Attribution, Prediction and Projection of Hurricane Activity Changes

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• How has hurricane activity changed?
• What has driven changes in hurricane activity?
• Tools to predict/project and understand hurricane activity changes
North Atlantic tropical cyclones

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

Figure: Tom Knutson

Emanuel (2007, J. Clim.)
North Atlantic tropical cyclones

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

Figure: Tom Knutson
Is the historical Atlantic TS record consistent with dynamical model projections of a weak (and possibly negative) sensitivity to warming?

Source: Emanuel (2006); Mann and Emanuel (2006) EOS. See also Holland and Webster (2007) Phil.Trans. R. Soc.A

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

Vecchi, Swanson and Soden (2008, Science)

Observed Activity
Relative Atlantic Temperature
Two Statistical Projections of Atlantic Hurricane Activity

Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)
Outline

• Tools:
  – Global climate models (with aside into lapse-rates)
  – High-resolution dynamical models
  – Observational records
  – Statistical models

• Attribution of recent increase in Atlantic activity
• Predictions of seasonal activity
• Century-scale projections
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Can global climate models give guidance about changes in Atlantic storm activity?
Not directly: Current computing power limits ability of global climate models to represent hurricanes...

But GCMs can give large-scale conditions that influence hurricane activity (e.g., shear, potential intensity (PI), SST, etc)

Hurricane Rita (2005): orange grid is representative of IPCC-AR4 *global* climate model resolution.
Projected 21st Century Changes in Vertical Wind Shear

Average of 18 models, Jun-Nov

“storm-friendly”  “storm-hostile”

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)
Bister and Emanuel (1998) Potential Intensity

\[ PI^2 = V_{red}^2 c_k \frac{T_s - T_o}{T_o} \left( k_s^* - k_a \right) \left| r_{max} \right| \]

- Defined locally from a sounding and SST.
- All other things equal: SST increase -> PI increase
  Both through direct impact on \( T_s \) and \( k^* \), as well as indirectly impacting \( T_o \) and \( k_a \)
- However, remote SST changes impact upper tropospheric temperature (e.g., Sobel et al 2002) changing \( T_o \) directly and indirectly, and enthalpy diff. indirectly: remote warming acts to reduce PI.


From GCMs, \( PI' - \langle PI' \rangle \sim 8 \cdot (SST' - \langle SST' \rangle) \)
In GCMs, \( |\langle PI' \rangle| \) smaller than \( |PI'| \), so \( PI' \sim 8 \cdot (SST' - \langle SST' \rangle) \)
Potential intensity tracks SST relative to tropical-mean, not local SST*

*global-mean PI changes still need to be explained, more soon.

Vecchi and Soden (2007, Nature)
Bister and Emanuel (1998) Potential Intensity

\[ PI^2 = V_{red}^2 \frac{c_k}{c_d} \frac{T_s - T_o}{T_o} \left( k_s^* - k_a \right) \]

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Model recovers many aspects of observed hurricane tracks

Observed

C180 Model

Zhao et al (2009, J. Climate)
GFDL C-X HiRAM GCMs

Family of global atmospheric models designed for better-representing tropical cyclone frequency. C90 - 1°, C180=1/2°, C360=1/4°, C720=1/8°

Adapted from AM2 with:

• Deep convection scheme adapted from Bretherton, McCaa and Grenier (MWR, 2004)
• Cubed sphere dynamical core
• Changes to parameterizations of cloud microphysics
• C90 Atm. resolution of 1°x1°

Idealized Forcing Experiments

If local SST the dominant control, as opposed to relative SST:

• Similar Atlantic Response to Atlantic and Uniform F’cing
• Little Pacific Response to Atlantic compared to Uniform
North Atlantic Response to Idealized SST

Change in Annual NA Storms from Idealized SST:
NATL, GLO, EQU

Atlantic Forcing

Uniform Forcing

Near-equatorial Forcing

Similar TS frequency response to:
0.25° local warming
4° global cooling

Vecchi et al (2010, in prep.)
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Clear increase in recorded number of Atlantic tropical storms since late-19th century

Ability to observe cyclones has also changed with time: e.g., ship track density

“Missing storm” adjustments to HURDAT storms (1878-2007)

Atlantic tropical storms (< 2 day duration) show a strong trend. Storms of >2 day duration - adjusted for “missing storms” - do not show a trend.

Adapted from Landsea et al (2010, J. Climate)
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Statistical models of TS frequency

Villarini, Vecchi and Smith (2010, MWR, Submitted)

• Build statistical models of TS frequency:
  • >2 day duration basin-wide with and without adjustment
  • Landfalling

• Explore range of models, sensitivity to:
  • Possible covariates:
    (NAO, SOI, Atlantic SST, Tropical SST)
  • Model structure (Poisson vs. Negative Binomial).
  • Penalizing criterion for extra predictors (SBC vs. AIC).
  • SST dataset (Extended NOAA vs. HadISST)

• Apply to GCM projections and other runs.
Tropical SST as predictor of cyclone activity?

• Remote SST changes impact Atlantic wind shear:
  – During El Niño (e.g., Gray 1975)
  – Warming-induced weakening of Walker circulation increases shear (Vecchi and Soden 2007)
  – Warming of Indo-West Pacific increases shear (Latif et al 2007, GRL)

• Remote warming acts to increase thermodynamic stability:
  – WTG hypothesis (Sobel et al 2002)
  – During El Niño, remote thermodynamic stabilization acts to damp NA Activity (Tang and Neelin 2004)
  – Potential intensity strongly influenced by warming relative to tropical-mean (Vecchi and Soden 2007, Ramsay and Sobel 2010-submitted)

• High-resolution studies indicate warming relative to tropical-mean relevant quantity:
Build statistical model of basin-wide tropical storms using Atlantic and Tropical-mean SST as covariates

Atlantic SST increases frequency.

Tropical-mean SST reduces frequency.

Factors in fit (w/standard error)

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<th>Uncorrected</th>
<th>Corrected</th>
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<td>Intercept</td>
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<td>2.11 (0.03)</td>
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<td>1.05 (0.15)</td>
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<td>-0.91 (0.20)</td>
<td>-1.05 (0.19)</td>
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</tbody>
</table>

Villarini, Vecchi and Smith (2010, MWR, Submitted)
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Change in Atlantic TS Frequency* Since 1982

* lasting two days or more

- TS Frequency and Variance has unambiguously increased since 1982.
- HiRAM AGCM Captures shift

Vecchi et al (2010, in prep.)
AGCM with and without tropical-mean SST change

100km AGCM

Vecchi et al (2010, in prep.)
1982-94 and 1995-2007 PDFs of NA TS Count*

★ 2005 Observed

★ lasting two days or more

Vecchi et al
(2010, in prep.)
Shift in mean TS counts attributable to “AMO” SST change across 1994-1995

What drove this SST change? Internal variability? Aerosols? Combination?


Response to decadal shift

Response to “AMO” forcing

AMO Index: Regression of SST onto NA SST
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Retrospective NA Hurricane Forecast With Persisted June SSTA

FCST
\[ r = 0.69 \]

AMIP
\[ r = 0.78 \]

Zhao, Held and Vecchi (2010, MWR Submitted)
Statistical downscale using SST-<SST> of GFDL experimental seasonal forecast system built on CM2.1: Initialized January

<table>
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<tr>
<th>Obs.</th>
<th>Fcst.</th>
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<tbody>
<tr>
<td>Observed Hurricane frequency</td>
<td>Retrospective forecast</td>
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<td>r=0.7</td>
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Hurricane frequency vs. years (1985-2005)
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21st Century Hurricane Activity Change: Four possibilities

Red/yellow = increase
Blue/green = decrease

Regional increase/decrease much larger than global-mean.
Pattern depends on details of ocean temperature change.

Sensitivity of response seen in many studies

e.g., Emanuel et al 2008, Knutson et al 2008, etc

Adapted from Zhao et al. (2009, J. Climate)
Divergence of 21st Century projections of TS Frequency Change

• Even sign of relationship between GHG and NA TS frequency unclear:
  – Not big help in decadal predictability

Anthropogenic-Influence: Projected Changes in NA TS Frequency


Is there any consistency in the various projections?
Dynamical models exhibit consistent relationship to MDR and tropical SSTs - all consistent with observations

Poisson model of 2-day duration TS (vertical) vs. dynamical downscaling results (horizontal)
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)
Strongest cyclones projected with double downscaling

Global Climate Models -> Regional Model -> Hurricane model

Large-scale  TS Frequency  Intensity
Overall frequency decrease, but strongest storms may become more frequent

Adapted from Bender et al (2010, Science)
Summary

- It is premature to conclude that human activity (particularly CO2) has already had an impact on Atlantic TS/HU frequency or PDI.
  - Cannot reject null that frequency has not changed over century-scale (no detection)
  - Competing dependence on SST (local and remote) prevents two-step attribution
  - Not clear that “committed warming” adds to decadal TC predictability

- Atlantic basin-wide activity controlled by SST changes in the Atlantic relative tropics:
  - Need to attribute and predict pattern of SST change
  - To develop confidence in predictions must understand mechanisms: what controls regional SST patterns? (for CO2 response see LeLoup and Clement 2009 GRL, Xie et al 2010 J. Clim.).

- 1994-95 change in mean TS freq. attributable to “AMO-ish” SST change
  - What drove SST?
  - When can we expect it to swing back (or even further out)? Are last few years sign of end?
  - What about shift in variance?

- Forecasts feasible using rel-SSTA from June (persistence) and January (using CGCM)

- Dynamical projections disagree largely due to different large-scale inputs:
  - Consistent sensitivity to relative warming and with historical record

- Atlantic: Little change to frequency (possibly fewer) but increase in intensity.

- Big question remains: what about vertical changes in atmospheric temperature?
What about tropical-mean PI change?

Not well constrained by SST changes

Vecchi and Soden (2007, Nature)
Tropical-mean surface enthalpy disequilibrium seems to set scale

\[ \text{PI} = \langle k^* - k \rangle \cdot (\frac{<TA>}{<SST>} - 1.97) \]

Relationship explains:
- IPCC-AR4 model decadal noise and response to 2xCO2, 4xCO2.
- NCEP Reanalysis trend.
Do we know vertical structure of warming well enough? Relatively small inter-model TA trend spread still gives large $<P_L'>$ spread ($\pm 2m/s$)

For now: assume GCM lapse rate response “reasonable” estimate.

Relative warming impacts precipitation: GFDL CM2.1 21st Century Projection

Precip change from non-uniform warming looks like SST pattern.

Precip change from uniform warming looks like mean precip.

Xie et al (2010)
Tropical storm duration exhibits a large decrease, even with adjustment: why?

From HurDay (unadjust) { 5-Year Trend = -1.8 days-Century$^{-1}$

After adjustment { 5-Year Trend = -1.2 days-Century$^{-1}$

HiRAM models can recover trends and variations in hurricane and TS frequency when forced with SST.

Correlation to obs. similar to that of model to itself.

For each basin:

\[ N'(t) = N_m(t) \cdot \frac{<N_o>}{<N_m>} \]

Trend of normalized model counts not distinguishable from obs.

Zhao et al (2010, J. Climate)
Simple statistical seasonal forecast persisting June relative SSTA performs well

Linear regression on June relative SSTA recovers much of persisted SSTA GCM hurricane frequency predictions.

Zhao, Held and Vecchi (2010, MWR Submitted)
NCEP and GCMs exhibit different lapse rate and PI trends
In GCMs, sign of sensitivity of tropical-mean PI scales with ratio of Tropospheric TA to SSTA

\[ \text{PI} = K \cdot (\frac{\text{TA}}{\text{SST}} - 1.97) \]

Where does magnitude (K) come from? Not a constant.
There is some recent evidence that overall Atlantic hurricane activity may have increased since in the 1950s and 60s in association with increasing sea surface temperatures…

PDI is proportional to the time integral of the cube of the surface wind speeds accumulated across all storms over their entire life cycles.

Source: Emanuel (2007)
Observed Activity Absolute MDR SST
If causal, can attribute to GHG.

e.g. CCSP-3.3

Storm count*duration has been a control of historical PDI changes (Maue and Hart (2007))

Vecchi, Swanson and Soden (2008, Science)
Observed Activity

Absolute MDR SST
If causal, can attribute to GHG.

Relative MDR SST
If causal, cannot attribute.

Vecchi, Swanson and Soden (2008, Science)
Atlantic Tropical Cyclone Power Dissipation Index Anomalies: Observed and Based on Sea Surface Temperature

Anomalies relative to 1981-2000 average: $2.13 \times 10^{-3}$ m$^2$s$^{-1}$

**Observed Activity**

**Absolute SST**

**Model Abs. SST**

**High-resolution model activity change**

Emanuel et al (08), Knutson et al (08), Oouchi et al (06), Bengtsson et al (07)

**Relative SST**

**Model Rel. SST**

*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)
NOAA ATTRIBUTES RECENT INCREASE IN HURRICANE ACTIVITY TO NATURALLY OCCURRING MULTI-DECADAL CLIMATE VARIABILITY*

Nov. 29, 2005 — The nation is now wrapping up the 11th year of a new era of heightened Atlantic hurricane activity. This era has been unfolding in the Atlantic since 1995, and is expected to continue for the next decade or perhaps longer. NOAA attributes this increased activity to natural occurring cycles in tropical climate patterns near the equator. These cycles, called “the tropical multi-decadal signal,” typically last several decades (20 to 30 years or even longer). As a result, the North Atlantic experiences alternating decades long (20 to 30 year periods or even longer) of above normal or below normal hurricane seasons. NOAA research shows that the tropical multi-decadal signal is causing the increased Atlantic hurricane activity since 1995, and is not related to greenhouse warming.

Research by NOAA scientists [...] and [...], currently in press with the *Journal of Climate*, describes the tropical multi-decadal signal and shows that it accounts for the entire inter-related set of conditions that controls hurricane activity for decades at a time.
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*EDITOR’S NOTE:* This consensus in this on-line magazine story represents the views of some NOAA hurricane researchers and forecasters, but does not necessarily represent the views of all NOAA scientists. It was not the intention of this article to discount the presence of a human-induced global warming element or to attempt to claim that such an element is not present. There is a robust, on-going discussion on hurricanes and climate change within NOAA and the scientific community.
Katrina's real name

By Ross Gelbspan | August 30, 2005

THE HURRICANE that struck Louisiana yesterday was nicknamed Katrina by the National Weather Service. Its real name is global warming.
News search on global warming and impacts
Two Statistical Projections of Atlantic Hurricane Activity

Observed Activity
Absolute Atlantic Temperature

Observed Activity
Relative Atlantic Temperature

Vecchi, Swanson and Soden (2008, Science)