Climate Change, Sea-Level Rise and the Vulnerability of Coastlines

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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 depopulation of entire islands. The bathymetry and topography of soft coastal margins (e.g. sandy shorelines) will be substantially changed. The concept of "mean sea level", as a surveyors' reference plane, will lose its meaning.

This paper draws heavily on the findings of the Third Assessment Report (the TAR; [1]) and of the Fourth Assessment Report (the AR4; [2]), published in 2001 and 2007, respectively, by the Intergovernmental Panel on Climate Change (IPCC).

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 ([2], 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 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.

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 [2], leading to warming of the oceans and melting of ice on land. The resulting global sea-level rise is shown in Figure 3. Church and White [7] 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 [9, 10], have indicated similar rates of rise during the 20th century.

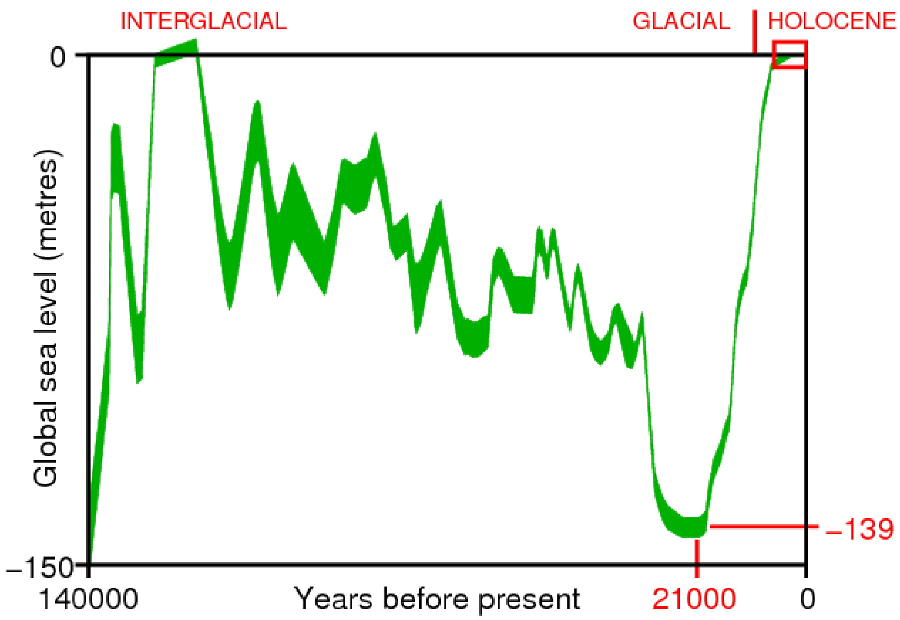

Figure 1. History of global sea level over the past glacial cycle. Thickness of green line represents uncertainty. Red rectangle indicates period shown in Figure 2. After [3]-[6].

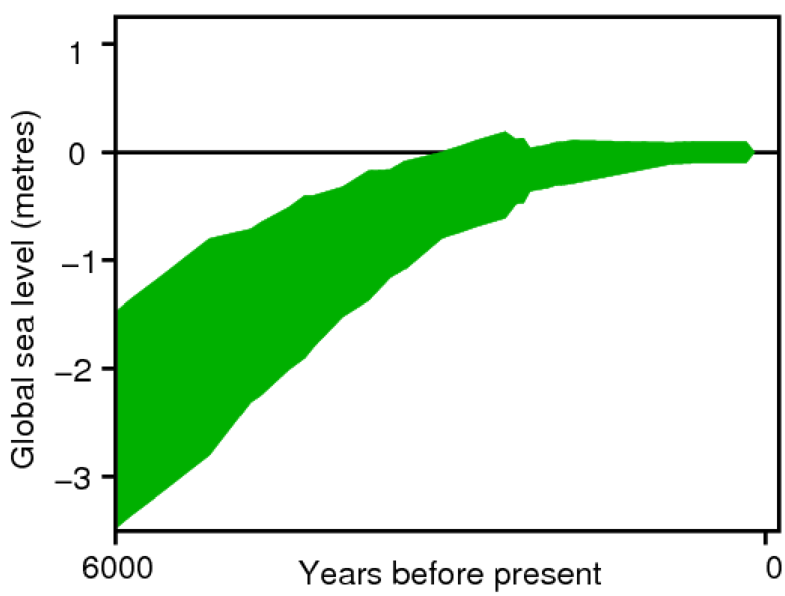

Figure 2. History of global sea level over the past 6000 years. Thickness of green line represents uncertainty. Record ends at about 1900. After [3]-[6].

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 [2]. The two largest and roughly comparable contributions are now thermal expansion and the melting of glaciers and ice caps (excluding Greenland and Antarctica, which are at present only making a smaller contribution) [2], although the exact contribution of thermal expansion is presently under review.

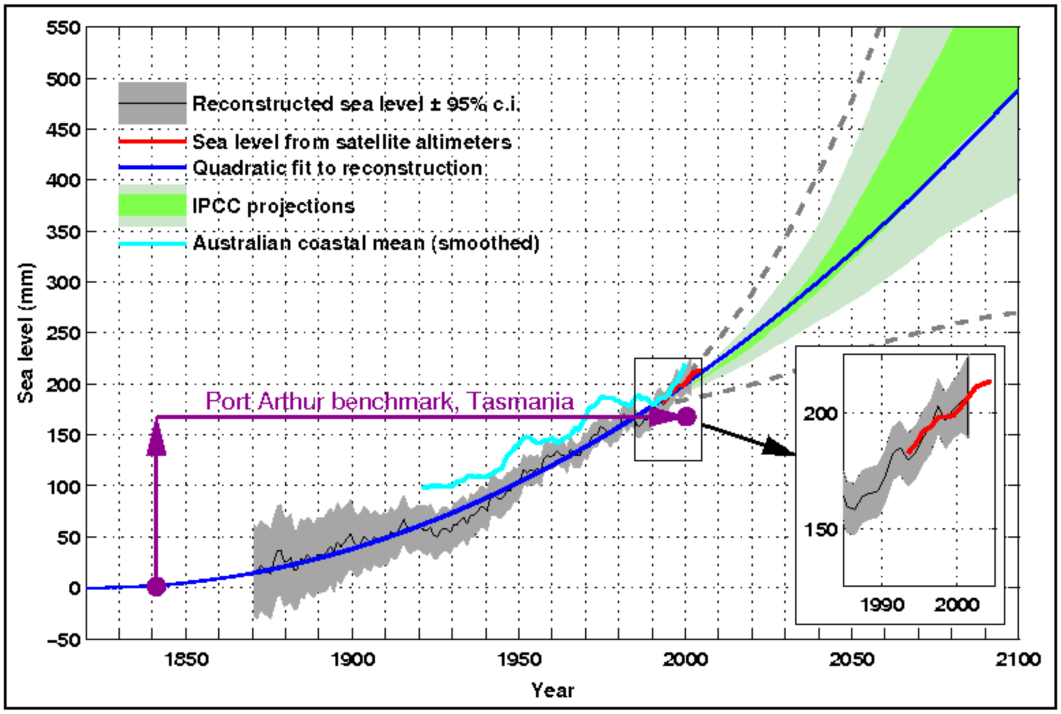

Figure 3. Sea-level reconstruction of Church and White [7] (black, with grey indicating ±95% confidence limits). Magenta dots and arrows indicate estimate of sea-level rise from 1842 to 2001 from Port Arthur, Tasmania [8]. Sea-level projections from IPCC Third Assessment Report [1] (outer dotted lines 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.

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 [2, 11]. The long tide-gauge records from the Australian ports of Fremantle and Fort Denison (Sydney) show (Figure 4 of this paper, [12]) that the return period[1] of flooding events that occur on annual to decadal time-scales

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

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.

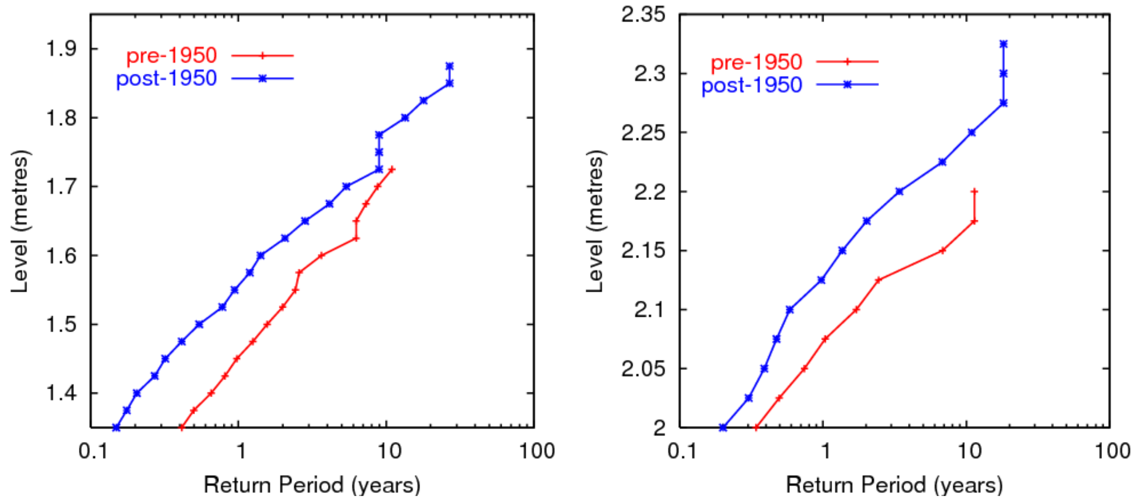

Figure 4. Change of return period for extreme high levels from pre-1950 to post-1950 conditions for Fremantle (left) and Fort Denison (right) [12]. Note that return periods are shown on a logarithmic scale on the horizontal axis.

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*[2], 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. Figure 5 shows projections of sea level relative to 1990[3] 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 lines represent the TAR [1] model projections of the minimum and maximum sea level for the B1 scenario, the vertical span indicating the "model" uncertainty. Similarly, the red lines represent the TAR model projections of the minimum and maximum projected sea level for the A1FI scenario. The magenta box shows the AR4 [2] model projections of the minimum and maximum sea level for the B1 and A1FI projections, respectively, over the period

[2] The main emission scenarios used for IPCC modelling are described in the Special Report on Emission Scenarios (SRES) [13].

[3] Strictly, the TAR related projections to 1990, while the AR4 related projections to the average over the period 1980 to 1999.

2090-2099[4]. 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).

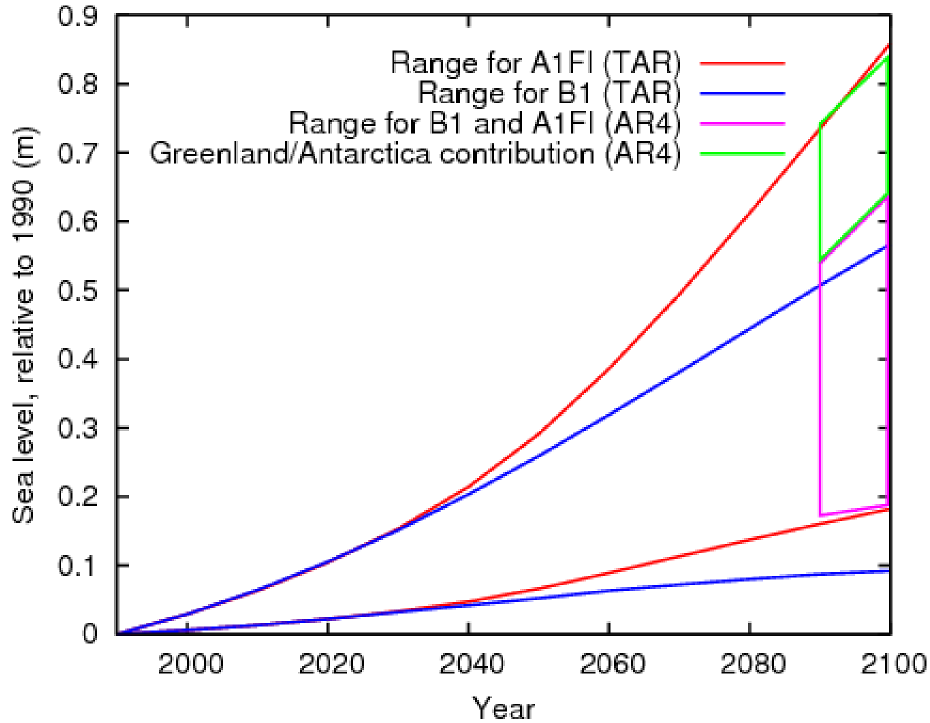

Figure 5. Projections of sea-level rise relative to 1990 from the IPCC Third Assessment Report (TAR; [1]) and the Fourth Assessment Report (AR4; [2]), for the B1 (low impact) and A1FI (high impact) scenarios.

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 [14] 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 [15]. Rahmstorf et al. [16] 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] 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. [17] showed that global greenhouse-gas emissions are now closely tracking 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 [1, 2]. If global temperatures are raised sufficiently, the Greenland ice sheet will reach a state where it will effectively shrink, possibly irreversibly[5]. It has been estimated ([2], Section 10.7.4.3, [18]) that this threshold will be reached when global temperatures are 2.3° C to 3.9° C [6] above pre-industrial levels, which is *likely*[7] 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 overlapped by the estimated *likely range*[8] of global temperature (1.9° C to 4.4° C) expected if the world ultimately equilibrates to a stabilised CO_2-equivalent greenhouse gas concentration of 550 ppm ([2], 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 [19] 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.

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 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 tidal records that are longer than 30 years. This multiplying factor has a range of 1.8

[5] Even if atmospheric greenhouse gas concentrations were reduced to preindustrial or present levels, the Greenland ice sheet may not be re-established [2].
[6] These limits are ± 1 standard deviation, which is almost equivalent to the “likely range” defined by the AR4 [2] (see footnote 8).
[7] The AR4 [2] defines "likely" as a better than 66% chance of occurrence.
[8] The “likely range” defined by the AR4 is assumed to represent 66% confidence limits.

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.

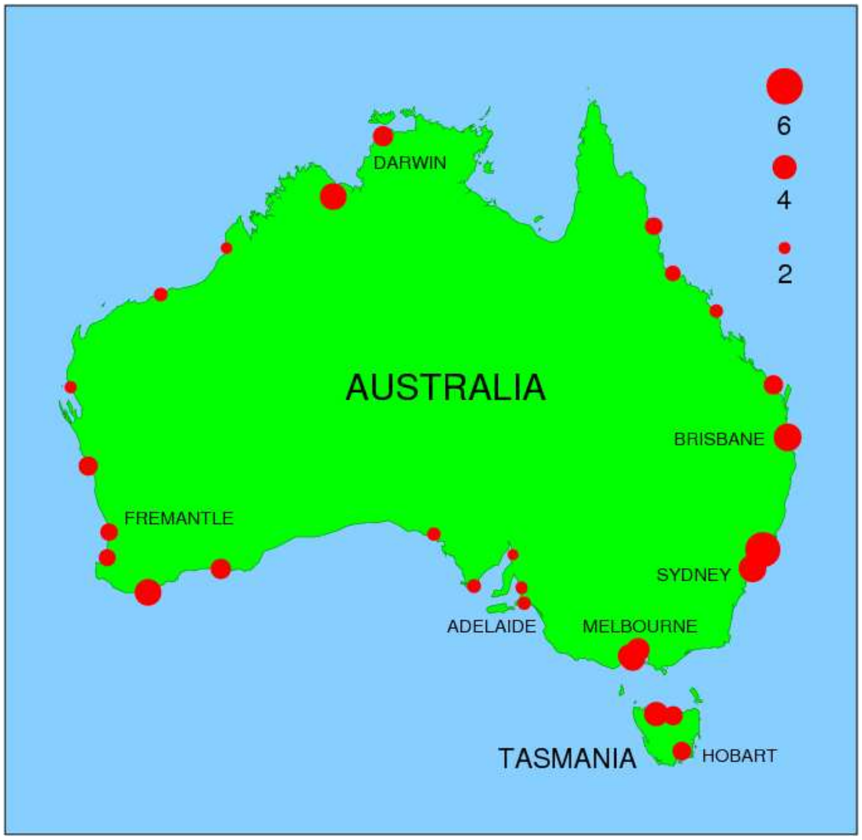

Figure 6. Estimated multiplying factor for the increase in the frequency of occurrence of high sea-level events (indicated by the diameter of the discs), caused by a sea-level rise of 0.1 m.

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 [20]. The process by which sea-level rise leads to this erosion may be approximately described by the Bruun Rule[9] [21], 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 estimates 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.

[9] The Bruun Rule is a very simplified approximation to the real world and has its detractors (e.g. [22, 23]). 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 [24].

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 [2] 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, increases in the frequency of high sea-level events and erosion of soft shorelines.

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. 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.

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