic storm surge model to simulate the sea levels resulting from a large number of randomly selected cyclones and tides. The storm surge model used is a state-of-the-art model that has been applied in a wide variety of previous modelling studies. Model simulations over the Cairns region are performed to examine the nature of the surges that occur in this region, and results are compared to previously conducted modelling studies. The characteristics of the cyclones for the Cairns region are determined from available cyclone records and distribution functions are fitted. Cyclones are then constructed from a random selection of the various cyclone characteristics and tidal times and used to run the storm surge model. One thousand storm surge simulations are performed, representing 5000 years of cyclone occurrence. Sea level heights in the current climate for return periods of 50, 100, 500 and 1000 years have been determined to be 2.0 m, 2.3 m, 3.0 m and 3.4 m respectively. In an enhanced greenhouse climate (around 2050), these increase to 2.4 m, 2.8 m, 3.2 m, 3.8 m and 4.2 m respectively. The implications of these results for planning purposes need to be established.

## References


AUSLIG, 1994; GEODATA TOPO-250K Data User Guide, Version 1 Data, Ed 2. Australian Surveying & Land Information Group, Commonwealth Department of Industry, Science and Resources, Canberra, Australia.

Basher, R.E. and X. Zheng, 1995: Tropical cyclones in the southwest Pacific: spatial patterns and relationships to Southern Oscillation and sea surface temperature. *J. Climate*, **8**, 1249-1260.

Betts, H., 1999: The implication of future climate change on floodplain planning at Gold Coast City. NSW Floodplain Managers' Conference, May 1999.

Harper, B., 1999: *Storm tide threat in Queensland: history, prediction and relative risks.* Queensland Department of Environment and Heritage, Conservation technical report no. 10. 24 pp.

Harper, B.A., R.J. Sobey and K.P. Stark, 1977: Numerical simulation of tropical cyclone storm surge along the Queensland coast, Part III - Cairns. Department of Civil and Systems Engineering, James Cook University, Townsville. 15 pp.

Holland, G.J., 1980: An analytical model of the wind and pressure profiles in hurricanes. *Mon. Wea. Rev.*, **108**, 1212-1218.

Holland, G.J., 1997: The maximum potential intensity of tropical cyclones. *J. Atmos. Sci*., **54**, 2519-2541.

Holmes, J.D. and W.W. Moriarty. 1999: Application of the Generalised Pareto Distribution to wind engineering. *J. Wind Engineering and Industrial Aerodynamics*. **83**, 1-10.

Hubbert, G.D., G.J. Holland, L.M. Leslie and M.J. Manton, 1991: A real-time system for forecasting tropical cyclone storm surges. *Weather and Forecasting*, **6**, 86-97.

Hubbert, G.D., L.M. Leslie and M.J. Manton, 1990: A storm surge model for the Australian region. *Quart. J. Roy. Met. Soc*., **116,** 1005-1020.

Hubbert, G.D. and K.L. McInnes, 1999a: A storm surge inundation model for coastal planning and impact studies. *J. Coastal Research*. **15,** 168-185,

Hubbert, G.D. and K.L. McInnes, 1999b: *Modelling storm surges and coastal ocean flooding.* In: 'Modelling coastal sea processes', Ed. B.J. Noye, World Scientific Publishing Co., 159-187.

IPCC, 1996: *Climate Change 1995: The Science of Climate Change*. Contribution of working group I to the second assessment report of the intergovernmental panel on climate change, Cambridge University Press, 572 pp.

Lourenz, A. 1981: Tropical cyclones in the Australian region: July 1909 to June 1980. Bureau of Meteorology report, October 1981.

Walsh, K., R. Allan, R. Jones, A.B. Pittock, R. Suppiah and P. Whetton, 1999*: Climate change in Queensland under enhanced greenhouse conditions*. Available from CSIRO Atmospheric Research, PMB 1, Aspendale, VIC. 3195, Australia. 84 pp.

Walsh, K.J.E. and B.F. Ryan, 2000: Tropical cyclone intensity increase near Australia as a result of climate change. To appear in *J. Climate*.

Yeh, G.-T., and F.-K. Chou, 1979: Moving boundary numerical surge model. *J. Waterw. Port Coastal and Ocean Div*., **105**, 247-263.

Zerger, A., 1996: Application of spatial analysis and GIS for modelling risk in storm surge prone areas of northern Queensland. *Proc. National Disaster Reduction Conference,* Surfers Paradise, Queensland, Sept. 1996, Inst. Eng. Australia.99-106.