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Advancing extreme event impact attribution: attributing multi-hazard impacts of Hurricane Ida in south Louisiana to past, present, and future climates

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Abstract

Extreme event attribution (EEA) research increasingly studies how the impacts of specific disasters can be linked to climate change. We use a multi-hazard, high resolution, and temporally dynamic framework to study these impacts for Hurricane Ida (2021) in Louisiana. This framework begins with hurricane wind modeling that produces wind fields at warming levels set at 30 year averages for 1971 (i.e. the storm that could have been), 2021 (i.e. the storm that was), and 2071 (i.e. the storm that could be). We then connect these wind fields to storm surge flood models as well to damage functions for both storm surge and wind impacts. Total damages from Hurricane Ida were 19% higher in 2021 than they would have been in 1971 due to historical climate change, and could be 76% higher in 2071 compared to 2021 under projected warming. Damage characteristics vary considerably by hazard (e.g. wind impacts increase at a higher rate than storm surge), time (e.g. greater future increases), space (e.g. climate change's imprint is higher in the areas with severe or moderate impacts), and by number of affected structures and structure type (e.g. residential structures increase at a higher rate for storm surge). Our findings demonstrate the value of a contextualized, multi-dimensional framework for EEA.

1. Introduction

Extreme event attribution (EEA) analyzes if, and to what extent, climate change makes extreme weather more extreme such as with hurricane wind speeds and flooding worsened with global warming (National Academies of Sciences, Medicine 2016, Otto 2017, Swain *et al.* 2020, Clarke *et al.* 2022). Recent work connects the EEA to human and environmental impacts in a field termed extreme event impact attribution (EEIA; Perkins-Kirkpatrick *et al.* 2022, 2024, Noy *et al.* 2024). In connecting EEA to impacts, EEIA provides insights to improve social understanding of health impacts (e.g. Vicedo-Cabrera *et al.* 2021, Park *et al.* 2024, Carlson *et al.* 2025) and economic damages (e.g. Strauss *et al.* 2021, Smiley *et al.* 2022, Newman and Noy 2023, Noy *et al.* 2023). It also gives local context to more general statements about climate change, and can provide evidence that climate change has impacts not just projected for the future, but with recent storms (Osaka and Bellamy 2020, Callahan and Mankin 2025, Cologna *et al.* 2025).

Using Hurricane Ida in south Louisiana in 2021 as the empirical focus, the present study advances EEIA research in three major ways. First, we calculate high resolution impacts. Much EEIA (and EEA)

research produces storm-level estimates of impacts (e.g. ‘\$X of economic damages attributed to climate change for the event’ or ‘Y deaths attributed to climate change for the event’; Frame *et al* 2020; Newman and Noy 2023, Mitchell *et al* 2016), but much less research studies impacts at local or regional scales which may be of greater utility to policy makers, planners, and local communities (Smiley *et al* 2022). Our approach links structure-level data with high resolution hazard models to identify localized impacts at multiple scales, from structures to neighborhoods to parishes to storm-affected regions.

Second, we use a multi-hazard framework. EEA research on hurricanes tends to focus on changes in precipitation (Risser and Wehner 2017, Wang *et al* 2018, Liu *et al* 2019, Villarini *et al* 2020, Reed *et al* 2022, Reed and Wehner 2023) including for impacts (Smiley *et al* 2022, 2025) more so than wind (but see Patricola-DiRosario and Wehner 2018, Gilford *et al* 2024, Malinina *et al* 2025) and also without a specific focus on storm surge. Researching how increased severity of winds affects impacts is important to better account for these underexplored hazards. Theory and modeling point to significant future increases in tropical cyclone (TC) wind speeds (Camelo *et al* 2020, Knutson *et al* 2020, Gilford *et al* 2024). TC winds respond to changes in the temperature of the ocean surface and changes in temperature in the upper troposphere (Emanuel 1987, Gilford *et al* 2017, Done *et al* 2022). Wind speed increases have already been detected in the historical record at the global scale (Knutson *et al* 2019, Kossin *et al* 2020). While TC wind changes at regional scales contain considerable uncertainty due to the high internal variability in regional event frequency, the strong scientific consensus for heavier hurricane rainfall and worsening storm surge (Knutson *et al* 2019) points towards a worsening hurricane hazard overall with continued global warming (Sobel and Emanuel 2025). In all, our study assesses two hazards associated with wind-driven impacts from hurricanes—storm surge flooding and wind impacts—and finds that their spatial and temporal patterns differ in ways that have practical implications for conducting EEA studies.

Third, we use attribution science to assess both contemporary and future impacts. We integrate high resolution data on multiple hazards with climate attribution data to assess both contemporary and future impacts of climate change. While some EEA studies examine what future impacts could be (e.g. Huprikar *et al* 2024, Weisheimer *et al* 2025), few EEA studies do with high resolution data across multiple hazards. Studying both attributable contemporary impacts as well as projected impacts creates additional analytical windows that may be useful in different ways depending on the stakeholder.

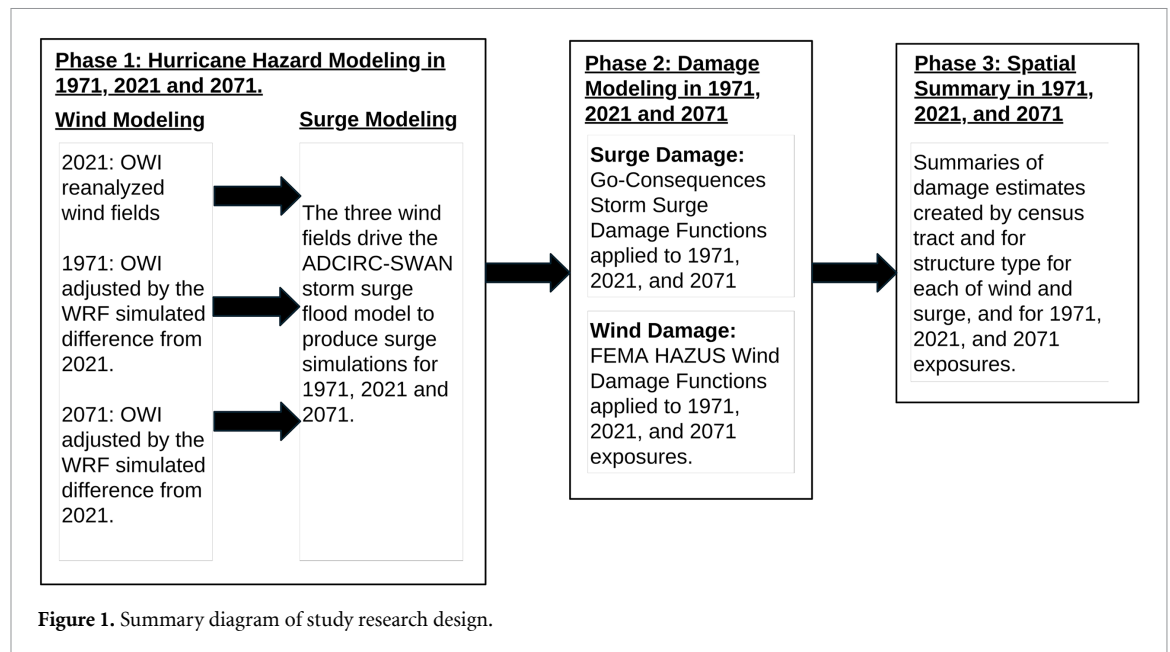
Hurricane Ida in south Louisiana is the case study for this work. Hurricane Ida made landfall on 29 August 2021 in Port Fourchon, Louisiana, and had severe impacts before taking a long northward path that included further impacts in New Jersey and New York. Ida was the sixth costliest hurricane in U.S. history (NOAA 2025). The storm produced significant flooding, especially from storm surge, and high winds resulting in large damages. The study area for this research is the state of Louisiana (i.e. all structures in the state).

2. Methods

2.1. Hurricane wind data and modeling

Our goal is to create wind fields for Hurricane Ida as it looked in 2021 and as it could have looked had Ida occurred under 1971 and 2071 climate conditions under historical and Shared Socioeconomic Pathway 370 (SSP370) future radiative forcing scenarios. Our approach therefore combines a reanalysis of the 2021 hurricane with physical modeling of the climate change effects on the wind field using the numerical weather research and forecasting model (WRF, Skamarock *et al* 2019). The impact modeling holds the track of the storm and the location of structures constant across the three years as well as the coastline, i.e. with no sea level rise or land subsidence.

We design and implement a multi-step modeling procedure from hurricane wind data to spatially granular damage estimations, which is detailed in figure 1. We first obtain the evolving spatial wind field of Hurricane Ida (2021) at high granularity from the Oceanweather (OWI) reanalysis (Cardone and Cox 2009). These spatial wind fields are on a 0.025 degrees grid every 15 min. We then simulate the wind fields as they could have looked had Hurricane Ida occurred in 1971 and 2071 using the WRF numerical model, in addition to simulating the 2021 storm. The WRF model is not constrained to keep the same hurricane track among the simulations. Yet for application to impact modeling where we desire to follow changes spatially across scenarios (see more below), we decided to retain the same hurricane track among the 1971, 2021, and 2071 events. We therefore do not use the WRF model simulations directly, but apply the statistics of the changes among the WRF model simulations back onto the reanalyzed wind field of Ida in 2021.

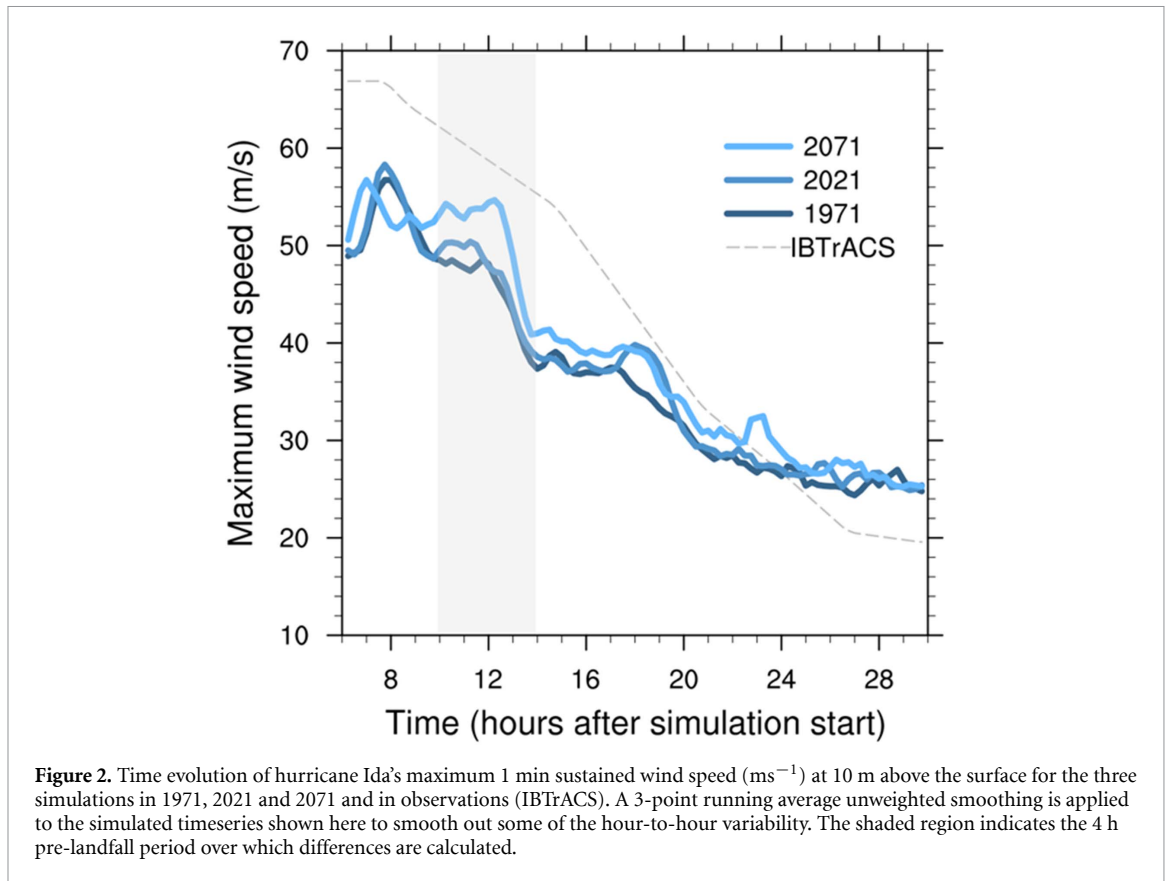


The WRF model is well established at successfully simulating hurricanes (Powers *et al* 2017). Simulations cover a 2100×2100 km area, run for 39 h starting 12 h before observed landfall, and are driven by ERA5 reanalysis data (Hersbach *et al* 2020). A 3 km grid spacing is able to simulate the detailed evolution of strong hurricane wind fields (Davis *et al* 2008, Davis 2018). WRF model physics follow the NCAR Tropical Suite of Physics packages. Wavenumber 2 spectral nudging for dynamical and thermodynamical variables is turned on above the boundary layer to guide the simulated hurricane track as close as possible to the observed track.

Climate change is included using the ‘storyline’ or pseudo-global warming (PGW) approach (Gutmann *et al* 2018, Shepherd 2019, Hall *et al* 2024). This approach has been used extensively in the literature to examine climate change effects on hurricanes (e.g. Hazeleger *et al* 2015, Lackmann 2015, Gutmann *et al* 2018, Carroll-Smith *et al* 2021). PGW applies climate change perturbations to the hurricane’s thermodynamic environment and then resimulates the hurricane. Forward and backward looking perturbations to sea surface temperature, air temperature, humidity, and geopotential height are calculated from the Community Earth System Model Large Ensemble Project 2 (Rodgers *et al* 2021). This global climate simulation from 1850–2100 consists of 100 members with a 1-degree spatial grid spacing and uses CMIP6 historical and SSP370 future radiative forcing scenario.

The forward looking changes are calculated as the change in August conditions between 30 year periods centered on 2021 and 2071. August was selected because it was the month that Ida made landfall. Similarly, the backward looking changes are calculated as the change in August conditions between 30 year periods centered on 2021 and 1971. Post-1970 is regarded as the modern warm period with a notable acceleration of climate warming alongside human emissions of CO₂ and other greenhouse gases (Beaulieu *et al* 2024). The applied changes in surface temperature over the Gulf is approximately -1.0 K for 1971 and $+1.7$ K for 2071. We choose not to explicitly add climate change perturbations to the environmental winds for two reasons. First, circulation changes are very uncertain, particularly on regional scales (Deser *et al* 2012, Shepherd 2014). Second, while climate change could indeed alter the track of the hurricane, large shifts in the hurricane’s track would be undesirable as comparisons of downscaled impacts (i.e. at census tract or parish level) might vary widely because of track differences. A further reason for retaining an identical track between the scenarios is that complimentary parts of the wider project (which are not presented in this article) are undertaken with surveys and interviews with south Louisiana residents and policy-relevant stakeholders, and obtaining data with a different track would generate concerns about data validity as these participants ground truth the data against their personal experiences.

Rather than applying these percent changes from the storyline attribution uniformly to the 2021 Ida wind field reanalysis, we allow the percent changes to vary as a linear function of the wind speed itself, from zero percent change to the weakest winds up to 9% (for the 2071 hurricane) for the strongest winds. This linear fit approximates the empirically-derived wind-speed dependent changes as simulated by the WRF model. A similar scaling approach that applies simulated changes to a reanalysis to ensure track consistency was recently used by Grimley *et al* (2024).



The time evolution of hurricane strength as simulated by the WRF model in 1971, 2021 and 2071 is shown in figure 2. The presently hourly timeseries shows strong variability from hour to hour associated with the volatility of the simulated maxima in the surface wind field, but overall we see a monotonic and significant increase in wind speed with climate warming. The 3 h observations are shown in the grey dashed line as reported by the International Best Track Archive for Climate Stewardship (IBTrACS version 4r01, Knapp *et al* 2010, Gahtan *et al* 2024). While the simulations have a slight weak bias prior to landfall, the response to climate change among the three simulations is likely credible as the three scenarios hold a similar temporal pattern to that of IBTrACS. The simulations better resolve the abrupt weakening at landfall compared to the 3 h observations.

2.2. Wind impact data and modeling

To quantify structure-level wind damages for Hurricane Ida under historical, present, and future climate conditions (1971, 2021, 2071), we developed a deterministic workflow that integrates modeled hurricane wind fields with structure-specific attributes and FEMA (Federal Emergency Management Agency) HAZUS (Hazard United States) wind damage functions (Vickery *et al* 2006, Orooji and Friedland 2021, Al Assi *et al* 2024). Hurricane Ida wind fields for 1971, 2021, and 2071 were provided as described in the preceding section. From these simulations, wind speeds were extracted for every grid cell and joined spatially with National Structure Inventory (NSI) data to assign a unique gust wind speed to each structure. The NSI supplied attributes including occupancy type, number of stories, structure type, and structure and contents replacement value.

Wind-related structural and contents losses were estimated using HAZUS-MH (HAZUS Multi-Hazard) damage functions, which express the percent damage of a structure or its contents as a function of wind speed. Each structure's applicable damage function was identified through a multi-stage mapping procedure consistent with FEMA HAZUS methodology. First, for structure scheme identification, each parish was assigned a structure-scheme name (e.g. Southeast Coastal or Southeast Inland) based on its county FIPS code. The scheme defines the regional construction standards and occupancy distributions used by HAZUS. Second, for occupancy-to-subtype distribution, we used HAZUS occupancy-mapping tables on the building's occupancy to translate these into a probabilistic distribution of structure types (SBTs). Structures were randomly distributed among SBTs according to these proportions within each occupancy class. Third, for structure characteristics assignment, HAZUS defines a probability distribution for each SBT of structural characteristics (e.g. roof shape, roof cover, roof

deck attachment, secondary water resistance, roof deck age, and framing type). These were sampled to assign a set of attributes, collectively forming the character description to every structure. Fourth, for wind structure identification (wbID), the concatenated character description was matched to the HAZUS Wind Building ID (wbID) lookup table to obtain the unique wbID representing that structural configuration. Each wbID links directly to the appropriate wind damage function. Fifth, for terrain classification, surface roughness values (z_0) from the FEMA HAZUS repository were used to assign a terrain ID for each structure ranging from open terrain to dense urban canopy. Sixth, for damage function selection, the final damage function was identified by the triplet (wbID, terrain ID, DamLossDescID), where DamLossDescID corresponds to the desired loss metric (structure, contents, or loss of use).

For each structure and scenario, the gust wind speed was used to interpolate percent damage from the corresponding HAZUS damage function. The percentage loss was multiplied by the structure's replacement value to obtain dollar losses for both structure and contents. This procedure yielded structure-level wind losses for all modeled years. Because the NSI inventory was held constant across scenarios, differences in loss estimates directly reflect the influence of climate-driven changes in wind intensity rather than shifts in exposure or vulnerability. Finally, wind impact modeling was carried out independently of storm surge impact modeling; while this is a multi-hazard study, it is not a compounding study. A compounding study would require identical structure data sets and a damage function that bears on both storm surge, wind, and any interaction between them.

2.3. Storm surge data and modeling

To simulate the storm surge and wave conditions for Hurricane Ida under present climate conditions (2021), the coupled ADCIRC-SWAN model system was employed (Luettich *et al* 1992). The ADCIRC-SWAN model has been extensively used to study storm surge events in the United States and worldwide (Dietrich *et al* 2010, 2011, Martyr *et al* 2013, Bass *et al* 2018). The computational mesh used in this study corresponds to the one developed for the Louisiana Coastal Master Plan 2023, specifically for the 'Existing Conditions' scenario (Cobell and Roberts 2021). The mesh includes the most accurate description of the landscape near the time that the storm made landfall, encompassing geophysical bathymetry, topography, vegetation cover, and the depiction of structural protection features. The forcings used in the model include river discharges, atmospheric wind fields, and tidal components. Tidal boundary conditions were derived from TPXO 7.2 (Egbert and Erofeeva 2002), while wind and pressure fields were obtained from Oceanweather Inc., and represent the best-track reconstruction of the storm (Cardone and Cox 2009). For meteorological forcing, the air pressure and wind direction remain the same for all simulations, with the only difference being the application of a scaling factor on the wind speed.

Past and projected future wind field conditions were created, with analysis enabling an adjustment of historical and future wind speed. The differences from the historical storm (e.g. 2021) and the future storm (e.g. 2071), were obtained by applying a wind-speed dependent adjustment factor to the wind speed fields. This adjustment was applied across the domain, while wind direction and atmospheric pressure fields remained unaltered. This approach enabled isolation of the effects of wind speed changes on surge and wave response. The model was run in hindcast mode, covering 14 d from August 25 to September 8, with an 18 d spin-up and a one-day spin-down. Output variables included water levels, current velocities, and wave characteristics, such as direction, period, and significant wave height. The spatial resolution of the wind field is 0.025 degrees, corresponding to about 2.5 km over Louisiana. The spatial resolution of the ADCIRC-SWAN outputs ranges from 50 m to 250 m in populated areas, 300 m to 500 m in wetlands, and more than 600 m in open water. Timeseries results were compared at the locations of four water level gauges from the United States Geological Survey that were operable at the time of Hurricane Ida. This comparison showed a correlation of 0.83 between this study's high water marks and those at the four gauges.

To determine storm surge flooding impacts on structures, we employed the Go-Consequences model, which is an open-source library by the U.S. Army Corps of Engineers that provides computational solutions for calculating economic consequences of flood events (Poulose and Kumar 2024). Go-Consequences uses flood event data from hydrodynamic models, such as ADCIRC, as an input and generates estimates of the direct economic damage associated with flooding. Direct economic losses in Go-Consequences are determined using three main inputs: maximum flood depth, structure characteristics (e.g. occupancy type, height of structure above ground elevation), and a depth-damage function. The maximum flood depths data comes from the ADCIRC-SWAN model. The structure characteristics are utilized from a structure inventory data from the Louisiana Watershed Initiative (LWI) which includes data from the NSI supplemented by parcel data from Lightbox and ATTOM data solutions, Microsoft's Building Footprints data base, and through machine learning of building attributes from Google Street View imagery (Chen *et al* 2022). This LWI data set includes characteristics such as property category

(residential, industrial, commercial or public), structure and contents value, among others. Damage functions correspond to how these structure characteristics relate to the maximum depth damages using the Go-Consequences model (Poulose and Kumar 2024). Finally, this research did not consider inland riverine or flash flooding or compound flooding as the modeling centered on storm surge flooding because of its outsized impacts during Hurricane Ida, and to match modeling capacities available.

2.4. Structural and geographic data

To compute economic damages spatially and by structure, a synthesized data set was built with social and geographic data. All calculations are made based on structures that had at least \$5000 damages to structure and contents in at least one of the scenarios for at least one of the hazards. The latitude and longitude of the structure-level impact data sets were joined to the NSI using a common identifier. The NSI data set included a census block identifier for each structure. A subset of structures in the storm surge data set ($n = 10\,104$) did not have identifiers that could be linked to the NSI, and these were joined to census block shapefiles from the U.S. Census. Census blocks are the smallest census scale available. Because census blocks are constituent units of census tracts, this enables us to aggregate data by census tracts to assess spatial heterogeneity. For structure-level analyses of sectors (i.e. residential, commercial, industrial, or public), we used NSI data for those structures that merged with the NSI, and used data from the LWI (see above) for structures that had not merged to the NSI. The NSI structure data and the LWI structure data are therefore highly similar given the similar geographic coverage and the common use of the NSI as a base data set. Still, because the analyses are conducted independently for wind and storm surge, we are unable to assess compound effects of the two hazards. In all analyses, damages are adjusted for inflation using the U.S. Bureau of Labor Statistics' Consumer Price Index inflation calculator to August 2021 dollars (i.e. the year of Hurricane Ida). Data set creation and analysis was conducted in R.

3. Results

3.1. Hurricane wind and surge modeling

The analysis centers on creating wind fields for Hurricane Ida across three scenarios, with climate conditions set at 1971 (i.e. 'the storm that could have been'), 2021 ('the storm that was'), and 2071 (i.e. 'the storm that could be'). Figure 3(a) shows a map of the storm lifetime maximum of these reanalyzed winds. The strongest winds lie to the right of the track where the storm-relative circulating winds combine with the forward speed of the hurricane. Climate change simulations produce stronger peak wind speeds for the 2071 hurricane, 9% higher than the 2021 hurricane as seen in figure 3. This 9% is an average over a 4 h pre-landfall period. The simulation of the 1971 storm produces weaker peak winds, 3% lower than the 2021 storm. The changes in the wind field from 2021 to 1971 and from 2021 to 2071 are shown in figures 3(b) and (c). The 1971 storm winds are weaker everywhere with the largest reduction for the region of strongest winds. The 2071 storm is stronger everywhere, again with the largest changes in the strongest winds.

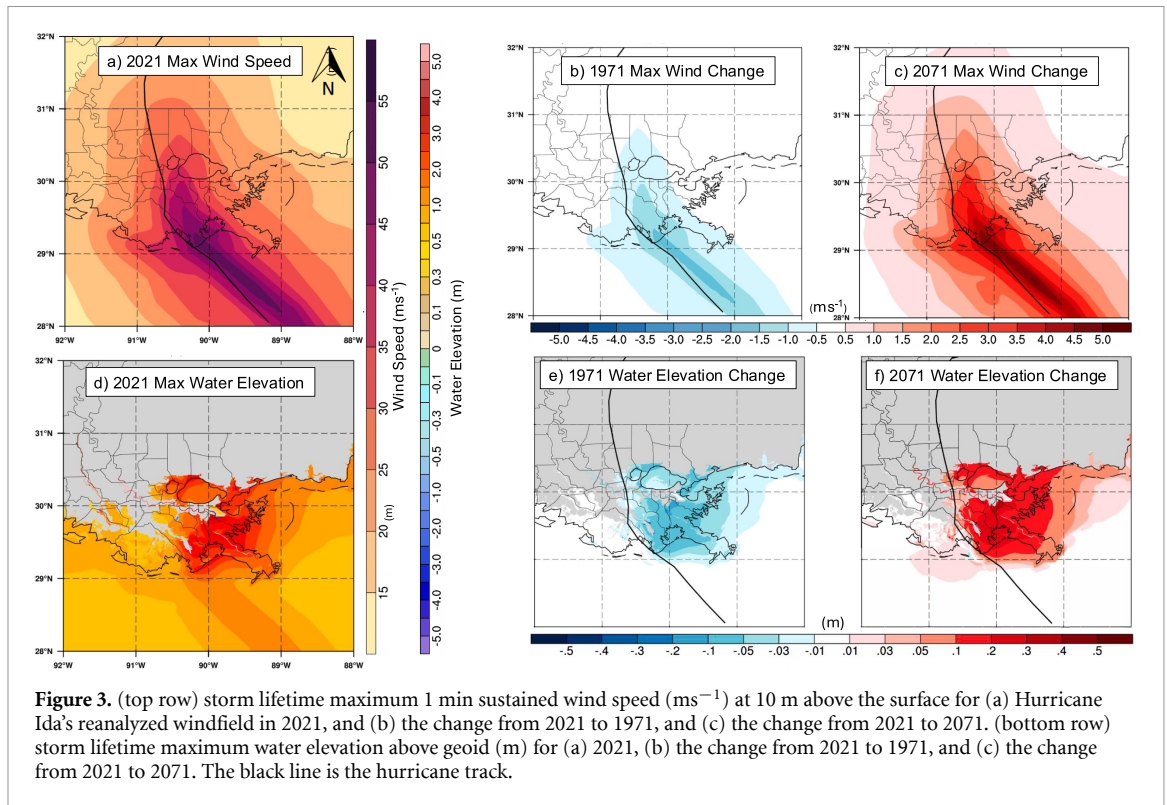
The time-varying past, current, and projected future wind fields (as shown as storm-lifetime maxima in figures 3(a)–(c)) and corresponding surface pressure fields were applied to drive the surge and wave model system. Figures 3(d)–(f) show the simulated maximum water height above geoid for the 2021 storm and the differences between the 2021 storm and the 1971 and 2071 storms. The 2021 storm shows an extensive inundated area with peak water heights confined to the right of the storm track that approaches 4 m. The weaker storm in 1971 results in an overall reduction in maximum water levels, with reductions mainly within 0.2 m. The stronger future storm shows increases in maximum water levels of up to 0.4 m, again mainly confined to the right of track.

3.2. Attribution of extreme weather event impacts

3.2.1. Economic damages to structures

We find that both wind and storm surge damages increase substantially and non-linearly over time due to climate change as indicated in figure 4. Overall, we estimate baseline damages (i.e. the 1971 scenario) from wind and storm surge to structure and contents as \$4.7 billion. Our modeled results favorably corresponds with external estimates⁶. With the backdrop of several important factors held constant (i.e. the storm track, location of buildings, and coastline), we compare the 1971 and 2021 scenarios to

⁶ The overall modeled property damages in this study were validated in comparison to overall property damages estimates from the Spatial Hazards and Events Losses Database of the United States (SHELDUS), version 23.0. Our modeled property damages for the



estimate the economic damages attributed to climate change from wind and storm surge flooding to be approximately \$885 million (19% increase) from Hurricane Ida in south Louisiana. This figure increases a further \$4.2 billion (76% increase from 2021 [and a 110% increase from 1971]) under projected climate conditions.

For wind impacts, total damages in a counterfactual 1971 climate totaled approximately \$2.2 billion. Under observed 2021 conditions, this figure rises to \$2.9 billion—an increase of \$713 million, or 33%. This difference represents the amount of damage attributable to the influence of climate change. Under future climate conditions, wind damages are projected to reach \$6.4 billion for an Ida-like storm in 2071, representing a 194% increase over the 1971 baseline and a 121% increase over 2021 damages.

Storm surge damages follow a smaller, but still notable, upward trend. Damages totaled \$2.5 billion in the 1971 simulation and rose to \$2.7 billion in 2021—an increase of 7% of damages attributable to climate change. Under 2071 climate conditions, storm surge damages are projected to grow to \$3.4 billion, marking a 36% increase relative to 1971 and a 27% increase over 2021 damages. These results show that wind impacts have a greater increase in severity compared to storm surge impacts because of climate change: for instance, wind damages increased by \$4.2 billion from 1971 to 2071—nearly five times the \$900 million increase in storm surge damages over the same period.

3.2.2. Number of affected structures

Beyond monetary damage estimates, figure 4 indicates that climate change is also expanding the number of structures affected by wind and storm surge flooding during a future Ida-like event. Under the observed 2021 climate conditions, approximately 74 700 structures experienced wind damage—approximately 13 000 more structures than under the 1971 conditions, representing a 21% increase attributable to climate change. Under 2071 conditions, that number is projected to rise to approximately 113 500 structures, a 52% increase relative to from 2021 and a 84% increase relative to 1971.

2021 storm total \$5.8 billion for combined wind and storm surge impacts. SHELDUS estimates property damages across Louisiana parishes for Hurricane Ida to be \$12.2 billion dollars. While the SHELDUS figure is higher, it can also include property damage impacts from hazards not covered here, namely riverine and pluvial flooding. Because the damages from SHELDUS are higher, we examined correlations between each data set's estimates at the county-level and found a very strong degree of correspondence between the data sets ($r = 0.95$ for 40 affected parishes; $r = 0.9$ for 10 most affected parishes). Further, this county-level correlation would further indicate that our relative changes (i.e. from 1971 and 2071 scenarios) are also valid given the emphasis on holding factors constant (i.e. building locations, hurricane track) in the downscaled approach. Because of this high correlation at the county-level, we believe that our estimates are valid.

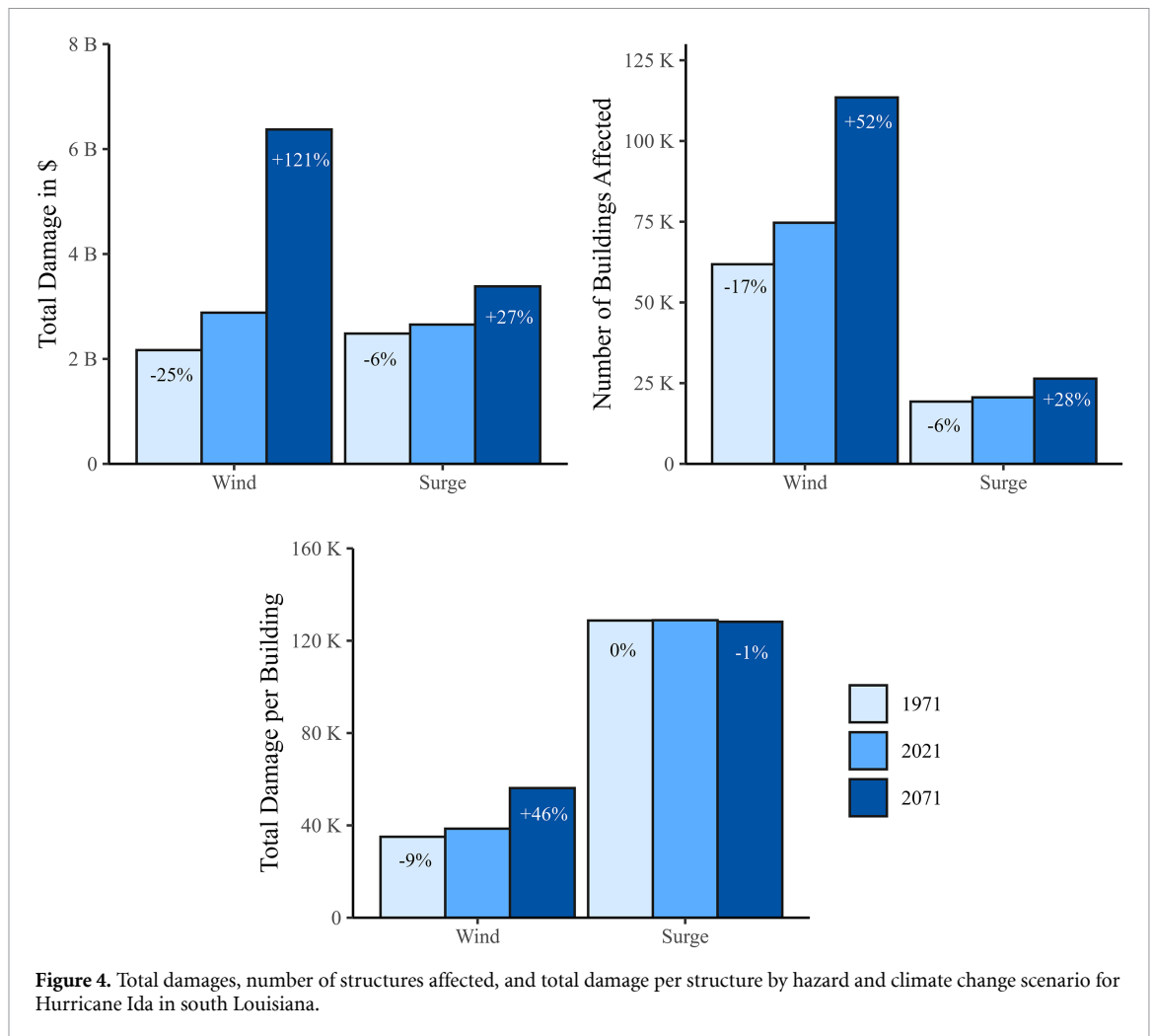


Figure 4. Total damages, number of structures affected, and total damage per structure by hazard and climate change scenario for Hurricane Ida in south Louisiana.

Storm surge exposure shows similar increases, albeit not as large as wind impacts. Under 2021 conditions, approximately 20 600 structures were affected by storm surge flooding, including approximately 1300 (6%) that would not have flooded under a counterfactual 1971 Ida-like storm in a climate without anthropogenic warming. For a 2071 Ida-like storm, the number of structures exposed to storm surge is projected to reach 26 400, a 28% increase from 2021 and a 37% increase relative to 1971. Climate change’s impact for storm surge hazards primarily is through the expansion of the number of structures exposed. As figure 4 shows, per structure damage for storm surge remains between \$128 200 and \$128 900 across the three scenarios. Impacts per structure were much higher for storm surge compared to wind. Our findings indicate that the damage curve is especially important, as non-linear impacts from wind involve great increases in impacts even with small increases in wind speeds at the same time that small amounts of storm surge depths cause considerable damage with additional depths causing proportionately less damage.

Using these statistics on damages per structure, we note that damages have so far been reported as absolute and relative changes over time. We found that wind damages and affected structures increase at a faster relative rate than surge damages and affected structures. An alternative view of changing damages is to quantify the rate of change in damages not by time but by the degree of warming. As reported earlier, the regional increase in surface temperatures along Ida’s track was approximately 1.0 K from 1971 to 2021 and an additional 1.7 K of warming from 2021 to 2071. Using this alternate framing, we again see a faster rate of change (or scaling) per degree of warming for wind impacts than surge impacts. We also find scalings with warming that roughly double for the future period than the historical period. While three data points (the three years 1971, 2021 and 2071) is insufficient to fully characterize economic scaling behavior, it is indicative of non-linearities in the mechanisms operating between climate warming and impact.

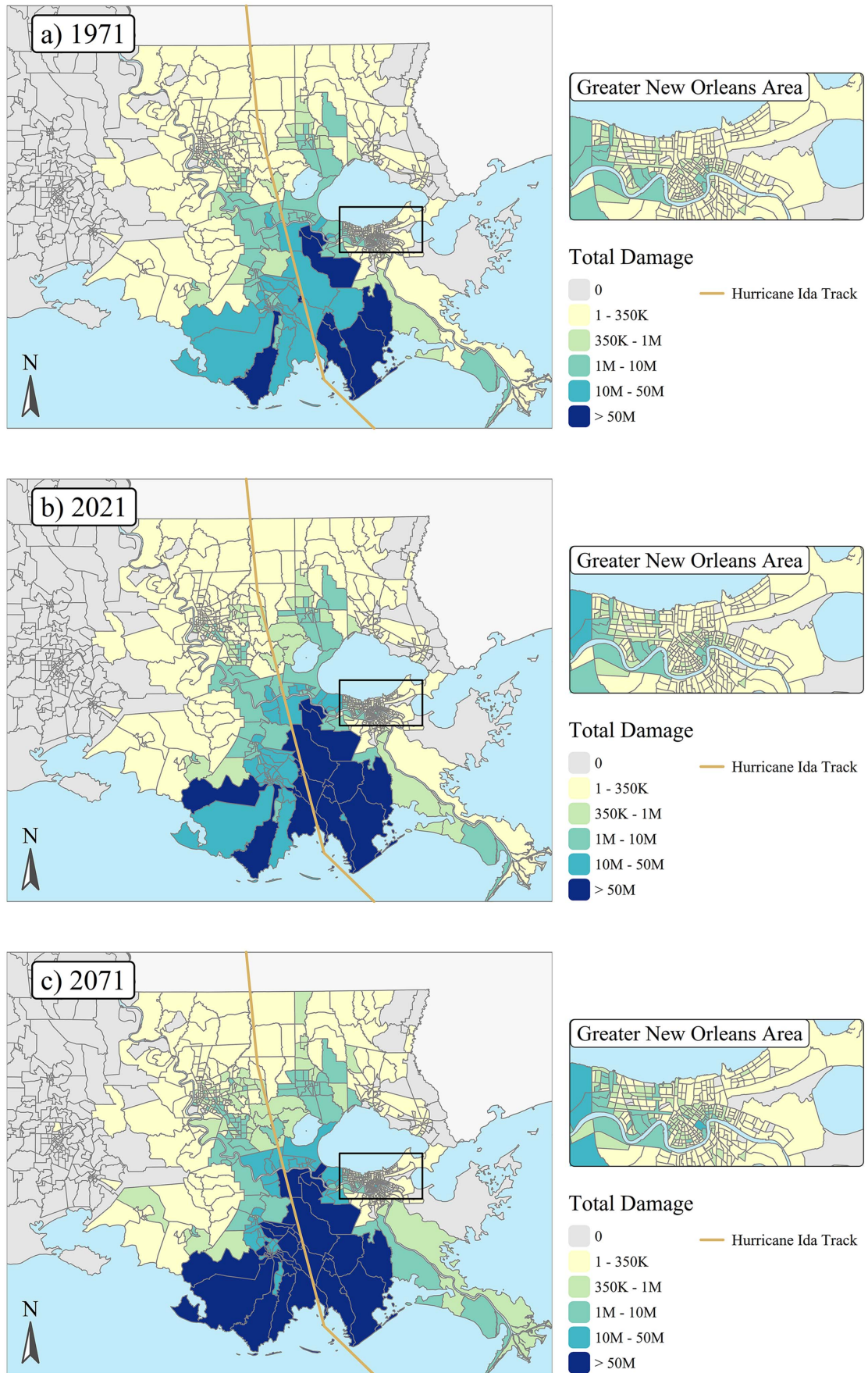
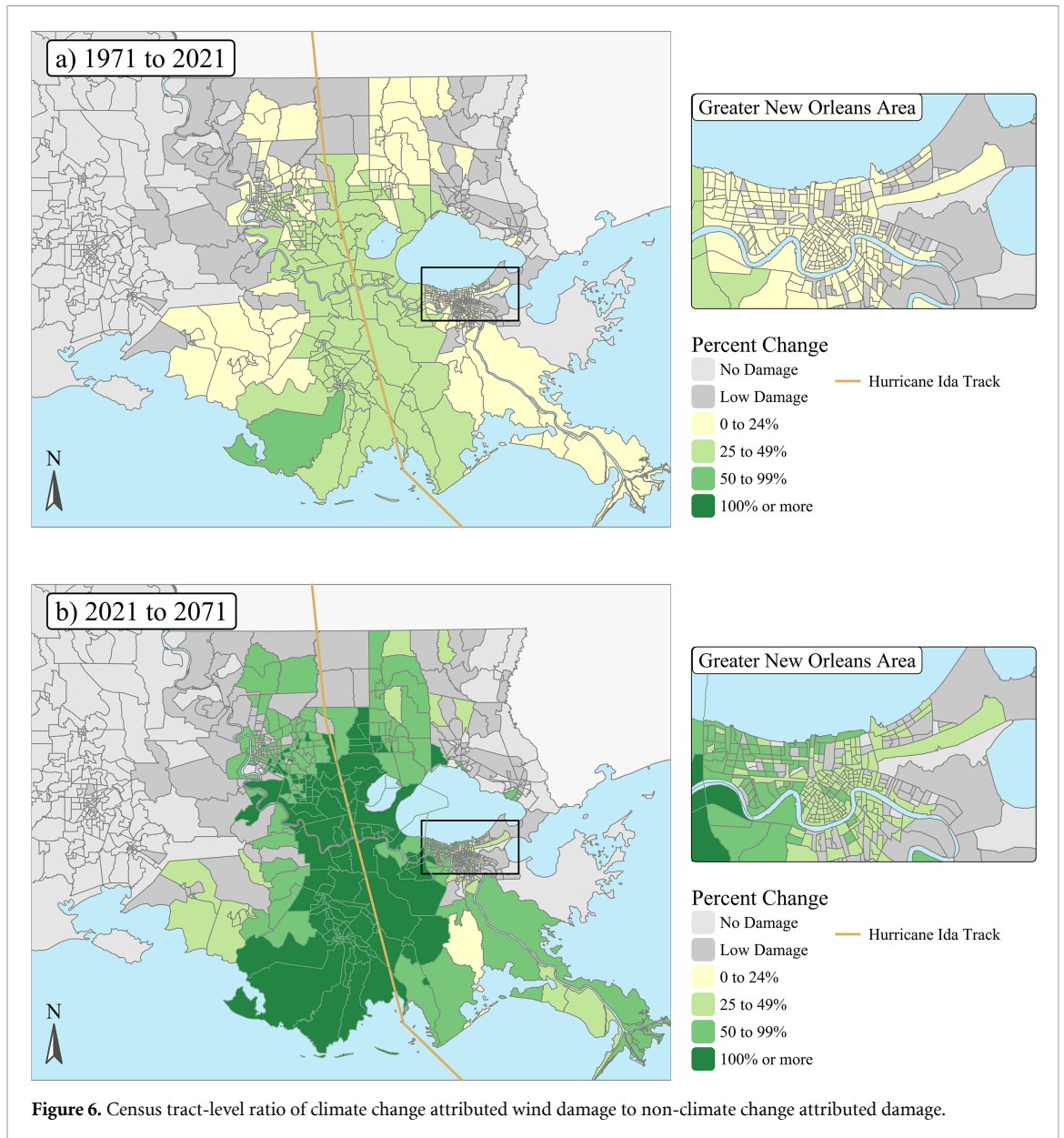


Figure 5. Total wind damage (in \$) in 1971, 2021, and 2071 scenarios by Census Tract in south Louisiana.



3.2.3. Regional differences

Climate change is also altering the geography of risk. Wind damages are higher because of climate change in both coastal areas and further inland especially along the hurricane's track as evinced in figures 5 and 6. Damages are estimated to be 25%–50% higher from 1971 to 2021 in these highly affected areas, and are projected to more than double between 2021 and 2071. These increased damages in figure 6 correspond to an area along and just east of the hurricane's track, and are the areas with the overall highest impacts as seen in figure 6.

Comparing 2021 and 1971 scenarios in figures 7 and 8 for storm surge impacts, model simulations found that surge-related damages as a percentage of previous census tract-level damage increased most in census tracts in coastal parishes such as Plaquemines, St. Bernard, Lafourche, and southern Jefferson parish. These were not always the most coastal tracts, as some of the most highly affected (i.e. 10% or greater change) between 1971 and 2021, for instance, were further inland. This also extended to areas on Lake Pontchartrain especially on the north shore of the lake. These same areas are projected to bear greater increases in storm surge impacts under the 2071 scenario. It is well worth noting that these impacts attributed to climate change are specific to Hurricane Ida: the damage profile, and the associated climate change imprint of that profile, of different areas will vary for a different hurricane. Importantly, our models were designed to isolate the effects of climate change and do not account for future sea level rise or land subsidence—meaning our estimates likely understate the future vulnerability of these areas.

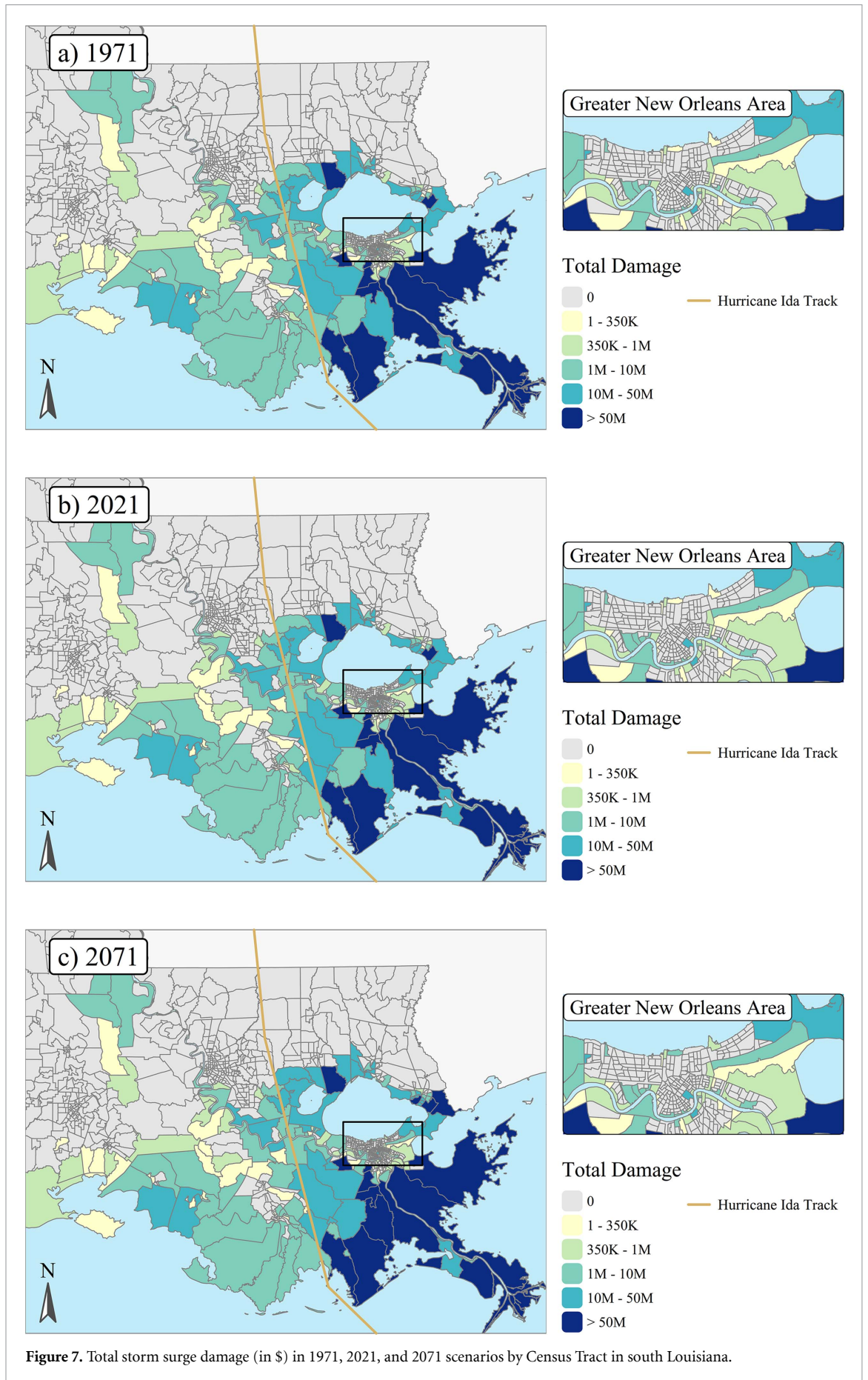
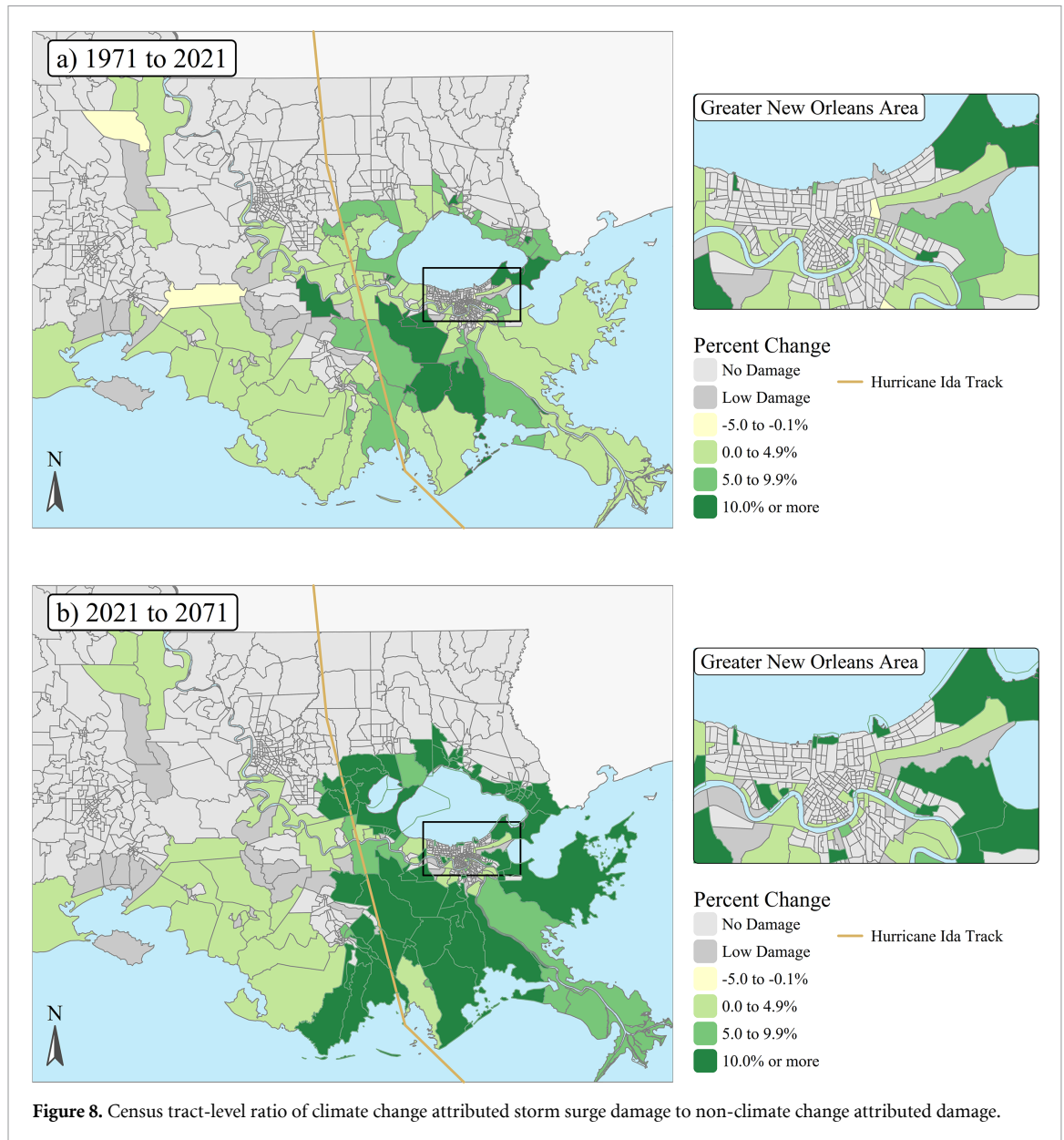


Figure 7. Total storm surge damage (in \$) in 1971, 2021, and 2071 scenarios by Census Tract in south Louisiana.

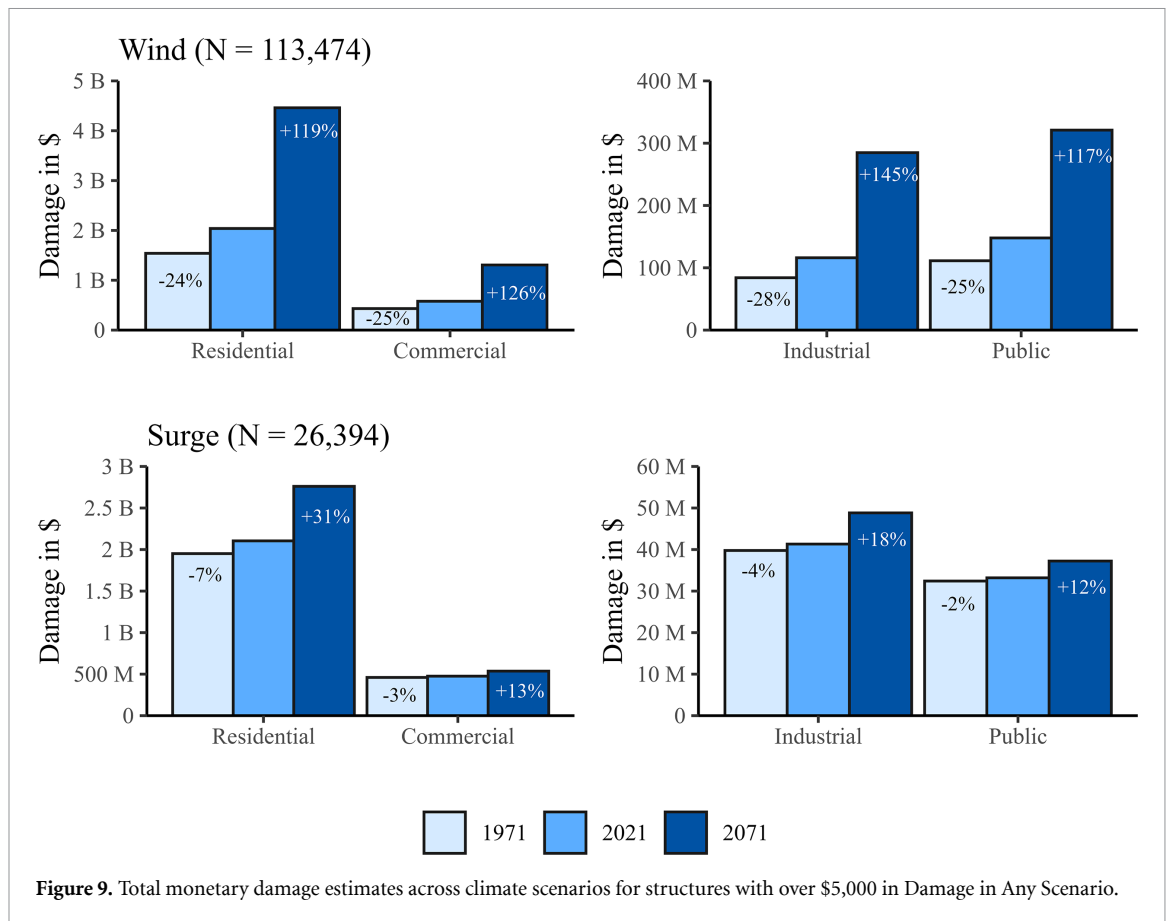


Taken together, our findings show that there is considerable heterogeneity across space, including by hazard, in where the impact of climate change is highest. This heterogeneity is primarily, though not totally, driven by increases in impacts in the most highly affected areas.

3.2.4. Differences by structure type

Here, we examine how damages are distributed across four structure types: residential, commercial, industrial, and public. Residential structures accounted for roughly 70% of wind-related damages and 79% of storm surge damages in the 1971 and 2021 scenarios. Figure 9 shows the changes in monetary damage estimates by structure type over time. For both hazards and across all three scenarios, the structure type most highly affected was, not surprisingly, residential, followed by commercial, with much smaller damage totals for industrial and public structures.

For wind, similar differences across structure type were evinced between 1971 and 2021 (between 24% and 28% lower damages), but more differences were found between 2021 and 2071 where industrial had the highest increase (145%) followed by commercial (126%), residential (119%), and public (117%). The differing rates of damage growth across structure types can be explained by variations in building characteristics, typical siting patterns, and hazard-specific vulnerabilities. Industrial buildings often have large roof spans, lightweight metal paneling, and wide door openings that make them highly sensitive to increases in wind speed. Industrial facilities are also frequently located in open terrain or along transportation corridors, which exposes them to higher gust factors and amplifies the



climate-driven wind increases shown in our simulations. For storm surge, residential structures saw greater impacts over time: 7% fewer impacts in the 1971 Ida-like storm compared to 2021 compared to between 2% and 4% for commercial, industrial, and public. From 2021 to 2071 for storm surge, 31% greater impacts were evinced for residential structures, with increases of 18%, 13%, and 12% for industrial, commercial, and public, respectively. In contrast, residential structures show the greatest growth in storm surge damages because they are more numerous in low-lying coastal and near-coastal areas and have lower first-floor elevations, ground-level utilities, and contents that are highly vulnerable to inundation. These structural and locational characteristics help explain why wind-driven damage growth is most pronounced for industrial buildings, while surge-driven increases are concentrated in residential structures.

4. Discussion and conclusion

Our research examined whether, and how, climate change made the impacts of Hurricane Ida in Louisiana more severe. To do so, high resolution data on structures was paired with hazard models underpinned by climate change attribution. We focused on multiple hazards—namely, wind and storm surge—and on multiple scenarios—to a past and to a future climate compared to the present—to study how the impacts may be more severe. A central insight from this work is that climate change amplified impacts of Hurricane Ida in south Louisiana unevenly across hazards, geography and structure types. We underline three ways in which our work advances existing EEIA research. First, we use high resolution data with structure-level damage functions of storm surge and wind impacts, and examine these impacts across census tracts and by structure type. Across geographies, results showed that the economic damages attributed to climate change were not homogenous across space, but instead heterogenous. The patterns especially indicated that the impact of climate change from Hurricane Ida was found in areas that were already highly affected by the hurricane as well as inland from the coast. This result is partly thanks to non-linearities in damage function such that the most extreme impacts become extreme. We also found differences by structure type and within structure type by hazard.

Second, we employed a multi-hazard framework to yield important varied patterns by wind and storm surge, in contrast to previous work that tends to focus more on precipitation (e.g. Wehner and Sampson 2021, Reed *et al* 2022). Specifically, wind impacts were more prevalent in terms of structures affected, and, in the 2071 Ida-like storm, in total number of damages. This striking increase is driven climatological changes at the same time that it is also underwritten by physical vulnerabilities. Climatological changes are greater because of the acceleration of warming, namely that the warming between 2021 and 2071 is greater than that between 1971 and 2021. Physical vulnerabilities to structures are greater in coastal Louisiana compared to some other Gulf states: for instance, the state of Alabama had more than 50 000 residences that met higher standards for roof quality (i.e. FORTIFIED roofs) in 2024 compared to 10 000 in Louisiana (IBHS 2025, Louisiana Department of Insurance 2025). Although we do not examine these physical vulnerability characteristics directly, our models suggest that relatively small increases to already-high wind speeds driven by climate change may have especially large impacts because structures are most vulnerable at these high speeds. By contrast, storm surge flooding tended to expand the structures affected but less so the damage per structure. These differences by hazard showcase how different relationships between hazards and structures, namely through damage functions, can affect results in substantive ways. Still, we did not study hurricane hazards such as fluvial or pluvial flooding nor did we examine compounding impacts of the two hazards, all of which may have patterns distinct from these (such as with greater flooding impacts inland for fluvial and pluvial flooding compared to storm surge).

Third, our use of attribution science to attribute contemporary impacts and project future impacts cross-cuts the importance of high resolution impact data and the multi-hazard framework. Simulated wind damage generated by Hurricane Ida had greater impacts attributed to climate change compared to storm surge, and both hazards had much greater changes in impacts projected in the future than what had changed already. These changes varied by the area and the type of structure under examination. Our results further underline the non-linearities of impacts at extreme values like that of a major hurricane like Ida because the increases in the latter period (i.e. 2021–2071) are greater than in the former period (i.e. 1971–2021). This reflects how small shifts in hazard intensity can produce disproportionately large increases in damage. Taken together, one important implication of EEIA research for EEA research is that changes in *impacts* (i.e. economic damages and affected structures) are often of a magnitude greater than changes in *hazards* (i.e. wind speed).

Our findings are subject to a degree of uncertainty across the modeling chain in at least three ways. First, uncertainty in the hazard modeling component arises from our choice of wind and surge models, our choice of emissions scenario, and the inherent uncertainty due to internal variability of the atmosphere and ocean (Hawkins and Sutton 2009). The relative importance of each varies by temporal and spatial scale. For the spatial scale of an individual hurricane, internal variability and choice of models matter far more than the choice of emissions scenario (Deser *et al* 2012). Our experimental design choice to keep the hurricane track fixed across the three years removes internal variability of track, but there remains uncertainty due to internal variability within the spatial wind field and its effect on the spatial surge field. We therefore assume that the climate change signals among the three years is larger than internal variability of the wind and surge fields around a fixed track. A multi-model approach would sample model uncertainty but is beyond the scope of this study. Results should therefore be interpreted in the context of a single model for wind and surge, and single point estimates (instead of confidence intervals, e.g.) associated with them. Second, the damage calculations contain uncertainties associated with incomplete knowledge of building characteristics, and with uncertainty in how structures respond to the hazards via the damage functions (i.e. HAZUS for wind, Go-Consequences for storm surge). Third, we did not study other aspects of environmental change relating to climate change, most notably land subsidence and future sea level rise. While this was purposeful for the research design to hold all elements constant across scenarios (such as for these factors, building locations, storm track, etc; see Methods), it does lead to enhanced uncertainty as land loss could contribute to stronger hurricanes and different patterns of impacts.

As a final concluding note based on our results, we reflect that while an EEA study might supply a single best estimate as an attribution statement, the attribution statement or statistic that one might use in an EEIA study could be many fold and highly varying. While our findings lead with a single best estimate as an attribution statement (namely, that approximately \$885 million of economic damages from wind and storm surge flooding can be attributed to climate change), our data synthesis shows that attribution statements could be crafted that are specific to the impact variable, the spatial unit, the structure type, the hazard—and combinations of these factors therein. Damage increases are different for wind and for surge, they are different in areas affected, and they are different by structure type. A key implication from our results is that an attribution statement could vary in generative ways depending

on the given scope. Whether this relationship of increased impacts that outstrip increased hazards holds for other hazards and other hurricane events is an area for future study. Still, there are practical implications for planning for climate change: impacts from extreme weather attributed to climate change can be variable across time, space, impact types, and much more. The utility of an attribution statement, for example, that is specific to these factors may make it more useable in policy and governance. It is important to further note uncertainties can be higher in more downscaled analyses which also can affect policy application. Textured climate change planning requires attentiveness to these scales and measures. Finally, the findings draw attention to a policy implication that a primary way to enhance adaptation to climate change is to mitigate climate change-causing emissions.

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Data availability statement

The data that support the findings of this study are available: https://github.com/kaylynn-m/ida_impact_attribution/blob/main/ida_impact_attribution.Rproj (Larrison 2026).

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