

A National View of Storm Surge Risk and Inundation

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ABSTRACT

The National Oceanic and Atmospheric Administration (NOAA), specifically the National Weather Service's (NWS) National Hurricane Center (NHC), utilizes the hydrodynamic Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model to simulate storm surge in 27 basins along the U.S East and Gulf Coasts. This information is provided to federal, state, and local partners to assist in a range of planning processes, risk assessment studies, and decision making. Based on climatology, tens of thousands of hypothetical hurricanes are simulated in each basin, and the potential storm surges are calculated. Storm surge composites—maximum envelopes of water (MEOWs) and maximum of maximums (MOMs)—are created to assess and visualize storm surge risk under varying conditions.

While MEOWs and MOMs provide a local assessment of storm surge risk, they do not provide a national perspective owing to the 27 discrete grids. National assessments must therefore merge the grids together, which is a laborious task requiring considerable SLOSH and hydrodynamic modeling expertise. This paper describes the technique used to create national inundation maps for category 1–5 hurricanes using the SLOSH MOM product, and it provides a simple quantitative assessment of the potential societal impacts. Approximately 22 million people along the U.S East and Gulf Coasts are vulnerable to storm surge. For all hurricane categories, a substantial portion of the coastal population and housing units are at risk, and many evacuation routes become inundated. Florida is the most vulnerable state with 40% of its population at risk. These maps and analyses provide a new way to view, analyze, and communicate national storm surge risk and inundation.

1. Introduction

Despite 49% of deaths from Atlantic tropical cyclones being directly attributed to storm surge (Rappaport 2014), and numerous extreme storm surge events occurring in the past decade, overall public awareness of this hazard and the associated risk remains extremely low (e.g., Morrow et al. 2015). This can be linked to the

complexity in describing the storm surge phenomenon, its impacts on the general public, and the limitations of the products available to raise awareness during land-falling tropical cyclone events (e.g., Morrow et al. 2011; Lazo and Morrow 2013; Morrow et al. 2015). Storm surge is defined as the abnormal rise of water generated by a storm, over and above predicted astronomical tides (NHC 2014c). In contrast to wind, the storm surge hazard is more abstract, and this phenomenon may never be personally experienced during a lifetime. Therefore, well-articulated communication material is needed to help people understand storm surge risk. Morrow et al. (2015) stated that high-quality visualization

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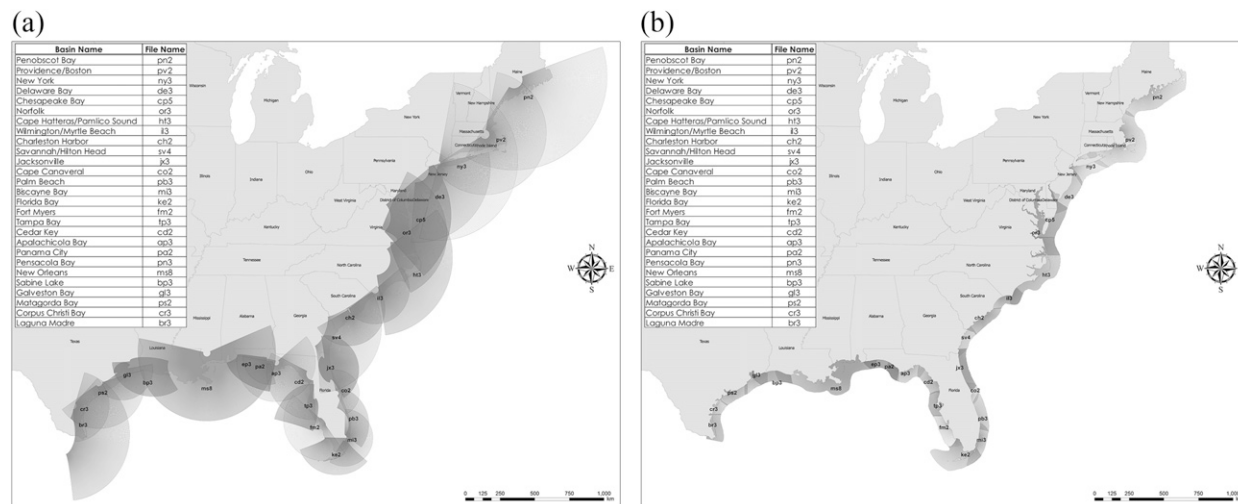


FIG. 1. The spatial extent of 27 SLOSH model basins (or grids) used in this study: (a) the full grid extents and (b) the grid extents after the grid refinement has been conducted.

material (e.g., maps, graphics, and photos) is essential for effective risk communication in current society, and that storm surge is most clearly depicted on a map that shows the height of water above the ground surface (i.e., inundation) and the inland extent of the flooding. The National Oceanic and Atmospheric Administration (NOAA) and the National Hurricane Center (NHC) have embarked on an intense outreach effort and are improving storm surge warning capabilities and products to help minimize the loss of life and property.

To aid in planning and operations, the NHC provides a set of storm surge products based on the hydrodynamic Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (Jelesnianski et al. 1992). These products have a wide variety of uses in the public, private, and government sectors. For example, the underlying SLOSH hydrodynamic data serve as the foundation to create the national hurricane evacuation zones. Currently, the SLOSH products are region specific, which often leads to confusion and improper use of the data. National SLOSH-based storm surge assessments are challenging, as there are 27 separate SLOSH basins (or grids) along the U.S. East and Gulf Coasts (see Fig. 1a). Merging these grids together is a laborious task requiring considerable SLOSH and hydrodynamic modeling expertise. Currently, to the authors' knowledge, there are no free and readily available SLOSH-based national storm surge inundation maps. This paper presents the methodology used to create high-resolution U.S. storm surge inundation maps using existing storm surge products created at the NHC, and provides a quantitative assessment of the societal impacts caused

by storm surge flooding from category 1–5 hurricanes based on the Saffir–Simpson Hurricane Wind Scale (SSHWS). The information, data, statistics, and storm surge risk maps presented in this paper are highly desired and invaluable to emergency managers, state and local elected officials, and academic and private sectors for various activities, including planning, education, outreach, and specific analyses.

2. Storm surge modeling

The NHC utilizes the SLOSH model to simulate storm surge to assist in a range of planning processes, risk assessment studies, and decision making. It has been used operationally for more than two decades. Over this time, SLOSH has provided valuable and accurate storm surge forecasts, including for Hurricane Sandy in 2012 (Forbes et al. 2014). For planning purposes, the NHC uses a representative sample of hypothetical storms to estimate the near-worst-case scenario of flooding for each hurricane category. These SLOSH simulations are used to create a set of operational and planning products, and represent the data used in this paper.

The NHC provides two products based on hypothetical hurricanes: maximum envelopes of water (MEOWs) and maximum of maximums (MOMs). MEOWs represent the maximum storm surge resulting from roughly 10 000 to 60 000 hypothetical storms of varying forward speed, radius of maximum wind (RMW), intensity (categories 1–5), landfall location, initial water level, and storm direction, simulated through each SLOSH grid (NHC 2014a). Although the NHC has disassociated storm surge from the SSHWS operationally, the SLOSH

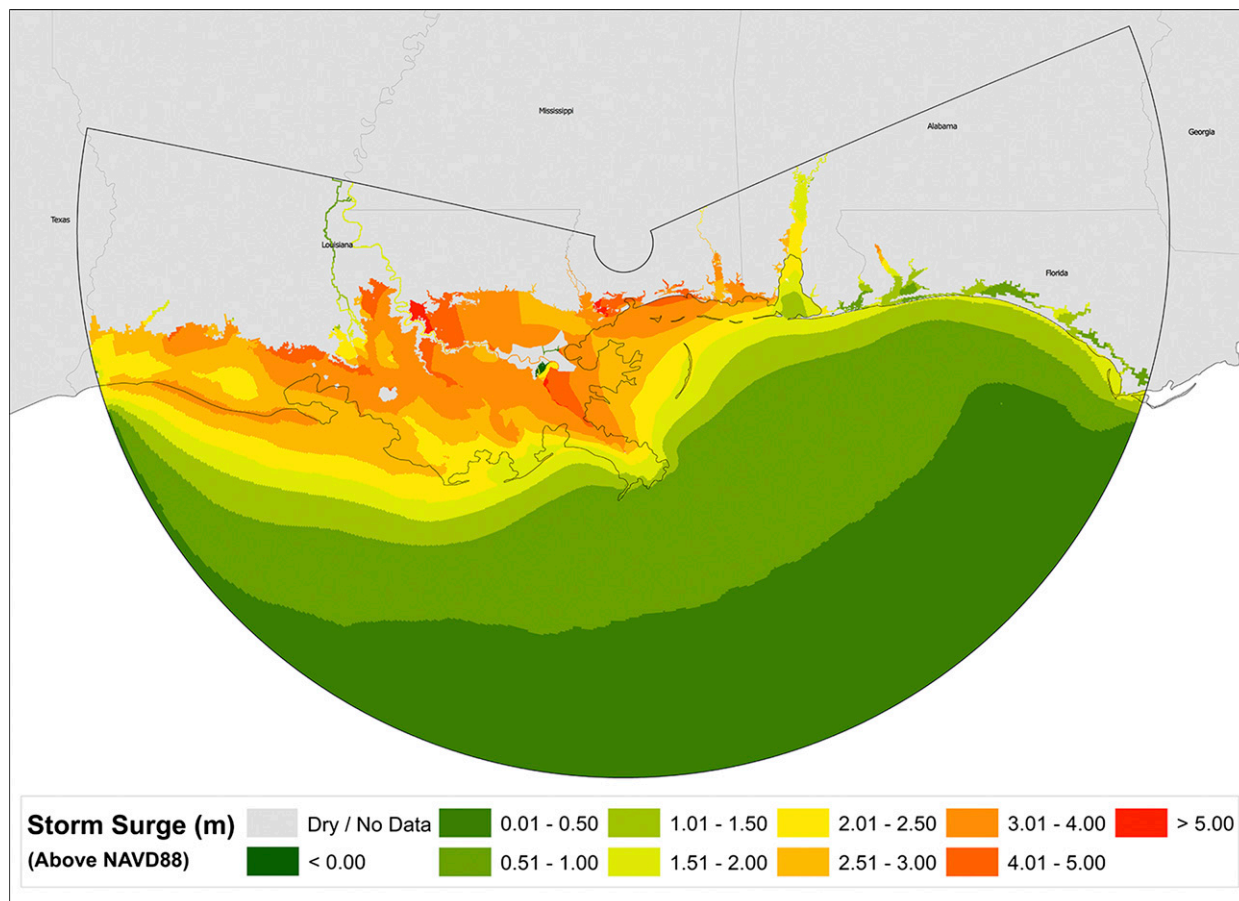


FIG. 2. The storm surge (m) depicted in the SSHWS category 2 SLOSH MOM product for the New Orleans (MS8) basin.

MEOW/MOM planning products are still linked based on stakeholder input. Since these products consist of hypothetical storms of varying characteristics, each category MOM will produce higher storm surge inundation than a lower category MOM. SLOSH products exclude category 5 storms north of the North Carolina–Virginia border, as thermodynamic factors become unfavorable (Emanuel 1987), and the farthest north category 4 landfall is Hazel in 1954 at the North Carolina–South Carolina border. For each storm combination and basin, parallel storms make landfall in 5–10-mi (~8–16 km) increments along the coast, and the maximum storm surge height in each grid cell is retained. MEOWs (and MOMs) can be viewed in the publicly available SLOSH Display Program (<http://slosh.nws.noaa.gov/sloshPub/>).

SLOSH model MOMs are an ensemble product of maximum storm surge heights (NHC 2014b). MOMs are created for each SLOSH basin by compositing all the MEOWs, separated by category and initial water level, and retaining maximum storm surge value in each grid cell. A zero initial water level is used in this analysis

[i.e., each individual SLOSH simulation was run with an initial water level anomaly of 0 m North American Vertical Datum of 1988 (NAVD88)]. MOMs represent the near-worst-case scenario of flooding, and no single hurricane will produce the flooding depicted in these products (including MEOWs). The MOM products are used in the analysis herein—a category 2 MOM for the New Orleans (MS8) basin is shown in Fig. 2.

Although these products and underlying data are widely used, some limitations exist and should be acknowledged. The three main contributors to the overall storm surge at a location are wind setup, wave setup, and pressure setup (i.e., inverse barometric effect). The MEOW and MOM products do not explicitly account for the increase in water level due to waves. Inclusion of wave setup would result in water levels 10%–50% higher (e.g., Dean and Walton 2009) in each individual SLOSH simulation and thus the SLOSH products. Also, SLOSH basins are not nested to larger grids, meaning any physical processes affecting the overall water level are not known outside of the grid (e.g., coastal-trapped

waves; Morey et al. 2006). Last, a dynamically forced tidal signal is not included in these products. With these limitations known, the data can be used and analyzed appropriately.

3. Elevation datasets

An accurate digital elevation model (DEM) takes considerable time, resources, and expertise to develop and is required to compute inundation. The importance of developing a high-quality DEM is often overlooked and ultimately determines the usefulness of an inundation map (assuming accurate storm surge data). Two datasets were used to create the DEM used in this study and are described below.

The NOAA Office for Coastal Management (OCM) recently developed a high-resolution seamless raster elevation dataset to analyze sea level rise (OCM 2014b). It uses the latest and best available lidar data for areas along the coast. According to OCM (2014a), individual DEMs can include raw and/or bare Earth lidar data, digitized breaklines, national hydrography dataset boundaries, national wetland inventory boundaries, levee centerlines, and elevations. The native resolution of the DEM is primarily $\frac{1}{3}$ arc second (~ 10 m). The RMSE for low-relief and high-relief terrain are 18.5 cm and 37.0 cm, respectively. Since storm surge risk extends beyond the OCM DEM extent, this dataset was augmented with the U.S. Geological Survey (USGS) National Elevation Dataset (NED). The NED is a seamless raster elevation dataset available in the contiguous United States at a resolution of 1 arc second (~ 30 m), and $\frac{1}{3}$ arc second (~ 10 m) and $\frac{1}{9}$ arc second (~ 3 m) for parts of the United States (Gesch 2007; Gesch et al. 2002). The NED was primarily derived from lidar data. Both the NED and OCM datasets have horizontal and vertical data referenced to NAD83 and NAVD88, respectively.

For this work, the NED and OCM DEMs were resampled to 1 arc second using a bilinear interpolation and mosaicked together to produce a seamless raster elevation dataset. The DEM was smoothed via a neighborhood circle approach with a radius of two grid cells (ESRI 2014) using the focal statistics tool in Esri ArcGIS Platform. This minor level of smoothing provides a less noisy map that is easier to interpret (Morrow et al. 2015), and ultimately a seamless DEM for storm surge inundation mapping (see Fig. 3).

4. Methodology

The process to create national inundation maps from the existing SLOSH MOM products requires several

technical steps. First, the usable areas of the SLOSH grids were reduced to ignore spurious data along the grid boundaries. Second, the maximum water levels in each MOM were merged onto a uniform grid for processing. Last, the merged MOM grids were processed through Esri ArcGIS to subtract the land elevation and to create a seamless raster of inundation. This section provides additional details on these steps.

a. SLOSH grid refinement

The SLOSH basins have considerable overlap to allow for complete storm surge coverage for planning and operations (see Fig. 1a). Merging these basins into a seamless product requires technical considerations. The process used in this paper leveraged both SLOSH basin building and surge modeling expertise at NHC. Since the grid boundaries yield unreliable data, basin overlap was minimized, and the high-resolution and center portions of grids were retained (see Fig. 1b). The basins were edited at the gridcell level to retain key subgrid-scale features (levees, roads, channels, etc.). Without changing the SLOSH modeling framework, this grid refinement technique is the most feasible and accurate approach to set the foundation for creating a seamless national product.

b. SLOSH basin merging

It is convenient to merge the variable resolution MOM data for each basin onto a regular grid for processing. Here, the data were merged onto the NWS National Digital Forecast Database (NDFD) Lambert conformal projected grid with a horizontal resolution of roughly 625 m (the actual resolution varies by latitude). Detailed specifications of the NDFD grid can be found in NWS (2014). Since each MOM consists of thousands of different SLOSH simulations, overlapping basins tend to produce a relatively seamless result after the aforementioned grid refinements have been applied (overlapping values are typically 0.15 m or less). In Esri ArcMap, the MOM data were spatially joined via the closest grid cell to the NDFD grid, and a mean of the MOM values (if applicable) was computed at each NDFD grid point. A merged NDFD grid was created for each MOM.

c. Storm surge inundation

Esri ArcMap and Python were used to compute inundation and to map the result. Since the DEM and NDFD grids have differing resolutions, the storm surge data were downscaled to the resolution of the smoothed DEM. A kernel interpolation was utilized to rasterize the NDFD points, and a bilinear interpolation down-scaled the resulting raster to the resolution of the DEM.

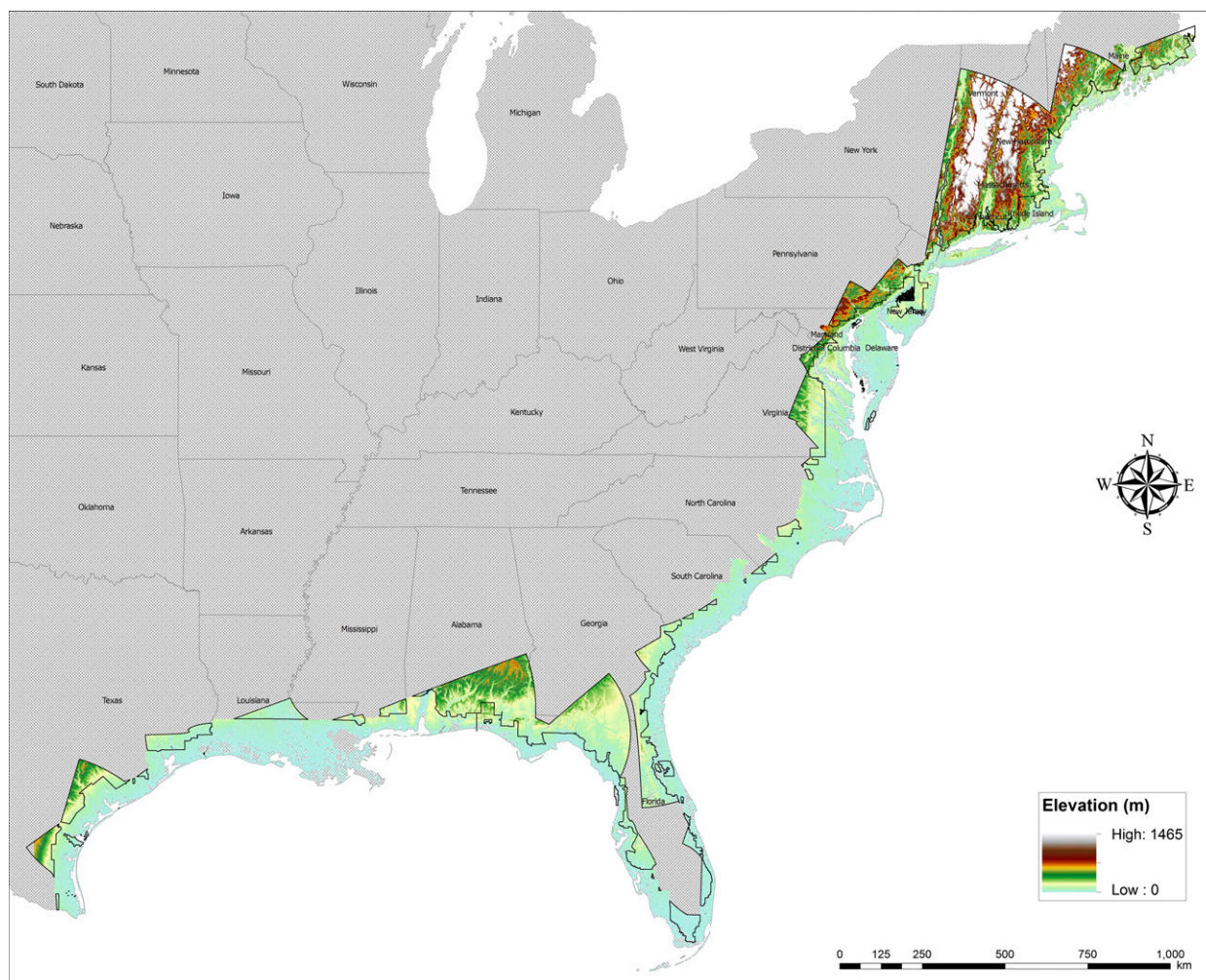


FIG. 3. The DEM used to compute inundation. The black polygons indicate regions where the USGS NED was utilized in the DEM. The gray cross-hatched area indicates land outside the bounds of the DEM. The remaining land area within the United States uses elevation data from the NOAA OCM sea level rise DEM.

Then, a simple subtraction of the elevation from the storm surge yields inundation.

As discussed above, high-quality maps are essential for effective risk communication, and the mapping process herein follows the recommendations outlined in [Morrow et al. \(2015\)](#). To capture the uncertainty in the storm surge modeling and the DEM, to visually simplify a complex phenomenon, and to provide a community-level analysis of the data, the inundation values were binned into four groups (i.e., colors): blue—up to 0.91 m (3 ft), yellow—greater than 0.91 m (3 ft), orange—greater than 1.8 m (6 ft), and red—greater than 2.7 m (9 ft) AGL. Inundation inside of specific levee systems for Texas and Louisiana, raised water levels over hydrographic features, or flooding over land that is normally wet due to tidal fluctuations (marshes, beaches, etc.) is not shown on the map or used in the analysis.

Therefore, the storm surge inundation maps only show flooding that occurs over land that is normally dry.

5. Analysis and discussion

Storm surge inundation maps for SSHWS category 1–5 hurricanes based on the SLOSH MOM products are shown in [Fig. 4](#). Interactive online maps that use the high tide version of the SLOSH MOM products (this paper utilizes the zero initial water level) can be found online (at <http://noaa.maps.arcgis.com/apps/StorytellingTextLegend/index.html?appid=b1a20ab5eec149058bafc059635a82ee>). All coastal states from Texas to Maine are vulnerable to storm surge inundation, and risk significantly increases with increasing hurricane category. Locations along the Gulf of Mexico are extremely vulnerable to storm surge, in terms of both height and inland

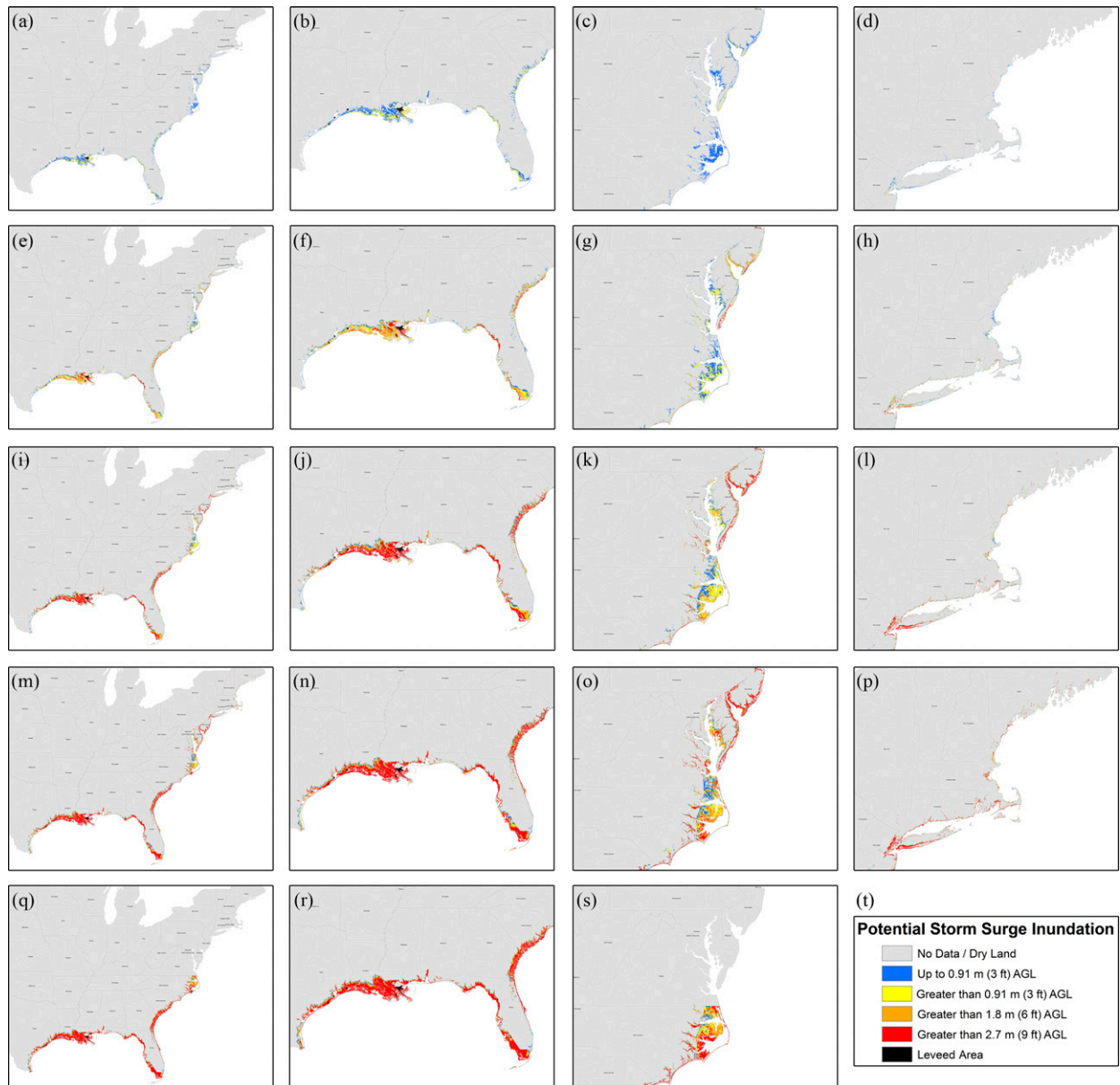


FIG. 4. Storm surge inundation (m) maps based on the SSHWS category 1–5 SLOSH MOMs product: (a)–(d) category 1, (e)–(h) category 2, (i)–(l) category 3, (m)–(p) category 4, and (q)–(s) category 5. SLOSH products do not include category 5 hurricanes north of the NC–VA border. (t) The legend for all figures.

extent. This is due to a wide and flat continental shelf over the majority of the region, and low-lying land elevations extending well inland. The Northeast United States is not as vulnerable, as the continental shelf is much steeper and narrower, and the land elevations increase relatively quickly with distance from the coast. Large bays, tidal rivers, etc. are extremely vulnerable to storm surge flooding. These relative risk profiles have been known for decades, and this work is in agreement with those assessments.

When evaluating storm surge inundation, it is imperative that the impacts are measured in a useful and understandable manner. To quantify the impacts of storm surge risk at the national level, four analyses were conducted. Each analysis was broken down by SSHWS category (and U.S. state), and includes estimates of 1) the total mathematical area of normally dry land inundated by storm surge, 2) the total population affected by storm surge inundation, 3) the total housing units affected by storm surge inundation, and 4) the length of

TABLE 1. The U.S. state breakdown of the total area, housing count, population count, and the length of FEMA evacuation route inundated by storm surge based on the SLOSH MOM products for each SSHWS category. The housing and population counts are estimated using the 2010 census block demographic information (USCB 2014). Based on the FEMA dataset, bridges, ramps, and tunnels were removed from the evacuation road length estimate (these attributes do not exist in FL and NC). Note that official FEMA evacuation routes do not exist in the states of ME, MA, NY, and NH, and that SLOSH products do not include category 5 hurricanes north of the NC–VA border.

Category	Statistic	U.S. State																			VA	Total
		AL	CT	DE	DC	FL	GA	LA	ME	MD	MA	MS	NH	NJ	NY	NC	RI	SC	TX			
1	AREA (km ²) × 10 ⁻²	5.06	<1.00	3.72	<1.00	74.7	17.6	162	<1.00	10.5	1.31	4.84	<1.00	10.7	1.83	41.2	<1.00	22.7	20.5	9.42	387	
	HOU (count) × 10 ⁻³	36.2	57.9	40.0	<1.00	819	52.6	159	46.5	114	111	30.0	6.44	264	260	167	25.4	167	59.7	164	2580	
	POP (count) × 10 ⁻³	41.4	116	55.3	<1.00	1210	105	375	63.5	223	178	60.5	11.4	437	549	258	45.3	237	90.0	371	4430	
	EVAC RTE (km)	45.3	<1.00	10.8	<1.00	822	2.15	743	—	80.2	—	7.78	—	157	—	342	8.43	26.1	5.02	43.9	2290	
2	AREA (km ²) × 10 ⁻²	7.48	1.37	5.75	<1.00	149	27.8	217	1.52	18.5	3.75	9.61	<1.00	17.2	5.17	65.8	<1.00	38.5	52.6	16.8	639	
	HOU (count) × 10 ⁻³	51.2	107	62.0	<1.00	1850	105	320	82.3	175	294	66.3	10.0	511	808	245	41.7	289	137	272	5420	
	POP (count) × 10 ⁻³	68.2	222	95.1	4.53	3070	219	777	112	331	554	138	17.8	906	1850	398	74.9	458	244	621	10200	
	EVAC RTE (km)	122	3.26	52.1	<1.00	2810	38.9	1370	—	229	—	47.4	—	539	—	809	35.5	150	52.9	154	6420	
3	AREA (km ²) × 10 ⁻²	10.0	1.99	8.14	<1.00	207	44.7	265	2.90	25.5	5.60	14.2	<1.00	22.6	7.70	94.2	1.14	56.6	91.1	25.9	885	
	HOU (count) × 10 ⁻³	61.6	148	96.0	2.20	2800	162	501	105	230	392	98.4	14.5	679	1270	312	60.8	379	288	464	8070	
	POP (count) × 10 ⁻³	88.4	312	153	7.14	5090	350	1210	153	439	747	210	23.4	1330	2970	529	113	639	609	1080	16000	
	EVAC RTE (km)	243	7.25	109	1.12	4650	146	1820	—	404	—	96.2	—	822	—	1260	76.5	313	187	379	10500	
4	AREA (km ²) × 10 ⁻²	11.6	2.62	10.8	<1.00	254	57.7	293	4.44	31.3	7.37	17.9	<1.00	27.3	9.58	112	1.50	75.6	128	38.1	1080	
	HOU (count) × 10 ⁻³	73.9	188	126	9.29	3390	187	605	122	266	491	129	18.4	822	1640	356	76.5	451	424	601	9980	
	POP (count) × 10 ⁻³	115	403	217	19.2	6290	408	1450	183	525	952	278	30.4	1680	3890	632	146	778	951	1420	20400	
	EVAC RTE (km)	355	14.2	171	6.89	6180	229	2100	—	552	—	136	—	1050	—	1580	108	485	327	683	14000	
5	AREA (km ²) × 10 ⁻²	12.8	—	—	—	292	63.4	311	—	—	—	20.6	—	—	—	124	—	87.2	165	—	1090	
	HOU (count) × 10 ⁻³	85.3	—	—	—	3920	196	669	—	—	—	140	—	—	—	397	—	489	564	—	6460	
	POP (count) × 10 ⁻³	140	—	—	—	7430	431	1600	—	—	—	305	—	—	—	727	—	860	1350	—	12800	
	EVAC RTE (km)	441	—	—	—	7400	272	2210	—	—	—	165	—	—	—	1880	—	619	473	—	14000	

Federal Emergency Management Agency (FEMA) evacuation routes inundated by storm surge. The population and housing data are based on the 2010 census block demographic information (USCB 2014). The hurricane evacuation routes are provided by FEMA (2014). Results indicate that a substantial portion of the coastal population, housing, land area, and evacuation routes are impacted by all hurricane categories (see Table 1). The population and housing units affected by storm surge represent an upper bound—the total census block was included even if it was not completely inundated. Subdividing the census block data is beyond the scope of this work, and the current analysis provides a reasonable estimate for planning purposes. In total, approximately 22 million people along the U.S. East and Gulf Coasts are at risk from storm surge flooding. Florida, New York, and New Jersey have the most population and housing vulnerable to inundation, but many other states are significantly impacted. Roughly 40% of Florida's population is vulnerable to storm surge. Based on the FEMA dataset, bridges, ramps, and tunnels were removed from the road length estimate where available (these attributes do not exist in Florida and North Carolina, and thus overestimate the risk), since these features are not explicitly resolved in the DEM. In a worst-case scenario (i.e., storm surge flooding associated with the highest category of storm simulated at each location), over 16 000 km of evacuation route is inundated. The top five states, in rank order, with the most evacuation routes inundated by storm surge are Florida, Louisiana, North Carolina, Maryland, and New Jersey, respectively. Note that official FEMA evacuation routes do not exist in the states of Maine, Massachusetts, New York, and New Hampshire. The top four states with the most land area flooded by storm surge are Louisiana, Florida, North Carolina, and Texas, respectively. For a category 5 MOM, about 23% of Louisiana's land is inundated by storm surge. Quantifying the impacts of inundation at the national level lends much perspective on the overall risk.

6. Concluding remarks

This paper provides a novel and documented approach to merging the SLOSH MOM products to create a seamless national view of storm surge inundation and risk for category 1–5 hurricanes from Texas to Maine. Using social science research, the carefully derived and high-quality inundation maps provide a means for effective risk communication and analysis. These data are valuable to federal, state, and local NOAA partners, and academic, private, and other various organizations. In addition to the analyses conducted herein, these data

can be used to evaluate risk to critical facilities and infrastructure, to estimate potential economic and insured losses, to analyze impact on supply chains, etc. The authors hope that this work promotes education and outreach of storm surge risk to help mitigate the loss of life and property during hurricane events, and that it facilitates new and novel analyses that could not have been conducted previously.

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