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Increasing sequential tropical cyclone hazards along the US East and Gulf coasts

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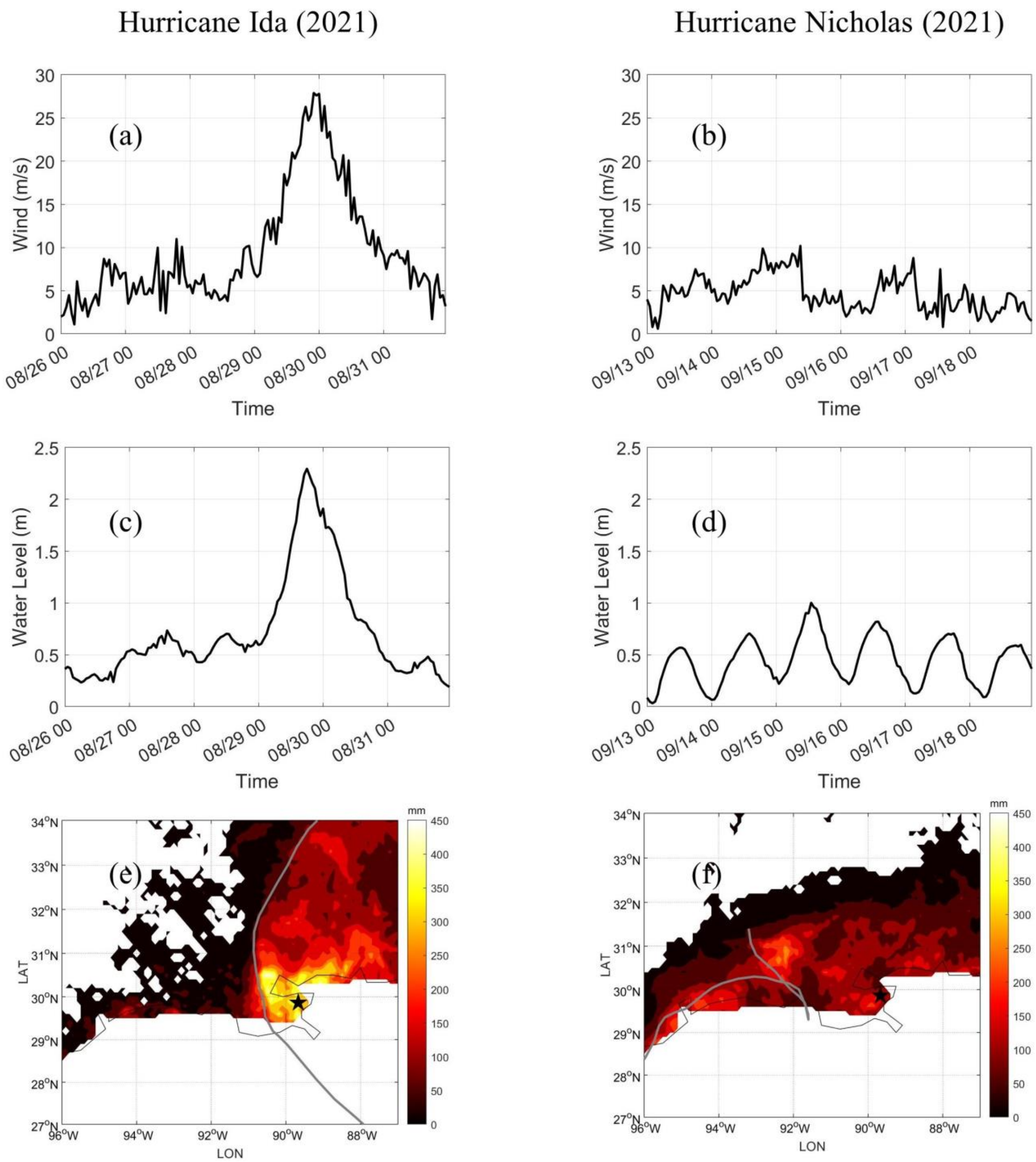

Figure S1. Hazards from Hurricanes Ida (2021) and Nicholas (2021). (a)(b). hourly wind speed at Shell Beach (LA) for Hurricanes Ida and Nicholas, respectively. (c)(d). hourly water level at Shell Beach (LA) for Hurricanes Ida and Nicholas, respectively. (e)(f). total rainfall from Hurricanes Ida and Nicholas, respectively. Location of the tidal gauge at Shell Beach is marked by black pentagram, and storm tracks are shown by grey solid line. The wind and surge observation are obtained from https://tidesandcurrents.noaa.gov/. The rainfall observation is obtained from Stage IV radar observation https://data.eol.ucar.edu/dataset/21.093.

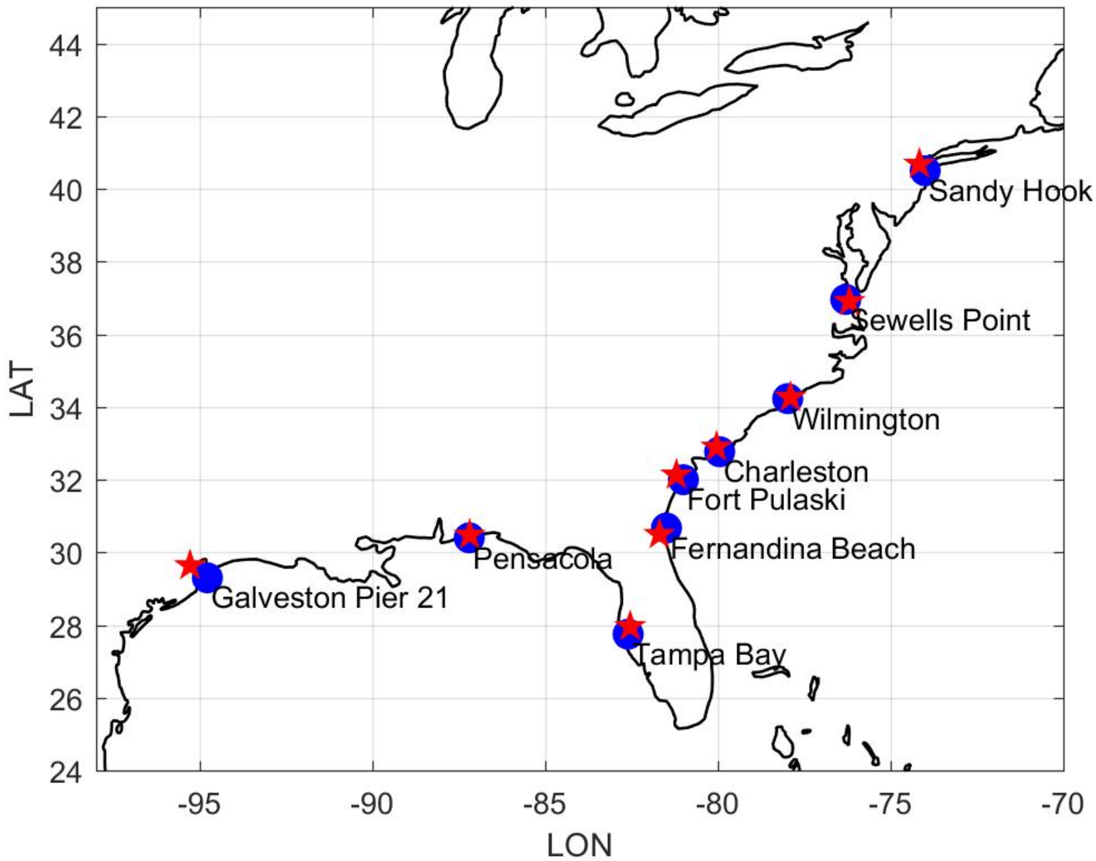

Figure S2. Selected locations along the U.S. coasts selected for historical analysis. Tidal gauge stations at these locations are shown by blue dots and weather stations by red pentagrams.

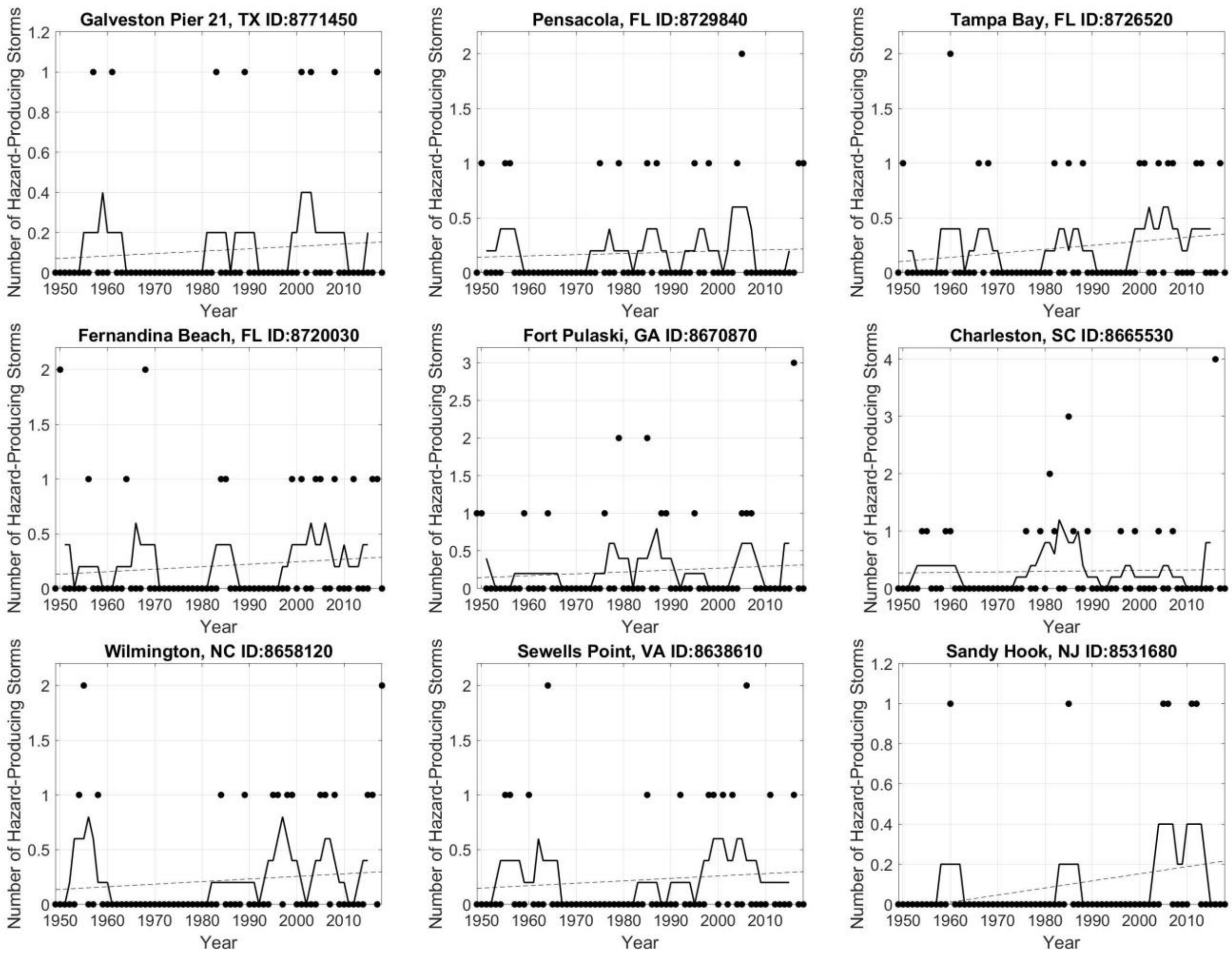

Figure S3. Number (black dots) of hazard-producing TCs. The results are shown for the period of 1949-2018 for the 9 selected locations. The solid line shows the 5-year moving average of hazard-producing TC numbers; the dashed line shows the fitted linear trend of the 5-year moving averaged hazard-producing TC numbers.

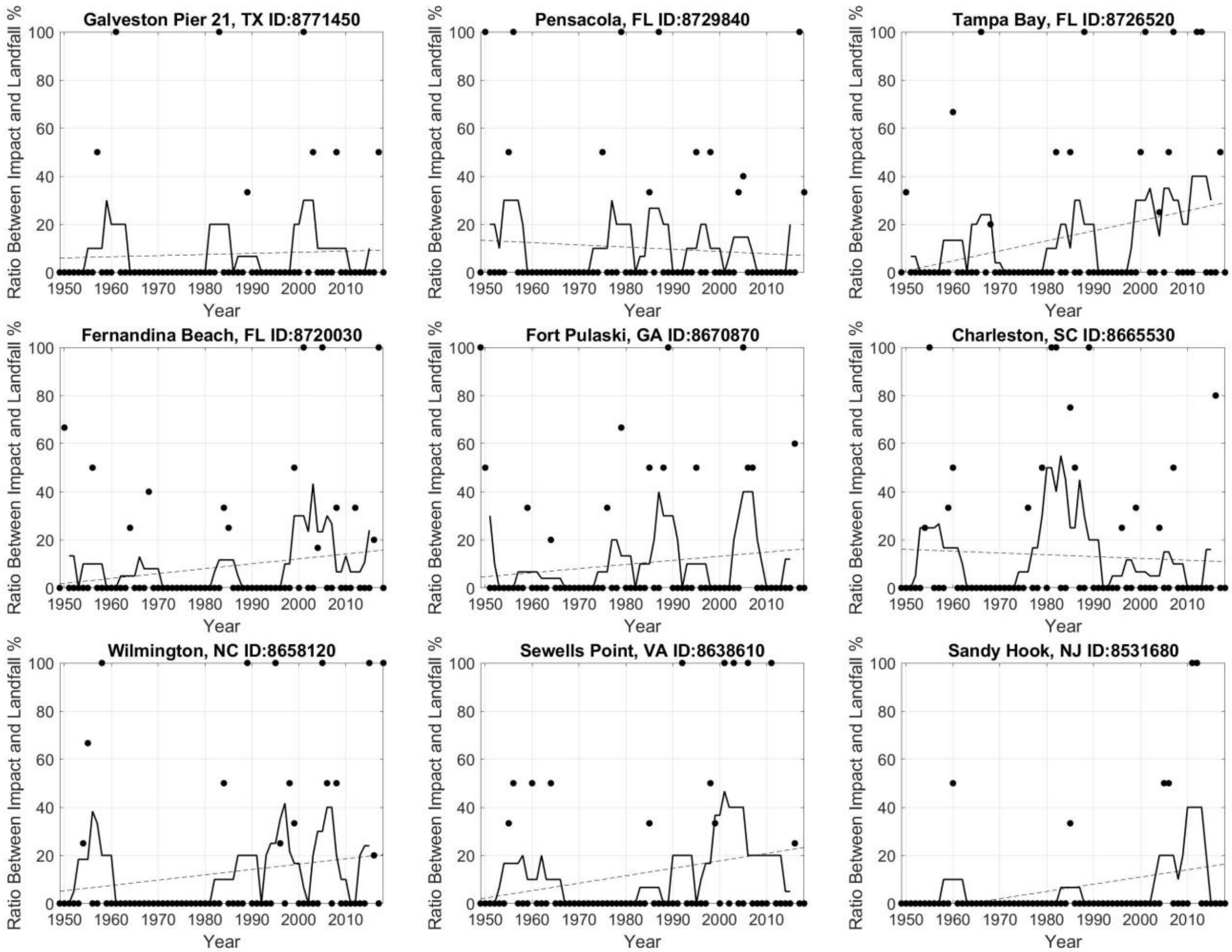

Figure S4. Ratio (black dots) between hazard-producing TCs and landfalling TCs. The results are shown for the period of 1949-2018 for the 9 selected locations. The solid line shows the 5-year moving average of hazard-producing TC ratio; the dashed line shows the fitted linear trend of the 5-year moving averaged TC hazard-producing ratio.

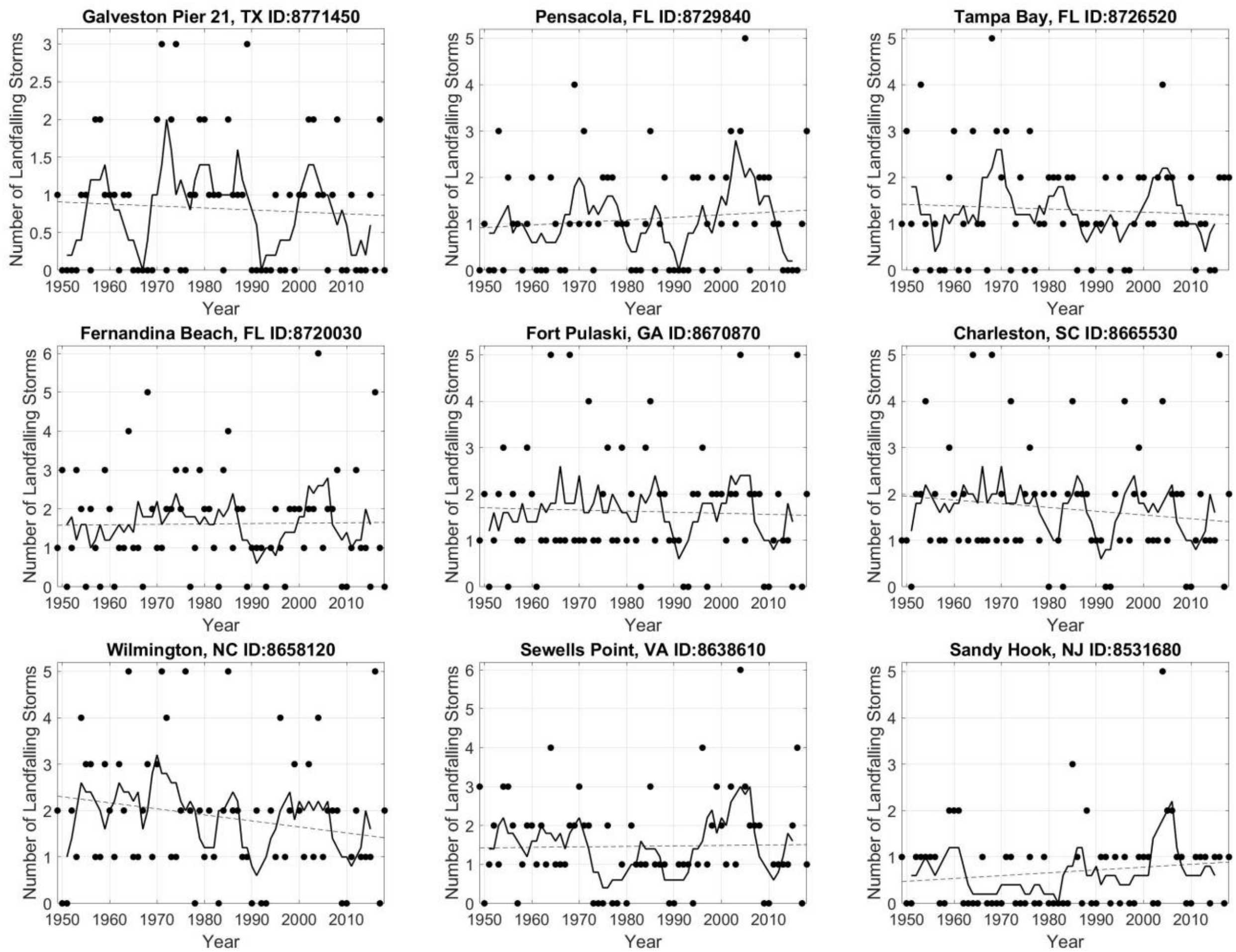

Figure S5. Number (black dots) of landfalling TCs. Results are shown for the period of 1949-2018 for the 9 selected locations. The solid line shows the 5-year moving average of landfalling TC numbers, while the dashed line shows the fitted linear trend of the 5-year moving averaged landfalling TC numbers.

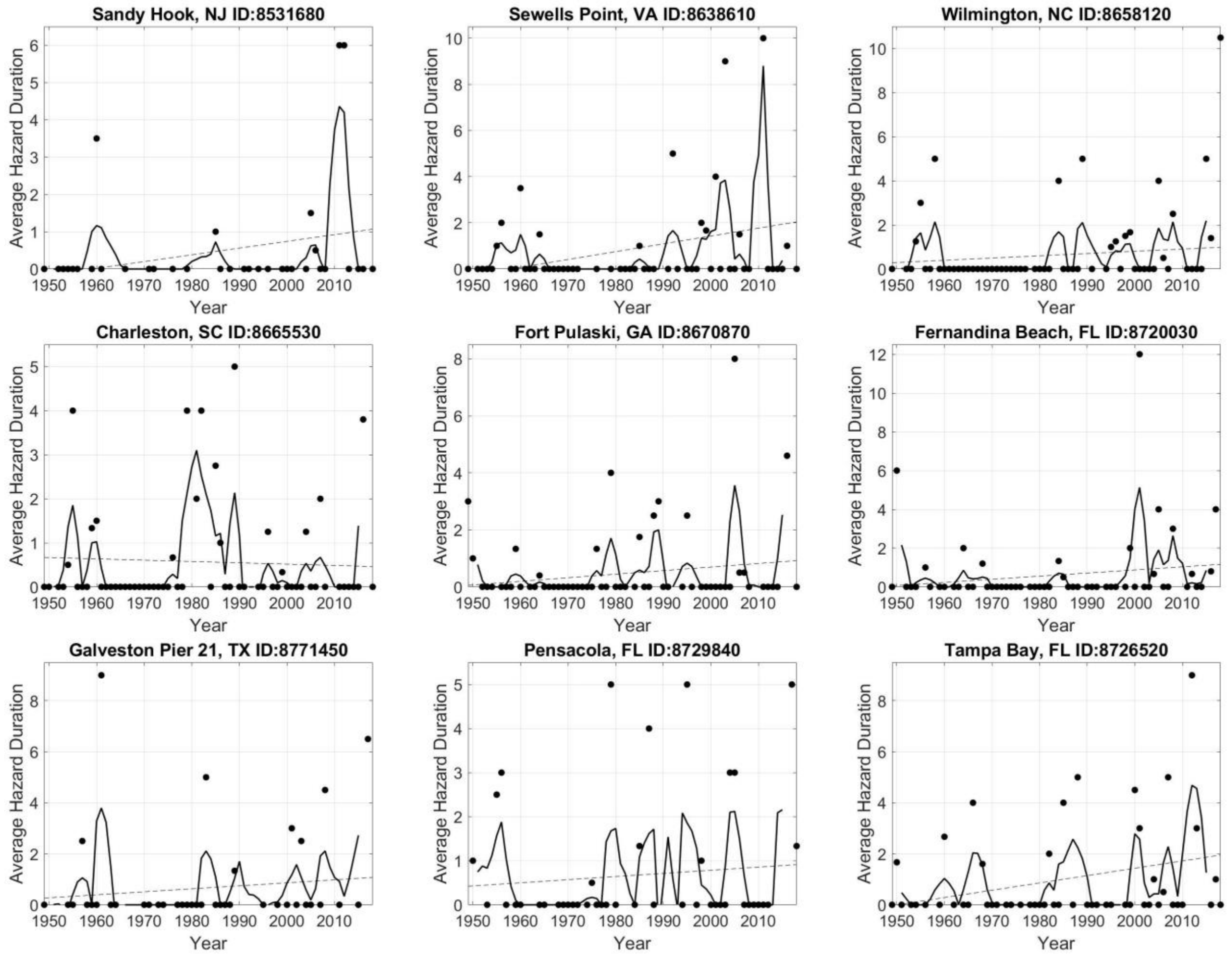

Figure S6. Average hazard duration (black dots) of landfalling TCs. Results are shown for the period of 1949-2018 for the 9 selected locations. The solid line shows the 5-year moving average of landfalling TC hazard duration; the dashed line shows the fitted linear trend of the 5-year moving averaged TC hazard duration.

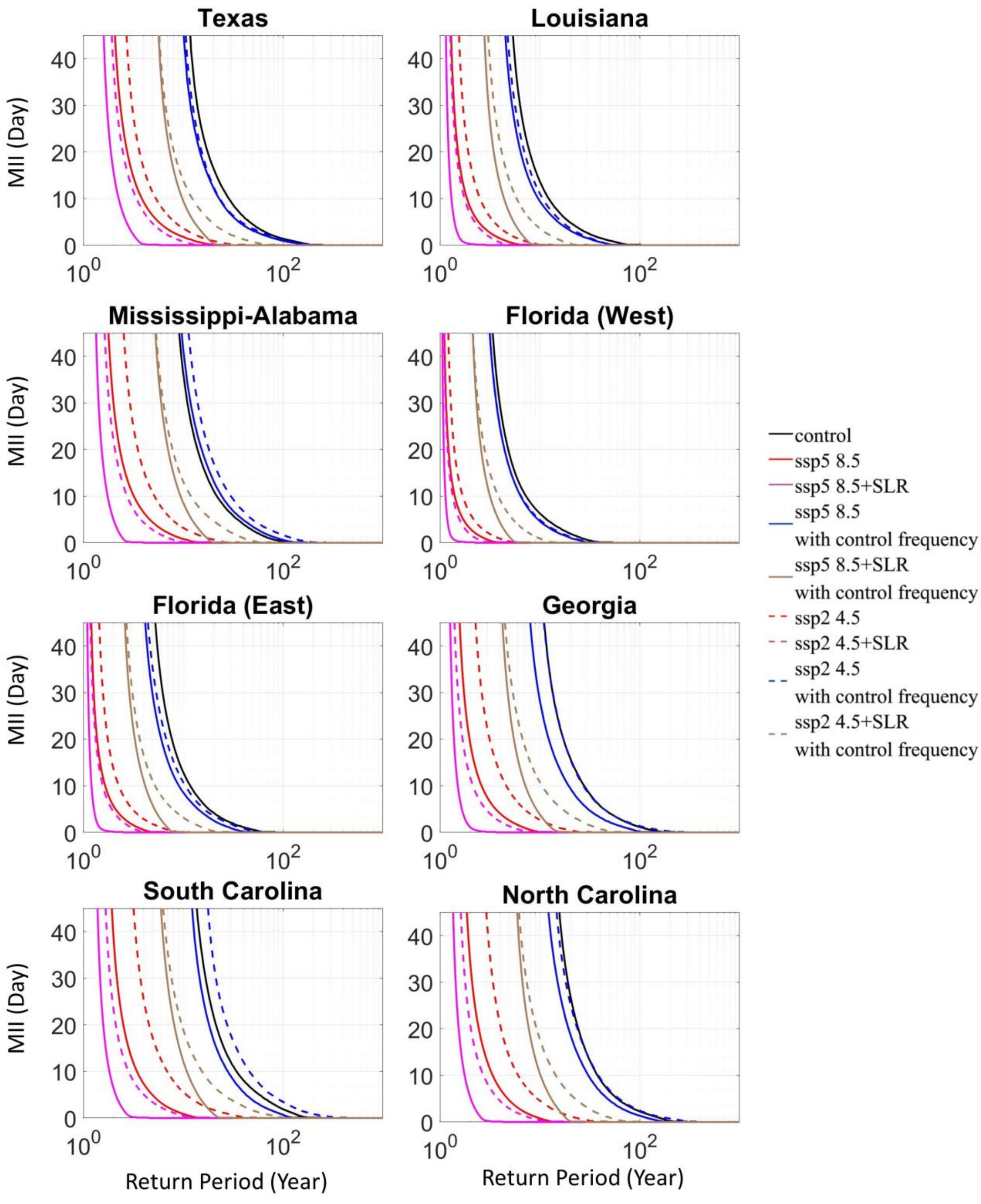

Figure S7. Same as Fig 2, but under the “90-th percentile definition” .

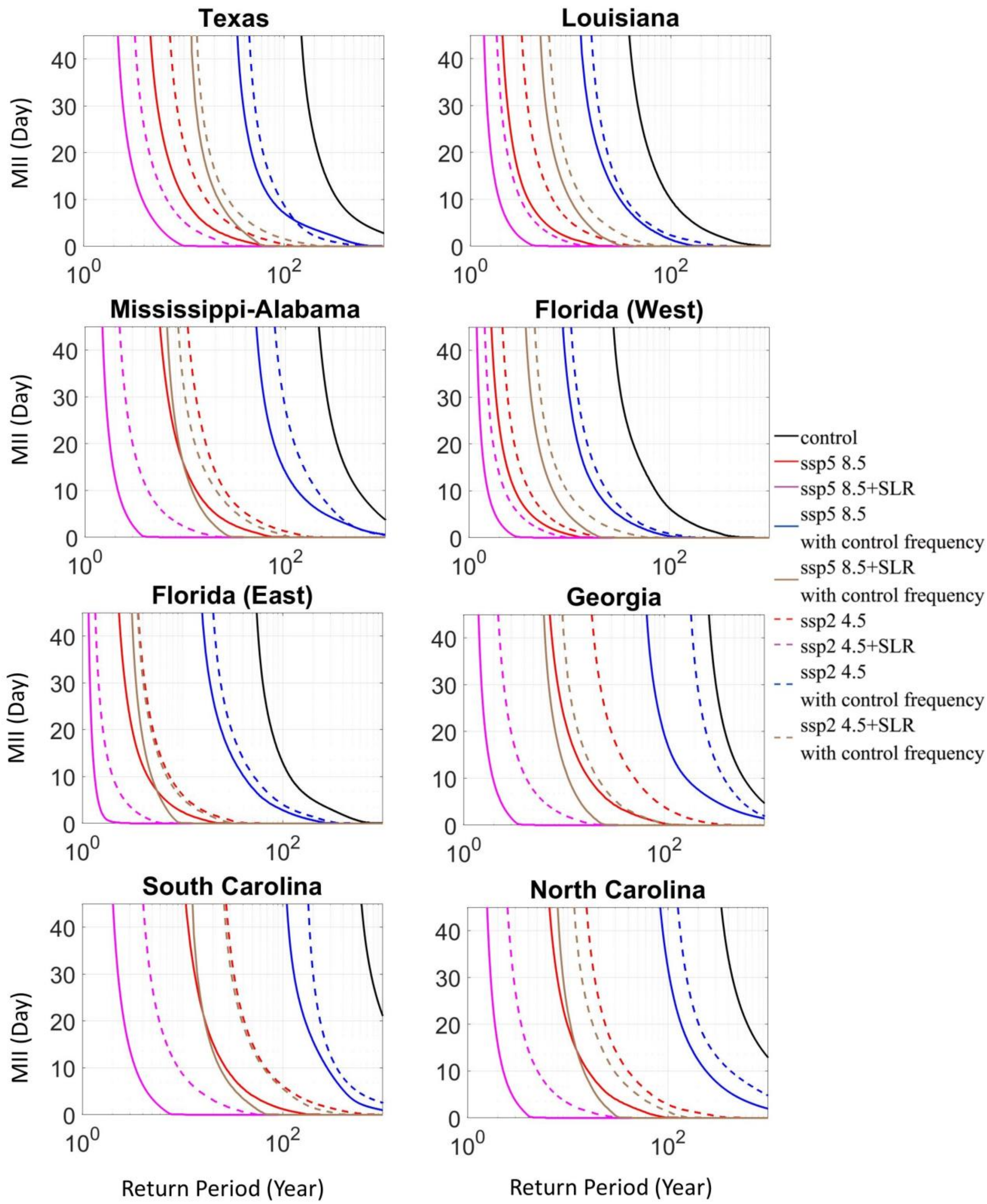

Figure S8. Same as Fig 2, but under the "99-th percentile definition" .

Projected Increase of Joint and At Least One Hazard from TCs by the End of 21st Century

Besides the analysis of sequential TC hazards in the main text, it is informative to analyze the future projection of joint and at least one hazard from TCs as they are not only important to our understanding of sequential TC hazard, but also important aspects of TC hazards by themselves. Figure S8 shows the change of the return period of the joint exceedance event, which is defined as the return period of three TC hazards (wind, surge, rainfall) jointly exceeding the return level of individual hazards. For example, in Louisiana, the return period of a landfalling TC producing the triple hazards that jointly exceed current 10-year return level is a 20-year event under the current climate, while the event will become a 3-year event under the SSP5 8.5 scenario with the consideration of SLR and a 4.5-year event without considering SLR. To evaluate whether the increase of the joint hazard is solely due to the increased TC frequency, the return period calculated with future storms and control frequency are also shown in Figure S9. It is shown that even if TC frequency has no change, the chances of joint hazards will still increase. Similar to the joint exceedance event, the probability of at least one of the three hazards of landfalling TCs exceeding the respective threshold will also increase in the future (Figure S10).

In the analysis of sequential TC hazards, a "hazard-producing" TC is defined as at least one hazard component exceeding the threshold. So, it is important to understand which hazard drives the increase of OEP, as OEP is directly linked to the occurrence rate of sequential TC hazards. The marginal increase of exceedance probability for each single hazard is thus investigated (Fig. S11). It is found that without SLR, rainfall increase is most significant, followed by the increase of wind hazard. If SLR is not considered, surge hazard shows the least increase. For example, in Texas, the probability for an event to exceed the 10-year return level is 0.12 (1 over the product of storm frequency and return period); in the SSP5 8.5 scenario, such probabilities for rainfall, wind, surge, and surge+SLR are 0.36, 0.27, 0.21, and 0.80, respectively. The differences of the extent of increase among the three hazard components are smaller in the high return period thresholds. SLR has profound influence on increasing the exceedance probability of surge hazard in low return period thresholds (i.e., 10-year), but its influence quickly decays for higher return period thresholds (e.g., the exceedance probability of the 100-year return level in Texas is 0.012 in the current climate and 0.05 for surge and 0.22 for surge+SLR under SSP5 8.5 scenario).

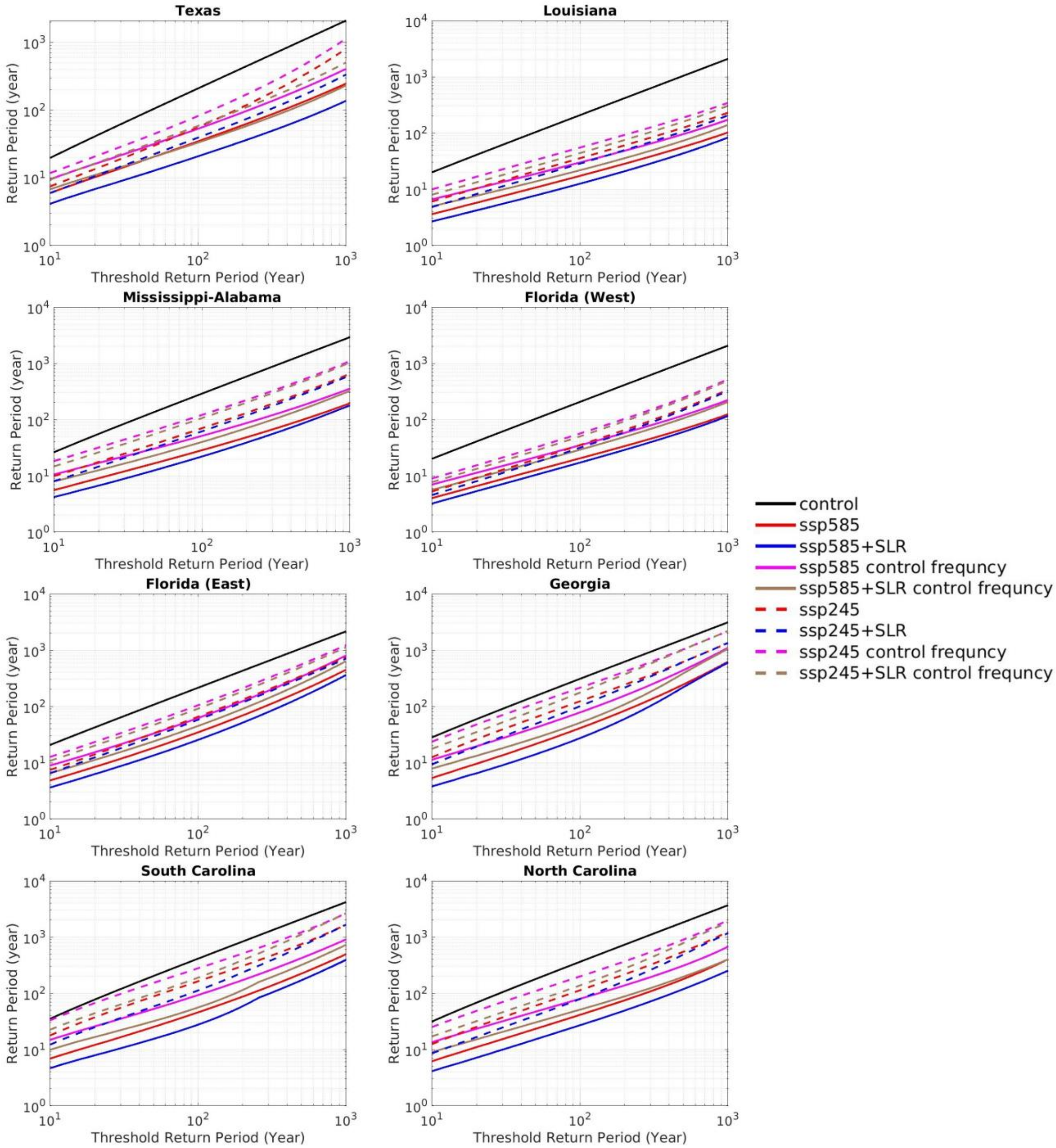

Figure S9. Return period of joint exceedance event. Black solid curve: control climate. Red solid (dashed) curve: SSP5 8.5 (SSP2 4.5) scenario without consideration of SLR; Blue solid (dashed) curve: SSP5 8.5 (SSP2 4.5) scenario with consideration of SLR. The curves are averaged from 6 climate models. Purple solid (dashed) curve: SSP5 8.5 (SSP2 4.5) scenario without consideration of SLR, but with storm frequency in control period; Green solid (dashed) curve: SSP5 8.5 (SSP2 4.5) scenario with consideration of SLR, but with storm frequency in control period. The curves are averaged from 6 climate models.

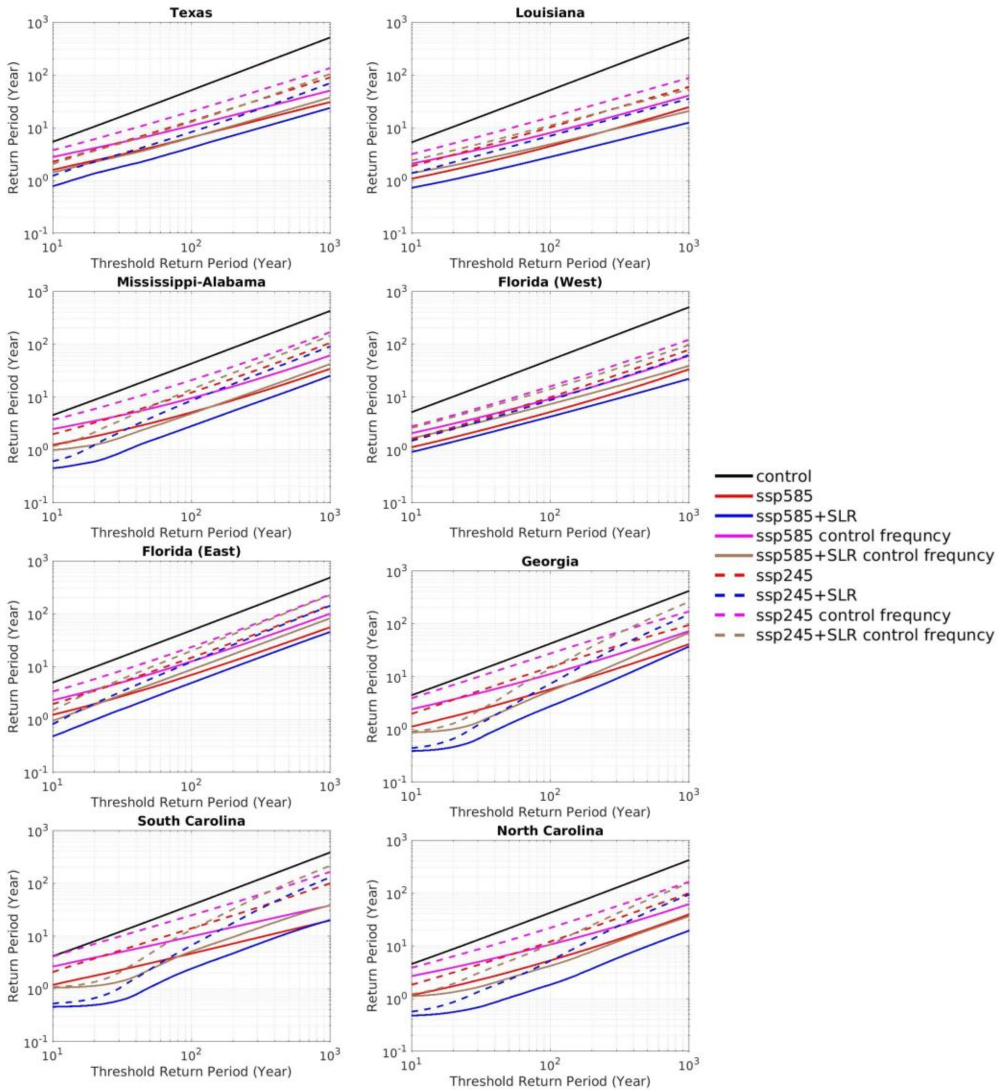

Figure S10. Probability of at least one hazard exceeding the threshold (OEP). Black curve: OEP in control climate. Red solid (dashed) curve: OEP in SSP5 8.5 (SSP2 4.5) scenario without consideration of SLR; Blue solid (dashed) curve: OEP in SSP5 8.5 (SSP2 4.5) scenario with consideration of SLR. The curves are averaged from 6 climate models. The colored squares are the estimations based on individual climate models.

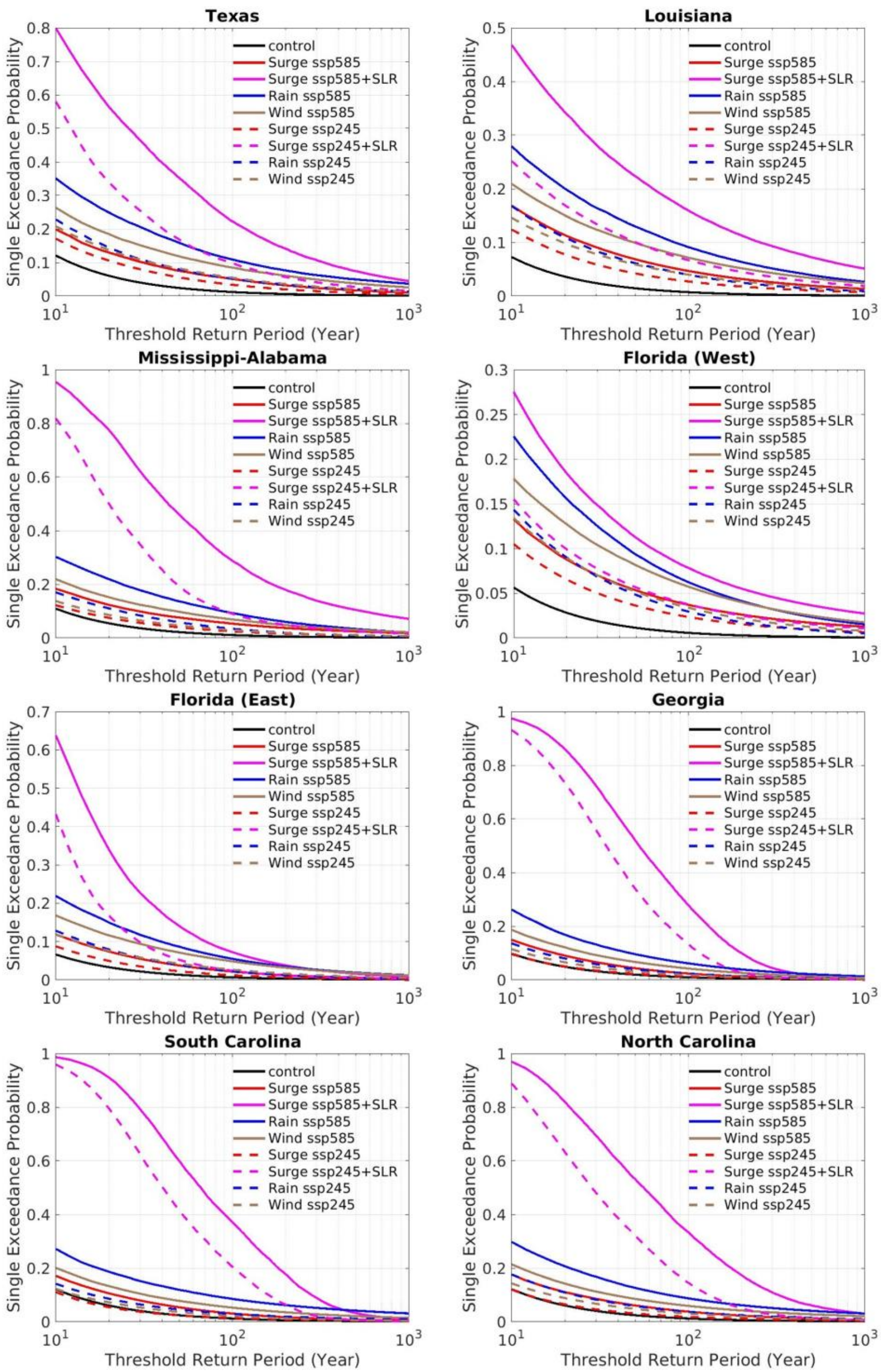

Figure S11. Exceedance probability of single hazard component.

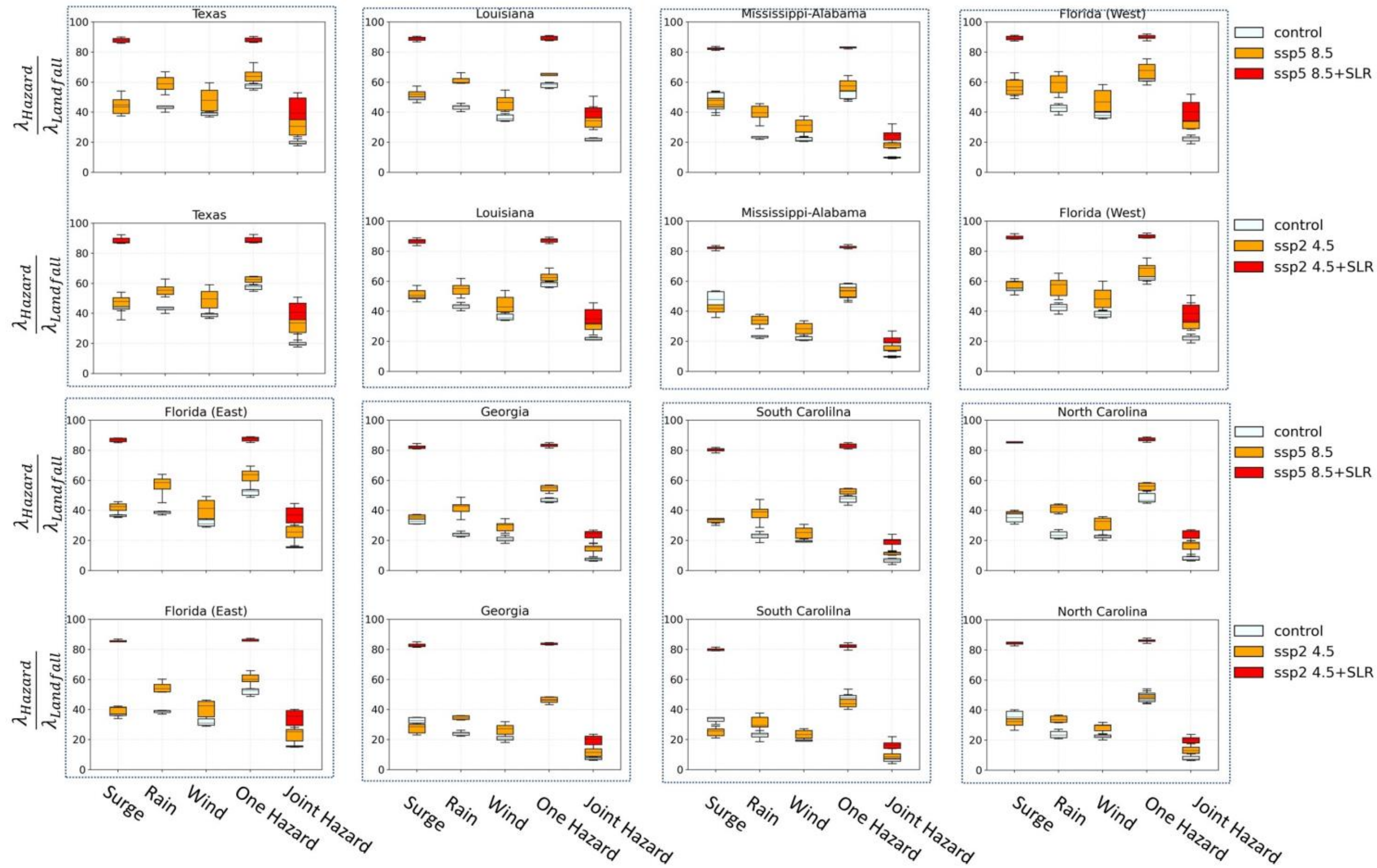

Figure S12. Same as Fig 4, but under the “90-th percentile definition”.

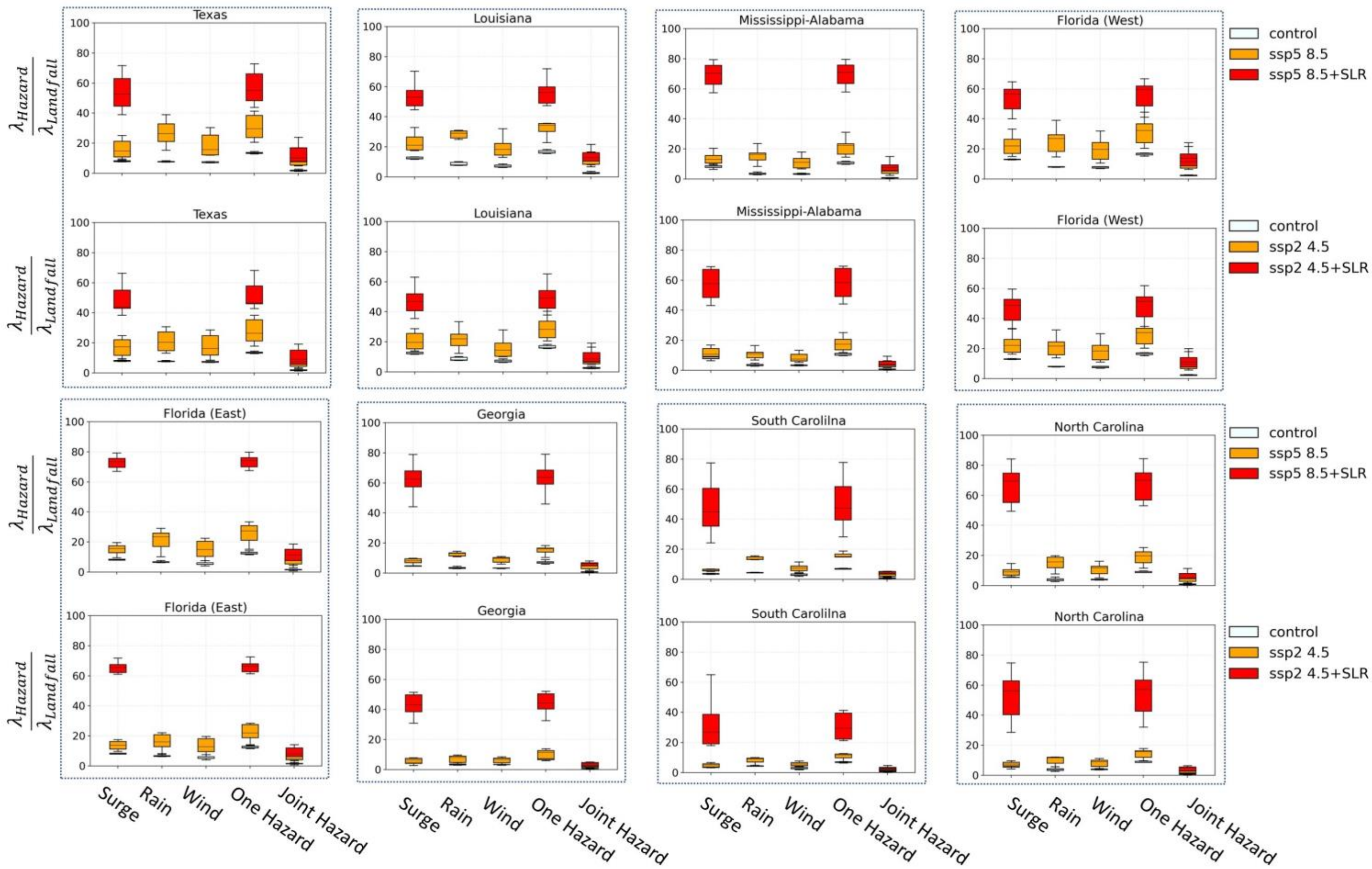

Figure S13. Same as Fig 4, but under the "99-th percentile definition" .

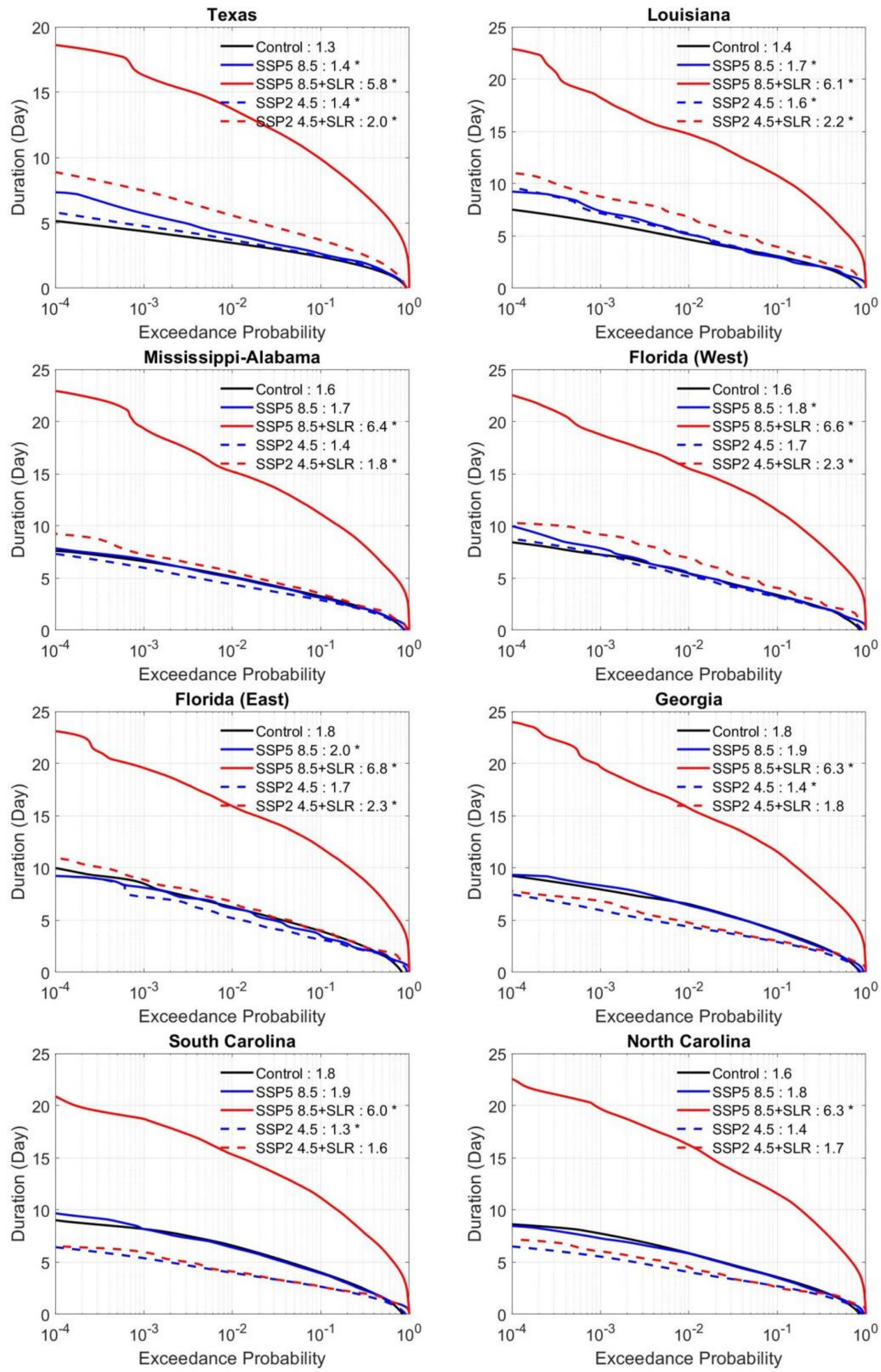

Figure S14. Same as Fig 5, but under the "90-th percentile definition" .

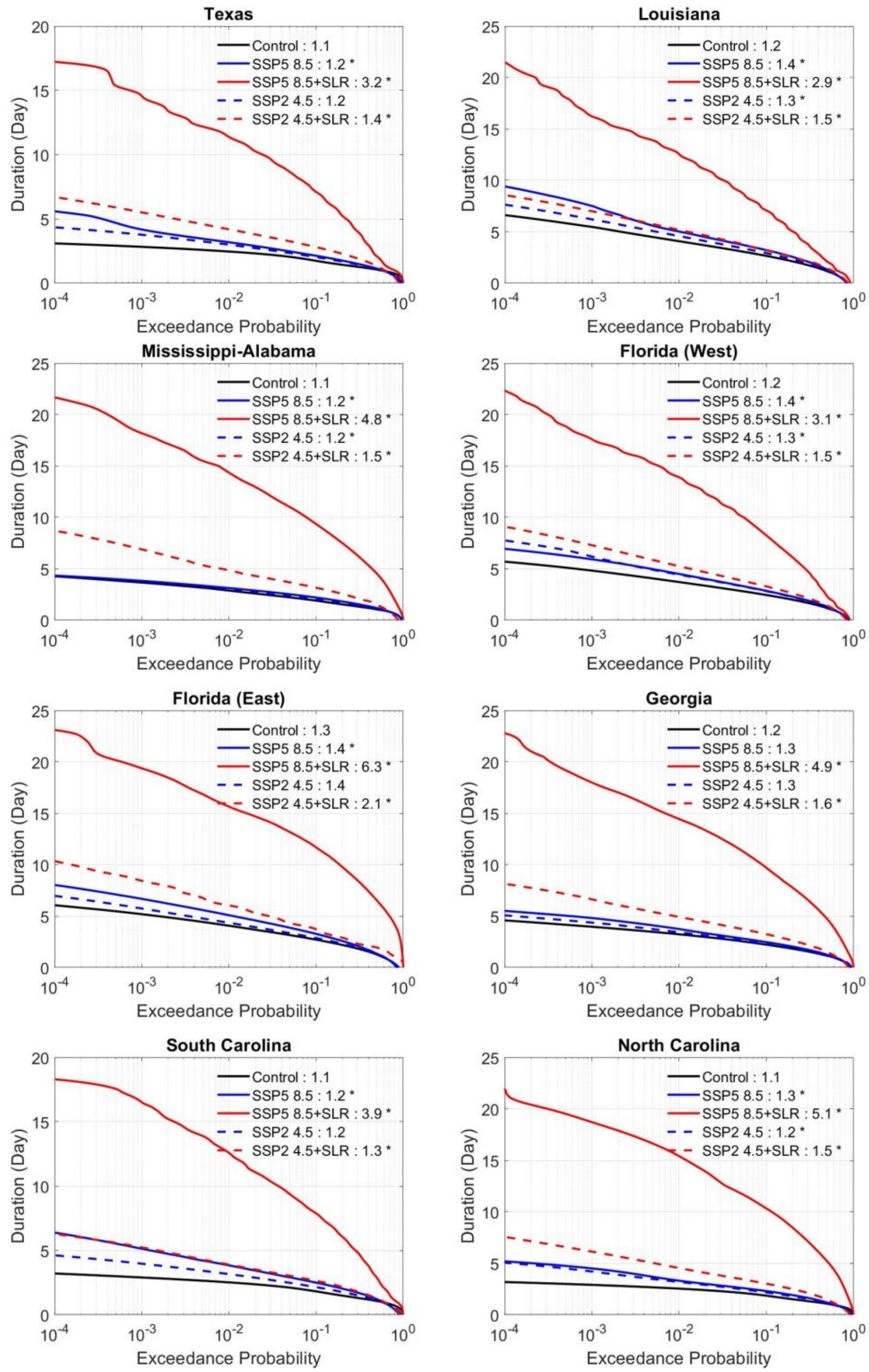

Figure S15. Same as Fig 5, but under the “99th percentile definition” .

Table S1. Relative decrease of MII return period under SSP5 8.5 scenario. The decrease is calculated based on 15-day MII in 2070-2100 from 1980-2005 averaged over the 6 climate models: Column 1. Defining impact as landfall; Column 2. Defining impact as hazard-producing and use modeled landfall frequency; Column 3. Same as Column 2 but also considering SLR; Column 4. Same as Column 2 but using landfall frequency in the control simulation; Column 5. Same as Column 3 but using landfall frequency in the control simulation. The mean change and the range (5-th and 95-th percentiles) of the change are shown.

	Landfall	Hazard	Hazard+SLR	Hazard+Control Frequency	Hazard+SLR+Control Frequency
Texas	-73.5% (-72.6%~-74.5%)	-89.6% (-88.4%~-90.0%)	-94.7% (-94.1%~-95.2%)	-41.0% (-34.3%~-47.7%)	-78.2% (-75.9%~-80.1%)
Louisiana	-60.6% (-59.8%~-61.6%)	-88.2% (-87.3%~-88.9%)	-91.9% (-91.3%~-92.3%)	-38.5% (-26.7%~-41.4%)	-73.6% (-71.0%~-75.1%)
Mississippi-Alabama	-76.1% (-75.2%~-76.8%)	-92.0% (-91.1%~-92.8%)	-96.7% (-96.4%~-97.1%)	-33.3% (-23.0%~-40/7%)	-84.6% (-82.9%~-86.0%)
West Florida	-50.6% (-49.5%~-51.2%)	-84.7% (-83.9%~-85.1%)	-88.7% (-87.9%~-88.8%)	-22.2% (-17.3%~-25.6)	-68.6% (-66.8%~-69.4%)
East Florida	-58.0% (-57.5%~-59.0%)	-89.5% (-88.8%~-90.1%)	-93.1% (-92.6%~-93.4%)	-41.2% (-33.3%~-44.6%)	-78.4% (-76.7%~-79.8%)
Georgia	-73.5% (-72.6%~-74.5%)	-94.4% (-93.6%~-95.0%)	-97.9% (-97.6%~-98.1%)	-58.2% (-52.0%~-63.8%)	-90.1% (-88.9%~-91.2%)
South Carolina	-78.7% (-77.8%~-79.4%)	-94.1% (-93.5%~-95.0%)	-98.1% (-97.9%~-98.4%)	-52.2% (-43.8%~-61.1%)	-89.6% (-88.2%~-91.4%)
North Carolina	-78.0% (-77.1%~-79.0%)	-94.4% (-93.6%~-95.2%)	-98.0% (-97.7%~-98.3%)	-42.5% (-31.3%~-51.9%)	-89.1% (-87.5%~--90.7%)

Table S2 Same as Table S1.1, but for the SSP2 4.5 scenario.

	Landfall	Hazard	Hazard+SLR	Hazard+Control Frequency	Hazard+SLR+Control Frequency
Texas	-68.3% (-67.0%~-69.5%)	-85.7% (-84.1%~-86.9%)	-92.2% (-91.3%~-92.9%)	-30.8% (-22.2%~-39.3%)	-71.8% (-68.6%~-75.0%)
Louisiana	-56.6% (-55.5%~-57.7%)	-82.9% (-81.4%~-83.7%)	-89.4% (-88.7%~-90.1%)	-31.2% (-20.0%~-31.3%)	-66.9% (-63.7%~-68.7%)
Mississippi-Alabama	-71.1% (-70.1%~-72.3%)	-87.4% (-85.9%~-88.9%)	-95.4% (-94.8%~-95.8%)	-21.6% (-8.7%~-31.9%)	-80.5% (-78.2%~-82.3%)
West Florida	-48.6% (-47.6%~-49.1%)	-81.7% (-80.6%~-82.1%)	-86.6% (-85.9%~-86.9%)	-28.3% (-23.4%~-31.4%)	-61.9% (-59.9%~-63.5%)
East Florida	-54.9% (-54.4%~-56.1%)	-85.2% (-84.2%~-86.1%)	-91.5% (-90.9%~-92.0%)	-29.4% (-25.0%~-35.3%)	-74.2% (-72.1%~-75.7%)
Georgia	-69.8% (-68.7%~-70.9%)	-90.2% (-88.8%~-91.2%)	-97.1% (-96.7%~-97.4%)	-31.3% (-20.0%~-41.3%)	-87.9% (-86.1%~-89.4%)
South Carolina	-74.0% (-72.9%~-74.9%)	-88.0% (-85.8%~-90.0%)	-97.1% (-96.8%~-97.6%)	-23.9% (-9.1%~-37.3%)	-87.0% (-85.6%~-89.6%)
North Carolina	-73.8% (-72.7%~-75.0%)	-89.3% (-87.5%~-90.1%)	-97.0% (-96.5%~-97.4%)	-17.5% (-0.1%~-30.9%)	-86.3% (-83.8%~-88.0%)

Table S3. Relative increase of hazard-producing probability. The rates are calculated for each hazard (surge, rain, wind, surge+SLR) and at-least-one hazard (hazard, hazard+SLR) by the end of this century under the SSP5 8.5 scenario. The numbers in green show the change is not statistically significant.

	Surge	Rain	Wind	Hazard	Surge+SLR	Hazard+SLR
Texas	18.6%	72.1%	47.6%	28.6%	185.5%	104.4%
Louisiana	19.1%	67.5%	52.7%	25.5%	135.7%	93.6%
Mississippi-Alabama	13.5%	118.1%	73.3%	27.8%	210.2%	153.7%
West Florida	14.3%	120.3%	72.7%	22.6%	217.1%	158.8%
East Florida	25.3%	81.7%	50.7%	39.3%	234.3%	134.8%
Georgia	28.9%	125.4%	68.9%	48.3%	364.9%	223.0%
South Carolina	23.3%	100.0%	62.2%	37.9%	379.1%	210.7%
North Carolina	24.9%	112.7%	53.8%	36..9%	327.2%	199.0%

Table S4. Same as Table S4, but for the SSP2 4.5 scenario

	Surge	Rain	Wind	Hazard	Surge+SLR	Hazard+SLR
Texas	24.5%	55.1%	49.1%	23.5%	179.8%	101.0%
Louisiana	15.9%	48.0%	44.4%	18.2%	123.0%	83.9%
Mississippi-Alabama	7.8%	77.1%	52.2%	16.9%	211.7%	154.4%
West Florida	17.7%	59.2%	49.3%	22.5%	113.6%	86.8%
East Florida	18.1%	61.2%	45.8%	30.6%	224.9%	128.7%
Georgia	3.1%	71.0%	45.5%	21.2%	352.9%	215.9%
South Carolina	-5.9%	45.9%	36.0%	7.8%	348.8%	193.6%
North Carolina	7.0%	68.7%	34.2%	17.8%	318.4%	192.7%