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# New approaches in sea-level research

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## Background

The current sea-level rise prediction estimates contained in the 2008 Ministry for the Environment guidelines, were based largely on the 4th IPCC report released in 2007. There is now a range of intriguing new research giving higher estimates and this article reviews these materials and considers their implication for coastal management and decision making. The first area of research involves detailed analyses of paleo-climatic records which contain information on ice sheet instability and sea-level change during past interglacial periods when temperatures became somewhat warmer than at present. The second is from a new generation of (semi-empirical) models that relate sea-level change to temperature change using century to millennial-scale calibration records.

The IPCC (2007) assessment produced estimates of sea-level rise that were strongly dominated by geophysical models focusing on the thermal expansion of sea water, and it was not possible at that stage to provide upper bounds for the rise this century due to uncertainty in the contribution from melting ice sheets. The IPCC (2007) estimate gave an additional ice sheet contribution (0.1 to 0.2 m) assuming that the difference between explained and observed 1993 to 2003 melt rates would increase linearly with global average temperature change over this century. However, new analysis of current causes of sea-level rise (Domingues et. al., 2009), show a greater contribution comes from glaciers and major ice sheet (about 50%) than was previously thought. Furthermore, satellite and airborne-based data indicate that ice mass loss from Greenland and West Antarctic mass, the major contributors, is accelerating (Cazenave and Llovel, 2010). Such situations provide the basis for the new approaches to future estimation of sea-level rise.

## Interglacial proxy evidence

It was noted in the IPCC (2007) that there had been increases in sea-level of up to 6 m due to reduction in ice sheets during the last warm period between ice ages (interglacial). Average temperatures were then more than 2°C warmer and that is comparable with what is now predicted for later this century. At the time of the IPCC (2007) assessment there was little published information on the rate at which sea level had previously responded to global warming on century time scales, so the longer-term estimate of 6 m could not be directly related to century-scale sea-level rise.

Significant paleo evidence from the previous warm period has come from high resolution oxygen isotopes from Red Sea cores (Rohling et. al., 2008). This investigation produced a record of sea-level for the period 124,000 to 119,000 yrs ago with sampling at about 300 yr intervals. These data show century scale rates of change in sea level between 0.6 m and 2.5 m with an average value of 1.6 m (see Figure 1 upper right panel). However, a recent study of kinematic constraints on glacial contributions to sea-level rise (Pfeffer et. al., 2008) concluded that increases above 2 m/century are untenable.

Dispite these paleo researchers taking due care, there are the inevitable issues surrounding proxy precision, i.e. the temperature indicator used to reconstruct past climates, and the issue of wider representation of their particular samples. Furthermore, these findings are not a straight analogy for the future as temperature increase is expected to be driven by greenhouse gases rather than variation in insolation due to changes in the Earth's orbit around the sun. Nonetheless, the results do quantify a potential range of sea-level change above the present level should major ice sheet collapse occur.

Other paleo studies provide some support for sea-level rise exceeding 1 m/century. An overview of past sea-level rise in response to global warming over the last 6 interglacial periods (see lower panel in Figure 1) by Berger (2008) concluded that there were several occasions when sea-level rise may have exceeded 1 m per century. Another study (Carlson et al., 2008) covers decay of the North American Ice Sheet during the present interglacial period (the Holocene) and suggests that a sea-level rise in excess of 1 m per century occurred during the onset of the present warm period when temperatures were generally higher than the present.

The upper left panel in Figure 1 depicts an east Australia example of a Holocene sea-level curve, in which the amplitude of the medium-term fluctuations ($10^3$ yrs) are dramatically less those from the previous interglacial example (NB upper right panel in Figure 1). We stress that while sea-level curves tend to be geographically specific, these data are at least suggestive that higher atmospheric temperatures may be associated with larger sea-level fluctuations and hence the increased likelihood of larger century-scaled sea-level rises.

The paleo-interglacial results are summarized in Table 1 and indicate century scale sea-level rise in excess of 1 m and perhaps as high as 1.5 m appear to be plausible. The present rate of sea-level rise is ~3mm/yr, so a linear increase up to 15mm/yr (1.5 m/century) over the next 100 years would result in a total sea-level rise of 0.89 m. However, the higher rate (1.5 m/100 yrs) could continue over subsequent centuries.

## Semi-empirical models

This approach uses statistical models based on observational data to establish the link between temperature and sea-level, and this relationship is extrapolated into the future to match the IPCC temperature predictions. These models are referred to as semi-empirical models and an example of such output is depicted in Figure 2.

Two sub-groups of semi-empirical models exist. The first by Rahmstorf (2007), Horton, (2008) and Vermeer and Rahmstorf (2009), use about 120 yrs of overlapping temperature and sea-level data and a two or three parameter model calibrated by using a least squares fitting routine. The latter study incorporates a second term that accounts for large and highly nonlinear ice discharges. The second group (Grinsted et al., 2010 and Jevrejeva et al., 2010) use more extensive observational data (1800 yrs) including paleo reconstruction plus more detailed mathematics with four parameters calibrated using an inverse Monte Carlo method. In addition, the latter study relates sea-level changes to change in natural and anthropogenic forcing. The resulting sea-level prediction ranges for the semi-empirical models out to 2010 are shown in Table 1, and it can be seen that they are about twice as high as the IPCC (2007) estimates shown at the base of the table.

Unlike the geophysical models used to predict sea-level rise in the IPCC (2007), the semi-empirical models combine and then extrapolate the effects of all sea-level rise contributors including dynamical ice sheet processes. As noted earlier, the linear assumption underlying the IPCC (2007) ice sheet contribution now appears to have been exceeded. In this regard, the semi-empirical models may provide more realistic sea-level projections. They are also more applicable than the century-scaled paleo predictions, because they can be more closely aligned with estimates for temperature rise over the present century.

However, there is a potentially serious limitation with the semi-empirical approaches in that they assume the historic relationship between temperature and sea-level will continue under future regimes which go beyond the model's calibration range. One potential problem relates to treating future temperatures as scenarios as this effectively decoupled temperature from the sea-level model so that possible feedbacks that sea level may have on temperature are not taken into account. For example, higher sea-level is likely to be associated with greater ice loss which may well influence global climate through albedo changes. While defining and quantifying such limitations is not presently possible, Grindsted (2010) showed that present day sea-level rise is dominated by a 200-300 yr response time to temperature, indicating that the historical relationship these models are based upon will likely prevail through the present century.

## Dealing with higher sea-level rise

How to implement an increasing range of sea-level rise estimates that include significant scientific uncertainty within decision-making is becoming increasingly important. The MfE (2008) recommends a risk-based approach which considers the acceptability of potential risk; this approach was described by Bell and Ramsay in an earlier issue (42) of Coastal News. Briefly, for each activity, the likelihood and magnitude of hazard consequences are assessed for different sea-level rise scenarios, together with potential adaptation costs - including those if sea-level rise, or other hazard driver effects, are underestimated.

The upper extreme would thus relate to major coastal infrastructure such as new highways, where economic losses and other consequences could be severe in the longer term, where there is minimal opportunity for subsequent adaptation, and where existing policy emphasizes hazard avoidance. In such cases there is virtually no allowance for failure and prudent planning is required with upper range sea-level rise estimates being appropriate, along with application of potential sea-level rise over a longer time-span.

At the other end of the coastal activity spectrum is an addition to an existing dwelling. In this case the worst consequence is destruction of that dwelling with only minimal chance of personal risk. The lower sea-level rise estimates would thus be appropriate for interim use (decades) or if hazard avoidance (relocation or removal) is viable.

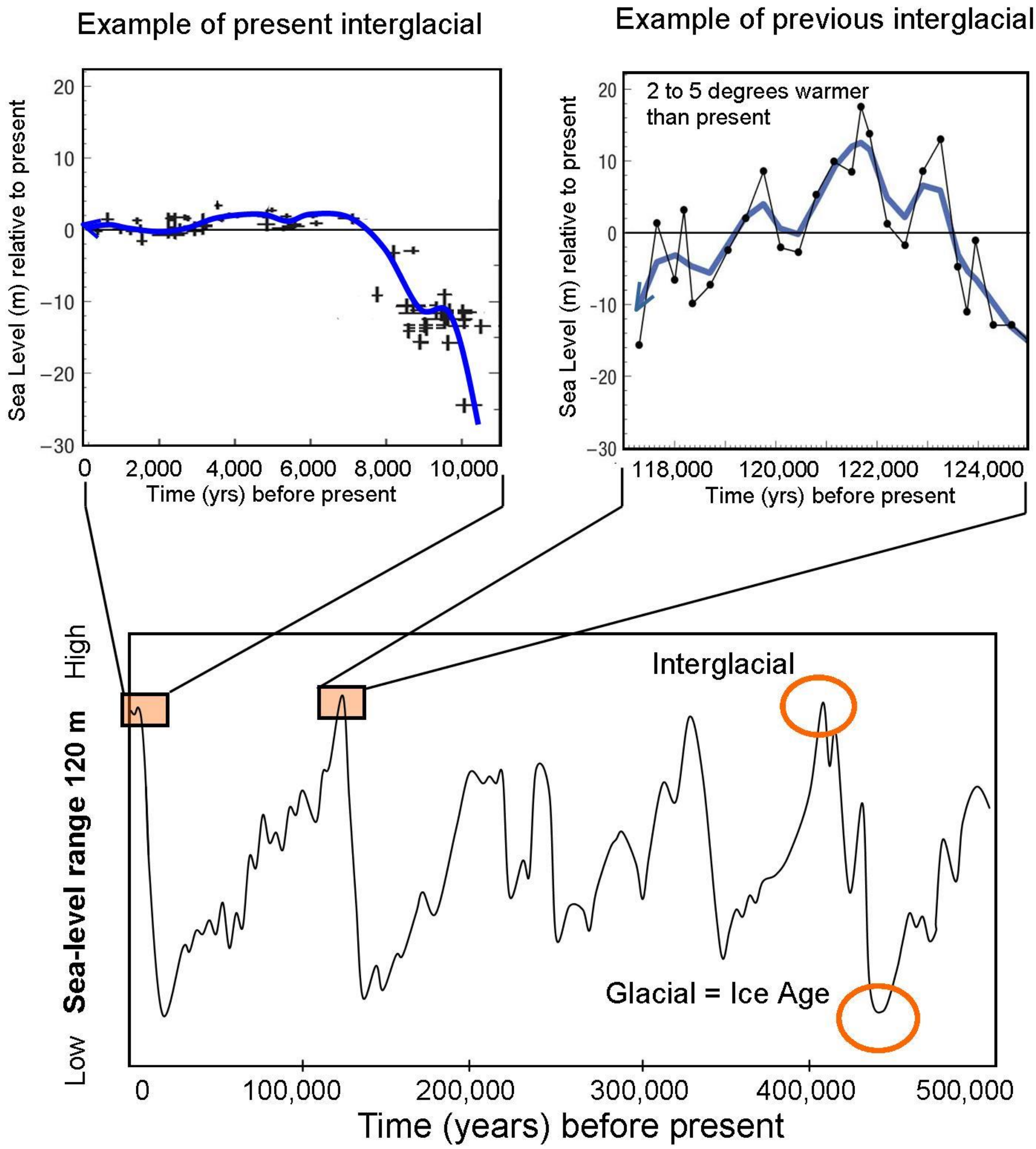


***Figure 1*** *Paleo sea-level curves. Lower graph shows an oxygen isotope-based sea-level record for the previous 500 kyr depicting 100 kyr glacial-interglacial fluctuations (adapted from Berger, 2008). Upper graphs illustrate contrasting "medium-term" sea-level fluctuations with graph on left depicting a higher resolution sea-level Holocene record from the Australian east coast (adapted from Milne et al., 2009), while graph on right shows a higher resolution record from the Red Sea for the previous interglacial (adapted from Rohling, 2008).*

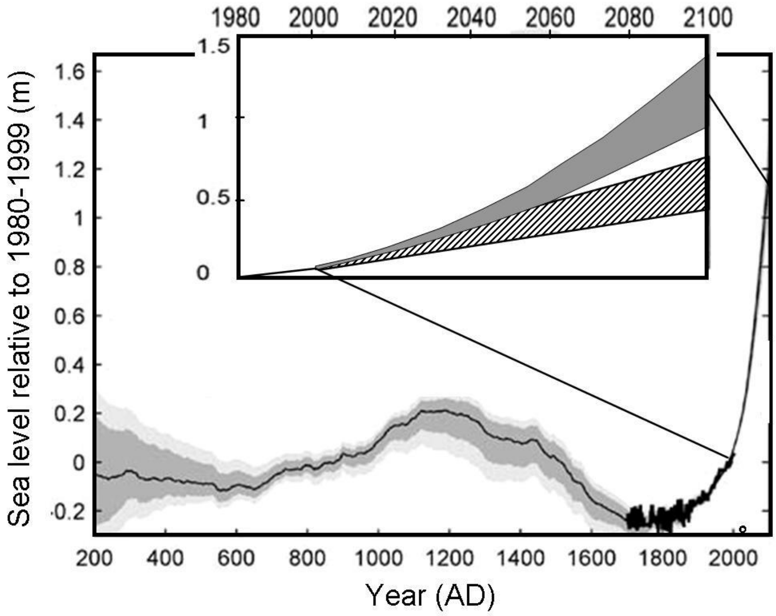


***Figure 2*** *An example of semi-empirical modelling using 1800 yrs of paleo-historical temperature-sea-level data with dark grey band defining ± one standard deviation about the median sea-level (bold line), and light grey band depicting 5-95 percentiles. Thick black line depicts 300 yrs of historical calibration data. Inset details the model projection with grey band depicting 5-95 percentiles. For comparison, diagonal infill band depicts a comparable range for the IPCC (2007) prediction. Adapted from Grinsted et al. (2010).*

***Table*** *Ranges of sea-level rise estimates from the studies described in the text.*

| MODELS | **Projected sea-level rise (m)**<br>0 0.5 1.0 1.5 2.0 |
|---|---|
| Century rates | |
| Berger (2008) | ←1.0-----------------------------------2.0 |
| Rohling (2008) | 0.6-----------------------------------------------→ 2.5 |
| Carlson (2009) | 0.7-------------------1.3 |
| | |
| Semi-empirical | |
| Rahmstorf (2007) | 0.5--------------------------------1.4 |
| Horton (2008) | 0.47------------------1.0 |
| Vermeer (2009) | 0.75--------------------------------------1.90 |
| Grinsted (2010) | 0.7-------------------------------1.6 |
| Jerejeva (2010) | 0.59-------------------------------------------1.80 |
| | |
| Present guidelines | |
| IPCC (2007) | 0.4-------------0.8 |
| MfE (2008) | 0.5---------0.8+ |

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