

Sea-level rise around the Australian coastline and the changing frequency of extreme sea-level events

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Sea-level rise is one of the well-known impacts of climate change. A recently completed analysis of available tide-gauge data for the period 1950 to 2000 indicates a global average rate of sea-level rise of 1.8 ± 0.3 mm per year. For this period, the analysis indicates a minimum sea-level rise to the northwest of Australia. Here, we find that the change of relative mean sea level around the Australian coastline for the period 1920 to 2000 is about 1.2 mm per year. There are only two records sufficiently long to examine changes in the frequency of extreme events, Fremantle and Fort Denison, Sydney. For both locations, there is a decrease in the average recurrence interval (ARI) by factors of about three for extreme sea levels from the pre-1950 period to the post-1950 period. We also demonstrate a method for estimating the frequency of extreme events from a combination of tides and storm surges for locations with little or no data. For Cairns, we find that the 1-in-100 year sea-level event increases in height from about 2.5 m to 2.9 m by 2050 as a result of a modest future sea-level rise and possible future changes in cyclone intensity. Equivalently, the ARI period of a 2.5 m event would decrease from 100 years to about 40 years.

Introduction

Sea-level rise is one of the well-known impacts of climate change and sea level is projected to continue to rise during the 21st century (Church et al. 2001).

Estimates of global mean sea-level (GMSL) rise for the second half of the 20th century are around 1.8 mm per year (Church et al. 2004) and for 1993 to the present are around 3 mm per year (Leuliette et al. 2004; Church et al. 2004). Estimates of sea-level rise around Australia have been controversial in the past,

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partly due to the use of records that are too short to give meaningful estimates, partly because records from different periods have been combined into a simplistic average for the Australian coastline and partly because the records have not been viewed in a global context. Despite this controversy there are only a few peer-reviewed studies published on the rate of 20th century sea-level change around Australia (e.g. Lambeck 2002). Here, we use the longer Australian tide-gauge records, together with sea-level estimates from a global reconstruction of sea level to estimate sea-level rise around Australia during the period 1920 to 2000.

Direct consequences of sea-level rise include shoreline retreat, loss of coastal infrastructure, flooding and ecosystem loss. These impacts will be felt through changes in mean sea level and perhaps more importantly through changes in the frequency or intensity of extreme sea-level events. Extreme sea-level events referred to here are those driven by severe weather such as tropical cyclones and mid-latitude storms. The accompanying strong winds and falling pressure can generate storm surges and severe wave conditions that in turn can produce severe erosion and coastal flooding on vulnerable coastlines. These surges are usefully characterised by their return period or average recurrence interval (ARI), which is the average time between events of a particular height. With no other changes to climate, rising regional sea levels will worsen the impact of these events by increasing the base sea level on which they occur. This impact can be thought of as higher sea levels during storms of a given magnitude, or alternatively, more frequent occurrences (shorter ARIs) of sea levels of a given height. We use the two longest Australian tide-gauge records (Fremantle and Fort Denison) to estimate the change in ARI for these locations during the 20th century.

Unfortunately, there is insufficient data to complete this analysis at other locations due to the paucity of tide-gauge records dating back to early in the 20th century and of sufficient length to reliably estimate changes in ARIs of extreme sea level. As a result, at many locations alternative methods, employing numerical modelling techniques, are required. This is particularly true in tropical Australia where storm surges occur in response to tropical cyclones. Walsh and Ryan (2000) used a regional model to argue that storm intensities are likely to increase under enhanced greenhouse conditions. In a higher resolution model, Walsh et al. (2004) found that under enhanced greenhouse conditions, the simulated numbers of tropical cyclones (TCs) did not change very much compared with those simulated for the current climate, nor was there much change in the regions of occurrence. However, they did find a 56 per cent increase in the

number of simulated storms with maximum wind speeds greater than 30 m s^{-1} . In addition, they found an increase in the number of intense storms simulated south of 30°S . On a global scale, recent observational evidence for an increase in the destructiveness of hurricanes (Emanuel 2005) and an increase in the number of category four and five hurricanes (Webster et al. 2005) has been found. We note that while these studies are consistent with the earlier expectations, there remains some concern about the quality of the earlier hurricane data and natural modes of climate variability may also influence cyclone behaviour.

The small geographic scale of tropical cyclones and hence the localised nature of the resulting storm surge, which may affect as little as several tens of kilometres of coastline, means that many tropical cyclone storm surges may not occur near, and hence be recorded by, a tide-gauge. We describe a technique (based upon an earlier study, McInnes et al. (2003)) for evaluating the impacts of climate change on storm surges, including their ARIs, for locations with short (or even non-existent) tide-gauge records. Here the technique is modified to account for the fact that in locations where cyclones are relatively rare, tides can make a significant contribution to sea levels at shorter recurrence intervals. This technique is then used to generate storm surge ARIs for Cairns (which is vulnerable to flooding) under present climate conditions. The impact of an estimated increase in intensity of tropical cyclones and also of a plausible sea-level rise by 2050 is examined.

Methods

Mean sea-level rise

The central dataset we use is monthly mean sea levels from the data archive of the Permanent Service for Mean Sea Level (PSMSL; Woodworth and Player 2003) downloaded from the PSMSL website (<http://www.pol.ac.uk/psmsl/>). We use this dataset to reconstruct global sea levels using the approach developed by Church et al. (2004). This approach uses the near global coverage from satellite altimetry to estimate the global covariance structure of observed sea-level variability from January 1993 to December 2001. We then use this covariance structure to interpolate the relatively sparse but longer tide-gauge records. Church and White (2006) used this technique to estimate global averaged sea level back to 1870 and to detect a 20th century increase in the rate of sea-level rise. Although the two longest tide-gauge records available for Australia are from Fremantle (from 1897) and Fort Denison, Sydney (from 1914), we restrict our comparison of the recon-

structed sea levels with observed sea level for locations around the Australian coastline to the period 1920 to 2000. As we are interested in long-term anomalies, we remove the annual and semi-annual signals from the records and the reconstruction. Although glacial isostatic adjustment (typically a few tenths of a millimetre per year for Australian locations) was allowed for in the reconstruction (following the techniques used in Church et al. 2004), the results presented here are for relative sea-level change at the coast.

Observed changes in the frequency of extreme events

The two longest Australian records from Fremantle (1897-2004) and Fort Denison, Sydney (1914-2004) serve as useful indicators of any observed change in extreme sea levels over the last century on the west and east coast respectively. These data are hourly data provided by the National Tidal Centre, Australia. The sea-level records from these ports have rather different characteristics, Fort Denison having approximately three times the astronomical tidal range as Fremantle, but only about twice the total sea-level variability. Meteorological and interannual variations in sea level are therefore more apparent at Fremantle. There is insufficient data to examine similar changes in the frequency of extreme events for other locations.

The hourly observations of sea level were divided into pre-1950 and post-1950 sections in order to investigate the change in frequency of extreme events during the last century. The data were not corrected for vertical land motion and therefore represent sea level relative to the land. The linear trend of the complete record was calculated. This trend was removed from the pre-1950 and post-1950 sections prior to the calculation of any statistics, but preserving the mean of each section. Alternative techniques were tried (no trend removal; removal of the individual trend from each section), resulting in only small (typically 0.01 metre) changes in the resultant exceedance levels.

Estimating changes in the frequency of extreme events for data-sparse locations

Unfortunately, most Australian sea-level records are short (of the more than 200 records in the PSMSL archive, only nineteen have more than 40 years of data and not all of these are continuous). This data sparsity, combined with the fact that in regions such as the tropics the cyclones that drive extreme sea levels are rare and localised in their impact, means that we need an alternative approach to estimate robustly changes in the frequency and intensity of extreme events. The approach described here requires development of a statistical representation of the extreme

weather conditions that cause storm surges based on the observational records of weather conditions in the region. The statistical model is then used to randomly generate a large number of plausible severe weather events for the region, and these conditions are used to drive a high resolution hydrodynamic model that simulates currents, sea-level heights and coastal inundation due to the effects of tides and storm surges. The model-simulated events are then analysed to produce storm surge ARIs. This method also allows us to estimate future changes in ARIs from projected climate change scenarios.

Cyclones occurring in the Australian region from 1907 to 1997 were used to develop probability distribution functions governing cyclone characteristics in the Cairns region. Since few cyclones have occurred in the immediate vicinity of Cairns during this time, cyclones over the broader coastal region from 14°S to 20°S were considered. The cyclone speed and direction of movement were each found to be approximately normally distributed. A Type I Generalised Extreme Value (Gumbel) distribution was fitted to the cyclone intensity. The cyclone size, characterised by the radius to maximum wind, was set to a constant 30 km due to lack of data. Both cyclones crossing the coast and those travelling parallel to the coast were considered. Cyclones that made landfall were constrained to cross the coast anywhere between 16°S and 17°S with equal likelihood, these boundaries being determined through modelling which showed that outside this stretch of coast, cyclones ceased to produce a positive storm surge effect at Cairns.

Cyclone intensity changes under enhanced greenhouse conditions were based on a study by Walsh and Ryan (2000) in which cyclone intensities were found to increase on average by about 10 per cent and their standard deviation increased by about five per cent. These changes were used to modify the cyclone intensity distribution to provide an alternative distribution for the enhanced greenhouse climate. We note that the changes to tropical cyclones obtained from Walsh and Ryan as applied in McInnes et al. (2003) are likely to constitute an upper threshold to possible future cyclone conditions. This is because in Walsh and Ryan (2000), the changed means and standard deviations were derived from downscaling cyclones with an assumed starting condition of 985 hPa. For less intense cyclones, it is possible that the average increase in intensity in future climate conditions would be somewhat less than this. Changes in numbers of cyclones in the Australian region caused by the enhanced greenhouse effect remain unknown, since they are strongly associated with the El Niño-Southern Oscillation (ENSO) phenomenon, the exact nature of which in a warmer world is currently poor-

ly known. Too little is also known about the effect of climate change on the mid-level winds that govern typical tropical cyclone directions of movement. Therefore, in this study, only changes in cyclone intensity were assumed.

A population of about 1000 cyclones was generated for each of the control climate and the enhanced greenhouse climate by randomly selecting the various characteristics defining the cyclone from the constructed probability distribution functions. Once selected, the time varying wind and surface pressure fields were generated using a parametric cyclone model (Holland 1980). These were applied as forcing to a high resolution coastal ocean model for tides and storm surge described in (Hubbert and McInnes 1999) at a horizontal grid spacing of 200 metres. A randomly selected date and time was assigned to each cyclone to allow for the random phasing of the astronomical tides with the storm surge.

Results

Mean sea-level rise

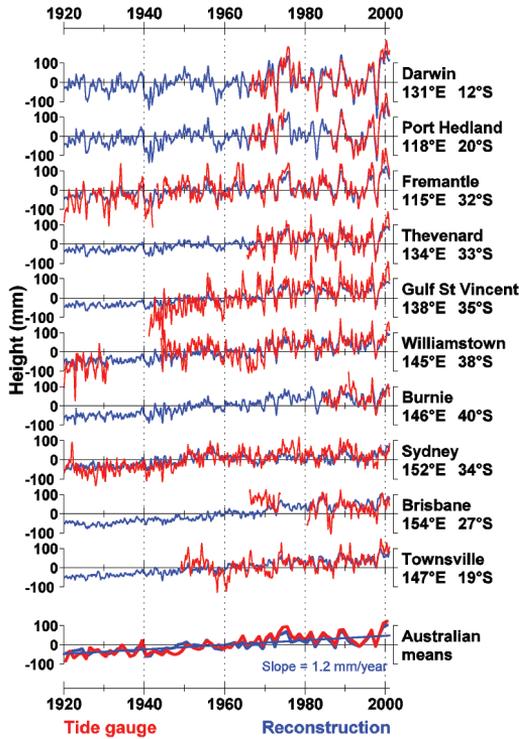
Monthly mean sea-level variations for the period 1920 to 2000 for all Australian locations where there were significant data available were analysed. However because of space limitations we have only shown a subset of these data in Fig. 1. The locations selected were chosen to be representative of all sections of the Australian coastline. We have also shown reconstructions of the sea level for the complete period 1920 to 2000 inclusive. Note that, as stated above, both the observed and reconstructed sea levels are relative sea levels; i.e. they are the height of the sea surface relative to coastal bench-marks and do not include corrections for vertical movement of the earth's crust.

The observed interannual sea-level variability is strongest at locations along the northwestern and western Australian coast. This variability is clearly related to El Niño–Southern Oscillation (ENSO) events and is transmitted through the Indonesian Archipelago from the equatorial Pacific Ocean and then anticlockwise around Australia. The signal is strongest in the north and west and gradually gets weaker further to the east. However, remnants of the ENSO signal can be seen through the Great Australian Bight and as far east as Williamstown and Burnie. The interannual variability on the east Australian coast is generally smaller in magnitude. Major features of the interannual variability, particularly the ENSO signal, are well produced in the reconstructed sea levels (correlations greater than 0.6, and as high as 0.89, for records longer than 30 years).

The observed records also show a long-term trend of rising sea level. This long-term trend is well reproduced in the reconstructed sea levels, with two exceptions. First, the Gulf St Vincent site is a composite record from three sites near Adelaide (Port Adelaide Inner Harbour, Port Adelaide Outer Harbour and Port Stanvac). Compaction of sediments with a subsequent sinking of the coastal tide-gauge is known to be occurring in this region leading to a larger relative sea-level rise (Belperio et al. 1993). This larger local sea-level rise is not reproduced in the reconstructions. Second, the short section of data around 1970 at Brisbane appears anomalous compared to the reconstruction and other sea-level time series. We do not have a definitive reason for this anomalous signal and suspect it may be related to a change in the datum of the tide-gauge between the two segments of data (John Broadbent, personal communication). The tide-gauges used here are from the PSMSL Revised Local Reference dataset. This means the data of the tide-gauges are regularly checked against a set of benchmarks to check for sinkage (and other changes) in the tide-gauge data and thus any bias in the data from the gauges should be small.

We have also shown in Fig. 1 estimates of variations in the Australian-average relative sea-level change. In this average, we have excluded the anomalous combined Gulf St Vincent record. We tried several different approaches to this average with little net impact on the result. There is good agreement between the reconstructed and the 'observed' sea-level time series for both the interannual variability and the long-term trend. When looked at over the complete 80-year record, these trends show a rise in relative sea level of about 1.2 mm per year. There are suggestions in both the Australian mean time-series and in a number of the individual records (e.g. Fremantle) that the rate of sea-level rise was at a minimum from the mid-1970s to the mid-1990s. This minimum occurs during the period of more frequent, persistent and intense ENSO events, as evidenced by the SOI since the mid-1970s (Folland et al. 2001). ENSO events significantly affect sea level along the west Australian coast. The results are also consistent with global analyses for the period 1950 to 2000 which show a global minimum in sea-level rise in the western equatorial Pacific and in the eastern Indian Ocean (Church et al. 2004) over this period. It is important to note that the global analysis gives a global eustatic (increase in ocean volume) sea-level rise of 1.8 mm per year over the period 1950 to 2000 despite these regional areas of lower rates of sea-level rise. The longer records (Fremantle and Fort Denison) and the reconstruction suggest that this period of low rate of rise has now passed.

Fig. 1 Observed (with coastal tide-gauges) and reconstructed sea levels for the period 1920 to 2000. The observed tide-gauge records are monthly average values and can be obtained from the PSMSL website. The Gulf St Vincent site is a composite record from three sites. The bottom panel shows the average observed and reconstructed sea-level record for all Australian sites (with the exception of the Gulf St Vincent site) around the Australian coastline.



Observed changes in the frequency of extreme events

Table 1 shows the increase in the median sea level (the level which is exceeded by half of the observations) and the 0.01 percentile sea level (the sea level which is exceeded by 0.01 per cent of the observations) from pre-1950 to post-1950 conditions for Fort Denison and Fremantle. In the relatively weak tidal regimes at both these sites, the median sea level is close to the mean sea level. The increases in the medians, indicative of a mean sea-level rise from the first to the second half of the last century, are 0.050 and 0.071 m, or rates of about 1.1 and 1.3 mm per year,

Table 1. Increase in the median and 0.01 percentile sea level from pre-1950 to post-1950 periods.

	<i>Fort Denison</i>	<i>Fremantle</i>
Median	0.050 m	0.071 m
0.01 Percentile	0.076 m	0.089 m

consistent with the average rise described above. At Fort Denison and, to a lesser extent at Fremantle, it is apparent that the rise in the ‘extreme’ (0.01 percentile) sea level is larger than the rise in median sea level, indicating other factors contributing to the changes in extremes, such as increased intra-annual, interannual or decadal variability. Note that interannual variability of global averaged sea level (Jevrejeva et al. 2006) and of sea-level records from sites in the Pacific (Church et al. 2006) was observed to be larger after the mid-1970s.

Figures 2 and 3 show the ARIs for a range of extreme levels at Fremantle and Fort Denison, for both pre-1950 and post-1950 conditions. Average return intervals were defined by counting sequential extreme events that occurred within a period of three days as a single event. For a given ARI, the increase in extreme level during the last century is broadly compatible with the increases of the 0.01 percentile levels shown in Table 1. Table 2 shows examples of the decrease in ARI for a given extreme level, showing that events that occur on annual to decadal time-scales increased their frequency of occurrence by a factor of about three during the 20th century.

Fig. 2 Changes in the average recurrence intervals for Fort Denison for the period 1914–2004.

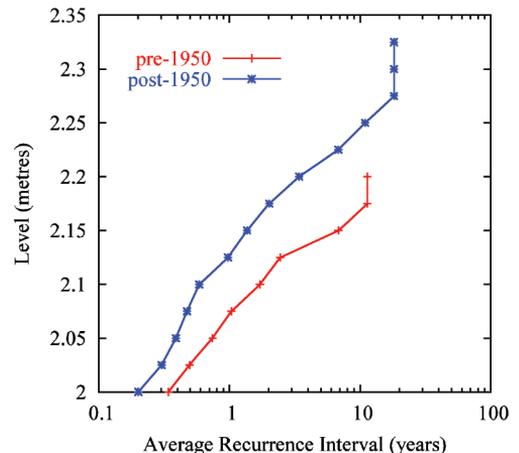
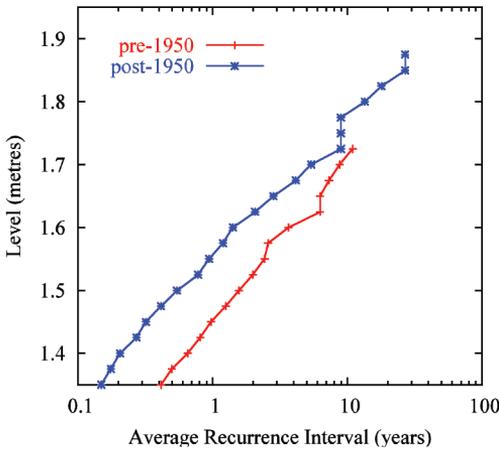


Fig. 3 Changes in the average recurrence intervals for Fremantle for the period 1897-2004.



Estimating changes in the frequency of extreme events for data-sparse locations

As indicated above, for locations with short sea-level records and for projecting future changes in extreme levels, an alternative approach is necessary. We demonstrate this approach for Cairns. The maximum sea-level heights from each of the 1000 simulations are sorted and ranked against their expected ARI (e.g. assuming one cyclone every five years, the highest event is the 1-in-5000 year event and the fifth highest is the 1-in-1000 year event). This is the approach that was adopted in McInnes et al. (2003) and represents the ARI of cyclone-induced storm tides. However, because the events are relatively uncommon, at the shorter return intervals (around 20 years), the magnitudes of the events will tend to be lower than the sea levels that occur due to tidal variations. This approach is not appropriate for planning considerations as ARI curves that do not consider the tidal influences could be misleading. To overcome this, the fitting procedure of McInnes et al. (2003) has been modified to also sample from a distribution of

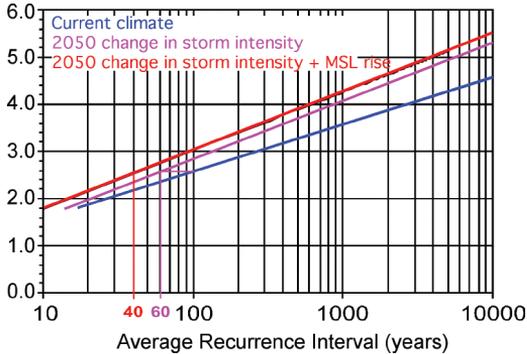
high tide values binned over an 18.6 year period (the time between successive highest astronomical tides). The line of best fit of the combination of storm tide and highest annual tide values against ARI was estimated using a least squares regression. Figure 4 presents ARIs for the current climate and the 2050 climate. Results for current climate yield a 100-year level of 2.5 m. The values obtained here are generally similar to those of Harper (1999). However, 100-year levels produced by Hardy et al. (2004) estimate a value of only 2.04 m. A difference in their approach compared to the current study and the study reported by Harper (1999) is that Hardy et al. selected their population of synthetic cyclones using an autoregressive model whose coefficients were derived from observed tropical cyclones over the Coral Sea from 1969 to 2001. The study described here used extreme value statistics applied to cyclones dating back to 1908 to evaluate the probabilities of cyclones which include those more intense cyclones than have been observed in the recent historical record. It should be noted that these figures do not include wave setup, which will further increase the values.

The ARI curve for the enhanced greenhouse climate indicates that increasing cyclone intensity could increase the height of the 1-in-100 year event from 2.5 m to 2.7 m. In addition the areal extent of overland flooding more than doubles from approximately 32 km² to 71 km² and encompasses much of the Cairns downtown region. We note that due to the relatively low horizontal resolution (200 m) of the model used in this study, these results should be seen as only broadly indicative of the areas most vulnerable to flooding due to extreme sea-level events. An alternative way to view the results is that in the present climate a 1-in-100 year event will become more frequent under the increased cyclone intensity scenario, occurring once every 60 years. When a mid-range projection for mean sea-level rise of 0.2 m by 2050 is also considered, the 1-in-100 year sea-level height increases further to 2.9 m and events of 2.5 m occur every 40 years. These results suggest that changes to cyclone intensity under enhanced greenhouse conditions and mean sea-level rise would cause

Table 2. Average Recurrence Intervals for given sea levels for the pre-1950 and post-1950 periods.

Level	Fort Denison		Level	Fremantle	
	Average Recurrence Interval (years)			Average Recurrence Interval (years)	
	Pre-1950	Post-1950		Pre-1950	Post 1950
2.1 m	1.7	0.6	1.5 m	1.6	0.5
2.2 m	11.4	3.4	1.6 m	3.7	1.4

Fig. 4 Storm tide average recurrence intervals for Cairns under current climate conditions, and in 2050 assuming an increase to tropical cyclone intensity and an increase in mean sea level. Results do not include wave setup.



a considerable increase in the risk to infrastructure in Cairns. In comparison, the study of Hardy et al. (2004) which also investigated a 10 per cent increase to the cyclone intensity found almost no change to extreme sea levels at Cairns at the 100-year ARI and a 0.3 m increase in sea levels at the 1000-year level.

Conclusions

Australian sea-level records for the period 1920 to 2000 clearly indicate a rise in *relative* mean sea level. Averaged around Australia, the rate of increase is about 1.2 mm per year. This value is less than the global increase in eustatic sea level for two reasons. First, the sea-level rises presented here are relative sea level and do not include any correction for ongoing crustal motion. To estimate eustatic sea-level change from the data from the Australian sites, the rates of sea-level rise would typically need to be increased by about 0.3 mm per year. Second, at least for the period 1950 to 2000, sea-level rise off western Australia is less than the global average (Church et al. 2004), possibly as a result of the trend to more frequent, persistent and intense ENSO events since the mid-1970s. As a result of this trend, the Australian mean sea-level time series and a number of the individual records (e.g. Fremantle) suggest there was a minimum in the rate of sea-level rise from the mid-1970s to the mid-1990s. It is important to note that the global analysis

gives a global sea-level rise of 1.8 mm per year over the period 1950 to 2000. The longer records (Fremantle and Fort Denison) and the sea-level reconstruction and also recent analyses by the National Tidal Centre (see, for instance, Table 1 of Mitchell 2006) suggest that this period of low rate of rise has now passed and since the early 1990s Australian sea levels have risen at a substantially higher rate than the long-term average of about 1.2 mm per year.

Analysis of extreme levels for the two longest records, Fremantle and Fort Denison, indicate a decrease in the ARI (i.e. increase in frequency) by factors of about three for extreme sea levels from the pre-1950 period to the post-1950 period. That is, a detectable reduction in the ARI of sea levels of a given value has already occurred, consistent with increased regional coastal flooding and beach erosion. The analysis suggests that enhanced intra-annual, interannual or decadal variability (as well as a mean sea-level rise) is contributing to the increase in extreme levels in the latter half of the 20th century at Fort Denison and, to a lesser extent, at Fremantle.

The analysis for Cairns suggests that changes to cyclone intensity under enhanced greenhouse conditions would cause a considerable increase in the risk to infrastructure in Cairns by 2050. This increased risk is further enhanced by sea-level rise and the risk will continue to increase through the 21st century (and most likely beyond) as sea level continues to rise. Similar studies should be completed for other locations potentially vulnerable to the combined effect of sea-level rise and changes in the intensity of cyclones.

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