A Statistical/Deterministic Approach to Hurricane Risk Assessment

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Wind Risk

• Tropical cyclones account for the bulk of natural catastrophe U.S. insurance losses
• Risk assessment is vital to the insurance industry and to government disaster preparedness programs
• Losses roughly follow a $v^3$ power law with maximum wind speed
• Repeat of Miami 1926 hurricane estimated to cost ~ $75 billion (Landsea and Pielke, 1998)
Current Methods

• Fit standard (e.g., Weibull) distribution functions to peaks winds within a specified radius of point of interest, taken from historical hurricane data (Georgiou et al, 1983; Neumann, 1987)

• Find universal distribution functions of wind normalized by potential intensity and interpolate to specific locations based on historical frequency (Darling, 1991; Chu and Wang, 1998)
• Generate large database of synthetic storm tracks using previous track history and local climatology; couple to historical intensity data (Vickery et al., 2000)
Our Approach

- **Step 1**: Use two largely independent techniques to generate large ($\sim 10^4$) numbers of synthetic TC tracks passing within specified radius of point of interest.

- **Step 2**: Run a deterministic coupled TC intensity model along each synthetic track.

- **Step 3**: Directly deduce wind speed exceedence probabilities at point of interest.
Synthetic Track Generation, Method 1: Markov Chains

- Tracks initiated by random draws from space-time PDF based on historical genesis data smoothed using a three-dimensional Gaussian kernel
Based on post-1970 HURDAT
• Tracks propagated in 6-hour steps by integrating in time the rates of change of direction and speed, by randomly drawing from the probability distribution

$$p_t \left( \dot{s}_i, \dot{\theta}_i \mid s_{i-1}, \theta_{i-1}, x_i, y_i, t_i \right)$$

Note: Probabilities of rates of change based on previous direction and speed, not their rates of change. Only last 6-hour step used.
• Conditional PDFs generated using multi-resolution kernel-smoothed non-parametric density estimates from raw histograms (Wand and Jones 1995)
• Rates of change of speed and direction in the raw histograms are discretized to 8 km and 3° /6h/6h, respectively
• Prior speed and direction discretized to 40km/6h (22 bins) and 20° (18 bins)
Multi-resolution representation of the pdfs of rates of change of speed and direction in space and time is used to sample the state variables according to a “schedule”:

<table>
<thead>
<tr>
<th>Space →</th>
<th>0.5° x 0.5° discretization</th>
<th>5° x5° discretization</th>
<th>Three manually constructed latitude belts</th>
<th>Global</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 time periods</td>
<td>Priority: 1</td>
<td>2</td>
<td>3</td>
<td>7</td>
</tr>
<tr>
<td>1 time period (annual)</td>
<td>4</td>
<td>5</td>
<td>6</td>
<td>8</td>
</tr>
</tbody>
</table>
• Tracks terminated when/where historical data no longer sufficient to determine PDF
Results:

60 HURDAT tracks

60 Markov tracks
6-hour zonal displacements in region bounded by 10° and 30° N latitude, and 80° and 30° W longitude.
6-hour meridional displacements in region bounded by 10° and 30° N latitude, and 80° and 30° W longitude
Synthetic Track Generation, Method 2: Use of Synthetic Wind Time Series

- Use genesis technique as in Method 1
- Postulate that TCs move with vertically averaged environmental flow plus a “beta drift” correction
- Approximate “vertically averaged” by weighted mean of 850 and 250 hPa flow
Synthetic wind time series

- Monthly mean, variances and co-variances from NCEP re-analysis data

- Synthetic time series constrained to have the correct mean, variance, co-variances and an $\omega^{-3}$ power series
250 hPa zonal wind modeled as Fourier series in time with random phase:

\[ u_{250}(x, y, \tau, t) = \bar{u}_{250}(x, y, \tau) + \sqrt{u'^2_{250}(x, y, \tau)} F_1(t) \]

\[ F_1 = \sqrt{\frac{2}{N} \sum_{n=1}^{N} n^{-3/2} \sin\left(2\pi \left(\frac{nt}{T} + X_{1n}\right)\right)} \]

where \( T \) is a time scale corresponding to the period of the lowest frequency wave in the series, \( N \) is the total number of waves retained, and \( X_{1n} \) is, for each \( n \), a random number between 0 and 1.
Example:

\[ \bar{u}_{250} = 30 \, ms^{-1} \]

\[ \sqrt{u'_{250}^2(x, y, \tau)} = 10 \, ms^{-1} \]

\[ N = 15 \]

\[ T = 15 \, days \]
250 hPa meridional wind:

\[ v_{250}(x, y, \tau, t) = \bar{v}_{250}(x, y, \tau) + \sqrt{v'^2_{250}(x, y, \tau)} \left( wF_1(t) + (1 - |w|)F_2(t) \right) \]

\[ w \equiv \frac{u'_{250} v'_{250}}{\sqrt{u'^2_{250} v'^2_{250}}} \]

Time series of 850 hPa wind similarly constructed, preserving co-variances with respective components of 250 hPa wind.
Track:

\[ V_{\text{track}} = \alpha V_{850} + (1 - \alpha) V_{250} + V_{\beta}, \]

Empirically determined constants:

\[ \alpha = 0.8, \]

\[ u_{\beta} = -0.6 \text{ m s}^{-1}, \]

\[ v_{\beta} = 2.7 \text{ m s}^{-1} \]
Results:
6-hour zonal displacements in region bounded by 10° and 30° N latitude, and 80° and 30° W longitude
6-hour meridional displacements in region bounded by 10° and 30° N latitude, and 80° and 30° W longitude
6-hour zonal displacements in region bounded by 10° and 30° N latitude, and 80° and 30° W longitude, using only post-1970 HURDAT
TC Intensity

• Run coupled deterministic model (CHIPS, Emanuel et al., 2004) along each track
• Use monthly mean potential intensity, ocean mixed layer depth, and sub-mixed layer thermal stratification
• Use shear from synthetic wind time series
• Initial intensity and rate of intensification specified as 15 m s$^{-1}$ and 6 m s$^{-1}$ day$^{-1}$
• Tracks terminated when v < 17 m s$^{-1}$
Radial structure:

Translation speed added to circular theoretical/empirical wind field given by

\[ V^2 = V_m^2 \left( \frac{r_0 - r}{r_0 - r_m} \right)^2 \left( \frac{r}{r_m} \right)^{2m} \left( \frac{1-b(n+m)}{n+m} \right)^{2(n+m)} + \frac{b(1+2m)}{1+2m} \left( \frac{r}{r_m} \right)^{2m+1} \]

\[ r_0 = 1200 \, km \quad m = 1.6 \quad b = \frac{1}{4} \quad n = 0.9 \quad r_m \text{ and } V_m \text{ given by intensity model} \]
Results

1000 North Atlantic tropical cyclones

- **Best track from 1950**
- **Method 1**
- **Method 2**

Number of events per millennium

Maximum surface wind speed (kts): 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 150, 160, 170, 180

- **40 kts**: Over 10,000 events
- **50 kts**: Over 7,000 events
- **60 kts**: Over 5,000 events
- **70 kts**: Over 3,000 events
- **80 kts**: Over 1,000 events
- **90 kts**: Over 500 events
- **100 kts**: Over 200 events
- **110 kts**: Over 100 events
- **120 kts**: Over 50 events
- **130 kts**: Over 20 events
- **140 kts**: Over 10 events
- **150 kts**: Over 5 events
- **160 kts**: Over 2 events
- **170 kts**: Over 1 event
- **180 kts**: Under 1 event
Miami

Miami, maximum within 100 km

- **HURDAT**: 29 events
- **Method 1**: 2937 events
- **Method 2**: 3706 events

![Graph showing the number of events per millennium for Miami, with bars for Best track from 1920, Method 1, and Method 2.](image)
Jagger et al., 2001: All of Dade County

Method 2: Point in downtown Miami
Miami, 30 random tracks, Method 2
Miami, 30 HURDAT
Miami, 30 worst tracks, Method 2
Miami, 30 worst tracks, Method 1
Miami, worst of 3706 storms, Method 2

Track number 3199, September
Boston

Boston, maximum within 100 km

- **HURDAT**: 27 events
- **Method 1**: 3084 events
- **Method 2**: 3599 events

![Bar chart showing the number of events per millennium by maximum surface wind speed (kts)]
Boston, 30 random tracks, Method 2
Boston, 30 HURDAT tracks
Boston, 30 worst tracks, Method 2
Boston, worst case of 3599 affecting downtown Boston, Method 2
Boston, worst case of 3084 affecting downtown Boston, Method 1
New York City

New York City, within 100 km

- **HURDAT**: 20 events
- **Method 1**: 2985 events
- **Method 2**: 3059 events

![Bar chart showing the number of events per millennium vs. maximum surface wind speed (kts). The bar chart includes three categories: Best track from 1851, Method 1, and Method 2. The y-axis represents the number of events per millennium, and the x-axis represents maximum surface wind speed in knots (kts).]
New York, worst event, Method 1
Comparison of Methods: Method 1

• Advantages:
  – Excellent track statistics
  – Nonlinear effects of extratropical transition accounted for

• Disadvantages:
  – Tracks good only where historical data plentiful
  – Shear largely independent of track
  – High latitude track statistics biased by surviving events: Overestimate of high latitude frequency (need a death algorithm)
Comparison of Methods: Method 2

• Advantages:
  – Only depends on historical genesis data; can be run anywhere
  – Tracks consistent with shear
  – Could potentially account for ENSO, NAO, PDO, etc.

• Disadvantages:
  – Does not account for nonlinear processes in extratropical transition: Underestimates extreme events at high latitude
Future Work

- Account for natural variability of upper ocean thermal structure
- Bin re-analysis statistics by phase of ENSO, NAO, PDO
- Use GCM output to estimate tracks/intensity in global warming scenarios (genesis PDFs problematic)
Appendix: A few other cities
Halifax:

Halifax: Maximum within 100 km

HURDAT: 32 events
Method 1: 3115 events
Method 2: 3580 events

Number of events per millenium

Maximum surface wind speed (kts)

Best track from 1851
Method 1
Method 2
Halifax: 20 random tracks, Method 2
Halifax: 20 worst tracks, Method 2:
Worst event, Method 2:

Track number 797, September
Worst event, Method 1

Track number 2352, September
San Diego

San Diego, 2416 tracks, maximum within 100 km

Number of events per millennium

Maximum surface wind speed (kts)
Worst event, Method 2
Honolulu

Honolulu, 3545 tracks, maximum within 100 km

Number of events per millennium

Maximum surface wind speed (kts)
Honolulu, 30 top tracks
Honolulu, worst event, Method 2