Sea-Level Rise and the Vulnerability of Coastlines

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INTRODUCTION

Anthropogenic global warming will undoubtedly cause substantial sea-level rise and shoreline movement during this century and beyond. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC, 2007a) has indicated a projected global sea-level rise of up to 0.79 metres in 2095 (relative to 1990) with the caveat that, because of uncertainties in future ice sheet flow, larger rises cannot be excluded. Such a rise will lead to coastal inundation, increases in the frequency of high sea-level events and erosion of soft shorelines.

At Fremantle and Sydney, the frequency of sea level extremes of a given height has already increased by a factor or about three during the 20th century, predominantly due to sea-level rise. In many parts of Australia, the expected sea-level rise during the 21st century is comparable with the tidal range, which will result in a marked change of tidal regimes – the frequency of extreme events will increase many times and regions that are presently intertidal or even "dry land" will become permanently submerged. High sea-level events which now only occur every 100 years will happen several times per year by the end of this century. In addition, the rise in mean sea-level will lead to the recession of "soft" shorelines (e.g. sand dunes) by tens to hundreds of metres.

HISTORIC SEA-LEVEL RISE

We are now living in a world in which the climate is being substantially modified by human activity (IPCC, 2007a). These changes are leading to a wide range of impacts, just one of which is a rise in sea level at a sustained rate which has not been experienced for at least 5,000 years (Church et al., 2008, Fig. 1 of that paper).

Beginning at the end of the 19th century, an increase in the concentration of greenhouse gases in the atmosphere, caused primarily by anthropogenic emissions, contributed to a warming of the climate. The rise in global temperature during the latter half of the 20th century and beyond was dominated by the effect of these anthropogenic greenhouse gases, compared with other influences, such as solar activity. From 1850-1899 to 2001-2005, global-average surface temperature increased by about 0.76°C (IPCC, 2007a), leading to warming of the oceans and melting of ice on land (Lemke et al., 2007; Bindoff et al., 2007). Church and White (2006) used a combination of tide-gauge records and satellite-altimeter data to reconstruct sea level from 1870 to 2001, showing a global-average rise of 0.17 metres during the 20th Century (Fig. 1) or an average rate of about 1.7 mm y^{-1}. Their reconstruction also suggests an acceleration of sea level from around zero rate of rise in 1820 to a rate of about 3 mm y^{-1} over the past decade. Other reconstructions, using only tide-gauge data (Holgate and Woodworth, 2004; Jevrejeva et al., 2006), have indicated similar rates of rise during the 20th century. Australian waters (Fig. 1) show a slightly lower rate of rise of about 1.5 mm y^{-1} (based on Church et al., 2006, and an Australian-average rate of land uplift of 0.3 mm y^{-1} (Lambeck, 2002)). All these estimates of sea-level rise have been adjusted for vertical land movement and hence are indicative of the change in volume of the oceans.

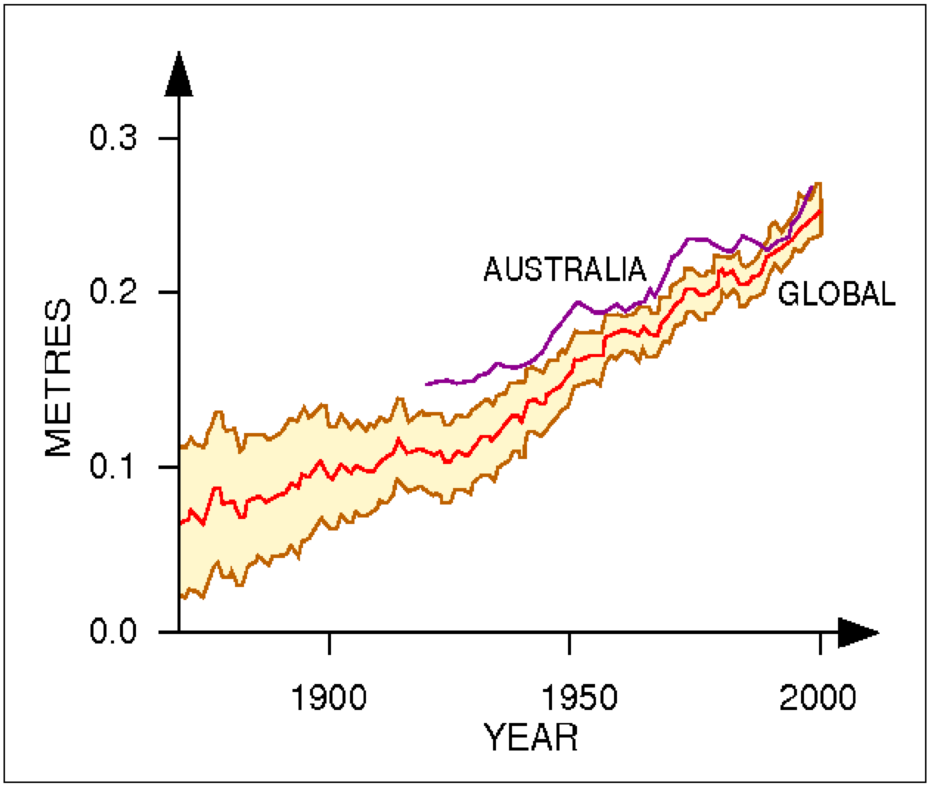

Figure 1. Global sea-level (red, with brown indicating ±95% confidence limits; redrawn from Church and White, 2006). Magenta line indicates reconstruction for Australian waters (redrawn from Church et al., 2006, and White, pers. comm.). The plotted offset between the global and Australian reconstructions is arbitrary.

Sea-level rise is caused mainly by thermal expansion of seawater and melting of ice on land (from mountain glaciers, ice caps, Greenland and Antarctica). Since 1961, thermal expansion has contributed about 40% of the total rise (Bindoff et al., 2007; Domingues et al., 2008).

HISTORIC CHANGES IN EXTREMES

Extremes of sea level depend both on changes in long-term mean sea level and in changes of sea level about that mean (caused, for example, by meteorologically-driven surges). Even in the absence of any increase in surges, a rise in mean sea level causes an increase in the frequency of flooding events of a given level, and an increase in the height of flooding events of a given frequency. Studies of extreme sea levels from many locations around the world have indicated that sea-level rise is generally the dominant cause of increases in the frequency of extreme sea-level events (Bindoff et al., 2007, Woodworth and Blackman, 2004). The long tide-gauge records from the Australian ports of Fremantle and Fort Denison (Sydney) show

(Fig. 2 of this paper; Church et al., 2006) that the Average Recurrence Interval (ARI)[1] of flooding events that occur on annual to decadal time scales decreased by a factor of about three from the pre-1950 period to the post-1950 period. This is mainly caused by sea-level rise, with a smaller contribution coming from changes to intra-annual, inter-annual or decadal variability, which may or may not be related to long-term climate change. The relatively small rise in sea level that has occurred during the 20th century has therefore already caused a significant change in the frequency of extreme sea-level events.

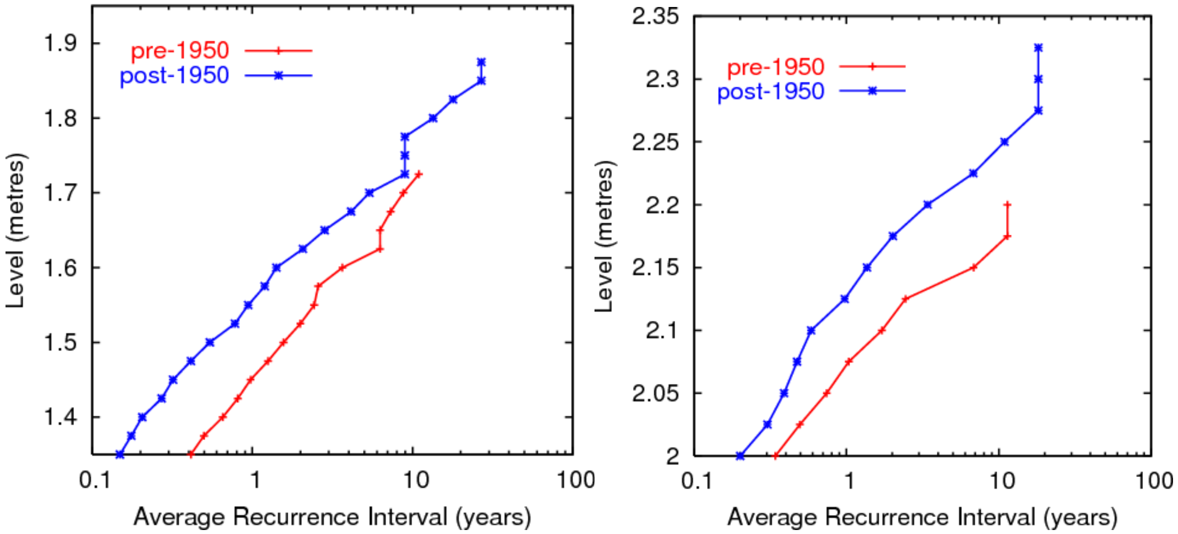

Figure 2. Change of average recurrence interval for extreme high levels from pre-1950 to post-1950 conditions for Fremantle (left) and Fort Denison (right) (Church et al., 2006). Note that return periods are shown on a logarithmic scale on the horizontal axis.

FUTURE SEA-LEVEL RISE

Computer modelling has been used to provide projections of the future climate over time scales of centuries. Two inherent uncertainties are involved. The first (the "scenario uncertainty") arises from the fact that the future social, economic and technological development of the world, and the consequent greenhouse-gas emissions, are poorly known. A range of plausible futures, or scenarios[2], have been used to describe the way in which emissions may change in the future. The second uncertainty (the "model uncertainty") is related to shortcomings in the present knowledge of the science of climate change, partly due to fact that we do not know exactly the present climate state (the "initial conditions"), and partly due to the fact that no model gives a perfect representation of the real world. The IPCC AR4 (IPCC, 2007a) provided projections of sea-level rise at 2095 relative to 1990 (strictly, the difference between the average sea level over 2090-2099 and over 1980-1999; Meehl et al., 2007). The rise projected by the models for this period was 0.18 to 0.59 m, for a range of scenarios covering B1 (low emission) to A1FI (high emission), and including an uncertainty estimate based on the range of projections from the

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[1] The *average recurrence interval* (also called the *return period*) is the average period between extreme events of a given height.

[2] The main emission scenarios used for the IPCC modelling are described in the Special Report on Emission Scenarios (SRES; Nakicenovic, et al., 2000).

different models (Fig. 3). The IPCC also recommended that an additional estimated uncertainty of up to 0.2 m to be added to the upper limits of the projections to account for processes involving land ice in Greenland and Antarctica that are not fully included in the models; it should be noted that the AR4 adds the caveat that "larger values cannot be excluded" (IPCC, 2007b). The resultant upper limit of the A1FI projection at 2095 is in good agreement with the similar projection from the Third Assessment Report (TAR; Church et al., 2001). The lower limit for B1 is roughly 0.1 m higher for the AR4 than for the TAR. In summary, the range of projected sea level at 2095 is 0.18 metres to 0.79 metres, relative to 1990.

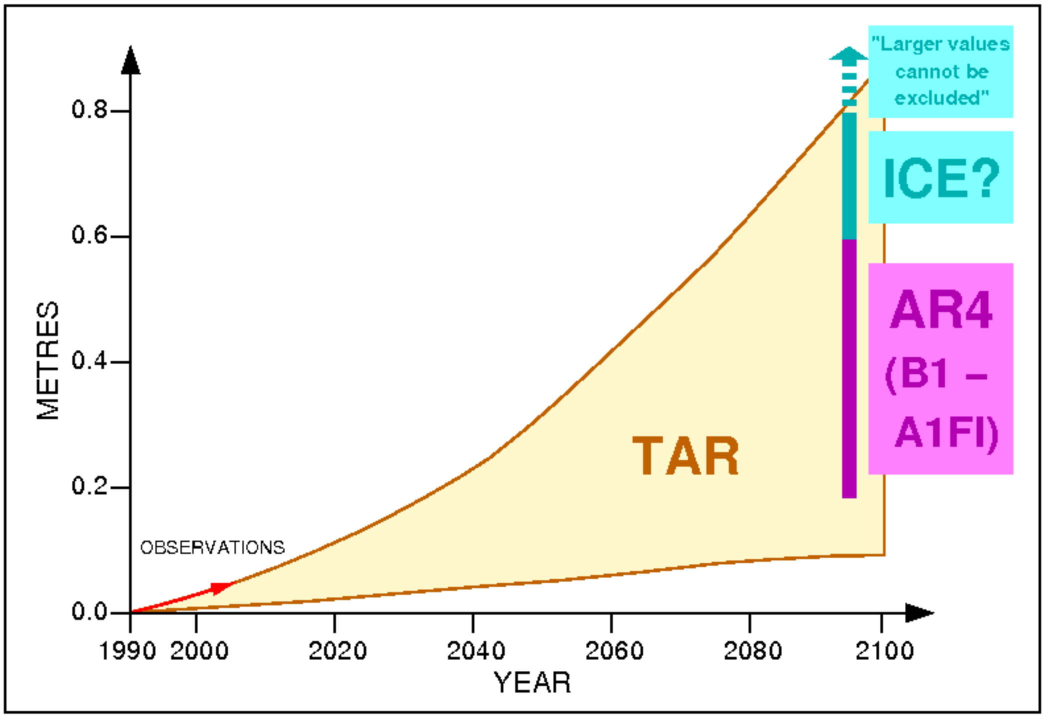

Figure 3. Projections of sea-level rise relative to 1990 from the IPCC Third Assessment Report (TAR; Church et al., 2001) and the Fourth Assessment Report (AR4; Meehl et al., 2007). The amber region indicates the full range of the TAR projections. The mauve bar indicates the range of AR4 model projections for the B1 (low impact) and A1FI (high impact) scenarios (which approximately represents the full range of model projections) at 2095. The cyan bar indicates an additional 0.2 m added to the upper limit of the AR4 model projections at 2095 to account for processes related to land ice that are not accounted for in the models. The cyan dotted error and the quote "larger values cannot be excluded" indicate that the upper AR4 projections are effectively unbounded (IPCC, 2007b). The red arrow schematically represents observations from 1990 to mid-2006, which closely follow the upper limit of the TAR projections (Rahmstorf et al., 2007).

The projections of the AR4 require some qualification. Even though the AR4 represents an extensive assessment of the state of climate science at the present time, some scientists have suggested that the sea-level projections may have been underestimated. Rahmstorf (2007) (and later Horton et al. (2008)) used the relationship between temperature and sea level during the 20th century to project sea level into the 21st century based on the TAR temperature projections (which are considered to be more reliable than the modelled sea-level projections). Rahmstorf's results suggested a rise of 0.5 to 1.4 metres at 2100 relative to 1990. Probably the most extreme projection comes from James Hansen, who has suggested that a rise of 5 metres over the 21st century is not implausible (Hansen, 2007). Rahmstorf et al. (2007) showed that, since 1990, both global temperature and global sea level (Fig. 3) have been tracking near the upper limit of the projections, again suggesting that the model projections may be underestimates. Finally, Raupach et al. (2007) and Canadell et al. (2007) have shown that global greenhouse-gas emissions are now tracking well above the (high-impact) A1FI scenario, and that the world is not yet following any reasonable mitigation pathway. Therefore, it seems reasonable to view the higher end of the AR4 projections as very plausible.

While the two largest contributions to present sea-level rise are thermal expansion and the melting of glaciers and ice caps, the melting of ice on Greenland and Antarctica (predominantly the West Antarctic Ice Sheet) will arguably become more important in coming centuries. The Greenland and the West Antarctic ice sheets have the potential to raise sea level by 7 metres and 6 metres, respectively (Church et al., 2001; Lemke et al, 2007). If global temperatures are raised sufficiently, the Greenland ice sheet will reach a state where it will effectively shrink, possibly irreversibly[3]. It has been estimated (Meehl et al., 2007; Gregory and Huybrechts, 2006) that this threshold will be reached when global temperatures are 2.3℃ to 3.9℃[4] above pre-industrial levels, which is *likely*[5] to be reached by 2100 even under the (mid-range) A1B emission scenario, let alone under the high impact A1FI scenario which the world is currently tracking. It is interesting to note that the above threshold range (2.3℃ to 3.9℃) is almost symmetrically overlapped by the estimated *likely range*[6] of global temperature (1.9℃ to 4.4℃) expected if the world ultimately equilibrates to a stabilised CO_2-equivalent greenhouse gas concentration of 550 ppm (Meehl et al., 2007). This level, which is the upper limit of the range (450-550 ppm CO_2-equivalent) suggested in the Stern Review (Stern, 2006) as an attainable global target, would therefore involve (on present evidence) a roughly 50% chance of melting of the Greenland ice sheet (possibly irreversibly). Removal of most of the Greenland ice sheet and a consequent rise of global sea level by around 7 metres would, however, probably take millennia.

FUTURE IMPACTS

Extremes

As indicated earlier, if the variability of sea level about the mean does not change, then sea-level rise leads to an increase in the frequency of extreme sea-level events of a given height. The relationship between the ARI and the extreme level is approximately logarithmic (see Fig. 2), indicating a Gumbel distribution (e.g. Pugh, 1996). The slope of this relationship may be used to estimate the increase in frequency for a given amount of sea-level rise. If a sea-level rise of h increases the frequency of occurrence by a factor r, then a sea-level rise of H increases the frequency of occurrence by a factor $r^{H/h}$ (a consequence of the form of the Gumbel distribution), which can become very large, even for modest increases in sea level. Fig. 4 shows the estimated increase in the frequency of occurrence of extreme high

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[3] Even if atmospheric greenhouse concentrations were reduced to preindustrial or present levels, the Greenland ice sheet may not be re-established (Meehl et al., 2007).

[4] These limits are ±1 standard deviation, which is almost equivalent to the "likely range" defined by the AR4 (see footnote 6).

[5] The AR4 defines "likely" as a better than 66% chance of occurrence.

[6] The "likely range" defined by the AR4 is assumed to represent 66% confidence limits.

levels, caused by a sea-level rise of 0.1 metres, for the 29 Australian sea-level records that are longer than 30 years. This multiplying factor has a range of 1.8 to 5.8 and a mean of 3.1, which is broadly consistent with the 20th century observations for Fremantle and Fort Denison (Fig. 2). For a typical mid-range 21st century rise of mean sea level of 0.5 metres (see earlier), the mean multiplying factor for Australia would therefore be $3.1^{0.5/0.1}$ or 286, indicating that events which now happen every few years would happen every few days in 2100. Fig. 4 shows that even larger increases in the frequency of extremes would occur around Sydney, Brisbane and in Bass Strait (the strait between Tasmania and mainland Australia).

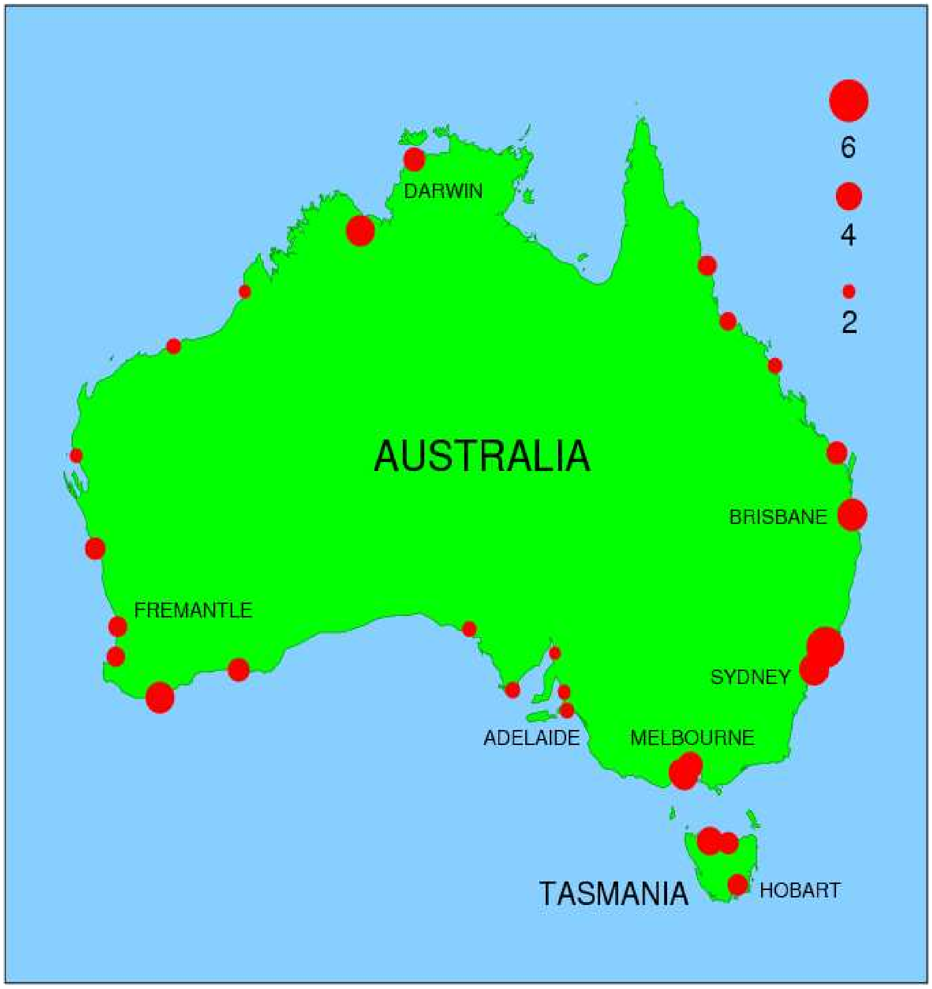

Figure 4. Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events (indicated by the diameter of the discs), caused by a sea-level rise of 0.1 m.

A method has recently been developed by the Antarctic Climate & Ecosystems CRC for the estimation of the probability of such flooding events occurring during a given period in the future, under conditions of (uncertain) rising sea level. The method relies only on sea-level (tide-gauge) observations from the specific location and modelled projections of sea-level rise. The results give engineers, planners and policymakers a way of estimating the probability that a given sea level will be exceeded during any prescribed period during the present century. Fig. 5 shows an example from Fort Denison, Sydney, under the (high) emission scenario A1FI. The red curve shows the probability that a given sea level will be exceeded (the *exceedance probability*) at least once during the period 2010 to 2100, with due allowance for projected sea-level rise and its inherent uncertainty. The blue curve indicates the exceedance probability for a 90-year period with mean sea level held constant at the 2000 value. The arrows show the amount by which planning levels would need to be raised in order to address specific risks of flooding by high sea level. If we are prepared to accept, say, an 80% probability of flooding of a particular piece of infrastructure at Fort Denison during the period 2010 to 2100, then Fig. 5 indicates that planning levels should be raised by about 0.3 m relative to their 2000 levels (i.e. the difference between the thick (middle) blue and red curves for an exceedance probability of 0.8; see right-hand vertical arrow in Fig. 5). However, if we take a more precautionary approach and are only prepared to accept a 30% chance of flooding, the planning levels should be raised by about 0.45 m relative to their 2000 levels (i.e. the difference between the thick (middle) blue and red curves for an exceedance probability of 0.3; see left-hand vertical arrow in Fig. 5). In other words, the amount by which planning levels need to be raised depends on the level of risk that is acceptable; diagrams like Fig. 5 provide a way of making the necessary choice.

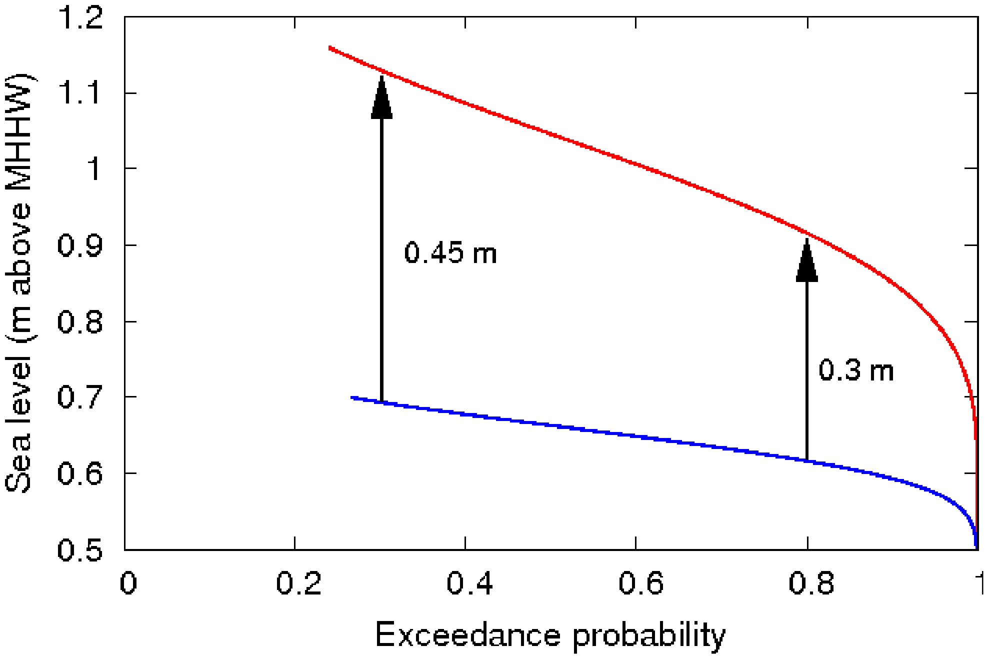

Figure 5. Exceedance probabilities for Fort Denison, emission scenario A1FI, for the period 2010 to 2100 (red). Also shown are equivalent exceedance probabilities for a period of 90 years with mean sea level held constant at the 2000 value (blue). Vertical arrows indicate amount that planning levels should be raised to cater for 80% and 30% flooding risks.

Shoreline Recession

In sandy coastal regions, it is now well-established that sea-level rise leads, on average, to erosion and consequent recession of the shoreline. At present 70% of the world's beaches are eroding and less than 10% are prograding (Bird, 1993). The process by which sea-level rise leads to this erosion may be approximately described by the Bruun Rule[7] (Bruun, 1962), which is a rule-of-thumb based on the conservation of sediment in an offshore direction (i.e. longshore transport is ignored). The Bruun Rule states that shoreline recession proceeds at a rate of roughly 100 times the amount of sea-level rise, equivalent to around 50 metres for a mid-range sea-level rise of 0.5 metre. Erosion of this magnitude will have significant impacts on coastal ecosystems, infrastructure, land tenure and public beaches. Of particular importance is the potential loss of coastal habitat where shoreline recession is inhibited by the presence of infrastructure, such as a seawall. Under natural conditions where recession is possible (e.g. the beach is backed be a low-lying erodible plain), the coastline and associated coastal habitats would be translated inland and the habitat function would be largely preserved. However such translation is not possible in the presence of non-erodible infrastructure. Planning for future adaptation should therefore include consideration of which items of infrastructure (e.g. roads) could most easily be moved inland in order to provide space for marine habitat.

Harvey and Woodroffe (2008) reviewed coastal vulnerability assessment in Australia, indicating the various regional approaches. In Tasmania, Sharples (2006) provided an assessment of the vulnerability of the Tasmanian coastline to sea-level rise, addressing both inundation and shoreline recession. The results were presented in terms of areas potentially subject to inundation and a linear encoding of the coastline, indicating the erosion potential. This latter technique has now been adopted for the whole of Australia as the National Shoreline Geomorphic and Stability Mapping Project, which will present its results in late 2008.

Low-lying Islands

Low-lying islands are particularly vulnerable to sea-level rise, for a number of reasons. Firstly, many islands only reach a meter or so above mean sea level, and their low profiles render them liable to flooding from higher sea levels and more frequent high sea-level events. Secondly, they often cover only a small area, such that there is little opportunity to retreat in the face of rising sea levels and/or receding shorelines. Thirdly, many small islands such as coral atolls are, by their nature, vulnerable to small changes in the environment. A coral atoll is generally sustained by a delicate balance of sediment transport, being fed from eroded coral from the fringing reef and constantly losing sediment to the atoll lagoon. Sea-level rise is just one factor which can disturb that balance, others being changes in the patterns of winds, waves or currents, and anthropogenic impacts such as sand mining.

CONCLUSION

The Fourth Assessment Report (IPCC, 2007a) has indicated a projected global sea-level rise of up to 0.79 metres in 2095 (relative to 1990) with the caveat that, because of uncertainties in future ice sheet flow, larger rises cannot be excluded.

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[7] The Bruun Rule is a very simplified approximation to the real world and has its detractors (e.g. Pilkey and Cooper, 2004; Nicholls and Stive, 2004). However, the general ideas surrounding the Bruun Rule form the basis of models of significantly greater sophistication, validity and utility, such as the Shoreface Translation Model (Cowell et al., 2006).

In Australia, at Fremantle and Fort Denison (Sydney), the frequency of sea-level extremes of a given height has already increased by a factor of about three during the 20th century, predominantly due to sea-level rise. Even a mid-range rise of about 0.5 metres during this century would lead to events which now happen every few years happening every few days in 2100, or the present ‘100-year event’ happening every few months.

A method of combining observations of present sea-level extremes with the (uncertain) projections of sea-level rise during the 21st century has been described. This provides engineers, planners and policymakers with a technique for estimating the probability that a given sea level will be exceeded during any prescribed period during this century, and therefore a way of choosing how planning levels should be raised to accommodate an acceptable flooding risk. It should be emphasised that this estimate relates only to the increase in the frequency of extremes caused by a rise in mean sea-level and not due to any additional increase in extremes relative to mean sea level, caused for example by more frequent and intense storminess. However, present evidence suggests that the rise in mean sea level is generally the dominant cause of the observed increase in the frequency of extreme events.

Such effects will not be confined to Australia as, in many parts of the world, the expected sea-level rise during the 21st century is comparable with the tidal range, which will result in a marked change of tidal regimes - the frequency of extreme events will increase many times and regions that are presently intertidal or even "dry land" will become permanently submerged. In addition, the rise in mean sea level will lead to the recession of "soft" shorelines (e.g. sand dunes) by tens to hundreds of metres. Low-lying islands in the Pacific and Indian Oceans are particularly vulnerable, given that their existence is often dependant on a delicate balance of sediment transport processes, which are in turn sensitive to sea level, and the important fact that retreat from shoreline recession is not an option on small islands.

In the longer term, unless realistic greenhouse-gas mitigation strategies are pursued with vigour, there is a significant probability of sea-level rise being ultimately measured in meters.

Finally, at the end of this paper is a bibliography of recent useful references.

ACKNOWLEDGEMENTS

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