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Relative sea-level rise and the conterminous United States: Consequences of potential land inundation in terms of population at risk and GDP loss

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ABSTRACT

Global sea-level rise poses a significant threat not only for coastal communities as development continues but also for national economies. This paper presents estimates of how future changes in relative sea-level rise puts coastal populations at risk, as well as affect overall GDP in the conterminous United States. We use four different sea-level rise scenarios for 2010–2100: a low-end scenario (Extended Linear Trend) a second low-end scenario based on a strong mitigative global warming pathway (Global Warming Coupling 2.6), a high-end scenario based on rising radiative forcing (Global Warming Coupling 8.5) and a plausible very high-end scenario, including accelerated ice cap melting (Global Warming Coupling 8.5+). Relative sea-level rise trends for each US state are employed to obtain more reasonable rates for these areas, as long-term rates vary considerably between the US Atlantic, Gulf and Pacific coasts because of the Glacial Isostatic Adjustment, local subsidence and sediment compaction, and other vertical land movement. Using these trends for the four scenarios reveals that the relative sea levels predicted by century's end could range – averaged over all states – from 0.2 to 2.0 m above present levels. The estimates for the amount of land inundated vary from 26,000 to 76,000 km^2. Upwards of 1.8 to 7.4 million people could be at risk, and GDP could potentially decline by USD 70–289 billion. Unfortunately, there are many uncertainties associated with the impact estimates due to the limitations of the input data, especially the input elevation data. Taking this into account, even the most conservative scenario shows a significant impact for the US, emphasizing the importance of adaptation and mitigation.

1. Introduction

Globally, human populations along the world's coasts are at a historic high and there are no signs of a slackening in growth (Martínez et al., 2007). Martínez et al. (2007) note that in the period 1992–2002, the world's coastal population increased by 56%, while the total global population increased by 14%. Estimates suggest almost half (~44%) of the world's population presently lives within 150 km of the shoreline (United Nations World Atlas, 2012), with eight of the ten largest cities located at the shore's edge (United Nations World Atlas, 2012). Trends in the population distribution of many nations by the end of century (Martínez et al., 2007) promise to yield spatial demographics showing a large percentage of the total population near the coast.

The increase in coastal populations worldwide is alarming for many reasons, not least for what it portends for the quality of the coastal environment, which is already threatened by high levels of eutrophication and toxic materials, over-fishing and habitat destruction (e.g., estuarine degradation) (Bricker et al., 1999). However, the prospect of an accelerating rise in global sea levels has captured international attention due to the magnitude of the hazards posed and their economic and political consequences. In the case of the Maldives, the continued existence of the nation-state is at risk (Titus, 1989). There is a growing consensus (cf. Solomon et al., 2007) that global sea levels will continue to rise at historically high rates for at least the remainder of the century. This projection is largely based on thermosteric expansion of the upper levels of the ocean (Solomon et al., 2007). Some scientists (Meier et al., 2007; Pfeffer et al., 2008) argue that such a scenario could underestimate the amount of rise that could accompany a substantial collapse of the West Antarctic Ice Sheet and rapid depletion of the remaining Greenland ice masses from surging outlet glaciers. However, even without considering this risk, the

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steric-based projections alone are unsettling, in view of rapidly rising coastal populations and when scaled against the sea-level record of the last two millennia (Kemp et al., 2011). Moreover, the tempo of change envisaged for these projections (Solomon et al., 2007) suggests that the time for accommodation is very limited and that the suite of economic and social conditions now prevailing may remain the same, if not worsen, should the global recession have a 'long tail'.

In this paper, we consider the consequences of four different scenarios of future sea-level rise in coastal communities and regional economies in the United States. The US presents a good test case for the impact of future sea levels on highly developed, post-industrial countries due to its size and the number of communities at risk, which differ in population size, economic activity and integration, as well as infrastructure type and density. Moreover, these many communities range across a number of coastal types, tidal and other oceanographic factors, on a regional and national scale. Since present rates of sea-level rise can differ significantly (Sallenger et al., 2012), using changes in *relative sea-level* (*RSL*) rise based on tide gauge records from across the entire continental US allows for a realistic prediction of the consequences of sea-level rise. Our analysis considers three indicators: land inundation, population at risk and decline in Gross Domestic Product (GDP). All three indicators can be viewed as general aggregate measures of vulnerability at the national level. Coastal populations and land loss, as well as GDP, provide both broad denominators for different impact categories and measurable and quantifiable outcomes.

We have decided to look at the permanent character of land inundation due to sea-level rise, which provides a possible impact analysis for the entire US coastline. Note that brief events such as hurricanes and storm surges can cause even more damage locally than projected in this research. We do not presume that an analysis of inundation is more important than storm surges, but rather that both types of analysis are complementary. For storm surge impact analysis we refer to Hoffman et al. (2010), who performed an extensive analysis relating to storm surge damage for the US east coast to 2030.

2. Methods

2.1. Tide gauges and sea-level scenarios

Whatever the estimates for present rates of global sea-level rise, such information is only appropriate for broad, synoptic assessments of coastal inundation and land loss (Nicholls and Leatherman, 1996). For local or even regional estimates (depending on the scale) only the changes that incorporate both ocean volume change and land level movement – i.e., *relative sea-level rise* – can be used for realistic decision-making, since factors such as vertical land movement from deltaic subsidence or postglacial rebound can either skew or even override the global signal rise (Emery and Aubrey, 1991). Four scenarios were developed to provide a balanced assessment of potential sea-level rise. The scenarios in this study are based on historic tide gauge records. The historic RSL per state were obtained from the Permanent Service for Mean Sea Level (PSMSL, 2012). Records that span the period 1950–2010 were used to ensure a uniform timespan for all states. The historic monthly RSL rise for each particular state was determined by averaging the monthly tide gauge data points for each state and running a linear regression through the averaged set of data points.

As there were no PSMSL tide gauge records for New Hampshire, Mississippi and Alabama that spanned the period 1950–2010, records from bordering states were used to calculate RSL rise for those states. The tide gauges used are listed in Table 1 in the column 'Tide Gauges Included'. With regard to the Pacific Coast, additional oceanographic factors must be taken into account. Wind stress curl changes along the Pacific Coast have likely dampened rates of RSL during the last 30 years (Bromirski et al., 2011), rendering tide gauge records for the period 1950–2010 not sufficiently representative of the actual long-term rise. Hence, only two very long-term tide gauge records (starting before 1900)

Table 1
Relative Sea-level (RSL) estimates for 2100, defined per state for the four scenarios: ELT, GWC2.6, GWC8.5 and GWC8.5+. The table includes the tide gauges used per state.

Coast	State	Tide gauges included (ID#)	Sea-level rise rate 1950–2010 (mm/year)	RSL in 2100 (m)			
				ELT	GWC2.6	GWC8.5	GWC8.5+
Atlantic Coast	ME	Portland (183); Eastport (322); Bar Harbour (525)	1.56	0.1	0.1	0.4	1.3
	NH	Boston, Massachusetts (235); Portland, Maine (183)	1.82	0.2	0.2	0.6	1.6
	MA	Boston (235); Woods hole (367)	2.42	0.2	0.2	0.7	1.9
	RI	Newport (351); Providence (430)	2.19	0.2	0.2	0.6	1.8
	CT	New London (429)	2.50	0.2	0.2	0.8	2.0
	NY	New York (12); Montauk (519)	2.94	0.3	0.2	0.8	2.1
	NJ	Philadelphia (135); Atlantic City (180); Sandy Hook (366)	3.70	0.3	0.3	1.1	2.4
	DE	Lewes (224)	3.35	0.3	0.3	1.1	2.3
	MD	Baltimore (148); Annapolis (311); Solomon's Island (412)	3.24	0.3	0.2	0.9	2.1
	D.C.	Washington D.C. (360)	2.98	0.3	0.2	0.9	2.0
	VA	Sewells Point (299); Kiptopeke Beach (636)	4.01	0.4	0.3	1.2	2.5
	NC	Wilmington (396)	2.31	0.2	0.2	0.6	1.6
	SC	Charleston I (234)	2.90	0.3	0.2	0.8	1.9
	GA	Fort Pulaski (395)	3.20	0.3	0.2	0.9	2.0
	FL	Key West (188); Cedar Key II (428); Pensacola (246); St. Petersburg (520); Fernandina Beach (112);	2.36	0.2	0.2	0.7	1.7
Pacific Coast	WA	Seattle (127)	2.00[a]	0.2[a]	0.2[a]	1.0[a]	2.2[a]
	OR	–	–	0.2[a]	0.2[a]	0.9[a]	2.1[a]
	CA	San Francisco (10)	1.55[a]	0.1[a]	0.2[a]	0.9[a]	2.1[a]
Gulf Coast	TX[b]	Galveston II (161); Port Isabel (497)	3.82[b]	0.3	0.2	1.0	2.3
	LA	Grand Isle (526)	9.42	0.8	0.6	2.5	4.3
	MS	Pensacola, Florida (246)	2.12	0.2	0.2	0.6	1.6
	AL	Pensacola, Florida (246)	2.12	0.2	0.2	0.6	1.6

[a] NB: Due to large local variability in vertical land movement, it is deemed impossible to provide an average sea-level rise prediction on the state level for the Pacific Coast states. The results here are based on two very long-term tide gauge records (Seattle, #127: 1899–2010 and San Francisco, #10: 1880–2010) and are listed to provide a basis for a 'what-if' impact analysis.
[b] Estimates for Texas are corrected for recent policy measures that can greatly influence RSL rise, as described in the text.