Past and Future Tropical Cyclone Activity

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- What is a tropical cyclone?
- What is cyclone “activity”?
- How has activity changed in the past? Why?
- How do we expect it to change in future? Why?
Miami After Hurricane Andrew

Source: wikimedia.org
North Atlantic tropical cyclones

- Recent increase in activity
  - Including extreme 2004-2005 seasons
- Why? Implications for future?

Emanuel (2007, J. Clim.)

Figure: Tom Knutson
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<th>Key concepts</th>
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Tropical cyclones

- Tropical cyclone not a big tornado
- Tropical cyclone, hurricane and typhoon same phenomenon, different location.

 Hurricanes Isabel (2003)  
Atlantic Ocean
(source: wikimedia.org)

Cyclone Gonu (2007)  
North Indian Ocean
(source: wikimedia.org)

Cyclone Tokage (2004)  
Northwest Pacific Ocean
(source: NASA)
Cyclones spin “cyclonically”

TC Kessiny (2002)
South Indian Ocean
Supertyphoon Nida (2009)
Northwest Pacific Ocean

source: NASA
Cyclones spin “cyclonically”

TC Kessiny (2002)  
South Indian Ocean

Supertyphoon Nida (2009)  
Northwest Pacific Ocean

source: NASA
### Saffir-Simpson Hurricane Scale

<table>
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<tr>
<th>Category</th>
<th>Wind speed</th>
<th>Storm surge</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>mph (km/h)</td>
<td>ft (m)</td>
</tr>
<tr>
<td>5</td>
<td>≥156 (≥250)</td>
<td>≥18 (&gt;5.5)</td>
</tr>
<tr>
<td>4</td>
<td>131–155 (210–249)</td>
<td>13–18 (4.0–5.5)</td>
</tr>
<tr>
<td>3</td>
<td>111–130 (178–209)</td>
<td>9–12 (2.7–3.7)</td>
</tr>
<tr>
<td>2</td>
<td>96–110 (154–177)</td>
<td>6–8 (1.8–2.4)</td>
</tr>
<tr>
<td>1</td>
<td>74–95 (119–153)</td>
<td>4–5 (1.2–1.5)</td>
</tr>
</tbody>
</table>

**Additional classifications**

<table>
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<tr>
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<th>Tropical storm</th>
<th>Tropical depression</th>
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<tr>
<td></td>
<td>39–73 (63–117)</td>
<td>0–3 (0–0.9)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0–38 (0–62)</td>
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<tr>
<td></td>
<td></td>
<td>0</td>
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*source: NOAA*
Conceptual view of a tropical storm

source: wikimedia.org
http://upload.wikimedia.org/wikipedia/commons/a/a9/Hurricane_structure_graphic.jpg
Warm water necessary for storm formation.

But warm water not enough, *e.g.* cyclones need a “calm” environment (without strong “wind shear” to disrupt them)
It’s not all local: El Niño events are associated with fewer Atlantic hurricanes, but warmer Atlantic
Theory of Maximum Potential Intensity

Potential Intensity = “Fuel” * “Efficiency”

“Fuel” increases as ocean warms
“Efficiency” increases as ocean warms, decreases as upper atmosphere warms

Tracks of known Atlantic Tropical Storms (1850-2008)

Winds averaged over lower atmosphere June-November
Measure of Activity
Measure of Activity

• Which measure?
  – Hurricane count
  – Landfalling storm count
  – Extremes in intensity
  – Shifts in average intensity
  – Sum of intensity

• Must balance demand with current understanding
  – Obs, models and theory limit.

• Differences must be communicated and understood

How can we know what hurricanes did in the past?
How can we estimate what hurricanes did in the past?

- Weather maps and reports
- Satellites
- Historical records (newspapers, etc)
- Sediments in marshes
Raw record of Atlantic tropical storms shows strong century-scale increase

Atlantic Hurricanes, Tropical and Subtropical Storms

Source: Vecchi and Knutson (2008, J. Climate)
Source: Emanuel (2006); Mann and Emanuel (2006) EOS.
See also Holland and Webster (2007) Phil. Trans. R. Soc. A
Can we be sure the long-term increase is real? Observational methods have changed with time.

Vecchi and Knutson (2008)
Characteristics of recorded storms exhibit strong secular changes, e.g., fraction of storms hitting land

Percent Tropical Cyclones Striking Land

1900 to 2006

100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
5
0

Year


75% - 1900 to 1965

59% - 1966 to 2006

...but we can estimate number of “missed” storms

*Landsea (2007)*: Assumes constant landfall fraction. Is this justified (see *Holland, 2007*)?

*Chang and Guo (2007), Vecchi and Knutson (2008)*: How many storms “slip” through ship tracks?
- Adjusted storm count trend since 1878 not distinct from “noise”
- Decadal swings not a simple “cycle”, either.
Using sediment overwashes to estimate tropical cyclones

Figure 1 | Overwash sediment records of landfalling hurricanes. Event histories are shown for New England (blue), Mid-Atlantic (red), the southeastern US coast (turquoise; grey denotes oyster-bed events not used for reasons discussed by ref. 28 and in the Supplementary Information), the Gulf Coast (yellow) and the Caribbean (green). The horizontal width of shaded rectangles indicates the ±1σ age model uncertainties. Circles indicate historical hurricane events.

Figure 3 | Long-term Atlantic tropical cyclone counts. Modern Atlantic tropical cyclone counts (red) compared both with statistical model estimates of tropical cyclone activity based on modern instrumental (AD 1851–2006; black) and proxy-reconstructed (AD 500–1850; blue) climate indices and an estimate of basin-wide landfalling Atlantic hurricane activity (AD 500–1991) derived from regional composites of overwash sediments (green). All series were smoothed at multidecadal (>40-year) timescales. The sediment composite record was standardized to have the same mean and multidecadal variance as the statistical model estimates. Uncertainties for the statistical model estimates (grey shading, indicating 95% confidence intervals) take into account the uncertainty in the statistical model itself (grey shading), and—in the case of the proxy-reconstructed indices (grey shading), the additional uncertainty due to the uncertainties in the proxy-reconstructed climate indices. Uncertainties for the sediment composite record (thin dashed black curves indicating upper and lower limits of the 95% confidence interval) are derived from jackknifing of the full composite with respect to each of the five contributing regional estimates, as discussed in the text.

How do we expect hurricane activity to change?
Can global climate models give guidance about changes in Atlantic storm activity?
But, current computing power limits ability of global climate models to represent hurricanes.

Hurricane Rita (2005): orange grid is representative of current **global** climate model resolution.

Size of grid limited by power of computers.
Nonetheless, tropical storms are affected by *large-scale* conditions that today’s climate models *can* represent.

Factors that favor storm development and intensification:

- Warm ocean surface
- Cool upper atmosphere
- Low vertical wind shear
- Moist middle atmosphere
- etc.

Vertical wind shear

Help define potential intensity

cf. Emanuel, Holland
From increasing greenhouse gases, we expect tropics to warm over current century.

Models also indicate that upper atmosphere should warm much more than the surface.

What is net effect?
Projected 21st Century Changes in Vertical Wind Shear

Average of 18 models, Jun-Nov

Over swath of tropical Atlantic and East Pacific, increased wind-shear.

What is net effect of increased potential intensity and wind shear?

Vecchi and Soden (2007, GRL)
Three-step assessment of impact of global warming on strongest storms

1) Global climate model projects large-scale climate changes from changes in greenhouse gases and aerosols.

2) Regional model projects change in hurricane counts from climate model output.

3) Hurricane model projects change in most intense hurricanes from regional model output.
Frequency of weakest storm projected to decrease. Frequency of strongest storms may increase.

Projected Changes in Atlantic Hurricane Frequency over 21st Century
bars indicate best estimate, dots indicate alternative estimates.


2-March-2010
Gabriel Vecchi, NOAA/GFDL, Princeton, NJ
Temperature “threshold” of TC formation increases with global warming

Ocean temperature when cyclone forms:

Present climate

Warmed climate
We expect continued variation of tropical storm frequency

Projected Atlantic Tropical Storm Frequency

(source: Villarini et al (2010))
My current interpretation of evidence

• Observations: can’t reject possibility of no change in frequency
  – Data issues and short records
  – We will never know how many storms we didn’t see, or what they were like. We can only estimate it.

• Multiple factors affect change in hurricane activity:
  – Pattern of temperature changes is key.

• Projected changes depend on measure chosen, e.g.:
  – Atlantic TC Frequency: small change, possible decrease
  – Atlantic TC Intensity: projected increase

• Year-to-year and decade-to-decade variations will still exist.

• Increased coastal population and wealth: increased vulnerability

• Sea level rise: same storm greater potential impact.

• This is a topic of vigorous scientific inquiry.

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2-March-2010

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Key concepts

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• False choice: global warming OR climate variability

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One Temperature Predictor of Atlantic Hurricane Activity

Observed Activity
Absolute Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)
Two Temperature Predictors of Atlantic Hurricane Activity

Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)

2-March-2010
Gabriel Vecchi, NOAA/GFDL, Princeton, NJ
Two Statistical Projections of Atlantic Hurricane Activity

Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)
...Add Dynamical Projections of Atlantic Hurricane Activity

Observed Activity
Absolute Atlantic Temperature

Dynamical Model Projections

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)
High-Resolution Comprehensive models

Assess TC sensitivity to climate change in a physically-consistent manner

GFDL regional model simulation.

Knutson et al (2007, BAMS)

Models ranging in 100km to 18km resolution.

GFDL global model simulation.

Zhao, Held, Lin and Vecchi (2009, J. Climate)
Given “large-scale” conditions, high-resolution models can reproduce observed changes in hurricane frequency.

Use these models to assess impact of model-projected large-scale response to doubled CO2.

Hurricane Katrina Coupled Model Forecast
Aug 27 02:30 UTC

Courtesy Morris Bender and Tim Marchok, NOAA/GFDL
Hurricane models project increasing hurricane intensities and rainfall rates with greenhouse climate warming …

Sources: Knutson and Tuleya, *J. Climate*, 2004 (left); Knutson and Tuleya, 2008; Cambridge Univ Press (right).