Hurricane Predictions and Projections

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Image: NASA.
Summary

• Premature to conclude we have seen hurricane change due to CO$_2$

• Models allow estimates of future activity:
  • Next couple of decades: internal variability dominant player (some may be predictable, some not)
  • NA Hurr. Response to CO$_2$: maybe fewer, probably stronger.
  • Aerosol forcing and response a key to next few decades.

• Encouraging results from long-lead (multi-season and multi-year) experimental forecasts using hybrid system:
  “past performance no guarantee of future returns”
  but good past performance nice start…

• High-resolution coupled and atmospheric models enable the next generation of hurricane prediction and projection.
Outline

• Historical hurricane records
• Projecting decadal to centennial hurricane activity
• Predicting seasonal hurricane activity
• Predicting multi-year hurricane activity
Historical Hurricane Records

Adjustments to storm counts based on ship/storm track locations and density

Landsea et al. (2009, J. Clim.)
Vecchi and Knutson (2011, J. Clim.)
Villarini et al. (2011, J. Clim.)
U.S. Landfalling Hurricanes

Basinwide Hurricanes

Fraction of Basinwide Hurricanes Making U.S. Landfall

Sources of & Limitations on climate predictability

Climatology
(what happens typically, including randomness)
need good observations

Evolution of initial conditions
(e.g., weather or El Niño forecast)
need good observations, models, initialization schemes

Climatology
Climate response to forcing
(e.g., CO₂, aerosols, sun, volcanoes)
need good models and estimates of forcing
In each grid cell:

- conserve momentum (F = m · a)
- account for changes in mass and composition
- conserve energy (radiation, latent, etc.)

“Force” with solar radiation, structure of continents and atmospheric composition (e.g., CO₂)

Models have land, ocean, atmosphere and ice components. Each encapsulates our best understanding of underlying processes controlling its evolution.
GCM Projections of 21st Century Changes in Large-Scale Environment

Based on 21 global climate models

Vecchi and Soden (2007, Nature)
But, current computing power limits ability of coupled global climate models to represent hurricanes.

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

Size of grid limited by power of computers.
“Downscale” Climate Model Projections With High-Resolution or Statistical Models

Global Climate Models $\rightarrow$ High-resolution Model

Large-scale $\rightarrow$ TS Frequency
Downscaling techniques for TC activity

- High-resolution global dynamical models (e.g., GFDL-HiRAM)
- High-resolution regional dynamical models (e.g., GFDL-ZETAC)
- Statistical models (e.g., $\text{Freq} = F(\text{SST}, \text{shear}, \ldots)$)
The GFDL High-Resolution Atmosphere Model (HiRAM)

- Non-hydrostatic Finite-Volume dynamical core on the cubed-sphere

- Designed for resolution between 1–100 km, capable of direct cloud simulation

- A PDF based 6-category cloud micro-physics with finite-volume vertical sub-grid reconstruction allowing vertically & horizontally sub-grid cloud formation

- A “non-intrusive” shallow convective parameterization (Bretherton scheme modified by Zhao et al. 2009)

- Options to couple with ocean and wave models

Slide: S-J Lin
Geographical distribution of TC tracks (1981-2009)

Observation

HiRAM-C180 AMIP simulation

Zhao et al. (2009)
Response of TC frequency in single 50km global atmospheric model forced by four climate projections for 21st century

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

*Adapted from Zhao et al. (2009, J. Climate)*

e.g., Emanuel et al. 2008, Knutson et al. 2008, Sugi et al. 2010, Villarini et al. 2011, Knutson et al. 2013, etc.
Use homogenized data and high-res models to build statistical models for exploration and projections.

\[ \text{Rate} = e^{a + bSST_{\text{ATL}} - cSST_{\text{TRO}}} \]

Family of statistical models based on observed and high-res. model hurricane activity and SST.

Use two predictors:
- Tropical Atlantic SST (positive)
- Tropical-mean SST (negative)

Consistent with high-res dynamical models, understanding on controls to hurricanes & “cheap”.

Projections of North Atlantic TS Count Trends Using Observationally-based Statistical Model and SST Projected by 23 CGCMs

Simple statistical model explains much of the spread across many high-res modeling studies

Differences in projected patterns of surface warming drive large uncertainties in hurricane projections

\[ \text{Rate} = e^{a + bSST_{\text{ATL}} - cSST_{\text{TRO}}} \]

Knutson et al. (2013, J. Clim.)
See also Villarini et al. (2011, J. Clim.)
Vecchi et al. (2008, Science)
Dynamical Projections of Atl. Hurricanes for end of 21st Century

Using GFDL-HiRAM

Adapted from Zhao et al. (2009, J. Clim.) and Held et al. (2013, submitted)
GFDL-CM3 indicates aerosols key for NA TS projections (projected aerosol clearing -> more storms)

Villarini and Vecchi (2012, Nature C.C.)

All Forcing
No future aerosol or O$_3$
No future aerosol
Global Climate Models $\rightarrow$ High-Res Model $\rightarrow$ Hurricane model

- Large-scale
- TS Frequency
- Intensity
Dynamical double downscaling for Atlantic: Overall **frequency decrease** projected, but **more of the strongest storms**

Adapted from Bender et al (2010, Science)
see also Knutson et al. (2008, Nature Geosci.); Knutson et al. (2013, J. Clim., in press)

<table>
<thead>
<tr>
<th>Change in number of storms per decade</th>
<th>Trop. Storm+</th>
<th>Cat. 2+3 Hurricane</th>
<th>Cat. 4+5 Hurricane</th>
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<td>-15</td>
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Projections of reductions in atmospheric aerosols contribute to projected increases in Atlantic hurricane activity.

Power Dissipation Index

\[ PDI = \sum_{\text{storms}} U_{\text{max}}^3 \]

Villarini and Vecchi (2013, J. Climate)
See also Knutson et al. (2013, J. Climate)
Historical aerosol forcing may have masked century-scale greenhouse-induced intensification in Atlantic storms.

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Villarini and Vecchi (2013, J. Climate)
Seasonal Hurricane Prediction

- What can we say about the character of the upcoming hurricane season months or seasons in advance?
25km HiRAM Seasonal hurricane predictions – initialized July 1

1990-2010 (Jul-Nov)

North Atlantic Basin (Hurricanes)

Resolution: 25 km, 32 levels
- 5-members initialized on July 1 with NCEP analysis
- SST anomaly is held constant during the 5-month predictions
- Climatology O3 & greenhouse gases are used

1. Chen and Lin 2011, GRL
2. Chen et al., submitted
Merge multiple tools and understanding to build experimental long-lead hurricane forecast system: skill from as early as October of year before.

Hi-Res AGCM in many different climates. Count storms.

Build statistical model of the response of hurricanes in HiRAM.

Use initialized coupled model to forecast future values of SST.

Initialized January: \( r=0.66 \)

April & onward forecasts fed to NOAA Seasonal Outlook Team.

HyHuFS

Observed  Ensemble-mean  Ensemble member

90% range  75% range  50% range

Seasonal Number of Atlantic Hurricanes

Seasonal Number of Atlantic Hurricanes


Make Prediction of Full PDF of Hurricane Activity

http://gfdl.noaa.gov/HyHuFS

Vecchi et al. (2011); Villarini and Vecchi (2012, submitted)
But, current computing power limits ability of coupled global climate models to represent hurricanes.

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

Size of grid limited by power of computers.
Resolution (computer power, good models & hard work) can help represent processes and phenomena.

Medium resolution (CM2.1)

High resolution (CM2.5)

Adapted from Delworth et al. (2012, J. Clim.)
Response of TCs in high-resolution global coupled model (GFDL CM2.5, Delworth et al. 2012, J. Climate; Kim et al. 2013 in prep.)

Observed Tracks

Coupled Model Tracks

CM2.5 Tropical storm density response to CO$_2$ doubling

More storms

Fewer storms
Key uncertainty sources to projections of decadal TS activity

Sources of uncertainty (after Hawkins and Sutton, 2009)

- **Variability**: ~independent of radiative forcing changes
- **Response**: “how will climate respond to changing GHGs & Aerosols?”
- **Forcing**: “how will GHGs & Aerosols change in the future?”
Simulated Atlantic Sea Surface Temperature
(based on GFDL CM2.1)

Can we predict the trajectory of Atlantic temperatures over the next several decades?

How about hurricane activity?

Slide: Tom Delworth (GFDL)
Sources of & Limitations on climate predictability

Decadal/multi-year prediction: New efforts focused mixed initial/boundary value problem

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  (what happens typically, including randomness)
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Experimental decadal predictions
Hybrid system: statistical hurricanes, dynamical decadal climate forecasts

- Retrospective predictions encouraging.
- However, small sample size limits confidence.
- Skill arises more from recognizing 1994-1995 shift than actually predicting it.
- This is for basinwide North Atlantic Hurricane frequency only.

**EXPERIMENTAL: NOT OFFICIAL FORECAST**

Vecchi et al. (2013 in press), see also Smith et al. (2010, Science)
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Removing observational inhomogeneity removes post-2004 upswing: need stable, sustained observations

Vecchi et al. (2013 in press)
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Vecchi et al. (2013 in press); Msadek et al. (2013, submitted)
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References

- Villarini, G. and G.A. Vecchi (2012.c): Seasonal Forecast of the North Atlantic Power Dissipation Index (PDI) and Accumulated Cyclone Energy (ACE), Sumbitted to J. Climate