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RESEARCH ARTICLE

Effective inundation of continental United States communities with 21st century sea level rise

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Recurrent, tidally driven coastal flooding is one of the most visible signs of sea level rise. Recent studies have shown that such flooding will become more frequent and extensive as sea level continues to rise, potentially altering the landscape and livability of coastal communities decades before sea level rise causes coastal land to be permanently inundated. In this study, we identify US communities that will face effective inundation—defined as having 10% or more of livable land area flooded at least 26 times per year—with three localized sea level rise scenarios based on projections for the 3rd US National Climate Assessment. We present these results in a new, online interactive tool that allows users to explore when and how effective inundation will impact their communities. In addition, we identify communities facing effective inundation within the next 30 years that contain areas of high socioeconomic vulnerability today using a previously published vulnerability index. With the Intermediate-High and Highest sea level rise scenarios, 489 and 668 communities, respectively, would face effective inundation by the year 2100. With these two scenarios, more than half of communities facing effective inundation by 2045 contain areas of current high socioeconomic vulnerability. These results highlight the timeframes that US coastal communities have to respond to disruptive future inundation. The results also underscore the importance of limiting future warming and sea level rise: under the Intermediate-Low scenario, used as a proxy for sea level rise under the Paris Climate Agreement, 199 fewer communities would be effectively inundated by 2100.

Keywords: climate change; sea level rise; coastal resilience; socioeconomic vulnerability; United States

1. Introduction

Sea level rise as a consequence of ongoing climate change poses a threat to millions of people worldwide (Hinkel et al. 2014). In the United States alone, the combination of global sea level rise, population growth and land use change is projected to expose between 4 and 13 million people to inundation by the year 2100 (Hauer et al. 2016). Left unabated, rising seas could affect upwards of 20 million US residents through the end of this century and beyond (Strauss et al. 2015).

While the number of people and communities affected by future inundation depends on the pace and magnitude of sea level rise, recurrent tidal flooding is already emerging as one of the most visible and quantifiable present-day signs of climate change. The East and Gulf Coasts of the US experienced some of the world's fastest rates of sea level rise during the 20th century (National Oceanic and Atmospheric Administration 2013a; Dangendorf et al. 2017). These rising seas have caused tidal flooding–coastal flooding that is driven in large part by routine tidal fluctuations rather than precipitation or storm surge–to become an increasingly frequent occurrence in US coastal communities. Whereas minor coastal flooding along the East, Gulf, and West coasts of the US occurred just once every one to five years in the 1950s, it was occurring about once every three months by 2012 (Sweet et al. 2014).

Sea level rise is expected to make recurrent tidal flooding both more frequent and more extensive (Sweet & Park 2014; Moftakhari et al. 2015; Dahl et al. 2017; Kulp & Strauss 2017). While the tidal datums associated with the mean higher high water (MHHW) mark could be revised upward as sea level rises, the water level at which a community begins to flood will not change, thus leading to an increase in flood frequency. With this increase, many areas will flood with such frequency—potentially facing dozens to hundreds of minor coastal floods per year by mid-century—that, in the absence of protective measures, they could be rendered unusable before they actually fall at or below the present day MHHW level.

The definition of an area permanently inundated by the ocean is conceptually and functionally straightforward: Any area that is under water at high tide would be considered permanently inundated. Sea level rise is projected to permanently inundate many coastal areas in the US this century [e.g. NOAA, 2017]. Many communities, however, are already facing disruptive, even transformative flooding

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long before they will be rendered permanently inundated (Spanger-Siegfried et al. 2014). In places such as Annapolis, Maryland, Norfolk, Virginia, and Miami Beach, Florida, substantial investments of time and money are being made to cope with frequent tidal flooding that disrupts daily life and business operations (City of Annapolis 2011; Applegate 2014; Weiss 2016).

As sea level rises, more coastal communities will begin to see increasingly frequent tidal flooding that is both expansive enough to preclude normal daily life in certain areas (hindering work and school transportation, impeding commerce, damaging property, etc.) and frequent enough to make adjusting to this disruption costly—in some cases prohibitively so—or untenable (Spanger-Siegfried et al. 2014; Sweet & Park 2014; Moftakhari et al. 2015; Moftakhari et al. 2017). Investments into protective measures such as bulkheads or pump systems can make a substantial difference to community-level flood severity (Allen 2016). While not specifically addressed in the present study, such measures have the potential to forestall the onset of disruptive flooding.

The consequences of frequent flooding for communities that already face socioeconomic challenges are likely to be even more disruptive than for those with greater resources. While the causes of socioeconomic vulnerability are complex and can encompass a wide range of variables—including income, race, education, and health insurance coverage—communities with high socioeconomic vulnerability are traditionally more impacted when faced with environmental hazards such as flooding and have fewer resources to cope and adapt (Adger et al. 2009; Lane et al. 2013; Dilling et al. 2015).

In this study, we examine what we call "effective inundation." We consider an effectively inundated area to be one in which flooding is so frequent that it renders the area's current use no longer feasible. In this sense, effective inundation is the point at which a community is forced to make changes to ensure its residents are safe and its infrastructure and services are functional.

Effective inundation exists along an inundation trajectory that begins with no tidal flooding, then shifts as sea level rises to infrequent tidal flooding, then advances further into frequent tidal flooding, which becomes effective inundation, and eventually, permanent inundation (**Figure 1**).

Despite a general understanding that sea level rise will bring more frequent flooding to many areas (Dahl et al., 2017 and others) and that permanent inundation is a long-term risk, there are few tools available to communities that assess the growing land area likely to be affected by frequent, disruptive flooding within timeframes associated with community planning horizons.

Previously published tools and studies have focused on either a) the frequency and intensity of coastal flooding, either tidally-driven or from storm surge, at defined time points in the future (e.g. Sweet & Park 2014; Moftakhari et al. 2015; Dahl et al. 2017); b) national-scale visualization and analysis of inundation with defined increments of sea level rise (e.g. 0.5 m, 1.0 m) relative to MHHW irrespective of the fact that sea level is not expected to rise uniformly along our coasts (Marcy et al. 2011; Climate Central 2014; Hauer et al. 2016); or c) local-scale visualizations and analyses reflecting the amount of sea level rise projected locally for a given year (e.g. TMAC, 2015).

The first approach (a) is useful in communicating the magnitude and extent of projected future flooding; however a frequency alone (e.g. 180 floods per year) without a tie to the area affected by such flooding limits how much a community can do with the information. The second approach (b) relies on users to have some *a priori* knowledge about the local pace of sea level rise as well as different sea level rise scenarios. For users whose expertise lies outside of sea level rise science, having to do additional research to link the mapped increments of sea level rise to timeframes could be an impediment to well-informed decision-making. The third approach (c) has its greatest utility for the communities that have undertaken such efforts, but is not universally available to all communities.

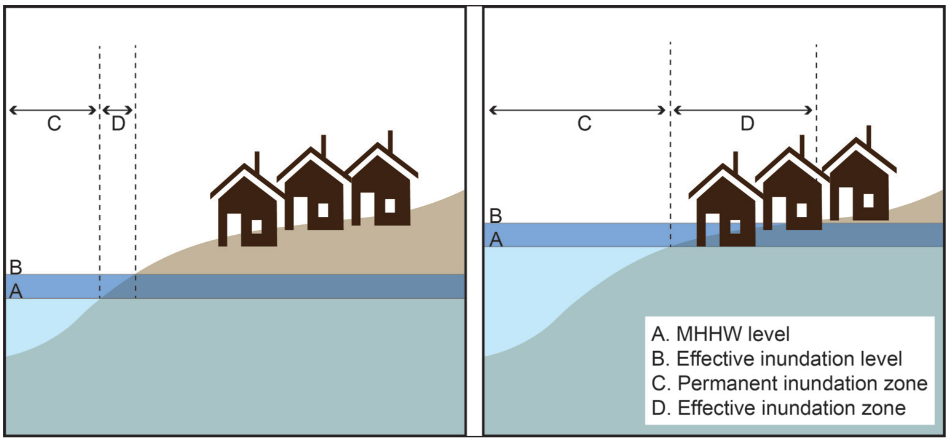

Figure 1: Sea level rise expands the zone of effective inundation. Areas that fall below the mean higher high water (MHHW; light blue) level today are permanently inundated, as infrastructure below the MHHW level would be inundated, on average, once daily. Areas that lie just above the MHHW level (darker blue) flood regularly enough that their use is limited. These areas are effectively inundated. Compared to today (left panel), sea level rise will expand both the permanent inundation zone and the effective inundation zone (right panel). DOI: https://doi.org/10.1525/elementa.234.f1

With all of these approaches, the link between potential reductions in greenhouse gas emissions and community-level coastal impacts is not explicit.

With these gaps in the existing decision-making tools in mind, we have undertaken a novel analysis that identifies where and when sea level rise effectively inundates coastal communities in the continental US through the end of this century. We also evaluated the intersection of this physical exposure and socioeconomic vulnerability as measured by the Social Vulnerability Index, recognizing that compounding risk factors will create additional challenges for many communities (SoVI; Cutter, Boruff, & Shirley, 2003; Martinich, Neumann, Ludwig, & Jantarasami, 2013).

We do this by:

1. Developing a method to quantify "effective inundation";
2. Mapping the extent of effective inundation within the 23 coastal states of the continental US at a series of time steps between now and 2100 using tide gauge-specific sea level rise projections based on three global sea level rise scenarios published for the Third US National Climate Assessment (NCA hereafter) (Parris et al. 2012; Walsh et al. 2014);
3. Explicitly connecting the concept of reductions in greenhouse gas emissions to effective inundation by using the NCA Intermediate-Low projection as a proxy for sea level rise under a scenario in which future warming is capped at 2°C;
4. Identifying cohorts of communities at the Census county subdivision level that meet the effectively inundated threshold for each future time horizon;
5. Evaluating the proportion of exposed communities that contain at least one Census tract with high socioeconomic vulnerability as defined by the SoVI;
6. Developing a practical online interactive planning tool that allows users to explore the extent of effective inundation at any location with different sea level rise projections at specific years in the future.

2. Methodology

2.1 Determining a frequency threshold

Flood risk tolerance will vary from community to community. In order to conduct a nationally-consistent spatial and temporal analysis, however, we defined a single flooding frequency associated with effective inundation and a land area threshold above which a community would be considered effectively inundated. In addition to reviewing the literature on tipping points in the flood frequencies that communities can cope with (Sweet & Park 2014), we conducted interviews with community experts in East and Gulf Coast communities including Annapolis, Maryland, Charleston, South Carolina, Broad Channel, New York, and consulted publicly available sources such as National Weather Service alerts to determine this frequency. These interviews are summarized in Table S1.

The current frequency of minor coastal flooding—often called nuisance flooding—in these communities ranges from approximately 24 in Charleston to 50 floods per year in Annapolis, on average (Dahl et al. 2017). Despite this large range, and speaking to the issue of different tolerance levels to flooding, each community was already developing or implementing a response to frequent flooding. A city official from Annapolis noted that the city initiated a response to flooding long before reaching the level of 50 floods per year (L. Craig, pers. comm.), while in the 1980s Charleston developed a comprehensive drainage master plan in response to flooding—when flooding was not as frequent as it is today (City of Charleston 2015). In Broad Channel, flooding on certain streets around each full and new moon (about 2 times per month) had driven the neighborhood association to lobby for and secure $28 million for sea walls and road elevation (Katz 2016).

These conversations conveyed that communities were responding to flooding, typically of limited areas, out of necessity and long before it reached the level of 50 events per year. Two of the four communities we spoke with—Charleston and Broad Channel—had taken action by the time they were coping with about 25 flood events per year.

This research suggests that 26 floods or more per year has, for affected communities, required substantial planning and investment. We therefore settled on this frequency as a threshold for defining effectively inundated areas.

In addition to defining a frequency threshold, we defined a threshold of affected land area above which we consider a community to be chronically inundated. Based on an evaluation of our results of present day effectively inundated communities and conversations with experts within those communities, we posit that if 10% or more of a community's usable land area is flooded 26 times per year or more, major municipal challenges will ensue in many cases. These challenges could include, for example, the need for: significant investments in shoreline protection structures; reallocation of land to open space to allow floodwaters to ebb and flow; raising homes, streets, and other infrastructure; or relocating coastal residents to inland areas.

In reality, the impact of flooding on a community has as much or more to do with *what* is being flooded as with *the area* being flooded. Based on our initial results of the effectively inundated area today, the communities of Annapolis, Maryland, and Miami Beach, Florida, do not experience flooding of 10% or more of their area 26 times per year or more. And yet frequent flooding of critical areas of those communities has prompted major investments of time and money (City of Annapolis 2011; Weiss 2016). In contrast, there are low-lying coastal communities where much more than 10% of the land area floods 26 or more times per year, but the flooded area is largely rural and uninhabited and thus does not affect the local people.

Our interviews with local experts revealed that there is no one land area threshold that applies universally to all communities. However, 80% of the 91 communities that meet both the frequency and 10% land area thresholds for flooding today largely fall within two regions with well-documented flooding problems: Louisiana and the Eastern Shore of Maryland. Frequent flooding in Isle de Jean Charles, Louisiana, for example, led residents there to seek and receive federal assistance for relocation (Maldonado et al. 2014). And the population on Smith Island, Maryland, has declined by more than one-third since 2010, in part due to frequent flooding (Holland 2016; TownCharts 2017). In speaking with local experts representing the majority of communities that met the effective inundation threshold today, both the area we mapped as effectively inundated and the frequency of inundation within that area were confirmed as consistent with their current observations and experience (Table S1). In one case (West Wildwood, New Jersey), very recent upgrades to bulkheads had reduced flooding below the extent and frequency indicated by our analysis, suggesting the importance of continuing to update local digital elevation models as protective measures are put in place.

Tidal events that exceed the effective inundation threshold could be affected by a number of factors in addition to tidal variability. These factors include storminess, long-term changes in regional climate patterns–such as the prevailing wind direction–or the Pacific Decadal Oscillation. This analysis does not attempt to separate out the differing causes of flood events. Tidally driven flood events tend to cluster around times when a new or full moon coincides with lunar perigee—the point at which the moon is closest to the Earth—because these conditions amplify the normal tidal range. These events tend to occur more in the spring and fall rather than being spaced evenly throughout the year.

2.2 Tide gauge data to identify the water level associated with 26 exceedances per year

In order to determine the physical areas of the US that are inundated at least 26 times per year, we utilized a set of 93 tide gauges (66 on the East and Gulf Coasts, 27 on the West Coast) maintained by the National Ocean Service. Using 20 years (1996–2015) of hourly, verified water level data for each gauge, we determined the threshold water level relative to the present MHHW level that was exceeded 26 ± 1 times annually (Table S2).

The water level at each gauge associated with the 26 floods per year threshold—hereafter referred to as the effective inundation threshold–could be influenced by a number of factors, both natural and anthropogenic in cause. On interannual and interdecadal timescales, the 18.6 year nodal tidal cycle and the 8.85 year cycle of lunar perigee are both known to influence mean sea level and MHHW along the US East and Gulf Coasts and elsewhere (Flick et al. 2003; Haigh et al. 2011; Wadey et al. 2014). The El Niño Southern Oscillation also affects sea level and extreme water levels on both the East and West Coasts of the US (Sweet & Zervas 2011; Hamlington et al. 2015). On shorter timescales, extreme sea levels such as occurred along the US East Coast in 2009–2010 have the potential to influence flood frequency and the water level associated with effective inundation threshold (Sweet et al. 2009; Goddard et al. 2015). By using 20 years of tide gauge data, our results encompass a full nodal tidal cycle, more than two cycles of lunar perigee, and several El Niño events.

While 30 years is typically considered the modern climate epoch, sea level has also risen substantially in that time period, which has caused an increase in the frequency of tidal flooding at the nuisance level and would likely affect the water level exceeded 26 times per year (Church & White 2011; Ezer & Atkinson 2014; Sweet et al. 2014; Hay et al. 2015; Moftakhari et al. 2015). In using 20 years of data, we aimed to use enough data to encompass the 18.6 and 8.85 year cycles mentioned above while also reasonably capturing modern sea level conditions. This is consistent with our previously published research (Dahl et al. 2017) and considerably longer than the tide gauge reference period used for projections of future flood frequency by previous studies (Sweet & Park 2014). Our projections assume that future tidal ranges will not differ substantially from those during the reference period, though there is evidence that sea level rise may increase tidal range (Flick et al. 2003; Passeri et al. 2016). While the sea level rise projections we use incorporate local rates of vertical land movement, we do not model any changes in coastal morphology, although such changes are likely to occur as sea level rises (FitzGerald et al. 2008; Lentz et al. 2016).

The effective inundation threshold was determined for each year (January–December) of the tide gauge record. Years for which 10% or more of the hourly observations were missing were excluded from the analysis (Table S2). The threshold water level for each gauge was determined recursively using a script that counted the number of exceedances of a specified water level starting with the MHHW level. The script then adjusted the water level in increments of 0.30 mm (0.0010 ft) and recounted the number of exceedances until the number of exceedances was 26 ± 1. This, and all other scripts used developed for this analysis, are available in a public GitHub repository at https://github.com/kristydahl/permanent_inundation.

We then used the mean threshold water level for all of the years to define the effective inundation threshold relative to MHHW for each gauge. We used the standard deviation about the mean effective inundation threshold for the full set of gauges as a component in the combined linear error used to define the time steps we analyzed from now through 2100 (see section 2.4).

It is important to note that tide gauges record variations in water levels relative to local benchmarks that are ideally situated on bedrock. This is not always the case, however. In Louisiana, where benchmarks are typically located tens of meters below the land surface, gauges are recording water level variations relative to those subsurface benchmarks (Jankowski et al. 2017). While this study does not attempt to correct for this phenomenon, it is important to note that in places like Louisiana, the determination of inundation thresholds could be affected by long-term deep subsidence.

2.3 Elevation data and inundated areas

Mapping the extent of the effectively inundated area based on water levels from tide gauges requires a digital elevation model (DEM). We obtained DEMs for the continental US from the National Oceanic and Atmospheric

Administration (Marcy et al. 2011). The resolution of the DEMs varies between ⅓ arc second (~10 meters) and 1/9 arc second (~3 m), though much of the East Coast is at the latter, higher resolution. The DEMs, which were used in the creation of NOAA's Sea Level Rise Viewer, are lidar-based and were conditioned and created specifically for sea level rise mapping (Marcy et al. 2011; NOAA 2017). Because the original data sources vary, so does the vertical uncertainty (root mean square error, or RMSE) of the DEMs. All of the DEMs meet or exceed the 18.5 cm RMSE standard for the National Flood Insurance Program (NOAA 2017). Investigation of the DEM metadata showed that RMSEs were less than 10 cm for most of the East Coast and higher for some parts of the Gulf Coast. Vertical accuracy data was not reported within the metadata of the West Coast DEMs. We assume an average RMSE of 9.25 cm, which we use in our calculations of combined linear error and minimum sea level rise interval below.

2.4 Sea level rise projections

To determine the height of the effective inundation threshold over time, we used local projections based on three global sea level rise projections originally developed for the 3rd National Climate Assessment (NCA; Parris et al. 2012; Walsh et al. 2014). The NCA Highest scenario, which projects 2 m of sea level rise globally by 2100, assumes ocean warming in accordance with IPCC AR4 projections and an estimate of maximum possible ice loss (Pfeffer et al. 2008). The NCA Intermediate-High scenario projects 1.2 m of sea level rise globally by 2100 and assumes warming associated with the upper end of the IPCC AR4 projections while ice loss is modeled using a semi-empirical approach (e.g. Horton et al., 2008; Vermeer & Rahmstorf, 2009; Jevrejeva, Moore, & Grinsted, 2010). The NCA Intermediate-Low scenario assumes that sea level rise is driven primarily by ocean warming with very little contribution of ice loss. This scenario is associated with an average global temperature increase of 1.8°C and a 0.5 m rise in sea level by 2100 (Parris et al. 2012).

There is no published sea level rise projection developed specifically with the goals of the Paris Climate Agreement–namely limiting warming to less than 1.5 or 2°C above preindustrial levels–as a basis. One recent study projects a 0.8 m rise above 2000 levels by 2100 with 2°C of warming, for example (Schaeffer et al. 2012). Another states that limiting warming to below 2°C is associated with sea level rise near or below 1 m by 2100 (Strauss et al. 2015). Because the warming associated with the NCA Intermediate-Low scenario is in line with the Paris goals and the scenario can be easily localized using USACE guidelines, we determined it to be the most useful proxy for a Paris Agreement sea level rise scenario.

The NCA scenarios described above represent globally averaged sea level rise. Sea level is not expected to rise uniformly, however, due to regional factors such as land subsidence, tectonics, changes in ocean circulation, gravitational fingerprinting, groundwater pumping, and dredging, which together account for local vertical land movement (Milliken et al. 2008; Moucha et al. 2008; Mitrovica et al. 2009; Konikow 2011; Ezer et al. 2013). We calculated local sea level rise projections (E) at each tide gauge and at each future time using the equation described by the US Army Corps of Engineers (Huber & White 2015):

$$E(t) = Mt + bt^2$$

Where:

- t is years since 1992
- M is the eustatic sea level rise rate (0.0017 mm/yr) plus the local vertical land movement rate (Huber & White 2015; Zervas et al. 2013)
- b is a variable that determines the pace of sea level rise. This variable is set to 1.56E-04, 8.71E-05, and 2.71E-05 for the NCA Highest, Intermediate-High, and Intermediate-Low scenarios, respectively (Huber & White 2015).

Estimates of vertical land movement (VLM) come directly from the tide gauge records. These estimates were derived by decomposing the records into a number of components, including seasonal variability and global sea level trends, to calculate average VLM rates over the length of each record (Zervas et al. 2013). In places like Louisiana, where subsidence rates are closely linked to rates of fluid extraction and have varied considerably over the last century, the average VLM rates used here may mask any accelerations or decelerations in subsidence rates over the last 20 years (Kolker et al. 2011). Because this average VLM is held constant when calculating future local sea level rise, this calculation could underestimate or overestimate future sea level rise in locations where VLM is highly variable, such as Louisiana.

2.5 Determining the minimum sea level rise increment

In order for the inundation zones for each time interval to be meaningfully different from each other, they must be spaced far enough apart to be outside of the range of statistical uncertainty associated with the underlying datasets (Gesch 2013). There are several sources of statistical uncertainty in this analysis:

1. The vertical accuracy of the DEMs (9.25 cm)
2. Tide gauge measurement errors (3.0 cm; National Oceanic and Atmospheric Administration, 2013a)
3. Datum uncertainty (1.5 cm; National Oceanic and Atmospheric Administration, 2013b)
4. Standard deviation about the mean effective inundation threshold (5.3 cm; this study)

Using the average values (reported above) for (1), (2), and (3), we calculated a cumulative vertical error of 11.2 cm using a sum of squares approach. We then calculate a combined linear error by multiplying the cumulative vertical error by 1.28 for the 80% confidence level. This confidence level is lower than that suggested by Gesch (2013), but consistent with the level employed by NOAA using the same underlying DEMs (NOAA 2017). We then calculate the minimum sea level by multiplying the combined linear error by two (Gesch 2013). These calculations result in an average minimum sea level rise interval of 28.6 cm that we apply across all tide gauges.

For each sea level rise scenario, we used the minimum sea level rise interval and the average of the projected sea level rise values for each year for all of the tide gauges to determine the years for future analysis. Because sea level is projected to rise quickly with the Highest scenario, we analyzed seven future years in addition to the present-day: 2030, 2045, 2060, 2070, 2080, 2090, and 2100. For the Intermediate-High scenario, we analyzed 2035, 2060, 2080, and 2100. For the Intermediate-Low scenario, we analyzed just 2060 and 2100.

2.6 Spatial analysis of inundated areas

Our spatial analysis largely follows the methods outlined by the National Oceanic and Atmospheric Administration (NOAA Office for Coastal Management 2012). We determined the effectively inundated areas by creating a transect of points perpendicular to the coast at each gauge and assigning the gauges and their associated transect points the height of the effective inundation threshold above MHHW. Analyzing the West and contiguous East and Gulf Coast regions separately, we then interpolated between those points using the natural neighbor method. This yielded a spatially variable water level surface above MHHW, which we then added to a MHHW surface developed and published by NOAA (NOAA 2016) and referenced to the NAVD88 vertical datum. This total water level surface represented the height of the effective inundation threshold above NAVD88. For future time steps, we added the corresponding projected amount of sea level rise for that gauge to the effective inundation threshold value and interpolated again to create a future water level surface.

We then subtracted the DEMs from the total water level surface to create an inundation surface for each time step. To ensure that the inundated areas were hydrologically connected to the ocean, not just low-lying areas that might, in actuality, be disconnected from the ocean by higher elevation barriers, we performed a region grouping and extracted only hydrologically connected areas (Figure S1).

2.7 Community-level area analysis

For the purposes of this study, we defined communities using US Census county subdivision areas. The Census defines county subdivisions as "the primary divisions of counties and equivalent entities" (US Census Bureau 2010). County subdivisions vary both in size and population. Unlike Census tracts or counties, county subdivisions tend to represent recognizable towns and their boundaries. Examples include Miami Beach, FL, Atlantic City, NJ, and Galveston, TX.

Using standard spatial analysis tools, we determined the area of each county subdivision above MHHW that was inundated at each time step. In order to assess how much of the inundated area was developed or developable land, we first did the area analysis including all county subdivision land areas above MHHW. We then removed wetland and areas protected by federal levees from each county subdivision and inundation surface and calculated the non-wetland area above MHHW that was inundated at each time step (US Fish & Wildlife Service 2016; USACE 2017). Leveed areas were removed because any errors in levee height or representation within the DEMs could results in false inundation. Additional protective structures such as bulkheads and seawalls were included to the degree with which they were represented within the DEMs.

For each time step, we define a cohort of effectively inundated communities (EICs) based on the percentage of usable land area inundated, excluding wetlands and leveed areas. The impact of coastal flooding on a community will depend highly on *what* is being inundated, not just the frequency, as discussed above. Given the variable levels of resilience to the percentage of land area exposed to flooding, we explored using a higher percentage threshold than the 10% discussed above. Using a higher threshold, e.g. 25% or 50% yields fewer EICs; however the trend—an increasing number of EICs as sea level rises—remains (see section 3.4).

2.8 Analysis of socioeconomically vulnerable communities

Our analysis of socioeconomically vulnerable communities relies on the social vulnerability index (SoVI; Cutter et al., 2003). SoVI provides a relative measure of vulnerability to environmental hazards based on 29 socioeconomic variables. These variables are collected primarily by the US Census Bureau and include economic measures (e.g. per capita income and median household value) as well as demographic measures (e.g. median age and race/ethnicity; see Hazards and Vulnerability Research Institute, 2013 for a full list of underlying variables). Census tract level data were developed and provided by Martinich et al. 2013. For each Census tract, the variables were normalized to z-scores with a mean of zero and a standard deviation of 1, then reduced to an overall SoVI score using a principal components analysis. The overall SoVI score helps to identify places that are significantly above or below mean levels of vulnerability.

Because socioeconomic vulnerability and its causes vary greatly, it does not lend itself to straightforward comparisons across regions. Therefore, the SoVI data were broken into four regions: North Atlantic (ME through VA), South Atlantic (NC through Monroe County, FL), Gulf Coast (Collier County, FL through TX), and Pacific (CA through WA) (Martinich et al. 2013). The overall SoVI scores were normalized within each region such that the mean SoVI score for a region is zero and the standard deviation is 1. We defined tracts with high vulnerability as those with SoVI scores greater than 0.5 standard deviations above the mean, as previous studies have done (Martinich et al. 2013).

We chose to use SoVI over other environmental justice indices (such as EJ Screen) or a smaller subset of variables because of its extensive use by previous studies (Dunning

& Durden 2013; Martinich et al. 2013) and because it encompasses a wide range of social, economic, and demographic variables, all of which can contribute to an overall level of vulnerability (Cutter et al. 2003).

After defining the cohort of EICs for each time horizon and sea level rise projection, we used GIS intersection tools to determine which EICs contain at least one Census tract with high socioeconomic vulnerability. Demographics change over time, and rising seas could force large-scale changes in coastal populations (Hauer et al. 2016). For this reason, we limit our primary analysis of the intersection between tracts with high vulnerability and inundated areas to time steps within the next 30 years (2030 and 2045 for the Highest scenario; 2035 for the Intermediate-High scenario).

2.9 Uncertainty

We assess sources of uncertainty, but do not conduct an explicit error analysis in this study. The primary source of uncertainty in projecting the impact of future sea level rise on coastal communities is likely the future pace and magnitude of the sea level rise itself, which will be a product of both past and future greenhouse gas emissions as well as the Earth system response to those emissions. Because future emissions trajectories are highly uncertain, we do not assign any probability or likelihood to the three sea level rise scenarios analyzed here, but rather see them as a range that brackets uncertainty in future emissions choices, the global ice sheet response to those emissions, and the associated magnitude of sea level rise over the course of this century. Future changes in coastal demographics are an additional source of uncertainty. Because SoVI is a static assessment of socioeconomic vulnerability, we cannot exclude the possibility that time and exposure to flooding will substantially change patterns of socioeconomic vulnerability along the coast.

Other sources of uncertainty derive from the data underlying our analyses–the vertical error in the DEMs, interannual variation in the effective inundation threshold, and tide gauge measurement and datum transformation errors. We have implicitly incorporated these combined errors into our analyses by following conventions for defining the minimum sea level rise interval for mapping (Titus et al. 2009; Gesch 2013). When using the same underlying elevation datasets, previous studies have mapped sea level rise intervals of 12 inches, on par with the 28.6 cm minimum sea level rise interval for this study (Marcy et al. 2011; Climate Central 2014). While recent attempts have been made to quantify errors in spatial sea level rise assessments of limited geographic scope (e.g. Leon, Heuvelink, & Phinn, 2014), there is also precedent for relying on best estimates of uncertainty in studies with a national or regional geographic scope (Weiss et al. 2011; Strauss et al. 2012). Because the underlying DEMs have varying degrees of accuracy, it is likely that the level of uncertainty in our results will also vary along the coasts. A full, strict uncertainty analysis may also be of limited value because future conditions rely on unknowns, such as the magnitude of sea level rise at a given location in a given year (Schmid et al. 2014). Having used the 80% confidence level to calculate the minimum sea level rise interval, we assume that differences in the results we present for sequential years are statistically significant at the 80% confidence level.

3. Results and Discussion

3.1 Tide gauge analysis

For the 93 gauges in our set, the mean height of the effective inundation threshold was 0.33 m above MHHW, and the mean standard deviation about that height was 5.27 cm (see supplementary online material). The threshold at most gauges falls between MHHW and the minor coastal flooding threshold set by the National Weather Service, which averages 0.56 m above MHHW for East and Gulf Coast gauges (Table S2).

3.2 Verification of present-day conditions

We identified EICs in which at least 10% of the non-wetland, non-leveed area above MHHW falls below the effective inundation threshold in the present day (**Figure 2**). Nationally, there are 91 EICs today that cluster into just 29 counties (**Figure 3**). Nearly half of the EICs (59) are in Louisiana, where high rates of land subsidence have exacerbated sea level rise to date (Kolker et al. 2011; Zervas et al. 2013). This present-day cohort includes widely reported coastal flooding hot spots such as Somerset and Dorchester Counties in Maryland (Gertner 2016), the Florida Keys (Union of Concerned Scientists 2015), and Terrebonne and St. Mary Parishes in Louisiana (Marshall et al. 2014). For each of the counties that contain EICs, we contacted local experts in an effort to ground truth our present day results. We spoke with representatives from local National Flood Insurance, sustainability, and environmental planning offices, as well as citizens, who confirmed that the extent of effective inundation we had mapped for the present day was representative of the frequency and extent of flooding observed locally (Table S1). It is important to note that additional shoreline protection measures (e.g. bulkheads, seawalls, etc.) would likely change the frequency and extent of flooding a community experiences, as was the case for one community expert with whom we spoke.

3.3 A flooded future

The number of EICs on a national basis increases steadily as sea level rises (**Figure 3**). By 2035, the number of EICs nearly doubles (to 167) compared to today with the Intermediate-High scenario. That number rises to 272, 365, and 489 in the years 2060, 2080, and 2100, respectively. In addition to the simple rise in the number of EICs, the land area inundated within the EICs increases over the course of the century. Whereas 47 of today's 91 EICs have 25% or more of their land area effectively inundated, by

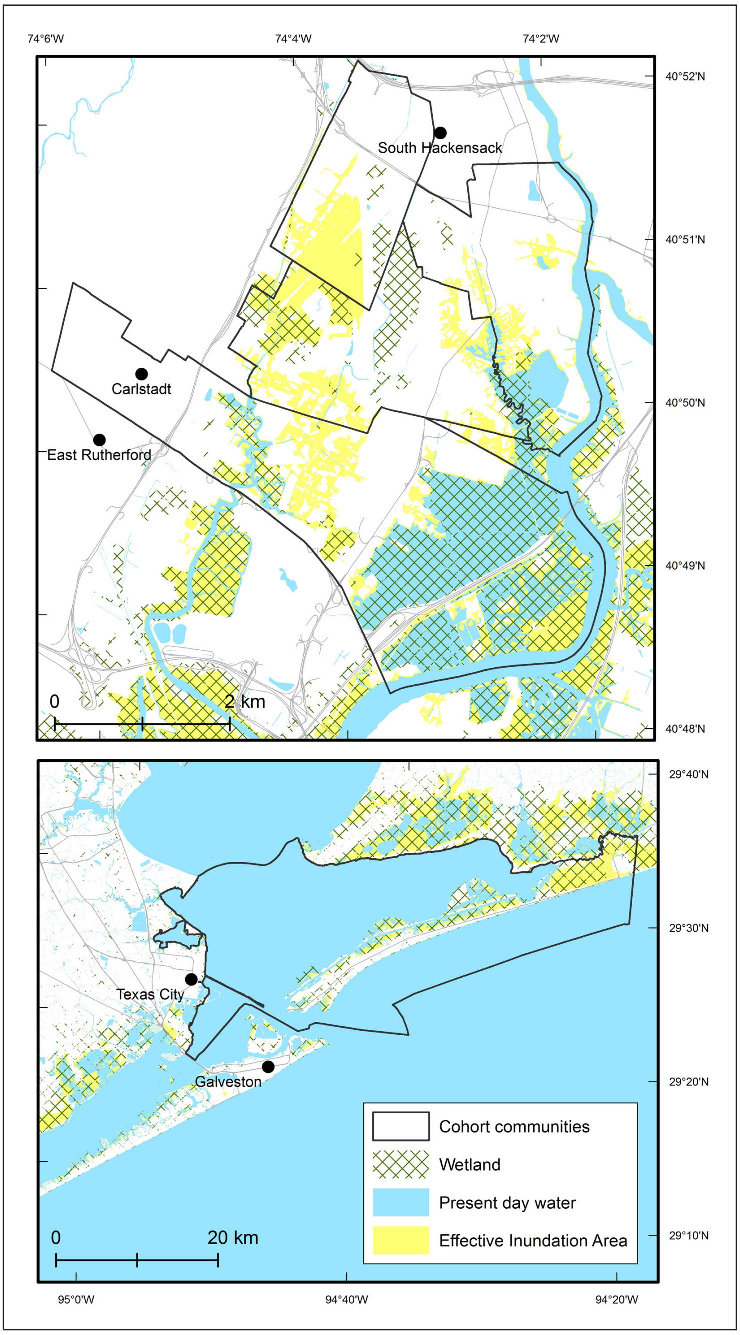

Figure 2: Present day effectively inundated areas. Areas below mean higher high water (blue) and below the effective inundation threshold (yellow) for two example regions within the national analysis: northern New Jersey **(a)**; and the Galveston, Texas, region **(b)**. Wetland areas are shown with cross hatching and present day cohort communities are outlined in black. DOI: https://doi.org/10.1525/elementa.234.f2

2100, 60% of the EICS (or 294 in all) are inundated at that level with the Intermediate-High scenario (**Table 1**). Full lists of communities inundated in year and scenario can be found in Table S3.

3.4 Early EICs: 2030 through 2045

More than 70 new communities face effective inundation by 2035 with the Intermediate-High scenario (**Figure 4**). These early EICs cluster in several regions: the eastern shore of Maryland, the mainland side of North Carolina's Pamlico Sound, the New Jersey shore, South Carolina's Lowcountry, Louisiana west of New Orleans, and the northern coast of Texas between the Louisiana border and Brazosport.

The Highest scenario projects a similar number of newly inundated communities in 2030 as the Intermediate-High scenario in 2035—178 for the Highest scenario compared with 167 for the Intermediate-High. The clusters of affected communities with the two scenarios are also similar. By 2045, with the Highest scenario, however, the number of EICs expands to 265—a rise of nearly 100 in the 15 years since 2030. And by 2045, with the Highest

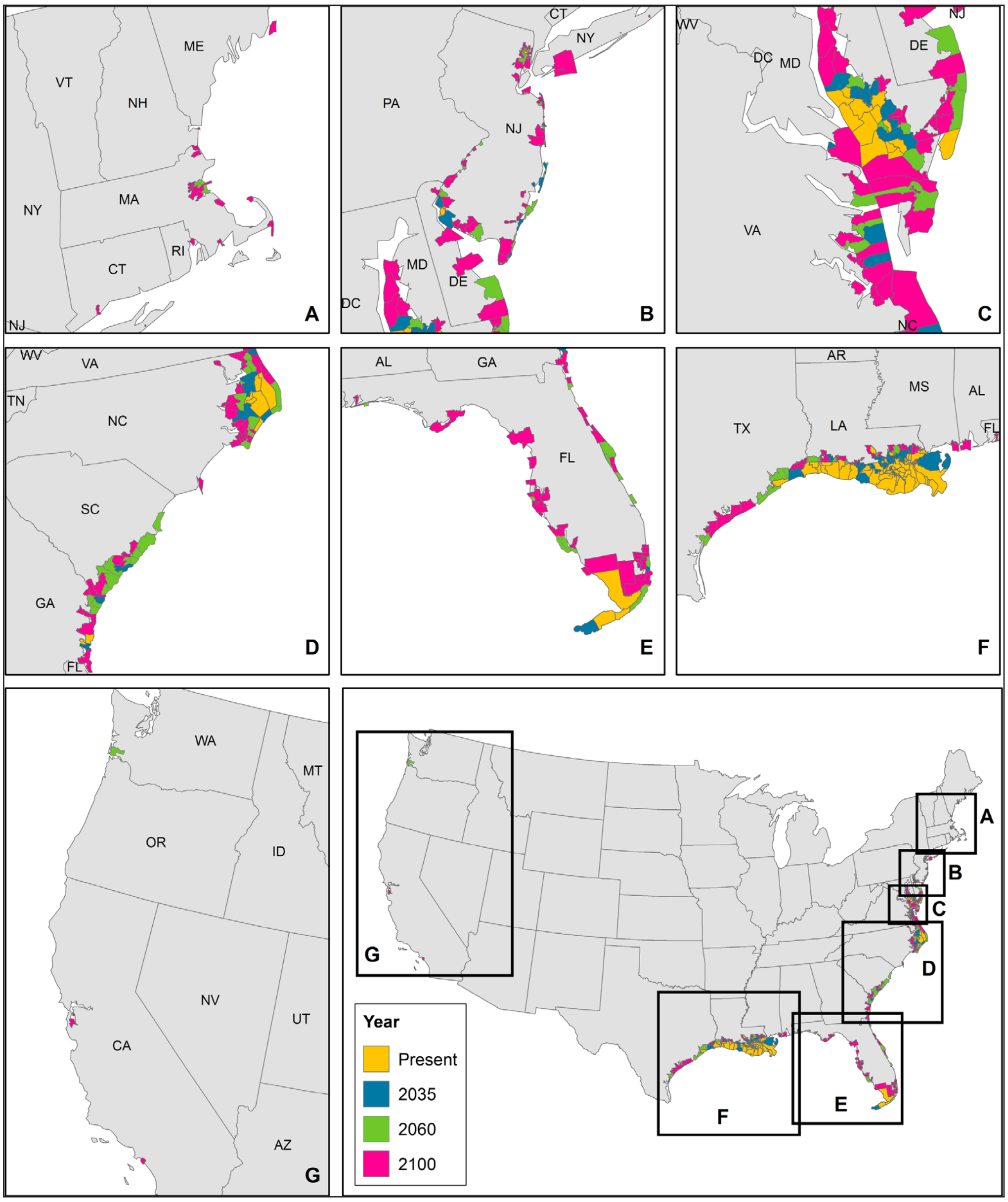

Figure 3: Effectively inundated communities for present and future time horizons. Effectively inundated communities with the NCA Intermediate-High sea level rise scenario for the present (yellow), and in 2035 (blue), 2060 (green), and 2100 (pink). DOI: https://doi.org/10.1525/elementa.234.f3

scenario, the Atlantic Coast of Florida goes from having just one EIC 15 years earlier to having 8. New Jersey also experiences a large increase in EICs between 2030 and 2045—from 26 to 55.

3.5 Mid-century EICs

Between 2035 and 2060, an additional 105 communities face effective inundation with the Intermediate-High scenario. Whereas the clusters of EICs in 2035 tend to simply expand areas with clusters of EICs today, by 2060 entirely new stretches of the coastline are exposed to effective inundation (**Figure 3**). South Carolina, for example, goes from just 2 EICs in 2035 to 12 in 2060, spanning most of the state's coastline. Likewise, Florida's Atlantic coast goes from just one EIC in 2035 to 8 in 2060, including Miami Beach. The greater Boston area, northern New Jersey, and the Atlantic coast of the Delmarva Peninsula, including Lewes, Delaware, and Ocean City, Maryland, all face effective inundation in 2060. Regional inundation patterns—as well as total numbers of EICs–with the Intermediate-High scenario in 2060 are similar to those of the Highest scenario in 2045.

The Highest scenario would expose an additional 88 communities to effective inundation by 2060 compared to the Intermediate-High scenario (Figure S2). Fifty of these communities—more than half—are concentrated in just three states: Florida (14 communities), New Jersey (18 communities), and North Carolina (18 communities). Additional regions with clusters of communities that would face effective inundation with the Highest scenario but not the Intermediate-High scenario in 2060 include

Table 1: Number of effectively inundated communities with each sea level rise scenario. Total number of effectively inundated communities for the present, Intermediate-Low, Intermediate-High, and High scenarios. Number of communities affected to different degrees of inundation reported for four classes of inundation: 10 – 25%, 25 – 50%, 50 – 75%, and >75%. DOI: https://doi.org/10.1525/elementa.234.t1

		Int-Low Scenario		Int-High Scenario				Highest Scenario						
% inundation	**Present**	**2060**	**2100**	**2035**	**2060**	**2080**	**2100**	**2030**	**2045**	**2060**	**2070**	**2080**	**2090**	**2100**
10–25%	44	63	112	64	103	133	195	75	109	132	165	208	226	240
25–50%	31	53	61	49	71	76	102	55	78	89	89	110	123	155
50–75%	12	42	58	37	50	74	59	30	44	71	69	71	81	76
>75%	4	25	59	17	48	82	133	18	34	68	104	134	170	197
Total	91	183	290	167	272	365	489	178	265	360	427	523	600	668

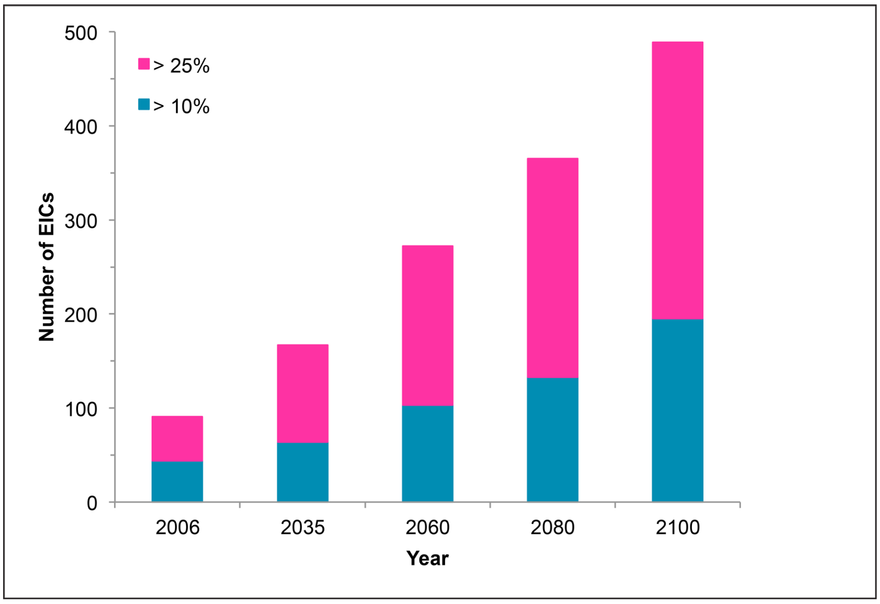

Figure 4: Number of effectively inundated communities nationwide. The number of effectively inundated communities (EICs) increases as sea level rises. Results shown here are for the NCA Intermediate-High scenario. Bar height is inclusive of all communities with 10% or more effective inundation; colors indicate the number of communities at 10 to 25% (blue) and >25% (pink) effective inundation. DOI: https://doi.org/10.1525/elementa.234.f4

the greater Charleston, SC, area, Iberville and St. Martin parishes in Louisiana, and Alameda, CA.

3.6 End of century EICs

By 2100, 489 communities–including nearly all of the immediate coastal communities in New Jersey, Maryland, northern North Carolina, South Carolina, Georgia, Louisiana, and northern Texas–face effective inundation with the Intermediate-High scenario (**Figure 3**). The 2100 cohort includes previous unaffected communities in the San Francisco region (San Mateo and Alameda) as well as the greater Los Angeles region (North Coast). Notably, there are 29 EICs with present day populations over 100,000, including Boston, MA, Newark, NJ, and St. Petersburg, FL (US Census Bureau, 2010).

An additional 179 communities would face effective inundation with the Highest scenario that would not be affected with the Intermediate-High scenario (**Figure 5**). Three-quarters (75%) of these communities fall into eight states—Florida, Louisiana, Maryland, Massachusetts, New Jersey, New York, North Carolina, and Virginia—all of which have 10 or more communities that would be effectively inundated with the Highest scenario but not the Intermediate-High scenario. Significant clusters of communities that fall into this category include the San Francisco Bay Area, much of the Georgia coast and the Florida Panhandle, Hancock County, MS, southern Texas, and Long Island, NY. With the Highest scenario, the number of EICs with present day populations over 100,000 rises to 52, including four of the five boroughs of New York City.

3.7 State trends

Today, the 23 states (including the District of Columbia) included in our analysis have a mean of four EICs. Whereas Louisiana has the most EICs (59), the majority (15) of those states have no EICs, and the mean number of EICs per state today is zero. By 2100, the mean number of

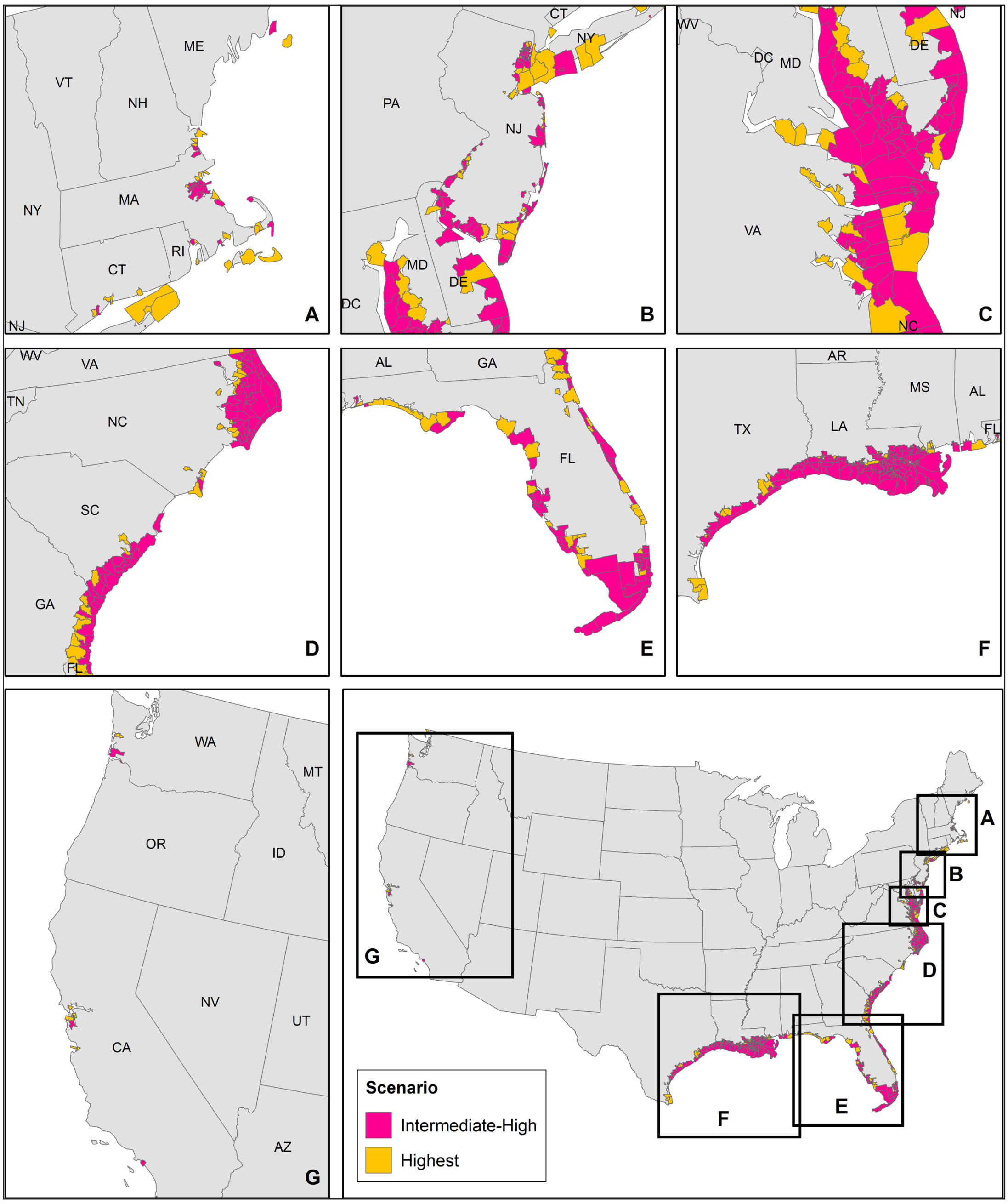

Figure 5: Effectively inundated communities in 2100 with the Intermediate-High and Highest scenarios. Effectively inundated communities with the Intermediate-High scenario in 2100 are shown in pink. Additional communities that would face effective inundation with the Highest scenario are shown in yellow. DOI: https://doi.org/10.1525/elementa.234.f5

EICs per state with the Intermediate-High scenario is 21: roughly a five-fold increase.

Averages, while useful, obscure stark differences in the number of EICs in each state as well as the pace of growth as sea level rises. For example, while the number of EICs in Louisiana grows rapidly—from 59 today to 131 in 2100 with the Intermediate-High scenario—the rate of the increase in EICs in New Jersey is faster (**Figure 6**). By 2100, there are 103 EICs in New Jersey compared to just 7 today—an increase of more than one order of magnitude. Several states—South Carolina, Massachusetts, Texas, and Georgia—go from two or fewer EICs today to 10 or more in 2100. By the end of the century, more than 40% (10) of the 23 coastal states are projected to have 10 or more EICs (**Table 2**).

3.8 Physically exposed and socially vulnerable

Hurricane Katrina and other natural disasters have highlighted the fact that socially vulnerable communities often bear the brunt of disasters and, in the aftermath, face additional challenges to restoring their living situations (Kuhl et al. 2014; Cleetus et al. 2015). Lack of transportation to evacuate a flooded area, living in older, less flood-resistant housing, or working minimum wage

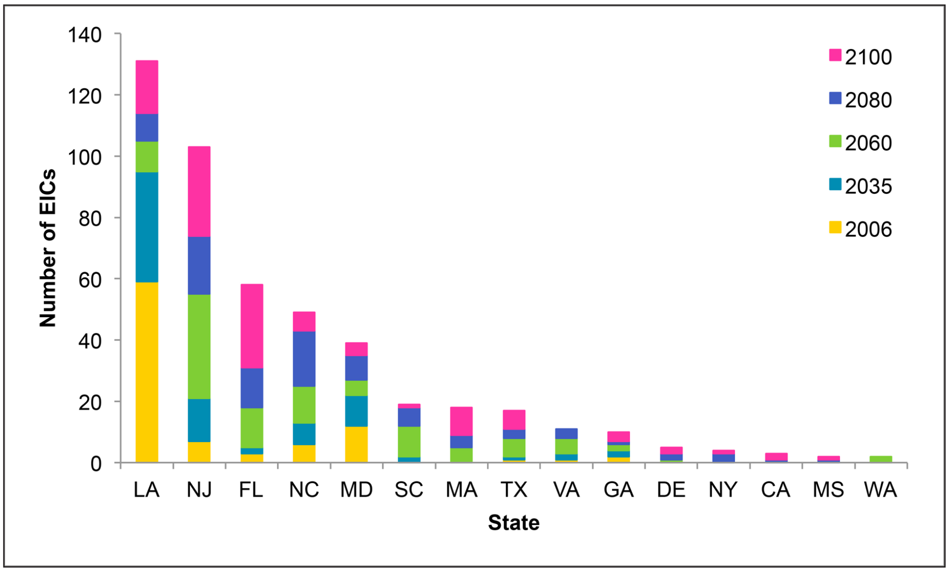

Figure 6: Effectively inundated communities by state. Effectively inundated communities (EICs) for each state with the Intermediate-High scenario. Total bar height represents the total number of EICs for each state by 2100. Note that states with one or zero EICs by 2100 are not shown. DOI: https://doi.org/10.1525/elementa.234.f6

service jobs in a flood-prone coastal region are just a few examples of how socioeconomic vulnerability contributes to heightened environmental risk. While extreme events provide a window into the additional challenges facing socially vulnerable communities, sea level's more gradual rise also has the potential to bring these challenges into closer view.

We find that, nationally, 55% of the 2035 EICs (92 out of 167 total under the Intermediate-High scenario) contain at least one Census tract with a high SoVI score (**Figure 7**). Similar to previous findings, over 40% (39) of these socially vulnerable EICs are in the Gulf Coast region (Martinich et al. 2013). Of those, the vast majority are in the state of Louisiana. Despite the Gulf Coast's concentration of socially vulnerable EICs, there are a number of clusters of EICs in other regions that stand out as well. These include: The Eastern Shore/Chesapeake Coast of Maryland; the mainland side of Pamlico Sound in North Carolina; the New Jersey Shore; Kiawah and Edisto Islands in South Carolina's Lowcountry; and the Florida Keys. At 54%, the percentage or EICs containing a tract with a high SoVI score is similar for both the 2030 and 2045 Highest cohorts. Our results suggest that these regions and communities will require particular attention, and potentially additional resources, as coastal communities begin to build resilience to coastal flooding.

The demographic variables driving high SoVI scores vary from place to place. Within the Gulf Coast region, for example, which has a large African-American population, high SoVI scores tend to be driven by poverty and race. Along Maryland's Eastern Shore, a large elderly population, likely with reduced mobility, contributes to high social vulnerability. The varying suite of factors contributing to social vulnerability within our cohort of EICs suggests that resilience building and/or coastal retreat strategies will need to vary in accordance with the specific social vulnerability challenges each community faces. A comprehensive analysis of the factors contributing to social vulnerability is beyond the scope of this work. However, the range of causes of social vulnerability noted here contributes to calls for tailored initiatives for enhancing preparedness and adaptive capacity in physically exposed, socially vulnerable areas (Emrich & Cutter 2011).

3.9 Comparisons with the Intermediate-Low scenario

The pace at which sea level rises has a great bearing on the number of communities that face effective inundation this century. Differences in the number of EICs between the three scenarios we analyzed are significant by 2060 and dramatic by 2100 (**Figure 8**). In 2060, the Intermediate-High scenario projects 272 EICs. That figure is 32% higher (360) with the Highest scenario and 33% lower (183) with the Intermediate-Low scenario. The percentage differences are similar for 2100, with the Highest scenario projecting 37% more EICs (668 in total) than then Intermediate-High, and the Intermediate-Low projecting 41% fewer EICs (290 in total).

With all three scenarios, and for all years, between 52 and 64% of EICs have 25% or more of their land area subject to effective inundation. While these percentages are relatively unvarying, there are large differences in the total numbers of EICs with 25% or more inundation. The Intermediate-High scenario projects 169 EICs with 25% or more inundation by 2060, and 294 by 2100. With the Highest scenario, those numbers rise to 228 and 428, respectively. With the Intermediate-Low scenario, they fall to 120 and 178.

In 2060, there are several clusters of communities that could be spared effective inundation with the Intermediate-Low scenario relative to the Intermediate-High (Figure S3). These clusters include the greater Boston area, northern New Jersey and 13 communities along the

Table 2: Effectively inundated communities by state. Number of effectively inundated communities per state for the present, Intermediate-Low, Intermediate-High, and Highest scenarios for each year analyzed. DOI: https://doi.org/10.1525/elementa.234.t2

		Intermediate-Low		Intermediate-High				Highest						
State	**Present**	**2060**	**2100**	**2035**	**2060**	**2080**	**2100**	**2030**	**2045**	**2060**	**2070**	**2080**	**2090**	**2100**
AL	0	0	0	0	0	1	1	0	0	1	1	1	1	2
CT	0	0	0	0	0	0	1	0	0	0	1	1	3	5
DE	0	0	1	0	1	3	5	0	1	3	5	5	6	7
DC	0	0	0	0	0	0	0	0	0	0	0	0	0	0
FL	3	5	19	5	18	31	58	5	18	32	48	69	85	90
GA	2	4	6	4	6	7	10	4	6	7	7	14	17	18
LA	59	97	112	95	105	114	131	89	101	110	116	129	139	146
ME	0	0	0	0	0	1	1	0	0	1	1	2	3	4
MD	12	23	30	22	27	35	39	23	27	35	37	41	44	51
MA	0	0	5	0	5	9	18	1	5	9	13	18	20	28
MS	0	0	0	0	0	1	2	0	0	1	2	2	4	5
NH	0	0	0	0	0	0	1	0	0	0	0	2	2	4
NJ	7	27	58	21	55	74	103	26	55	73	87	110	120	131
NY	0	0	1	0	0	3	4	0	0	3	4	6	9	14
NC	6	15	26	13	25	43	49	20	26	43	47	53	61	63
PA	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RI	0	0	0	0	0	0	1	0	0	0	0	2	3	3
SC	0	3	12	2	12	18	19	3	10	18	19	20	20	22
TX	1	5	10	2	8	11	17	3	7	10	15	18	20	26
VA	1	4	8	3	8	11	24	4	7	11	20	25	34	38
CA	0	0	0	0	0	1	3	0	0	1	2	3	6	7
OR	0	0	0	0	0	0	0	0	0	0	0	0	0	0
WA	0	0	2	0	2	2	2	0	2	2	2	2	3	4

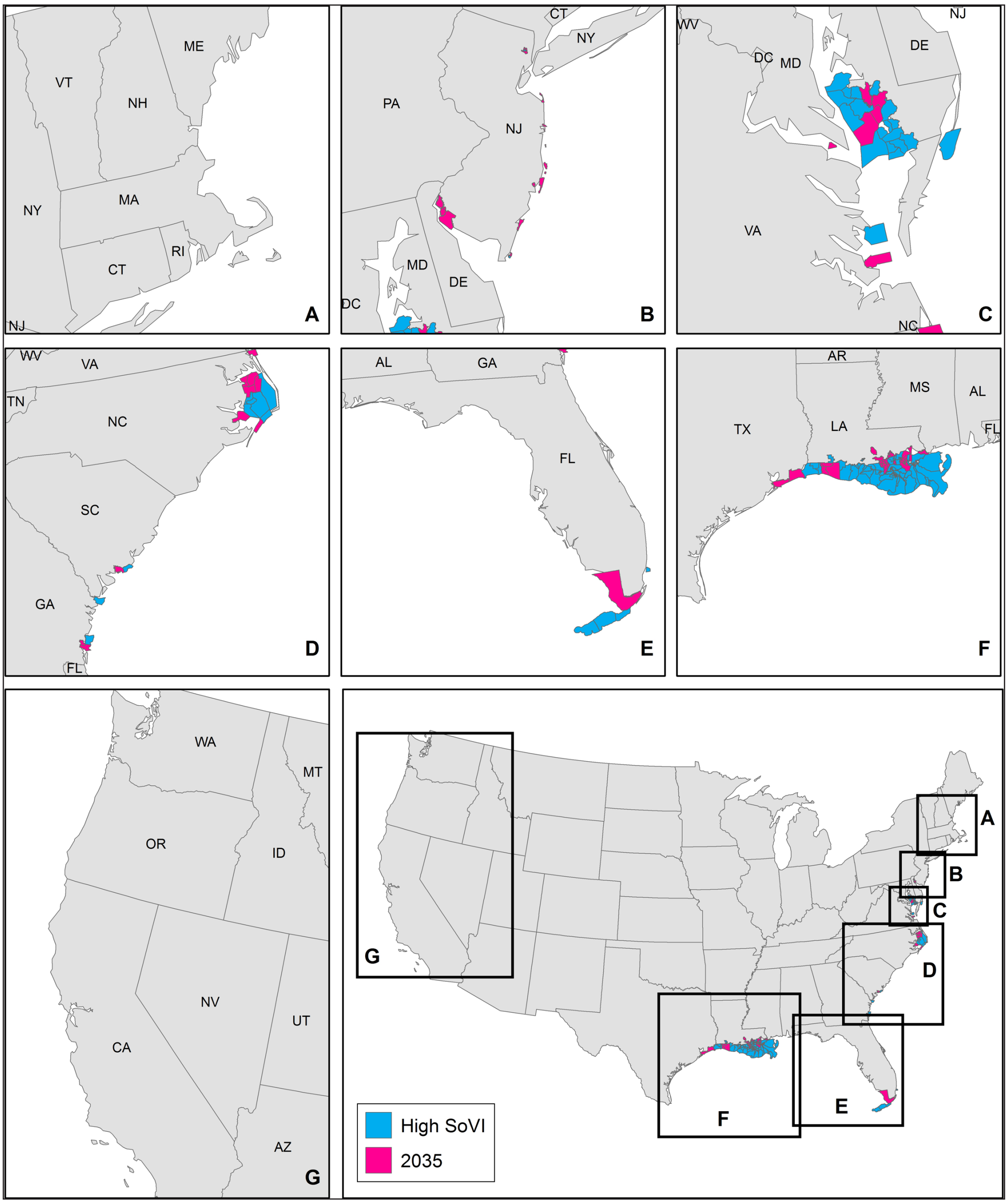

Figure 7: Effectively inundated communities with high socioeconomic vulnerability. Effectively inundated communities in 2035 (pink) with the Intermediate-High scenario. Affected communities with at least one Census tract with a high SoVI score are shown in blue. Note that the regions shown in panels A and G do not have any effectively inundated communities in 2035 with high SoVI. DOI: https://doi.org/10.1525/elementa.234.f7

New Jersey Shore, the Atlantic coast of Florida (including Miami Beach) and the Gulf Coast of Florida off the coast of Cape Coral.

By 2100, the clusters of spared communities mentioned above grow in area (**Figure 9**). Large stretches of the Delaware, Maryland, Virginia, and North Carolina, Florida, and Texas coasts also stand to gain greatly if sea level rise follows the trajectory of Intermediate-Low scenario rather than the Intermediate-High. Large population centers (>100,000 people today) stand to also gain greatly from a slower pace of sea level rise (**Figure 10**). With the Intermediate-Low scenario, only 3 of the 29 large population centers included in the 2100 Intermediate-High cohort would face effective inundation. Communities that would be spared inundation would include four of the five boroughs of New York City, Miami, and San Mateo.

Using the Intermediate-Low scenario as one potential approximation of the magnitude of sea level rise if the goals of the Paris Climate Agreement were met, these results suggest that the emissions choices we make in the coming decades—and ice sheet responses to those choices—could have profound impacts on communities in the coastal US.

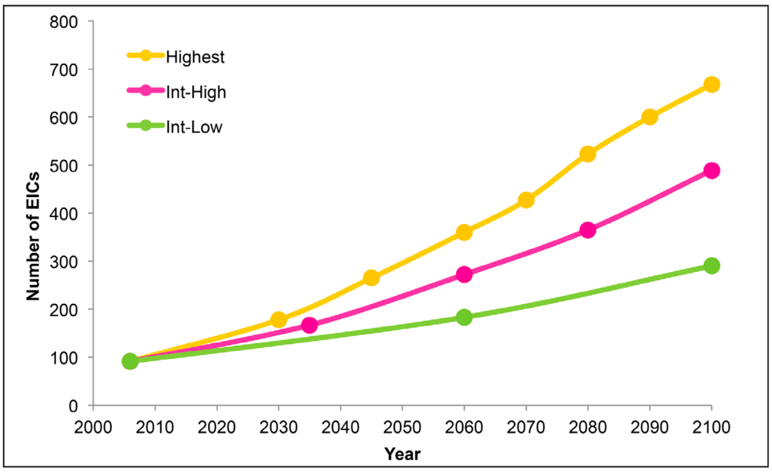

Figure 8: Number of effectively inundated communities for each sea level rise scenario. Number of effectively inundated communities by year for the three scenarios analyzed in this study: Highest (yellow); Intermediate-High (pink); Intermediate-Low (green). DOI: https://doi.org/10.1525/elementa.234.f8

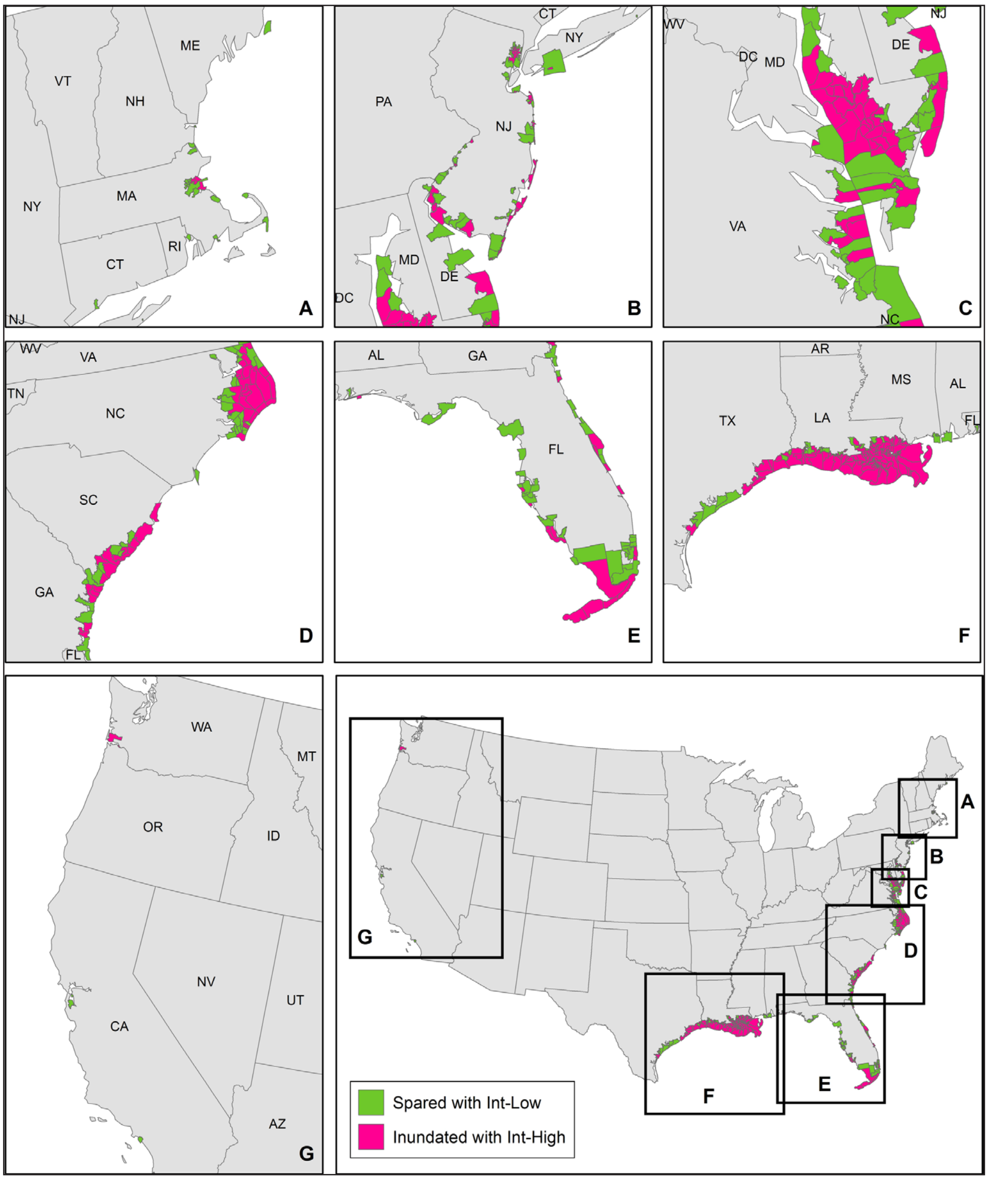

Figure 9: Comparison of effectively inundated communities in 2100 with the Intermediate-Low and Intermediate-High scenarios. Effectively inundated communities with the Intermediate-High scenario are shown in pink. Communities shown in green would be effectively inundated with the Intermediate-High scenario, but spared with the Intermediate-Low. DOI: https://doi.org/10.1525/elementa.234.f9

Figure 10: Effectively inundated communities with populations over 100,000. Locations of effectively inundated communities in 2100 with populations over 100,000 with the three scenarios analyzed in this study: Highest (yellow); Intermediate-High (pink); Intermediate-Low (green). DOI: https://doi.org/10.1525/elementa.234.f10

3.10 Online tool

Links to interactive maps showing the extent of inundation at each future time horizon and for each scenario can be found at http://www.ucsusa.org/RisingSeasHitHome (Union of Concerned Scientists 2017). Examples from the tool are shown in Figure S4 and Figure S5.

4. Conclusions

In this study, we have defined effective inundation and mapped its extent for the continental United States for three distinct and localized sea level rise scenarios. Our approach yielded national-level snapshots of the communities most exposed to sea level rise for specific time horizons through the end of this century that can be used for assessing effective inundation at the local level. This community-focused, time horizon-based approach fills a gap in the existing suite of publicly available tools in that it allows users to visualize future inundation based on specific future time horizons and scenarios.

These results show that, in the absence of measures to manage increased flooding, effective inundation of coastal communities could become widespread within the next 40 years and encompass much of the coast by the end of the century. The growth of effective inundation suggests that communities will face stark choices about their ways of life in the decades to come. From homes and streets being elevated at high cost in Broad Channel, NY, and Norfolk, VA to the value of real estate declining in flood-prone parts of Miami-Dade County, FL, the cost of adapting to rising seas and more frequent flooding is already becoming apparent (Gregory 2013; Urbina 2016; Ruggeri

2017). In places such as Tangier Island, MD, and coastal Louisiana, there are ongoing public discourses about the cost and practicality of saving homes and communities from complete inundation (Gertner 2016; Coastal Protection and Restoration Authority of Louisiana 2017).

Over half of the effectively inundated communities we project for the year 2035 are home to socioeconomically vulnerable populations, which suggests that resources for building climate resilience will need to account for the fact that many communities face not only physical exposure to climate hazards, but also socioeconomic challenges to building resilience.

Using the NCA Intermediate-Low scenario as a proxy for projected sea level rise under a scenario where global warming was capped at 2°C, these results suggest that hundreds of communities in the US could be spared effective inundation were the international community to adhere to the goals of the Paris Agreement.

Whether or not those goals are met, in the coming decades, local, state, and federal governments will need comprehensive plans to provide resources and safe options for communities facing effective inundation, with particular attention to areas with vulnerable populations.

Data Accessibility Statement

Python scripts: public GitHub repository www.github.com/kristydahl/permanent_inundation.

Supplemental Files

The supplemental files for this article can be found as follows:

- **Table S1.** Interview summary regarding present day flooding: uploaded as online supporting information. DOI: https://doi.org/10.1525/elementa.234.s1
- **Table S2.** Tide gauge information: uploaded as online supporting information. DOI: https://doi.org/10.1525/elementa.234.s2
- **Table S3.** Percentage of inundation within communities for all years and scenarios: uploaded as online supporting information. DOI: https://doi.org/10.1525/elementa.234.s3
- **Figure S1.** Schematic diagram of the spatial analyses underlying this study. DOI: https://doi.org/10.1525/elementa.234.s4
- **Figure S2.** Effectively inundated communities in 2060 with the Intermediate-High and Highest scenarios. DOI: https://doi.org/10.1525/elementa.234.s5
- **Figure S3.** Effectively inundated communities in 2060 with the Intermediate-High and Intermediate-Low scenarios. DOI: https://doi.org/10.1525/elementa.234.s6
- **Figure S4.** Inundated areas of Miami Beach, Florida in 2060 as indicated in online tool. DOI: https://doi.org/10.1525/elementa.234.s7
- **Figure S5.** Inundated areas of Oakland, California in 2100 as indicated in online tool. DOI: https://doi.org/10.1525/elementa.234.s8

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Competing interests

The authors have no competing interests to declare.

Author contributions

- Contributed to conception and design: KD, ESS
- Contributed to acquisition of data: KD
- Contributed to analysis and interpretation of data: KD, ESS, AC, SU
- Drafted and/or revised the article: KD, ESS, AC, SU
- Approved submitted version for publication: KD, ESS, AC, SU

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