SEA-LEVEL CHANGE
Living with uncertainty

Willem P. de Lange and Robert M. Carter

Foreword by Professor Vincent Courtillot

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Foreword

By Professor Vincent Courtillot

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Sea level change is a naturally occurring process. Since the last glacial maximum, some 18,000 years ago, de-glaciation has taken place and this natural global warming has led to sea-level rise of on average 120 m or so. At some times, pulses of melt water coming from large peri-glacial lakes led to rates of sea-level rise as high as 3 m per century. The rate slowed down some 7000 years ago and since then has been naturally fluctuating by only a few meters. The remaining global sea-level rise has been about 20 cm in the 20th century. Has this led to global disasters? The answer is no. If the projected rise over the 21st century is double what was seen in the 20th, is it likely that it will result in global disasters? Again, the answer is most likely no; human ingenuity, innovation and engineering, and the proper material and financial resources should solve local problems if and when they arrive, as they have in the 20th century (see the Dutch example).

In this short and accessible monograph, Willem de Lange and Robert Carter describe and explain sea-level change, including the many remaining uncertainties in our full understanding of what exactly drives this change, and discuss the implications, mainly regarding coastal management. The monograph is intended for policy makers, but it should be informative for any educated reader. De Lange and Carter analyse the causes of sea-level change, and describe how it has been measured – with tide gauges over the past 100 to 150 years and from satellites over the past 30 years. Their key message is to recall that sea-level change is a *local* phenomenon, with high variability and multiple causes. In the 20th century, for a global average rise of 20 cm, there has been sea-level rise of up to twice that value in some places, but in others a drop of the same amount! Because of the melting of a large former ice cap over the Baltic area, the Earth's viscous mantle is slowly deforming and as a result sea-level is decreasing in the North of the British Isles at the same time as it is rising on the south coast. Moreover, we have known since Darwin and understood since the plate tectonics revolution that atolls in the Pacific form over slowly subsiding volcanoes and will eventually drown (but at a slower 'geological' rate, due to thermal subsidence of the lithosphere on which they stand). In any case, the global average has no practical value in local or regional coastal management.

And the global average rates are debated. The rate indicated by tide gauges over a 100 year period is about 2 mm per year; but the rate indicated by satellites over the past 30 years is about 3 mm per year. Is this apparent acceleration real? It is always slightly worrying to see a change in rate at the time of a major change in measurement method. If one looks carefully at the various curves, one finds that sea-level varies on many time scales, from a few years to a century and probably much more. Measured over only a decade, the rate changes. The recent apparent acceleration may simply be part of a shorter oscillation linked to decadal and multi-decadal changes in the Pacific and North Atlantic oscillations. In that case, the average over 100 years is more significant than that over a few recent decades: the 'least unreasonable' forecast for the 21st century would be the same value as in the 20th century: a rise of 20 cm. This is actually, as recalled by de Lange and Carter, at the lower end of the range of the IPCC's forecasts. And, as suggested above, even a rate twice as fast would be unlikely to lead to unmanageable global disasters. If a correlation with global temperature curves is sought (global temperatures raise at least as many questions as sea-level: the rise over the past 100 years is very likely but very small, fluctuations occur on decadal to multi-decadal time scales and there is an apparent plateau or standstill since the mid 1990s), the recent plateau might suggest that sea-level rise will slow down. The question is the unknown time-delay between temperature change and ice-melting, deeper ocean water warming or ocean thermal expansion. The occurrence of a succession of 30-year periods of successively slower and faster warming (hence the existence of a 60 year periodicity of as yet unknown origin – possibly due to changes in solar activity or position due to gravitational effects from Jupiter and Saturn) would lead to the (empirical) forecast of no temperature change and slower sea-level change over the next one or two decades. After that who knows? The average warming of the 20th century could be extrapolated, but no prediction beyond, say, a decade is reasonably certain. A recent paper by my colleague Anny Cazenave and co-authors (Nature Climate Change, 2014) finds that:

> Since the early 1990s, sea level rose at a mean rate of ~3.1 mm yr^{-1}. However, over the last decade a slowdown of this rate, of about 30%, has been recorded. It coincides with a plateau in Earth's mean surface temperature evolution, known as the recent pause in warming.

Although the authors interpret this otherwise (Anny Cazenave knows we disagree on this), one may propose that the simplest conclusion is that indeed decadal fluctuations occur and that this recent deceleration cancels the previous acceleration and confirms that the mean rate over the 20th century still applies. But this discussion of global data, as emphasized by de Lange and Carter, may not be of much practical use, as they clearly show that 'for environmental management purposes sea-level change should be assessed at local to regional scales, and not globally'. They conclude that 'The one certainty is that future sea-level will continue to change at differing rates and in different directions at locations around the world, as it always has in the past'.

De Lange and Carter finally discuss the interesting practical policy example of the Thames Estuary 2100 Plan, which they suggest is as 'an excellent template for application'. In order to suggest what the best policy outcome may be, they underline the large uncertainty in our understanding of such complex natural processes and as a result in any forecast. They rightly point out the absurdity of following the (hard version of the) precautionary principle and conclude that 'the appropriate policy should be one of careful preparation for, and adaptation to, hazardous events as and when they occur'. This is also true for earthquakes, tsunamis or volcanic eruptions, i.e. most natural hazards. As a French citizen, I remain appalled that this principle was introduced in our Constitution! Whereas the concepts of precaution should be taught at a young age in both family and schools, I do not see how a constitutional judge would find rational bases for deciding that someone failed to follow the principle in all cases of 'lack of full scientific certainty'. The final recommendations of de Lange and Carter are in my view scientifically sound and based on common good sense, which can be as secure as trusting too much the outputs of huge, complex, uncertain computer models.

Vincent Courtillot
Paris, March 2014

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About the authors

Willem de Lange

Willem de Lange is a coastal oceanographer with a background in numerical modelling and coastal hazard assessment and mitigation. He studied computer science, earth science and geochemistry at the University of Waikato, New Zealand, and was a founding member of the Coastal Marine Group, an interdisciplinary research team investigating a range of coastal issues. He has been an expert witness for the High Court and Environment Court, dealing with the impacts of sea level rise and coastal hazards, for more than 30 years. In the 1990s he was involved with the IPCC Second Assessment Report and prepared climate change impact assessments for the New Zealand Government. More recently he co-wrote a chapter in the second NIPCC assessment report.

Robert (Bob) Carter

Bob Carter is a geologist and environmental scientist with degrees from the Universities of Otago and Cambridge. Since 1981 he has been based in Townsville, Australia where he was Professor and Head of the Geology Department at James Cook University until 1999. His research concentrated on marine geology, including studies of the history of the Great Barrier Reef, sea-level change and the oceanographic and climatic history of the south-west Pacific Ocean. He has held a variety of senior management and administrative posts, including Chairman of the Australian Marine Science and Technology Advisory Committee, member of the Australian Research Council and chair of its Earth Sciences Panel, and Director of the Australian Office of Ocean Drilling Program. Carter is an Honorary Fellow of the Royal Society of New Zealand and an Emeritus Fellow of the Institute of Public Affairs.

Summary

1. Global sea-level corresponds to a notional world-wide average and is determined by the interaction between the volume of the ocean basins, the volume of water that they contain and the effect of Earth's gravitational field.

2. Change in global sea-level is caused by:

   - a change in ocean basin volume, controlled by geological forces
   - a change in seawater density, resulting from variations in ocean temperature or salinity;
   - the addition or subtraction of water from the ocean by the melting and freezing of glaciers and ice-caps.

   Global sea-level is estimated using averaged measurements from a worldwide network of coastal tide-gauges or from satellite-borne instruments. Because they represent a worldwide average, neither of these figures has any useful application to coastal management in specific locations. Instead, a knowledge of local relative sea-level change, as measured at specific coastal locations, is the basis for practical coastal management. Local sea-levels are rising or falling in different parts of the world, depending upon the direction and rate of movement of the underlying land (tectonic change).

3. Sea-level change is mainly a coastal management issue, but the position of sea-level is only one of several important factors that controls the position and changes in the disposition of the shoreline. Other important forces and controls that have to be considered include:

   - the rise or fall of the land
   - the supply of sediment
   - the weather and climate (short and long-term temperature, wind, rainfall)
   - the oceans (waves, tides, storms, tsunami)
   - erosion and gravitational collapse (for cliffed shorelines).

4. In its natural state, a sedimentary shoreline may shift landwards or seawards by metres to many tens of metres over periods between days and decades. In the past, coastal inhabitants have adapted to such changes, and trying to prevent them by controlling the amount of carbon dioxide in the atmosphere is neither practical nor cost-effective.

5. Coral atolls depend upon the interaction of a shallow ocean seafloor (generally the top of a submerging volcano), the growth and erosion of a coral reef, and the natural forces of winds, waves and tides. The integrity of an atoll is constantly under threat from entirely natural erosive forces. On top of this, human activities such as sand mining, construction project loading and groundwater withdrawal all cause local lowering of the ground surface, and thereby encourage marine incursion. It

is this human interference, in combination with episodic natural hazards like tides and storms, and not global sea-level change that provides the alarming footage of marine flooding on atolls that from time to time appears on television news screens.

6. Changes in sea-level over long periods of time (millions of years) are inferred from geological evidence. These long-term changes suggest that any sea-level rises in response to temperature increases decelerate rather than accelerate over time. Such changes also indicate a maximum rate and duration of natural sea-level rise of about 30 mm/y over periods of a century or so.

7. Based on these geological studies, it appears that slow *global sea-level rise* – typically less than 10 mm/y – has been taking place over the last 10,000 y. At specific localities, this rising trend interacts with changing land levels due to a range of geological processes and multi-decadal climatic oscillations to produce different patterns of *local relative sea-level change* throughout the world – in some places rising, in others static and in others falling.

8. The long-term tide-gauge data record a 20th century average global sea-level rise of about +1–2 mm/y. It is established by many studies, too, that over the last 150 years global sea-level has been rising at an average rate of about 1.8 mm/y, which is inferred to represent the slow continuation of a melting of the ice sheets that began about 17,000 years ago.

9. Based on the same records, the IPCC has estimated an average rate of global rise between 1900 and 2000 of 1.6 mm/y (2007; 4th Assessment Report) or between 1901 and 2010 of 1.7±0.2 mm/y (2013; 5th Assessment Report). This global average ignores both short-term and multi-decadal changes in sea-level that are known to be associated with meteorological and oceanographic oscillations, and the local and regional effects of land movement. These additional factors are likely to continue to be important for future sea levels, and so should be considered in conjunction with projections of global sea level. The dominance of such processes in sea-level change means that for environmental management purposes sea-level changes should be assessed at local to regional scales, and not globally.

10. Satellite measurements of global sea-level have only been available since 1992, and the technology is therefore in its infancy. Complex computation and statistical analysis is required to transform raw satellite measurements into a sea-level curve, including the correction and piecing together of records collected over many years by ageing, and ultimately different, satellite vehicles. In recent years, it has been claimed on the basis of satellite measurements that the rate of sea-level rise since 1992 is greater than 3 mm/y – twice that measured using tide-gauge data for earlier periods, although the IPCC's 5th Assessment Report considers it likely that similar rates occurred between 1930 and 1950. This apples-to-oranges comparison has formed the basis of claims that the rate of rise is accelerating, as required by the global warming hypothesis.

11. Most policy discussions regarding sea-level change are conducted in terms of computer modelled projections, rather than of factual information. In its 4th Assessment

Report in 2007, the IPCC used physics-based computer simulations of the Earth and its climate to project a rise of sea-level of between 18 and 59 cm by 2100. The bottom end of this range corresponds with the 18-cm rise in sea-level predicted by empirical models and matches the long-term tide-gauge rate of rise of 1.8 mm/y.

12. Semi-empirical models produce the highest and most alarming estimates of rates of future sea-level change so far published (between 0.8 and 1.8 m by 2100). Strong controversy exists over the likely accuracy and policy usefulness of these results. Given that both empirical and deterministic modelling yield more modest projections of future sea-level, the semi-empirical models can at best only be viewed as a work in progress.

13. The IPCC estimates that 1.1 mm of the 20th century sea-level rise of 1.8 mm/y can be accounted for by the combined effects of continuing ice melt (~0.7 mm/y) and ocean expansion due to warming (~0.4 mm/y), with the remaining ~0.7 mm/y relating to dynamic oceanographic and meteorological factors. The relatively small contribution from melt water indicates that there is no scientific basis for the claim that global warming will imminently melt so much ice that sea levels will rise dramatically; by 20 ft in the imagination of Al Gore (Gore, 2006) or by 5 m in that of Jim Hansen (Hansen, 2007; Hansen and Sato, 2012).

Conclusions

Current global sea-level policy, supported by many governments, is to reduce the quantity of carbon dioxide in the atmosphere in order to slow a global warming that is apparently no longer happening, in a vain attempt to reduce the rate of global sea-level rise. This policy attempts to moderate a theoretical environmental variable, ignores local sea-level and coastal management realities, is ineffectual in significantly reducing sea-level rise and is not cost effective compared to incremental adaptation.

Global sea-level policy as currently practiced by governments is therefore scientifically uncertain and both financially and politically unsustainable.

Policy recommendations

Based on the material presented in this paper we recommend the implementation of three policy guidelines.

- Abandonment of 'let's stop global sea-level rise' policies: No justification exists for continuing to base sea-level policy and coastal management regulation upon the outcomes of speculative deterministic or semi-empirical sea-level modelling. Even were the rate of global sea-level change able to be known accurately, the practice of using a notional global rate of change to manage specific coastal locations worldwide is irrational, and should be abandoned.

- Recognition of the local or regional nature of coastal hazard: Most coastal hazard is intrinsically local in nature. Other than periodic tsunami and exceptional storms, it is the regular and repetitive local processes of wind, waves, tides and sediment supply that fashion the location and shape of the shorelines of the world. Yes, local relative sea-level is an important determinant, but in some localities that is rising and in others falling. Accordingly, there is no 'one size fits all' sea-level curve or policy that can be applied. Crucially, coastal hazard needs to be managed in the context of regional and local knowledge, using data gathered by site-specific tide-gauges and other relevant instrumentation.

- Use of planning controls that are flexible and adaptive in nature: Many planning regulations already recognize the dynamic nature of shorelines, for example by applying minimum building setback distances or heights from the tidemark. In addition, engineering solutions (groynes, breakwaters, sea-defence walls) are often used in attempts to stabilize a shoreline. To the degree that they are both effective and environmentally acceptable, such solutions should be encouraged. Nevertheless, occasional damage will continue to be imposed from time to time by large storms or other unusual natural events, and that no matter how excellent the pre-existing coastal engineering and planning controls may be. In these circumstances, the appropriate policy should be one of careful preparation for, and adaptation to, hazardous events as and when they occur.

It is the height of folly, and waste of money, to attempt to 'control' the size or frequency of damaging natural events by expecting that reductions in human carbon dioxide emissions will moderate climate 'favourably' – whether that be putatively sought from a moderation in the frequency and intensity of damaging natural events or by a reduction in the rate of global average sea-level rise itself.

1 Introduction

Sea-level rise is one of the most feared impacts of any future global warming (Nicholls, 2011), but public discussion of the problem is beset by poor data, misleading analysis and an over-reliance on computer model projections. This has led to unnecessary alarm.

A proper understanding of the risks associated with sea-level change can only be attained by maintaining a clear distinction between *global* (or eustatic) sea-level and *local relative* sea-level. Sea-level changes are measured against a reference level (the geoid[1]) that is difficult to define over regional and global scales, because contrary to popular belief the Earth's surface is not static.

This briefing paper provides a summary of these complex issues at a level suitable for policymakers. A fuller and more technical explanation is provided by de Lange and Carter (2013).

Global sea-level change

Global sea-level change is measured relative to an idealised reference level, and is a function of the volume of the ocean basins and the volume of water that they contain. Global changes are brought about by three main mechanisms:

- changes in ocean basin volume caused by tectonic and sedimentary processes
- changes in seawater density caused by variations in ocean temperature or salinity
- changes in the volume of water caused by the melting or freezing of glaciers and ice-caps

Ocean basin volume changes occur too slowly to be significant over human lifetimes and it is therefore the other two mechanisms that drive contemporary concerns about sea-level rise.

Warming temperature in itself is only a minor factor contributing to global sea-level rise, because seawater has a relatively small coefficient of expansion and because, over the timescales of interest, any warming is largely confined to the upper few hundred metres of the ocean surface.

The melting of land ice – including both mountain glaciers and the ice sheets of Greenland and Antarctica – is a more significant driver of global sea-level rise. For example, during the glacial–interglacial climatic cycling over the last half-million years, glacial sea-levels were about 120 m lower than the modern shoreline (e.g. Lambeck and Nakada, 1990). Moreover, during the most recent interglacial, about 120,000 years ago, global temperature was warmer than today as a result of enhanced seasonality, and significant extra parts of the Greenland ice sheet melted. As a consequence, global

[1] The geoid is defined as the equipotential surface of the Earth's gravity field which best fits, in a least squares sense, global mean sea level (http://www.ngs.noaa.gov/GEOID/geoid_def.html). This illustrates one of the difficulties with measuring global sea level changes, which is that the reference level is in itself a function of the parameter being measured.

sea-level was several metres higher than today (see e.g. Murray Wallace and Belperio, 1991).

As explained in more detail in Section 3, tide-gauge measurements indicate that global sea-level has been rising at a rate of about 1.8 mm/y for the last 100 years,[2] whereas the shorter satellite record suggests a rise of more than 3 mm/y. However, a recent reanalysis of the satellite data, alongside the possible contributions from recent warming and ice-melt estimates, has given a rise of 1.3 ± 0.9 mm/y for 2005–2011, which is more consistent with the tide-gauge measurements (Leuliette, 2012).

Around the world, significant regional variations occur in the rate and direction of sea-level change; while some regions of the world's oceans are today rising faster than hitherto, in other regions sea-level fall is occurring. In part this is due to variations in the rate of warming and salinity changes between different regions, and proximity to discharges of meltwater. Mostly it reflects the influence of major ocean circulation systems that redistribute heat and mass through the oceans. The upshot of these processes is that at any location around or within the oceans, the observed sea-level behaviour can differ significantly from the smoothed global average. Furthermore, when attempts are made to estimate global sea-level from studies at specific locations, it is found to constantly vary through time. For example a recent study in the Kattegat Sea estimates that, after correction for local tectonic and other effects, rates of 'eustatic' sea-level change since 5,000 years ago have varied through time by between -3.1 mm/y and +3.7 mm/y (Hansen, 2014).

Conclusion

Because they represent a worldwide average, neither the tide-gauge nor the satellite estimates of global sea-level have any useful application per se to coastal management in specific locations.

Local sea-level change

Local relative sea-level is measured at specific coastal locations. The measurements are therefore affected by the local movement up or down of the land as well as by the notional global sea-level. Local sea-level change therefore occurs at greatly different rates and directions at different locations (Figure 1). In some locations the land is rising: for example, places that were depressed under the weight of the ice caps 20,000 years ago started to rise again as the ice melted.[3] In consequence, in Scandinavia for example, the land is rising at rates of up to 9 mm/year, and local relative sea-level is therefore now falling through time despite the concurrent slow long-term rise in global sea-level.

[2] Credible estimates of this value range between about 1.0 and 2.0 mm/y. For the purposes of this paper we have accepted the estimate in the IPCC's Third Assessment Report (2001), which is that 20th century sea-level rise occurred at a rate of 1.8 mm/y, partitioned as 0.4 mm/y for thermal expansion, 0.7 mm/y for ice melt and 0.7 mm/y for dynamic oceanographic factors.

[3] The process is called isostasy, and is caused by slow adjustment flowage at depth in response to the addition or removal of loads at the Earth's surface. The compensating flows occur in a hot, semi-plastic layer of the mantle (the athenosphere) at depths of 70–250 km, just below Earth's rigid outer shell (lithosphere).

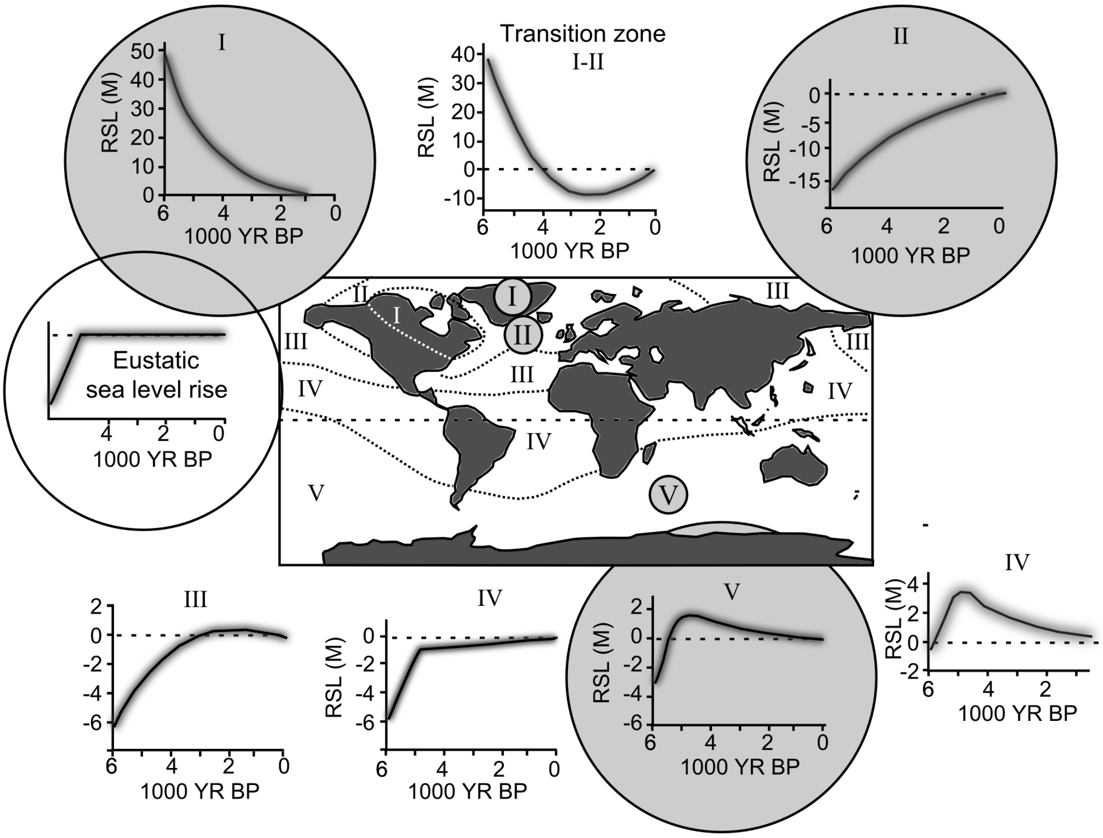

Figure 1: Local relative sea-level curves for the last 6000 years, modelled to include hydro-isostatic and glacio-isostatic effects combined with an idealised eustatic curve (after Clark and Lingle, 1979). Note the widely varying patterns of sea-level change at different places around the world, caused by deep-seated plastic flow in response to changing surface loads of ice and water.

Conversely, at locations distant from polar ice caps, such as Australia, no such glacial rebound is occurring, which results in local sea-level change in many places being similar to the global average rate of rise. Therefore, at many but not all locations around the Australian coast, sea-level has risen over the last century at rates between about 1 and 2 mm/y, with an absolute range between −6.9 mm/y and +4.3 mm/y.

Conclusion

Local relative sea-level change is what counts for purposes of coastal planning, and this is highly variable worldwide depending upon the differing rates at which the land is uplifting or subsiding.

Public confusion about sea-level change

In general, the UN's Intergovernmental Panel on Climate Change (IPCC), and government planning and management authorities, use the unqualified and ambiguous term 'sea-level' when discussing this issue. In nearly all instances, this usage refers to global average sea-level.

This leads to great confusion in the public mind. First, because most people think that when government scientists or ministers talk about sea-level change they are referring to what is actually happening on the nearest coastline rather than discussing a global statistic. Second, and after people have had the distinction between local and global sea-level explained to them, they are (rightly) puzzled as to why a planning agency would use a notional global average value rather than direct measurements made at nearby coastal locations of interest. After all, houses do not have their heating and air-conditioning designed to cope with the global average temperature range, but with the known (and measured) local temperature range; why should coastal planning and sea-level matters be any different?

Conclusion

On its own, a knowledge of global sea-level behaviour does not enable the determination of likely future shoreline positions; it is therefore of little value for coastal management and environmental protection purposes.

2 Coastal processes

It is not recognised widely that, as a potentially hazardous environmental variable, sea-level change bears almost exclusively on the issue of coastal management: outside of very shallow coastal water, whether the sea-level is higher or lower is of no practical concern. Thus at the heart of the issue of sea-level policy lies the need for an understanding of coastal processes.

The position of a shoreline and the stability of that position depend upon a number of factors. One of these is indeed local mean sea-level, but several other important processes also operate within and upon the coastal environment - some natural and some influenced by human development.

What controls the position of a low-lying continental shoreline?

As well as rebound from the last ice age and tectonic changes, other factors may also cause vertical displacement of the land surface, including consolidation, compaction and liquefaction of sub-surface sedimentary layers, intrusion of molten rock – magma – into underlying strata, and the extraction of oil, gas or water. Some of these processes are relatively constant, while others only occur episodically.

Along shorelines made up of easily moved and transported gravel, sand and mud, the wind, waves and tides cause the movement of shorelines. It is increasingly recognised that there are interannual and decadal scale fluctuations in the frequency and

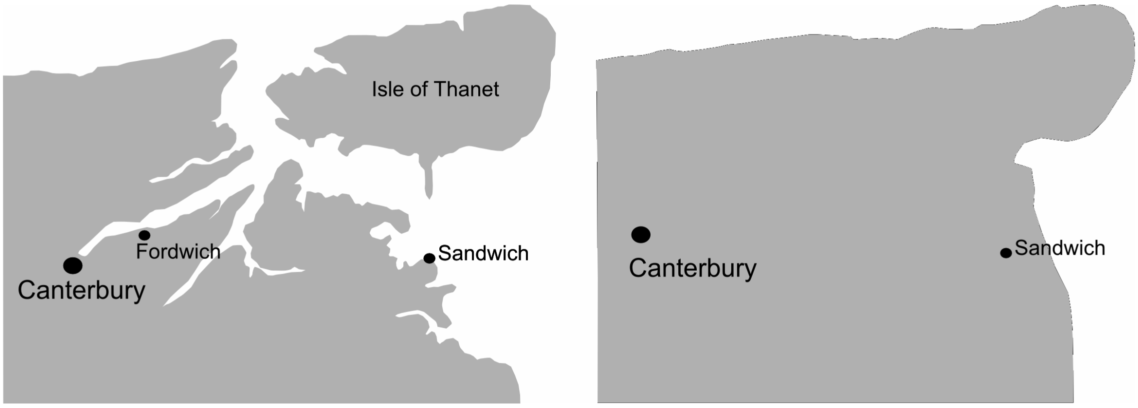

Figure 2: Geography of eastern Kent. Left: As it was between the first and fifteenth centuries. Right: As it is today.

magnitude of storms, which means that there are several time scales over which mobile shorelines can advance and retreat in response to storms. This implies that it is not advisable to use short-term records to assess coastal responses to sea-level rise and changing climate.

Another factor that affects the position of a shoreline is variation in the sediment supply. Over time, the provision or loss of sediment can exercise a dramatic influence on the location of the shoreline. For example, the delta of the Indus River has expanded noticeably in recent decades because of increased sediment supply.

A well-known example of quite dramatic change in shoreline over a short period of time concerns the geography of eastern Kent, U.K. (see Figure 2; Robinson and Cloet, 1953; Perkins, 2007). Between Roman times and about 1400 AD, the Thanet region was an island, fully separated from the English mainland. A port existed at Fordwich, near Canterbury. Thereafter, the shallow seaway that separated the Isle of Thanet disappeared consequent upon gentle uplift (Teferle et al. 2006), which involved both long-term tectonic uplift and interglacial isostatic subsidence (Waller and Long, 2003). Sediment infill resulted in the former island becoming an integral part of the Kent mainland. What was formerly seabed is today farmland or towns, and many of the former ports of the region are now located well inland. Because the historic pattern of global sea-level change is a slow and declining rise (cf. Figure 3), and given that the land has also been rising slowly, local relative sea-level is unlikely to have changed much over the last 500 years (So, 1965), and the change in geography probably results largely from sedimentary infill of the former seaway. The message is that high rates of sea-level change are not a necessary accompaniment to significant coastal and shoreline change.

Importantly, all such shoreline changes are site specific, and different changes may occur over quite short distances of a kilometre or two. For instance a recent study of Holocene marine highstand shoreline deposits in Brazil by Hein et al. (2014) demonstrated 'the nonlinearity of coastal response to sea-level change, and the site specificity of conditions associated with the formation of each highstand deposit type, even within a single small embayment, demonstrates the non-uniformity of that response'.

In many places in the world, appropriate responses to shoreline change and changing sea-level have been made by use of local engineering works. For example, beach stability has been encouraged by the introduction of groynes to entrap sand, and the building of sea walls and protective dykes has combated sea-level rise. In applying such measures, the Dutch and others have sensibly based their coastal engineering plans on scientific knowledge of locally observed rates of shoreline and sea-level change (Bakker, 2013).

Cliffs are constantly attacked and eroded by marine processes. On exposed coasts with high rates of erosion, long term landward retreat of the cliff edge may occur at rates of 1 m/y or higher. As many residents of the eastern UK know, for houses located near to an eroding modern cliff edge it is therefore usually a matter of when, rather than if, cliff and house collapse occurs. Unlike soft sediment shorelines, cliffs do not recover after an erosion event.

Conclusion

Shorelines are dynamic geographic features. The average position of a sedimentary shoreline may shift landwards or seawards by distances of metres to many tens of metres over periods between days and years, in response to variations in the amount of sediment supply, the occurrence of calms and major storms, and variations in local mean sea-level. In the past, coastal inhabitants have adapted to such changes.

What about coral atolls?

Relentless media attention has ensured that the alleged threat to coral atolls from sea-level rise remains in the public eye, with the Tuvalu Islands receiving the most publicity.

The origin of coral atolls was famously first explained by Charles Darwin, who noted that they were reef sandbank complexes situated on top of sinking, extinct volcanos. Such atolls are made up of detrital coral sand that has been eroded from the living reef communities that develop as a volcano submerges and which is washed into shallow banks. Subsequently, some of these sand banks develop a small freshwater lens, derived from rainfall, and become temporarily stabilised by vegetation to the point that they can sustain human habitation. Seldom more than a metre or two above sea-level, all atolls and related sand-cay islands are at the continuing mercy of the same wind, waves, tides and weather events that built them. They are dynamic features of the seascape, and over timescales of decades to centuries they erode here, grow there, and sometimes disappear beneath the waves forever. Thus a coral atoll is not so much a 'thing' as it is a process, and they are obviously not good places in which to develop major human population centres.

Because they are located so close to sea-level, it is commonly assumed that atolls are vulnerable to rising sea-level. However, investigations into the processes that govern their formation, evolution and stability indicate that they are very resilient to sea-level changes, provided human activities do not disrupt the natural processes. Perhaps counterintuitively, overwashing of the islands – by storm waves, storm surges, high tides and tsunami – is an important mechanism for increasing their elevation, depositing new layers of sediment each time (Kench et al. 2006).

Webb and Kench (2010) recently showed that 23 out of the 27 Pacific atolls that they studied remained unchanged or increased in area during the last part of the 20th century. Moreover, for most Pacific coral islands the rate of long-term sea-level rise is less than the current global average rate; and no data exists that demonstrates an increasing, unusual or unnatural rate of sea-level change for Pacific atolls.

Conclusion

The dynamic nature of an atoll is exacerbated, and its integrity jeopardized, when it is subjected to the environmental pressures created by a growing human population. Sand mining, construction project loading, and rapid groundwater withdrawal all cause local lowering of the ground surface, and thereby encourage marine incursion quite irrespective of any sea-level change. It is these processes in combination with episodic natural hazards like tides and storms, and not global sea-level change, which provide the alarming footage of marine flooding that from time to time appears on our television news screens.

The hazards of coastal living

The fear about rising sea-levels swamping coastal properties, or even swallowing whole Pacific atolls, has been generated by two factors. The first is the misidentification of what causes coastal flooding today, and the second is the use of rudimentary computer models that project unrealistic estimates of future temperature and sea-level rise.

Modern coastal flooding is driven by the occurrence of rare natural events, most notably high spring tides, heavy rainfall over the interior and large storm surges, each of which can add a transitory metre or so to local sea-level height, or even 2–3 m if combined – a height which can then be doubled for the storm surge associated with a very large hurricane. Over the last 100 years, the majority of locations (though not all) around the world's coastlines have experienced a sea-level change of between about −50 cm and +50 cm. This amount is too small to have effected noticeable changes in shorelines that are subject to daily and seasonal variations in weather and sediment supply. When, from time to time, beach erosion, river outlet clogging or cliff fall has made the media headlines, mostly the cause has been a storm event, or natural or human interference with the flow of sediment: sea-level changes that might have occurred over previous decades are rarely identifiable as a significant hazard contributor, although of course they may have slightly enhanced or diminished the precise level reached by a flood peak.

Conclusion

In essence, and even when considered in the context of the flooding and erosion risks already inherent in coastal locations, the likely local sea-level change over the next 100 years is in most places too small to require a major planning response. Moreover, it is generally the occurrence of other events in conjunction with sea-level rise that creates the hazard, indicating that mitigating or avoiding the associated events is a better management approach. However, if the time horizon considered is expanded to the geological scale of, say, 1000 years hence, then allowance will need to be made for changes of between about −5.0 metres and +5.0 metres by AD 3010. It is, perhaps, a little early yet to be spending money on dealing with that distant, still small and anyway hypothetical problem.

3 Measuring sea level

Over millennia and more – geological evidence

Changes in sea-level over long periods of time (up to millions of years) are inferred from geological evidence. A global sea-level curve for the period since the last ice age is shown in Figure 3. It shows very rapid melting, at rates up to 26 mm/y for short periods, between about 15,000 and 8,000 years ago, after which the rate of rise lessens to 1–2 mm/y.

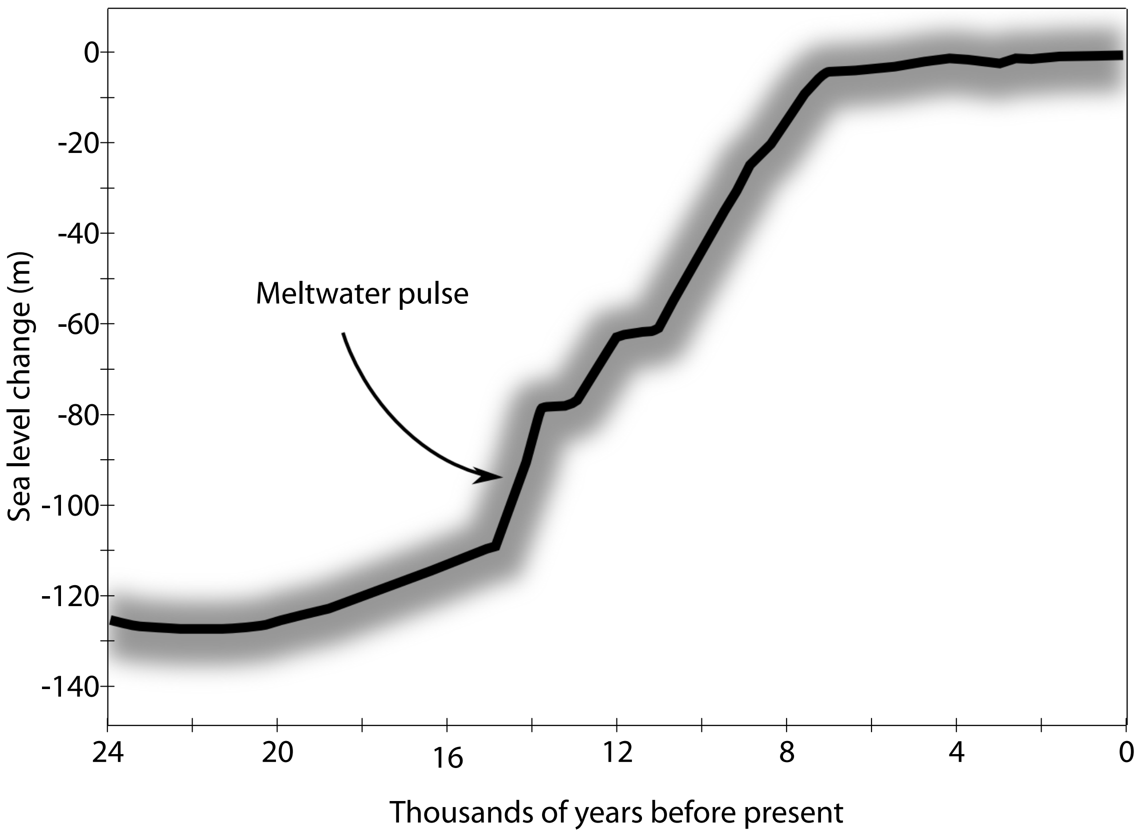

Figure 3: Reconstructed global sea-level since the last glacial maximum, 20,000 years ago, based on dated worldwide coral and peat deposits (after Fairbanks, 1989; Toscano and McIntyre, 2003).

The maximum rates of rise occurred in short bursts, referred to as melt-water pulses, that may be caused by breakout floods from large northern hemisphere pro-glacial lakes. No such large meltwater lakes exist today, so such high rates of rise are unlikely to be repeated at this point in the Holocene melt cycle.

So although initially rapid during early post-glacial melting, thereafter sea-level rises associated with past warmings appear to have quickly slowed (PALSEA, 2010).

Over the last 100 years – tide-gauge measurements

Local relative sea-level has traditionally been measured at ports using tide-gauges, some of which have records that extend back to the 18th century. These measurements tell us about the change that is occurring in actual sea-level at particular coastal locations, which includes rises in some places and falls at others. After correction for any site-specific tectonic or oceanographic-meteorologic distortions of the underlying local sea-level signal, a number of geographically dispersed tide-gauge records can be averaged to provide an estimate of the global (eustatic) sea-level curve.

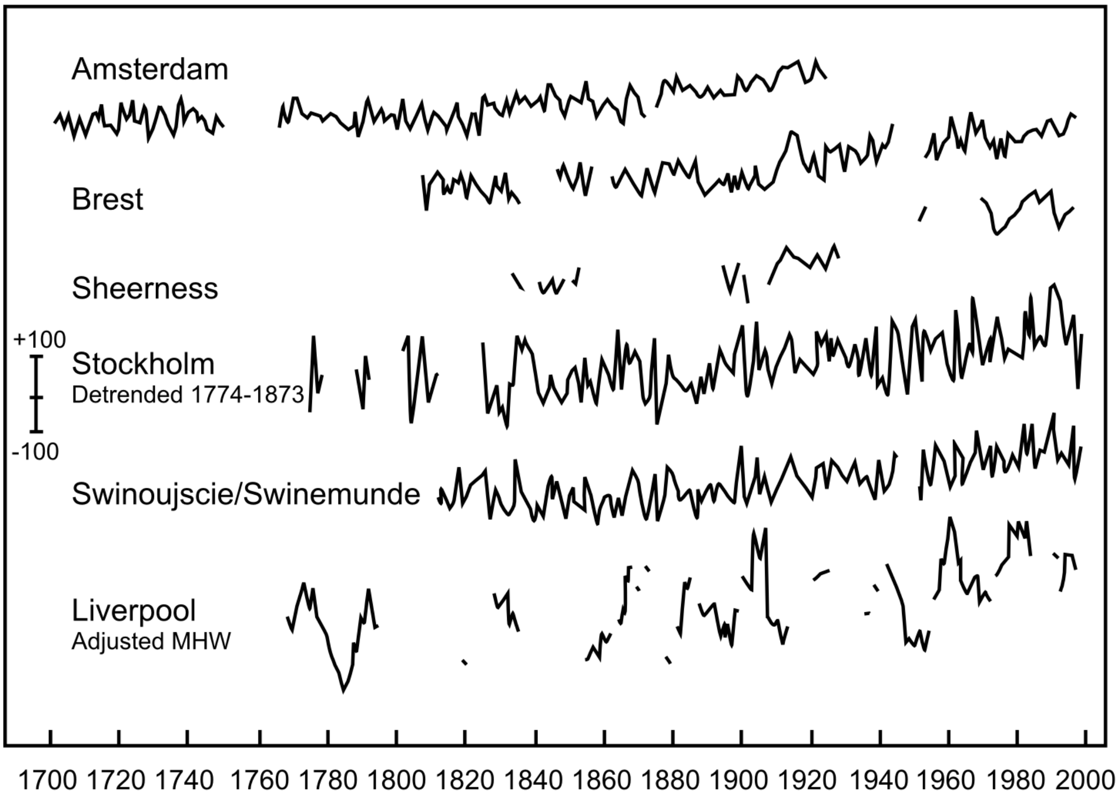

Figure 4: Long, northern hemisphere tide-gauge records of sea-level change, 1700–2000. After Hadley Centre and IPCC, TAR.

The longer term tide-gauge data, after correction for subsidence, record a 20th century sea-level rise of +1–2 mm/y (see Figure 4). Based on these records, IPCC (2001) estimated an average global rate of rise between 1900 and 2000 of 1.6 mm/y. However, the calculations are highly sensitive to the start and end points selected for the data set being considered, and the derived average also ignores short-term and multi-decadal changes in sea-level known to be associated with meteorological and oceanographic oscillations. Using different time periods, low rates of 0.5–1.2 mm/y over historic or late Holocene time have been reported by several other authors (viz. Gehrels & Woodworth, 2013; Miller et al., 2009; Morner, 2004, 2012).

Over the last 20 years – satellite measurements

Estimates of sea-level change made using satellite-collected data for the moment remain problematic, because of the many uncertainties that exist with their collection and processing. In particular, there is inconsistency between the results derived by different research groups, all of which anyway depend upon the accuracy of complex adjustments, some of which both increase the apparent rate of rise and lack independent verification (Houston and Dean, 2012).

One widely used summary of processed satellite measurements of sea-level change is provided in Figure 5. This record indicates an average rate of rise between 1993 and 2010 of 2.9 mm/y. This is notably discrepant with the tide-gauge record over the same and earlier periods. However, recent recalculations of a slightly longer dataset by Cazenave et al. (2014) suggest that a 30% decline (from 3.5 mm/y to 2.4 mm/y) in the rate of satellite-measured sea-level rise has occurred since 2002.

Conclusion

As concluded by Wunsch et al. (2007) with respect to the satellite measurements:

> At best, the determination and attribution of global-mean sea-level change lies at the very edge of knowledge and technology…Both systematic and random errors are of concern, the former particularly, because of the changes in technology and sampling methods over the many decades, the latter from the very great spatial and temporal variability…It remains possible that the database is insufficient to compute mean sea-level trends with the accuracy necessary to discuss the impact of global warming – as disappointing as this conclusion may be. The priority has to be to make such calculations possible in the future.

Is the rate of global sea-level rise accelerating?

The important question is not 'is the long-term rate of sea-level rising', for the geological, tide-gauge and satellite record all agree that it is and, other things being equal, will continue to do so. Rather, to provide evidence for increased rates of rise due to human influence necessitates that the question be 'is the *rate* of sea-level rise accelerating?'. The answer is 'no'.

For example, in its Third Assessment Report the IPCC (2001) wrote 'no significant acceleration in the rate of sea-level rise during the 20th century has been detected'. In 2007 they said that:

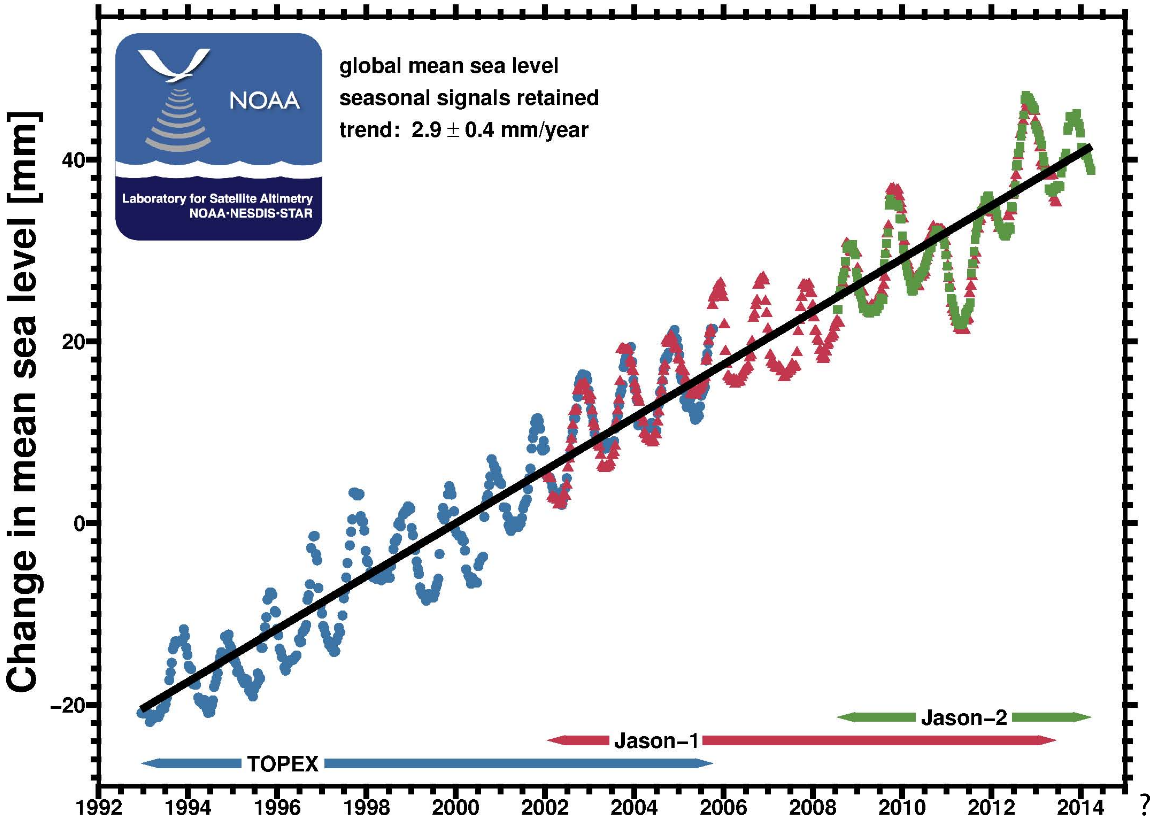

Figure 5: NOAA satellite altimetry, global sea-level change since 1992. Dataset composite, collected from successive satellites (coded in colour), and plotted monthly without seasonal corrections. http://www.star.nesdis.noaa.gov/sod/lsa/SeaLevelRise/ /LSA_SLR_timeseries.php.

> …global average sea-level rose at an average rate of 1.8 [1.3–2.3] mm per year over 1961 to 2003. The rate was faster over 1993–2003: about 3.1 [2.4–3.8] mm per year. Whether the faster rate for 1993 to 2003 reflects decadal variability or an increase in the longer-term trend is unclear.

This latter interpretation was based on a comparison of satellite altimetry data (the recording of which only started in 1991) and tide-gauge data, and is therefore represents an 'apples-to-oranges' comparison. That the satellite data produce a higher rate of sea-level rise than do the tide-gauge data (Wunsch et al. 2007) does not provide evidence of acceleration.

Subsequently, many authors have directly tested the proposition of acceleration in sea-level rise for regional datasets. Watson (2011) analysed the three longest sea-level records for Australasia, and found *deceleration* over the later parts of the 20th century and into the 21st (i.e. a slowing of the rate of rise). Other authors who have provided evidence for a slowing rate of sea-level rise during the late 20th and 21st centuries include Hannah (1990; 2004), Hannah and Bell (2012), Holgate (2007), Houston and Dean (2011, 2012), Boretti (2012a,b), Gehrels et al. (2012), Houston (2013), Chen et al. (2014) and Cazenave et al. (2014).

Church and White (2006, 2011) suggested that the long-term sea-level rise accelerated during the late 20th century. Because their work is based on merged satellite and tide-gauge datasets, these studies are problematic and have to be used with caution. Break point and other statistical analyses indicate a significant change in the underlying characteristics of the data around 1992 (Chambers et al. 2012), i.e. at the commencement of satellite measurements. This implies either that a fundamental change in sea-level processes occurred in 1992, or that the satellite data behave differently to the tide-gauge data – the latter view being supported by Wunsch et al. (2007) and Domingues et al. (2008). But in any case, linear trends calculated over periods as short as 20–30 years (as the satellite data are) cannot be viewed as reliable indicators of the long-term rate of sea-level change.

There is, however, general agreement that sea-level rise began to accelerate in or before the 19th century (e.g. Jevrejeva et al. 2008), despite the paucity of tide-gauge records that extend back beyond that. Woodworth et al. (2009) reviewed the available reconstructions for the 20th century and concluded that sea-level rise accelerated around 1920–1930 and decelerated around 1960.

The presence of both decadal and 60-year-long fluctuations in rates of sea-level change like these (Holgate, 2007; Church and White 2011) indicates that it is too soon to attempt to identify any late 20th century acceleration based upon satellite altimetric measurements.

Conclusion

Although it is possible to demonstrate with a high degree of confidence that global sea-level is currently rising at a decelerating rate, the concept of a measured global rate of sea-level rise that has widespread significance is untenable. Spatial and temporal fluctuations at several scales make it difficult to relate observed sea-level at any one location with a global trend in sea-level change.

4 Projections of sea-level change

Graphs that project future sea-level can be constructed in three different ways.

Empirical prediction

The first method, empirical projection, has already been discussed incidentally in Section 3. This method involves extrapolation of current trends to project future sea-level positions; importantly, this method provides rigorous estimates of the uncertainty of the projections made.

In general, for empirical prediction the extrapolation cannot extend very far beyond the limits of the original data (say 10%) before the confidence limits diverge widely. Therefore, empirical models cannot usefully predict sea-level very far into the future. Nonetheless, a good quality 100-year-long tide-gauge record should provide predictions 20 years into the future with reasonable confidence limits. This should be sufficient to manage coastal development with a short design life, and is also a good basis on which to develop longer term adaptive and mitigation strategies.

IPCC deterministic modelling

The second method, at the other extreme to empirical modelling in terms of computational complexity, involves computer simulations, often referred to as GCMs (general circulation models). Starting from scenarios of future economic activity, these models use the laws of physics to estimate changes in temperature, the response of the oceans and the cryosphere, and hence changes in sea-level. Such modelling proceeds on the assumption that all relevant factors are known and taken into account, and that adequate theoretical understanding exists and can be expressed mathematically; these assumptions are not necessarily true, and GCM models have not been able to recreate past sea-levels well.

The range of possible future sea-level changes has progressively decreased since the earliest reports produced for the UN (Hoffman et al. 1983). In its Third Assessment Report in 2001, the IPCC provided a range of computer-generated projections for sea-level rise by 2100 of between 11 cm and 77 cm. Subsequently, in the Fourth Assessment Report in 2007, and using similar modelling, the IPCC adjusted the projected rise of sea-level in 2100 to lie within the bounds 18–59 cm. It is noteworthy that the bottom end of this range corresponds with the 18-cm rise in sea-level that results from extrapolating the long-term tide-gauge rate of rise of 1.8 mm/y out to 2100.

Semi-empirical models

The published results from semi-empirical models produce the highest and the most alarming estimates of rates of future sea-level change so far published (between 80 cm and 180 cm by 2100), and conflict with projections based upon empirical or deterministic modelling. Accordingly, they are controversial and have attracted substantial scientific criticism (Holgate et al. 2007; Schmith et al., 2007; Rahmstorf, 2007). The controversy surrounding these models remains unresolved. Given their scientific uncertainty, and given that both empirical and GCM modelling yield more modest projections of future sea-level, the semi-empirical models can at best only be viewed as a work in progress.

As Gregory et al. (2012) have pointed out, semi-empirical methods for projecting sea-level depend upon there being an established relationship between global climate change and the rate of global sea-level change, and such a relationship is weak or absent during the 20th century.

Conclusions

Many complicating factors and uncertainties underlie any projected estimate of future global sea-level change. Of the three types of modelling that can be used to make such estimates (empirical, semi-empirical and deterministic), empirical models yield the most useful result. This is because empirical projections are rooted in site-specific measurements that establish real-world trends and can be used for practical coastal management and planning.

5 How is sea-level likely to change around the world in the near future?

The one certainty is that future sea-level will continue to change at differing rates and in different directions at locations around the world, as it always has in the past. Two different procedures are involved with assessing these future sea-level changes. They are, first, an understanding of past and present environmental conditions and rates of change; and, second, a theoretical analysis and projection of likely changes to environmental conditions and rates of change.

Past environmental conditions and rates of change

Modern coastlines result primarily from sea-level change at the glacial–interglacial level, as it occurred over thousands and tens of thousands of years (Figure 3). We have explained the dynamic nature of the processes that cause shoreline change and migration (see Section 2) and noted that one, but only one, of the determinants of that coastal change is sea-level; other factors, such as the overall sediment budget, may be more important at specific times or localities. In Section 3, we showed that worldwide the rate of sea-level change is locality specific, and encompasses places where the contemporary level is falling and others where it is rising. In addition, the rate of sea-level change constantly varies through time. Consequently, changes in both relative sea-level and coastal geography are commonplace along the shorelines of the world, and have been observed by mankind for many centuries.

Another important factor requiring consideration is the variable time lags that accompany changes in global temperature, ice melt, runoff and sea-level response. This may vary from a year or two for the expected direct thermosteric response to heating of the shallow ocean,[4] to hundreds of years for ice melt and runoff processes, and to more than a thousand years if deep-ocean circulation of heat is taken into account. In other words, the cause–effect relationship between global temperature and sea-level change is far from being as simple as is customarily assumed. This is highlighted for the historical record by the review of Gregory et al. (2012) who found that the relationship between global climate change and global mean sea-level rise was 'weak or absent during the twentieth century'.

Conclusion

The first key to projecting future change is to document and understand all the environmental variables that apply to any shoreline location of interest – including, though not exclusively, its historic pattern of sea-level change.

[4]The term *thermosteric* refers to the effect of direct heating on the ocean water body, which causes it to expand and thus sea-level to rise concomitantly.

Future environmental conditions and rates of change

In late 2012, the UK Met Office caused minor sensations by acknowledging that no global warming had occurred since 1997, i.e. for the previous 16 years, and predicting that the lack of warming would continue into the future (Whitehouse, 2013). Although this was simply the public dissemination of a reality that had been acknowledged in the scientific literature several years earlier (e.g., Keenlyside et al., 2008), it flew directly in the face of continuing advice from the IPCC as to the necessity of preventing dangerous global warming.

It is now generally acknowledged amongst scientists that the mild Late 20th Century Warming episode has been superseded by atmospheric temperature stasis or even slight decline. The cause of this change is generally believed to relate to changes in the behaviour of the important Pacific decadal and Atlantic multi-decadal climatic oscillations. Since 2003, ocean temperatures have also been cooling slightly (Lyman et al., 2006; Willis et al., 2007; 2008). Indeed, Harrison and Carson (2007), studying ocean temperature change between 1950 and 2000, suggested that the oceans may have been cooling since the late 1970s.

These conclusions immediately cast doubt on the current claims by the IPCC (2007) that extra heat has accumulated in the oceans since 1960, and that sea-level rise driven by thermal expansion of the water will be the inevitable result. In fact, analyses of global sea-level budgets over the last decade attribute around twice as much of the recent rise to meltwater contributions (caused by atmospheric warming) as they do to thermal expansion (e.g., Leuliette and Willis, 2011).

Regarding the projection of future sea-level and shoreline change, we therefore arrive at an impasse. The IPCC and its scientific advisers remain committed to the view that global warming, albeit temporarily suspended, will resume and that sea-levels will rise. Other equally qualified but independent scientists, including a number of solar astrophysicists (viz. Bonev et al. 2004), are of the view that over the next few decades cooling is more likely than warming. Meanwhile, real-world climate is exhibiting an increasingly long stasis, with temperature trends well below the IPCC projected mean rate of 0.2–0.3°C per decade.

Conclusion

The reality is that no scientist can tell you, with credible probability attached, whether 2030, 2050 or 2100 will be cooler or warmer than today, and hence whether global (or individual local) sea-level changes will accelerate, continue at a steady rate, decelerate, or even reverse. It would therefore be prudent management to prepare to adapt to any and all of these alternative futures.

The IPCC's Fifth Assessment Report: what's new on sea-level?

The Summary for Policymakers (SPM) of the IPCC's Fifth Assessment Report (5AR), released in September 2013, treats sea-level change in the same unsatisfactory fashion as did the predecessor Third and Fourth reports. The focus of attention is again on deterministic computer model projections of future global mean sea-level, whilst the practical advice needed for managing coastal hazard, which requires close attention to tide-gauge measurements that record the variability of local relative sea level change, is ignored apart from the following statement (p. SPM-19):

> Sea level rise will not be uniform. By the end of the 21st century, it is very likely that sea level will rise in more than about 95% of the ocean area. About 70% of the coastlines worldwide are projected to experience sea level change within 20% of the global mean sea level change.

The key phrase here is '…of the ocean area'. IPCC's modelling of global mean sea-level change does not take into account the many and varied local and regional changes in coastal basement level that occur around continental and island margins, caused by processes like glacial rebound, thermal decay, hydro-istostasy and tectonic activity. These models, and the IPCC in general, therefore provide no guidance that is of practical value to those who are responsible for coastal management.

About its model projections, IPCC asserts (p. SPM-18):

> Confidence in projections of global mean sea level rise has increased since the AR4 because of the improved understanding of the components of sea level, the improved agreement of process-based models with observations, and the inclusion of ice-sheet dynamical changes.

The projections contained in AR5 assume an 'increased ocean warming and increased loss of mass from glaciers and ice sheets' which is not currently occurring. This notwithstanding, and relative to the years 1986–2005, the IPCC now projects rises in global mean sea-level by 2081–2100 for different socio-economic scenarios as shown in Table 1.

Table 1: IPCC projections of sea-level rise

Scenario	**Minimum rise** cm	**Maximum rise** cm	**Mid-point rise** cm
SRES A1B	36	59	47
RCP2.6	26	55	40
RCP4.5	32	63	47
RCP6.0	33	63	48
RCP8.5	45	82	63

Note that scenario RCP8.5 is the most extreme (i.e. has the strongest greenhouse gas forcing) of the four scenarios examined, and sets the total greenhouse gas forcing at 8.5 W/m^2, or the equivalent of a 1313 ppm CO_2 concentration by the year 2100. The rapid rates of sea level rise projected for RCP8.5 therefore do not result under the other three scenarios considered. It is noteworthy that the 'consensus' 40–50-cm rise by 2100 that is projected by the three less extreme scenarios, while very similar to the projections B1, B2 and A1T scenarios in the 4th Assessment Report, is still high compared to the 18-cm rise indicated by naïve projection of measured 20th century rates of sea-level change.

All the RCP scenarios assume an initial rate of sea level rise between 2007–2013 of 3.7 mm/y, followed by different rates of acceleration. This startling rate of sea level rise is higher than currently observed by either satellite altimetry or tide gauges. At the same time, a 40–50-cm rise is also one third or less of the extreme changes projected by semi-empirical modelling (e.g., Rahmstorf, 2007) or by Gore (2006). The AR5 report notes that there is no consensus about the reliability of semi-empirical models and assigns low confidence to their projections.

Based on the AR5 projections, and across the different scenarios, ocean thermal expansion accounts for 30-55% of modelled sea-level rise and ice melt for 15–35%. These figures differ little from those asserted in earlier reports. For example, AR4 estimated that ~0.4 mm (22%) of the 1.8-mm average annual sea-level rise was accounted for by thermal expansion, that ice-melt accounted for ~0.7 mm/y (39%) and that the remaining 0.7 mm/y (39%) probably related to dynamic oceanographic and meteorological factors. In the warming world that IPCC assumes, however, increased snowfall is probable in the interior of both Greenland and Antarctica. Taking this into account, IPCC now estimates that the likely amount of sea-level rise due to ice melt by 2100 will be just 3–20 cm.

In essence, IPCC's Fifth and Fourth Assessment Reports AR5 report differ little in their conclusions about future sea-levels. The unknowns are the same (future emission levels; future temperature; future mass balance changes in Antarctica and Greenland; ocean dynamics), the projections are still highly qualified, the probabilities of occurrence are ignored and the range of sea level projections remains essentially the same.

Conclusion

Policymakers concerned about the effects of sea-level change on coastal infrastructure will be better served by taking advice from competent coastal engineers (see Thames Estuary 2001 Plan, 7 below) than they will by attempting to apply the IPCC's uncertain projections of global sea-level.

6 What then is the problem?

Based on geological studies, it appears that slow global sea-level rise has been taking place over about the last 10,000 y (Figure 3). It is established by many studies, too, that over the last 150 years global sea-level has been rising at an average rate of about 1-2 mm/y, which represents the slow continuation of post-glacial ice melting. At specific localities, this rising global trend interacts with tectonic factors, glacial rebound and multi-decadal rhythmicity to produce patterns of local relative sea-level change that vary from place to place and region to region.

If they continue to melt, glaciers and ice caps are expected to contribute another 12±4 cm to sea-levels by 2100 by Church et al. (2011) and 3–20 cm by IPCC (AR5).

These projected ice sheet contributions remain uncertain because of large variations in estimates of ice volume losses, but an upper limit based on extrapolating a short record is 56 cm of extra sea-level rise by 2100 (Pfeffer, 2011).

There is, therefore, no scientific basis for Mr. Al Gore's claim (Gore, 2006) that global warming will imminently melt so much ice that sea-levels will rise by as much as 20 ft.

Conclusion

The problem is not global sea-level change (which, using a naïve forecasting approach,[5] is likely to rise by 18 cm or less by 2100). Rather it is uncertainty. That uncertainty applies to future global temperature, future rates of ice mass-balance change, future global sea-level change and future socio-economic scenarios; and it is profound.

7 An example of practical policy in action: the Thames Estuary 2100 plan

The Thames Estuary coast is threatened by marine inundation which has the potential to negatively affect 1.25 million residents and infrastructure valued at £200 billion (Environment Agency, 2012). The region is presently protected from flooding by a system of embankments and floodgates, including the Thames Barrier completed in 1982. This system is part of ~1200 km of coastal defenses in England and Wales, which in combination protect about a third of the coastline (de la Vega-Leinert and Nicholls, 2008). Sea-level rise is a factor that has been identified as needing to be considered in relation to coastal protection (French, 1997).

For the purpose of assessing sea-level rise and its potential impacts, the coast of the United Kingdom can be subdivided into distinct regions, or coastal cells. Based on the exchange of sediment along the coast, 14 coastal cells separated by barriers to sediment transport are recognized and form the basis for current coastal management (French, 1997). De la Vega-Leinert and Nicholls (2008) argue that due to changes in the coastal types present, the cells also reflect vulnerability to coastal erosion and flooding, and hence sea-level rise. Comparing the sea-level trends around the United Kingdom (Woodworth et al., 1999; Shennan and Horton, 2002) with the coastal cells indicates that they are undergoing differing relative land movements, primarily in response to isostatic adjustments since the last glaciation, the result of which is higher rates of relative sea-level rise in the south. Hence, the southeast coast, including the Thames Estuary and London, is vulnerable to sea-level rise (de la Vega-Leinert and Nicholls, 2008; Penning-Rowsell et al., 2013).

Storm surges and river floods represent a further climate-related hazard that is associated with sea-level rise, because for any given magnitude of storm surge or river flood, a higher background sea-level will result in a higher level of inundation. However, the level of inundation is also a function of tidal elevation and timing of the surge or flood peak relative to high water, so storm and flood hazards are also linked to tidal characteristics. As sea-levels change, the propagation of tidal waves and storm surges change, particularly on the North Sea coast, which alters both the mean sea-level and extreme sea-level distributions (Hinton, 1995; Shennan and Horton, 2002). Further, the magnitude and frequency distributions of storm surges and floods may change in response to climate (de la Vega-Leinert and Nichols), particularly if the trajectories of storm systems change. Hence, the impact of climate and relative sea-level changes on coastal hazards is complex and strongly site specific.

The TE2100 project assessed the vulnerability of the City of London to storm surge and flood impacts associated with relative sea-level rise, and claims to be the first major flood risk assessment for the United Kingdom to place climate change adaptation at its core (Environment Agency, 2012; Penning-Rowsell et al., 2013). Although, the project based sea-level projections on global estimates (Penning-Rowsell et al., 2013), it considered site-specific factors such as an average 7 m tidal range, subsidence due to consolidation of sediments of 1.5 mm/y, and forecast changes to storm surge magnitude and frequency (Environment Agency, 2012). Their analysis found that the higher projections of sea-level rise were highly unlikely, and that storm surge frequency and magnitude were likely to decrease. This led to a downward revision of maximum water levels (storm surge + tide + sea-level rise) for 2100 from +4.2 to +2.7 m (Environment Agency, 2012).

The TE2100 project also investigated a range of adaptation options to mitigate the identified climate change impacts. This involved both a cost-benefit analysis and a multi-criteria analysis to evaluate 5 flood risk management policies and 9 protection options (Penning-Rowsell et al., 2013). These analyses concluded that London and the Thames Estuary should continue to be protected, but that the existing coastal defenses would provide the necessary level of protection until at least 2070. Further, improving the coastal defenses now is not justified by the cost-benefit analysis, and the most important factor driving this analysis appears to be socio-economic factors and not climate (except for the most extreme projected climate scenarios). Finally, the TE2100 project demonstrated that the rate of risk increase is sufficiently slow that there is time to plan and maintain existing coastal defenses incrementally, rather than front-load the response based on long-term projections (Environment Agency, 2012; Penning-Rowsell et al., 2013).

Conclusion

Crucially for its success, the Thames Estuary 2100 Plan was implemented in an adaptive rather than a preventative ('stop global sea-level rise') way. Likely future coastal changes around the estuary were examined within a framework of hard, factual measurements of the local environment, and the computer modelling involved was rooted in these measurements rather than in speculative global averages. This type of plan represents an excellent template for application, in conjunction with the particular local circumstances, at other places around the world.

8 What is the best policy outcome?

Two key issues are important for making decisions about sea-level and coastal management policy.

Certainty or uncertainty?

The first is certainty, as just discussed. Can we or can we not predict with a specified probability what rates of sea-level change (note 'change', not 'rise') will occur over the next 100 years, either globally or in specific localities?

The answer to both questions is 'no'. For global sea-level change, an empirical approach of extrapolating the 20th century rate suggests a rise of 18 cm by 2100. For local relative sea-level change, assumed to be the principal driver of coastal impacts (Nicholls, 2011), convolving this assumed 18-cm rise with knowledge of the other environmental factors that characterise different locations (including tectonics) will provide many and varied estimates of the rise or fall of sea-level by 2100, most of which will range between about $\pm$ 1-2 mm/y. But in none of these cases can a meaningful statistical probability be assigned to the accuracy of the projection for either the global or for the many different local sea-level curves.

The precautionary principle

The existence of strong uncertainty is often used to advance the dangerously false argument that, because the science is uncertain, we should take action to curtail sea-level rise 'just in case'.

Most often this argument is badged under the term precautionary principle. First formulated at a United Nations environment conference in Rio de Janiero in 1992, this states that: 'Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation.' An influential and colloquial restatement of the 'principle' is that in case of possible hazard to the planet we should 'give Earth the benefit of the doubt'.

Ironically, invocation of the precautionary principle into an argument in the first place is an open acknowledgement that no compelling scientific evidence for alarm exists. Second, rarely if ever is a rigorous analysis undertaken of the costs and benefits of precautionary action as opposed to inaction. British philosopher Max Moore has recently argued that a better way of handling environmental risk is to apply a proactionary principle (Moore, 2013). Recognising that stagnation is not a realistic option for a world community that wishes to continue to raise living standards for the many, proactionary policies stand for the proactive pursuit of progress in a way that improves our world (including through technological solutions) and handles deleterious effects through compensation and remediation.

We find ourselves in agreement with both Moore and the United Kingdom House of Commons Select Committee on Science and Technology (2006) that the precautionary principle is inappropriate for use in the formulation of effective public environmental policy – which must instead be rooted in evidence-based science. Scientific principles acknowledge the supremacy of experiment and observation and do not bow to instinctive feelings of alarm nor to untestable moral propositions.

It is the simplest of logic that if we don't know in advance the direction and rate of sea-level change, either globally or locally, then we cannot take precautions to try to mitigate or prevent change. It is obvious that in such circumstances different coastal management policies will be necessary in different places depending upon whether local sea-level is either stable, rising or falling.

Conclusion

At its simplest, the precautionary principle cannot be applied in any meaningful global sense if all that we know is that sea-level will rise in some locations and remain stable or fall in others.

Cost–benefit analysis

The second key issue is making judgments about the cost-effectiveness of any suggested policies, i.e. the undertaking of cost–benefit analyses, which are needed at both global and local level.

Local–regional: traditional coastal policy formulation

In most countries, coastal management is traditionally undertaken by a local or regional council of some type, operating within a legal framework that is provided by either a state or national parliament (French, 1997). Matters that are dealt with include beach erosion, harbour dredging, and planning and building regulations about what types of structures may be built, and where. In implementing coastal policy, councilors and their staff have traditionally been guided by experienced, legally accountable, professional coastal engineers and scientists.

Because such management is always predicated on knowledge of local environmental factors, which differ from place to place, it differs in detail amongst the myriads of coastal councils and planning authorities that exist worldwide. However, in democratic countries at least, management procedures and decisions proceed within the framework of the more or less rigorous cost–benefit analysis that is provided by regular council elections: nothing concentrates the mind so wonderfully towards sensible and cost-effective solutions as the knowledge that one's job will be terminated by ratepayers should signs of policy silliness, financial self-interest or budget extravagance become apparent.

Continuing and effective cost–benefit analysis of coastal policy was therefore until recently generally alive and well at the local and regional level of governance and administration.

Global: post-1988 policy formulation

Things are different, however, at the global level: the natural variability of coastal environments and rates of local sea-level change, and the complexity of the various dynamic processes involved in shaping a coastline, make it impossible to undertake any meaningful overall cost–benefit analysis of policies designed to influence future sea-level change on a worldwide basis. Not surprisingly therefore, at least so far as we know, no-one has attempted to undertake a cost–benefit analysis of the different policies that might be applied to coastal management with respect to the issue of global sea-level alarm. Indeed, it is hard to imagine how one could meaningfully even approach such a task.

Nevertheless, in 1988 an international agency – the IPCC – was charged with advising governments about global sea-level change through the relationship that exists between sea-level and global temperature. The advent of IPCC's global warming advice short-circuited the traditional policy process, whereby governments and councils drew their advice about sea-level change from statutory authorities concerned with harbour and tidal management, and from formal governmental scientific agencies. With this change in advisors, the attention of governments shifted from seeing sea-level change as an issue related to beaches, ports, harbours and navigation to seeing it as an environmental issue that was related to hypothetical global warming putatively caused by human carbon dioxide emissions. At about the same time, the basis of public policy on sea-level shifted from tide-gauges to satellite measurements.

By the turn of the 20th century, governments around the world, and their advisory scientists, were basing their sea-level planning almost exclusively on the advice of the IPCC, i.e. on unvalidated hypothetical computer model predictions that are not tied to local sea-level measurements, but to a theoretical model of the shape of the earth (the geoid) that floats in mathematical space.

Because IPCC sea-level predictions were and are for a global average sea-level, we have arrived at our present unsustainable position, which is one of governments fashioning policy and new laws on the basis of a notional statistic, and in almost complete disregard of the local real, and in general accurate, measurements that are available from tide-gauge networks.

For the purposes of the argument, let us accept the IPCC's estimate that 0.7 mm/y of the current rate of global sea-level rise is ice melt and 0.4 mm/y is due to thermal expansion. Let us calculate out to 2100 and, noting that no thermal expansion is occurring at the moment because ocean temperatures are not rising, assume that thermal expansion will recommence at the IPCC's estimated rate in 2050. Calculation then shows that there would be a 6-cm rise in sea-level by 2100, i.e. one third of the 18-cm rise known for the 20th century. No actual shoreline changes can be attributed specifically to the small 20th century rise in global sea-level, for the very good reason that an 18-cm change lies well within the range of natural variations in local relative sea-level; and this condition would be even more true for a rise as small as 6 cm. Given that the cost of implementing measures to cut carbon dioxide emissions by even 20% would run into trillions of dollars (Leahy, 2012), and that they might reduce our anticipated sea-level rise from 6 cm to 4.8 cm, it is beyond heroic to argue that such a course of action is either sensible or cost effective.

In this context, it must be remembered that in many countries recent legislation or regulation requires coastal authorities to base their planning on the IPCC's previously assumed 59-cm rise by 2100, or higher; for example, the Australian states of Victoria and New South Wales have set planning benchmark levels of 80 cm and 90 cm, respectively.

The result of shifting from the traditional empirical methods and adopting (and sometimes embellishing) the IPCC's uncertain model-based sea-level projections has been the introduction of much additional unrecognized uncertainty into coastal management policy. First, because of the uncertainty of the global temperature projections that feed into sea-level modelling and second because of the lack of certainty also of the relationship between global temperature change and land-based polar ice melting rates.

Conclusion

Current global sea-level policy, supported by many governments, is to reduce the amount of carbon dioxide in the atmosphere in order to slow a theoretical global warming that is apparently no longer happening. The intention is to reduce the heat expansion of the ocean and the amount of ice-melt, and thereby to reduce the rate of global sea-level rise.

These policies attempt to moderate a theoretical environmental variable, ignore local sea-level realities, are ineffectual in significantly reducing sea-level rise and are not remotely cost effective. The policies are therefore financially and politically unsustainable.

9 Recommended policy guidelines

Based on the material presented in this paper, we recommend the implementation of three policy guidelines.

1. Abandonment of 'let's stop global sea-level rise' policies

No justification exists for continuing to base sea-level policy and coastal management regulation upon the outcomes of deterministic or semi-empirical sea-level modelling. Such modelling remains speculative rather than predictive.

The practice of using a global rate of sea-level change to manage specific coastal locations worldwide is irrational, and should be abandoned.

2. Recognition of the local or regional nature of coastal hazard

Most coastal hazard is intrinsically local in nature. Other than periodic tsunami and exceptional storms, it is the regular and repetitive local processes of wind, waves, tides and sediment supply that fashion the location and shape of the shorelines of the world. Local relative sea-level is an important determinant too, but in some localities that is rising and in others falling. Accordingly, there is no 'one size fits all' sea-level curve or policy that can be applied.

Coastal hazard needs to be managed in the context of regional and local knowledge, using data gathered by site-specific tide-gauges and other relevant instrumentation.

3. Use of planning controls that are flexible and adaptive in nature

The shoreline naturally moves around over time in response to changing environmental conditions. Many planning regulations already recognize this, for example by applying minimum building setback distances or heights from the tide mark. In addition, engineering solutions (groynes, breakwaters, sea-defence walls) are often used in attempts to stabilize a shoreline. To the degree that they are both effective and environmentally acceptable, such solutions should be encouraged.

Nevertheless, occasional damage will continue to be imposed from time to time by large storms or other unusual natural events. This will happen no matter how excellent the pre-existing coastal engineering and planning controls may be. In these circumstances, the appropriate policy should be one of careful preparation for, and adaptation to, hazardous events as and when they occur.

It is the height of folly, and waste of money, to attempt to 'control' the size or frequency of damaging natural events by expecting that reductions in human carbon dioxide emissions will moderate climate 'favourably', whether that be putatively sought from a moderation in the frequency and intensity of damaging natural events or by a reduction in the rate of global average sea-level rise.

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References

Bakker, W.T. 2013. Coastal dynamics. Advanced series on ocean engineering, volume 34. World Scientific, New Jersey.

Bonev, B.P., Penev, K.M. and Sello, S. 2004. Long-term solar variability and the solar cycle in the 21st Century. The Astrophysical Journal Letters, 605(1): L81.

Boretti, A.A. 2012a. Short term comparison of climate model predictions and satellite altimeter measurements of sea-levels. Coastal Engineering, 60: 319–322.

Boretti, A.A. 2012b. Is there any support in the long term tide-gauge data to the claims that parts of Sydney will be swamped by rising sea-levels? Coastal Engineering, 64: 161–167

Cazenave, A., Dieng, H.-B., Meyssignac, B., von Schuckmann, K., Decharme, B., Bertheir, E. 2014. The rate of sea-level rise. Nature Climate Change. doi:10.1038/nclimate2159

Chambers, D.P., Merrifield, M.A. and Nerem, R.S. 2012. Is there a 60-year oscillation in global mean sea-level? Geophysical Research Letters, 39(18): L18607,

Chen, X, Feng, Y and Norden, E.H. 2014. Global sea level trend during 1993-2012. Global and Planetary Change, 112: 26–32

Church, J. A. and White, N. J. 2006. A 20th century acceleration in global sea-level rise. Geophysical Research Letters, 33: L01602.

Church, J.A. and White, N.J. 2011. Sea-level rise from the late 19th to the early 21st century. Surveys in Geophysics, 32: 585–602.

Church, J.A., Gregory, J.M., White, N.J., Platten, S.M. and Mitrovica, J.X. 2011. Understanding and projecting sea-level change. Oceanography, 24(2): 130–143.

De Lange, W. and Carter, R.M. 2013. Observations: the hydrosphere and oceans. Climate Change Reconsidered II: Physical Science. 2013 Report of the Non-governmental International Panel on Climate Change (NIPCC), pp. 729–824.
http://www.climatechangereconsidered.org.

de la Vega-Leinert, A.C. and Nicholls, R.J. 2008. Potential implications of sea-level rise for Great Britain. Journal of Coastal Research, 24(2), 342–357.

Domingues, C.M., Church. J.A., White, N.J., Gleckler, P.J., Wijffels, S.E., Barker, P.M. and Dunn, J.R. 2008. Improved estimates of upper-ocean warming and multi-decadal sea-level rise. Nature, 453(7198): 1090–1093.

Environment Agency 2012. TE2100 Plan: Managing flood risk through London and the Thames Estuary. Thames Estuary 2100: London, Environment Agency.

Fairbanks, R.G. 1989. A 17,000 year glacio-eustatic sea-level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Paleoceanography, 342: 637–642.

French, P.W. 1997. *Coastal and Estuarine Management*. Routledge, London.

Gehrels, R. and Woodworth, P.L. 2013. When did modern rates of sea-level rise start? Global and Planetary Change, 100: 23–277.

Gehrels, W.R., Callard, S.L., Moss, P.T., Marshall, W.A., Blaauw, M., Hunter, J., Milton, J.A. and Garnett, M.H. 2012. Nineteenth and twentieth century sea-level changes in Tasmania and New Zealand. Earth and Planetary Science Letters, 315/316: 94–102.

Gore, A. 2006. *An Inconvenient Truth: The planetary emergency of global warming and what we can do about it*. Rodale Books, Emmaus, Pennsylvania.

Gregory, J. M., N. J. White, J. A. Church, M. F. P. Bierkens, J. E. Box, M.R., van den Broeke, J. G. Cogley et al. 2012. Twentieth-century global-mean sea level rise: Is the whole greater than the sum of the parts? Journal of Climate, 26(13): 4476–4499.

Hannah, J. 1990. Analysis of mean sea-level data from New Zealand for the period 1899–1988. Journal of Geophysical Research, 95(12): 399–12, 405.

Hannah, J. 2004. An updated analysis of long-term sea-level change in New Zealand. Geophysical Research Letters, 31: L03307:

Hannah, J. and Bell, R.G. 2012. Regional sea-level trends in New Zealand. Journal of Geophysical Research, 117: C01004–C01004.

Hansen, J. 2007. Scientific reticence and sea-level rise. Scientific Research Letters, 2: 1–16.

Hansen, J.E. and Sato, M. 2012. Paleoclimate implications for human-made climate change. In: Berger, A., Mesinger, F. and Sijacki, D. (Eds), *Climate Change*. Springer, Vienna, p. 21-47.

Hansen, J.M. 2014. After melt down of the Scandinavian icecap sea-level change rates of the Kattegat Sea shifted many times between -3.1 and $+3.7$ mm a^{-1}. Geophysical Research Abstracts 16, EGU2014-2345, 2014. EGU General Assembly 2014.

Harrison, D.E. and M. Carson. 2007. Is the world ocean warming? Upper-ocean temperature trends: 1950–2000. Journal of Physical Oceanography 37: 174–187.

Hein, C.J., FitzGerald, D., de Menezes, J.T., Clearly, W.J., Klein, A.H.F. and Albernaz, M.B. 2014. Coastal response to late-stage transgression and sea-level highstand. Geological Society of America, Bulletin.

Hinton, A.C. 1995. Holocene tides of The Wash, U.K.: The influence of water-depth and coastline-shape changes on the record of sea-level change. Coastal Evolution in the Quaternary: IGCP Project 274, 124: 87–111.

Hoffman, J.S., Keyes, D. and Titus, J.G. 1983. Projecting future sea-level rise: methodology, estimates to the year 2100, and research needs. United Nations Environmental Programme.

Holgate, S.J. 2007. On the decadal rates of sea-level change during the twentieth century. Geophysical Research Letters, 34, L01602.

Holgate, S., Jevrejeva, S., Woodworth, P., and Brewer, S., 2007, Comment on 'A semi-empirical approach to projecting future sea-level rise'. Science, 317: 1866–1866.

House of Commons Science and Technology Committee 2006. Scientific Advice, Risk and Evidence Based Policy Making. Seventh Report of Session 2005-06. http://www.publications.parliament.uk/pa/cm200506/cmselect/cmsctech/900/900-i.pdf.

Houston, J. 2013. Global sea-level projections to 2100 using methodology of the Intergovernmental Panel on Climate Change. Journal of Waterway, Port, Coastal, and Ocean Engineering, 139: 82–87.

Houston, J.R. and Dean, R.G. 2011. Sea-level acceleration based on U.S. tide-gauges and extensions of previous global-gauge analyses. Journal of Coastal Research, 27: 409–417.

Houston, J.R. and Dean, R.G. 2012. Comparisons at tide-gauge locations of glacial isostatic adjustment predictions with global positioning system measurements. Journal of Coastal Research, 28(4): 739–744.

Intergovernmental Panel on Climate Change (IPCC) 2001. Climate Change 2001. 3rd Assessment Report of the IPCC.

Intergovernmental Panel on Climate Change (IPCC) 2007. Climate Change 2007: The Physical Science Basis. Summary for Policy Makers. 4th Assessment Report of the IPCC.

Intergovernmental Panel on Climate Change (IPCC) 2013. Climate Change 2013: The Physical Science Basis. Summary for Policy Makers. 5th Assessment Report of the IPCC.

Jevrejeva, S., Moore, J.C., Grinsted, A. and Woodworth, P.L. 2008. Recent global sea-level acceleration started over 200 years ago? Geophysical Research Letters, 35: L08715–L08715.

Keenlyside, N.S., Latif, M., Jungclaus, J., Kornblueh, L. and Roeckner, E. 2008. Advancing decadal-scale climate prediction in the North Atlantic sector. Nature, 453: 84–88.

Kench, P.S., McLean, R.F., Brander, R.W., Nichol, S.L., Smithers, S.G., Ford, M.R., Parnell, K.E. and Aslam, M. 2006. Geological effects of tsunami on mid-ocean atoll islands: The Maldives before and after the Sumatran tsunami. Geology, 34: 177–180.

Lambeck, K. and Nakada, M. 1990. Late Pleistocene and Holocene sea-level change along the Australian coast. Palaeogeography, Palaeoclimatology, Palaeoecology, 89: 143–176.

Leahy, S. 2012. At the edge of the carbon (sic) cliff. *Guardian*, U.K. http://www.guardian.co.uk/environment/2012/dec/18/carbon-emissions-climate-change.

Leuliette, E. 2012. The budget of recent global sea-level rise 2005–2012. NOAA National Environmental Satellite, Data and Information Service.

Leuliette, E. and Willis, J. 2011. Balancing the sea-level budget. Oceanography, 24(2): 122–129.

Lyman, J.M., Willis, J.K., and Johnson, G.C. 2006. Recent cooling of the upper ocean. Geophysical Research Letters, 33: L18604.

Miller, K.G. Sugarman, P.J., Browning, J.V., Horton, B.P., Stanley, A., Kahn, A., Uptegrove, J., and Aucott, M. 2009. Sea-level rise in New Jersey over the past 5000 years: Implications to anthropogenic changes. Global and Planetary Change, 66: 10–18.

Mörner, N.A. 2004. Estimating future sea-level changes from past records. Global and Planetary Change, 40(1–2): 49–54.

Mörner, N.A. 2012. Sea-level is not rising. SPPI Reprint Series. http://scienceandpublicpolicy.org/blog_watch/sea_level_is_not_rising.html.

Moore, M. 2013. The Proactionary Principle. http://www.maxmore.com/proactionary.htm.

Murray Wallace, C.V. and Belperio, A.P. 1991. The last interglacial shoreline in Australia – a review. Quaternary Science Reviews, 10, 441–461.

Nicholls, R.J. 2011. Planning for the impacts of sea-level rise. Oceanography 24(2): 144–157.

PALSEA 2010. The sea-level conundrum: case studies from palaeo-archives. Journal of Quaternary Science, 25: 19–25.

Penning-Rowsell, E.C., Haigh, N., Lavery, S. and McFadden, L. 2013. A threatened world city: the benefits of protecting London from the sea. Natural Hazards, 66: 1383–1404.

Perkins, D. 2007. The long demise of the Wantsum sea channel: a recapitulation based on the data. Archaeologia Cantiana, 127: 249–259

Pfeffer, W.T. 2011. Land ice and sea-level rise. Oceanography, 24(2), 95–111

Rahmstorf, S. 2007, Response to Comments on 'A semi-empirical approach to projecting future sea-level rise'. Science, 317: 1866–1866.

Robinson, A.H.W. and Cloet, R.L. 1953. Coastal evolution in Sandwich Bay. Proceedings of the Geologists' Association, 64(2): 69–82.

Schmith, T., Johansen, S. and Thejll, P. 2007. Comment on 'A semi-empirical approach to projecting future sea-level rise'. Science, 317: 1866–1866.

Shennan, I. and Horton, B. 2002. Holocene land- and sea-level changes in Great Britain. Journal of Quaternary Science, 17: 511–526.

So, C.L. 1965. Coastal platforms of the Isle of Thanet, Kent. Transactions of the Institute of British Geographers, 37: 147–156.

Teferle, F.N, Bingley, R.M., Williams, S.D.P, Baker, T.F. and Dodson, A.H. 2006. Using continuous GPS and absolute gravity to separate vertical land movements and changes in sea-level at tide-gauges in the UK. Philosophical Transactions of the Royal Society A, 364(1841): 917–930.

Toscano, M.A. and Macintyre, I.G. 2003. Corrected Western Atlantic sea-level curve for the last 11,000 years based on calibrated 14C dates from *Acropora palmata* framework and intertidal mangrove peat. Coral Reefs, 22(3): 257–270.

UK Met Office 2012. Cited in Rose D., Global warming stopped 16 years ago, reveals Met Office report quietly released... and here is the chart to prove it. *Mail on Sunday*, 13 October 2012. http://dailym.ai/1dipYXj.

Waller, M.P. and Long, A.J. 2003. Holocene coastal evolution and sea-level change on the southern coast of England: a review. Journal of Quaternary Science, 18(3–4): 351–359.

Watson, P.J. 2011. Is there evidence yet of acceleration in mean sea-level rise around mainland Australia? Journal of Coastal Research, 27: 368–377.

Webb. A.P. and Kench, P.S. 2010. The dynamic response of reef islands to sea-level rise: Evidence from multi-decadal analysis of island change in the Central Pacific. Global and Planetary Change, 72: 234–246.

Whitehouse D. The Global Warming Standstill. GWPF Report 10, 2013.

Willis, J.K. et al. 2007. Correction to 'Recent cooling of the upper ocean'. Geophysical Research Letters 34: 16.

Willis, J. K., Chambers, D.P. and Nerem, R.S. 2008. Assessing the globally averaged sea-level budget on seasonal to interannual timescales. Journal of Geophysical Research, 113: C06015.

Woodworth, P.L., White, N.J., Jevrejeva, S., Holgate, S.J., Church, J.A. and Gehrels, W.R. 2009. Evidence for the accelerations of sea-level on multi-decade and century timescales. International Journal of Climatology, 29: 777–789.

Woodworth, P.L., Tsimplis, M.N., Flather, R.A. and Shennan, I. 1999. A review of the trends observed in British Isles mean sea-level data measured by tide-gauges. Geophysical Journal International, 136(3): 651–670.

Wunsch, C., Ponte, R.M. and Heimbach, P. 2007. Decadal trends in sea-level patterns: 1993–2004. Journal of Climate, 20(24): 5889–5911.

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