Climate Risk Modeling

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Input from Cindy Bruyere, Greg Holland and Asuka Suzuki-Parker
Part 1: Overview
- climate risk: a multiscale, multicomponent problem.
- limitations of traditional risk assessments.
- the value of dynamical models for risk assessment.

- modeling current and future hurricane activity.
- direct impact assessment.
• 1950-2008: 80% of worldwide insured losses were weather related, dominated by tropical cyclones.

• Extreme events are subject to high volatility and uncertainty.

• Reduction and sharing of risk at local, regional and global levels through private and public means.

• Competitive edge: new products; new markets; sophisticated portfolio underwriting.
Data Needs

Many questions require predictions of weather statistics, particularly of extreme weather events, and their impacts on decadal timescales with regional clarity:

- a challenging problem with high computational demands.
Hazard: defined by location, intensity, size and probability of occurrence.
Exposure: infrastructure at risk, building type, age, design code, location.
Vulnerability: susceptibility to the hazard (based on physical relationships)
Loss: cost to repair/replace and business interruption.

Exceedance probability curve.
Probability that a given loss will occur in a given time.

Uncertainty?
Traditional hazard modeling samples from probability distributions fitted to historical data.

Limitations of using an historical archive as a base dataset:

- assumption of stationarity;
- artificial trends due to changes in data collection methods;
- unresolved temporal variability and trends by short archives;
- independence between hazards.
A Role for Dynamical Modeling

Information Across Scales
Dynamical Model-Based Hazard Event Sets

- Include the effects of climate variability and change.
- Include events outside the historical range.
- Consistent data – no artificial trends.
- Model error but independent of errors in the historical archive:
  - a complimentary view of risk.
Hazard Clustering and Dependency
Information on Critical Hazard Parameters

- Area of damaging winds
- Rainfall
Simulating Turbulence in a Hurricane Eyewall
Thanks to R. Rotunno, Y. Chen, G. Bryan and W. Wang

Vertical motion at 600 m

Grid spacing of 62 m

Instantaneous max wind speed = 270mph

For reference, a Category 5, 1-minute average wind speed is >155mph
Limitations of the Dynamical Model Approach

• Limited value without uncertainty estimates.
• The ideal: large ensemble of high resolution simulations.
  - scaling, I/O limited models.
  - overwhelming data volumes.
• As a result the role of dynamical models is currently limited to informing the development of simple (fast, efficient) models.
Inform Development of Simple Models

Example: hurricane wind fields.

1) Hurricane winds from a dynamical model

2) Simple model

3) Use simple model to create wind fields around storm tracks
Dynamical models and large computational resources will play a critical role in next generation weather and climate risk assessments.

This field of research is wide open. A fertile ground for interdisciplinary collaboration and progress.
Part 2. Example Project: Hurricane Risk

- Important changes to hurricanes are projected that require an alternative approach to risk modeling.

- Exploring how to create event sets using dynamical models.

- A multi-tiered approach:
  - dynamical downscaling.
  - explore sensitivities.
  - statistical downscaling.
  - impact assessments.
Global Model: - 1950 to 2100 under A2 scenario.
Nested Model: - 3 time slices: 1995-2005, 2020-2030 and 2045-2055. - 36km and 12 km;
Higher resolution impacts: frequency; formation mechanisms; structure (spiral rain bands, wind field); intensity; upscale impacts.
# Computational Demands

<table>
<thead>
<tr>
<th></th>
<th>36 km domain</th>
<th>12 km domain</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wall clock time:</td>
<td>~ 2.5 months</td>
<td>~ 6 months</td>
</tr>
<tr>
<td>Processors per job:</td>
<td>128</td>
<td>512</td>
</tr>
<tr>
<td># Simultaneous jobs:</td>
<td>3</td>
<td>32</td>
</tr>
<tr>
<td>Processor hours:</td>
<td>3M</td>
<td>18M</td>
</tr>
<tr>
<td>Tb of data:</td>
<td>~75</td>
<td>~200</td>
</tr>
</tbody>
</table>
Precipitable Water: 12 km Domain
Tropical Cyclone Tracks

Base Climate (14.7 obs)

- 2020-2030
  - 36km: 7.6
  - 12km: 17.3

- 2045-2055
  - 36km: 8.5
  - 12km: 17.6

IMA - April 13th, 2011
Interannual Variability in Storm Count

Interannual correlation ($r^2$) between 36 and 12 km simulations = 0.06

Why so low?
Simulations are sensitive to small perturbations in the initial state due to non-linear dynamic and thermodynamic relations and multiscale feedbacks that govern the climate system.

• Puts a predictability limit on details of weather to about 2 weeks.

• Open question: What is the impact of IV on tropical cyclones? - could be important for large regional domains.

Aim: Distinguish the reproducible climate change signal from the component due to IV.
Sensitivity to Initial Condition

Experimental Design: 12km domain

Continuous simulation

Discrete annual simulations

2045 2046 2047 2048

Jan 2045 Jan 2048

1 May – 1 Dec
Differences in annual frequency and interannual variability

Differences are similar to the interannual variability.
Experimental Design: Discrete annual simulations on 12 km domain.

**Sensitivity to Machine**

IBM bluegene: 1 May – 1 Dec

CRAY: 1 May – 1 Dec
• Differences in annual frequency and interannual variability
• Differences are similar to the interannual variability.
No one-to-one correlation between individual storms - role for stochastic processes

Differences on scale of the Gulf of Mexico.
Dynamical Downscaling: Summary

• Known and unknown sensitivities within the dynamical framework:
  - cost prohibitive to complete a full sensitivity assessment.

• Motivates the need for fast multiple assessments:
  - achieved through statistical downscaling.
Statistical Downscaling

Genesis Potential (GP) Index:

\[ GP = 10^5 \eta \left( \frac{RH_{700}}{30} \right)^3 \left( \frac{V_{pot}}{70} \right)^3 \left( 1 + 0.1V_{shear} \right)^{-2} \]

\( \eta \) = absolute vorticity

\( V_{pot} \) = potential intensity

\( V_{shear} \) = shear between 850hPa and 200hPa

GP for North Atlantic Basin using Reanalysis Data

\[ r^2: \begin{array}{l}
0.83 \text{ (seasonal)} \\
0.12 \text{ (annual)}
\end{array} \]

IMA - April 13th, 2011

Cindy Bruyere (NCAR)
GP - A Different Approach

$r^2$ is annual. ($r^2$) is 5y running mean

<table>
<thead>
<tr>
<th>Annual TC Frequency</th>
<th>Basin</th>
<th>GOM</th>
<th>MDR</th>
<th>EMDR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storms forming in area</td>
<td>0.12</td>
<td>0.00</td>
<td>0.16</td>
<td>0.20</td>
</tr>
<tr>
<td>Storms that moved through the area</td>
<td>0.12</td>
<td>0.00</td>
<td>0.18</td>
<td>0.20</td>
</tr>
<tr>
<td>All storms in NA basin</td>
<td>0.12</td>
<td>0.00</td>
<td>0.41</td>
<td>0.45</td>
</tr>
<tr>
<td>Storms that move though the GOM</td>
<td>0.08</td>
<td>0.00</td>
<td>0.16</td>
<td>0.19</td>
</tr>
</tbody>
</table>

Zonal mean GP average (color), and observed number of TC’s (both 5y running means)

Cindy Bruyere (NCAR)
Correlate GP with North Atlantic Storms

<table>
<thead>
<tr>
<th>Variable</th>
<th>Correlation Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>GP</td>
<td>0.67 (0.79)</td>
</tr>
<tr>
<td>pi*s</td>
<td><strong>0.72 (0.90)</strong></td>
</tr>
<tr>
<td>vort</td>
<td>-0.18 (-0.31)</td>
</tr>
<tr>
<td>rh</td>
<td>-0.02 (-0.14)</td>
</tr>
<tr>
<td>pi</td>
<td>0.68 (0.89)</td>
</tr>
<tr>
<td>s</td>
<td>0.62 (0.72)</td>
</tr>
</tbody>
</table>

Cindy Bruyere (NCAR)
Future Predictions using GP on Global Model

Predicted number of storms

- Increasing numbers of storms, consistent with dynamical downscaling.

Cindy Bruyere (NCAR)
Statistical Downscaling: Summary

- Empirical relationships between storms and their large-scale environment can be used to extract storm information from global climate models.

- Can be used to generate large ensembles of future projections and sample the range of possible scenarios.
Overarching aim:

Utilize model predictions to provide improved decision-support tools for society.

• Quantitative assessments of industry/societal/environment impacts based on model predictions.
• Application to:
  - weather forecasts for real-time assessments for short-term planning;
  - future climate scenarios to assess future changes in impacts for long-term planning (e.g. assess benefits of future engineering advances).
Generate waves up to 90 ft.

- Damage to infrastructure:
  - platforms, pipelines;
  - refineries (50% of U. S. capacity);
  - shore bases.

- Affect cost of new facilities.

- Generate evacuation costs ($100-$500 M/yr).

- Changes in future hurricanes will affect all of the above.

- Advanced warning could mitigate future costs.
Active Gulf of Mexico Offshore Platforms

Source: Minerals Management Service (MMS) data as interpreted by API. Data current as of 08/07/08.
**Goal:** To assess future changes in hurricane damage.
- initial focus on offshore facilities in the Gulf of Mexico.

**Requirements**
- Assessments use only information available in real-time warnings.
- All parameters available from seasonal forecasts and climate models.

**Approach:**
- Identify relationships between storms and damage and develop a damage Index.
- Apply index to model storms to assess future changes in damage. Assumption: no changes in engineering design.
Data:
• Willis Energy Loss Data (WELD) for the Gulf of Mexico (7 hurricanes) inflated to 1998 values.

Critical Hurricane Parameters:
• The amount of energy dissipated at the surface by maximum winds;
• The radial extent and character of the surface wind field (n mile);
• The translational speed of the hurricane (kt).
Combined these are a proxy for waves, currents and storm surge.
Method:

• Base development largely on physical principles with care not to over specify the use of the small available data base;

• Independent testing to come from application during 2011 hurricane season;

• Combine the three critical factors in an additive formula for the Willis Hurricane Index (WHI):

\[
WHI = a \left( \frac{v_m}{v_{m0}} \right)^{aa} + b \left( \frac{R_h}{R_{h0}} \right)^{bb} + c \left( \frac{v_t}{v_{t0}} \right)^{-cc},
\]
Parameter Contributions

**Mean Intensity**

- $r^2 = 0.23$

**Radius of Max Winds**

- $r^2 = 0.48$

**Translation Speed**

- $r^2 = 0.71$
Parameter Contributions

\[ WHI = a\left(\frac{v_m}{v_{m0}}\right)^{aa} + b\left(\frac{R_h}{R_{h0}}\right)^{bb} + c\left(\frac{v_t}{v_{t0}}\right)^{-cc}, \]

- Set \( aa = 3 \) following Emanuel (2005) Power Dissipation Index
- Normalise by setting \( v_{m0} = 65 \) kt
- Constrained to hurricanes \( v_m > 65 \) kt
- Set \( a = 1 \) through experimentation and sensitivity analysis
Parameter Contributions

\[ WHI = a \left( \frac{v_m}{v_{m0}} \right)^{aa} + b \left( \frac{R_h}{R_{h0}} \right)^{bb} + c \left( \frac{v_t}{v_{t0}} \right)^{-cc}, \]

- Set \( bb=1 \) for consistency with areal coverage of storm winds, given translation
- Normalize by setting \( R_{h0}=50 \) n mile
- Set \( b=5 \) through experimentation and sensitivity analysis
Parameter Contributions

\[
WHI = a\left(\frac{v_m}{v_{m0}}\right)^{aa} + b\left(\frac{R_h}{R_{h0}}\right)^{bb} + c\left(\frac{v_t}{v_{t0}}\right)^{-cc}
\]

- Set cc=2 from regression on available data
- Normalize by setting \(v_{t0}=15\) kt
- Set c=5 through experimentation and sensitivity analysis
The WHI for the Gulf of Mexico

\[ WHI = \left( \frac{v_m}{65} \right)^3 + 5\left( \frac{R_h}{50} \right) + 5\left( \frac{v_t}{15} \right)^{-2} \]

\[ v_m > 65, \]

If \( v_t < 7 \), \( v_t = 7 \),
Application to Gulf Losses

Average WHI vs Losses

\[ r^2 = 0.91 \]
Lat/Lon box used for Calculations

Active Gulf of Mexico Offshore Platforms

Source: Minerals Management Service (MMS) data as interpreted by API. Data current as of 08/07/08.
Modeled Gulf Storms: 36 km

- **Base Climate:** 15
- **2020 – 2030:** 10
- **2045 - 2055:** 20
Model Gulf Storms: 12 km

- Base Climate
- 2020 – 2030
- 2045 - 2055

15% formed in black box (25% in obs)
Hurricane Losses: 36 km vs 12 km

1. **Average Hurricane Loss**
   - Base: $5 bn (1998)
   - 2045-2055: $3 bn (1998)
   - Comparison: 36 km vs. 12 km

2. **Maximum Hurricane Loss**
   - Base: $12 bn (1998)
   - Comparison: 36 km vs. 12 km
## WHI Breakdown: 36 km vs 12 km

<table>
<thead>
<tr>
<th>Parameter</th>
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<th>2045-2055</th>
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<tr>
<td># Cyclones</td>
<td>15/16</td>
<td>10/13</td>
<td>20/11</td>
</tr>
<tr>
<td># 6-hourly data points</td>
<td>96/108</td>
<td>50/75</td>
<td>78/33</td>
</tr>
<tr>
<td>Average Intensity (kt)</td>
<td>50/55</td>
<td>49/63</td>
<td>25/50</td>
</tr>
<tr>
<td>Maximum Intensity (kt)</td>
<td>72/87</td>
<td>67/91</td>
<td>73/88</td>
</tr>
<tr>
<td>Average Rmax (nm)</td>
<td>44/49</td>
<td>24/31</td>
<td>31/34</td>
</tr>
<tr>
<td>Average Trans. Speed (kt)</td>
<td>10/12</td>
<td>12/15</td>
<td>11/19</td>
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<tr>
<td>Average Intensity Term</td>
<td>3.7/5.4</td>
<td>3.4/7.6</td>
<td>3.7/4.1</td>
</tr>
<tr>
<td>Average Size Term</td>
<td>7.3/8.2</td>
<td>4.0/5.2</td>
<td>5.2/5.7</td>
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<td>Average Speed Term</td>
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<td>11.9/14.1</td>
<td>13.9/8.9</td>
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Total Annual Losses: 12km Storms

- Loss (bn 1998$)
- Number of Storms

IMA - April 13th, 2011
Most Damaging Storm: 2004 Storm #12

1998$12.8bn

Vmax = 76knots
Rmax = 64nm
Tspeed < 7knots

intensity term = 11.1
size term = 10.7
speed term = 23.0
WHI = 44.8

IMA - April 13th, 2011
• Application of WHI provides a first order assessment of possible changes in net damage to off-shore facilities.

• Results are limited by small sample size:
  - incorporate damage index into statistical downscaling specific to Gulf of Mexico storms.
- Dynamical models and large computational resources will play a critical role in next generation climate risk assessments.

- The statistical-dynamical approach is a powerful combination, yet methods of combining the two are largely unexplored.

This field of research is wide open. A fertile ground for interdisciplinary collaboration and progress.

The need for synergy between climate science, computational science, mathematics, statistics, engineering, decision science, government and industry.