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PERSPECTIVE

Sea-level rise: towards understanding local vulnerability

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Projections of global sea-level rise into the future have become more pessimistic over the past five years or so. A global rise by more than one metre by the year 2100 is now widely accepted as a serious possibility if greenhouse gas emissions continue unabated. That is witnessed by the scientific assessments that were made since the last IPCC report was published in 2007. The Delta Commission of the Dutch government projected up to 1.10 m as a 'high-end' scenario (Vellinga *et al* 2009). The Scientific Committee on Antarctic Research (SCAR) projected up to 1.40 m (Scientific Committee on Antarctic Research 2009), and the Arctic Monitoring and Assessment Programme (AMAP) gives a range of 0.90–1.60 m in its 2011 report (Arctic Monitoring and Assessment Programme 2011). And recently the US Army Corps of Engineers recommends using a 'low', an 'intermediate' and a 'high' scenario for global sea-level rise when planning civil works programmes, with the high one corresponding to a 1.50 m rise by 2100 (US Army Corps of Engineers 2011).

This more pessimistic view is based on a number of observations, most importantly perhaps the fact that sea level has been rising at least 50% faster in the past decades than projected by the IPCC (Rahmstorf *et al* 2007, IPCC 2007). Also, the rate of rise (averaged over two decades) has accelerated threefold, from around 1 mm yr^{-1} at the start of the 20th century to around 3 mm yr^{-1} over the past 20 years (Church and White 2006), and this rate increase closely correlates with global warming (Rahmstorf *et al* 2011). The IPCC projections, which assume almost no further acceleration in the 20th century, thus look less plausible. And finally the observed net mass loss of the two big continental ice sheets (Van den Broeke *et al* 2011) calls into question the assumption that ice accumulation in Antarctica would largely balance ice loss from Greenland in the course of further global warming (IPCC 2007).

With such a serious sea-level rise on the horizon, experts are increasingly looking at its potential impacts on coasts to facilitate local adaptation planning. This is a more complex issue than one might think, because different stretches of coast can be affected in very different ways. First of all, the sea-level response to global warming will not be globally uniform, since factors like changes in ocean currents (Levermann *et al* 2005) and the changing gravitational pull of continental ice (Mitrovica *et al* 2001) affect the local rise. Secondly, superimposed on the climatic trend is natural variability in sea level, which regionally can be as large as the climatic signal on multi-decadal timescales. Over the past decades, sea level has dropped in sizable parts of the world ocean, although it has of course risen in global mean (IPCC 2007). Thirdly, local land uplift or subsidence affects the local sea-level change relative to the coast, both for natural reasons (post-glacial isostatic adjustment centred on regions that were covered by ice sheets during the last ice age) and artificial ones (e.g., extraction of water or oil as in the Gulf of Mexico). Finally, local vulnerability to sea-level rise depends on many factors.

Two interesting new studies in this journal (Tebaldi *et al* 2012, Strauss *et al* 2012) make important steps towards understanding sea-level vulnerability along the coasts of the United States, with methods that could also be applied elsewhere.

The first, by Strauss and colleagues, merges high-resolution topographic data and a newly available tidal model together with population and housing data in order to estimate what land area and population would be at risk given certain increments in sea level. The results are mapped and tabulated at county and city level. They reveal the 'hot spots' along the US coast where sea-level rise is of the highest concern because of large populations living near the high-tide line: New York City and Long Island; the New Jersey shore; the Norfolk, Virginia, area; near Charleston, South Carolina; coastal cities across Florida, especially its southeast and the Tampa area; New Orleans; the San Francisco Bay Area and San Joaquin Delta; and greater Los Angeles. Overall, 3.7 million people across the US are estimated to live within 1 m of the present high-tide line.

The second paper, by Tebaldi *et al*, specifically looks at storm surges and how their frequency is expected to change along the US coastline in the coming four decades due to rising sea levels. They first estimate future local sea-level rise relative to the land by combining the observed local trend of the past fifty years with a future acceleration due to global warming as estimated by a semi-empirical model (Vermeer and Rahmstorf 2009). Then they use past storm surge statistics for many different locations and shift the return level curves according to the projected sea-level rise. The authors find that by mid-century, in some locations what is now a once-per-century flooding event could become an annual event. Those are exceptional places—but at about a third of the sites investigated, a century flood could become a once-per-decade flood.

Of course, many of these events need not have dramatic impacts: in fact, locations where rare floods are quite small in amplitude (and hence presumably modest in their impacts) are precisely those where the return period decreases most dramatically. In a place where the once-per-century flood is only 50 cm higher than the annual flood, a typical 30 cm rise in sea level makes a bigger difference than one in a place where the century flood is 2 m higher than the annual flood. Nevertheless, the expected large changes in return periods and return levels of storm surges clearly demonstrate that accounting for accelerating sea-level rise is vital in the planning and design of coastal infrastructure.

But most importantly, these studies highlight the fact that the modern world, with many millions of people living right by the coast, is highly vulnerable to even modest sea-level rise. Losing just 1% of the present continental ice would raise sea level globally by about 75 cm—a tiny amount in the perspective of palaeoclimate history, e.g. the 120 m rise at the end of the last ice age, but a large amount in terms of impacts on human society. We should do everything we can to limit global warming and thereby sea-level rise to a manageable level.

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