Examples of extreme event modeling in tornado and hurricane research

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Are Tornadoes More Likely Over Smooth Terrain?

Problem: Tornado reports are not tornadoes

- How can we extract information about tornadoes from the limited tornado reports?
- There are more tornado reports near cities and towns, but it's unlikely that cities are causing tornadoes.

- We need to control for non-weather influences if we want to understand what factors cause more tornadoes in certain regions.
- For instance, we suggest terrain roughness will disrupt the flow of air into the meso-cyclone making a tornado less likely.
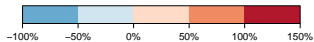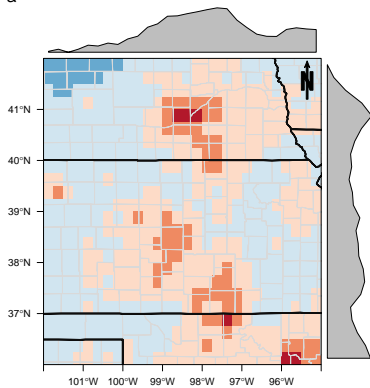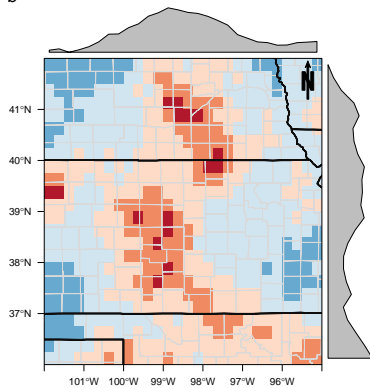

www.romeantephotography.com
© John Allen 2013

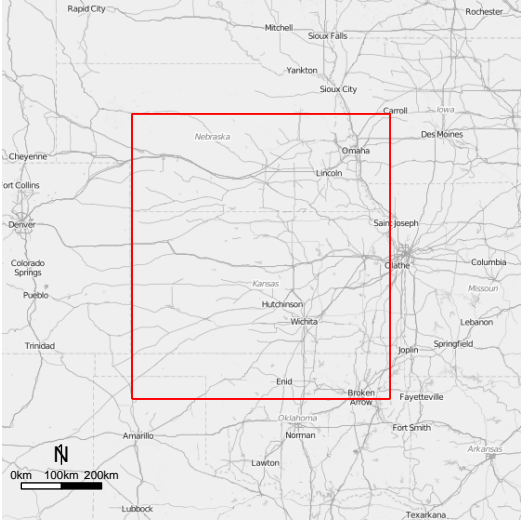# If we solve this problem, then this map
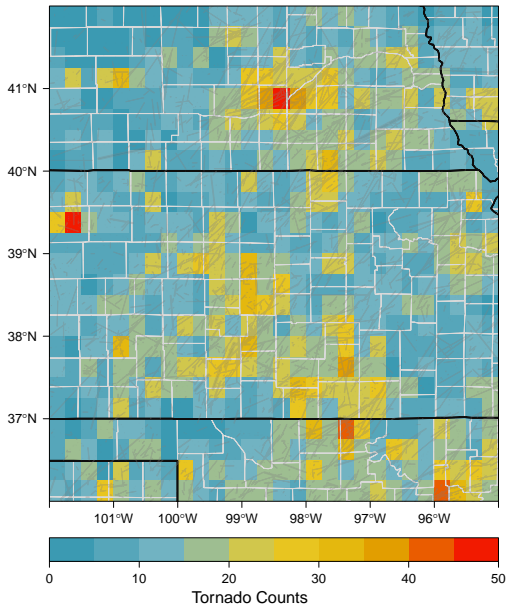
Becomes these maps

a

b

Smoothed Tornado Report Anomalies
(Above/Below Regional Average)

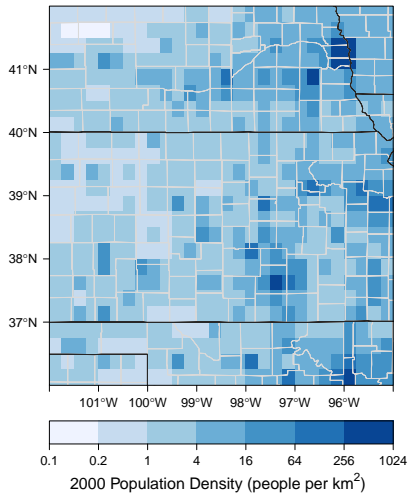−100% −50% 0% 50% 100% 150%

Unexplained Tornado Report Anomalies
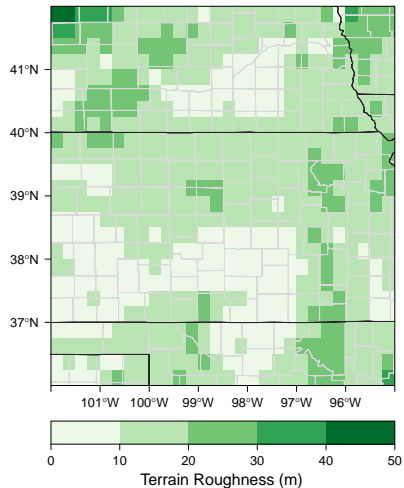(Above/Below Regional Average)

−60% −40% −20% 0% 20% 40% 60%

Case study
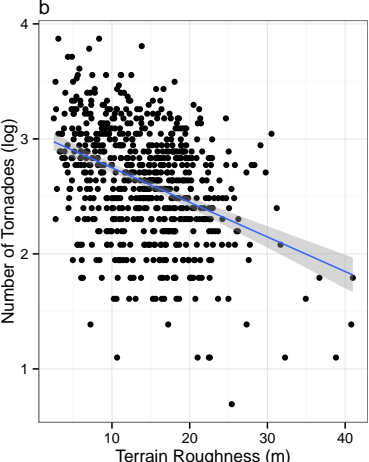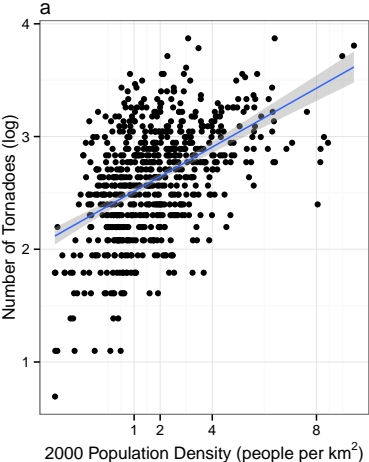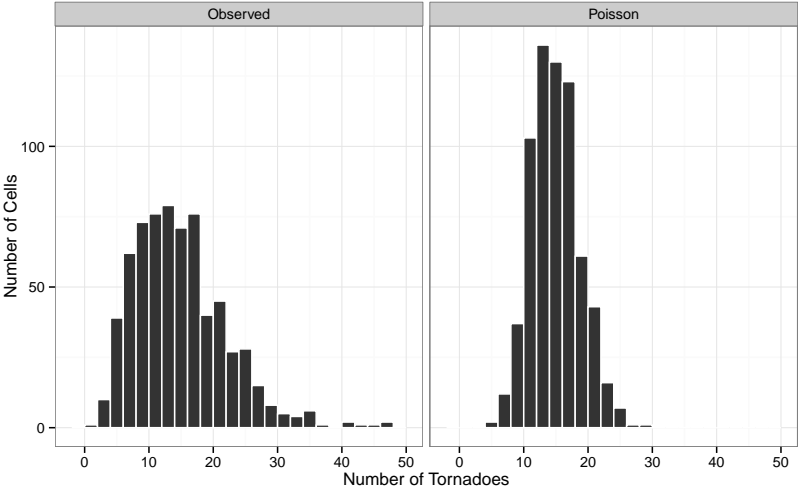
Population & terrain roughness variables

Exploratory analysis

Exploratory analysis

Model

$$
\begin{aligned}
T_s|\mu_s, n &\sim \text{NegBin}(\mu_s, n) \\
\mu_s &= \exp(\nu_s) \cdot \text{area}_s \\
\nu_s &= \beta_0 + \beta_{Pop} \cdot \log_2(\text{Pop}_s) + \beta_{TR}\text{TR}_s + u_s,
\end{aligned}
$$

where $\text{NegBin}(\mu_s, n)$ indicates that the conditional tornado count $(T_s|\mu_s, n)$ is described by a negative binomial distribution with mean μ_s and dispersion n. The mean depends on the cell area (exposure) and is linearly related to the fixed and random effects through the logarithmic link function (ν_s). The fixed effects include population density (Pop_s) and terrain roughness (TR_s).
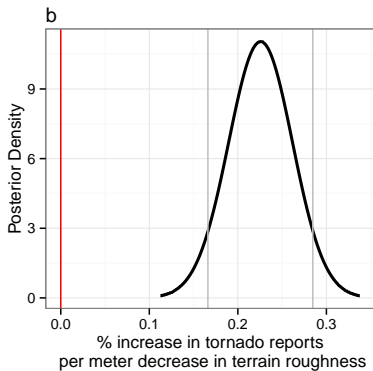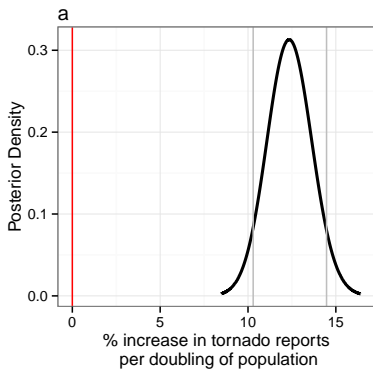
Spatial autocorrelation

The random effect (u_s) follows a Besag formulation where

$$u_i|u_j, i \neq j, \tau \sim N\left(\frac{1}{m_i}\sum_{i \sim j} u_j, \frac{1}{m_i}\tau\right)$$

where N is the normal distribution with mean $1/m_i \cdot \sum_{i \sim j} u_j$ and variance $1/m_i \cdot \tau$ where m_i is the number of neighboring cells and τ is the precision; $i \sim j$ indicates cells i and j are neighbors.

Fixed effects

Sensitivity

Table: Terrain roughness effect in models of tornado activity. The effect has units of % increase in tornadoes per meter decrease in roughness.

Start Year	EF Range	Grid Size	Tornado Reports	Terrain Roughness Effect (per m decrease in roughness)
1955	EF0+	.250°	6749	2.2% (1.5%,3.0%)
1975	EF0+	.250°	4898	2.2% (1.4%,3.1%)
1995	EF0+	.250°	2940	2.5% (1.4%,3.6%)
1955	EF1+	.250°	3054	2.5% (1.6%,3.4%)
1955	EF2+	.250°	1159	3.2% (1.9%,4.4%)
1955	EF3+	.250°	368	3.7% (2.0%,5.4%)
1955	EF0+	.125°	6749	2.0% (1.4%,2.6%)
1955	EF0+	.0625°	6749	1.7% (1.3%,2.1%)

Spatial random effect

Unexplained Tornado Report Anomalies
(Above/Below Regional Average)
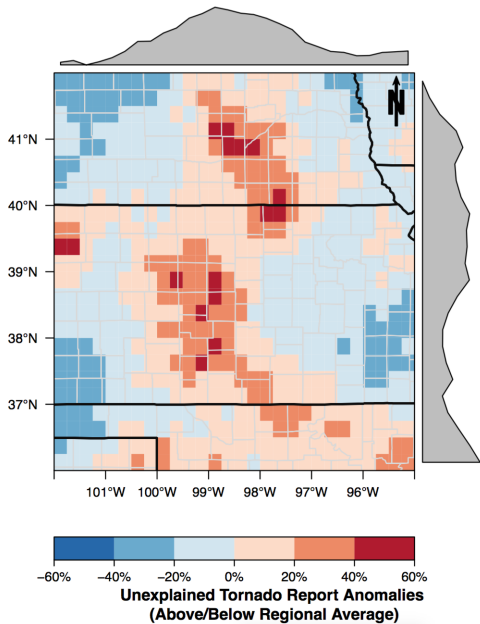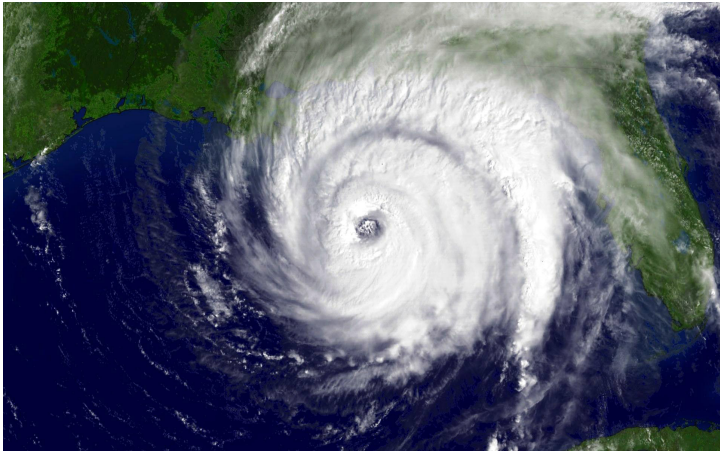
How Sensitive Are Hurricanes to Ocean Heat?

Photo Credit: NOAA

Problem

- We know what hurricanes are like today. When, where, how often. They are sometimes deadly and destructive.
- What about tomorrow? Will there be more? Will they be stronger?
- How do we get answers to these questions?
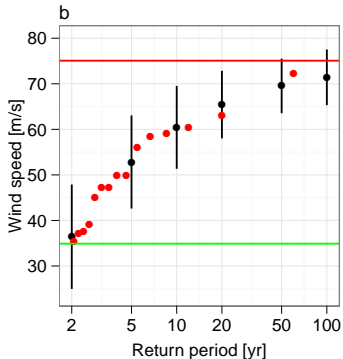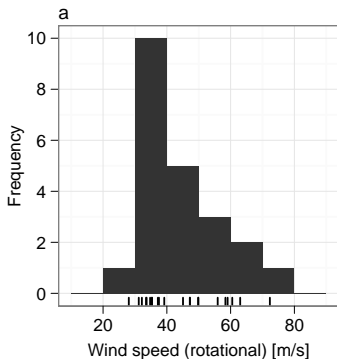
Unfortunately there are no simply ways.

- Theory is limited. We don't have a theory of climate. We don't know all the processes that affect hurricanes.
- Models don't adequately represent the atmosphere or the ocean. And they don't adequately resolve hurricanes.
- Datasets are of limited length and of variable quality.

Solution

Start with the available theory. Use quality data to estimate a key quantity from the theory. Estimate the same quantity using model data. Make comparisons.

- Available theory: Hurricanes as heat engines and the statistics of extreme values.
- Quality data: National Hurricane Center's best-track data with modifications.
- Models: Global Climate Models from CMIP5 used by the IPCC.

Hurricanes as heat engines

Photo credit: *Popular Mechanics*

Maximum Potential Intensity (MPI) Theory

$$\text{MPI} \sim \frac{\text{SST}}{T_o}\text{BL}_f(\text{SST})$$

MPI is the highest wind speed (rotational) in units of meters per second. SST is the ocean temperature at the surface, T_o is the temperature at the top of the hurricane and $\text{BL}_f(\text{SST})$ are heat fluxes involving potential temperature of saturated air. The heat fluxes depend on SST.

Extreme value theory

Limiting intensity (LI) is the red line in panel b: A statistical estimate that we can use to compare with theoretical MPI. How should we make this comparison? Absolute values of LI are not as important as how LI changes with ocean temperature (SST). How do we estimate how LI changes with SST?
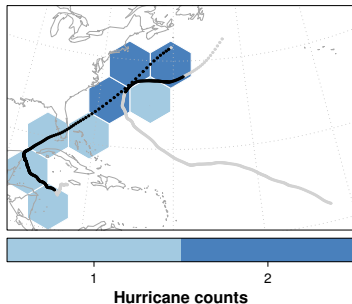
Data

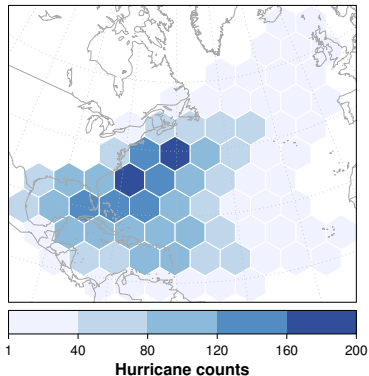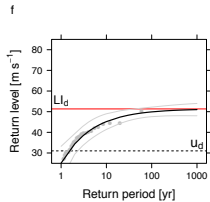Hurricanes travel over seas having varying temperature. So we need to match SST with hurricane intensity.

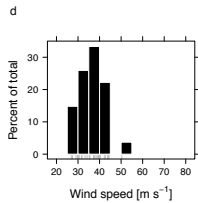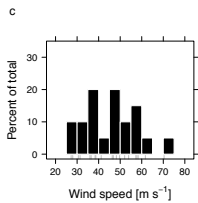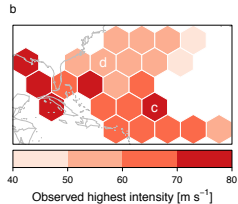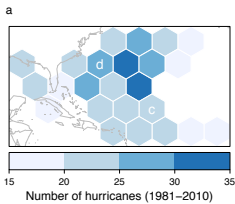Sea Surface Temperature (°C)
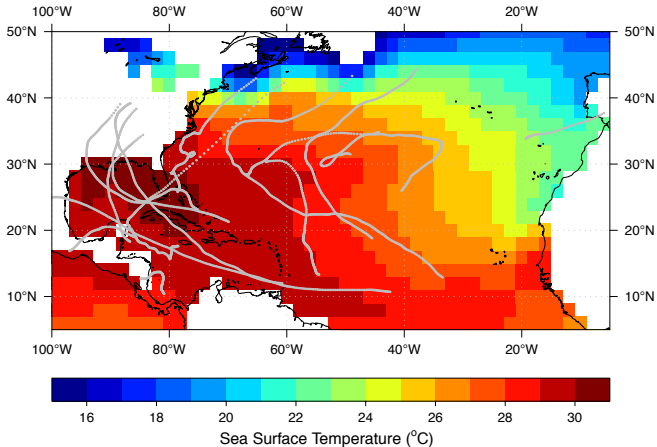
Grid cells

We collect information about each hurricane as it passes through each cell. The cells only cover areas where hurricanes occur. Hexagons efficiently tile the region.
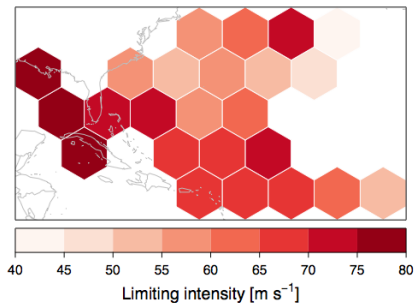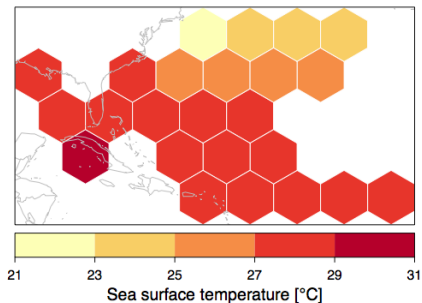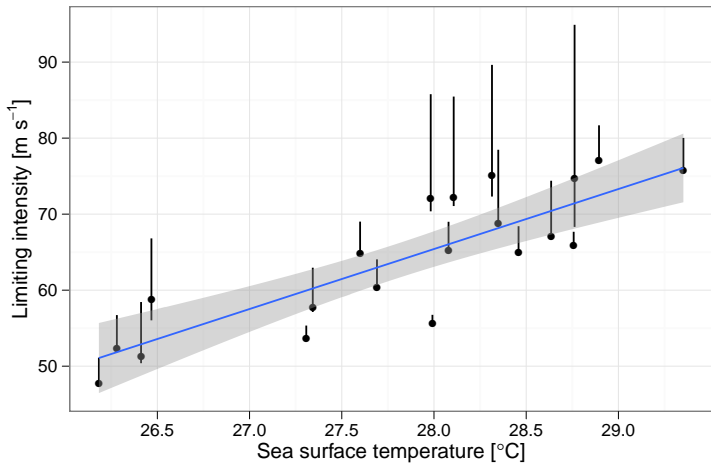
a

b

Number of hurricanes (1981–2010)

15   20   25   30   35

Observed highest intensity [m s^{-1}]

40   50   60   70   80

c

Percent of total

Wind speed [m s^{-1}]

d

Percent of total

Wind speed [m s^{-1}]

e

Return level [m s^{-1}]

LI$_c$

u$_c$

Return period [yr]

f

Return level [m s^{-1}]

LI$_d$

u$_d$
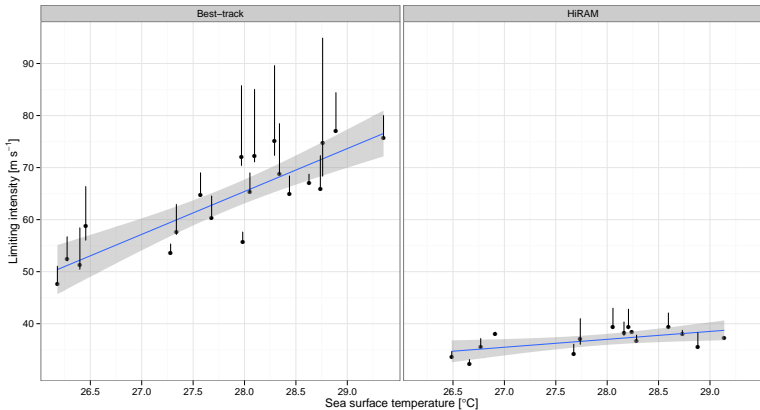
Return period [yr]
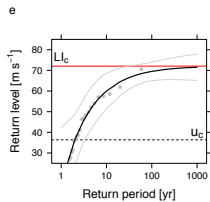
Sea surface temperature (SST) & limiting intensity (LI)

Sea surface temperature [°C]

Limiting intensity [m s^{-1}]

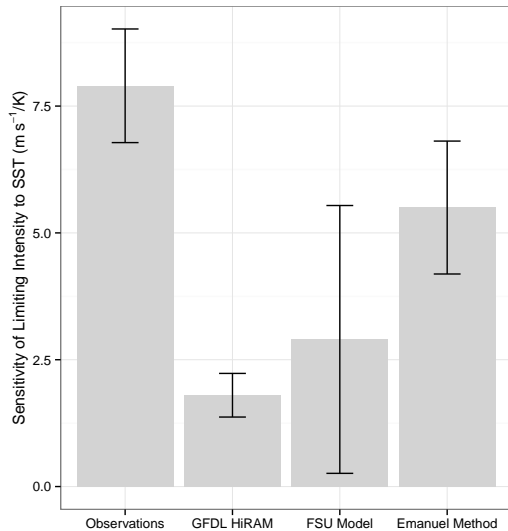We estimate the sensitivity to be 8 ± 1.2 m s^{-1} K^{-1} (s.e.) for hurricanes over seas hotter than 25°C.

Observed vs climate model sensitivity

Observed sensitivity (left) = 8 m s^{-1} K^{-1}
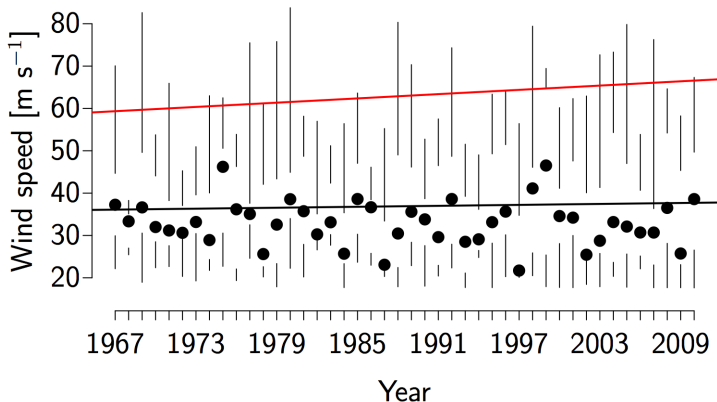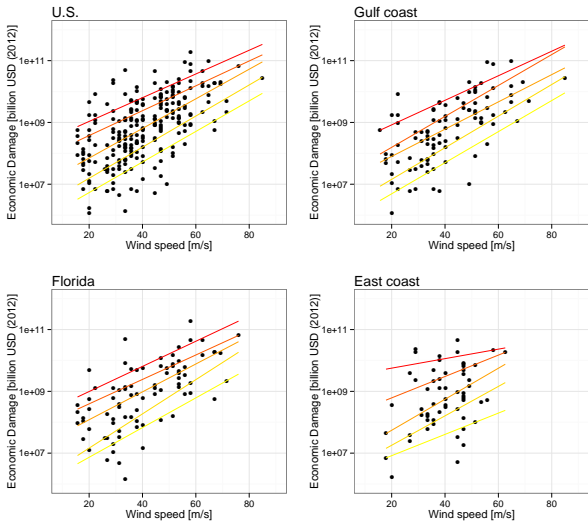HiRAM sensitivity = 2 m s^{-1} K^{-1}

Observed vs climate model sensitivity

Why is this important?

The strongest hurricanes are getting stronger at a rate of 1 m s^{-1}/decade.

Losses increase by 5% per 1 m s^{-1} increase in wind speed.

Thank you

Questions?

`myweb.fsu.edu/jelsner/StateTornadoModel.html`