Hurricanes: Their physics and relationship to climate

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Topics

- Overview of Tropical Cyclones
- Tropical Cyclone Physics
- What have TCs been like in the past, and how will they be affected by global warming?
Brief Overview of Tropical Cyclones
The View from Space
Hurricane Structure: Wind Speed

Azimuthal component of wind

< 5 m/s - > 70 m/s
Vertical Air Motion

Updraft Speed

Strong upward motion in the eyewall
Hurricane Temperature Perturbations

No temperature difference -> 16°C (29°F) warmer
Tropical Cyclones, 1945–2006

Saffir-Simpson Hurricane Scale:
- tropical depression
- tropical storm
- hurricane category 1
- hurricane category 2
- hurricane category 3
- hurricane category 4
- hurricane category 5
Annual Cycle of Tropical Cyclones

Northern Hemisphere (NH)
Southern Hemisphere (SH)

Number of Events per Month

Jan Feb Mar Apr May Jun Jul Aug Sep Oct Nov Dec NH
Jul Aug Sep Oct Nov Dec Jan Feb Mar Apr May Jun SH
Physics of Mature Hurricanes
Distribution of Entropy in Hurricane Inez, 1966

Source: Hawkins and Imbembo, 1976
Carnot Theorem: Maximum efficiency results from a particular energy cycle:

- Isothermal expansion
- Adiabatic expansion
- Isothermal compression
- Adiabatic compression

Note: Last leg is not adiabatic in hurricane: Air cools radiatively. But since environmental temperature profile is moist adiabatic, the amount of radiative cooling is the same as if air were saturated and descending moist adiabatically.

Maximum rate of energy production:

\[ P = \frac{T_s - T_o}{T_s} \dot{Q} \]
Theoretical Upper Bound on Hurricane Maximum Wind Speed:

\[ |V_{pot}|^2 \approx \left( \frac{C}{k} \right)^2 \left( \begin{array}{c} T - T_s \\ C - T_o \\ 0 \end{array} \right) \begin{pmatrix} k & * & -k \\ 0 & \end{pmatrix} \]

- \( V_{pot} \): Potential wind speed
- \( C, k \): Exchange coefficients of enthalpy and momentum
- \( T, T_s, T_o \): Surface, outflow, and temperature
- \( C, D \): Coefficients
- \( k, * \): Ratios of exchange coefficients
- \( * \): Air-sea enthalpy disequilibrium
Maximum Wind Speed (m/s)

$\mathcal{H} = 0.75 \quad \frac{C_k}{C_D} = 1.2$
Hurricanes and Climate: Some Empirical Results
Intensity Metric:

Hurricane Power (Power Dissipation Index)

\[ PDI \equiv \int_{0}^{\tau} V_{\text{max}}^3 \, dt \]

A measure of the total frictional dissipation of kinetic energy in the hurricane boundary layer over the lifetime of the storm.
Atlantic Tropical Cyclone Power Dissipation during an era of high quality measurements, 1970-2011 (smoothed with 1-3-4-3-1 filter)
Atlantic Tropical Cyclone Power Dissipation and Sea Surface Temperature during an era of high quality measurements, 1970-2011 (smoothed with 1-3-4-3-1 filter)

$r^2 = 0.87$
Use Linear Regression to Predict Power Dissipation back to 1870 based on sea surface temperature:
Now Compare to Observed Power Dissipation

Predicted vs Observed Atlantic Power Dissipation

$r^2 = 0.60$
Tropical cyclone power dissipation has more than doubled since the 1980s, though there has been an increase of only 0.5° C in sea surface temperature.
What is Causing Changes in Tropical Atlantic Sea Surface Temperature?
10-year Running Average of Aug-Oct Northern Hemisphere Surface Temp and Hurricane Region Ocean Temp
Tropical Atlantic SST (blue), Global Mean Surface Temperature (red), Aerosol Forcing (aqua)

Best Fit Linear Combination of Global Warming and Aerosol Forcing (red) versus Tropical Atlantic SST (blue)

The Genesis Puzzle
Global Tropical Cyclone Frequency, 1980-2011

Global Number of Tropical Cyclones

Data Sources: NOAA/TPC and NAVY/JTWC
Tropical Cyclones Often Develop from Cloud Clusters: When/Why Does Convection Form Clusters?
Monsoonal Thunderstorms, Bangladesh and India July 1985
Simplest Statistical Equilibrium
State:
Radiative-Convective Equilibrium
Vertically integrated water vapor at 4 days (Nolan et al., QJRMS, 2007)
Vertically integrated water vapor at 4 (a), 6 (b), 8 (c), and 10 (d) days  (Nolan et al., QJRMS, 2007)
Variation of tropical relative humidity profiles with a Simple Convective Aggregation Index (SCAI).

_Courtesy Isabelle Tobin, Sandrine Bony, and Remy Roca_
Empirical Necessary Conditions for Self-Aggregation
(after Held et al., 1993; Bretherton et al., 2005; Nolan et al.; 2007)

- Small vertical shear of horizontal wind
- Interaction of radiation with clouds and/or water vapor
- Feedback of convective downdraft surface winds on surface fluxes
- Sufficiently high surface temperature
Self-Aggregation is Temperature-Dependent
(Nolan et al., 2007; Emanuel and Khairoutdinov, in preparation, 2012)
Extension to Rotating Planet

Distance between vortex centers scales as $V_{pot}/f$.
TC-World Scaling

- Frequency $\sim \frac{f^2}{V_{pot}^2}$
- Intensity $\sim V_{pot}$
- Power Dissipation $\sim V_{pot} f^2$
Hypothesis

- At high temperature, convection self-aggregates
  - Horizontally averaged humidity drops dramatically
  - Reduced greenhouse effect cools system
  - Convection disaggregates
  - Humidity increases, system warms
  - System wants to be near phase transition to aggregated state
Recipe for Self-Organized Criticality
(First proposed by David Neelin, but by different mechanism)

- System should reside near critical threshold for self-aggregation
- Convective cluster size should follow power law distribution
Hypothetical Subcritical Bifurcation

PDF of weather noise

\[ V_{\text{max}} \]

Stable

Unstable

SST
Future Tropical Cyclone Risk
MIT Approach to Downscaling Tropical Cyclones from Climate Models

**Step 1:** Seed each ocean basin with a very large number of weak, randomly located vortices

**Step 2:** Vortices are assumed to move with the large scale atmospheric flow in which they are embedded

**Step 3:** Run a coupled, ocean-atmosphere computer model for each vortex, and note how many achieve at least tropical storm strength; discard others

**Step 4:** Using the small fraction of surviving events, determine storm statistics.
60 Synthetic U.S. Landfalling tracks (color coded by Saffir-Simpson Scale)
Wind Swath

New York
Track number 602

Knots

20 30 40 50 60 70 80 90
Accumulated Rainfall (mm)

Newyork
Track number 602
Cumulative Distribution of Storm Lifetime Peak Wind Speed, with Sample of 1755 Synthetic Tracks

90% confidence bounds
Application to Future Climates

- Apply to global climate model simulations run in support of the upcoming IPCC report
- Run for historical simulations, 1950-2005
- Run for CMIP5 emissions scenario RCP 8.5
Application to Other Climates

Federov et al., 2010
Hurricanes are giant Carnot heat engines that convert thermal energy into wind.

Tropical cyclones may be a subclass of aggregated convection, which may tend toward self-organized critical states, thus stabilizing tropical climate.
Simple but high resolution coupled TC model can be used to ‘downscale’ TC activity from global climate data sets.

Hurricane power is increasing in the Atlantic and is projected to increase globally as temperatures rise.