

Effects of climate change on extreme coastal sea levels



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Introduction

Contributions to changes in extreme sea level result from a number of components that have been studied extensively over recent years. In assessing the hazards to coastal communities it is important to understand the interactions between the different sea level contributions and their capacity for co-occurrence. Accurate estimates of extreme coastal sea level rise require knowledge of global mean sea level (MSL) changes (e.g. Church et al., 2001) and observed regional trends (Woodworth et al., 1999), regional land movements (Shennan, 1989) and changes to storm surge behaviour due to modified climatic winds resulting from increased levels in atmospheric carbon dioxide (Lowe et al., 2001). When considered alongside geological data on trends in land movement, UK tide gauge data suggest absolute sea level trends over the past century of approximately 1-1.5 mm/year. This value is consistent with, but at the lower end of, the range of uncertainty given in the IPCC Third Assessment Report (Church et al., 2001) which gives a range of sea level rise for the next 100 years of between 9cm and 88cm with a central value of 48cm. An important ancillary question is whether there is a more recent acceleration of sea level rise toward the latter half of the 19th century.

Tidal response to mean sea level

If mean sea level changes, and there is also a change in regional meteorology, then there will be changes in storm surge characteristics, tidal propagation, waves and consequently extreme water levels. These changes will impact on the environmental and socio-economic infrastructure at the coast. An increase in mean sea level will increase the tidal wavelength and modify the amphidromic system of any basin: at a given location tidal range could either increase or decrease, depending on the resonance properties of the region. Changes in MSL can also affect bottom friction and thus the dissipation of tidal energy.

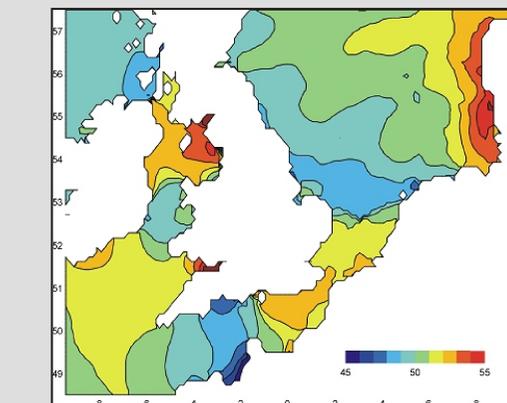


Fig 1. Change (cm) in mean tidal high water due to a 48cm rise in MSL

Fig. 1 shows the change in mean tidal high water due to a 48cm rise in MSL, computed using POL's 12km resolution barotropic tide-surge model. This shows higher mean high water in the eastern North Sea, probably because of reduced frictional dissipation. Increases in high water levels are seen in the Bristol Channel and Irish Sea since these areas are near resonance for the main semidiurnal constituent M_2 . It is important to note that the tidal response in Fig. 1 only varies by about 10cm - the larger part of the increase is the imposed change to MSL - but small changes in tidal phase may prove significant for surge behaviour in a future climate. Fig. 2. depicts an analysis of tide gauge data from Immingham on the east coast of the UK, where it is seen that whilst surges less than 0.5m (black) occur at most phases of the tide, larger surges (blue) represents those greater than 1.5m) occur most frequently four hours before or after high water. The tide-surge interaction that causes this behaviour is sensitive to small changes (as little as 0.01 of a cycle) in tidal phase, particularly for the largest surges. Any systematic adjustment to the frequency distribution in Fig. 2 (which is typical of UK ports in the North Sea) will affect the statistics of extreme tide-surge combinations and the subsequent calculation of return periods.

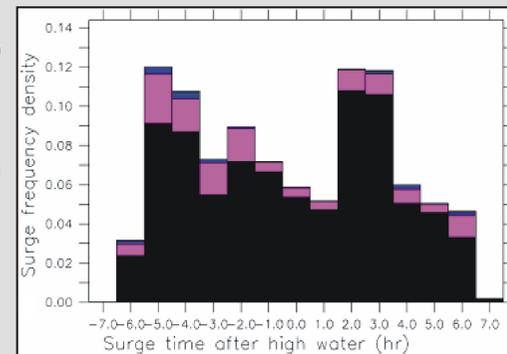


Fig 2. Normalised surge frequency with respect to time of high water for 70 years of data from Immingham on the UK east coast. The data represent 3037 discrete surges and the blue fraction represents those larger than 1.5m

Extreme surges in future climates

Increased water depth also affects the generation and response of the storm surge component to sea level. The surge climate will change further if the storm climate itself varies. Aspects of storminess that are thought to be relevant are the path of depressions, their intensity and frequency, their seasonal variability, and the mean strength of prevailing winds. The most important aspect of surge dynamics in shallow water is the direct influence of the winds giving rise to a momentum transfer that is inversely proportional to depth. An overall increase in water depth would modify the forcing such as to reduce typical surge elevations. However, this result could be outweighed by increased elevations due to future changes in storm intensity. Several studies have attempted to quantify future extremes of sea level by generating a long time series of meteorological data with atmospheric models based on assumed future levels of carbon dioxide (e.g. Lowe et al., 2001). In the numerical experiments performed here using POL's tide-surge model coupled to the Danish Meteorological Institute's climate model (May and Roeckner, 2001), two 30 year timeslices are simulated; a control run representing present day

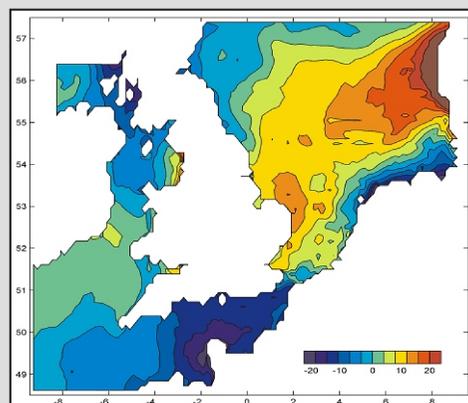


Fig. 3. Change (cm) in 50-year return period surges (2070-present day) computed with a 12km grid model

values are then compared. The contours in Fig. 3 show the difference in the 50-year surge elevation (S50) that might be expected for the year 2070 in a twice CO_2 scenario. These results suggest that S50 may increase along the Norwegian coast, and along the eastern UK, but may decrease in the English Channel.

To illustrate one possibility of future extreme sea level we can combine the tidal and surge effects discussed above with a medium IPCC sea level rise of 48cm to arrive at the extreme level distribution shown in Fig. 4. This illustrates the change in extreme sea level (cm) relative to the land for 2070, and values range from +10cm to +80cm. The distributions are a combination of several components, each of which has a large uncertainty associated with it, but are representative of the usefulness of modelling techniques.

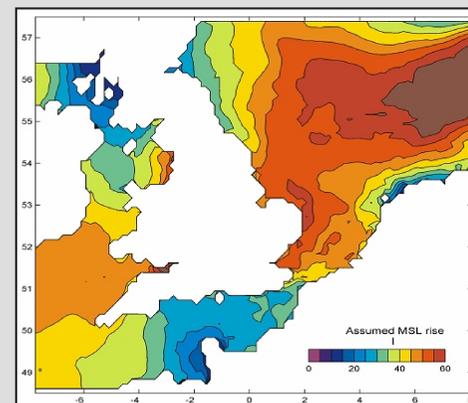


Fig. 4. Model estimate of extreme water level around the UK for the year 2070, incorporating predictions of MSL, mean high water and S50

Discussion

Results from model studies such as this must be interpreted with care. The control (present day) meteorology must accurately portray the storm climate of the control timeslice. Furthermore, the predicted changes in future surge extremes (S50) must be significant compared to natural variability over the 30 year runs, and must be related specifically to the future scenario. Since return period is a statistical derivation, one must ensure that the same increased value cannot be obtained simply by re-sampling the control data in a different way. Surges tend to be underestimated in climate models due to the coarse resolution in both space and time. The latest generation of climate models (e.g. Hadley Centre HaDCM3) offer improved surge representation on a shelf sea scale. Application of extreme value statistical methods to spatial modern domains can also be problematical since different techniques within the field of extreme value analysis (see, for instance, Dixon and Tawn, 1997) can yield different results for the same model run as can be seen in Fig. 5.

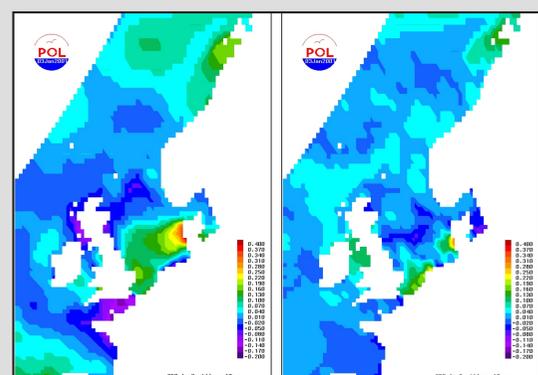


Fig 5. Difference (2070-present day) in S50 for a twice CO_2 scenario using GEV (left) and Gumbel (right) distributions

Quantifying the natural variability from long model runs is difficult, since an analysis of several subsets does not provide statistical independence. Despite these limitations, models like these are very useful for providing a likely future envelope against which engineers and planners can work. Prototype

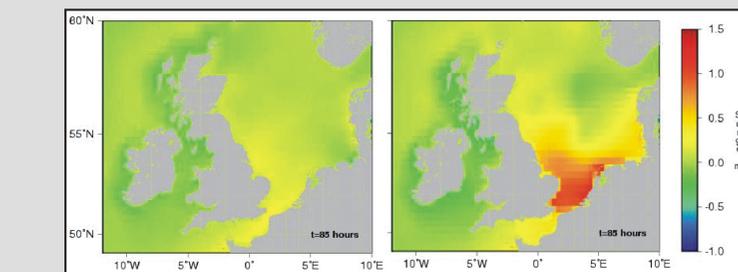


Fig. 6. Surge elevation (m) from two of a 24 member ensemble run

ensemble meteorological-surge forecast models are now being developed by POL and the UK Met Office, and Fig. 6 indicates the surge contours from two members of an initial condition ensemble set, highlighting the scope for uncertainty. Fig. 7 shows the surge height at Sheerness in the Thames estuary from five members of the ensemble. The spread of values allows a statistical determination of likelihood, and research is directed at identifying useful diagnostic variables to distinguish the more likely forecast trajectories. Recent computational improvements allow higher spatial resolution of both the shelf-wide surge models and the forcing climate models. Work is underway to repeat these analyses using the latest knowledge of relative, regional sea level with future sea level statistics derived from new climate model runs and including the effects of surface wind waves.

Wave heights in the North Atlantic, as seen in altimeter and direct measurements, have increased over the past 25 years where monthly means have increased by approximately 0.5m. Prediction of future impacts requires an understanding of the variability of wave properties over decadal timescales and their future evolution (e.g. Wolf and Woolf, 2005).

Quantification of the inherent uncertainties will be provided by the use of 17 member ensembles of the HadRM3 regional climate model runs provided by the Hadley Centre as a dataset from the UK Climate Impacts Programme (UKCIPnext).

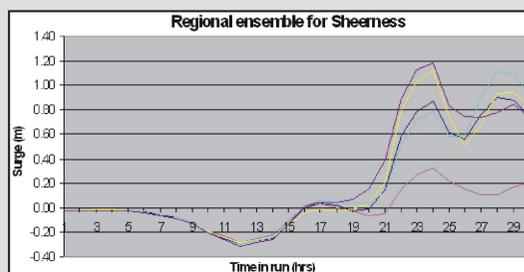


Fig. 7. Time series of surge development at Sheerness (Thames estuary) from five members of a 24 member ensemble run forced by regional meteorology

Final remarks

Sea level is a robust indicator of climate change and there is a need for high quality datasets maintained over very long timescales. For maximum utility, sea level measurements must be complemented by the most accurate observations of land movement. In order to interpret the long term sea level rise, we must better understand the seasonal and inter-annual variability of the signal. Numerical models can play a valuable role in removing noise from the MSL signal, and can also be used for predicting the combined impacts of MSL rise, tidal extremes and surges on vulnerable coastlines. Since the integrated effects of climate change are regional, we can use regional climate models coupled to ocean models and wave models to increase understanding and to assist policy makers. In this manner, future envelopes of extreme sea level can be estimated from model projections by combining contributions from MSL, tide, storm surge and land movement. It is important to appreciate that each component has a large uncertainty whose quantification remains a challenge.

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