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Supplemental Material

Assessing United States County-Level Exposure for Research on Tropical Cyclones and Human Health

G. Brooke Anderson, Joshua Ferreri, Mohammad Al-Hamdan, William Crosson, Andrea Schumacher, Seth Guikema, Steven Quiring, Dirk Eddelbuettel, Meilin Yan, and Roger D. Peng

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Figure S4. Differences in the counties assessed as "exposed", based on different exposure metrics, for a sample of storms. These sample storms were selected as the storms with largest extent (as measured by the number of counties exposed based on any metric) from each of the clusters shown in the Jaccard heatmap in the main text (Figure 7; a similar map for Hurricane Ivan in 2004 is shown in Figure 6 of the main text).

Table S1. Reasons behind the choices of thresholds for binary exposure classifications, as well as discussion of some other reasonable choices. These are provided for the three exposure metrics for which our database includes continuous data, and so a threshold is selected to determine binary exposure based on the metric. This table provides reasoning for the choice of threshold used in this paper as well as guidance on other thresholds that could be considered, depending on the hypothesized pathways for an epidemiological study.

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Table S3. Agreement between wind-based exposure assessment and a distance-based proxy of storm exposure for tropical cyclones with at least 200 counties assessed as exposed based on at least one exposure metric considered in this study. Numbers are out of 2,396 counties in the study area (states in the eastern half of the US; Figure 1 of the main text). Exposure assessment is based on the thresholds given in Table 1 of the main text. The Jaccard index shown in Figure 7 of the main text is calculated as the value in the second column divided by the sum of numbers in the second through fourth columns. Storms are ordered based on the number of counties assessed as exposed to at least one of these two exposure metrics.

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Table S5. Agreement between flood-based exposure assessment and a distance-based proxy of storm exposure for tropical cyclones with at least 200 counties assessed as exposed based on at least one exposure metric considered in this study. Numbers are out of 2,396 counties in the study area (states in the eastern half of the US; Figure 1 of the main text). Exposure assessment is based on the thresholds given in Table 1 of the main text. The Jaccard index shown in Figure 7 of the main text is calculated as the value in the second column divided by the sum of numbers in the second through fourth columns. Storms are ordered based on the number of counties assessed as exposed to at least one of these two exposure metrics.

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References

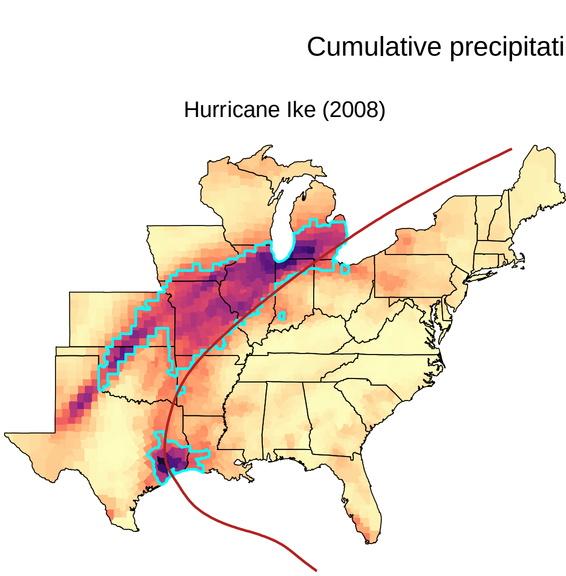


Figure S1: Examples of storms where some storm-related rainfall occurred 500 km or further from the storm's track. The red line on each map shows the track of the storm. The color of each county in the map gives the cumulative precipitation in the county from two days before to one day after the storm's closest approach (in mm). The blue outline identifies the collection of counties that were classified as "exposed" based on the rainfall exposure criteria (Table 1 of main text), which includes the constraint that the storm must have come within 500 km of the county.

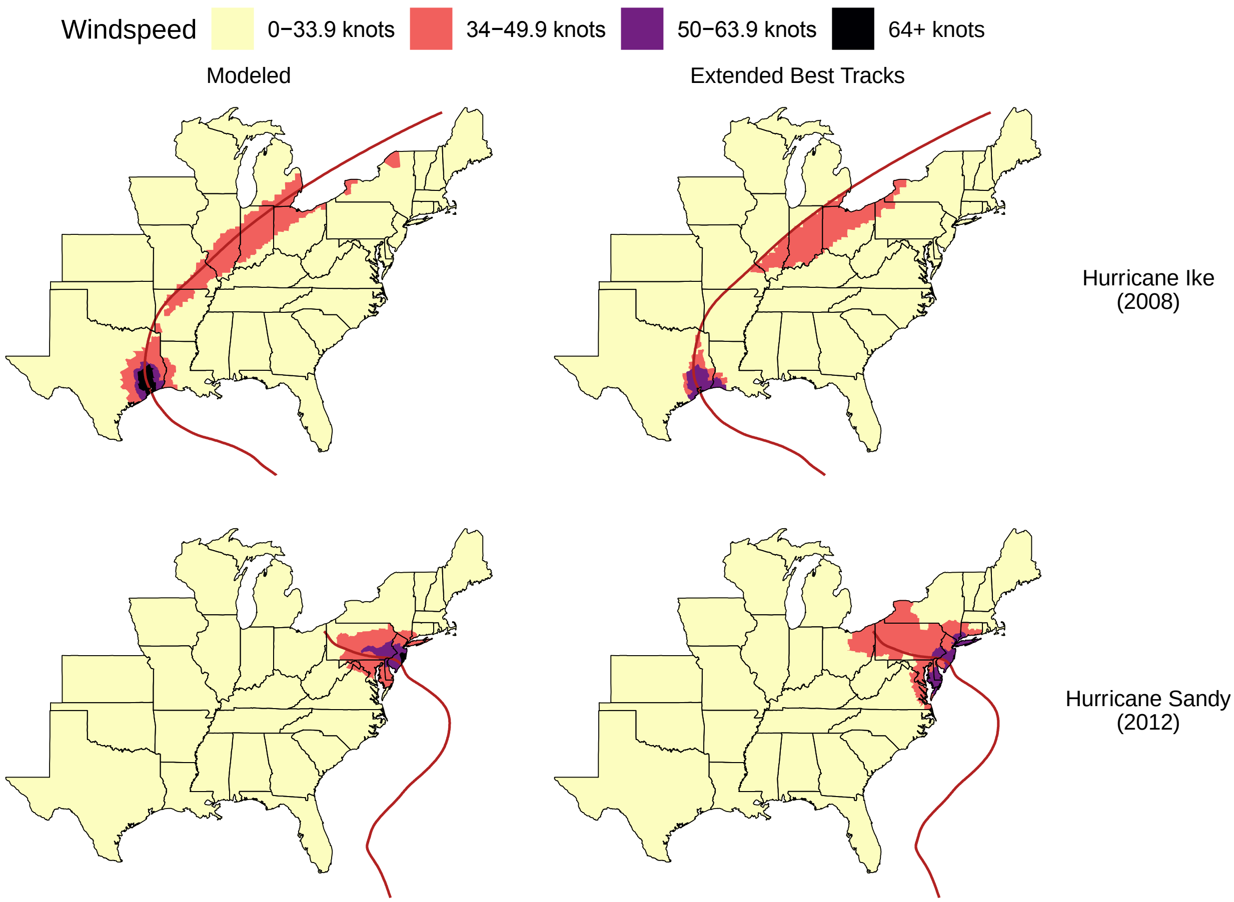


Figure S2: Comparison of county-level estimates of peak sustained surface wind for Hurricane Ike in 2008 (top) and Hurricane Sandy in 2012 (bottom). Each map shows the estimated peak sustained surface wind classification (<34 kt; 34–49.9 kt; 50–63.9 kt; ≥64 kt) for each study county. The maps labelled "Modeled" (left) shows the classifications based on modeled peak sustained surface wind, which were included in the open-source data as the main wind metric and used in further analysis in this research. The maps labelled "Extended Best Tracks" (right) show classifications based on the wind radii given in HURDAT2 (included as a secondary wind metric in the open-source data). The red lines show the storms' tracks.

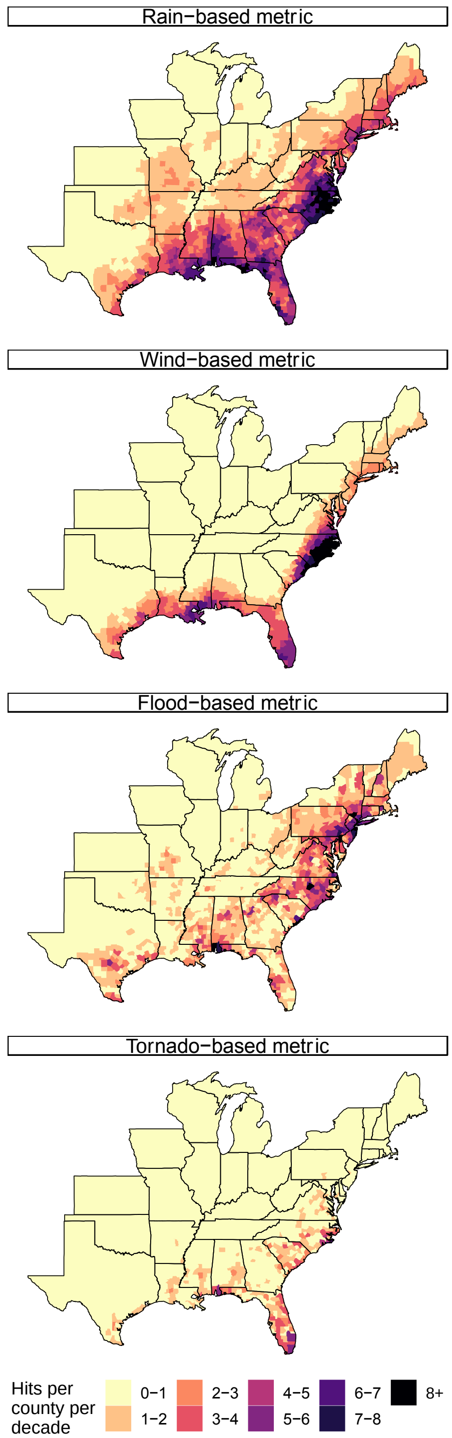
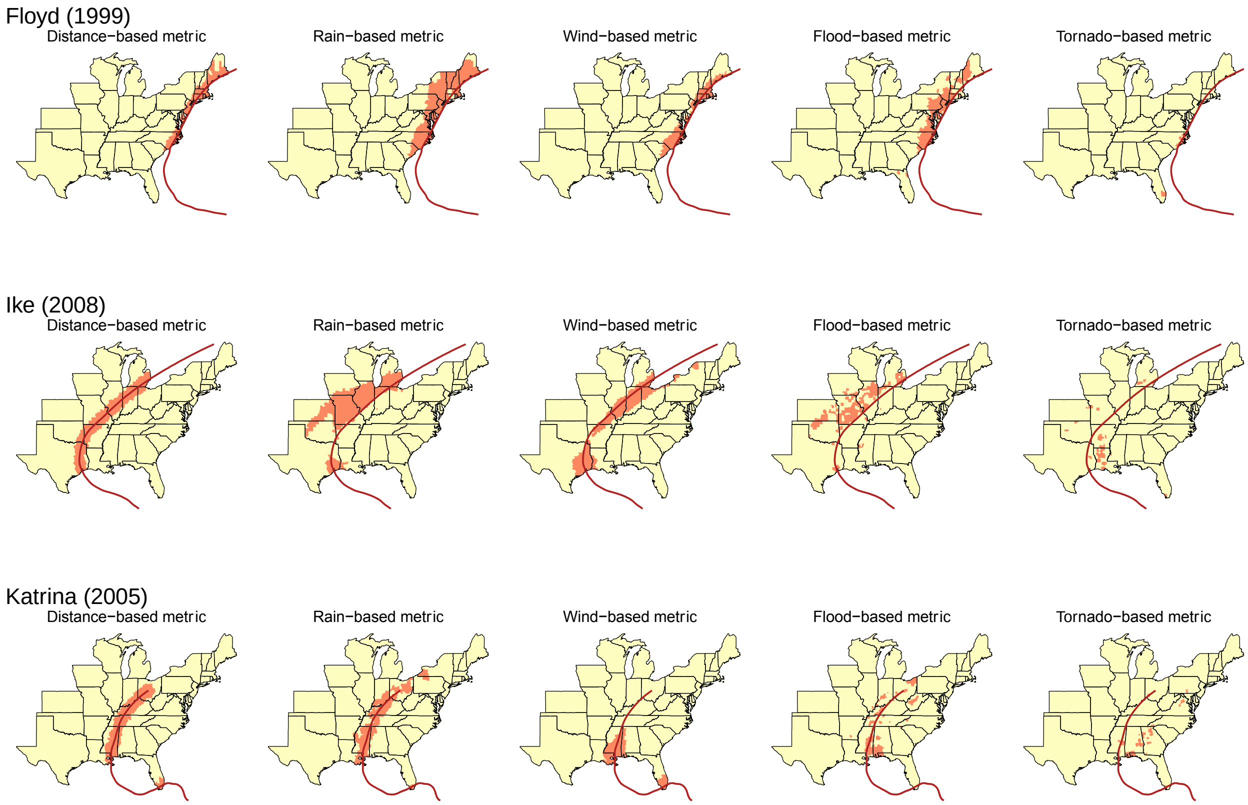


Figure S3: Average number of storm exposures per decade in U.S. counties for each single-hazard exposure metric, limited analysis to years for which data on all five exposures were available (1996–2011). The criteria behind each of the five metrics is given in Table 1 of the main text.



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Metric	Threshold choice
Distance	Distance-based exposure was determined based on whether the storm track came within 100 km of county population mean center. This threshold has been used in prior research as a proxy for exposure to hazards from the storm (e.g., Grabich et al. 2015a). Tropical cyclones vary dramatically in size: US tropical cyclones have been observed with radii to maximum winds as small as 20 km and as large as 200 km (Mallin and Corbett 2006; Quiring et al. 2011), and dangerous winds can extend beyond these maximum winds. One study assessed county-level risk and exposure based on a three-tiered definition, with primary counties being those closest to the storm track on either side, secondary counties being adjacent to primary counties, and tertiary counties adjacent to secondary counties, which resulted in an average distance radius of 120 km on either side of the storm track (Czajkowski et al. 2011). Other distance thresholds that could be considered include 60 km and 30 km, both of which have been used in previous research (Grabich et al. 2015a; Grabich et al. 2015b; Currie and Rossin-Slater 2013). However, based on the results presented in the main manuscript, hazard-based metrics should often be used directly rather than a distance-based proxy.
Rain	Rain-based exposure was determined based on whether the county had cumulative rainfall of ≥75 mm over the period from two days before to one day after the storm's closest approach and the storm track came within 500 km of the county population mean center. One recent study has highlighted that a two-year rainfall value (which is the median annual maximum rainfall) for a location can provide a useful threshold in identifying rainfall events with potential for societal impacts (Bosma et al. 2020). For some of the more northern, inland communities included in our study area, the two-year rainfall value for two-, three- and four-day windows is in the 65–85 mm range. For example, Pittsburgh, PA, has two- year rainfall values of 69 mm for a two-day window, 74 mm for a three-day window, and 78 mm for a four-day window (US NOAA 2020), consistent with the 75 mm threshold we selected for exposure classification in this paper. However, other thresholds, particularly higher thresholds, would be reasonable in some cases. For example, the two-year rainfall values tend to be much higher in counties of the study area that are further south and close to the coast. The two-year rainfall value for Miami for a three-day window, for example is 180 mm (US NOAA 2020). A variety of definitions have been used previously to identify both extreme or heavy rain (whether associated with a tropical cyclone or not) and tropical cyclone–associated rain. In defining precipitation associated with tropical cyclones, studies have used thresholds of 12.5 mm per day as a metric of regions of "moderately heavy" rainfall (Zhou and Matyas 2017) and, as a lower threshold, a lower limit of 10 mm of total storm precipitation—in conjunction with proximity to the storm's center—in identifying tropical cyclone precipitation events at a location (Feldmann et al. 2019). Other definitions of extreme rain events—including but not limited to tropical cyclone–associated rainfall—are higher than the threshold we use here—for example, one paper defined extreme rain events as cases in which a gauge reported 125 mm or

	more of rain in 24 hours (Schumacher and Johnson 2006). Studies have also used definitions that are relative to the norms for a given location (e.g., 24 hour rainfall totals over the 50-year return value for the location, which the part of the US east of the Rocky Mountains range from 3.5 in [89 mm] to 13 in [330 mm]) (Schumacher and Johnson 2006; Schumacher and Johnson 2005; Stevenson and Schumacher 2014).
Wind	Wind-based exposure was determined based on whether modeled storm-associated peak sustained surface wind was ≥34 kts at the county's population mean center. This threshold is being applied to local winds for each county, and it represents the threshold for gale-force winds on the Beaufort wind scale. This limit is used as the outer limit in measuring storm size through the US National Hurricane Center's wind radii for tropical cyclone forecasts (Cangialosi and Landsea 2016). Other thresholds could be selected based on other points on the Beaufort scale—for example, ≥48 kts for capturing storm-force winds or ≥64 kts for capturing hurricane-force winds. As a note, hurricane-force winds will be rarely experienced for counties, as it will likely only be observed for very severe storms and even for those, only for counties near the storm's landfall. Many presentations of the Beaufort wind scale include descriptions of the conditions that winds in each category would produce both over land and at sea.

Table S2: Precipitation correlation during all versus high-precipitation events. The same sample of counties is shown as in Figure 2 of the main text. Events are cases where a tropical cyclone came within 500 km of each of the listed counties. The number of total events gives the sum of all points shown on the main plot for the county in Figure 2 of the main text. The Spearman correlation for all events is the same as that shown in Figure 2 of the main text. High-precipitation events are those for which storm-associated precipitation was 75 mm or higher based on at least one of the two measures considered in this comparison (NLDAS-2 reanalysis data and ground-based stations). The Spearman correlation between these two precipitation data sources is given for these high-precipitation events in the last column of the table.

	All events		High-precipitation events	
County	Number of events	Spearman correlation	Number of events	Spearman correlation
Miami-Dade, FL	65	0.94	18	0.49
Harris, TX	38	0.93	10	0.84
Mobile, AL	50	0.95	20	0.57
Orleans, LA	55	0.89	13	0.95
Fulton, GA	48	0.95	12	0.69
Charleston, SC	73	0.94	17	0.65
Wake, NC	61	0.98	12	0.84
Baltimore, MD	33	0.92	5	0.70
Philadelphia, PA	52	0.96	6	0.77

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Table S3: Agreement between wind-based exposure assessment and a distance-based proxy of storm exposure for tropical cyclones with at least 200 counties assessed as exposed based on at least one exposure metric considered in this study. Numbers are out of 2,396 counties in the study area (states in the eastern half of the US; Figure 1 of the main text). Exposure assessment is based on the thresholds given in Table 1 of the main text. The Jaccard index shown in Figure 7 of the main text is calculated as the value in the second column divided by the sum of numbers in the second through fourth columns. Storms are ordered based on the number of counties assessed as exposed to at least one of these two exposure metrics.

Storm	Exposed for both distance metric and wind metric	Exposed for distance metric but unexposed for wind metric	Exposed for wind metric but unexposed for distance metric	Unexposed for both distance metric and wind metric
Frances (2004)	44	277	13	2,062
Cindy (2005)	17	304	4	2,071
Dennis (2005)	18	274	26	2,078
Ike (2008)	166	67	82	2,081
Ivan (2004)	29	255	27	2,085
Jeanne (2004)	41	256	7	2,092
Allison (2001)	21	266	0	2,109
Isidore (2002)	29	239	7	2,121
Katrina (2005)	66	175	32	2,123
Gordon (2000)	11	244	6	2,135
Fay (2008)	54	198	7	2,137
Gustav (2008)	36	198	23	2,139
Bertha (1996)	179	4	62	2,151
Danny (1997)	45	184	12	2,155
Arlene (2005)	4	232	0	2,160
Bill (2005)	19	211	0	2,166
Dennis (1999)	17	183	13	2,183
Hanna (2008)	135	57	12	2,192
Isabel (2003)	105	42	56	2,193
Ernesto (2006)	93	99	4	2,200
Helene (2000)	18	174	0	2,204
Rita (2005)	26	139	20	2,211
Fran (1996)	46	105	30	2,215
Earl (1998)	133	36	11	2,216
Floyd (1999)	124	15	40	2,217
Irene (2011)	114	6	46	2,230
Lee (2011)	34	110	0	2,252
Josephine (1996)	62	61	3	2,270
Hermine (2010)	22	101	1	2,272
Bonnie (2004)	0	109	0	2,287
Frances (1998)	15	47	0	2,334

Table S4: Agreement between rain-based exposure assessment and a distance-based proxy of storm exposure for tropical cyclones with at least 200 counties assessed as exposed based on at least one exposure metric considered in this study. Numbers are out of 2,396 counties in the study area (states in the eastern half of the US; Figure 1 of the main text). Exposure assessment is based on the thresholds given in Table 1 of the main text. The Jaccard index shown in Figure 7 of the main text is calculated as the value in the second column divided by the sum of numbers in the second through fourth columns. Storms are ordered based on the number of counties assessed as exposed to at least one of these two exposure metrics.

Storm	Exposed for both distance metric and rain metric	Exposed for distance metric but unexposed for rain metric	Exposed for rain metric but unexposed for distance metric	Unexposed for both distance metric and rain metric
Frances (2004)	207	114	257	1,818
Ivan (2004)	124	160	288	1,824
Isidore (2002)	134	134	186	1,942
Ike (2008)	113	120	213	1,950
Dennis (2005)	48	244	124	1,980
Fay (2008)	72	180	163	1,981
Jeanne (2004)	144	153	113	1,986
Lee (2011)	106	38	230	2,022
Gustav (2008)	126	108	137	2,025
Allison (2001)	106	181	67	2,042
Bill (2003)	110	120	117	2,049
Cindy (2005)	78	243	11	2,064
Floyd (1999)	129	10	170	2,087
Katrina (2005)	195	46	58	2,097
Danny (1997)	82	147	54	2,113
Rita (2005)	64	101	103	2,128
Gordon (2000)	5	250	7	2,134
Arlene (2005)	39	197	23	2,137
Dennis (1999)	90	110	56	2,140
Ernesto (2006)	124	68	63	2,141
Irene (2011)	119	1	106	2,170
Hanna (2008)	100	92	33	2,171
Hermine (2010)	44	79	102	2,171
Fran (1996)	89	62	73	2,172
Earl (1998)	72	97	38	2,189
Bertha (1996)	103	80	20	2,193
Helene (2000)	28	164	11	2,193
Frances (1998)	27	35	139	2,195
Josephine (1996)	94	29	77	2,196
Bonnie (2004)	56	53	56	2,231
Isabel (2003)	88	59	17	2,232

Table S5: Agreement between flood-based exposure assessment and a distance-based proxy of storm exposure for tropical cyclones with at least 200 counties assessed as exposed based on at least one exposure metric considered in this study. Numbers are out of 2,396 counties in the study area (states in the eastern half of the US; Figure 1 of the main text). Exposure assessment is based on the thresholds given in Table 1 of the main text. The Jaccard index shown in Figure 7 of the main text is calculated as the value in the second column divided by the sum of numbers in the second through fourth columns. Storms are ordered based on the number of counties assessed as exposed to at least one of these two exposure metrics.

Storm	Exposed for both distance metric and flood metric	Exposed for distance metric but unexposed for flood metric	Exposed for flood metric but unexposed for distance metric	Unexposed for both distance metric and flood metric
Ivan (2004)	79	205	238	1,874
Frances (2004)	103	218	122	1,953
Dennis (2005)	21	271	87	2,017
Jeanne (2004)	80	217	77	2,022
Allison (2001)	68	219	71	2,038
Cindy (2005)	52	269	29	2,046
Ike (2008)	48	185	101	2,062
Isidore (2002)	30	238	64	2,064
Fay (2008)	23	229	60	2,084
Bill (2003)	39	191	65	2,101
Gustav (2008)	36	198	57	2,105
Katrina (2005)	47	194	47	2,108
Gordon (2000)	7	248	19	2,122
Arlene (2005)	11	225	29	2,131
Danny (1997)	39	190	31	2,136
Floyd (1999)	100	39	120	2,137
Fran (1996)	46	105	77	2,168
Dennis (1999)	38	162	19	2,177
Ernesto (2006)	44	148	27	2,177
Hanna (2008)	52	140	26	2,178
Helene (2000)	13	179	20	2,184
Bertha (1996)	27	156	17	2,196
Irene (2011)	108	12	79	2,197
Rita (2005)	4	161	26	2,205
Earl (1998)	4	165	11	2,216
Lee (2011)	18	126	36	2,216
Hermine (2010)	16	107	40	2,233
Isabel (2003)	39	108	9	2,240
Josephine (1996)	27	96	32	2,241
Bonnie (2004)	10	99	29	2,258
Frances (1998)	8	54	23	2,311

Table S6: Agreement between tornado-based exposure assessment and a distance-based proxy of storm exposure for tropical cyclones with at least 200 counties assessed as exposed based on at least one exposure metric considered in this study. Numbers are out of 2,396 counties in the study area (states in the eastern half of the US; Figure 1 of the main text). Exposure assessment is based on the thresholds given in Table 1 of the main text. The Jaccard index shown in Figure 7 of the main text is calculated as the value in the second column divided by the sum of numbers in the second through fourth columns. Storms are ordered based on the number of counties assessed as exposed to at least one of these two exposure metrics.

Storm	Exposed for both distance metric and tornado metric	Exposed for distance metric but unexposed for tornado metric	Exposed for tornado metric but unexposed for distance metric	Unexposed for both distance metric and tornado metric
Frances (2004)	6	315	66	2,009
Ivan (2004)	36	248	55	2,057
Cindy (2005)	27	294	11	2,064
Jeanne (2005)	13	284	22	2,077
Dennis (2005)	0	292	6	2,098
Allison (2001)	14	273	9	2,100
Katrina (2005)	8	233	38	2,117
Fay (2008)	15	237	26	2,118
Isidore (2002)	1	267	6	2,122
Ike (2008)	4	229	31	2,132
Gordon (2000)	1	254	8	2,133
Gustav (2008)	9	225	28	2,134
Bill (2003)	4	226	22	2,144
Arlene (2005)	2	234	7	2,153
Danny (1997)	9	220	4	2,163
Rita (2005)	8	157	41	2,190
Dennis (1999)	0	200	1	2,195
Helene (2000)	5	187	6	2,198
Ernesto (2006)	2	190	1	2,203
Hanna (2008)	0	192	1	2,203
Bertha (1996)	13	170	4	2,209
Earl (1998)	8	161	7	2,220
Fran (1996)	1	150	4	2,241
Lee (2011)	14	130	11	2,241
Isabel (2003)	0	147	1	2,248
Floyd (1999)	11	128	1	2,256
Hermine (2010)	1	122	12	2,261
Josephine (1996)	7	116	12	2,261
Bonnie (2004)	13	96	22	2,265
Irene (2011)	9	111	0	2,276
Frances (1998)	1	61	10	2,324

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