

# Implications of recent sea level rise science for low-elevation areas in coastal cities of the conterminous U.S.A.

## A letter

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**Abstract** Recently published work estimates that global sea level rise (SLR) approaching or exceeding 1 m by 2100 is plausible, thus significantly updating projections by the Fourth Assessment of the Intergovernmental Panel on Climate Change. Furthermore, global greenhouse gas (GHG) emissions over the 21st century will not only influence SLR in the next ~90 years, but will also commit Earth to several meters of additional SLR over subsequent centuries. In this context of worsening prospects for substantial SLR, we apply a new geospatial dataset to calculate low-elevation areas in coastal cities of the conterminous U.S.A. potentially impacted by SLR in this and following centuries. In total, 20 municipalities with populations greater than 300,000 and 160 municipalities with populations between 50,000 and 300,000 have land area with elevations at or below 6 m and connectivity to the sea, as based on the 1 arc-second National Elevation Dataset. On average, approximately

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9% of the area in these coastal municipalities lies at or below 1 m. This figure rises to 36% when considering area at or below 6 m. Areal percentages of municipalities with elevations at or below 1–6 m are greater than the national average along the Gulf and southern Atlantic coasts. In contrast to the national and international dimensions of and associated efforts to curb GHG emissions, our comparison of low-elevation areas in coastal cities of the conterminous U.S.A. clearly shows that SLR will potentially have very local, and disproportionate, impacts.

## 1 Introduction

The science surrounding projections of global sea level rise (SLR) as a result of human-caused climate change has grown rapidly in recent years, updating and exceeding the most recent projection by the Intergovernmental Panel on Climate Change (IPCC) of 0.26–0.59 m of global SLR by 2100 for the A1FI emissions scenario (Meehl et al. 2007). Independent estimates of future sea level now indicate that global SLR could approach or possibly exceed 1 m by 2100 (Pfeffer et al. 2008; Vermeer and Rahmstorf 2009), even with moderate reductions of greenhouse gas (GHG) emissions over the rest of this century (Vermeer and Rahmstorf 2009). Importantly, global GHG emissions over the twenty-first century will not only influence SLR in the relative near term of the next ~90 years, but will also continue to drive SLR over subsequent centuries. Temperatures by 2100 may be warm enough to commit Earth to at least 4–6 m of global SLR over following centuries as the polar ice sheets adjust to the comparatively rapid and largely irreversible global warming that occurs this century (Meehl et al. 2007; Overpeck et al. 2006; Overpeck and Weiss 2009; Schneider et al. 2007; Solomon et al. 2009). Particular to coasts of the conterminous U.S.A., state-of-the-art SLR science also demonstrates that weakening of the Atlantic meridional overturning circulation during this century could result in 1 m of regional SLR occurring along the northern Atlantic coast earlier than the global mean arrival time (Yin et al. 2009, 2010).

These recent studies constitute a worsening prospect of substantial SLR over this and subsequent centuries. As a result, assessing and anticipating potential SLR impacts to coastal areas is now of increased importance. This is especially true where accentuated regional SLR may occur, such as along the northern Atlantic coast of the conterminous U.S.A. In this letter, we report a new geospatial dataset of low-lying coastal elevations for the entire conterminous U.S.A. that helps delineate areas prone to impacts from the amounts of SLR now plausible from continued high global GHG emissions over the next ~90 years. Analysis of elevation data in the context of projected SLR serves a fundamental role in identifying coastal areas that may face issues such as accretion and erosion, temporary flooding, and permanent inundation. Authors of numerous previous studies have analyzed elevation data to map different coastal areas in the conterminous U.S.A. that may be affected by SLR impacts (see review by Gesch et al. 2009). The work in this letter is unique in that it utilizes delineated low-lying coastal areas to make a nationwide assessment of municipalities with elevations at or below 6 m, a possible amount of SLR we commit to this century. Our purpose here is to raise awareness about implications of the latest SLR science

by applying our dataset to the calculation of low-elevation areas in coastal cities of the conterminous U.S.A. potentially impacted by SLR in this and following centuries.

## 2 Methods

We used the National Elevation Dataset (NED; Gesch et al. 2002) with 1 arcsec ( $\sim 30$  m) horizontal resolution to delineate low-lying coastal areas of the conterminous U.S.A. that may confront SLR issues based on their elevation and eight-way connectivity (Poulter and Halpin 2008) to the sea. Though not explicitly addressed in this letter, identified areas may correspond to potential SLR impacts such as accretion, erosion, flooding, or inundation. The NED is a digital elevation model (DEM) produced by the U.S. Geological Survey (USGS) with 1/9 ( $\sim 3$  m), 1/3 ( $\sim 10$  m), and 1 arcsec versions. At present, only the 1 arcsec NED (NED<sub>1arc</sub>) has complete coverage of the conterminous U.S.A. The NED<sub>1arc</sub> incorporates source data from digital photogrammetry and light detection and ranging (lidar) topographic surveys where available, in addition to 1/3 and 1 arcsec DEMs with cartographic contour source data. The USGS resamples DEMs of finer resolution for production of the NED<sub>1arc</sub>. The NED<sub>1arc</sub> has an absolute vertical linear error of  $\pm 4.75$  m (95% confidence interval) for the entire conterminous U.S.A. (Gesch 2007). However, the absolute vertical accuracy of the NED<sub>1arc</sub> along coasts is typically better than the nationwide average (Gesch 2009; Gesch et al. 2009). NED<sub>1arc</sub> values reference the North American Vertical Datum of 1988 (NAVD 88)—the mean sea level at Rimouski, Quebec, Canada—and not a local sea level datum. The average differences between local mean high water (MHW) and the NAVD 88 zero value (i.e., local MHW-NAVD 88) at NOAA tide gauge stations are 0.4 m (range,  $-0.2$ – $2.7$  m) for the Atlantic coast, 0.2 m (range,  $-0.5$ – $0.7$  m) for the Gulf coast, and 1.9 m (range,  $1.3$ – $2.9$  m) for the Pacific coast. Both the inherent vertical error and NAVD 88 vertical reference of the NED<sub>1arc</sub> place uncertainty on the delineation of low-lying coastal elevations.

To specify the land–sea boundary in the NED<sub>1arc</sub> by where local tides periodically submerge areas, we designated MHW as the shoreline in our analysis using vector shoreline data from the National Oceanic and Atmospheric Administration Coastal Services Center ([www.noaa.csc.gov](http://www.noaa.csc.gov)). We created a geoprocessing algorithm that performs iterative cell-by-cell analysis of DEMs to select all cells with elevation values less than or equal to a particular value, and with locations adjacent or connected by cells of equal or lesser value to the sea. We applied this algorithm to the NED<sub>1arc</sub> for each integer value from 1–6 m to delineate areas potentially subject to SLR. We note that our analysis is based on modeled present-day elevations and does not predict future shorelines, nor include processes that may affect local elevation such as glacial isostatic adjustment, tectonics, subsidence, or erosion and accretion (e.g., Engelhart et al. 2009; Tornqvist et al. 2008; Zhang et al. 2004).

We utilized municipal boundaries used for the 2000 census by the U.S. Census Bureau ([www.census.gov](http://www.census.gov)) to calculate land area within coastal cities of elevations at or below 1–6 m landward of the present-day MHW line. The municipal boundaries are geographic information system (GIS) shapefiles that are part of the Census Bureau's Topologically Integrated Geographic Encoding and Referencing (TIGER)

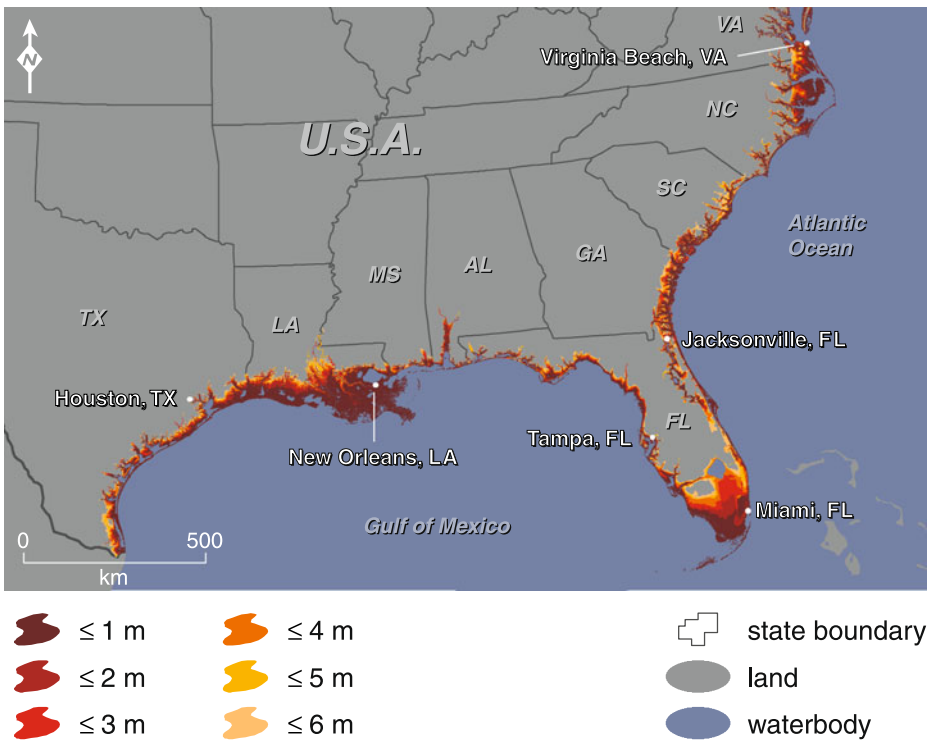
database, and delineate the extent of legally defined boundaries of governmental units used in censuses and survey programs. As some municipal boundaries include area designated as sea in the previously computed elevation datasets, we separated out the portions of municipalities that only occur over areas designated as land. We then calculated the areal overlap between the land portion of each municipality and our datasets delineating areas with elevations at or below 1–6 m.

Tidal wetlands do occur above the MHW mark as a result of extreme tidal events such as spring high water (e.g., Titus and Wang 2008), and thus may be present within our designated municipal boundaries and lead to an overestimate of land area at or below elevations from 1–6 m. To determine possible effects that high marsh might have on areal overlap calculations of the elevation and municipality datasets, we acquired wetland GIS shapefiles from the U.S. Fish and Wildlife Service (2010). We removed parts within municipal land areas where the estuarine and marine wetland type appeared, and recalculated the areal overlap between the land portion of each municipality and our datasets delineating areas with elevations at or below 1–6 m. We performed all geospatial data analyses with ESRI ArcGIS Desktop™ software. All map figures are in an Albers equal area projection. For this letter, we focus on results for coastal municipalities with populations greater than 50,000 as of the 2000 census, with a particular emphasis on those with populations greater than 300,000 (hereafter major municipalities).

### 3 Results

Coastal areas of the conterminous U.S.A. with elevations at or below 1–6 m and connectivity to the sea are most apparent along the Gulf and southern Atlantic coasts, especially in southern Louisiana and southern Florida (Fig. 1). The northern Atlantic and Pacific coasts have relatively less low-lying area visible, although within these regions there are discernable areas with elevations at or below the 6-m mark (SOM1, SOM2). Such places include the Chesapeake Bay near Washington, DC and the San Francisco Bay and San Joaquin–Sacramento river delta in northern California. State averages for the percent of land area within municipalities of elevations at or below 1–6 m reflect these regional-scale patterns (SOM3, SOM4). Average land area percentages of elevations at or below the 1-m contour for municipalities with populations greater than 50,000 surpass the nationwide average of 9.7% in Florida, Georgia, Louisiana, Mississippi, South Carolina, Texas, and Virginia. These states, along with Alabama, Delaware, and New Jersey, have average percentages of municipal land area with elevations at or below the 6-m line greater than the national average of 35.8%.

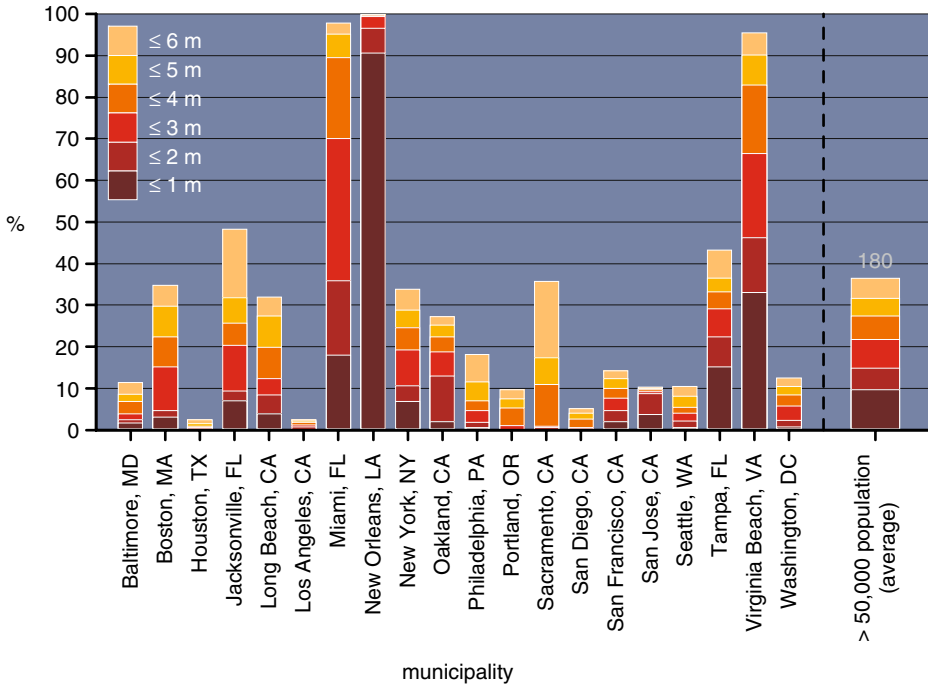
Along all coasts of the conterminous U.S.A., 20 major municipalities with populations greater than 300,000 (Fig. 2) and 160 municipalities with populations between 50,000 and 300,000 (SOM4) have land area with elevations at or below 6 m and connectivity to the sea. For the major municipalities of Miami, FL, New Orleans, LA, Tampa, FL, and Virginia Beach, VA, land area percentages at or below 1 m of elevation exceed the 180-municipality national average of 9.7% (Figs. 2 and 3). These major municipalities, along with Jacksonville, FL (Fig. 2, SOM5), also have land area percentages higher than the 180-municipality national average of 35.8% for elevations at or below 6 m. Most striking is that more than 90% of Miami, FL,



**Fig. 1** Parts of the conterminous U.S.A. along the Gulf and southern Atlantic coasts with elevations at or below 1–6 m and connectivity to the sea. Labels denote coastal state abbreviations and municipalities with populations greater than 300,000 as of the 2000 census (i.e., major municipalities)

New Orleans, LA, and Virginia Beach, VA are at or below the 6-m elevation mark (Figs. 2 and 3). For New York, NY—the most populous major municipality—land area percentages at or below the 1–6 m elevation contours closely follow those of the 180-municipality national average. Land area percentages at or below the 1–6 m elevation contours for Washington, DC—the national capitol—are less than those of the 180-municipality average for the nation. Overall, land area percentages along all coasts of the conterminous U.S.A. for both the 20 major municipalities (Figs. 2 and 3, SOM5, SOM6, SOM7) and the 160 municipalities with populations between 50,000 and 300,000 (SOM4) demonstrate a wide range of land area at or below elevations from 1–6 m.

Tidal wetlands above MHW lead to overestimates of municipal land area percentages for elevations at or below 1–6 m in approximately two-thirds of coastal states in the conterminous U.S.A. Accounting for tidal wetlands above MHW reduces the 180-municipality national mean of land area percentages at or below the 1–6 m elevation contours by an average of 0.5% (SOM4). For statewide averages, reductions in municipal land area percentages at or below 1–6 m are less than 2.3% for Delaware, Florida, Louisiana, Maine, Massachusetts, New Jersey, New York, North Carolina, Rhode Island, Texas, Virginia, and Washington. For Georgia, Mississippi, and South Carolina, average decreases in municipal land area percentages at or below 1–6 m

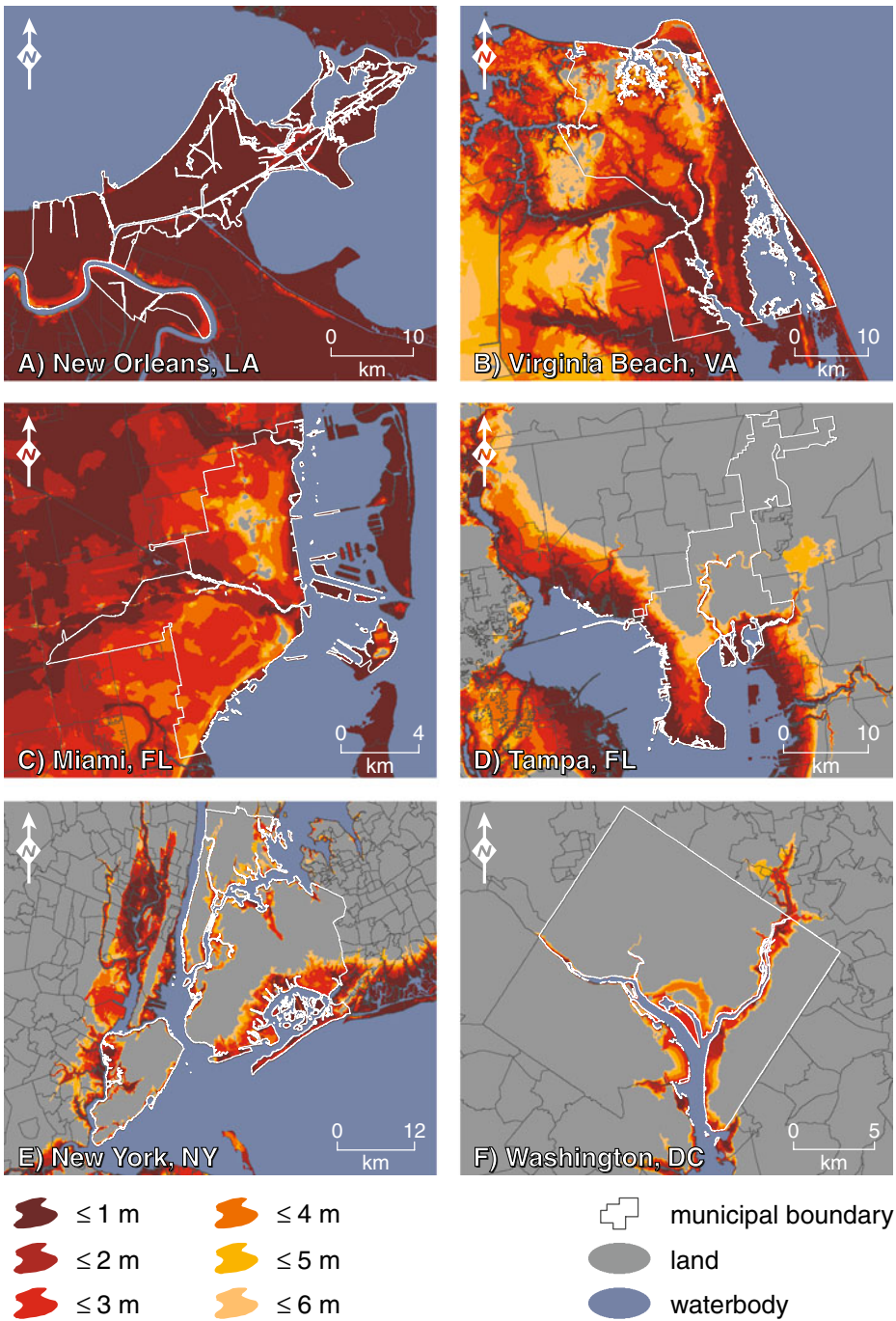


**Fig. 2** Land area percentages of major municipalities (2000 census population greater than 300,000) with elevations at or below 1–6 m and connectivity to the sea. The average land area percentage for all 180 municipalities (2000 census population greater than 50,000) with elevations at or below 1–6 m and connectivity to the sea is on the right

range between 2.5% and 9.6%. Tidal wetlands above MHW do not affect statewide averages in Alabama, California, Connecticut, the District of Columbia, Maryland, Oregon, and Pennsylvania. For the 20 major municipalities, tidal wetlands above MHW lessen land area percentages at or below 1–6 m by less than 1.1% for Boston, MA, Houston, TX, Miami, FL, New Orleans, LA, and Seattle, WA. These reductions range between 1.4% and 2.0% for New York, NY and Tampa, FL, and between 0.4% and 5.3% for Jacksonville, FL and Virginia Beach, VA. Tidal wetlands above MHW do not occur in the other 11 major municipalities.

#### 4 Discussion

Several technical considerations are important in order to produce scientifically sound geospatial datasets of low-lying coastal elevations that help delineate areas prone to SLR impacts (Gesch et al. 2009; Titus and Wang 2008). For this current version of our dataset, we incorporated hydrological connectivity and the presence of tidal wetlands landward of our specified shoreline. Hydrological connectivity models the paths that water from rising sea levels could traverse on the surface and accounts for features recognizable at the spatial scale of the DEM that may either facilitate or impede advancing seas such as channels or levees. In applications of low-lying coastal



**Fig. 3** Areas of selected major municipalities (*land boundaries in white*) with elevations at or below 1–6 m and connectivity to the sea. Map figures for the other 14 major municipalities are in [SOM5](#), [SOM6](#), and [SOM7](#)

elevation datasets that quantify potential socioeconomic and ecological impacts of SLR, omission of hydrological connectivity may result in overestimations of possible impacts. Exclusion of tidal wetlands landward of specified shorelines also may generate impact estimates that are too high. Incorporating tidal wetlands above MHW improved our estimates of land area percentages for elevations at or below 1–6 m within coastal municipalities of the U.S.A., mostly for a small number of coastal cities that include the major municipalities of Jacksonville, FL and Virginia Beach, VA.

The most important technical consideration that our current dataset does not incorporate is elevation data uncertainty that stems from the inherent vertical error and vertical datum of the  $NED_{1arc}$ . These sources of uncertainty affect the elevation zone delineations that we present and the accuracy of land area percentages that we report. At the national level, the inherent vertical error of the  $NED_{1arc}$  does not adequately support delineation of low-lying coastal areas at 1-m increments (Gesch 2007; Gesch et al. 2009). To be completely suitable for such an analysis, a DEM would minimally need to have a vertical error of  $\pm 0.5$  m (95% confidence interval), a range of uncertainty equal to the increment of analysis (Gesch et al. 2009). However, vertical error of the  $NED_{1arc}$  along coasts is typically better than the nationwide average (Gesch 2009; Gesch et al. 2009), suggesting that delineation of low-lying coastal areas at increments between 2 and 6 m is fully appropriate in many areas. Furthermore,  $NED_{1arc}$  from source data of highly accurate digital photogrammetry and lidar topographic surveys (e.g.,  $\pm 29.4$  cm 95% confidence interval for lidar Gesch et al. 2009) in limited coastal areas properly supports analysis at 1-m increments. As a consequence of  $NED_{1arc}$  vertical error, we most confidently interpret our results at the 6-m elevation contour.

At present, the optimal way to address inherent vertical error of modeled elevations is to use DEMs with high vertical accuracy that are based on data from digital photogrammetry and lidar topographic surveys. As a comparison (not shown), areal coverage of our dataset at or below the 1-m elevation contour in the San Francisco Bay region largely underestimates that which is based on lidar data in a similar study by Knowles (2010). An overall underestimation of areal coverage at or below the 1-m elevation mark by the  $NED_{1arc}$  in comparison to the lidar-based 1/9 arcsec NED also appears to be the case in North Carolina, though inherent vertical error of the  $NED_{1arc}$  may reverse this conclusion (Gesch 2009). However, as DEMs of such high vertical accuracy are not yet available for all coastal states of the conterminous U.S.A., use of the relatively coarser and less accurate  $NED_{1arc}$  is necessary for national-level assessments. Comparison of a DEM with an independent elevation reference such as National Geodetic Survey global positioning system benchmarks is one way to assess DEM vertical accuracy and generate confidence intervals of both delineated elevation zones and potential SLR impacts (Gesch 2009; Gesch et al. 2009).

Confidence intervals for elevation zones and potential SLR impacts can also incorporate differences between the vertical reference of the DEM and a local sea level datum (Gesch et al. 2009). Alternatively,  $V_{Datum}$  ([vdatum.noaa.gov](http://vdatum.noaa.gov); Parker et al. 2003) or other vertical transformation methods (e.g., Titus and Wang 2008) can systematically adjust DEM values to a particular local datum for analysis of elevation data in the context of projected SLR. For our current dataset, error introduced by the NAVD 88 vertical reference of the  $NED_{1arc}$  is of greatest regional concern along



the Pacific coast, where the average difference between local MHW and the NAVD 88 zero value is 1.9 m. Nonetheless, as relatively little area along the Pacific coast appears for elevations at or below 2–6 m, potential SLR impacts may still be less extensive there than in other regions of the conterminous U.S.A. for elevations at or below approximately 4 m. We plan to integrate technical considerations regarding the vertical uncertainty of DEMs in future versions of our dataset.

More detailed future studies that help identify low-lying coastal elevations prone to SLR impacts also need to consider geoscience issues regarding amount, range, and timing of recent global and regional SLR projections. Addressing these aspects of future sea level enhances estimates and interpretations of elevation zone delineations and potential socioeconomic and ecological impacts due to SLR. For example, elevation zone delineations could track projection model averages and ranges of global and regional SLR amounts for the twenty-first century that are calculated under different emissions scenarios established by the IPCC (e.g., Vermeer and Rahmstorf 2009; Yin et al. 2009, 2010). Much as elevation data uncertainty forms confidence intervals for elevation zones and potential SLR impacts, SLR projection averages between and ranges within emissions scenarios establish upper and lower bounds for elevation zones and potential SLR impacts at future points in time. Given that lower, mean, and upper estimates of SLR now approach or exceed 1 m by 2100, analysis of elevation data in the context of SLR projections over the next ~90 years requires DEMs with sub-meter vertical accuracy (Gesch 2009).

Elevation data analysis is only one of the components needed to fully identify coastal areas that may confront potential SLR impacts such as accretion, erosion, flooding, or inundation (Gesch et al. 2009). This is particularly true for natural environments where, in addition to SLR, complex and dynamic processes driven by storms, biota, and sediment flux can change coastlines. The best application of our results is to coastal areas where inundation will be the primary SLR impact. Inundation is the most likely impact in developed areas, such as the municipalities we examined in this letter, as well as in natural areas that have a lack of biota, low sediment influx, gently sloping land, and a small tidal range (Gesch et al. 2009; Kirwan et al. 2010). However, amounts of global SLR as considered in this letter may outpace the ability of most coastal wetlands to adapt to rising sea levels and increase the amount of natural environments potentially impacted by inundation (Kirwan et al. 2010).

Our new geospatial dataset of low-lying coastal elevations for the entire conterminous U.S.A. raises awareness about implications of the latest SLR science and provides a meaningful comparison of coastal regions and cities potentially affected by SLR in this and subsequent centuries. Despite technical limitations stemming from both the NED<sub>1arc</sub> and our methodology, results clearly highlight that continued high global GHG emissions and the ensuing rise in sea level have the potential to impact numerous coastal cities of the conterminous U.S.A. Potential SLR impacts will be very local and disproportionate, in contrast to the national and international dimensions of and associated efforts to curb GHG emissions.

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