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Potential impacts of sea-level rise on the Mid- and Upper-Atlantic Region of the United States

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Abstract We made projections of relative sea-level rise, horizontal inundation, and the associated impacts on people and infrastructure in the coastal portion of the Mid- and Upper-Atlantic Region (MUAR) of the United States. The output of five global climate models (GCMs) run under two greenhouse gas scenarios was used in combination with tide gauge observations to project sea-level increases ranging from 200 to 900 mm by 2100, depending on location, GCM and scenario. The range mainly reflects equal contributions of spatial variability (due to subsidence) and GCM uncertainty, with a smaller fraction of the range due to scenario uncertainty. We evaluated 30-m Digital Elevation Models (DEMs) using 10-m DEMs and LIDAR data at five locations in the MUAR. We found average RMS differences of 0.3 m with the 10-m DEMs and 1.2 m with the LIDAR data, much lower than the reported mean RMS errors of 7 m for the 30-m DEMs. Using the 30-m DEMs, the GCM- and scenario-means of projected sea-level rise, and local subsidence estimates, we estimated a total inundation of 2,600 km^2 for the MUAR by 2100. Inundation area increases to 3,800 km^2 at high tide if we incorporate local tidal ranges in the analysis. About 510,000 people and 1,000 km of road lie within this area. Inundation area per length of coastline generally increases to south, where relative sea-level rise is greater and relief is smaller. More economically developed states, such as New York and New Jersey, have the largest number of people and infrastructure exposed to risk of inundation due to sea-level rise.

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1 Introduction

Sea-level rise accelerated by global climate change is likely to have profound impacts on coastal communities. By the end of the century, increases in sea level could lead to inundation of low-lying coastal regions, more frequent flooding, and worsening beach erosion (Mclean et al. 2001; Scavia et al. 2002). This is particularly relevant to the Mid- and Upper-Atlantic Region (MUAR) of the United States (coastal states from Virginia to Massachusetts) for two main reasons. First, the rate of relative sea-level rise in this region is higher than the global average. This is primarily a result of local subsidence driven by post-glacial rebound (Davis and Mitrovica 1996) and groundwater withdrawal (Davis 1987). Based on a variety of climate models and emission scenarios, Najjar et al. (2000) estimated that by the end of this century the combined effects of global climate change and local subsidence for the whole region could raise sea level by 66 cm on average, ranging from 39 to 102 cm. This assessment, however, did not account for any local variation in relative sea-level rise within the region, which can be significant (Zervas 2001). The second reason why sea-level rise is particularly hazardous for the MUAR is that the area is characterized by high population density and rapid development. According to the Bureau of Census (2005), the population of the coastal counties in this region increased by 15% between 1990 and 2000—a growth rate nearly twice the national average of 8%. According to the NPA (1998) population projection, this trend is likely to continue.

In order to understand the broad-scale ramifications of accelerated sea-level rise on human society, vertical sea-level rise projections need to first be translated into estimates of inundation (horizontal area flooded) and second into estimates of the amount of people, property and infrastructure exposed to this inundation. Although many small-scale case studies on the impacts of sea-level rise exist (Gornitz et al. 2002; McInnes et al. 2003; Wu et al. 2002), extensive studies covering large areas are rare. The most recent large-scale study was conducted by Titus and Richman (2001), who produced maps of all land that exists below 1.5 m and between 1.5 and 3.5 m in each US state on the Atlantic and Gulf coasts. The 1.5-m (5-ft) contour was chosen because it was the lowest elevation that could be consistently resolved over large regions with the available data at the time. These maps have limited utility for sea-level rise studies, however, because projections of sea-level rise for this century are generally much less than 1.5 m. Moreover, there are no large-scale studies that quantify impacts of sea-level rise on people, property and infrastructure. Over the last several years, the United States Geological Survey (USGS) refined its national digital elevation models (DEMs), producing them at horizontal resolutions of 30 m for the whole US and 10 m for selected areas. At the same time, many coastal states have commissioned the collection of high resolution data obtained by Light Detection and Ranging (LIDAR). With this improvement of available data, a revised estimation of the potential impact of sea-level rise is possible and necessary.

The present study has three major objectives. First, we make sea-level rise projections for the MUAR that account for spatial variability, and consider errors due to local effects (e.g., subsidence) and the range of climate model projections of global sea-level rise. We show that future estimates of sea-level rise depend significantly on local effects, and that those effects vary substantially throughout the MUAR. Furthermore, we show that uncertainty in future estimates of sea-level rise in the MUAR mainly arises from global climate model uncertainty as opposed to uncertainty in local effects. Second, using LIDAR data, we evaluate DEMs as a tool for making inundation estimates for selected portions of the MUAR, and demonstrate that DEMs are acceptable for this purpose. Third, and finally, we use the DEMs to make inundation estimates throughout the MUAR and quantify the impacts on people, property and infrastructure.

Four major sections follow. Section 2 gives a brief description of the study area—the Mid- and Upper-Atlantic Coast. Section 3 details the methods and data used in this study. Section 4 presents sea-level projections, DEM evaluations, and inundation estimates and their impacts. Section 5 provides a summary of our findings.

2 Study area—the Mid- and Upper Atlantic coast

Figure 1 shows the study area of the mid and upper Atlantic coast. It covers 85 coastal counties in the states of the mid- and upper-Atlantic: Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania, Maryland, Delaware and Virginia. These states constitute the study area of the Consortium for Atlantic Regional Assessment (CARA), a research and outreach effort funded by the US Environmental Protection Agency. CARA's goal is to provide scientific information and tools through internet resources that government agencies, communities, citizens, businesses and other stakeholders can use for exploring and adapting to potential impacts from changes in land use and climate in the MUAR. Other publications from CARA focused on projections of climate (Najjar et al. 2008) and space conditioning (heating and cooling) expenses (Shorr et al. 2008) for the MUAR during the twenty-first century.

The MUAR occupies only 5.5% of the land area of the contiguous US, but accommodates 23% of its population. 44% of the MUAR population lives in its coastal counties, which make up only 14% of its land area. The coastal region also includes some of the biggest metropolitan areas of the nation, such as New York, Philadelphia, Baltimore, Washington DC and Norfolk. Although the MUAR is dominated by forest and agricultural land use, the coastal counties have a much higher percentage of land devoted to commercial, industrial and residential uses (see Table 1). This pattern of population and land use distribution means that with sea-level rise, greater amounts of people, property and infrastructure will be exposed to either direct inundation or higher risk of flooding.

3 Methodology and data sources

3.1 Sea-level rise projection

Relative sea-level change at a given location—that measured by a gauging station fixed to land—is a combination of local vertical land movement and the local absolute change in sea level. Tide gauge observations can help to constrain the rate of local effects, including subsidence, and global climate models (GCMs) can be used to estimate the future rate of absolute sea-level rise. We modeled relative sea-level change at a given future time and at a given location from the increase in the global-mean absolute sea level and a local term, which reflects land subsidence plus any

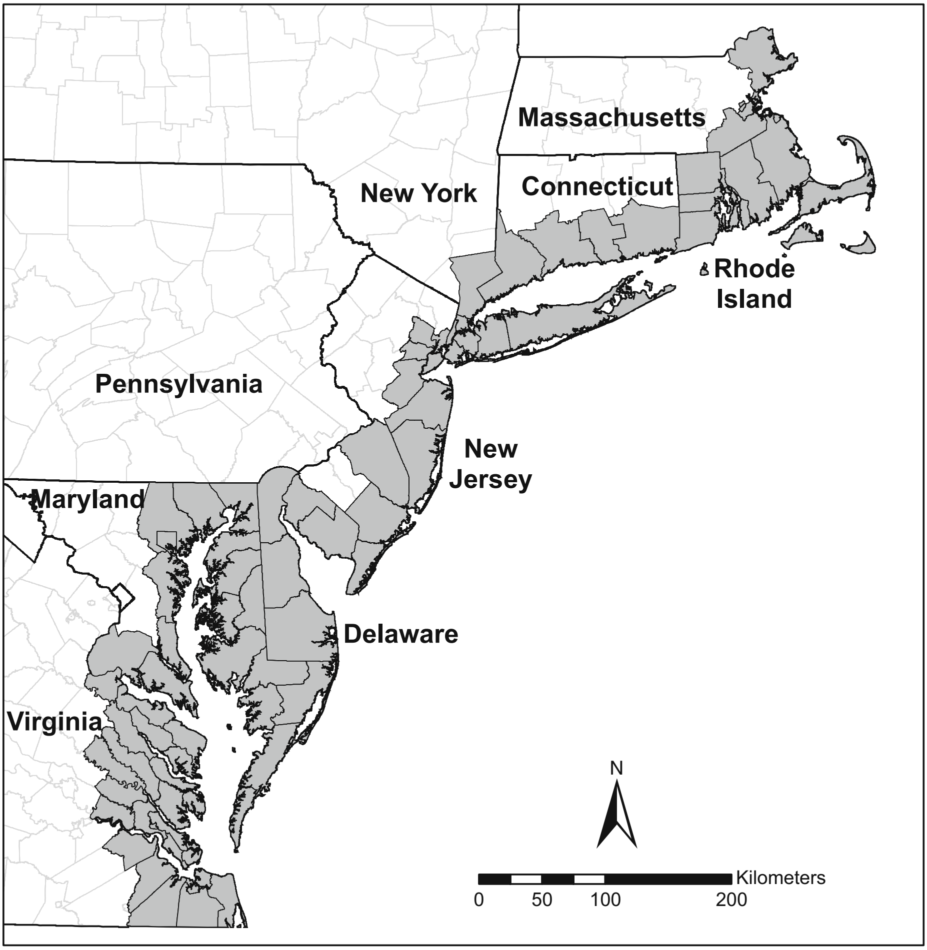

Fig. 1 Mid and Upper Atlantic Coast study area. Coastal counties are shaded in *grey*

local changes in absolute sea level. The local term was determined by extrapolating linearly the observed difference between global mean sea-level rise and the locally measured relative sea-level rise. Sea-level change was modeled with respect to a reference time chosen as 1990 to be consistent with model projections.

Table 1 Land use in MUAR region and MUAR coastal counties

Land use categories	% of total land area in coastal counties	% of total land area in MUAR region
Forest	43.1	64.5
Agriculture	23.3	25.0
Developed	16.9	3.6
Wetland	11.6	4.1
Water	3.8	1.6
Other	1.2	1.2

Source: National Land Cover Dataset (USGS 1992)

Table 2 Climate models used to drive simple model of global sea-level rise

Model name	Centre	Reference
CSIRO	Commonwealth Scientific and Industrial Research Organization	Gordon and O'Farrell (1997)
ECHAM	Max Planck Institute for Meteorology	Roeckner et al. (1996)
GFDL	Geophysical Fluid Dynamics Laboratory	Knutson et al. (1999)
HADC	Hadley Centre for Climate Prediction and Research	Gordon et al. (2000)
NCAR	National Center for Atmospheric Research	Washington et al. (2000)

The change in global mean sea level was derived from a simple climate model tuned to reproduce the output of five GCMs (Table 2) that were run under two greenhouse gas emissions scenarios (A2 and B2) used in the IPCC (Intergovernmental Panel on Climate Change) 2000 climate assessment (Church et al. 2001). These scenarios were chosen because they are commonly used by climate modelers and because they reflect the middle range of the six main scenarios developed by the IPCC for their 2000 assessment (Nakićenović and Swart 2000). The more recent multi-model mean sea-level projections from the IPCC (Meehl et al. 2007), which became available while this paper was being reviewed, are within 10% of those from the 2000 assessment.

Figure 2 shows the mean predictions for each of the five models in Table 2 for the A2 and B2 scenarios. Global average sea level is projected to rise from 1990 to 2100 by 290 to 590 mm (model mean of 450 mm) for the A2 scenario and 240 to 500 mm (model mean of 380 mm) for the B2 scenario. Except for the NCAR model before 2050, the global climate models predict greater sea-level rise than an extrapolation of

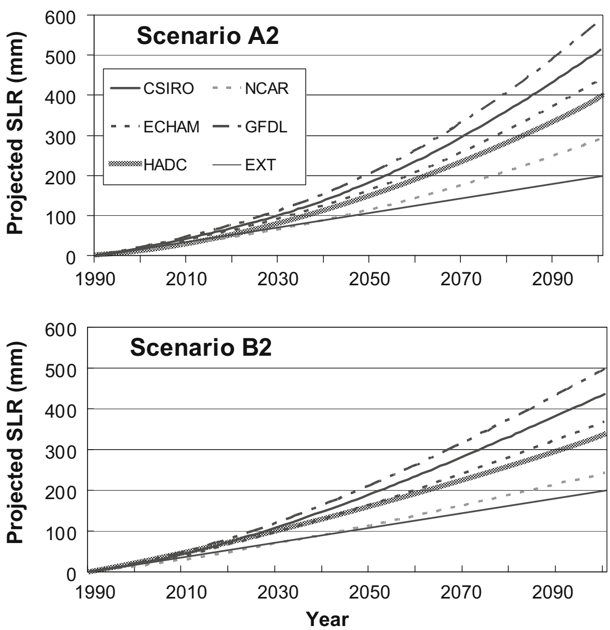

Fig. 2 Projections of global mean sea-level change produced by forcing a simple model with the output of five global climate models run under the A2 (*top panel*) and B2 (*bottom panel*) emission scenarios. Also shown is an extension (EXT) of the observed linear trend for 1950–2000 (Church et al. 2004)

the observed linear trend between 1950 and 2000 (Church et al. 2004). As has been observed for the twentieth century (Church and White 2006), all models show an acceleration of sea-level rise in the twenty-first century. However, by 2100 the five-model means for A2 and B2 are higher than the predicted range, 280–340 mm, based on the observed acceleration determined by Church and White (2006). Note that the range due to scenario (model-mean of A2 minus B2 = 70 mm) is smaller than that due to choice of GCM (300 mm for A2, 260 mm for B2). This would still be true if we had considered all six main IPCC scenarios, because Church et al. (2001) showed that the six-scenario range by 2100 is approximately 180 mm.

Accurate sea level measurements have been made for decades at coastal tide-gauge stations in the United States. These stations make up the National Water Level Observation Network, which is run by the National Ocean Service. The MUAR contains about 30 stations, but we only used the 18 for which linear trends have been computed for the time period 1950–1999 (Zervas 2001). The rate of sea-level change has a range of 1.82 to 4.48 mm year^{-1}, a mean of 2.91 mm year^{-1} and standard deviation of 0.80 mm year^{-1}. The errors of the linear fit vary between 0.20 and 0.35 mm year^{-1}, with a mean value of 0.26 mm year^{-1}. The rate of global sea-level rise was taken to be 1.8 ± 0.3 mm year^{-1}, which was computed by Church et al. (2004) for the period 1950–2000. We thus made predictions of sea-level rise from 1990 through 2100 for each GCM, scenario, and tide-gauge station. Errors in local and global rates of sea-level change were propagated assuming that they are uncorrelated. We also made predictions for each station assuming that the historical rate of local sea-level change is constant.

3.2 DEM evaluation

There are two main types of elevation data that are commonly available: DEMs and LIDAR data. The USGS 7.5-min DEM is the highest resolution elevation data set that covers the entire nation. However, with its root mean squared error (RMSE) of 7 m, which easily surpasses most estimates of projected sea-level rise over the next 100 years, it may not be valid to use this DEM to assess impacts of sea-level rise on coastal areas. LIDAR data are much more accurate, but their coverage is limited to thin strips of land, typically 300 to 500 m wide, along selected coastlines.

Although the USGS 7.5-min DEM has an RMSE of 7 m, this error is not evenly distributed. Because of the interpolation methods used in deriving the DEM from its 7.5-min topographical maps, it is reasonable to assume that such error will be small in relatively flat terrain and large in rapidly changing terrain. Since most coastal areas are relatively flat, DEMs covering these areas likely have smaller error than average. Therefore, we compared DEM data with the LIDAR data in order to determine the level of accuracy of the DEMs in coastal areas and the associated error in the inundation estimates.

LIDAR data are available through NOAA Coastal Services Center's Topographic Change Mapping website (http://maps.csc.noaa.gov/TCM/). The raw LIDAR data are collected as millions of georeferenced "x,y,z" points. The densities are variable, but are typically 30 points per 100 m^2. The data are referenced to the World Geodetic System 1984 (WGS 84) ellipsoid and the International Terrestrial Reference Frame 1994 (ITRF 94) datum. The horizontal accuracy is 1.5 m in the worst case, which is due to uncertainties related to the altitude of the aircraft. The vertical accuracy is about ±15 cm over the beach. Datum transformation introduces ±8 cm of vertical error.

DEM data are available through USGS's national data distribution site (http://seamless.usgs.gov/). The DEM data for 7.5-min units correspond to the USGS 1:24,000- and 1:25,000-scale topographic quadrangle map series for all of the United States and its territories. They are created from interpolation of digital line graph hypsographic and hydrographic data. The USGS 7.5 min DEM comes in two horizontal resolutions: 30 and 10 m. The 30-m DEM covers the whole nation whereas the 10-m DEM is a work in progress and will eventually cover the entire nation. DEM data are organized in three classification levels in terms of their accuracy. Level-1 DEMs, which are the most accurate and what we used in this study, have a vertical RMSE of 7 m.

Five sites were chosen in MUAR region (Table 3). Each site covers a stretch of coastal area of 0.5–1 km wide and 3–5 km long. These sites were chosen to be representative of the major coastal states in MUAR, and also on data availability. For each site (except Maryland), both 30-m and 10-m DEMs (DEM30 and DEM10) were used. For the Maryland site, only the 30-m DEM were available. Because one of the primary purposes of LIDAR data is to monitor the dynamics of coastal changes, many coastal states collect LIDAR data repeatedly over important stretches of the coast. For each site, all available LIDAR measurements were used, ranging from 1 (for New Jersey) to 4 (for Virginia and Maryland) time periods (Table 3). The original LIDAR data, in the form of x,y,z points, were interpolated to a 5-m grid. In total, 23 data layers for 5 sites were collected (Table 3). All layers were converted to Universal Transverse Mercator (UTM) projections. The horizontal datum is North American Datum 1983 (NAD83) and the vertical datum is North America Vertical Datum 1988 (NAVD88).

Major discrepancies between DEMs and LIDAR occur in places where there are man-made structures (mainly buildings). DEMs always depict ground elevation, whereas LIDAR data show top-of-building elevations. In most inundation analyses a place is deemed as flooded when the ground is flooded, even if the top of the building may remain above water. Therefore, areas covered by buildings were eliminated from the comparison. To achieve this, a 3 by 3 (15-m by 15-m) neighborhood range filter was passed through the LIDAR data to detect the edges of buildings. All cells within the edges were eliminated from the analysis.

Table 3 Data layers for DEM and LIDAR comparison

State	Site	Longitude, latitude	Area (km^2)	DEM layers	LIDAR layers
Massachusetts	Cape Cod	70°11′08″ W 42°04′01″ N	5.0	30 m, 10 m	1998, 2000
New York	Long Island	73°07′30″ W 40°39′04″ N	1.5	30 m, 10 m	1998, 1999, 2000
New Jersey	Cape May	74°38′34″ W 39°12′50″ N	4.5	30 m, 10 m	2000
Maryland	Assateague Island	75°14′03″ W 37°55′35″ N	2.9	30 m	1996, 1997, 1998, 2000
Virginia	Virginia Beach	75°59′02″ W 36°52′43″ N	1.1	30 m, 10 m	1996, 1997, 1998, 1999

All DEM layers were resampled to 5-m grids using the nearest neighbor method. For each site, we compared elevation values of the DEMs with those of the mean of all LIDAR layers at each grid point. The mean, RMS, and maximum difference in elevation were calculated. The internal variations among the LIDAR layers were also calculated. Results for all sites were pooled together by calculating the area-weighted mean and RMS differences to summarize the average discrepancies between DEM and LIDAR over all sites.

We also calculated areas that will be inundated under different sea-level rise scenarios, using all DEM and LIDAR layers. The sea-level rise scenarios used were 0.38, 0.66 and 1 m, which were based on low, medium and high sea-level rise projections made by the Mid-Atlantic Regional Assessment of potential impacts of climate change (Najjar et al. 2000). The inundated areas derived from different data sets were compared for each site, and the results were also pooled to determine the average differences in results derived from DEM and average LIDAR across all sites.

3.3 DEM inundation and impact estimates

In order to assess the impact of sea-level rise on the region in terms of land area at risk of being inundated and people and infrastructure exposed to this flood risk, we first calculated the arithmetic mean of adjusted sea-level rise of all tidal stations located in one state (for a given scenario and model) to get the state-average sea-level rise. Based on these values in sea-level rise, we then used DEMs to model the area that will be inundated under different future sea-level rise scenarios. The areas were then divided by the length of the coastline of the state to estimate distance of coastline retreat due to inundation only, if no shoreline protection measures were present.

In the final step, we estimated the potential impacts of sea-level rise in terms of people and infrastructure that will be affected. We first added the state average tidal height (i.e. half the tidal range) on top of the sea-level rise values to project future high tide water levels, assuming some areas will become future tidal land even if not permanently inundated by sea-level rise. People and infrastructure in those areas will also be affected. Based on resulting values in future high water level, we then used DEMs to model the areas that will be inundated at high tide under different future sea-level rise scenarios. Finally, we overlaid the inundation map with 2000 census block data, land use data (National Land Cover Dataset 1992) and road network data to assess the amount of developed land, people and roadway that will be exposed to high risk of inundation.

4 Results

4.1 Sea-level rise projection

Depending on location, model, and scenario, sea-level rise projections vary from 200 to 900 mm by 2100. In all cases, the climate models project greater sea-level rise than the linear extrapolation of the tide gauge trends, reflecting the fact that the model sea-level rise rates tend to be higher than the historical average. Table 4 presents model-mean sea-level rise projections at the 18 tide gauge stations for the year 2100

Table 4 Projected sea-level rise (SLR) (mm)

Name of station	State	Mean SLR A2 scenario	Mean SLR B2 scenario
Boston	MA	471	401
Woods Hole	MA	512	442
Newport	RI	508	437
Providence	RI	449	379
New London	CT	468	398
Montauk	NY	535	465
Willets Point	NY	475	404
The Battery	NY	548	478
Sandy Hook	NJ	624	554
Atlantic City	NJ	741	670
Philadelphia	PA	551	480
Lewes	DE	584	513
Baltimore	MD	550	479
Annapolis	MD	599	528
Solomon's Island	MD	620	549
Washington, DC	DC	596	525
Gloucester Point	VA	684	613
Sewells Point	VA	742	671

under the B2 and A2 scenario. The spatial variation is captured in the map shown in Fig. 3. The range of about 300 mm demonstrates that spatial variability in projected sea-level rise, even within the relatively small area of the MUAR, is substantial. Figure 3 also suggests that estimates of sea-level change generally increase toward the south. This is consistent with glacial isostatic adjustment (GIA) model predictions (Davis and Mitrovica 1996). In North America, glaciation affected the northern part of the continent, but not the southern part. Therefore the post-glacial rebound of northern North America is causing a corresponding downward movement of the southern half of the continent. New England states in our study area (MA, RI and CT) lie approximately at the pivot line between rising and sinking land and therefore have little subsidence, whereas the states further south (such as DE, MD and VA) have more subsidence. The correlation between latitude and relative sea-level rise, where variance is largely caused by local subsidence, is clearly seen in Fig. 4. This is important, because as noted below, coastal regions are also relatively flat in the south and thus more susceptible to inundation for a given amount of sea-level rise.

As a rough estimate of the model uncertainty, we use the overall model range, which is about 200 mm by 2100. As a general estimate of scenario uncertainty, we use the difference between A2 and B2, which is about 70 mm by 2100. These ranges can be compared with the uncertainty in projected sea-level rise due to local effects, ~80 mm by 2100, which is derived directly from uncertainty in the trends in sea level at the different tide gauge stations (Zervas 2001) and global sea level (Church et al. 2004) over the latter half of the twentieth century. Clearly model uncertainty dominates the overall uncertainty in projected sea-level rise over the twentieth Century. If we assume that the three error estimates are independent, then we derive an overall uncertainty of approximately 220 mm by 2100, which is between about 40 and 60% of model- and scenario-mean projections, depending on location.

To help put the sea-level rise projections into perspective, we compared them with the observed increase over the past 50 years and the mean annual range, the

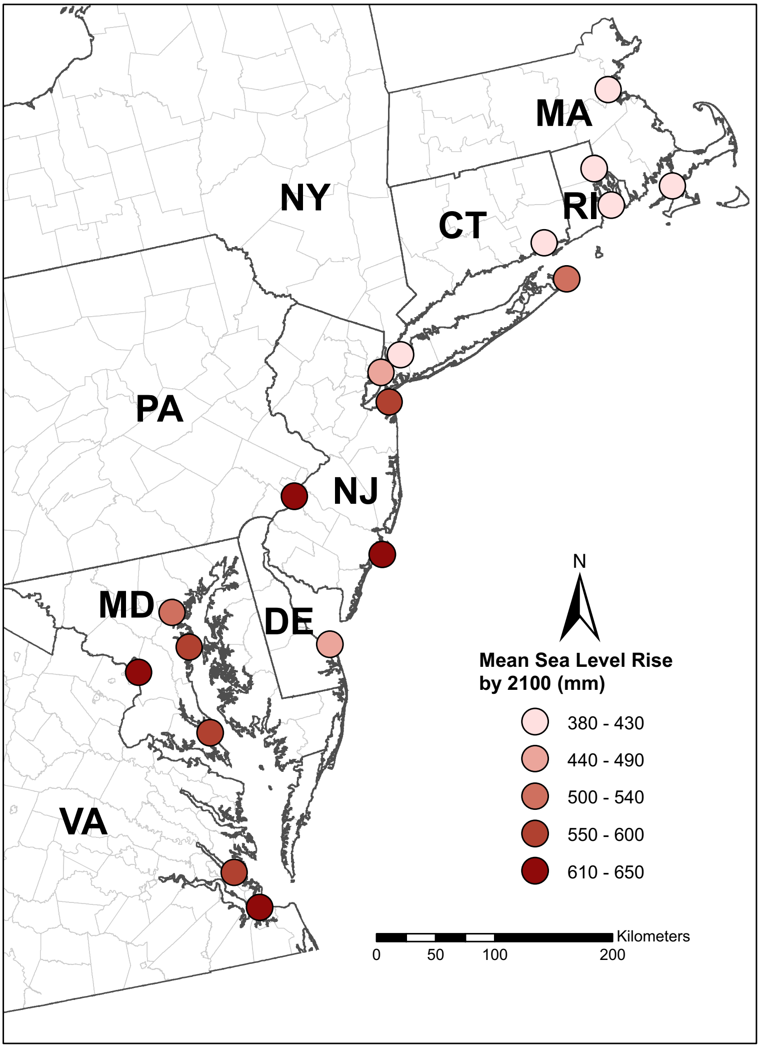

Fig. 3 SLR predictions for 2100 throughout the MUAR with respect to 1990. This represents the average of all models under B2 Scenario

mean tidal range, and the maximum water level observed at a given station, all based on data compiled by Zervas (2001). The overall mean (by station, model and scenario) projected sea-level rise for the MUAR is 530 mm by 2100. In contrast, station-averaged sea-level rise over the past 50 years in the MUAR is 150 mm, which is also equal to the station-averaged mean annual range in sea level. The station-averaged mean tidal range is considerably larger at 1,120 mm, as is the station-averaged maximum water level on record, 2,510 mm. Thus, sea-level rise projections lie above existing seasonal and decadal changes, but below changes that occur on the time scales of the tides and strong meteorological events (days).

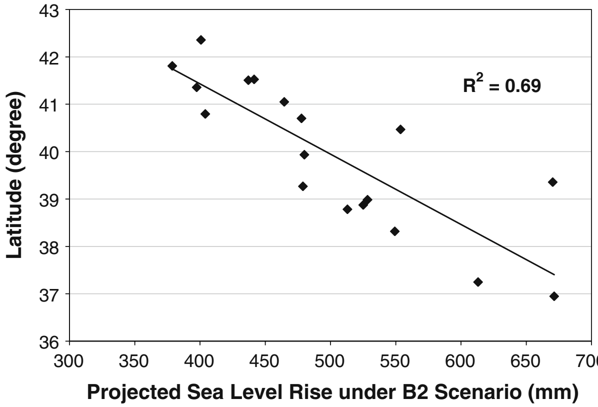

Fig. 4 Correlation between latitude and relative sea-level rise projections (B2 scenario)

4.2 Differences between DEM and LIDAR

The mean differences between DEM and LIDAR data for all sites are summarized in Table 5. DEM30 and DEM10 are highly consistent with each other, which is to be expected given that the two DEMs share the same source data, USGS 7.5 min topographical maps. For different LIDAR layers, the average difference is 0.24 m and the RMS difference is 0.94 m. This may result from the fact that LIDAR data capture short-term dynamic changes of the coast, such as shifting of sand dunes and beach erosion. Vegetation also increases the variability of elevation measurements. Comparison of LIDAR elevation measurements to elevation measurements collected on the ground within vegetation do not always agree. Factors such as vegetation density, type, and survey season all affect elevation measurements over vegetation. These all contribute to the variations among different LIDAR layers for the same area.

Comparing the DEMs with the mean of LIDAR layers reveals that the average difference between the DEMs and LIDAR is less than 0.15 m, and RMS difference is 1.17 m and 1.13 m for DEM30 and DEM10 respectively. The RMS difference is far smaller than the 7 m RMSE estimated for all DEMs, and in fact is not very different from the internal variations among different LIDAR layers. This result supports the idea that DEM errors are smaller in coastal areas where the terrain is generally flat. Comparing different sites, RMS difference between DEM10 and the LIDAR mean is lowest in the very flat Virginia Beach area (0.35 m) and highest in Cape Cod (1.34 m) where the topographic relief is larger.

Table 5 Differences between DEM and LIDAR data sets (m)

	Mean difference	RMS difference	Maximum difference
DEM30 and DEM10	0.02	0.33	8.04
DEM30 and LIDAR mean	0.14	1.17	23.33
DEM10 and LIDAR mean	0.13	1.13	16.48
Among LIDAR layers	0.24	0.94	62.56

4.2.1 Sensitivity of inundation to such differences

The inundation results for all sites are summarized in Table 6. On average there is less than 9% difference in calculated areas that will be inundated under different sea-level rise scenarios. On average, a 0.66-m sea-level rise seems to yield the smallest discrepancies, though this result is not consistent across all individual sites. Among different sites (not shown), the difference between the DEMs and LIDAR range from 5% to 39%. The discrepancies among different LIDAR layers range from 0% to 37%, but mostly below 10%. DEM10 yields similar results as DEM30, and hence provides no significant improvement in accuracy.

In summary, the average difference between the DEMs and LIDAR is less than 0.15 m, and the RMS difference is 1.17 m for the five coastal sites we evaluated. The average discrepancies between the DEMs and LIDAR in calculating areas inundated by projected sea-level rise are between 4 to 9% under different scenarios. DEM10 is very consistent with DEM30. Therefore, we conclude that DEM30 is appropriate for making inundation estimates due to future sea-level rise.

4.3 Impact of sea-level rise

In Section 4.1, we showed that the modeled mean sea-level rise projections for the MUAR by 2100 range from 0.4 to 0.7 m (Table 4). The station values were averaged for each state. To show the range of model/scenario variability in projected sea-level rise, the minimum and maximum of all model values are presented together with mean model values under both A2 and B2 Scenarios (Table 7). The min and max model values serve as a practical lower and upper bound for future sea-level rise. The average high tide above mean sea level is also presented in Table 7. Table 8 shows the corresponding estimates of area inundation at mean sea level by state under different scenarios. Since the differences in modeled inundated area under different sea-level rise scenarios are too small to be depicted effectively on a state map, we chose mean model values under the B2 scenario as a reasonable medium projection to map inundation. In most coastal regions, inundated area would extend no more than a few kilometers inland, and is too small to see on maps of small scale such as the coastal map of the whole study area, or even of each state. Therefore, we chose three sections of the MUAR coast to illustrate the relatively low, medium and high inundation regions (Fig. 5). Northern states, such as MA, RI and CT, tend to have smaller land area exposed to high risk of inundation by sea-level rise because of their smaller amount of projected sea-level rise and relatively steep terrain along the coast. In contrast, Southern states, such as MD, DE and VA, contain more land that is vulnerable to sea-level rise owing to greater sea-level rise and the low

Table 6 Areas inundated by 0.38, 0.66 and 1 m sea-level rise using DEM and LIDAR

Sea-level rise	Inundated area (km^2)			Difference with LIDAR (%)	
	DEM30	DEM10	LIDAR mean	DEM30	DEM10
Below 0.38 m	8.84	8.80	8.11	9.00	8.51
Below 0.66 m	8.97	8.98	8.53	5.16	5.28
Below 1 m	10.29	10.33	9.47	8.66	9.08

Table 7 The amount of mean sea-level rise (SLR) under different scenarios[a] (mm)

State	Minimum	B2 mean	A2 mean	Maximum	High tide[b]
Massachusetts	285	421	492	632	860
Rhode Island	272	408	478	619	264
Connecticut	262	397	468	609	391
New York	313	449	519	660	503
New Jersey	476	612	683	823	664
Delaware	377	513	583	724	621
Maryland	383	519	589	730	167
Virginia	507	642	713	854	370

[a]Mean sea-level rise projections have been adjusted for datum differences
[b]This refers to the average height of high tide above mean sea level, i.e. half of the tidal range

topographic relief of their coastal regions. Moreover, the sensitivity of the amount of inundated land to different sea-level rise scenarios also depends on terrain profile. In the northern states with steep coastal profiles, the maximum amount of sea-level rise is more than double that of the minimum, but the increase in inundation area is less than 20%. On the relatively flat VA coastline, however, a 68% increase from the minimum to maximum sea-level rise scenario leads to more than 50% increase in inundation area. In order to show the spatial variation in areas of inundation due to both relative sea-level rise and topography, we calculated the area of inundation per length of shoreline (Table 9). This helps to explain why, for example, Delaware has six or seven times as much inundation as Rhode Island (Table 8), even though their coastlines have similar lengths.

The amount of inundated land at high tide is presented in Table 10, using the combination of sea-level rise values and the average tidal range presented in Table 7. Results of the impact of inundation at high tide on developed land, people and roadways are presented in Tables 11, 12 and 13. The impact of future sea-level rise is greatest in more economically developed states such as New York and New Jersey. New York is impacted the most among the eight states considered in terms of developed land and people despite the fact it is ranked fifth in inundation area. This is because the fraction of inundated area that is developed is much higher in New York, ∼25% under the maximum high tide scenario compared to 2–15% for the other states. Maryland, on the other hand, which has the greatest amount of inundation, is ranked in the middle (fourth or fifth) in terms of impacts on people, roads and infrastructure, because it is relatively undeveloped. New Jersey ranks high

Table 8 The amount of area subject to inundation at mean sea level under different SLR scenarios (km^2)

State	Minimum	B2 mean	A2 mean	Maximum
Massachusetts	140	150	155	168
Rhode Island	32	34	35	38
Connecticut	76	80	81	85
New York	247	266	275	292
New Jersey	337	404	424	468
Delaware	210	224	230	243
Maryland	764	841	893	1,051
Virginia	506	572	675	768
Total	2,312	2,571	2,767	3,112

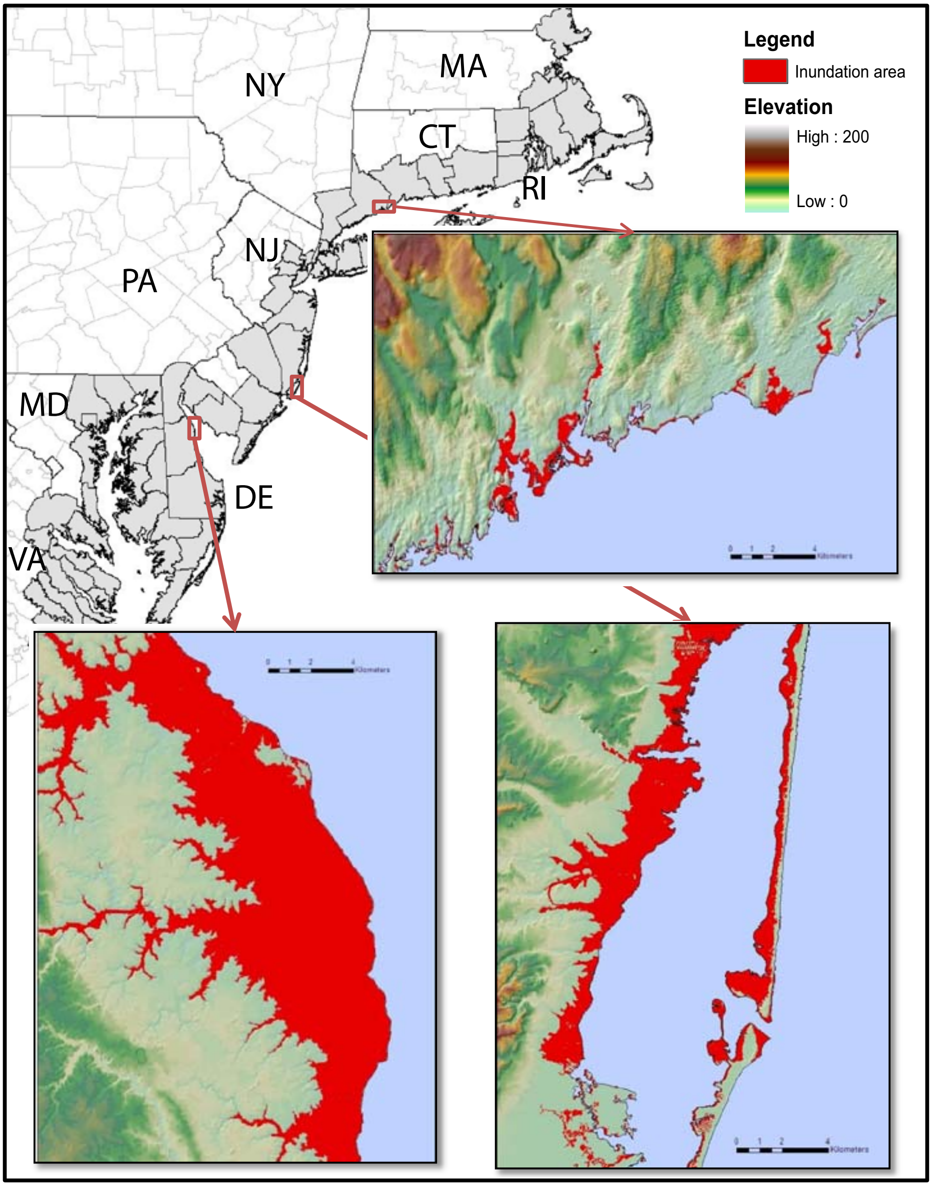

Fig. 5 Inundation due to sea-level rise in three sections of MUAR coast

in these categories both because of the large inundated area and because of its high coastal development.

It should be noted that this assessment is made based on elevation only. Although the maps may indicate a certain level of risk to future sea-level rise, they do not depict future shorelines, since there are a variety of other factors that will affect the shape of future shorelines, such as coastal erosion, wetland accretion, and the existence of

Table 9 Inundation area per length of shoreline under different SLR scenarios[a] ($km^2\ km^{-1}$)

State	Minimum	B2 mean	A2 mean	Maximum
Massachusetts	0.21	0.23	0.24	0.26
Rhode Island	0.18	0.19	0.20	0.21
Connecticut	0.45	0.47	0.48	0.50
New York	0.35	0.37	0.39	0.41
New Jersey	0.80	0.96	1.01	1.11
Delaware	1.25	1.33	1.37	1.44
Maryland	0.70	0.77	0.82	0.97
Virginia	0.40	0.45	0.53	0.61

[a]The length of general coastline is derived from map at 1:3,000,000 scale

Table 10 The amount of area subject to inundation at high tide under different SLR scenarios (km^2)

State	Minimum	B2 mean	A2 mean	Maximum
Massachusetts	226	234	239	270
Rhode Island	44	46	47	48
Connecticut	101	104	106	109
New York	311	329	340	367
New Jersey	709	877	942	1,008
Delaware	281	321	353	542
Maryland	856	1,017	1,170	1,430
Virginia	779	882	920	1,120
Total	3,307	3,810	4,117	4,894

Table 11 The amount of developed land subject to inundation at high tide under different SLR scenarios (km^2)

State	Minimum	B2 mean	A2 mean	Maximum
Massachusetts	21	22	23	25
Rhode Island	4	4	4	4
Connecticut	14	15	15	16
New York	67	75	80	93
New Jersey	57	70	75	84
Delaware	5	6	6	10
Maryland	17	21	24	31
Virginia	42	47	49	58
Total	227	260	276	322

Table 12 The number of people (thousands) subject to inundation at high tide under different SLR scenarios

State	Minimum	B2 mean	A2 mean	Maximum
Massachusetts	32.7	37.0	38.0	43.7
Rhode Island	3.5	3.9	4.0	4.4
Connecticut	21.5	22.2	22.9	26.4
New York	161.4	204.8	185.9	211.0
New Jersey	124.9	142.6	152.8	160.0
Delaware	4.1	5.3	6.2	8.9
Maryland	34.4	34.9	44.2	60.8
Virginia	48.0	57.6	119.4	149.1
Total	430.4	508.5	573.3	664.2

Table 13 The amount of roads subject to inundation at high tide under different SLR scenarios (km)

State	Minimum	B2 mean	A2 mean	Maximum
Massachusetts	104	107	111	114
Rhode Island	12	13	15	16
Connecticut	45	47	48	50
New York	192	212	232	252
New Jersey	295	345	395	445
Delaware	21	29	38	47
Maryland	56	72	89	106
Virginia	129	151	172	193
Total	854	977	1,099	1,223

man-made shoreline protection structures/projects, to name but a few. These maps represent a useful first-order assessment, based on which more detailed analyses can be conducted at finer spatial scales.

5 Conclusions

We have used historical tide gauge records, estimates of global historic sea-level rise, and global climate model output to make projections of sea-level rise for the coastal portion of the Mid and Upper Atlantic Region of the United States. Our projections of model- and scenario-mean sea-level rise by 2100 in the region vary from 400 to 700 mm depending on location, which reflects different rates of subsidence. In general, relative sea-level rise will be less in the northern and more in the southern portion of the MUAR. Uncertainty in sea-level rise is dominated by the uncertainties of different global climate models, as opposed to uncertainty due to greenhouse gas forcing or local effects. The overall estimated error for sea-level rise in the MUAR by 2100 is about 200 mm.

Estimated errors in sea-level rise inundation due to errors in DEMs were found to be relatively small compared to the expected error based on the overall RMSE in the DEMs themselves, about 7 m. By evaluating the DEMs with LIDAR data, we found that DEM errors in coastal regions are much smaller, closer to about 1 m. Inundation estimates have errors of typically less than 10%. This encouraging result indicates that DEMs are adequate for regional scale estimates of inundation due to sea-level rise.

Sea-level rise is predicted to have profound impacts on the MUAR coast. It is likely to inundate 2,600 km^2 of land under a medium-range greenhouse gas emissions scenario. Because of the high level of development and high population density in the region, this can affect as many as 510,000 people living in low lying areas.

There are several reasons why this assessment may underestimate the societal risk from future sea-level rise. First, the IPCC climate models used in this study to generate future global sea-level rise scenarios do not take into account drastic reduction in polar ice sheets, which, as indicated by several recent observations (Joughin 2006; Kerr 2004), may well be happening in the time frame of this study. Second, the assessment does not take into account coastal erosion, which may greatly accelerate with sea-level rise, contributing to a greater amount of land lost to higher sea level. Third, this study does not take into account future population growth or a change in land use patterns. Both factors may increase the number of people and amount of infrastructure vulnerable to future sea-level rise. All these factors require further detailed research in order to refine the impact assessment of future sea-level rise.

Lastly, this study only considers the impact of sea level rise in terms of inundation. Sea level rise has other important impacts that will affect coastal communities. These include elevated storm surges, loss of coastal wetland, and salt water intrusion, to name just few. These are beyond the scope of this study, but are important components to consider if a comprehensive impact study of sea-level rise is conducted.

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