Estimating Sea-Level Extremes in a World of Uncertain Sea-Level Rise

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Abstract

Estimation of expected extremes, using various combinations of observations and model simulations, is common practice. Many of these techniques assume that the background statistics are stationary and that the resulting estimates may be used satisfactorily for any time in the future. We are now however in a period of climate change, during which both average values and statistical distributions may change in time. The situation is further complicated by the considerable uncertainty which accompanies the projections of such future change. Any useful technique for the assessment of future risk should combine our knowledge of the present, our best estimate of how the world will change, and the uncertainty in both.

Historic mean sea level and its extremes are summarised, and the expected effect of sea-level rise on future extremes is indicated. A method of combining observations of present sea-level extremes with the (uncertain) projections of sea-level rise during the 21st century is then described, using Australian data as an example. 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, at some specified time in the future.

1. INTRODUCTION

We are now living in a world in which the climate is being substantially modified by human activity. 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. This rise in sea level is being felt, and will be felt, through an increased frequency of flooding events, coastal erosion and substantial changes to the bathymetry and topography of soft coastal margins (e.g. sandy shorelines).

This paper draws heavily on the findings of the Third Assessment Report (the TAR; Church *et al*., 2001) and of the Fourth Assessment Report (the AR4; IPCC, 2007), published by the Intergovernmental Panel on Climate Change (IPCC).

2. HISTORIC SEA-LEVEL RISE

Climate has changed throughout the Earth's history. Over the past 400,000 years, the climate has followed four glacial cycles (IPCC, 2007, Ch. 6), which are believed to be driven by small changes of the Earth's orbital parameters causing subtle changes in the amount and timing of incoming solar radiation. This small effect is amplified by processes such as changes in the reflectivity of the ground when covered by ice or snow, and removal of carbon dioxide (a greenhouse gas) from the atmosphere (for example by absorption into a cooler ocean). The cooling during glacial cycles leads to the build-up of ice on land, primarily in the Northern Hemisphere, causing sea level to fall by more than 100 metres. Figure 1 shows the history of global sea level[1] over the past 140,000 years (covering the last glacial cycle), inferred from proxy records such as fossil corals and coastal morphology. After the peak of the last ice age (the "glacial maximum"), 21,000 years ago, sea level rose at rates up to about 3 metres per century. At about 2,000 years before present (BP), this sea-level rise had almost ceased (Figure 2) and, from 1,000 BP (1,000 AD) to the late 19th century, sea level was confined within a range of about 0.2 metres. It is important to note that the sea-level variation over the glacial cycles was predominantly driven by melting and freezing of ice on land with only a small contribution coming from thermal expansion or contraction of sea water.

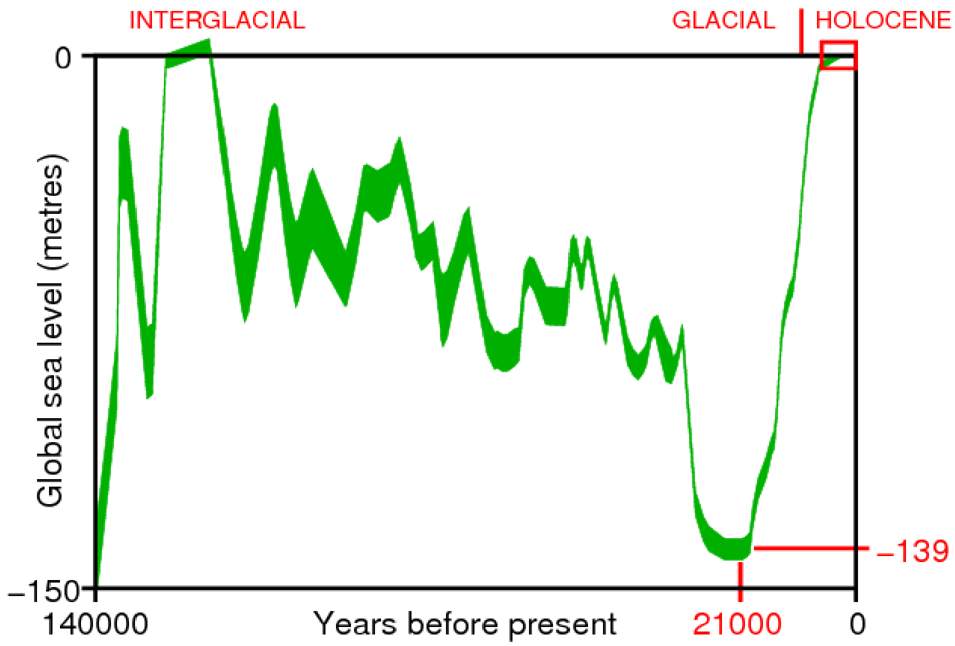

Figure 1. History of global sea level over the past glacial cycle. Thickness of green curve represents uncertainty. Red rectangle indicates period shown in Figure 2. After Lambeck & Chappell, 2001, Lambeck *et al.*, 2002, Lambeck, 2002, Lambeck *et al.,* 2004.

Around the end of the 19th century, an increase in the concentration of greenhouse gases in the atmosphere, caused primarily by anthropogenic emissions, led to a warming of the climate. The rise in global temperature during the latter half of the 20th century and beyond was dominated by these anthropogenic greenhouse gases, compared with other influences, such as solar activity. From 1850-1899 to 2001-2005, global temperature increased by 0.76°C (IPCC, 2007), leading to warming of the oceans and melting of ice on land. The global sea-level rise over a similar period is shown in Figure 3. Church and White (2006) used a combination of tide-gauge records and satellite-altimeter data to reconstruct sea level from 1870 to 2004, showing a global-average rise of 0.17 metres during the 20th century. Figure 3 also shows that the sea-level rise for Australia is comparable with, but slightly less than, the global value. The 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 & Woodworth, 2004; Jevrejeva *et al.*, 2006), have indicated similar rates of rise during the 20th century.

Unlike the sea-level variations associated with the glacial cycles, thermal expansion of the warming ocean plays an important role in 20th century sea-level rise (IPCC, 2007). The two largest and roughly comparable contributions are now thermal expansion and the melting of glaciers and ice caps

[1] In this instance "global sea level" refers to the sea level that would be observed due to melting and freezing of ice, if there were no adjustment of the crust of the Earth to the change of weight of overlying ice or water (called "postglacial rebound" or "glacial isostatic adjustment"). It is therefore differs in detail from the sea-level which would be observed, relative to the land, as a specific location and which is called "relative sea level".

(excluding Greenland and Antarctica, which are at present only making a smaller contribution) (IPCC, 2007), although the exact contribution of thermal expansion is presently under review.

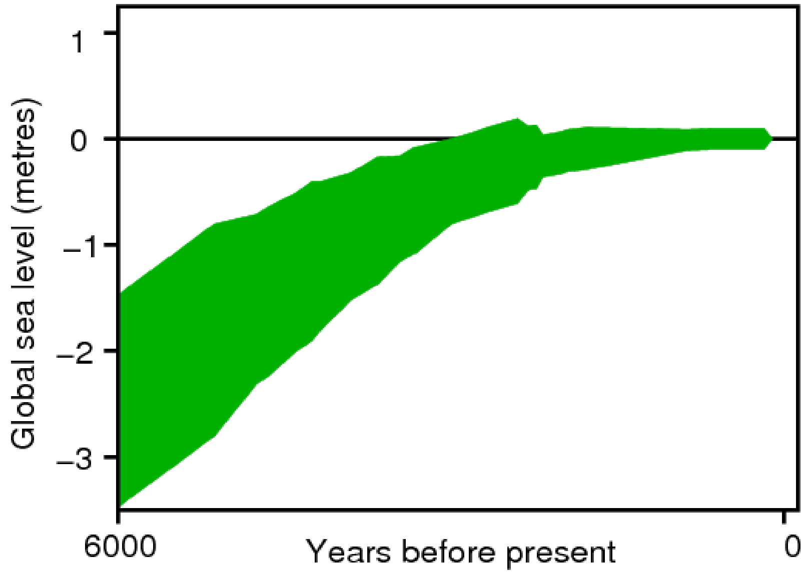

Figure 2. History of global sea level over the past 6000 years. Thickness of green curve represents uncertainty. Record ends at about 1900. After Lambeck & Chappell, 2001, Lambeck *et al*., 2002, Lambeck, 2002, Lambeck *et al.* 2004.

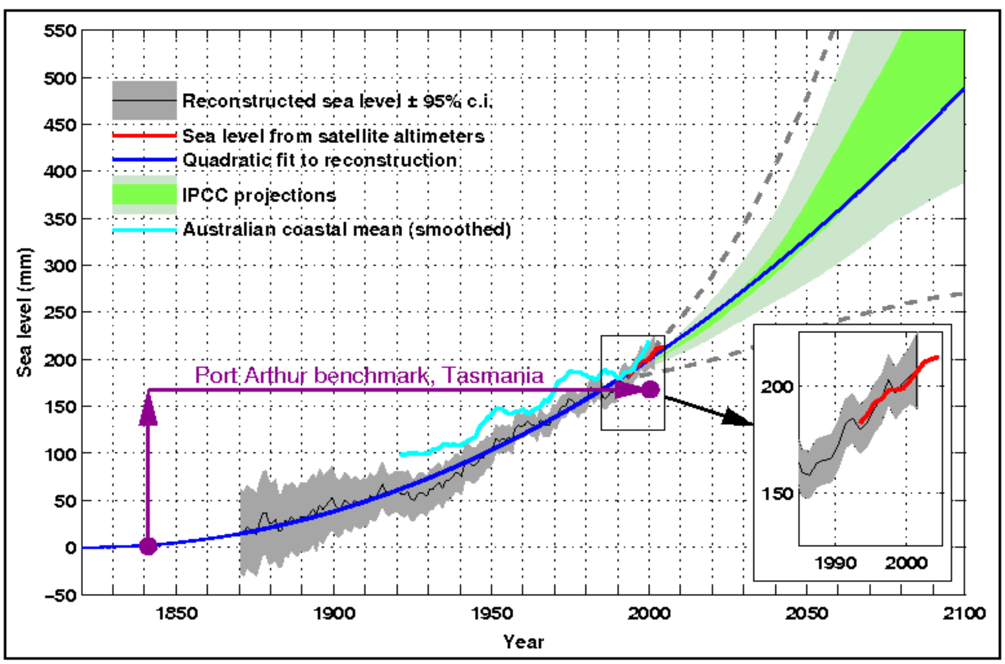

Figure 3. Sea-level reconstruction of Church and White (2006) (black, with grey indicating ±95% confidence limits). Magenta dots and arrows indicate estimate of sea-level rise from 1842 to 2001 from Port Arthur, Tasmania (Hunter *et al.*, 2003). Sea-level projections from IPCC Third Assessment Report (Church *et al.*, 2001) (outer dotted curves indicate limits of projections; see Fig. 11 of Third Assessment Report for description of light and dark green regions). Image courtesy of Neil White, CSIRO.

3. 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 (IPCC, 2007; Woodworth & Blackman, 2004). The long tide-gauge records from the Australian ports of Fremantle and Fort Denison (Sydney) show (Figure 4 of this paper; Church *et al.*, 2006) that the return period[2] 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 enhanced 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.

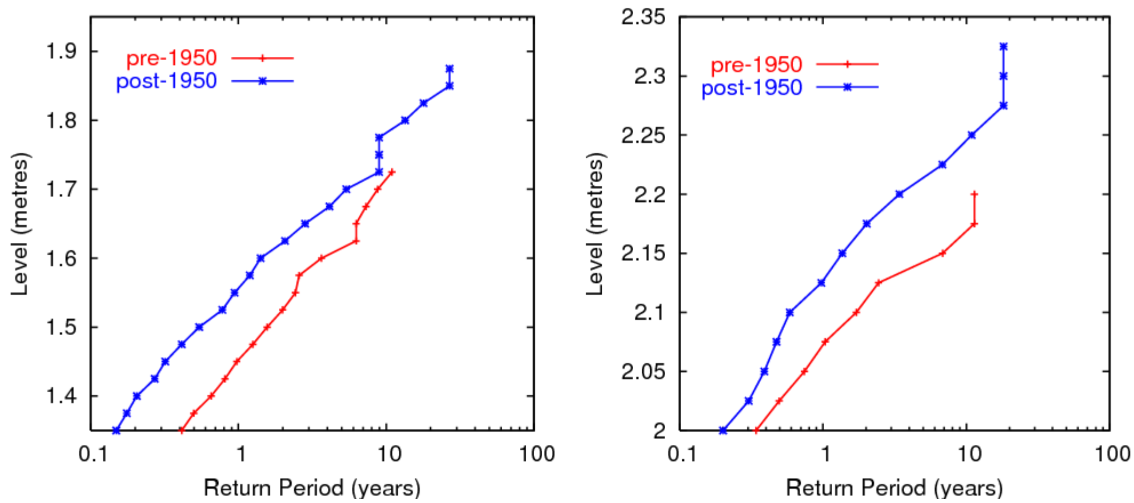

Figure 4. Change of return period for extreme high levels from pre-1950 to post-1950 conditions for Fremantle (left) and Fort Denison (right) (Church *et al.*, 2006). Note that return periods are shown on a logarithmic scale on the horizontal axis.

4. FUTURE SEA-LEVEL RISE

Computer models are 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. Modellers therefore use a range of plausible futures, or *scenarios*[3], 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.

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

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

Figure 5 shows projections of sea level relative to 1990[4] for a "low-impact" (B1) and "high-impact" (A1FI) scenario (this choice spans almost completely the full range of 35 SRES scenarios used for climate modelling). The blue curves represent the TAR (Church *et al.*, 2001) model projections of the minimum and maximum sea level for the B1 scenario, the vertical span indicating the "model" uncertainty. Similarly, the red curves represent the TAR model projections of the minimum and maximum projected sea level for the A1FI scenario. The magenta box shows the AR4 (IPCC, 2007) model projections of the minimum and maximum sea level for the B1 and A1FI projections, respectively, over the period 2090-2099[5]. For this box, the vertical span indicates both the “scenario” and the “model” uncertainty, and the slanting edges represent the rates of sea-level rise estimated by the models for this period. The green box represents an additional estimated uncertainty of up to 0.2 metres 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". It is seen from Figure 5 that the upper limits of the A1FI projections for the TAR and the AR4 are in good agreement at 2090-2099, while the lower limit for B1 is roughly 0.1 metre higher for the AR4 than for the TAR. In summary, the range of projected sea level at 2090-2099 is 0.18 metres to 0.79 metres, relative to 1990 (or strictly, the average over 1980 to 1999).

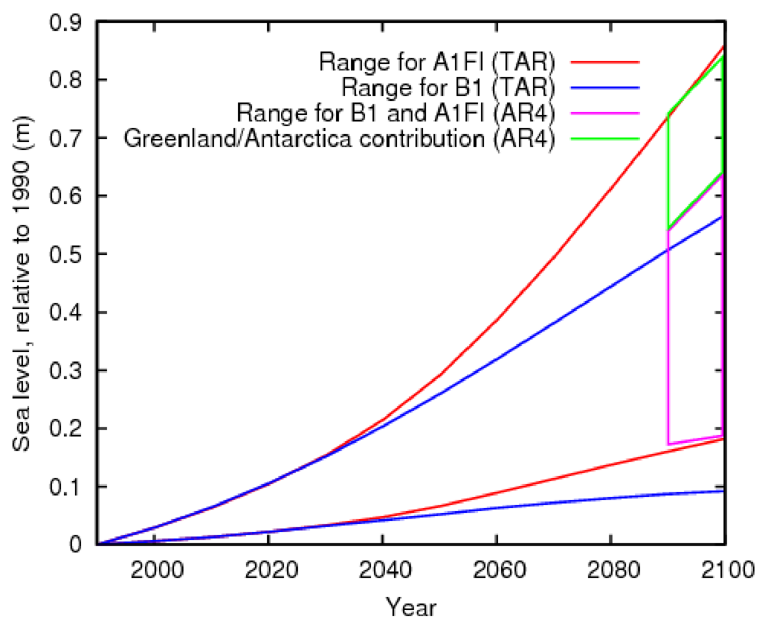

Figure 5. Projections of sea-level rise relative to 1990 from the IPCC Third Assessment Report (TAR; Church *et al.*, 2001) and the Fourth Assessment Report (AR4; IPCC, 2007), for the B1 (low impact) and A1FI (high impact) scenarios.

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 (2006) 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. His 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 have been tracking the upper limit of the projections, again suggesting that the model projections may be underestimates.

[4] Strictly, the TAR related projections to 1990, while the AR4 related projections to the average over the period 1980 to 1999.
[5] The AR4 has not at the time of writing published time series of projected sea levels, and their uncertainties, throughout the 21st century.

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; IPCC, 2007). If global temperatures are raised sufficiently, the Greenland ice sheet will reach a state where it will effectively shrink, possibly irreversibly[6]. It has been estimated (IPCC, 2007, Section 10.7.4.3; Gregory & Huybrechts, 2006) that this threshold will be reached when global temperatures are 2.3°C to 3.9°C [7] above pre-industrial levels, which is *likely*[8] 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° C to 3.9° C) is almost symmetrically overlapp ed by the estimated *likely range*[9] of global temperature (1.9°C to 4.4° C) expected if the worl d ultimately equilibrates to a stabilised CO_2-equivalent greenhouse gas concentration of 550 ppm (IPCC, 2007, Section 10.7.2). 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 irreversible melting of the Greenland ice sheet. 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.

5. FUTURE 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 present relationship between the return period and the extreme level is approximately logarithmic (see Figure 4), indicating what is known as a Gumbel distribution. 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. Figure 6 shows the estimated increase in the frequency of occurrence of extreme high 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 (Figure 4). 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. Figure 6 shows that even larger increases in the frequency of extremes would occur around Sydney, Brisbane and in Bass Strait.

[6] Even if atmospheric greenhouse gas concentrations were reduced to preindustrial or present levels, the Greenland ice sheet may not be re-established (IPCC, 2007).
[7] These limits are ± 1 standard deviation, which is almost equivalent to the “likely range” defined by the AR4 (IPCC, 2007) (see footnote 9).
[8] The AR4 (IPCC, 2007) defines "likely" as a better than 66% chance of occurrence.
[9] The “likely range” defined by the AR4 is assumed to represent 66% confidence limits.

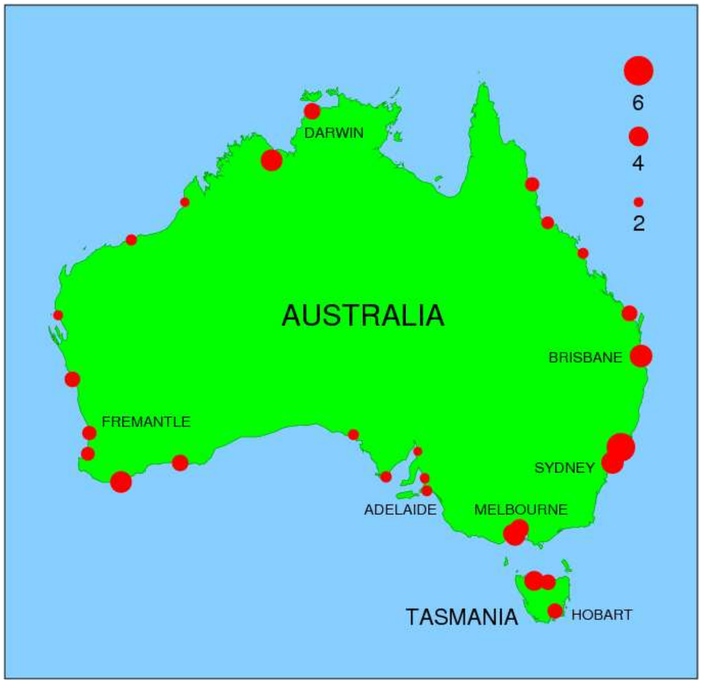

Figure 6. Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events (indicated by the diameter of the discs), caused by a sea-level rise of 0.1 m.

The present statistics of extreme sea levels may be integrated with projections of the rise in mean sea level (and their associated uncertainties), in order to provide estimates of the statistics of future extremes. Again, this analysis depends on the assumption that the change in extremes will be dominated by the rise in mean sea level rather than by any change in the variability. The technique used here is illustrated in Figure 7. The red curve represents the *exceedance probability*[10] of sea level in 2000, for a specific *asset life*[11] and relative to some prescribed vertical datum (e.g. Australian Height Datum). It would generally be derived from existing historical sea-level records (from a tide gauge), from numerical modelling of the factors affecting sea-level variability, or from a combination of both. In this study, the exceedance probability was fitted to a *Generalised Extreme Value (GEV)* distribution using the methods of Coles (2001). The blue curve represents the estimated probability distribution of sea-level rise at 2100, relative to 2000[12]. Neither the TAR nor the AR4 indicated appropriate forms for such a distribution, so two possible distributions have been assumed in this work: a normal distribution and a boxcar (or uniform distribution). It will be shown that the results for each distribution are similar, suggesting that the exact choice of distribution is not critical. The projections used were those of the TAR, rather than the AR4, because, at the time of writing, published time series of the projections and their uncertainties were not available throughout the 21st century. It is however evident from Figure 5, that the TAR and AR4 projections of sea level are very similar[13]. It was assumed that, for any one

[10] The *exceedance probability* is the probability that a specific level will be exceeeded at least once during a prescribed period (here called the *asset life*).

[11] The *asset life* is the duration of time over which exceedance statistics are required. It would generally be chosen as the expected life of a particular item of infrastructure. The period of time spanned by the asset life is called the *asset period*.

[12] It should be noted that this example is illustrative only, so other "base" years could be chosen instead. The IPCC, in its Assessment Reports, has consistently chosen 1990 as the base year for projections.

[13] While the upper limit of the projections for the TAR and the AR4 are very similar, the lower limit of the AR4 projections is roughly 0.1 m higher than the lower limit of the TAR projections at 2100. The use of TAR projections, rather than those of the AR4, would therefore cause the derived extreme levels to be biased slightly low. This bias should probably be less than 0.05 m, even at the end of the 21st century.

SRES scenario, the upper and lower limits given by the TAR projections are given approximately by $\mu \pm 1.5\sigma$ where μ is the mean and σ is the standard deviation of the assumed uncertainty distribution[14]. The mauve curve is the estimated exceedance probability of sea level in 2100 (relative to the prescribed vertical datum), derived by a convolution[15] of the distributions given by the red and blue curves; this is the primary output of this analysis.

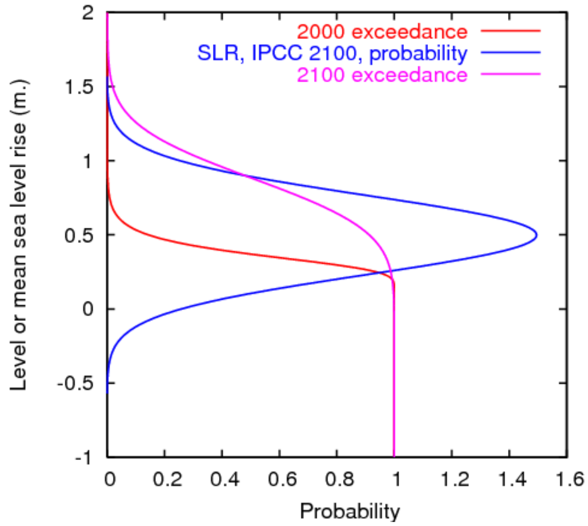

Figure 7. Example of combination of statistics of tides and surges with the uncertainty of sea-level projections (actual values are illustrative only; they do not represent real data).The red curve is the exceedance probability of sea level in 2000, for a specific asset life and relative to some prescribed vertical datum. The blue curve represents the uncertainty in sea-level rise at 2100 (relative to 2000) for a specific SRES scenario (e.g. A1FI), in this case approximated by a normal distribution (the other choice for this investigation being a boxcar, or uniform, distribution). Convolution of these two distributions yields the mauve curve, which is an estimate of the exceedance probability of sea level in 2100 (relative to the prescribed vertical datum).

An important assumption in the above analysis is that the exceedance statistics remain stationary during the asset period. While this may be approximately true of the deviations from mean sea level[16] (such as surges), it is certainly not true of mean sea level itself, which we expect to generally increase monotonically throughout the 21st century (Figure 5). A further assumption is therefore made: that the true exceedance probability may be adequately modelled by considering the case of a (raised) sea level which remains constant over the asset life. For most situations, it is probably satisfactory to select this level from the projected sea-level rise at the *middle* of the asset period[11]. For more conservative assessments it may be preferable to select the level from the projected sea-level rise at the *end* of the asset period.

The above analysis has been applied to the 29 Australian sea-level records that are longer than 30 years' duration (the relevant locations are shown in Figure 6), for three emission scenarios (B1 (lower

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[14] The factor of 1.5 was derived from elementary order statistics (see, for example, `mathworld.wolfram.com/OrderStatistic.html`), and the assumption that the spread of the IPCC TAR projections for any one scenario is the result of taking about 10 samples from the population of possible projections (most of the uncertainty for each scenario is due to disagreement between the seven climate models used, while a smaller amount is due to 'uncertainty in land-ice changes, permafrost changes and sediment deposition' (Church et al., 2001, Figure 11.12)).

[15] Convolution is a way of mathematically combining two distributions. Smoothing is a simple example of convolution. A helpful explanation is given at `mathworld.wolfram.com/Convolution.html`.

[16] In this instance, "mean sea level" implies a relatively short averaging time, such as a year.

impact), A1B (medium impact) and A1FI (higher impact), for a number of times during the 21st century and for a range of asset lives. Here, the results for Burnie and Hobart (Tasmania) are discussed briefly.

Figure 8 shows the result of this analysis for Burnie for scenario A1FI and an asset life of 10 years. The blue curves show the exceedance probabilities for 2000 (the middle curve is the maximum likelihood value and the outer curves are the 95-percentile confidence limits). The red curves show the exceedance probabilities for 2060 (the middle pair of curves are the maximum likelihood values, the outer pairs are the 95-percentile confidence limits, and each pair corresponds to approximating the projection uncertainty by normal and boxcar (uniform) distributions). It is evident that the choice of normal or boxcar distributions does not markedly affect the results. It should be noted that the vertical datum used here is Mean Higher High Water (MHHW) which, although being a fixed level (and hence robust datum) at a particular location, depends on the magnitude of the local tides and hence varies from place to place. However, the advantage of relating extremes to a "high" tidal level such as MHHW[17], is that it removes much of the tidal variation from the result, so that the levels presented on the vertical axis of plots such as Figure 8 are more likely to be applicable to nearby locations as well as to the location itself. The curves are terminated at the "low-probability" end of the plot when the return period at 2000 exceeds four times the record length, which represents a reasonable limit of extrapolation of the observations (Pugh, 1996). It is evident that the projected exceedance probabilities for 2060 are raised and spread over a larger range of levels, relative to the equivalent values for 2000, as a result of sea-level rise and its inherent uncertainty. Figure 9 shows equivalent results for 2100, indicating further sea-level rise and an increased spread of the exceedance probabilities. Figure 10 show the results for Hobart for 2100, which are similar to those for Burnie in Figure 9, although the range of levels at 2000 is somewhat larger; this is primarily a result of the stronger tides at Burnie, which tend to "flatten out" the distribution of exceedance probabilities.

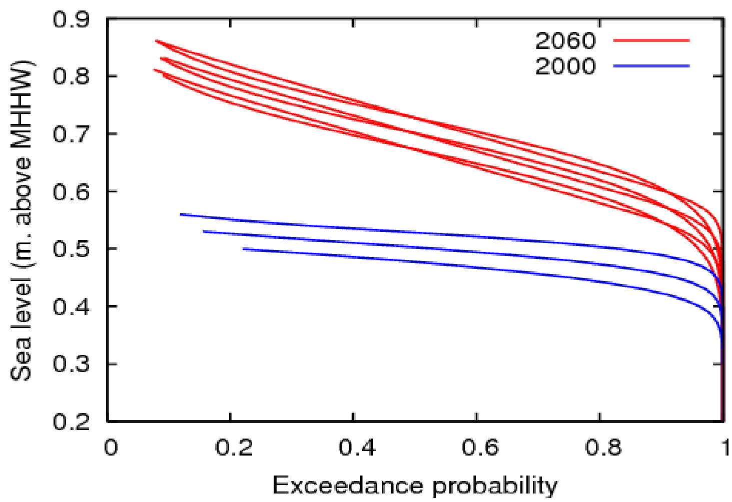

Figure 8. Exceedance probabilities for Burnie, Tasmania, 2060, scenario A1FI and asset life of 10 years (red; middle pair of curves are maximum likelihood values, outer pairs are 95-percentile confidence limits; each pair corresponds to approximating the projection uncertainty by normal and boxcar (uniform) distributions). Also shown are equivalent exceedance probabilities for 2000 (blue; middle curve is maximum likelihood value, outer curves are 95-percentile confidence limits).

[17] At other locations, Mean High Water Springs, or MHWS, may be a more appropriate reference level.

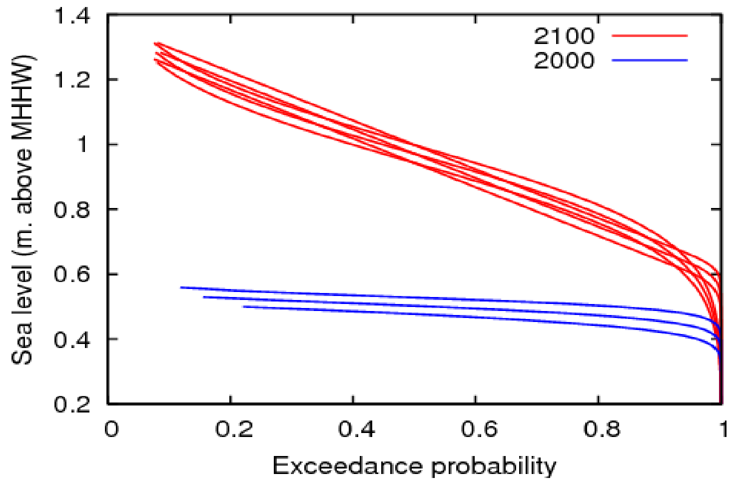

Figure 9. Exceedance probabilities for Burnie, Tasmania, 2100, scenario A1FI and asset life of 10 years (red; middle pair of curves are maximum likelihood values, outer pairs are 95-percentile confidence limits; each pair corresponds to approximating the projection uncertainty by normal and boxcar (uniform) distributions). Also shown are equivalent exceedance probabilities for 2000 (blue; middle curve is maximum likelihood value, outer curves are 95-percentile confidence limits).

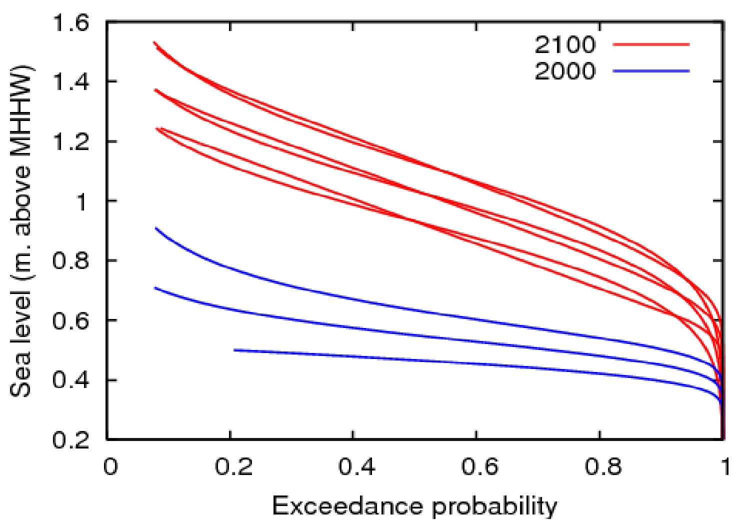

Figure 10. Exceedance probabilities for Hobart, Tasmania, 2100, scenario A1FI and asset life of 10 years (red; middle pair of curves are maximum likelihood values, outer pairs are 95-percentile confidence limits; each pair corresponds to approximating the projection uncertainty by normal and boxcar (uniform) distributions). Also shown are equivalent exceedance probabilities for 2000 (blue; middle curve is maximum likelihood value, outer curves are 95-percentile confidence limits).

An important consequence of the spreading of the exceedance distribution (caused by the uncertainty in the projections of sea-level rise) is that the amount by which design levels need to be raised depends on the chosen exceedance probability. Taking Burnie as an example, then if it is deemed that an appropriate risk of flooding a specific asset is 0.5 (i.e. 50%) in 10 years, then the design level should be raised by about 0.5 m from 2000 to 2100 (from about 0.5 m to 1.0 m above MHHW; Figure 9). However, if the desired risk of flooding is reduced to 0.1 (10%) in 10 years, then the design level should be raised by about 0.8 m from 2000 to 2100 (from about 0.5 m to 1.3 m above MHHW). In other words, the more "risk averse" the policy, the more the design level needs to be raised to account for sea-level rise and its associated uncertainty.

Another consequence of the uncertainty in projections of sea-level rise is that, as the uncertainty increases, the concept of a characteristic "return period" loses its meaning. The reason for this is that the analysis described above combines statistics of two inherently different types. The present exceedance distribution is essentially a *frequentist* description of the occurrence of extreme levels. For any given level, the average time between exceedances may be described by the *return period*, and the probability of exceedance is approximately equal to the *asset life* divided by the *return period* (so a longer asset life gives a higher probability of occurrence). However, the statistics describing the uncertainty of the sea-level projections are of a fundamentally different type, describing our lack of knowledge of the future rather than a fluctuation over time. The mean sea level at Burnie will be a single value in 2100, but at present we do not know it exactly what it will be. We therefore describe the future mean sea level by a best estimate and an uncertainty. While this uncertainty will reduce as we gain more knowledge, it is unaffected by the *asset life.* This field of statistics is called *Bayesian*. As an extreme case, if sea level had no variability other than a steady rise, then the concept of a return period would have no meaning at all. The sea level in 2100 (say) would be described solely by a best estimate and an uncertainty; it would be independent of the asset life.

It is proposed that future design levels for policy, planning and building purposes be based on analyses similar to those described above. It is no longer sufficient to rely solely on a derived return period. Instead, the design levels should be chosen from consideration of the probability that a given level will be exceeded during the lifetime of a structure or other asset (the asset life).

It should, however, be noted that presently available data is generally inadequate for the derivation of design levels corresponding to a reasonably low risk of flooding *even for the present time*. Standards Australia (2005; Table 5.4) gives useful guidelines concerning appropriate design criteria for coastal structures. For example, they suggest that "residential developments" of "high property value", having a working life of at least 100 years, should be designed for a 1 in 2000 (i.e. 0.05%) annual exceedance event. This implies an exceedance probability of about 5% for an asset life of 100 years. Unfortunately, most sea-level records for Australia are not much longer than 30 years in duration. Therefore, even after extrapolation to four times the record length (Pugh, 1996), the maximum return period that can be confidently estimated falls far short of the 2000 years which corresponds to the 1 in 2000 annual exceedance event. This problem may be alleviated, at least partially, using hydrodynamic modelling to extend the effective return period (e.g. McInnes et al., 2003) and by resorting to the precautionary principle (for example, by adding some further allowance to the derived design level).

The analysis described above satisfies what is probably the most common requirement for risk analysis; it yields an estimate of the probability that an undesirable occurrence (in this case, flooding) will occur *at least once* over the asset life. However, there are other possible situations, such as cases of where flooding is more a nuisance than a disaster, and where it would be permissible to allow flooding a certain number of times each year (e.g. a road that would have to be closed each time it flooded). In this case, the initial probability distribution (the equivalence of the blue curve in Figure 7) would describe the probability that flooding would occur either a given number of times, or *at least* a given number of times, over the asset life. This probability distribution may be derived directly from the return period for each level and from the properties of a Poisson distribution. The distributions shown in Figures 8 to 10 are just a special case of this more general analysis; they indicate the probability that flooding would occur *at least once*, over the asset life.

6. CONCLUSIONS

The Fourth Assessment Report (IPCC, 2007) 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. Even a mid-range rise of about 0.5 metres would lead to significant coastal inundation and increases in the frequency of high sea-level events.

In Australia, at Fremantle and 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. Without significant curbs on greenhouse emissions, sea-level rise during the 21st century will cause substantial changes to the Australian coastal environment, such that events which now occur once every few years will occur once every few days in 2100. 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; regions that are presently intertidal or even "dry land" will become permanently submerged.

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, using Australian data as an example. 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, as some specified time in the future.

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