Assessing United States county-level exposure to tropical storms and investigating the association between tropical storm exposure and community-wide mortality risks

CSU Atmospheric Sciences Colloquium

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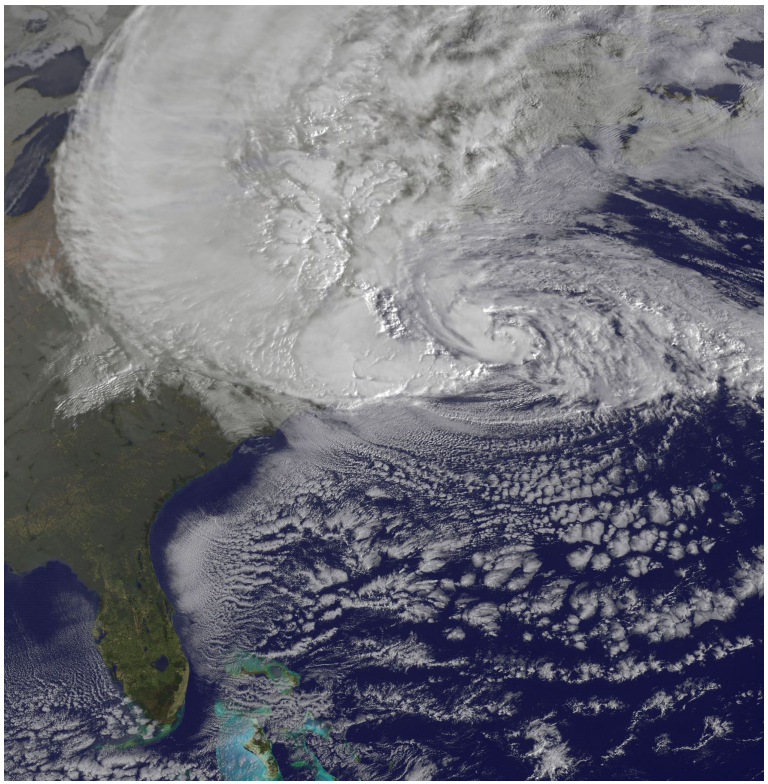
Health risks associated with Hurricane Sandy (2012)



Source: NOAA / NASA GOES Project

Health risks in storm-affected areas

- Change in patterns of emergency department visits (Kim et al. 2016)
- Increased outpatient cases of food and waterborne disease among elderly (Bloom et al. 2016)
- Increased rate of myocardial infarctions (Swerdel et al. 2014)
- Increased hospitalizations for dehydration (Lee et al. 2016)
- Difficulty obtaining medical care, medications, and medical equipment (Davidow et al. 2016)

Hazard-specific tropical storm metrics

Tropical storm hazard metrics

- Distance from the storm
- High winds
- Rainfall
- Storm surge
- Flood events
- Tornado events

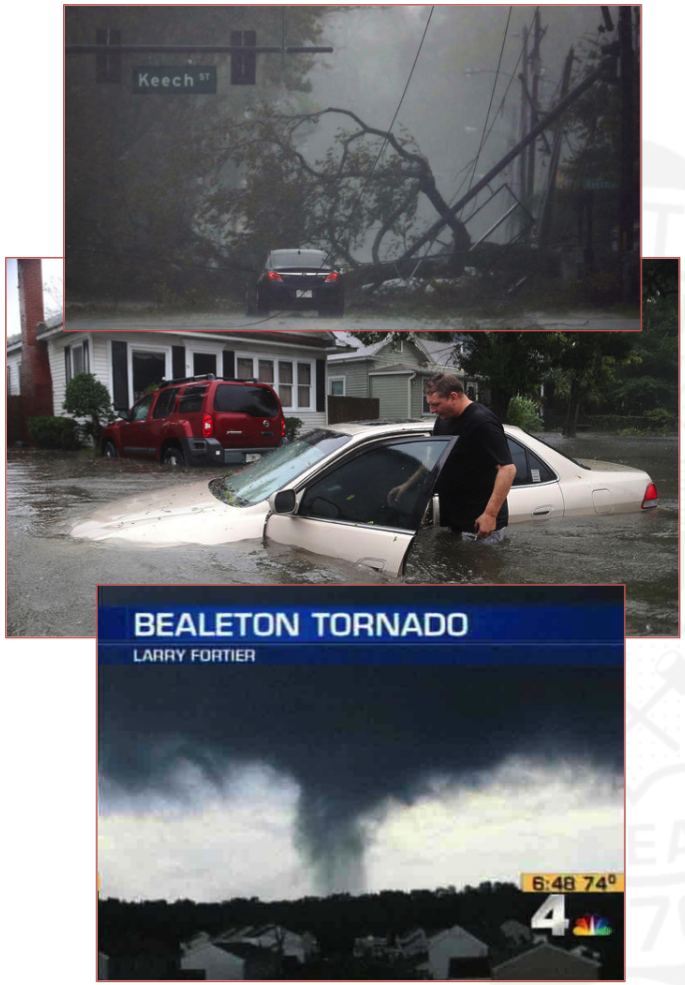


Image sources: Los Angeles Times, NBC

Assessing tropical storm exposure

Challenge for epidemiological research

How should we determine whether a county was exposed to a tropical storm for epidemiological research?

Assessing tropical storm exposure

Challenge for epidemiological research

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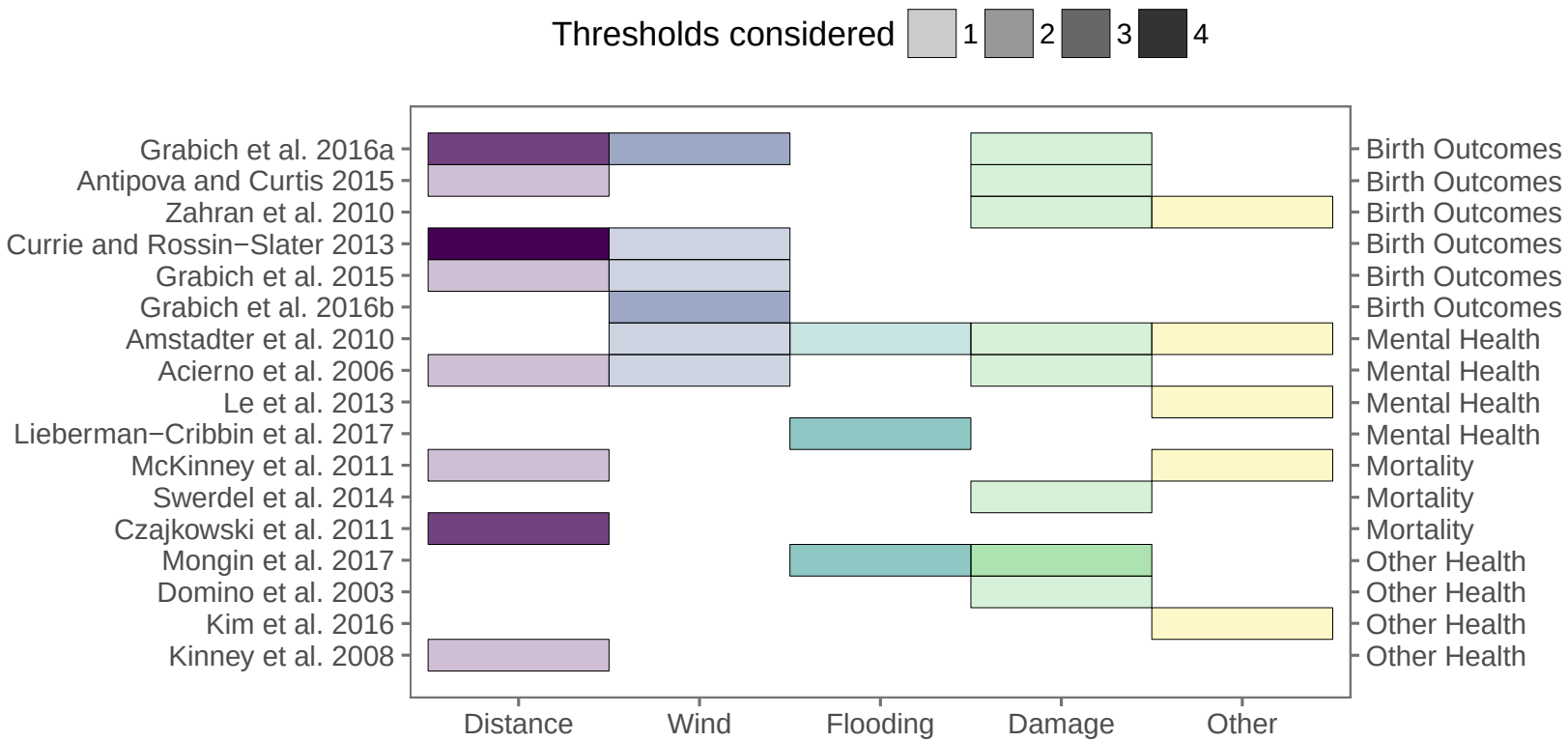
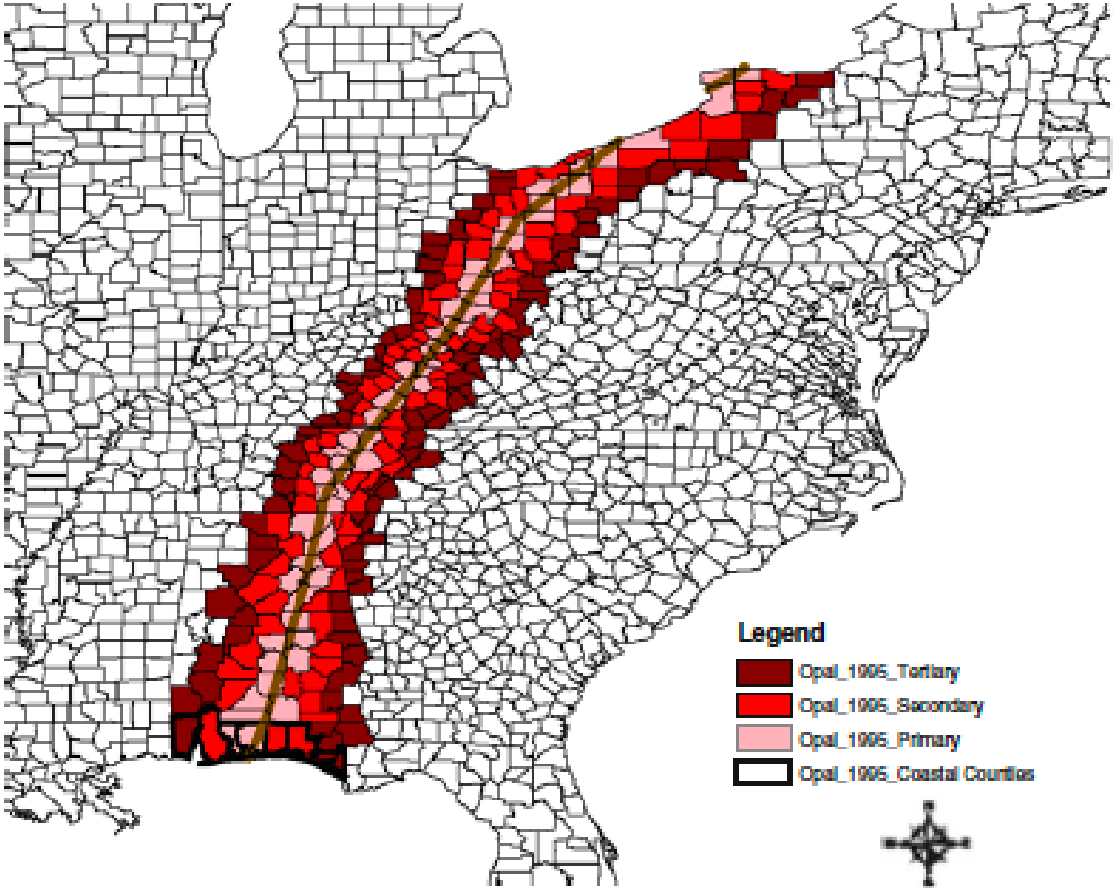


Assessing exposure

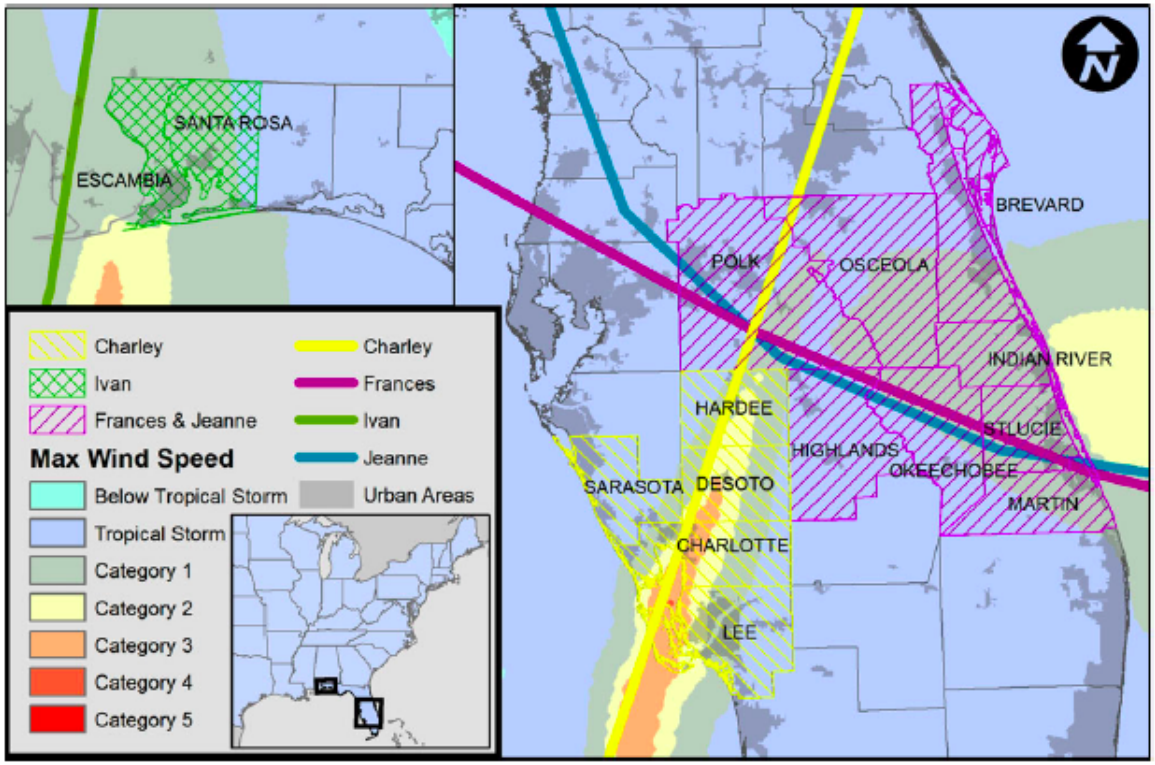


Czajkowski et al. 2011

Example exposure assessment

Czajkowski et al. (2011) classified counties based on distance to storm tracks to study mortality risks.

Assessing exposure



McKinney et al. 2011

Example exposure assessment

McKinney et al. (2011) classified counties based on distance to storm tracks, evacuations, and wind to study mortality risk.

Project aims

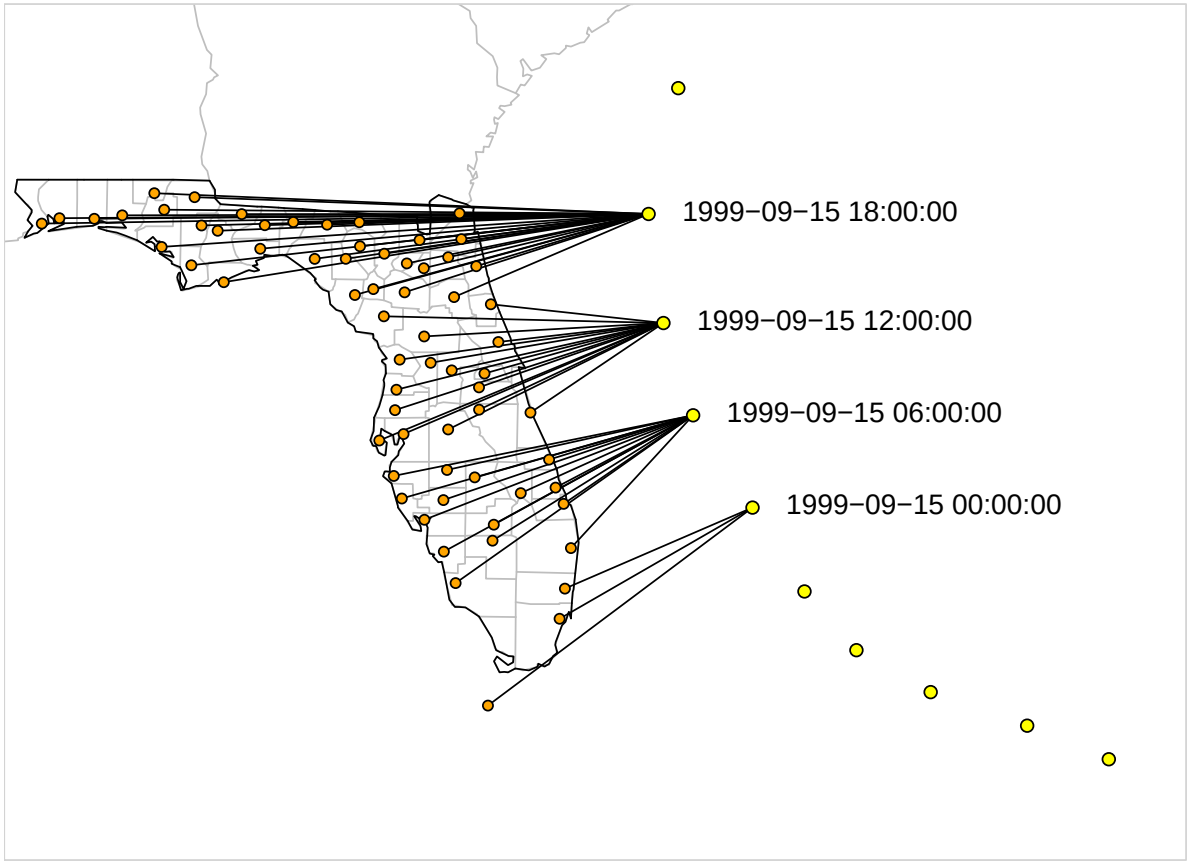
Project aims

- Develop exposure classifications of all U.S. Atlantic basin tropical storms, 1988–2011, based on reasonable measurements of tropical storm hazards
- Make exposure assessments accessible to other researchers for epidemiological and other impact studies
- Assess agreement between hazard-based classifications for (1) storm severity and (2) county-specific classification
- Investigate mortality risks associated with tropical storm exposures in U.S. communities

Assessing exposure to tropical storms

Distance from storm

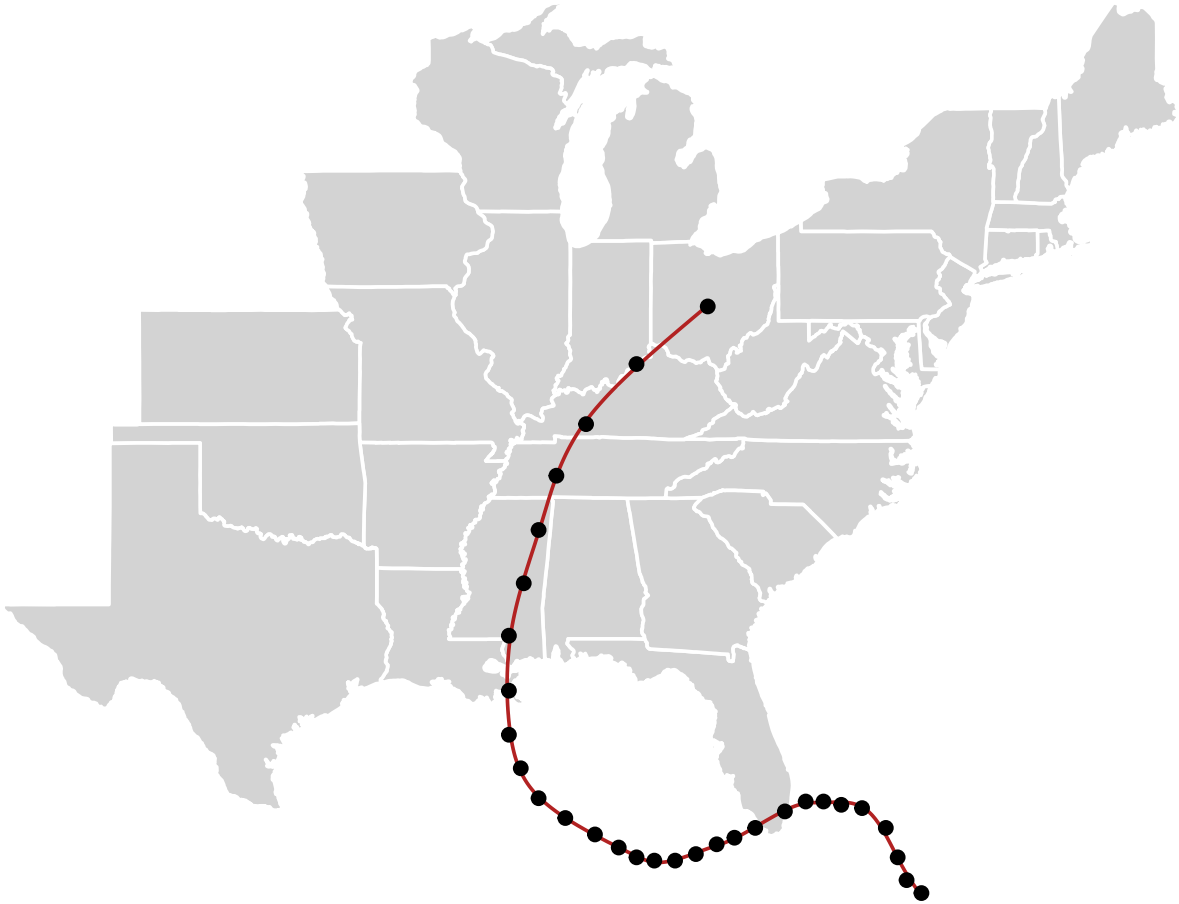
Tropical storm "Best Track" data



Distance metric

We matched storm tracks to county population mean centers to determine the closest approach and date of closest approach of each storm to each county.

Wind exposure

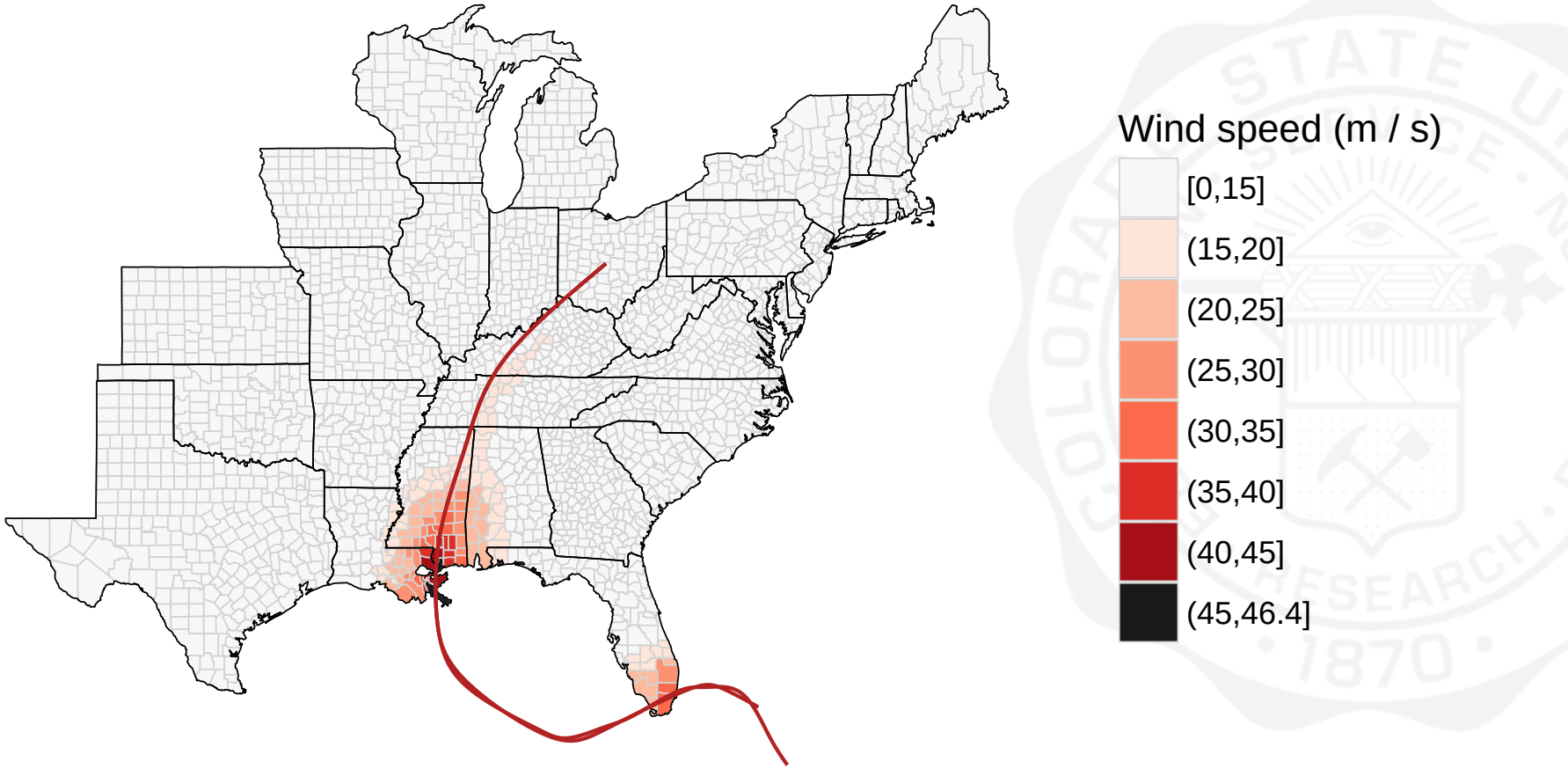


Wind metric

We modeled county winds with a wind model based on a Willoughby et al. paper. This model inputs storm location and maximum wind from best tracks data.

Wind exposure

Modeled winds, Katrina, 2005



Rain exposure

Rain during Tropical Storm Lee

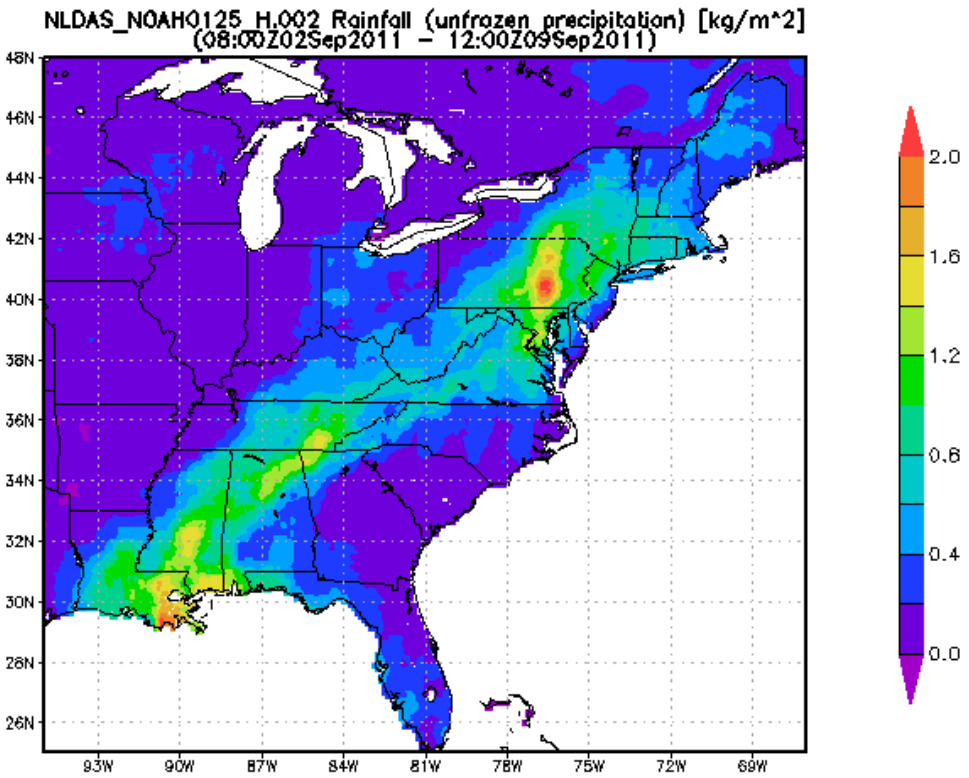


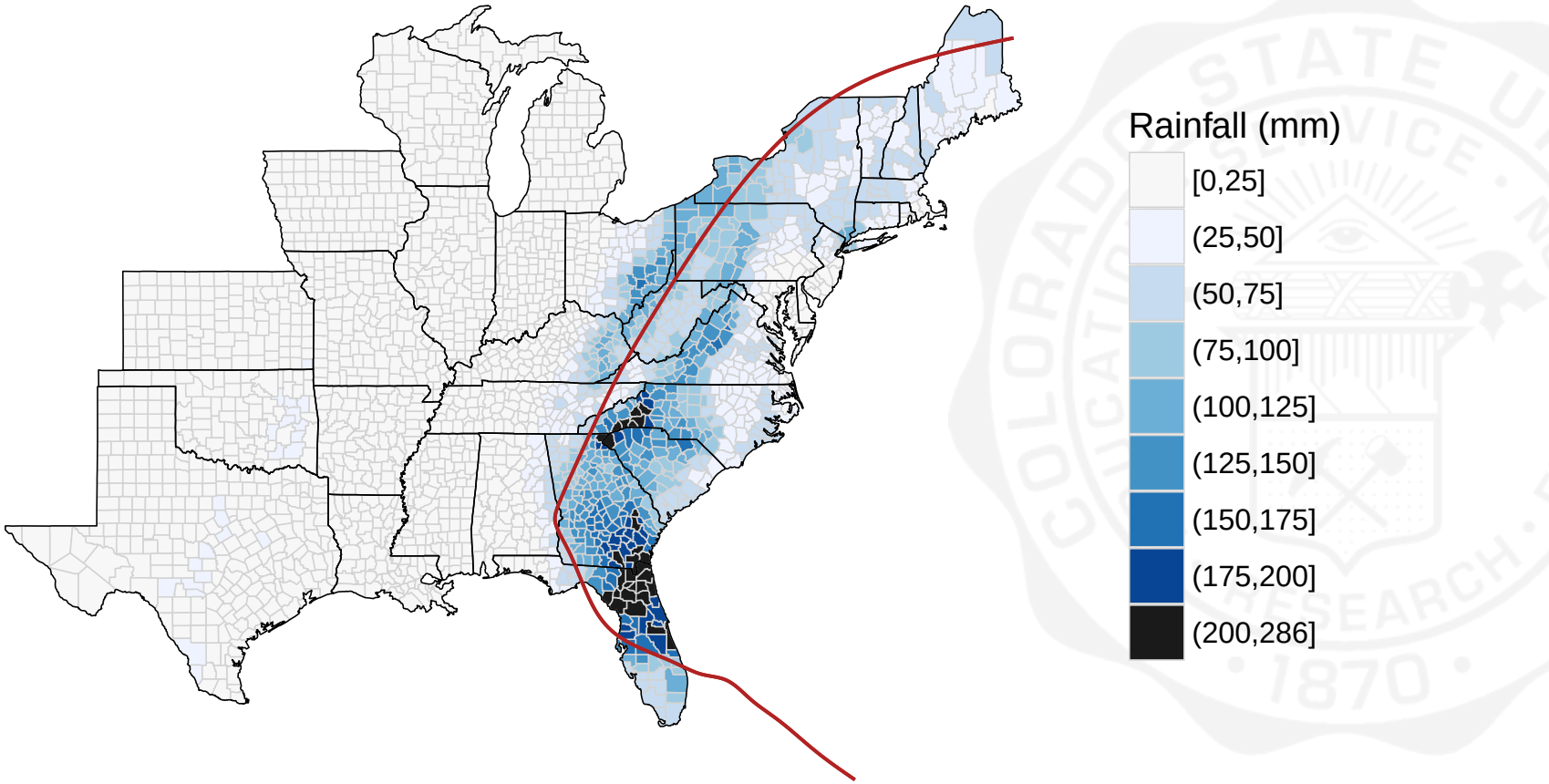
Image source: Goddard Earth Sciences DISC

Rain metric

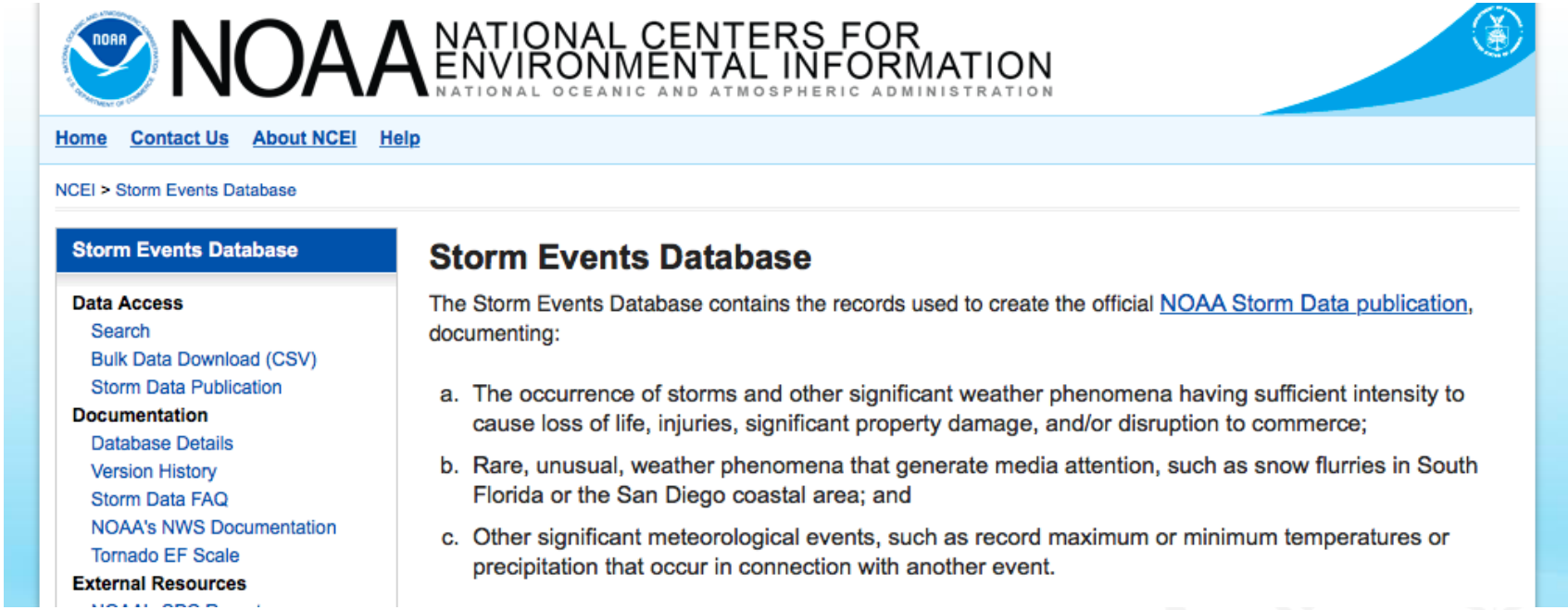
We used NLDAS-2 precipitation data to assess county rainfall. We summed rain from two days before to one day after the storm. We include a distance threshold for the rain metric.

Rain exposure

Rainfall during Frances, 2004



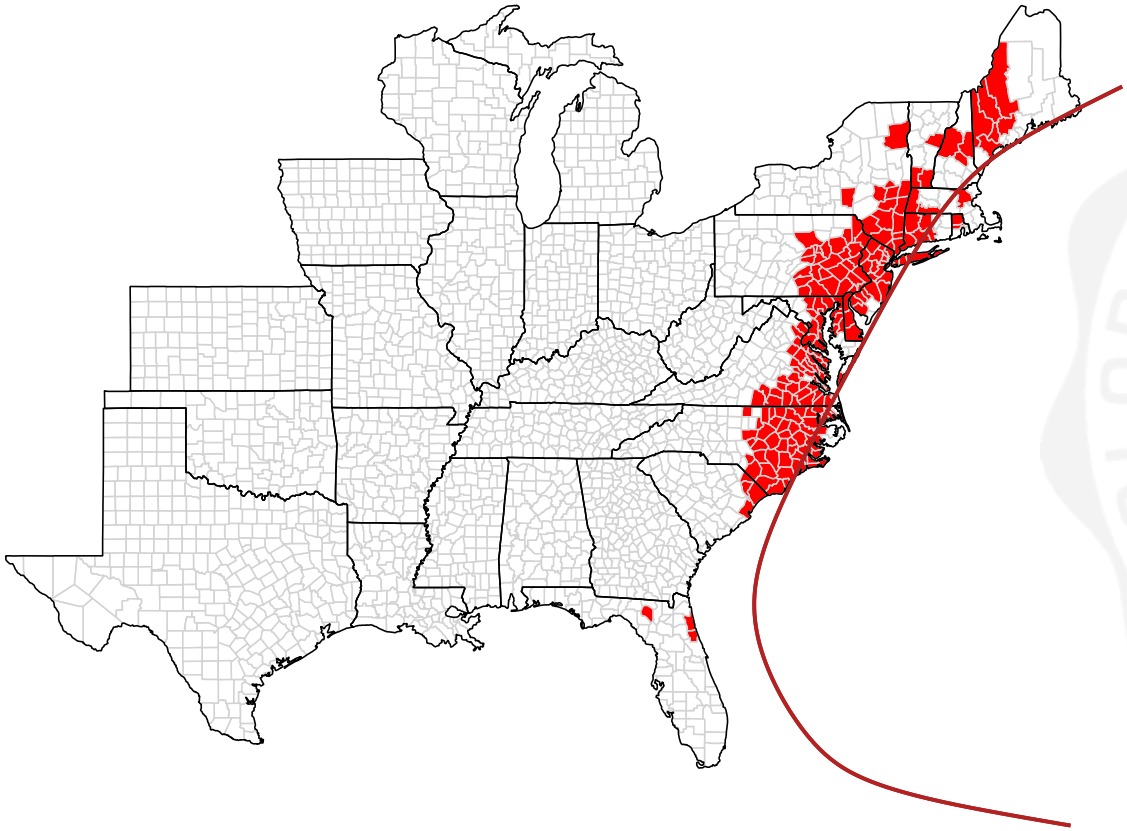
Flood and tornado events



Website: https://www.ncdc.noaa.gov/stormevents/

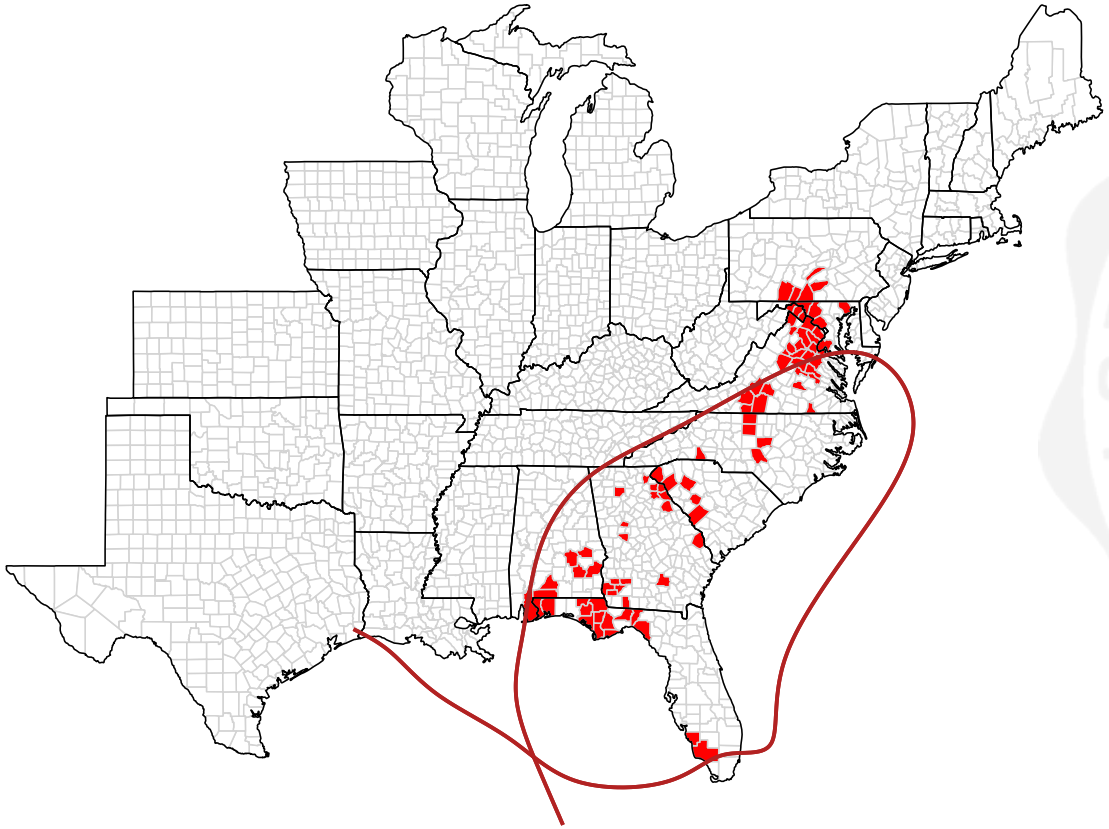
Flood and tornado events

Flood events during Floyd, 1999



Flood and tornado events

Tornado events during Ivan, 2004



Project software

'hurricaneexposure'

Create county-level exposure time series for tropical storms in U.S. counties. Exposure can be determined based on several hazards (e.g., distance, wind, rain), with user-specified thresholds. On CRAN.

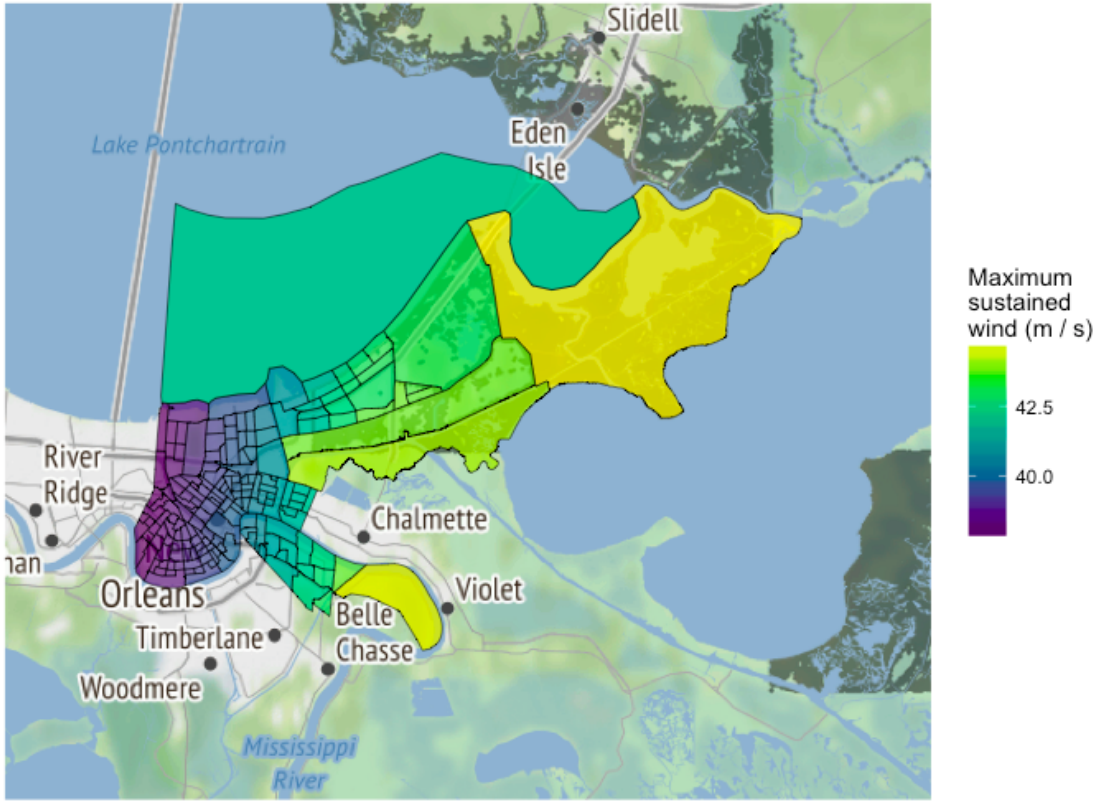
```
county_rain(counties = c("22071", "51700"), rain_limit = 100,
            start_year = 1995, end_year = 2005, dist_limit = 100,
            days_included = c(-1, 0, 1))
```

```
## # A tibble: 4 x 5
##       storm_id  fips closest_date storm_dist tot_precip
##          <chr> <chr>        <chr>      <dbl>      <dbl>
## 1    Bill-2003 22071   2003-06-30   38.78412      141.1
## 2 Charley-2004 51700   2004-08-14   43.01152      136.2
## 3   Cindy-2005 22071   2005-07-06   32.21758      113.2
## 4   Floyd-1999 51700   1999-09-16   46.50729      207.5
```

Project software

'stormwindmodel'

Model storm winds from Best Tracks data at U.S. locations. Includes modeling sustained and gust winds, as well as duration of sustained and gust winds above a specified threshold. On CRAN.



Project software

‘countyweather‘, ‘countyfloods‘

Download weather monitor data through NOAA and USGS APIs by U.S. county. Includes functions to map available monitors / gages for each county. On CRAN.

‘noaastormevents‘

Download and explore listings from the NOAA Storm Events database. Includes the ability to pull events based on a tropical storm, using events listed close in time and distance to the storm’s tracks. On CRAN.

‘countytimezones‘

Convert time-stamps from UTC to local time zones for U.S. counties based on county FIPs. Facilitates merging weather observations with locally measured data, including health outcomes. On CRAN.

Agreement between exposure metrics

Storm exposure

Exposure metric	Criterial for exposure
Distance	County population mean center within 100 km of storm track
Rain	County received 75 mm or more rain over the period from two days before to one day after the storm's closest approach and the storm passed within 500 km of the county
Wind	Modeled wind speed at county's population mean center met or exceeded 15 m / s during the storm
Flood	Flood event listed with a start date within two days of the storm's closest approach and county within 500 km of storm track
Tornado	Tornado event listed with a start date within two days of the storm's closest approach and county within 500 km of storm track

Storm exposure

Exposure metric	Median number of exposed counties (IQR)	Storm with most counties exposed
Distance	62 (12, 156)	Beryl, 1994 (330)
Rain	32 (4, 133)	Frances, 2004 (464)
Wind	26 (3, 65)	Ike, 2008 (355)
Flood	9 (0, 39)	Ivan, 2004 (317)
Tornado	1 (0, 9)	Ivan, 2004 (91)

*Note: Flood and Tornado events only include storms in 1996–2011. All other event listings cover storms in 1988–2011.

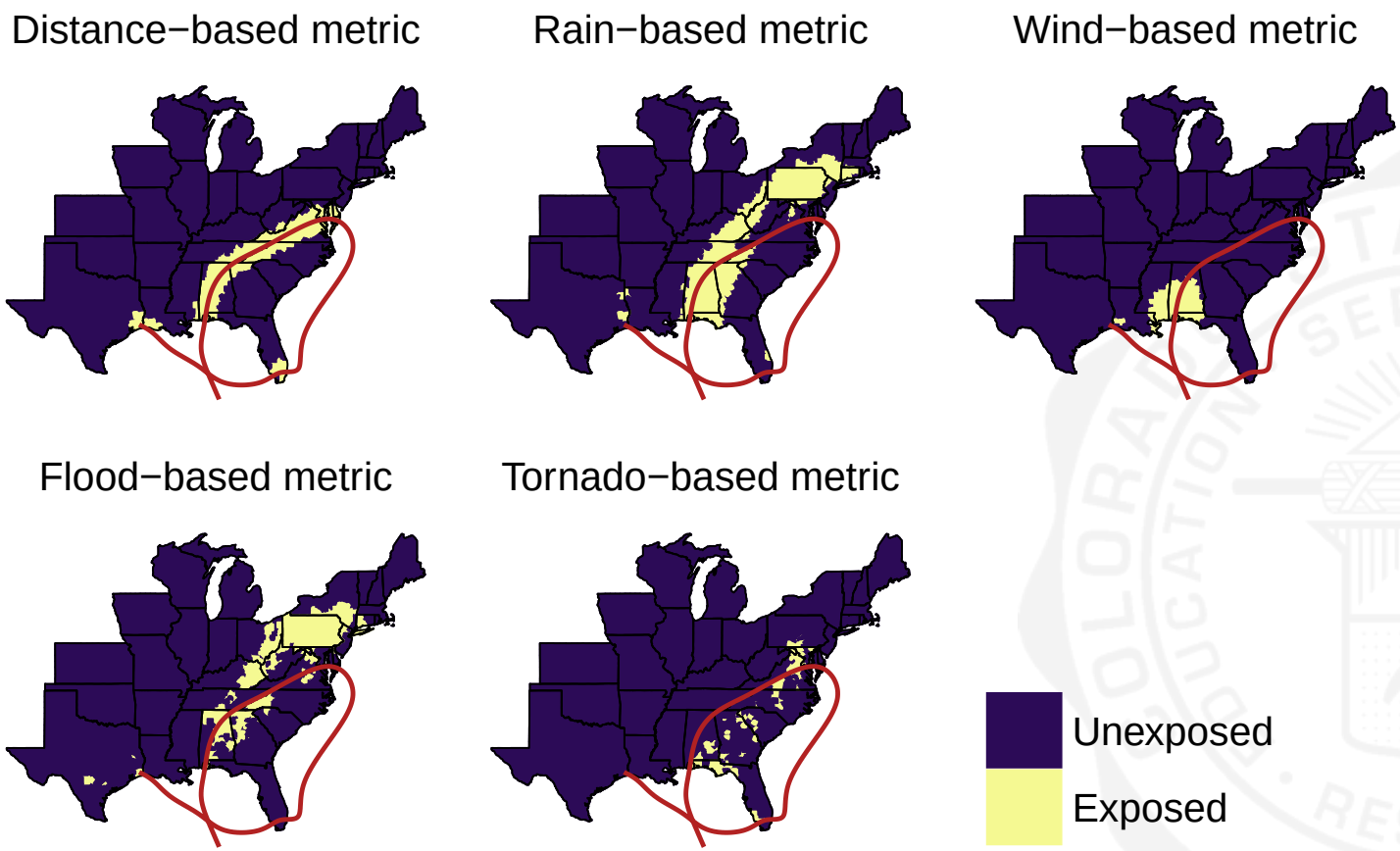
Storm-specific extent

Rank correlation in storm extent for exposure metrics

	Distance	Rain	Wind	Flood	Tornado
Distance	-	-	-	-	-
Rain	0.60	-	-	-	-
Wind	0.52	0.51	-	-	-
Flood	0.35	0.43	0.32	-	-
Tornado	0.32	0.38	0.34	0.62	-

The table gives Kendall's τ for each pair of exposure metrics. All comparisons that include flood or tornado metrics are limited to storms since 1996.

County-level exposure to Hurricane Ivan (2004)



Criteria for exposure classifications: **Distance:** Within 100 kms of storm track. **Rain:** $\geq$ 75 mm of rain total for two days before to one day after storm. **Wind:** Modeled wind of $\geq$ 15 m/s. **Flood, Tornado:** Listed event in NOAA Storm Events database.

County-level agreement in storm exposure

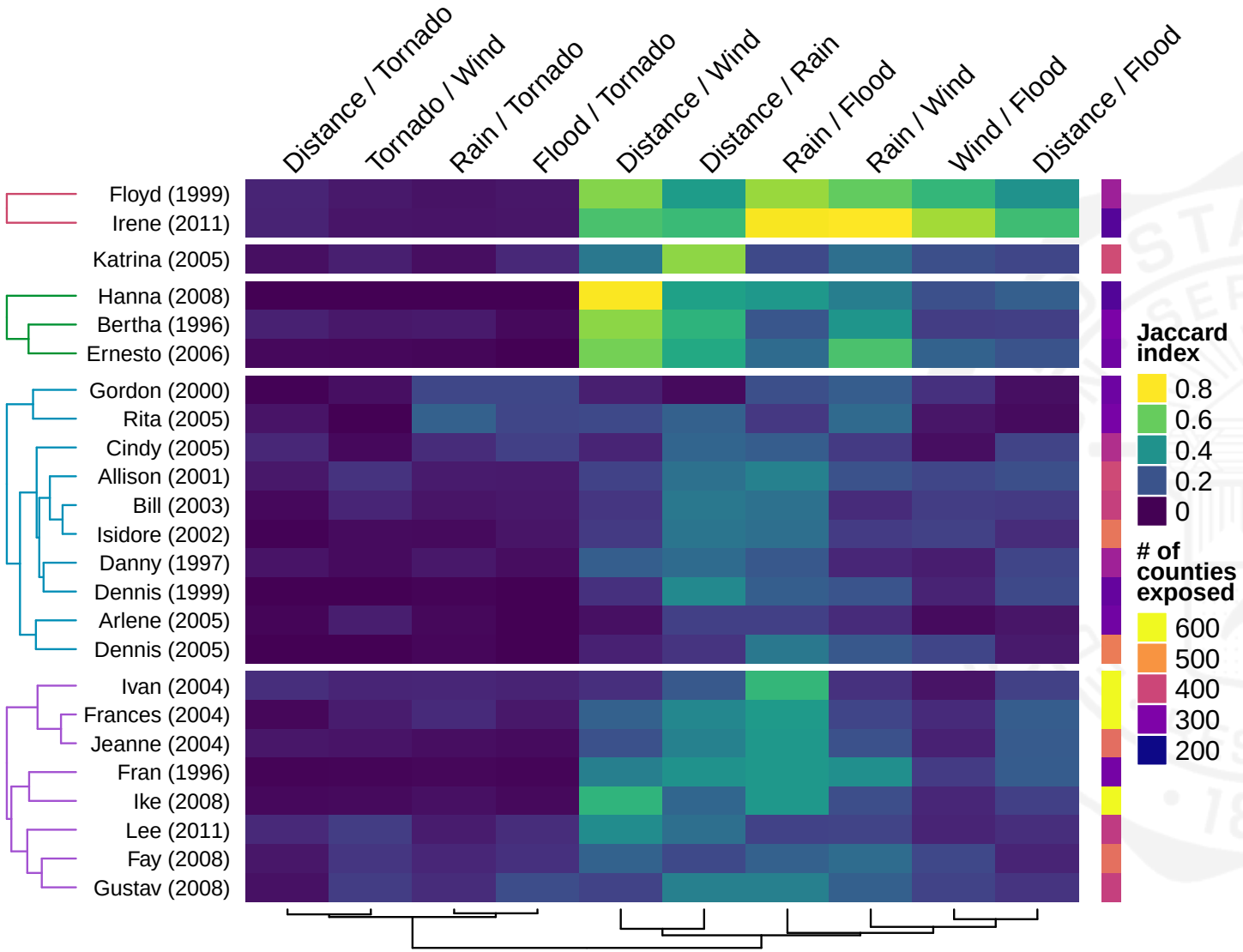
Assessing agreement in county classifications

For each storm and each pair of metrics, we measured the *Jaccard index* as a measure of county-level agreement in exposure classification for a storm:

$$J = \frac{X_1 \cap X_2}{X_1 \cup X_2}$$

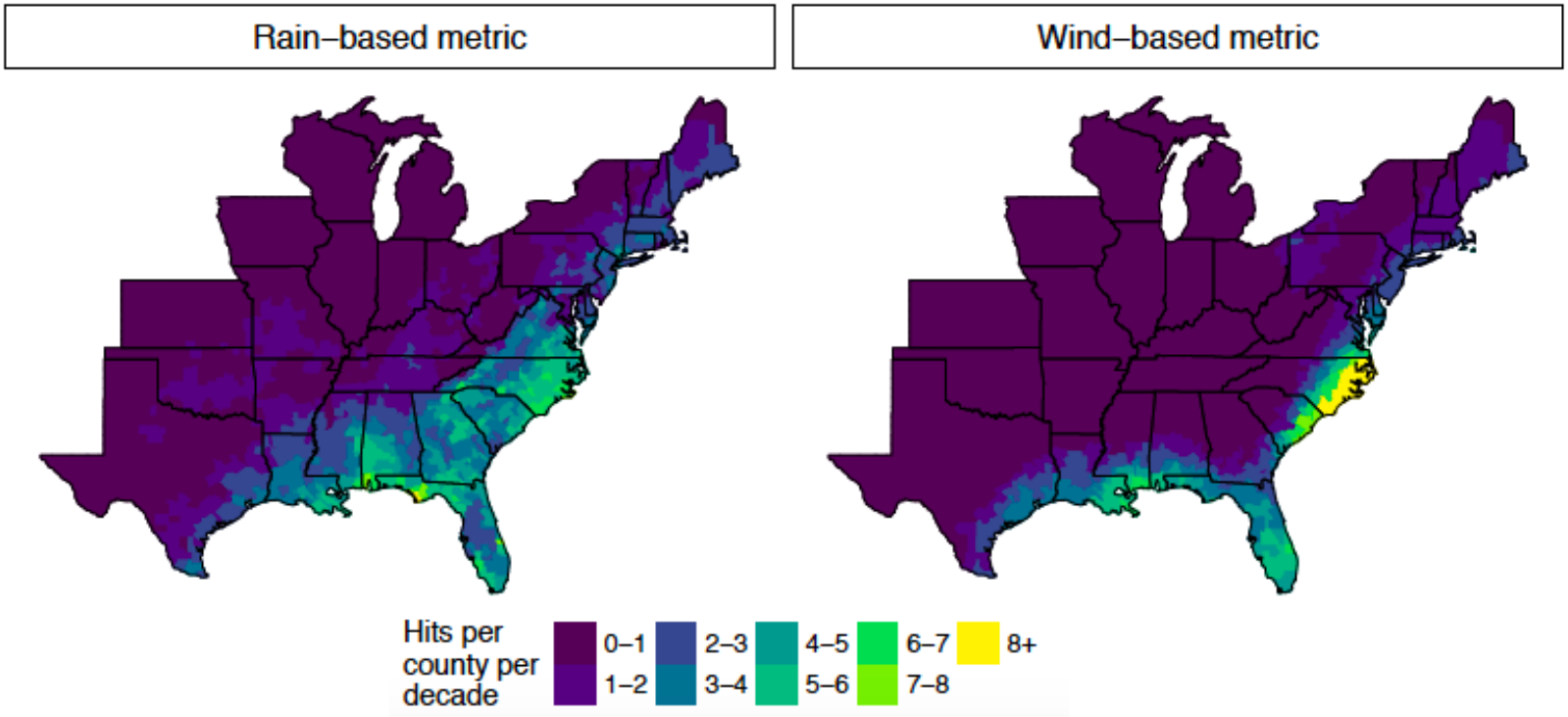
where X_1 is the set of counties exposed to a storm based on the first metric and X_2 is the set of counties exposed to the storm based on the second metric.

County-level agreement in storm exposure



Tropical storm exposure in U.S. counties

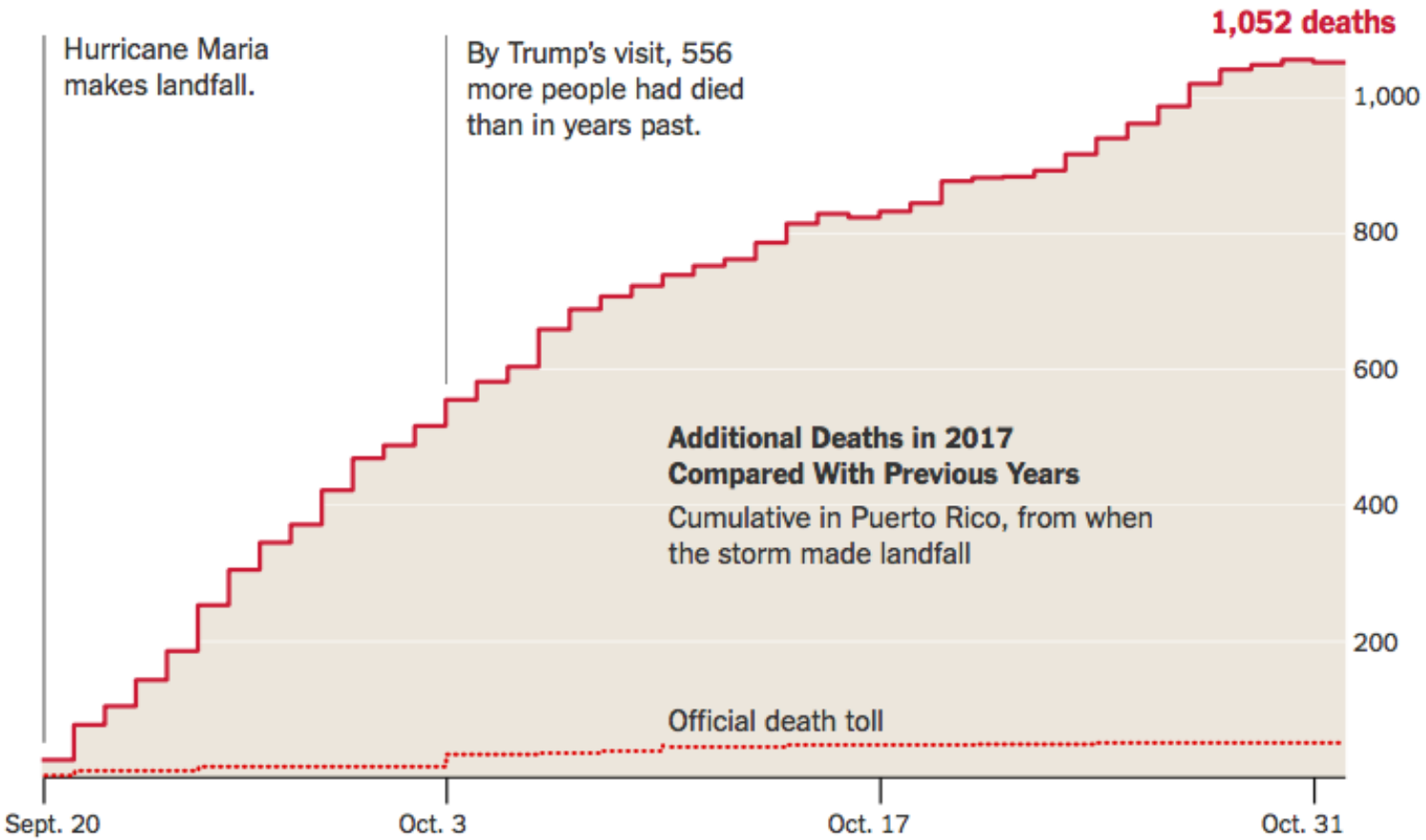
Storm hits per county per decade based on rain (left) and wind (right) exposure metrics.



Criteria for exposure classifications: **Rain:** $\geq$ 75 mm of rain total for two days before to one day after storm. **Wind:** Modeled wind of $\geq$ 15 m/s.

Tropical storms and mortality risks

Hurricane Maria example



Source: The New York Times

Reporting cause of death

CAUSE OF DEATH (See instructions and examples)

32. **PART I.** Enter the chain of events--diseases, injuries, or complications--that directly caused the death. DO NOT enter terminal events such as cardiac arrest, respiratory arrest, or ventricular fibrillation without showing the etiology. DO NOT ABBREVIATE. Enter only one cause on a line. Add additional lines if necessary.

Approximate interval: Onset to death

IMMEDIATE CAUSE (Final disease or condition ---------> resulting in death)
a. Crushed chest
Due to (or as a consequence of):

Sequentially list conditions, if any, leading to the cause listed on line a. Enter the **UNDERLYING CAUSE** (disease or injury that initiated the events resulting in death) **LAST**
b. Shed collapsed during hurricane
Due to (or as a consequence of):
c.
Due to (or as a consequence of):
d.

PART II. Enter other significant conditions contributing to death but not resulting in the underlying cause given in PART I.

Head trauma

33. WAS AN AUTOPSY PERFORMED? ☐ Yes ■ No

34. WERE AUTOPSY FINDINGS AVAILABLE TO COMPLETE THE CAUSE OF DEATH? ☐ Yes ■ No

35. DID TOBACCO USE CONTRIBUTE TO DEATH?
☐ Yes ☐ Probably
■ No ☐ Unknown

36. IF FEMALE:
☐ Not pregnant within past year
☐ Pregnant at time of death
☐ Not pregnant, but pregnant within 42 days of death
☐ Not pregnant, but pregnant 43 days to 1 year before death
☐ Unknown if pregnant within the past year

37. MANNER OF DEATH
☐ Natural ☐ Homicide
■ Accident ☐ Pending Investigation
☐ Suicide ☐ Could not be determined

Source: https://www.cdc.gov/nchs/data/dvs/hurricane_certification.pdf

Reporting cause of death

CAUSE OF DEATH (See instructions and examples)

32. **PART I.** Enter the chain of events--diseases, injuries, or complications--that directly caused the death. DO NOT enter terminal events such as cardiac arrest, respiratory arrest, or ventricular fibrillation without showing the etiology. DO NOT ABBREVIATE. Enter only one cause on a line. Add additional lines if necessary.

Approximate interval: Onset to death

IMMEDIATE CAUSE (Final disease or condition ---------> resulting in death)
a. Acute respiratory failure — 4 hours
Due to (or as a consequence of):

Sequentially list conditions, if any, leading to the cause listed on line a. Enter the **UNDERLYING CAUSE** (disease or injury that initiated the events resulting in death) **LAST**
b. Severe emphysema
Due to (or as a consequence of):
c. Heat and loss of air conditioner power from hurricane
Due to (or as a consequence of):
d.

PART II. Enter other significant conditions contributing to death but not resulting in the underlying cause given in PART I.

33. WAS AN AUTOPSY PERFORMED? ☐ Yes ■ No

34. WERE AUTOPSY FINDINGS AVAILABLE TO COMPLETE THE CAUSE OF DEATH? ☐ Yes ■ No

35. DID TOBACCO USE CONTRIBUTE TO DEATH?
☐ Yes ☐ Probably
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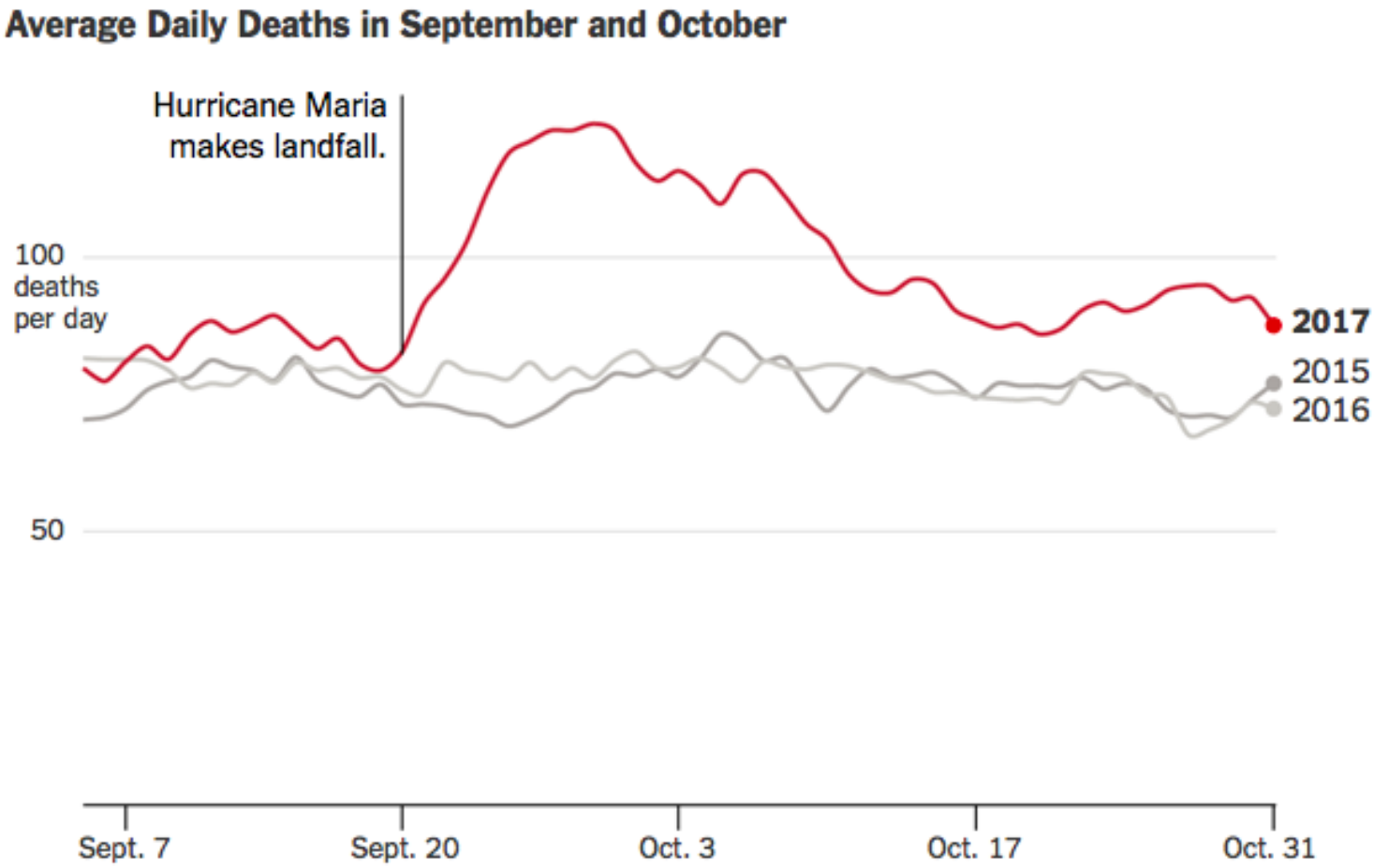
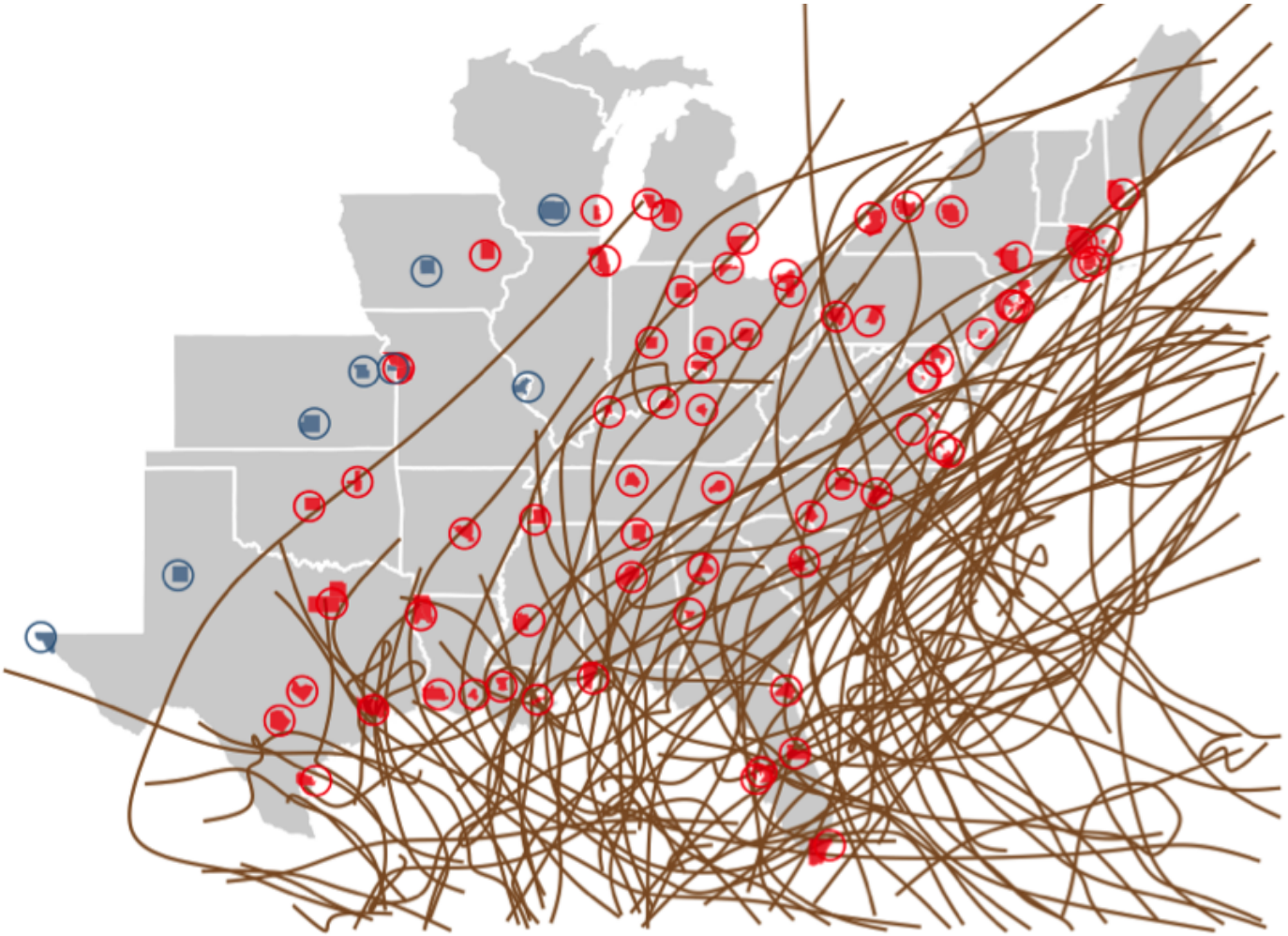
Hurricane Maria example



Source: The New York Times

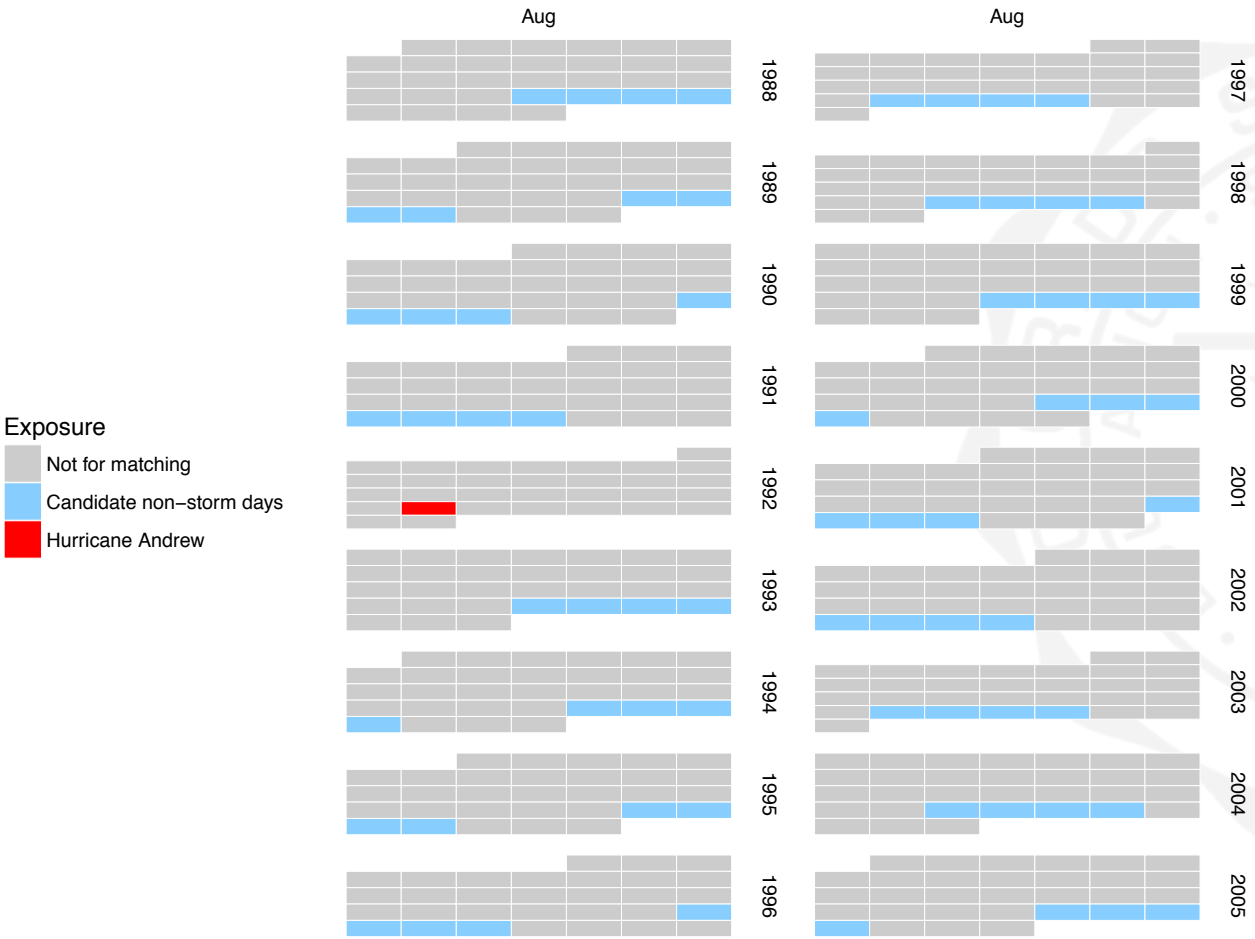
Study storms and communities

Storms and communities considered, 1988–2005



Identifying matched days for comparison

For each storm, we identified matched comparison days in the same community and time of the year.



Relative risk of mortality associated with storm exposure

Relative risk of mortality associated with storm exposure

We aimed to measure the *relative risk (RR)* of mortality during the storm compared to what would have been expected the same days if there had not been a storm:

$$RR = \frac{\#\text{ deaths during storm}}{\text{Expected }\#\text{ of deaths without storm}}$$

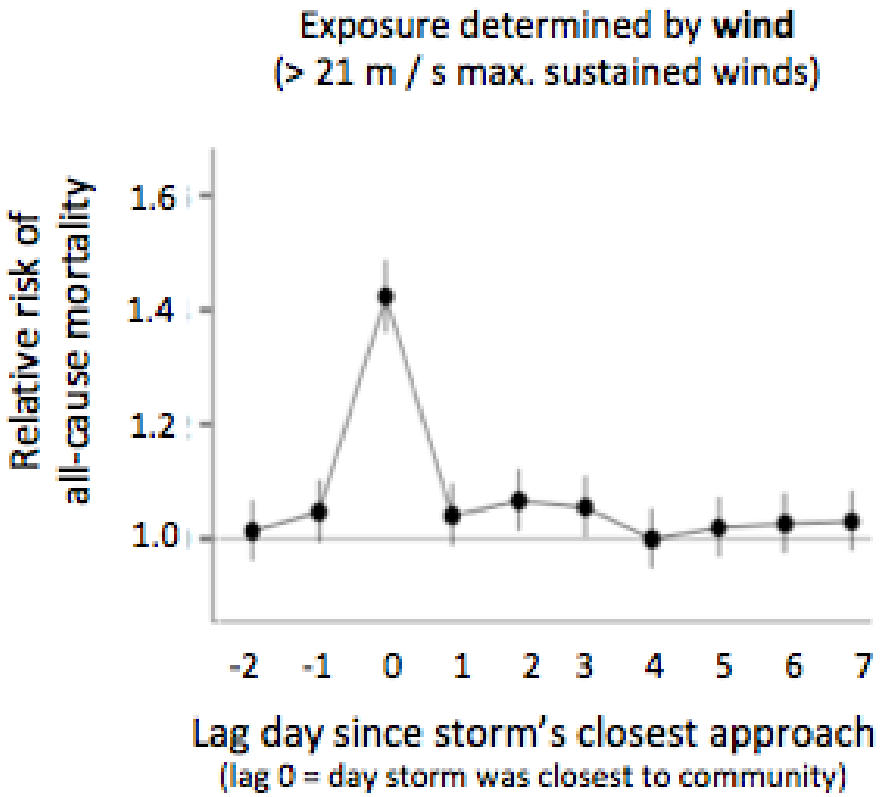
We assessed this relative risk for (1) specific days during the storm period (two days before to seven days after storm's closest approach) and (2) the total storm period.

Relative risk of mortality during storms

Relative risks of mortality associated with tropical storm exposures, as determined by maximum windspeed > 21 m / s

Cause of death	RR on closest day	RR over storm period
All-cause	1.42 (1.36, 1.49)	1.90 (1.58, 2.29)
Cardiovascular	1.15 (1.06, 1.24)	1.30 (0.97, 1.76)
Respiratory	1.13 (0.92,1.38)	1.54 (0.70, 3.39)
Accidental	12.03 (10.87, 13.32)	161.41 (61.62, 422.80)

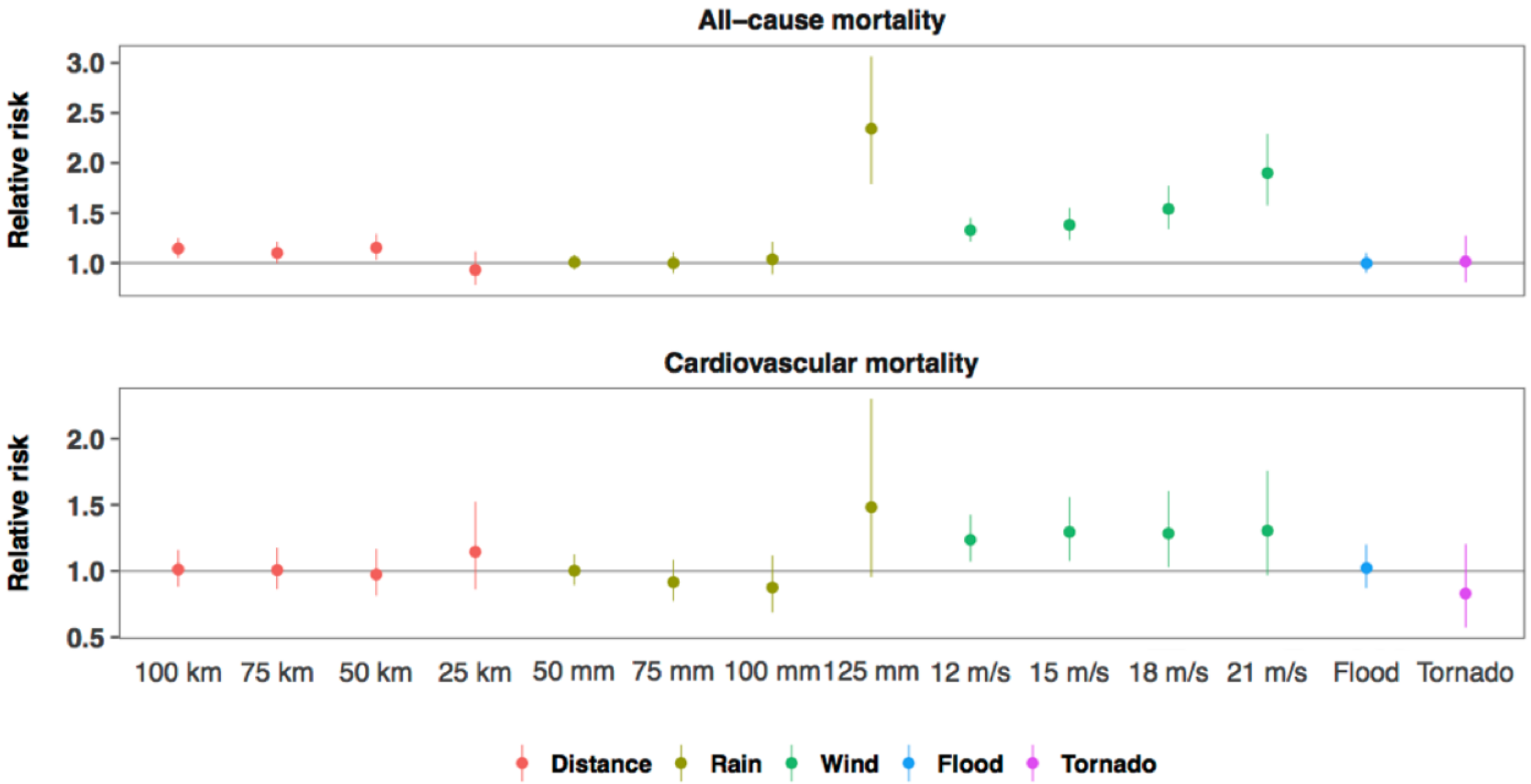
Mortality risks by day during storm period



Risks by day

- For all-cause deaths, RRs were highest on storm's closest day
- There was some evidence of elevated risk before and after the storm
- Lag patterns were similar for cardiovascular and accidental deaths

Mortality risk by exposure metric



Continuing / future work

- Improving flood exposure metric
- Improving wind model for inland locations
- Influence of most notable storms on mortality risk estimates
- Effect modification of power outages
- Hospitalization impacts among Medicare beneficiaries

Acknowledgements

Funding

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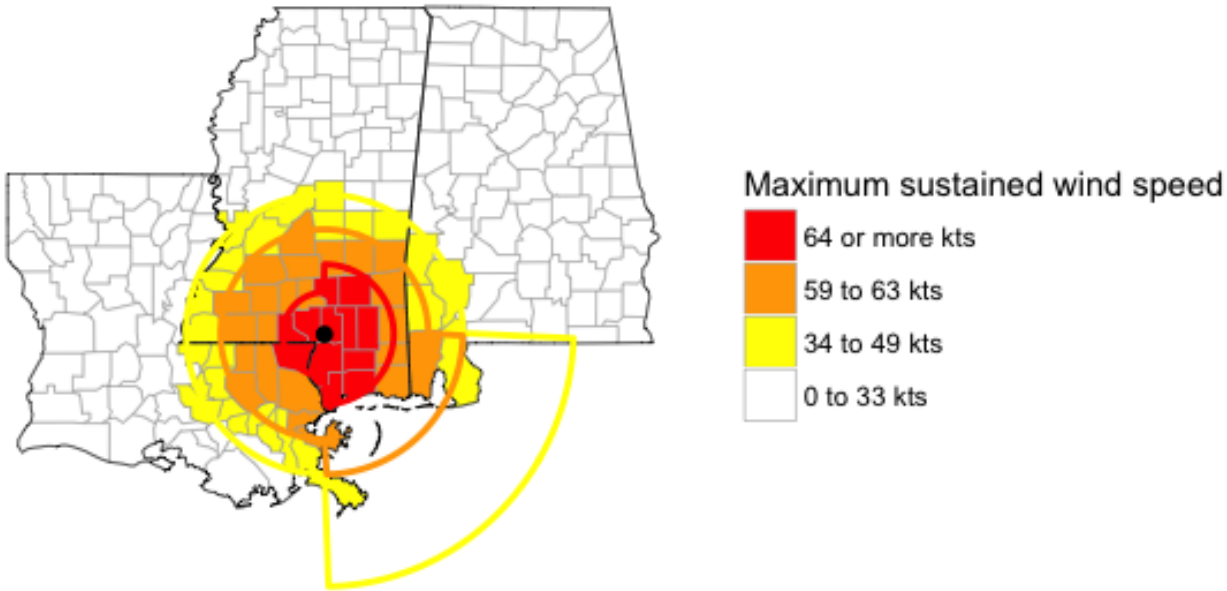
Collaborators

Meilin Yan, Joshua Ferreri, Ander Wilson, Roger Peng, Dirk Eddelbuettel, Mohammad Al-Hamdan, William Crosson, Andrea Schumacher, Seth Guikema, and Steven Quiring collaborated on research and software shown here.

Wind exposure

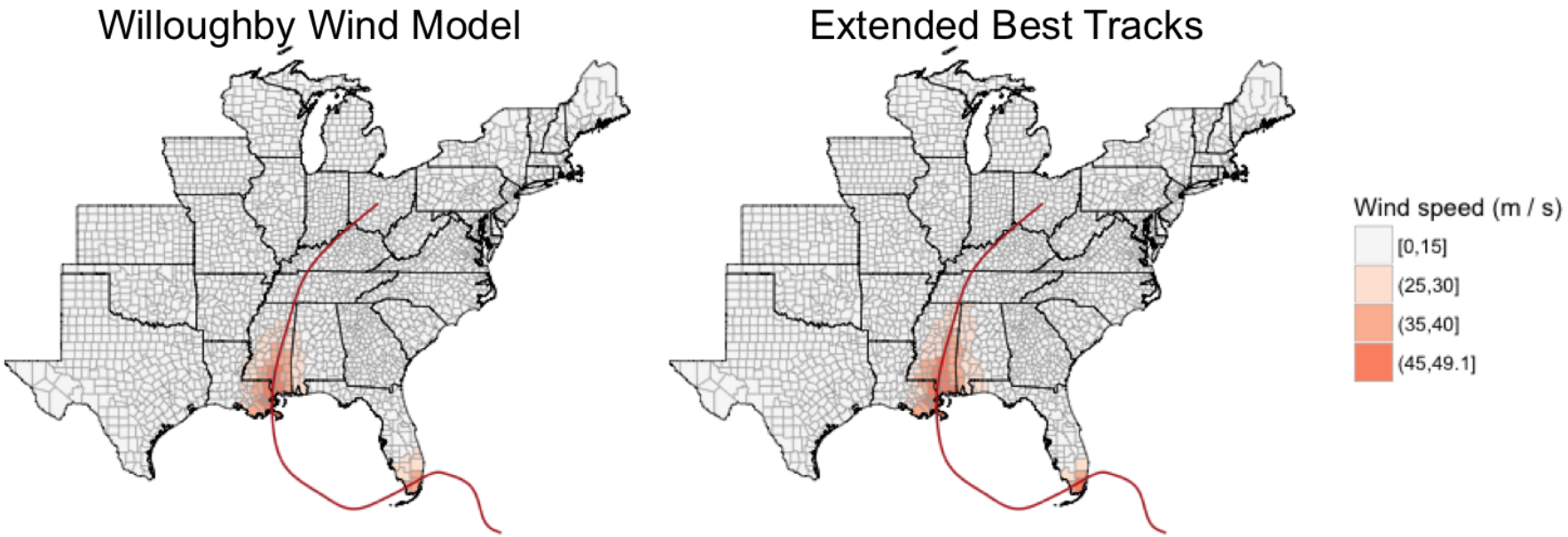
Assessment

To assess results of the storm wind model, we compared modeled results with wind radii from the Extended Best Tracks for each storm.



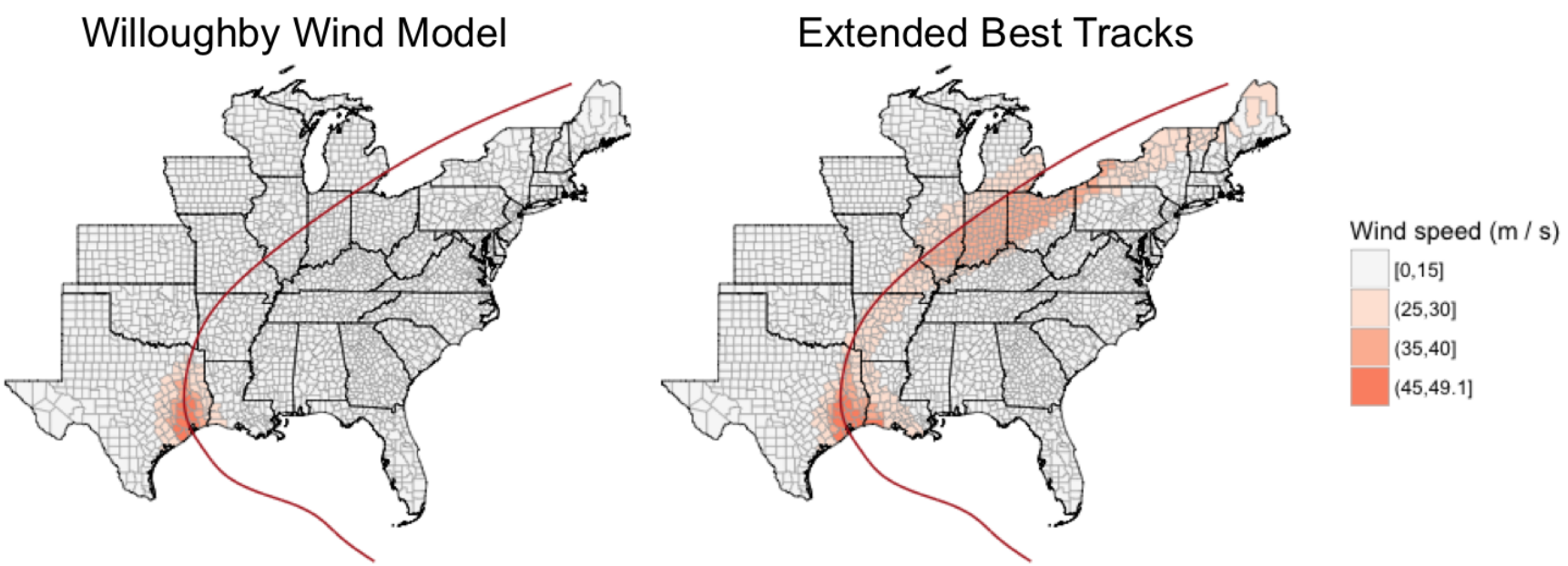
Wind exposure

Comparison of modeled wind versus wind radii, Katrina, 2005



Wind exposure

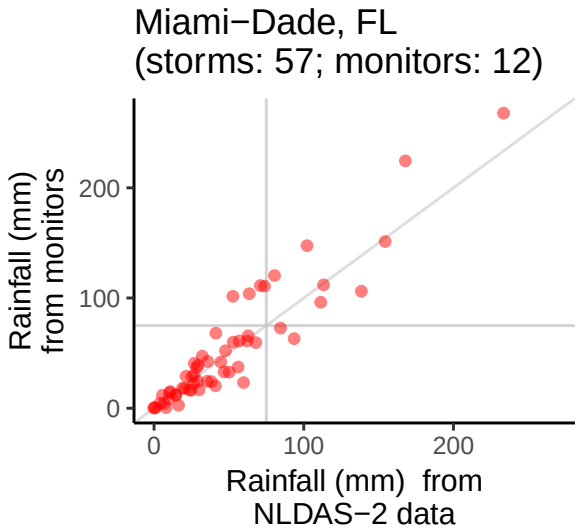
Comparison of modeled wind versus wind radii, Ike, 2008

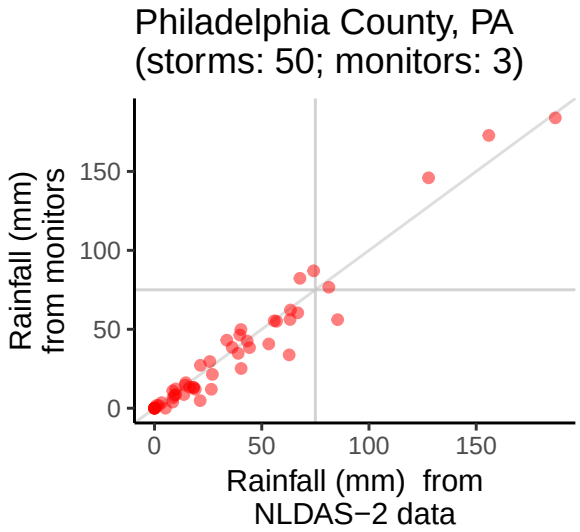


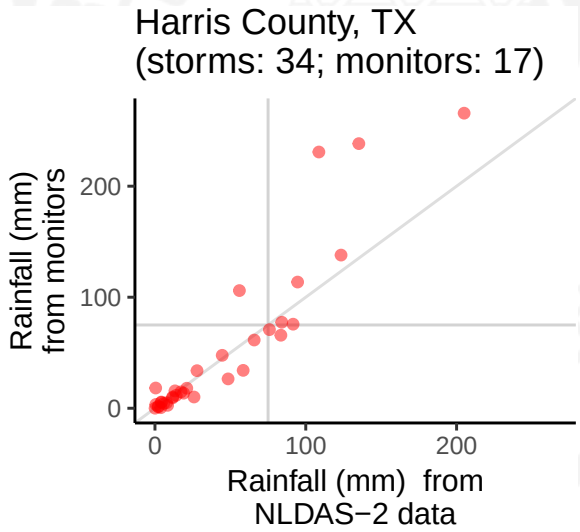
Rain exposure

Assessment

To assess this rain metric, we compared it to rainfall measured at weather stations. X-axis: Rainfall summed for days near storm; y-axis: average of summed rain at each monitor for the same days.

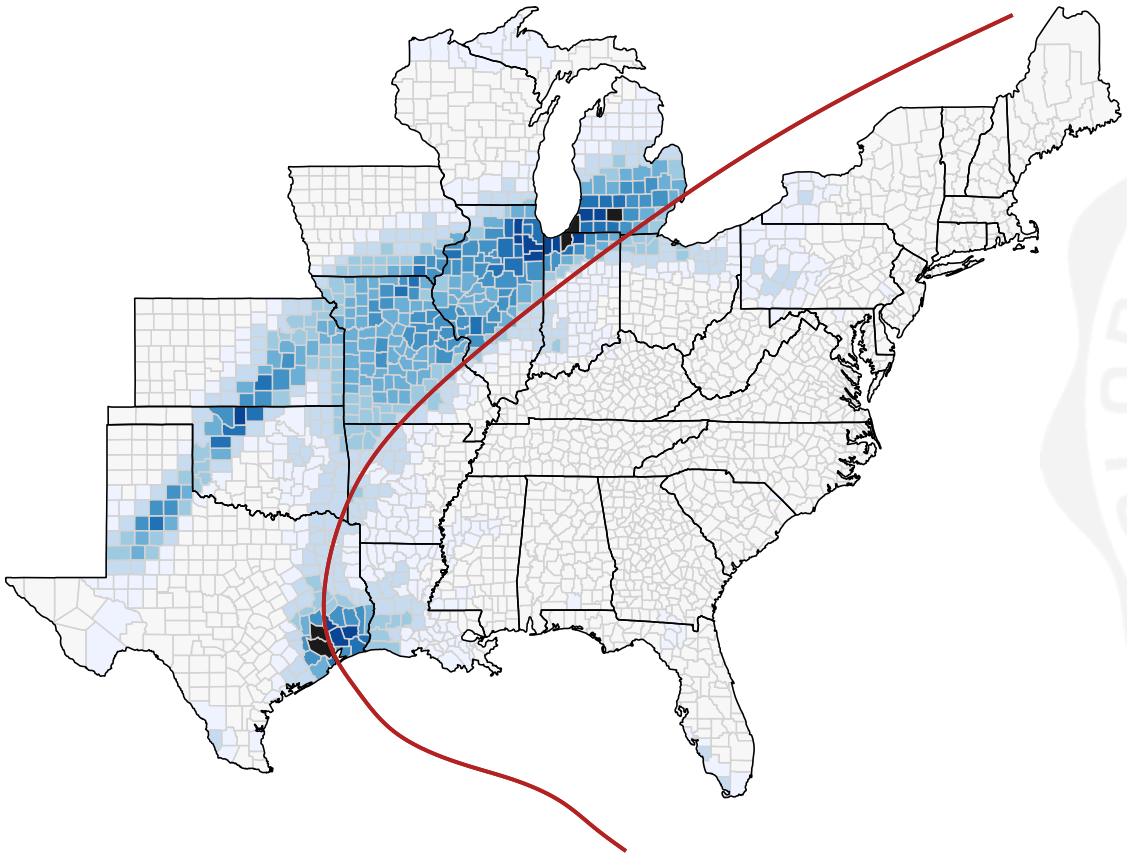






Rain exposure

Rainfall during Ike, 2008



Rain exposure

Rainfall during Lee, 2011