Future flood risk exacerbated by the dynamic impacts of sea level rise

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Abstract

A growing concern of coastal communities is an increase in flood risk and non-monetary consequences as a result of climate-induced impacts such as sea level rise (SLR). While previous studies have outlined the importance of quantifying future flood risk, most have focused on broad aggregations of monetary loss using bathtub SLR-type models. Here we quantify, for the first time at the multi-state scale, actual impacts to coastal communities at the census block level using a dynamic, high-resolution, biogeophysical modeling framework that accounts for future sea-levels and coastal landscapes. We demonstrate that future SLR can increase the number of damaged residential buildings by 600%, the population of displaced people by 500% and the need for shelter assistance of up to 460% from present-day conditions. An exponential increase in flood damage associated with increasing sea level deems it essential for stakeholders to plan for plausible future conditions rather than the current reality.

Introduction

Floodplain management has been experiencing a shift from quantifying flood hazards to assessing flood risk. Flood risk is defined as a measure that combines a flood hazard(s) with exposure and is the probability that damage may occur over a certain period of time (e.g., one year)[1,2]. A flood hazard is typically quantified as the likelihood a flood event may occur (e.g., 1% annual chance flood) and flood exposure is the consequence, or at-risk elements (vulnerability), and is dependent on socioeconomic factors. The 1% and 0.2% annual chance flood (commonly referred to as the 100- and 500-year flood, respectively) have been used as guides in the United States for planning and development decisions and to inform the public on flood insurance premiums. Yet, using these traditional measures of risk alone has proven to be inefficient in resilience planning, especially in an uncertain future[3,4]. Using current flood exposure and related risk for future planning is not appropriate. Consequently, there is a need to quantify flood exposure and risk using projections of both future sea levels and the respective changes to landscapes.

There is a growing concern of increasing flood risk among coastal residents, city planners, and local government[5,6]. These trepidations are warranted based on historic and recent events of large-scale coastal flooding that has resulted in tens of thousands of NFIP (National Flood Insurance Program) claims and billions of dollars in economic losses (e.g. Hurricanes Michael, Florence, Harvey, Maria, Irma, Sandy, Irene, Katrina)[7]. In resilience planning, it is important to consider the potential for increased risk and to manage property for trajectory changes as opposed to steady-state or historical baselines[8]. Historically, growing coastal populations have been the main driver of increased flood risk[9,10]; however, in the future, rising sea levels as a result of global climate change will play a more substantial role in amplified flood risk[11,12]. In addition, increasing wealth, investments and property values in flood-prone areas will contribute to the increasing cost of flood damages[13]. These ongoing changes combined with the rate of development of new floodplain boundaries by the Federal Emergency Agency (FEMA)[4] may lead to a number of homes and people left in a situation where they are unaware of their actual risk.

Therefore, it is important to advance the science in how flood hazard information and socioeconomic impacts are combined for a more holistic view of flood risk, especially in the face of climate change and SLR, in particular[14].

Flood hazard and risk has been quantified across local, regional, national [15–17] and recently global scales[5,9,11,18,19]. However, studies spanning large regions rely on broad aggregations of depth-damage relationships and coarse hydrodynamic models (and potentially limited physics) or tide gage records at broadly-spaced locations. In contrast, regional and local studies can benefit from finer socioeconomic information and may engage more complex hydrodynamic models. However, previous efforts have focused on a single (often historical) storm or range of storms that follow the Saffir-Simpson scale, which does not reflect the wide range of potential flooding scenarios[20,21] and have not focused on the coastal effects of climate change beyond sea level rise (SLR)[22]. Furthermore, it has been too computationally expensive to run contemporary, high-resolution, storm surge (and wave) models for large regions to derive a probabilistic flood depth surface (e.g. 1% annual chance flood).

Coastal flood hazard modeling has experienced considerable advancements in the last several years, specifically in the examining the role of climate change and SLR on elevated peak storm surges using high-resolution hydrodynamic models[23–27]. Until recently, flood hazard studies did not account for the dynamic effects of SLR on flood depths and considered SLR only as a linear superposition to current flood hazard information. Methods involving a linear increase in flood depths for a given SLR, commonly referred to as a bathtub model, neglect the nonlinear and spatio-temporal changes in flood levels, specifically across the coastal landscape in normally dry regions (within populated areas). Such changes in flood levels are substantial and do not always increase by a given SLR amount and are driven not only by SLR but also by SLR- and other climate-induced changes to the coastal landscape[23,28–32]. With this in mind, the Coastal Dynamics of Sea Level Rise (CDSLR) framework was developed to shift the paradigm in how coastal flood hazard and risk assessments are performed under climate change conditions, with particular focus on SLR[28,33].

We aim to translate the results of the CDSLR-driven biogeophysical models using FEMA's HAZUS tool to assess increasing flood risk to residential structures and people to a metric that is easily communicated to stakeholders and policy makers. It has been found that the public perception of risk, as communicated in probabilistic-based information, may not always be accurate and can affect their choice in choosing whether to buy flood insurance, for example[34]. Additional research suggests people are more likely to be motivated to hold insurance if they anticipate substantial damages to occur to their homes or businesses, or if they have previous experience with floods[35]. Furthermore, although people may correctly or even overestimate their potential for flooding, in terms of probability, they underestimate their potential for flood damage given their level of exposure[36,37]. A study in North Carolina, for example, found that 75% of survey participants who live near the coast may understand the potential effects and risk of SLR, such as a retreating shoreline and increased flooding, yet only half of property-owners believe it will affect them personally[38]. There exists the opportunity for better communication of the potential for major damage or total loss of a home due to a catastrophic flood. Compounding these issues is the impact that SLR and SLR-induced changes to the landscape will have on future flood exposure and risk.

An important human impact is the flooding of roads and structures that can lead to the temporary or long-term displacement of people. For example, in 2005 Hurricane Katrina displaced approximately 400,000 people, of which 24,600 needed public shelter[39]. Recovering from extensive home damage can take years and may have long-lasting economic effects to impacted individuals such as a drop in their credit scores, increased debt, bankruptcy, mortgage delinquency and foreclosures[40]. As sea level rises, we expect a more expansive floodplain and deeper flood depths for 1% and 0.2% annual chance floods thus changing not only the likelihood of a flood but increasing the likelihood of extensive/total loss of structures. In fact, we have demonstrated that just an intermediate rise in sea level (1.2 m) will result in a dramatic conversion of what is today defined as the 500-year return period floodplain into the 100-year floodplain[41]. In turn, this has the potential to increase the number of people that will likely be displaced and in need of shelter, straining public and private resources.

Our study is focused on the coastal counties of Mississippi, Alabama, and the Florida Panhandle. This region has experienced a number of costly flood events, from 1996–2016 the NFIP has paid out over $6 billion in claims in these states. In 2005, major damage from hurricane Katrina and Dennis, resulted in 41,012 NFIP claims, totaling over $3 billion. Less impactful, yet still significant, were the damages observed in the 2004 hurricane season (Ivan and Frances): 26,854 NFIP claims were filed amounting to nearly $1.5 billion [42] . Understanding the potential impacts of storm surge under SLR can contribute to climate adaptation planning, enhancing hazard mitigation plans, post-disaster re-development plans, prioritizing areas of floodplain reclamation and restoration, and areas to increase building code requirements and budgets for disaster mitigation and recovery funding.

We extend previous efforts of computing the percent annual chance coastal stillwater floodplains under the CDSLR approach using a high-resolution storm surge and wind-wave model to quantify probabilistic flood impacts[24]. The model contains resolution as fine as 15 m at the coastline and was rigorously validated by comparing modeled data with observed astronomic tides and time-series water levels, significant wave heights, wave period, direction, and high water marks for Hurricanes Ivan, Dennis, Katrina, and Isaac[43]. The storm surge model was set up to reflect present-day conditions and four SLR scenarios[44] as well as their respective influence on coastal dune elevations, beach width, marsh collapse and migration, and land use land cover change[23,45,46]. Each of the five model configurations was forced by a suite of 219 synthetic storms in order to derive the 1% and 0.2% annual chance floodplain and related flood depths[24].

To develop actionable information regarding the effects of SLR and other climate changed-induced coastal touches on flood frequency and potential damage to homes and people we used the HAZUS-MH software (version 3.2) with refined input data to identify percent-damage to buildings and the potential number of displaced people and shelter needs (i.e. people who require short-term shelter due to flooding).

Here we applied an approach to quantify flood risk at the meso-scale with damages aggregated at the census block level across the northern Gulf of Mexico coast (Fig. 1 shows an example of the modeling scales zoomed in to the Pascagoula, MS region). Herein, our focus of flood risk quantification (using detailed biogeophysical modeling to obtain the 1% and 0.2% annual exceedance probability of stillwater elevation) is not on monetary losses, but on actual impacts such as building damage, displaced people, and people requiring shelter.

Results show that residential buildings currently within coastal flood zones substantially increase flood risk more than those that become inundated in the future as the envelope of floodplain expands. We demonstrate that future SLR results in non-linear increases to the number of damaged residential buildings by 600%, the population of displaced people by 500% and the need for shelter assistance of up to 460% from present-day conditions. The modeling methods and results highlight the necessity for coastal stakeholders to plan for future conditions rather than the current reality. We see various applications from our modeling methods and results, with special consideration in light of the current COVID-19 global pandemic. Assessments of losses, such as displaced populations and people requiring shelter, is necessary to develop comprehensive and integrated resilience measures for compound climate risks[47] and cascading impacts to human well-being.

Results

Annual exceedance probability (AEP) stillwater elevations

The coastal flood hazard across the NGOM is exemplified by the 1% and 0.2% AEP stillwater elevations for present day and four SLR scenarios derived through the CDSLR approach (Fig. 2)[33,41]. The AEP values shown in Fig. 2 are simplified for illustration purposes, but the authors want to note that the AEP used within the calculation of flood risk (presented in the following sections) utilize the full, high-definition, coastal hazard model results along the shoreline and across the coastal floodplain into normally dry areas. The highest stillwater elevations occur along the Mississippi coast (Hancock, Harrison, and Jackson Counties) and near Florida's Big Bend (Franklin and Wakulla Counties) with 1% AEP water levels ranging from 4.5–6.3 m and 4.2-6.0 m for present-day and the high SLR scenario, respectively. Mississippi is known to have larger storm surges due to the wide and flat Mississippi-Alabama outer continental shelf. The big bend region of Florida can have large surges due to coastally trapped Kelvin waves that enhance coastal water levels, particularly when hurricanes track parallel to the wide and shallow west Florida shelf[43,48].

Building damage

The number of substantially damaged residential buildings (damages greater than 50%, herein referred to as damaged buildings) for each SLR scenario are shown in Fig. 3A and B for the full NGOM domain. Over 5,400 (1% AEP) and 14,100 (0.2% AEP) residential buildings are damaged under present day sea level. The number of damaged buildings increase with increasing sea levels and reach maximum values of over 38,100 (606% increase) and 63,400 (350% increase) for the 1% and 0.2% floodplains, respectively. The percent increase is non-linear when compared to the percent increase in sea level (200% increase for the high scenario of 2.0 m of SLR). Even at a modest increase in SLR for the intermediate-low scenario (0.5 m SLR) the number of damaged buildings increase by 72% and 62% for the 1% and 0.2% AEP coastal flood events, respectively.

The number of substantially damaged residential buildings were aggregated across all coastal counties for each SLR scenario based on the 1% and 0.2% annual chance flood (Fig. 3C and D). The results illustrate where coastal floods are expected to have large impacts on residential infrastructure for present and future sea levels. The largest values of damaged buildings occur along the Mississippi and Alabama coast and in Bay County, FL in the eastern Florida panhandle. Under present-day sea level, Hancock County includes the largest number of damaged buildings at 1,314 for the 1% AEP; however, under the high SLR scenario, Jackson County shows the largest damage building count of 7,400. These counties have some of the highest population densities in the northern Gulf of Mexico and feature a high level of exposure to the present 1% annual chance, in contrast to densely developed regions of Mobile County, where presently, there are relatively low numbers of damaged buildings for 1% AEP (92 buildings). Similarly, Okaloosa and Escambia Counties have the lowest present-day value of one damaged building, although they feature centers of high-intensity development (Fort Walton Beach and Pensacola); Gulf County is the lowest under the high scenario at 705 buildings, primarily as a result of low population density in comparison to Bay, Okaloosa, and Escambia counties. (Fig. 3C). Bay County, home of Panama City, features one of the largest increases in building damage under the intermediate-high and high scenarios. For the 0.2% AEP flood event the largest damaged building count is found in Harrison County (3,143) for present-day, but Jackson County drastically exceeds all other counties under the high scenario with 13,843 damaged buildings (Fig. 3D). These results signify that regional hot-spots in flood risk are substantially altered under different SLR scenarios and forewarn that regions of low risk today may not be so in the coming years if population growth continues at the coastal land margin.

Damaged building counts are separated based on residential buildings that reside within census blocks that are within the 1% AEP floodplain (black bars in Fig. 4) and those that are then effected when the 1% AEP floodplain expands under SLR (gray bars in Fig. 4) (Fig. 4 shows a select set of counties. See supplemental material for all counties). The low and intermediate-low SLR scenario across all counties show minimal increases in damaged building counts for buildings that are newly exposed to flooding. Nevertheless, the total count of damaged buildings increases to illustrate that flood risk is driven by buildings currently within the extent of the present day 1% AEP floodplain. It is not until the intermediate-high and high SLR scenarios where damaged buildings increase for areas newly exposed to the 1% AEP floodplain. A similar pattern is present for the 0.2% AEP floodplain (see supplemental material). Counties along the Florida panhandle show the largest increase in damaged building counts for the high scenario (see Bay County, FL in Fig. 4). Damaged building counts for Wakulla County, FL do not increase as fast under SLR scenarios as the other counties. This is due to limited residential development across the county. However, Wakulla County is ripe for development under present flood risk assessment methodology. Future development may translate the flood risk of Wakulla County to reflect Bay County.

Figure 5 presents the percentage of buildings that are exposed to flooding and substantially damaged for each census block in the study area. There is an increase in the number of damaged homes (and a rise in damage per home) that are exposed to flooding with increasing sea level. The damage impact is being compressed to 100% damage (i.e. upward shift in the y-axis) when greater than 50% of the buildings are damaged within a census block and additional census blocks appear in the chart due to increasing flood depth and extent (i.e. shift to the right along the y-axis). An increase in census blocks achieving total damage (i.e. 100%) indicates that every building exposed to the flood hazard is substantially damaged. Furthermore, the results suggest non-linearity among the response of substantially damaged buildings under climate change.

Displaced people and people needing shelter

Displacement of people due to flooding considers census blocks where people may not have access to their homes as a result of flooding (flood depth of 6 inches or more) (FEMA 2013). Within the present-day 1% AEP, a total of 65,785 people is subject to displacement and 140,903 within the present-day 0.2% AEP. The coastal counties of Jackson, Harrison, and Hancock have some of the highest numbers of people exposed to displacement. Under SLR the displacement of people can drastically increase (> 500%) for the 1.2 and 2.0 m SLR scenarios. The SLR scenario when the population of displaced people and people needing shelter from the 1% AEP stillwater floodplain are equal to or move beyond quantities from the 0.2% AEP stillwater floodplain is shown in Fig. 6. The threshold scenario for both displaced people and people needing shelter for coastal Mississippi is the high and intermediate-high scenario. Moving east, the thresholds move to lower SLR scenarios of intermediate-high (Alabama) to intermediate-low and some portions of low into Bay, Gulf, Franklin, and Wakulla Counties in Florida.

Much of the region of coastal Harrison and Jackson Counties, MS shows a threshold under the high scenario for displaced people and people needing shelter. This region experiences the highest return period storm surges and is also densely populated along the coast. Much of the densely populated areas are already within the 1% AEP flood zone, compared to those outside of this zone, thus making the threshold high to meet. Conversely, areas in Baldwin County, AL (Fig. 6B & E) and further west along the Florida panhandle (Fig. 6C-F) show lower transition thresholds. These areas reside outside the 1% AEP flood zone. Further, some of the most populated centers within the western portion of the Florida panhandle and those in Alabama are beyond the reach of the 1% and 0.2% AEP floodplains. Moving east, Wakulla County, FL has a low population relative to the other coastal counties in the region. Many of the populated census blocks are located away from the coastal floodplain, yet a few populated blocks do exist within the FEMA 1% AEP floodplain. Under SLR, displacement thresholds occur at the low and intermediate-low scenario, which is due to the gentle sloping landscape and sparsely population of the region.

Of the total number of displaced individuals, a small portion (ranging from 2–8% of the county total) will need shelter. Within the present-day 1% AEP a total of 3,364 individuals are likely to need shelter. The largest populations of those requiring shelter are found in Jackson (3,348), Harrison (1,779), and

Hancock Counties (954). Within the 0.2% AEP (present-day scenario), a total of 9,016 exposed people would need shelter assistance. SLR increases the need for shelter assistance by 24% and up to 460% for a 1% AEP and 7-206% for a 0.2% AEP under the various SLR scenarios, respectively.

Discussion

Considering the cost of natural disasters, the increasing population, and aging infrastructure it is of paramount importance to increase resilience, thus increasing the ability of communities to prepare, plan for, absorb, recover from or more successfully adapt to actual or potential adverse events' through preventative action[49]. One tenant in building resilience is to manage for trajectory change as opposed to steady-state or historical baselines[8]. Thus, it is essential to consider the potential for increased risk as a result of human development, changing landscapes and ecosystems, and SLR all happening at once[12,50–53]. Although other studies have assessed the potential increase in impacts to infrastructure from storm surge under SLR[19,54], they have focused on a single storm scenario or a range of scenarios following the Saffir-Simpson scale. The Saffir-Simpson scale approach is limited in that it does not reflect the wide range of potential flood depths and extent outcomes for various hydrodynamics factors associated with surge generation[20]. The results herein highlight the varying levels of current exposure as well as a change in exposure under climate change-induced impacts including SLR, landscape change (including marsh loss and upland migration, shoreline/barrier island morphology), and urbanization (land use land cover change). Different counties face disparities within and outside the current 1% and 0.2% AEP floodplains, thus resilience planning is not a one size fits all and requires localized prioritization and actions.

First, we have shown it is possible to use our novel CDSLR framework to assess flood risk at the census block level for a multi-state coastal region using results from a contemporary, high-resolution, numerical hurricane storm surge model. To our knowledge, this is the first study to derive coastal flood risk by linking a dynamic modeling framework that includes various aspects of a changing climate, including SLR and landscape changes, to a detailed (census block level) natural hazard analysis tool. Furthermore, our focus on flood risk quantification is not on monetary losses, but on actual impacts such as property damages, displaced people, and people requiring shelter. One of the major direct socio-economic impacts due to storm surge are losses associated with the built environment. Loss of homes has reverberating impacts in a community and can result in a number of social and health effects such as financial impacts, stress, and anxiety[55,56]. Our study demonstrates that the exponential increase in flood damage associated with increasing sea level scenario makes it necessary for emergency managers to plan for what will be the future rather than the current reality.

Residential buildings located in census blocks already within the 1% AEP floodplain substantially drive up the increase in flood risk more than those that become inundated in the future as the envelope of the 1% AEP floodplain expands. As sea level increases, these homes become fully (100%) damaged and our quantification of flood risk reaches a ceiling under the higher SLR scenarios. These total-loss scenarios can impact the ability of homeowners to rebuild after such an event. For example, a study by Turnham, et al. [57] found that in the aftermath of Hurricane Katrina, buildings with extensive flood damage were 39% less likely to be rebuilt. It is important to consider that rebuilding after a total loss may be beyond the coverage of the NFIP limits ($250,000 for the building and $100,000 for the building contents). Also, a 2019 report found that many communities in areas of extreme risk to natural hazards (such as the Atlantic and Gulf Coasts) can suffer from underinsurance as a result of increasing building and labor costs that may not be factored into the insurance valuation and coverage estimates [58] . The impacts of underinsurance have recently been observed in California wildfires over the last few years, where 80% of affected homed were underinsured [59] . Catastrophic losses can have long-term impacts to the economic health of individuals, increasing the amount of debt and resulting in lower credit scores for years after the event [40] .

The transition of flood risk quantities (including displaced people and people needing shelter) from the 0.2% today to the 1% AEP under a changing climate is critical information for coastal stakeholders. The approach applied herein can be used to develop actionable and informational material for planners and emergency managers who want to better understand the current and future flood risk, particularly in locations outside the current floodplain where there is the option for voluntary flood insurance. Most of the Federal Flood Insurance policies are held within the Special Flood Hazard (SFHA) area (100-year floodplain). Uptake in the coastal counties presented in this study vary from 20%-80%, yet outside the SFHA the flood insurance uptake rate can be very low. Thus, as the flood risk increases under SLR, the probability of homeowners to experience a catastrophic loss will rise both inside and outside SFHA. In addition to insurance and reconstruction concerns, public assistance and infrastructure will be needed to house displaced people temporarily or for people with homes that are severely damaged for an extended period. In addition, people who suffer from severely damaged homes are likely to need financial disaster assistance and aid in navigating the application process while also dealing with additional financial issues and health problems[60].

Considering the current COVID-19 global pandemic, the assessment of displaced people and people requiring shelter is critical. Such information is necessary to develop comprehensive and integrated resilience measures beyond natural hazards that include preparations for ancillary hazardous impacts to society - recently coined as *compound climate risks* by *Phillips, et al.* [47]. For example, the number of emergency shelters will need to increase as capacity for individual shelters is reduced to meet social distancing guidelines. Preparation for the next pandemic, coupled with SLR and expanded floodplains, will demand further assessments as we have begun herein to include cascading impacts related to compound climate risks and human well-being.

Some limitations to this study should be noted. First, we do not consider effects of local wave runup or damage due to winds. These effects would likely increase the number of damaged buildings; however, since we are using present-day hazard results as a baseline without local wave runup or wind damage, our major conclusions and implications would not change. Second, while our biogeophysical modeling considered future SLR scenarios and coastal dynamics, the human environment is based on current conditions and we did not directly consider new development or future populations beyond considering land use land cover changes according to each SLR scenario. With the continuing upward trend of coastal development worldwide, flood risk and impacts will only increase[9,10]. Therefore, future studies should more directly incorporate projections of future populations and development as increased economic exposure is likely to be the greatest driver of coastal risk[14]. For example, flood risk in Jefferson County may increase and look similar to Jackson County given a future increase in population and residential development. Third, this work is limited by the quality of flood depth-damage relationships. Recent work by Wing, et al. [61] has improved depth-damage functions using over 2 million NFIP data claims. Furthermore, future work could also include the incorporation of natural and nature-based features (NNBF) into our approach in order to understand how such natural infrastructure can reduce the coastal hazard and risk. Such information could be combined with other economic impact measures to provide a tool for coastal communities. Finally, the hazard and exposure modeling framework conducted herein is not specific to the NGOM region. Such efforts can be translated to other shorelines, both coastal and riverine.

Data And Methods

Percent Annual Chance Stillwater Elevations

The 1% and 0.2% annual chance stillwater storm surge heights were calculated using the high-resolution SWAN + ADCIRC wave and storm surge model of the northern Gulf of Mexico[24,43]. The stillwater surge heights were developed for present-day and four sea level rise (SLR) scenarios for the year 2100 of low (0.2 m), intermediate-low (0.5 m), intermediate-high (1.2 m), and high (2.0 m)[44]. For each SLR scenario (and linked to their respective carbon emission scenario), the storm surge model represents likely scenarios of the coastal landscape, including intertidal salt marsh, beach width, dune height, and land use land cover[23,32,46,62].

The storm surge model was forced by 219 synthetic storms that represents the present-day tropical cyclone storm climatology for the northern Gulf of Mexico (Mississippi, Alabama, and the Florida panhandle) as derived by the Joint Probability with Optimum Sampling (JPS-OS) method[63–65]. The synthetic storms are described by central pressure deficit, radius to maximum winds, forward velocity, storm heading, and landfall location[66]. Future storm climatology was not considered in this study due to the large uncertainty in projecting the response of tropical cyclones to global warming[67].

The 1% and 0.2% annual chance stillwater maps are available at gomsurge.org and detailed information on their development can be found in Bilskie, et al. [24].

Exposure and vulnerability modeling

To assess socio-economic impacts of storm surge and sea level rise, this work utilized HAZUS-MH software, a Geographic Information System (GIS) based modeling tool developed by the Federal Emergency Management Agency (FEMA) to estimate physical, economic, and social impacts of natural disasters such as floods, earthquakes and hurricanes. The HAZUS database comes integrated with aggregate and site specific inventory that includes: demographic data, General Building Stock, agricultural statistics, vehicle inventory, essential facilities, transportation systems, utility systems (among other sensitive facilities), all of which can be manipulated and enhanced by user-specified information[68]. The ability to perform multiple levels of analysis and to incorporate user-developed data into HAZUS, makes this an easy to use, low cost and flexible tool for adaptation planning[69].

User-defined inundation scenarios were utilized to identify building assets at risk and to estimate cost of damages. HAZUS Flood Module applies depth-damage curves from the Federal Insurance Administration and the US. Army Corps of Engineers to estimate damage[70]. These damage curves consider building type, first floor elevation, and design level (pre or post- Flood Insurance Rate Maps) to estimate percent damage in relation to the depth of flooding. Losses are calculated and summarize by census block and presented as area-weighted estimates of damage, where cost is considered a percent of the replacement cost[70]. Output reported in this publication include full replacement cost for buildings, for both pre- and post- FIRM structures.

Socio-economic impacts of the 1% and 0.2% annual chance surge depths were assessed for each SLR scenario. Increase in population and development were not incorporated in future scenarios. Rather, the results portray the current and potential change in socio-economic impact to current communities.

Data availability

The stillwater floodplain datasets that support the flood risk modeling of this study are available from the National Oceanic and Atmospheric Administration National Centers for Environmental Information (DOI:10.7289/V5FQ9TVX). Datasets of building damage, displaced populations, and people requiring shelter are available from the corresponding author upon reasonable request.

Declarations

Author Contributions

M.V.B. and S.C.H. were responsible for carrying out the storm surge simulations and calculating AEP probabilities calculations of stillwater floodplains. D.Y. and D.D. carried out the damage modeling. All authors contributed to data analysis and were involved in the writing of this paper.

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Figures

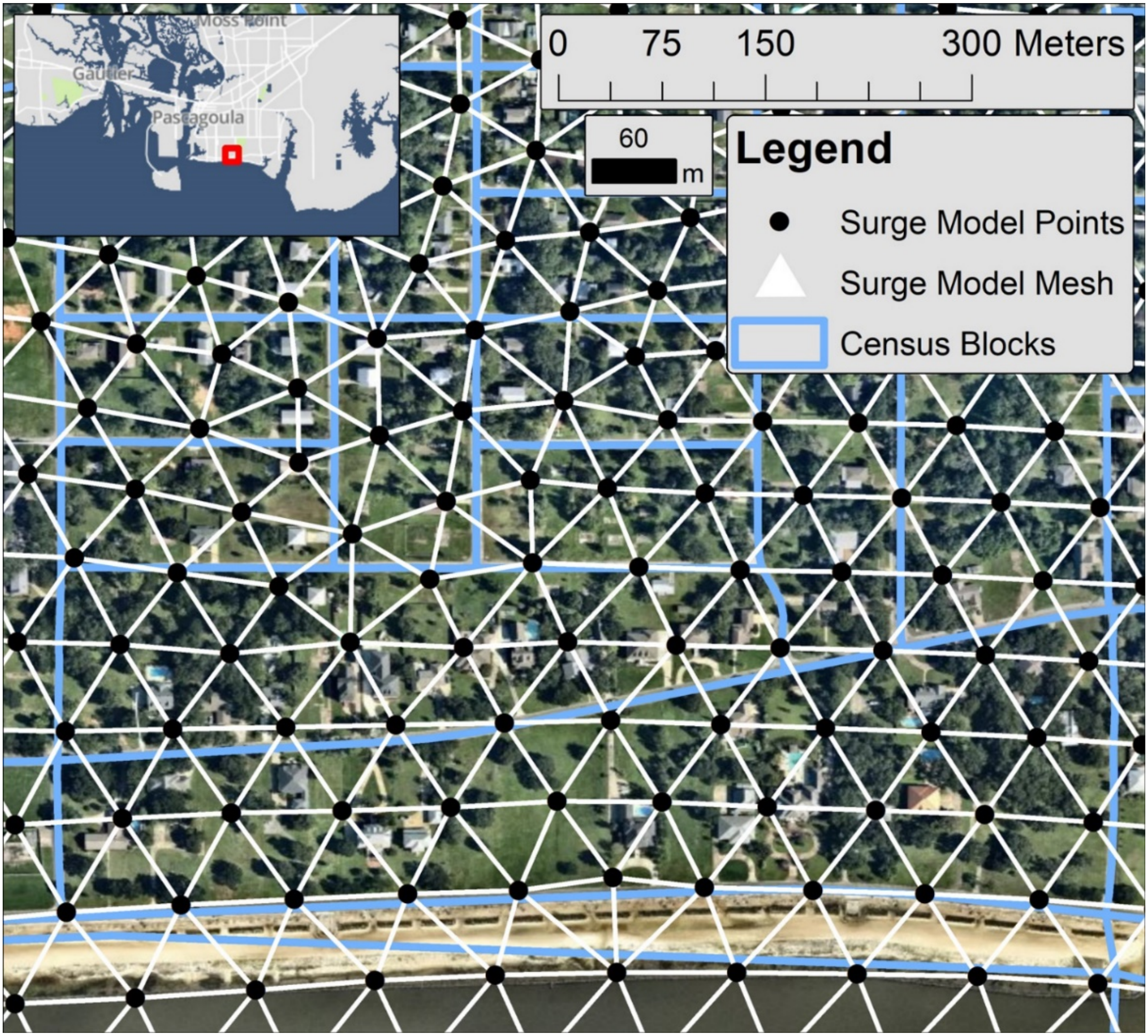

Figure 1

Representation of the relative spatial scales for the storm surge model and census blocks along the Gulf of Mexico coastline in Pascagoula, MS. The horizontal spatial resolution of the storm surge model is ~60 m in this region. Census blocks can span just a few hundred meters and contains numerous storm surge model points and mesh elements.

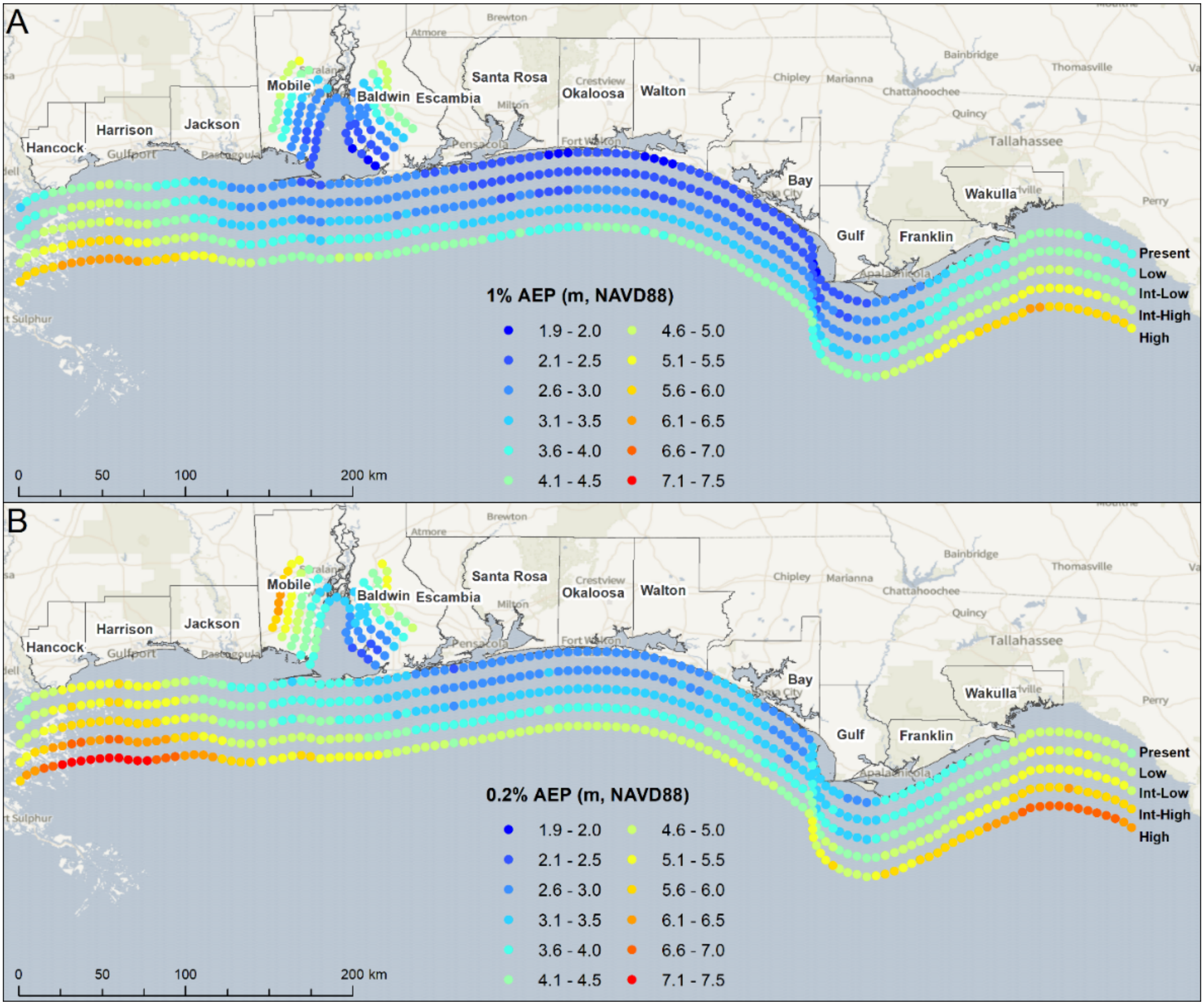

Figure 2

Maps showing the computed 1% (A) and 0.2% (B) annual exceedance probability (AEP) stillwater elevation (m, NAVD88) across the northern Gulf of Mexico for each SLR scenario. AEP elevations for all SLR scenarios are taken from a simplified shoreline represented by the present-day points. The points along the shoreline for the SLR scenarios are offset so they can fit on the same Figure. The SLR scenarios are low (0.2 m), intermediate-low (0.5 m), intermediate-high (1.2 m), and high (2.0 m)44 and reflect the non-linear growth of surge events at the coast.

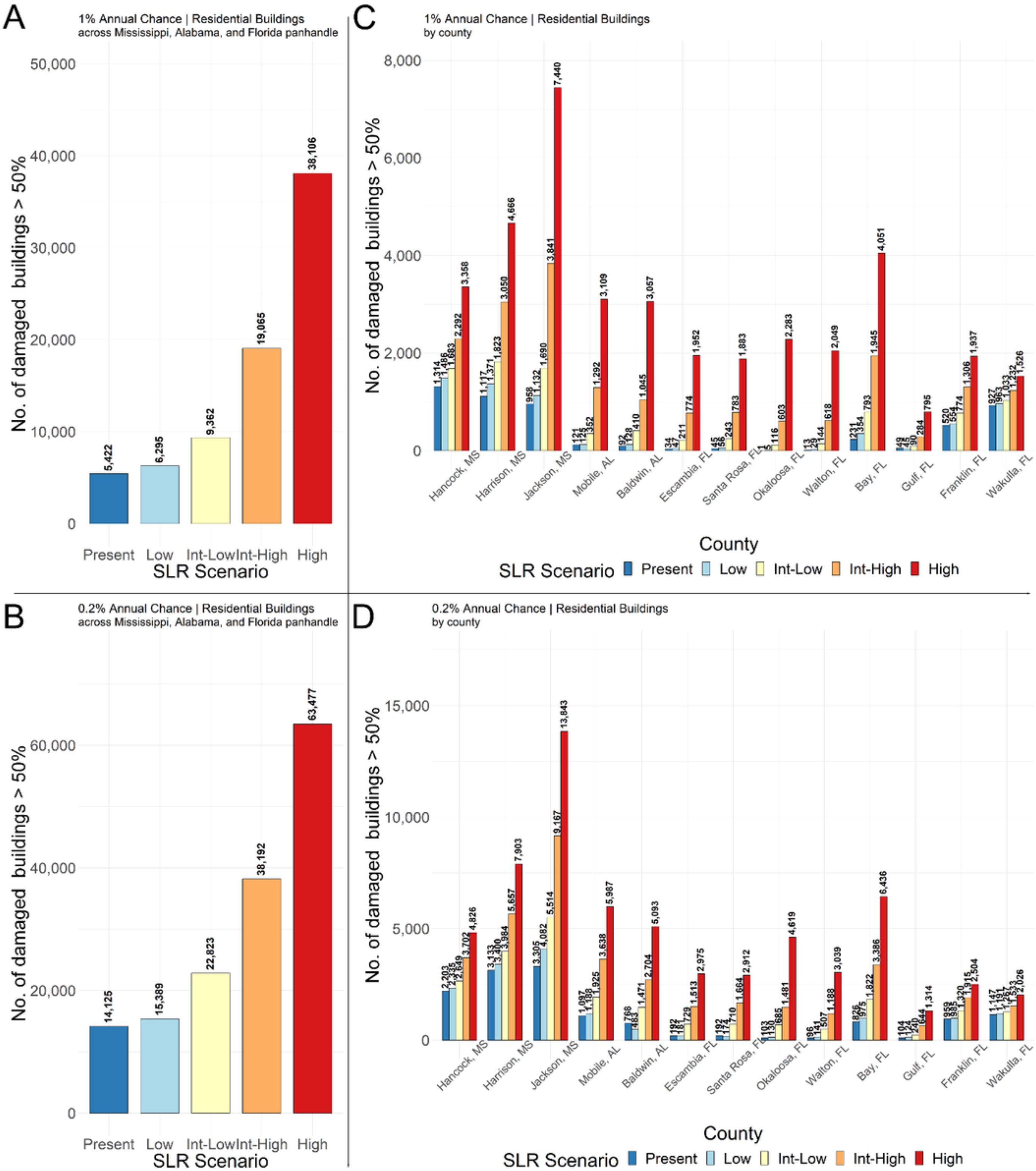

Figure 3

The (A) 1% and (B) 0.2% annual chance number of substantially damages buildings across the northern Gulf of Mexico due to coastal flooding. The (C) 1% and (D) 0.2% annual chance number of substantially damages buildings across for each coastal county. Substantially damaged buildings are classified as greater than 50% damaged. Damages are summed by county.

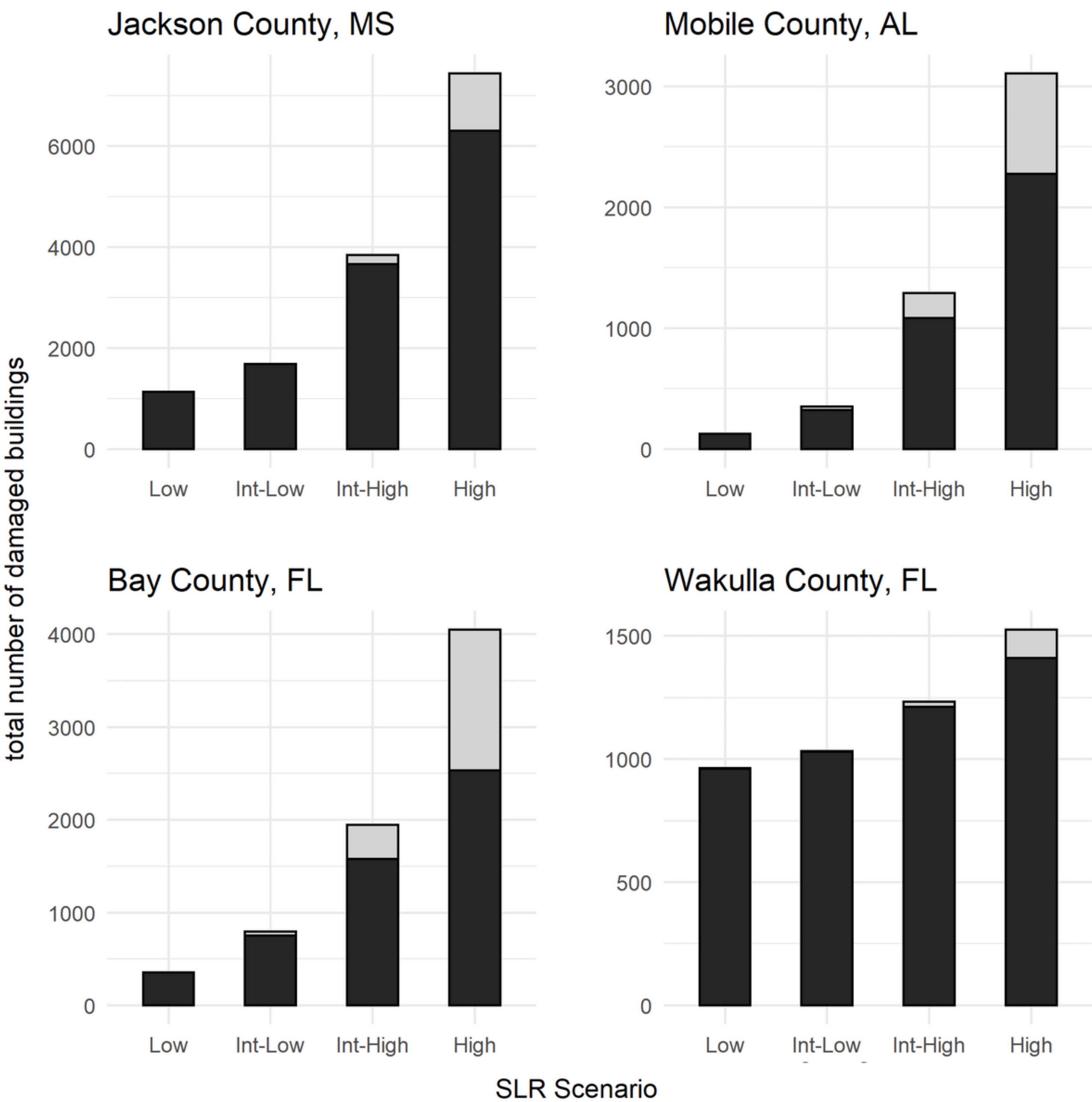

Figure 4

Total number of substantially damaged residential buildings for each SLR scenario categorized by increasing damages for buildings in the present 1% annual chance floodplain and new buildings exposed under SLR. Black bars represent building exposed to the present-day 1% AEP flood and gray bars represent new buildings exposed to the 1% AEP under SLR. Substantially damaged buildings are classified as greater than 50% damaged. Damages are summed by county. See supplemental materials for results of all counties for the 1% and 0.2% AEP (Figures S1 and S2).

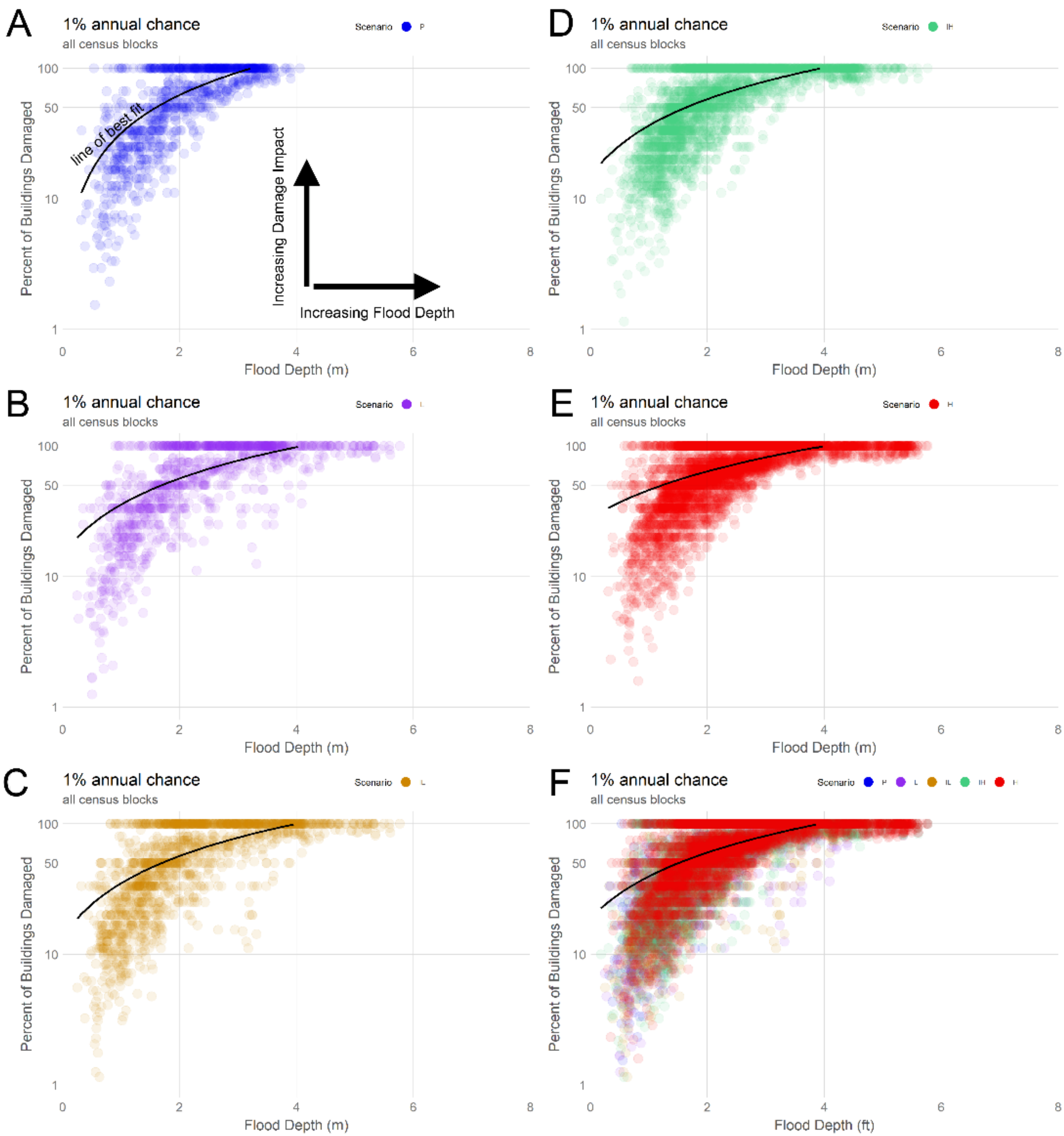

Figure 5

Percentage of residential buildings substantially damaged for a given flood depth for the 1% AEP flood for (A) Present day, (B) low, (C) intermediate-low, (D) intermediate-high, (E) high, and (F) all scenarios. Building damages are aggregated by census block (i.e. each circle in the plot represents an individual census block). Percent of building damages represent the total number of buildings with damages exceeding 50% divided by the total number of buildings exposed. Census blocks with values of 100% indicate all buildings exposed are substantially damaged. The black line is the line of best fit.

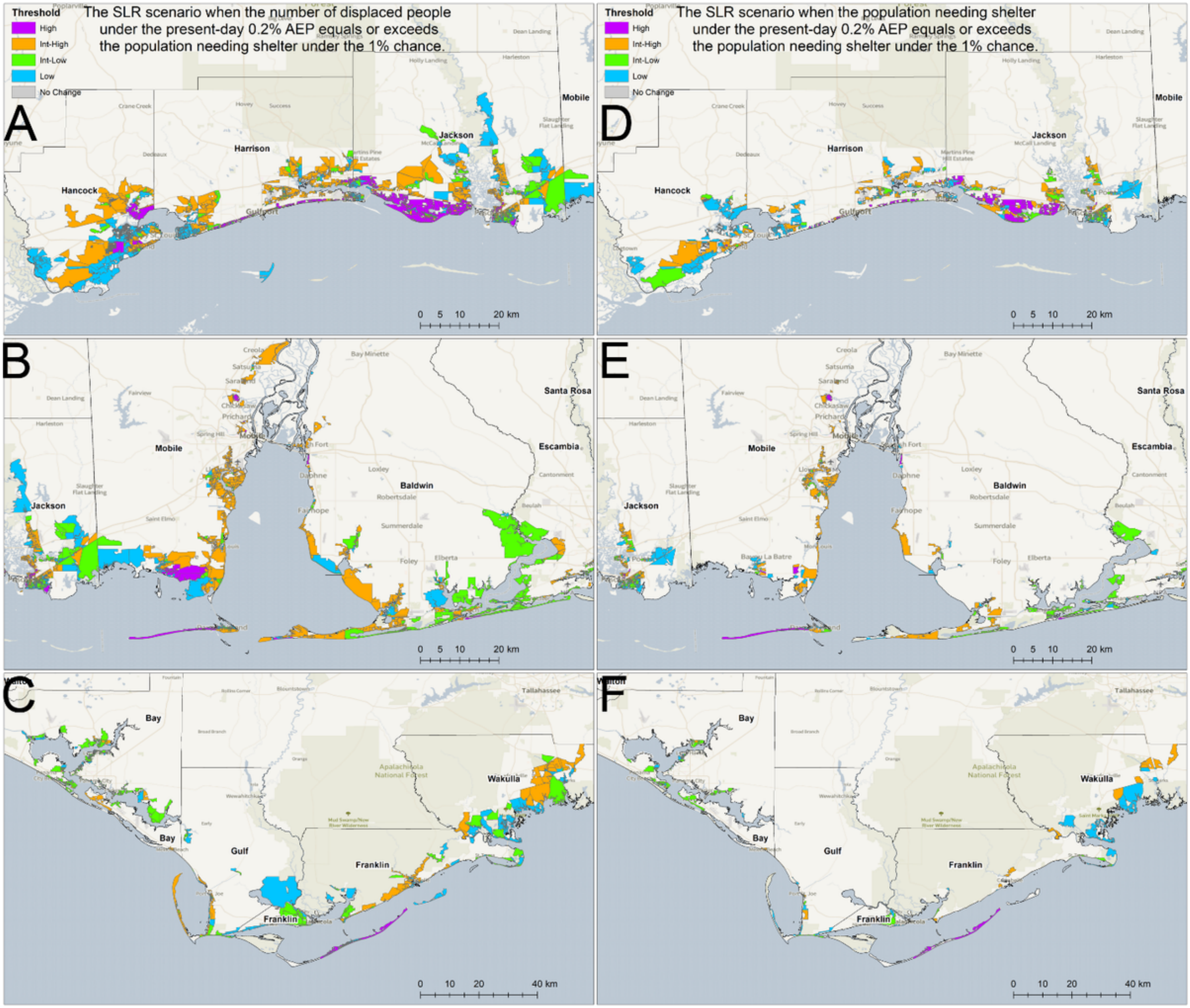

Figure 6

Transition of flood risk at the census block scale as the 0.2% AEP becomes a 1% AEP. (A-C) The SLR scenario when the present-day 0.2% AEP equals or exceeds the number of displaced people under the 1% AEP for (A) Hancock, Harrison, and Jackson Counties, MS, (B) Mobile and Baldwin Counties, AL, and (C) Bay, Gulf, Franklin, and Wakulla Counties, FL. (D-F) The SLR scenario when the present-day 0.2% AEP equals or exceeds the population needing shelter under the 1% AEP for (D) Hancock, Harrison, and Jackson Counties, MS, (E) Mobile and Baldwin Counties, AL, and (F) Bay, Gulf, Franklin, and Wakulla Counties, FL.

Supplementary Files

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