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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.

were used (e.g., Seattle, Washington, PSMSL ID #127; San Francisco, California, PSMSL ID #10). Since there were no very long-term tide gauges available for Oregon: (The Astoria tide gauges is unfortunately influenced by the Columbia River outflow (PSMSL, 2012)), the results for this state were estimated as the average of the outcomes for Washington and California.

The RSL for the four scenarios in 2100 was used to calculate the socioeconomic impact and the impact on land for each state on the Pacific, Atlantic and Gulf coasts of the conterminous United States. The four scenarios represent the lower (ELT and GWC2.6 scenarios) and upper limits (GWC8.5 and GWC8.5+ scenarios) predicted for RSL rise. Thus, a plausible range of possible outcomes is provided.

2.1.1. Scenario 1 – Extended Linear Trend (ELT)

The ELT Scenario is an extrapolation of the linear trend from the 1950–2010 Permanent Service for Mean Sea Level (PSMSL, 2012) tide gauge records to 2100. As described above, the RSL rise for a particular state was determined by averaging the monthly tide gauge data points for each state and by running a linear regression through the new set of data points. Since global sea-level rise is expected to increase in an exponential, non-linear fashion (Solomon et al., 2007), such a linear forecast can effectively serve as a lower limit for future sea-level rise, simply extrapolating present conditions.

2.1.2. Scenario 2 – Global Warming Coupling: radiative forcing 2.6 W/m² in 2100 (GWC2.6)

Recent estimations of sea levels indicate that sea-level rise is proportional to the magnitude of warming above the temperatures of the pre-industrial age (cf. Rahmstorf, 2007). These considerations are incorporated into the GWC2.6 scenario by employing a simple linear Eq. (1) to link the global atmospheric surface temperature change to relative sea-level rise (RSLR) in a given month n:

$$RSLR_n = \frac{1}{12}(\alpha \cdot \Delta T + \beta). \tag{1}$$

In this scenario and in the other Global Warming Coupling scenarios (GWC8.5 and GWC8.5+), α was determined *for each state* by the slope between the historic annual sea level for that state (as mentioned) and the global land-ocean temperature index (Hansen et al., 2010). Thus, a specific α was obtained for each state.

The IPCC fifth assessment (AR5) RCP2.6 emission scenario was used for ΔT. The RCP2.6 scenario assumes a strong mitigative pathway, which results in a 'peak & decline' radiative pathway, leading to 2.6 W/m^2 in 2100 (Taylor et al., 2009; Riahi et al., 2011; van Vuuren et al., 2011). The ΔT was determined by T_n–T_{n-12} to smooth seasonal signals. The RCP2.6 scenario is a so-called 'low-end' scenario as it depicts a lower limit of predicted global warming, meaning the GWC2.6 scenario is also 'low-end'.

β represents the major geophysical variable of glacial isostatic adjustment (GIA), which influences rates of RSL rise at mid to high latitudes. This phenomenon characterizes most of the US Atlantic coast and the US northwest Pacific coast. It can take the form of rebound of the earth's crust in areas that were within the coverage of the Laurentide (Atlantic Coast) or Cordilleran (Pacific Coast) ice sheets, and increases in rate from the area of the former ice margins to the centres of greatest ice accumulation (e.g., Hudson's Bay). Conversely, it can take the form of forebulge collapse (subsidence), beginning south of former ice margins during the late Wisconsin Maximum (ca. 18–21 ka), and decreasing in rate as we move further south. Present rates of GIA can be considered constant, as changes are negligible over the time scale of this study. The GIA data (Peltier, 2004) for the selected tide gauge records in each state were averaged to obtain a state-level adjustment (note that updated GIA models (e.g., Engelhart et al., 2011) will be available from: http://www.psmsl.org).

2.1.3. Scenario 3 – Global Warming Coupling: radiative forcing 8.5 W/m² in 2100 (GWC8.5)

The GWC8.5 scenario follows Eq. (1), with α and β being the same. The IPCC fifth assessment (AR5) RCP8.5 emission scenario was used for ΔT. The RCP8.5 assumes a high population growth and relatively slow income growth, with modest rates of technological change and energy intensity improvements, which results in a rising radiative pathway, leading to 8.5 W/m^2 in 2100 (Taylor et al., 2009; Riahi et al., 2011). The RCP8.5 scenario is a 'high-end' scenario as it depicts an upper limit of predicted global warming, meaning the GWC8.5 scenario is also 'high-end'.

2.1.4. Scenario 4 – Global Warming Coupling: radiative forcing 8.5 W/m² in 2100 & accelerated glacier and ice cap melting (GWC8.5+)

New evidence indicating a possible acceleration of glacier and ice cap (G&IC) melting (Meier et al., 2007; Pfeffer et al., 2008; Jevrejeva et al., 2010; National Research Council, 2012) could substantially change the range of potential global sea levels by the end of the century. We developed the GWC8.5+ scenario to accommodate such an acceleration into the GWC8.5 scenario, resulting in Eq. (2) for relative sea-level rise (RSLR) for any given month n:

$$RSLR_n = \frac{1}{12}(\alpha \cdot \varphi \cdot \Delta T + \beta + \gamma) \tag{2}$$

Here α, β and ΔT are the same as the GWC8.5 scenario. The factor γ is the additional annual sea-level rise from accelerated glacier and ice cap melting, and is obtained by determining the annual RSL rise and averaging the prediction by Meier et al. (2007) and the 'low1′ and 'high1′ scenarios by Pfeffer et al. (2008). The contribution of glaciers and ice caps included in the IPCC assessment (or non-accelerated G&IC melting) were subtracted from γ as this was already accounted for under the GWC8.5 scenario. Again, the IPCC fifth assessment (AR5) RCP8.5 scenario was used for ΔT. As in equation (1), ΔT was determined by T_n–T_{n-12} to smooth seasonal signals.

The IPCC has been challenged for its apparent underestimation of global warming and sea-level rise (Horton et al., 2008; Grinsted et al., 2010; Jevrejeva et al., 2010). In the fourth IPCC assessment report, a −40% and +60% range of the model outcome was assumed to be likely (Solomon et al., 2007). We use the value $\varphi = 1.6$, corresponding to the upper range of this uncertainty (Solomon et al., 2007), although in the final AR5 the assumed range of likely outcomes might be smaller. The GWC8.5+ scenario is classified as a very high-end scenario that shows a plausible upper limit for sea-level rise.

2.2. The significance of α

Correlations between the global mean temperature (Hansen et al., 2010) and the annual mean RLS rise (significant at 1%, $r > 0.7$) were found for 12 of the 14 Atlantic coastal states. For the Gulf Coast, only Mississippi and Alabama showed lower correlations ($r = 0.69$), but they were still close to significant at 1%. All three Pacific Coast states showed lower correlations for the relationship between global mean temperature and the annual mean sea-level rise per state ($0.4 < r < 0.6$) over the period 1950–2010. As noted, Bromirski et al. (2011) attribute this disparity to the suppression of sea-level rise due to anomalous wind stress curl during the last three decades. Nevertheless, when comparing the global mean temperature with the very long-term tide gauge records for the Pacific Coast, significant correlations were found for both Seattle (1899–2010; $r = 0.79$) and San Francisco (1880–2010; $r = 0.78$).

Since it can be argued that the suppression effect of persisting wind stress on sea-level rise on the Pacific Coast will cease in the near future (Bromirski et al., 2011), the relationship found for the long-term records was used as α for the Pacific Coast.

2.3. Hindcasting sea-level changes from 1950–2010

A hindcast using Eqs. (1) and (2) was performed and analyzed for the period 1950–2010 using the confidence interval method for trendlines posed by Santer et al. (2000). For the GWC2.6 and GWC8.5 scenarios it was found that for 8 of 22 coastal states (including Washington D.C.), the null hypothesis '*the trends are not significantly different from the historic trend*' had to be rejected. For those eight states we must conclude, with a 95% confidence interval, that the '*the trends are significantly different from the historic trend*', or, in other words, that the trendline of the hindcast did not conform to reality. Eq. (3) was used to correct the predicted sea level for 2100 for the states for which the null hypothesis had to be rejected. Washington and California were excluded from this correction, as it was already expected that the hindcast would be different from the real values due to the suppressed sea-level rise trends for the last 30 years (Bromirski et al., 2011), and thus that the values found were therefore considered valid:

$$Adjusted\,RSL_{n_0-n} = RSL_{n_0-n} + \Delta Trend * (n - n_0) \qquad (3)$$

The adjusted RSL for 2100 was calculated by adding Δ *Trend* (mm/year), multiplied by the time period (n_0 = 2010, n = 2100), to the predicted RSL for 2100. The Δ *Trend* for the GWC2.6 and GWC8.5 scenarios were calculated by *historic trend (1950–2010) – scenario trend (1950–2010 hindcast)*. As a result, the RSL_{2100} will be adjusted down when the trend is overestimated and up when the trend is underestimated.

For the GWC8.5+ scenario, the same null hypothesis had to be rejected for the majority of the states. This was to be expected since the uncertainty attribute φ in the GWC8.5+ scenario causes the hindcast to be off by a factor of 1.6. Since the attribute φ represents an uncertainty in sea-level rise in the future, the GWC8.5+ results can still be considered valid as a plausible *future* sea-level scenario.

2.4. Estimated impact on the population and GDP for each state

The results for RSL rise per state shown in Table 1 served as the input for the impact assessment. The impact of RSL rise on the US coasts was analyzed by using ArcMap 10, ArcGIS® software by Esri. To assess inundation due to RSL rise, National Elevation Dataset (NED) files with a spatial resolution of 1 arc second were obtained from the database of the US Geological Survey (Gesch et al., 2002; Gesch, 2007). All NED data for the conterminous United States were referenced to the North American Vertical Datum of 1988 (NAVD88).

Erosion and land accretion and migration were not considered. Since they depend on specific local factors (e.g., geology, sediment supply, wave energy), they are unsuitable as broad denominators for national-scale national assessments. For instance, the relative short stretch of shore in Georgia shows erosion rates of $>$ 2 m/year at some points, and accretion rates of $>$ 2 m/year at others (Hammar-Klose and Thieler, 2001). However, erosion is of great concern and therefore we refer to Leatherman (2001), Hammar-Klose and Thieler (2001), Gutierrez et al. (2007), FitzGerald et al. (2008) and the National Research Council (2012) for extensive discussions on erosion, accretion and migration.

Inundation maps were created for the projected sea levels in 2100 for each of the different scenarios and translated into km^2 per state. State and county cartography were obtained from the Tiger (*Topologically Integrated Geographic Encoding and Referencing*) database (available from: http://www.census.gov/geo/maps-data/data/tiger-line.html). To assess the population at risk, population density data (GRUMPv1) was obtained from the Centre for International Earth Science Information Network (CIESIN et al., 2004). Gridded population density for 2000 was used because it has the highest resolution (30 arc seconds) for a national-scale assessment. The GRUMPv1 data was resampled to a cell size of 1 arc second to match the inundation map resolution (as resampling from 30 arc-second cells to 1 arc-second cells was done, there was no loss of accuracy). The population at risk was calculated by the overlap of the population density data with the inundation maps. To assess hindrance to GDP production, we assumed that GDP is produced where people live. To calculate the portion of GDP production affected by sea-level rise, we multiplied *GDP per capita for each county* by the population density data to create a GDP distribution map. *GDP per capita for each county* was calculated using the corresponding databases of *GDP for each county* and *total population for each county* from the Spatial Trends in Coastal Socioeconomics (STICS) database of the National Oceanic and Atmospheric Administration (available from: http://coastalsocioeconomics.noaa.gov/download/download2.html). GDP per capita for each county was also resampled from 30 arc seconds to 1 arc second so that the resulting GDP distribution maps matched the resolution of the inundation maps. The GDP distribution maps were assembled using GRUMPv1 data, which is partially based on night-time street lighting. Therefore, the GRUMPv1 algorithm also distributes population to tourist areas, even if there are no persons registered in such seashore addresses.

2.5. Data limitations

Before discussing the results, it is important to consider the current difficulties involved in sea-level rise impact assessments, as there are many compounding uncertainties involved. Uncertainties in measuring RSL rise, challenges in predicting the magnitude of change, and the difficulty in acquiring appropriate data and determining methodologies to quantify impacts, all add up and make sea-level rise impact assessments difficult (Kettle, 2012). Several papers discuss these uncertainties in detail (Gesch, 2009; Gesch et al., 2009; Lichter et al., 2011; Gesch, 2012; Kettle, 2012; Mondal and Tatem, 2012). We strongly recommend that these papers are considered in addition to this impact analysis. We have addressed several uncertainties by using sufficiently long tide gauge records (>50 years), including hindcasts, and by providing four different scenarios, ranging from low to very high impact. However, it is important to discuss the inherent error in the data used in more detail.

National-scale and local-scale assessments suffer from the inherent vertical error of the elevation data. Unfortunately, for national-scale assessments, the NED dataset is the most accurate set available that spans the conterminous United States. The vertical error for the dataset, determined by RMSE, is 2.44 m (Gesch, 2007). This puts the results presented in Table 1 within the bounds of statistical uncertainty. This is true for previous national-scale and local-scale assessments, but is more than often ignored (Gesch, 2009; Gesch et al., 2009; Lichter et al., 2011; Gesch, 2012). More accurate LiDAR elevation data is becoming available, but currently this data is still lacking for many coastal areas (Gesch, 2009; Gesch et al., 2009; Evans, 2013).

The same limitation is true for population data. However, inherent errors are more difficult to quantify. In this analysis we used GRUMPv1 population data, but other models such as LandScan are available. Mondal and Tatem (2012) have analyzed the difference between the two and found that 'tract-level count data used as input resulted in very similar population distributions for the US, as quantified by LandScan and GRUMPv1, producing

Table 2
Impact of RSL rise on the inundation of land, population at risk and GDP production for the US coastal states. State abbreviations are given as well as the length of the coastline per state, which is based on calculations by NOAA (2012).

Coast	State	Coastline (km)	Inundated land (km^2)				Population at risk ($\times$ 1000)				GDP affected (USD $\times$ billion)			
			ELT	GWC2.6	GWC8.5	GWC8.5+	ELT	GWC2.6	GWC8.5	GWC8.5+	ELT	GWC2.6	GWC8.5	GWC8.5+
Atlantic Coast	ME	5597	366	366	470	706	12	12	16	28	0.21	0.12	0.32	0.63
	NH	211	29	29	36	62	4	4	4	10	0.05	0.05	0.06	0.25
	MA	2445	26	26	83	246	15	15	48	115	0.89	0.89	3.39	6.73
	RI	618	48	48	80	126	21	21	32	53	0.50	0.50	0.77	1.23
	CT	995	10	10	40	78	5	5	18	36	0.29	0.29	0.94	1.91
	NY	4225	154	120	260	496	131	96	228	550	2.93	1.87	5.37	14.95
	NJ	2884	665	665	1157	1907	157	157	262	536	4.08	4.08	7.93	18.96
	DE	613	30	30	266	584	3	3	11	34	0.16	0.16	0.50	1.66
	MD	5130	711	492	1568	2455	71	58	106	177	1.17	0.94	2.06	4.00
	D.C.	–	2	1	4	6	2	2	5	8	0.41	0.34	0.78	1.32
	VA	5335	886	702	1757	2724	58	50	132	347	1.32	1.08	3.78	11.80
	NC	4432	1432	1432	3939	6501	32	32	65	128	0.59	0.59	1.43	3.09
	SC	4628	662	539	1300	2764	34	25	55	129	0.93	0.69	1.72	4.88
	GA	3772	592	496	1347	2219	9	7	27	69	0.28	0.22	0.90	2.55
	FL	13,576	2585	2585	6662	13,655	349	349	722	2823	7.31	7.31	18.19	98.20
Pacific Coast	WA	4870	31	31	132	532	7	7	15	46	0.18	0.18	0.18	0.93
	OR	2270	10	10	54	254	2	2	4	14	0.00	0.00	0.03	0.27
	CA	3427	1026	1053	1281	2300	29	53	83	241	0.80	1.03	2.96	11.52
Gulf Coast	TX	5406	400	260	1315	6163	15	13	31	210	0.55	0.49	1.19	8.29
	LA	12,426	20,329	17,128	27,000	31,048	925	851	1391	1764	53.43	49.41	77.74	94.62
	MS	578	28	28	152	548	1	1	11	36	0.02	0.02	0.20	1.20
	AL	977	129	129	237	881	4	4	6	13	0.03	0.03	0.07	0.26
	Total	84,415	30,150	26,181	49,140	76,256	1885	1750	3272	7367	76	70	130	289

only 0.1% differences between the two Population At Risk estimates, despite substantial Low Elevation Coastal Zone (LECZ) populations in excess of 25 million'. Even though GRUMPv1 and LandScan are currently best suited for impact analysis along the US coast, Mondal and Tatem (2012) note that there is a great need of accurate, contemporary and detailed census data for use in climate change impact studies.

The calculation of GDP is based on a general assumption that GDP is produced where people live (or more precisely, it is based on the GRUMPv1 population distribution). This, of course, causes discrepancies, which we have partly accounted for, as in the example of tourism. However, large industrial areas (e.g., oil and gas production fields) could have a very low population count in the GRUMPv1 data and would therefore not be accounted for in this research. Results found on GDP could therefore be significantly higher in those areas with large-scale industry in sparsely populated coastal regions. The results presented here could thus be considered minimum potential impacts on GDP for each scenario.

Furthermore, we used the NAVD88 vertical datum to extrapolate the impact of sea-level rise. Another approach would be to convert the vertical datum to the Mean High Water (MHW) level. However, there are additional uncertainties and limitations to such an approach (Allen et al., 2010) and therefore we did not adopt this vertical datum. Note that for detailed analyses it could be more appropriate to use the MHW.

By using RSL, the work presented improves on previous national-scale assessments, but must still be used with caution until more accurate data is available. Data provided in Table 2 should not be used as absolute true values but should rather be considered as minimum indicative values for the different scenarios. The values allow for a comparison between states in terms of land inundation, population at risk and GDP affected, which offers an improved understanding of the potential impact of sea-level rise.

3. Results

3.1. Relative sea-level rise by state

Table 1 presents the results of the scenarios of RSL rise for each state along the Atlantic, Pacific and Gulf coasts. The averages over all states of the estimated RSL rise are 0.3, 0.2, 0.9 and 2.0 m for the ELT, GWC2.6, GWC8.5 and GWC8.5+ scenarios, respectively. Of all the states, the lowest levels for all scenarios is Maine and the highest Louisiana. Differences in vertical land movement show distinct variations in RSL rise for the Atlantic, Pacific and Gulf coasts. We included the sea-level rise rates calculated for the period 1950–2010. Note that, as explained, these are averages of tide gauges, and the calculated rate of sea-level rise for the individual tide gauge records in one state can vary. This can be explained by (1) the distance between the tide gauges and consequent influence of the GIA process and (2) local effects on the tide gauges. A trade-off between accuracy and scale is inevitable when using local tide gauges for state or national-level assessments.

A correction was made to the estimation of the RSL rise for Texas to account for past and future policies designed to prevent land subsidence. A decrease in subsidence was found to take place in Texas after the formation of the Harris-Galveston Coastal Subsidence District and the implementation of extraction reduction policies (Holdahl et al., 1989; Emery and Aubrey, 1991; Nicholls and Leatherman, 1996). The impact of this change was incorporated by calculating a new α for the Galveston tide gauge (#161). This was done through the removal of the residual component (mm/year) (representing local subsidence, Nicholls and Leatherman, 1996) from the historic data, and the calculation of a new relation for α. This new α represents the cessation of local subsidence, and a new estimate for RSL rise was then derived by averaging results for Port Isabel (#497) and Galveston (#161).

Along the Atlantic Coast, RSL rise steadily increases from the northeast to the mid-Atlantic Coast and then steadily decreases to the south Atlantic. Engelhart et al. (2009) used a database of late Holocene sea levels for the Atlantic Coast and found roughly similar trends, attributing them to Glacial Isostatic Adjustment. Nicholls and Leatherman (1996) found that, especially in Virginia, the influence of local effects such as subsidence is very high, whereas in North Carolina the influence of local subsidence is very low (possibly due to tectonic uplift of the Cape Fear Arch, as mentioned by Thieler and Hammar-Klose, 1999). With the inclusion of the results for Virginia and North Carolina provided by Nicholls and Leatherman (1996), our results show a similar general pattern as found by Engelhart et al. (2009). Note that since the Wilmington tide gauge (#396) is located on the Cape Fear Arch, other parts of North Carolina might show RSL rise that is more comparable to Virginia and South Carolina (Kemp et al., 2011). The opposite is true for Sandy Hook (#366) and Atlantic City (#180), due to sediment compaction and groundwater withdrawal (Sun et al., 1999; Horton and Miller, 2010). Unfortunately, such local variations add uncertainty to national-scale assessments. This is an inevitable drawback of such a national-scale assessment.

The relatively low variability in the results for the Pacific Coast can be largely attributed to the lack of additional useful data, as noted above. However, a more fundamental problem is that the Pacific Coast is characterized by large differences in vertical land movement. These differences occur due to differential processes associated with the Cascadian Subduction Zone. Rates and directions of vertical movement can often vary over small areas (Nicholls and Leatherman, 1996; Thieler and Hammar-Klose, 2000b; Verdonck, 2006; Mazzotti et al., 2008; Mote et al., 2008; Komar et al., 2011; National Research Council, 2012). Furthermore, large earthquakes along the Pacific Coast could cause sudden subsidence, potentially leading to an additional rise in RSL of up to a metre or more (National Research Council, 2012). This complex situation cannot be easily modelled for a national-scale assessment, so we left the scenarios as they were. We refer to the report of the National Research Council (2012) for an extensive overview of sea-level rise on the Pacific Coast.

Land subsidence in the northern Gulf of Mexico is the most significant feature of the US Gulf Coast, exemplified by coastal Louisiana. Extraction of subsurface fluids and hydrocarbons (Kolker et al., 2011; Morton et al., 2006) is likely to be the leading cause of subsidence in the region, but other processes, including deep-crustal loading and the natural compaction of sedimentary deposits, can also contribute depending on the location (Emery and Aubrey, 1991). The tight coupling of anthropogenic fluid withdrawal and subsidence (Morton et al., 2006) leads us to conclude that in these regions, human intervention through policy can greatly affect the rate of subsidence. The Louisiana subsidence rates seem to show a temporal pattern that compares well with the pattern of onshore oil production (Morton et al., 2006; Morton and Bernier, 2010; Kolker et al., 2011). In 2012, the Coastal Protection and Restoration Authority of Louisiana published *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (Coastal Protection and Restoration Authority of Louisiana, 2012). However, the plan presents no measures to reduce subsidence. Therefore, it is assumed here that subsidence will continue at rates comparable to historic subsidence rates.

3.2. Economic and social impacts

The estimated impacts of RSL rise on population and GDP are summarized in Table 2. The values give estimates of the minimum impact in the case of no adaptive or mitigative measures being taken to counteract the threat of sea-level rise. As mentioned above, the results for RSL rise for the Pacific Coast do not reflect the great variability of vertical land movement along the Pacific Coast. Furthermore, far inland, gauges such as the Seattle tide gauge could potentially be influenced by local currents that differ from those of the open ocean. However, the results are still considered reasonably valid because the relatively high impact observed in the Puget Sound and San Francisco Bay Area accounts for the largest share of the total impact on the Pacific Coast. The total estimated area of inundated land is ~30,000, ~26,000, ~49,000 and ~76,000 km^2 for the ELT, GWC2.6, GWC8.5 and GWC8.5+ scenarios, respectively. The total estimated population at risk is ~1.9, ~1.8, ~3.2 and ~7.4 million and the GDP production is hindered by ~USD 76, 70, 130 and 289 billion per year for the ELT, GWC2.6, GWC8.5 and GWC8.5+ scenarios, respectively. Louisiana faces the biggest impact for most scenarios on all three indicators. Florida also faces major impacts on all three indicators. New York and New Jersey have relatively low levels of inundation, but because of extensive development of the coastline and high population density, the impact on population and GDP is relatively high. The opposite is true for North Carolina and Texas, with high levels of inundation, but a low impact on population and GDP. Due to the complexity of the human response to sea-level rise, we have not accounted for the growth of population and GDP in the results presented in Table 2, as including them would increase the uncertainty of the results. Therefore, we stress that the results represent a *minimum* impact under a scenario without adaptation or mitigation.

To obtain a better perspective on the vulnerability of the different coastlines, the impact shown in Table 2 is calculated as a ratio of inundated land, population at risk and GDP hindrance per 1000 km of shoreline and is shown in Fig. 1(a). The lengths of the coastlines were obtained from NOAA (2012). Washington D.C. is not included, as no information on the length of the coastline was available.

The impact of sea-level rise is different for each state due to different coastal characteristics and the difference in RSL rise. The North Atlantic Coast is highly variable in coastal landforms, but is mainly dominated by rocky coastline and cliffs (Hapke et al., 2010). Since this region also sees low RSL rise, the impact on land inundation is moderate. The Mid-Atlantic Coast is characterized by a chain of barrier islands backed by estuaries and lagoons (Thieler and Hammar-Klose, 1999; Morton and Miller, 2005). The South Atlantic Coast shows the same characteristics, but also has long stretches of linear beaches and extensive marshes (Morton et al., 2004; Morton and Miller, 2005). Wetlands are common along the Mid-Atlantic and the South Atlantic coasts (see Stedman and Dahl, 2008, for an analysis of wetland density in the US). Since these coasts are naturally low-lying areas with little or no slope, they are highly vulnerable to inundation due to RSL rise. Table 1 shows that RSL rise is high among the Mid-Altantic states. Combined with low-lying terrain, this results in increased inundation, as shown in Table 2 and Fig. 1(a).

The Gulf Coast shows features similar to the Mid and South Atlantic coasts and in general is characterized by barrier islands, lagoons and marshes that run along the coast (Thieler and Hammar-Klose, 2000a; Morton et al., 2004). Most regions are low-lying terrain, which in combination the extremely high RSL rise (due to subsidence) makes Louisiana in particular extremely sensitive to inundation. The Pacific Coast shows low values for inundation per kilometre of coastline despite the moderate RSL rise estimated. On the Pacific Coast, the Juan de Fuca plate slides under the North American plate, which causes the land to show a steep elevation from the coastline inland, reducing vulnerability to inundation (National Research Council, 2012). California shows higher results on inundated land because of the geography of the San Francisco Bay Area and a more gradual slope of the land along the coast in southern California (Thieler and Hammar-Klose, 2000b; National Research Council, 2012). While northern California has an irregular coast with steep cliffs and offshore islands, southern California has long stretches of beachfront (Hapke et al., 2006; National Research Council, 2012), making it more vulnerable to inundation. Due to lack of data, the results for long-term RSL rise are based on the San Francisco Bay Area and the Puget Sound. The results in this paper do not show the complex pattern of uplift and subsidence occurring along the Pacific Coast. But as discussed above, because the impact is significantly larger in the San Francisco Bay Area and Puget Sound than elsewhere along the Pacific Coast it still should provide a relatively good indication of the impact on land, population and GDP.

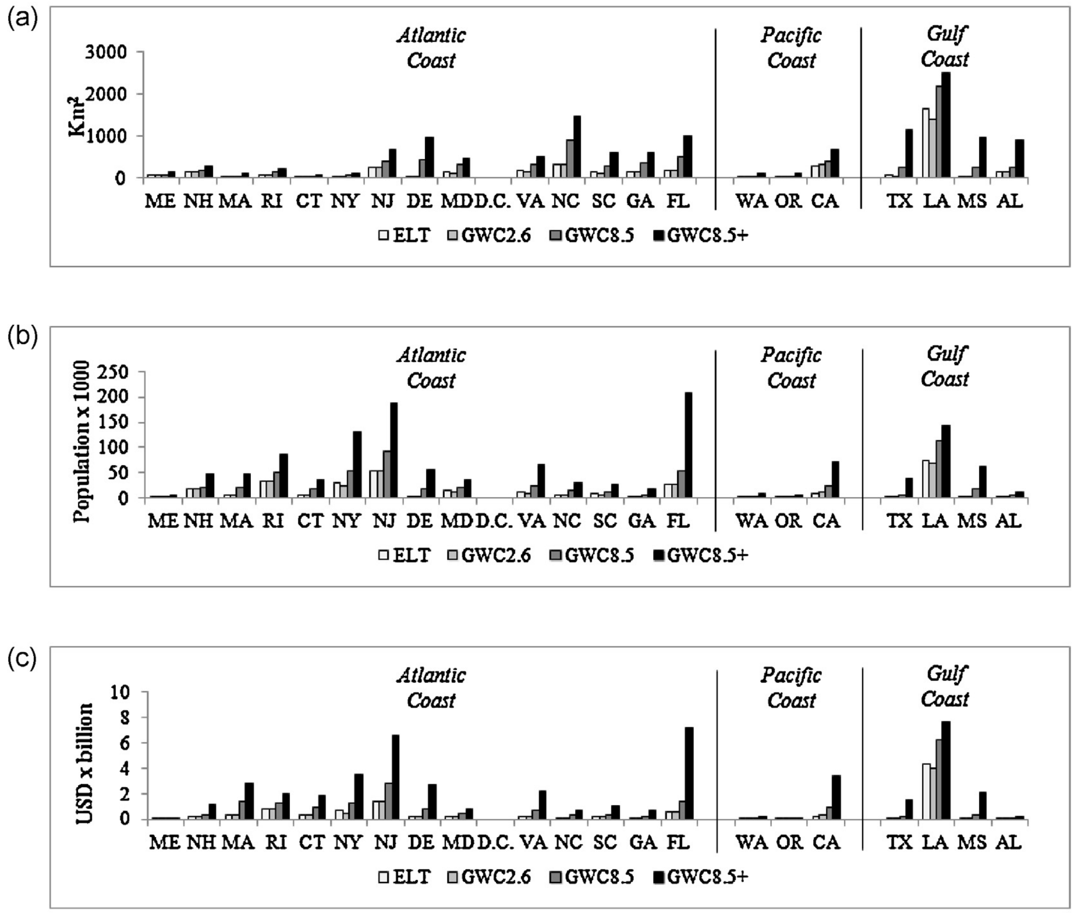

Fig. 1. Results for the ELT, GWC2.6, GWC8.5 and GWC8.5+ scenarios on: (a) km^2 of land inundated per 1000 km coastline, (b) population at risk per 1000 km coastline, and (c) GDP production affected per 1000 km coastline.

To demonstrate the socioeconomic vulnerability of the states more clearly, the impact on population and GDP, as presented in Table 2, is calculated per 1000 km of shoreline and is shown in Fig. 1(b) and (c). As GDP is related to population density, Fig. 1(b) and (c) are relatively similar, with differences occuring due to different GDP per capita for each county. Note that the results presented are an average for the whole state. The impact varies greatly on the local scale: inundation in urban areas has a far greater impact on population than inundation in rural and uninhabited areas. This becomes apparent when Fig. 1(a) is compared to Fig. 1(b) and (c). States with a relatively low density of coastal wetland and with large cities located at the sea front show a high level of population at risk despite low inundation levels due to RSL rise. This is especially true for many northeastern Atlantic coastal states (Massachusetts, Rhode Island, Connecticut, New York and New Jersey). New Jersey shows a particularly high impact on population and GDP compared with the level of land inundation. This is due to the development of all but one of its barrier islands and the tendency to fill coastal marshes for development (Titus et al., 2009). In Massachusetts, the Boston area is most vulnerable to sea-level rise due to beach shores. This coincides with the fact that the Boston area is heavily developed, with large population centres at the ocean front (Hapke et al., 2010). Therefore, the impact on population is relatively high, despite low levels of inundation. The same can be seen in Rhode Island and Connecticut. The state of New York faces the ocean at Long Island, which is moderately to densely developed (Hapke et al., 2010). However, closer to New York City, development increases. New York City itself is one of the most densely populated cities in the world. Sea-level rise impact on population is therefore large despite low levels of inundation. The majority of the states on the Mid and South Atlantic coasts that have a relatively high density of coastal wetlands show a low level of population at risk per 1000 km of coastline. This is further attributed to the fact that states such as Virginia, North Carolina, South Carolina and Georgia have most of their developed land further inland from the coast (Titus et al., 2009). Fig. 1(b) and (c) show that RSL rise will have a significant impact on population in Florida, whose coast is flat and which has large cities located near the shore. Florida is well known for its popular beachfronts and there are numerous tourist centres located at the seafront. Considering absolute impact, as shown in Table 2, Florida is one of the most vulnerable states due to its extremely long coastal border.

Compared to the Atlantic Coast, the impact on the Pacific Coast is small, except for southern California. Along the Pacific Coast, California sees the highest impact on population. This can be partly attributed to the fact that California faces the highest level of inundation, as shown in Fig. 1(a). In addition to higher levels of inundation, southern California is the most densely populated part of the Pacific Coast, with communities right by the sea (Hapke et al., 2006). The northern part of California and the coasts of Oregon and Washington are rugged and inaccessible and therefore sparsely populated, so that the impact on the population in these regions is very low (National Research Council, 2012).

Along the Gulf Coast, impact on population is moderate for Texas, Mississippi and Alabama, and is especially high in Louisiana.

This is somewhat mitigated by the fact that Louisiana has a long stretch of coast characterized by wetlands. If the absolute impact is considered, as shown in Table 2, it is clear that Louisiana is under great threat. This stems mainly from the fact that New Orleans is already below sea level, and that Louisiana continues to have rapid subsidence.

As is apparent here, each coast and each state faces a different level of threat from RSL rise. It is important to note that on a local scale, even a state with a low level of impact on the three indicators could face serious local problems. However, on a higher aggregate level, this paper provides an indication of what the minimum impact will be if no adaptive or mitigating action is taken.

4. Discussion

In this paper we estimated the consequences for land inundation and loss, for coastal populations and GDP using a straightforward relationship between global warming and RSL rise, following a similar, but simplified, relationship proposed by Rahmstorf (2007). Projected sea levels based on this approach parallel the range found by others (Rahmstorf, 2007; Horton et al., 2008; Pfeffer et al., 2008; Jevrejeva et al., 2010) and provide for comparable overall scales of land inundation along the US coast as described by Titus et al. (1991) – as well as the coastal population affected (Strauss et al., 2012) – at a certain level above present sea-level rise estimates. Titus et al. (1991) found a combined loss of dry and wetlands of ∼14,000–34,000 km^2 with a sea-level rise of 50 cm. For 100 cm of sea-level rise, they found a combined loss of dry and wetlands of ∼22,000–49,000 km^2. For 200 cm of sea-level rise, Titus et al. (1991) estimated ∼31,000–66,000 km^2 of lost land. Strauss et al. (2012) found that in the US there are approximately 3.7 million people at risk at ∼1 m sea-level rise, 5 million at ∼1.5 m sea-level rise and 6 million at ∼1.8 m sea-level rise. When compared to Table 2, these numbers fall more or less in the same range as found here. However, disparities arise due to differences in methodology and data input, and because the future estimates used here were based on *RSL trends* for every state and not a uniform figure, as employed by Titus et al. (1991) and Strauss et al. (2012). This is particularly clear, for example, for the state of Louisiana, where subsidence accounts for up to 80% of the present sea-level rise.

With respect to the economic impact, a fundamental limitation of many analyses, apart from the quality of the databases and methods (cf. Darwin and Tol, 2001), is the lack of incorporation of dynamic response factors for changes in land values due to macroeconomic inputs (the present global recession being a classic example) and how the market perception of risk may affect the desirability of coastal property if sea-level rise accelerates to a degree to which the threat would be hard to ignore. Bosello et al. (2007) point out a way in which such analyses could be undertaken, but again assume a uniform sea-level rise rather than the more accurate RSL rise. Even though we believe our research significantly improves upon previous work by employing sea-level scenarios based on RSL rise data, we do not claim that it is directly applicable to realistic coastal planning studies such as the highly focused analyses of particular localities by Ayyub et al. (2011) and Heberger et al. (2011). However, there are inevitable trade-offs in any approach on a continental scale. Hoffman et al. (2010) analyzed the average annual storm surge losses for the entire US east coast in combination with sea-level rise. Their research demonstrated a valid approach for calculating the economic impact. Extrapolation of their work from 2030 to 2100 will potentially reveal the damage that will be caused by storm surges and sea-level rise. In this research, we approached the economic impact from another angle. The use of GDP (this study) per year, linked to population density in an area inundated under different scenarios, provides a measure of the *minimum* impact at the state level for accelerated sea-level rise. As an assessment of the aggregate state-level indicator for the conterminous United States, it excludes costs such as infrastructure damage or modifications to accommodate higher sea levels, new construction in harbours, impact on recreation, not to mention the potential loss of ecosystem services. Infrastructure costs, in particular, are some of the least tractable of the array of economic factors that should be assessed, as there is little national data available on the number of structures, their age, present condition and vulnerability to permanent increases in sea level.

In addition to difficulties with economic analyses, predicting future climate processes also remains difficult. For example, it is still unclear how glaciers and ice caps will respond to continued global warming. It has been argued that global warming could cause the accelerated breakdown of the Greenland and Antarctic ice sheets (Solomon et al., 2007). Evidence of this process is already found by authors such as Meier et al. (2007) and Pfeffer et al. (2008) and it was incorporated into the very high-end scenario of this paper. However, acceleration of glacier and ice cap melting could raise sea levels even further, aggravating the impact on coastal societies and emphasizing the need for mitigation. Furthermore, the melting of ice caps could have different impacts on different regions. The US is, for instance, far more vulnerable to the melting of the Antarctic ice cap than Greenland, due to factors such as the rotation of the earth (Mitrovica et al., 2001) and gravitational forces (Spada et al., 2013). Although it is beyond the scope of this research to model such effects, these are some of many important factors to take into consideration in further analyses. Even with mitigation, sea-level rise will continue, and even if greenhouse gas emissions are reduced. Nicholls and Lowe (2004) state that even if 'greenhouse gas concentrations were (hypothetically) stabilized today, sea level would still eventually rise by more than 1 m due to thermal expansion alone, although this would take more than 1000 years'. They argue that sea-level expansion shows a lag phase of decades, or even centuries, with respect to global warming, due to the slow mixing of warm surface water with deep ocean water. This was confirmed by Meehl et al. (2012) who investigated future sea-level rise under a scenario of aggressive mitigative efforts as represented in the RCP2.6 scenario (Taylor et al., 2009; Riahi et al., 2011; van Vuuren et al., 2011), which relies on negative CO_2 emissions in 2070. Meehl et al. (2012) show that even under a scenario of decreasing global temperatures (+0.83 °C in 2100, to +0.66 °C in 2200 and +0.55 °C by 2300), sea-level rise due to the mixing of warm surface water with deeper ocean water would cause a rise in sea level from +14.2 cm in 2100 to +20.7 cm in 2200 and +24.2 cm in 2300. Although Meehl et al. (2012) do note that large uncertainties might influence the exact outcomes, the mechanism of continued sea-level rise, even with global mitigative efforts, is evidently clear. Thus, even if global warming is halted by the reduction of greenhouse gas emissions, the oceans will continue to rise long after the temperature has stabilized.

Furthermore, storm surges and other extreme events will cause brief but devastating damage if no action is taken accordingly. Findings such as those presented here therefore show a minimum (but permanent) impact and should be viewed in combination with those of others, such as Hoffman et al. (2010) and Tebaldi et al. (2012), to gain a more complete understanding of permanent inundation, increased storm surge heights and changing storm patterns.

Finally, this research shows the potential impact of sea-level rise if no action is taken. However, it is clear that action will be taken. It is estimated that adaptation strategies can reduce the impact by a factor of 10 to 100 (Parry et al., 2007). Policymakers and local coastal managers will play an important role in determining the right adaptive strategy to limit negative effects

(Tribbia and Moser, 2008). This being true, Titus et al. (2009) note that along the US Atlantic Coast property owners and land use agencies often do not incorporate sea-level rise in decision-making. Titus et al. (2009) estimate that 60% of coastal dryland below 1 m along the Atlantic Coast will be developed without planning for the future impact of sea-level rise. Only 9% of the dryland has been designated for conservation (Titus et al., 2009). This lack of long-term vision will eventually lead to increasing costs as more land and developments will require protection. Choosing the right mix of adaptive responses for each state strategy will determine whether costs will indeed increase exponentially, or whether they will remain manageable.

5. Conclusions

By using RSL rise per state, a more accurate and precise view of the consequences of rising seas can be obtained. Unfortunately, there are many uncertainties associated with the impact estimates due to the limitations of the input data, especially the input elevation data. More accurate data is needed to make sea-level rise impact assessments more robust. Taking this into account, the results presented in this paper do signal the importance of a timely response to sea-level rise, both by adaptation and mitigation. Even under the most conservative GWC2.6 scenario, a minimum of ~1.8 million inhabitants would be at risk and ~USD 70 billion in GDP production could be affected. Careful consideration of coastal management could significantly reduce the impact for seafront communities. This is true for both existing development and future planning. Furthermore, a global effort is needed to reduce greenhouse gas emissions to prevent an even further negative impact. Considering the significant minimum impact found in this paper, it is of utmost importance for local, national and global policymakers to act now and not pass on the problem to future generations.

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