Attribution of Recent Increases in Atlantic Hurricane Activity

Kevin E Trenberth
NCAR
Issues for detection and attribution of changes in hurricanes

- What has happened?
- How good is the observational record?
- How should hurricanes change as climate changes?
- Are models adequate?
- What is the role of global warming?
- What is the role of natural variability?
- What do models reveal?
Ivan
15 Sept 2004
1850 UTC

Image courtesy of MODIS Rapid Response Project at NASA/GSFC
Katrina’s aftermath

Refugees in USA
Aug 31
North Atlantic Hurricanes 2005
A record breaking year:

- Strongest Gulf hurricane month of July (Dennis)
- Most named storms (27*: normal 10)
- First ever V, W, α, β, γ, δ, ε, ζ
- Strongest hurricane on record: Wilma (882 mb)
- Strongest hurricane in Gulf: Rita (897 mb)
- Most cat. 5 storms in season (4 vs 2 in 1960,1961)
- Deadliest hurricane in US since 1928 (Katrina)
- Costliest natural disaster in US history (Katrina)
  - Highest insured losses ~$40-60B vs Andrew $21B
  - Total losses ~$125-200B
  - 6 of the 8 most damaging occurred Aug 04-Oct05: Charlie, Ivan, Francis, Katrina, Rita, Wilma
- Hurricane Vince (October) first to hit Portugal/Spain

*Note: The number of hurricanes did not include the one in the Atlantic, which was counted as one hurricane.
Atlantic Tropical Cyclone Trends

North Atlantic Tropical Cyclones 1905-2005

- Individual Year
- Satellites
- 9-Year Running Mean
- Start of aircraft surveillance

Greg Holland
Atlantic Hurricane Trends

1995

Named Storms

Hurricanes

Cat 1+2

Cat 3-5

Greg Holland
Changes in hurricane frequency in the North Atlantic Ocean
Landfalling hurricanes are a very small fraction of all hurricanes and the sample is small. Where they make landfall is chance, and 10 miles (e.g., Andrew) can make a huge difference to damage.

The increased vulnerability of people with increased property value building in coastal zones, placing themselves in harms way, makes changes in hurricane intensity even more important.

100 years of tropical storm tracks in Atlantic
Hurricanes:

- Depend on SSTs > 26°C (80°F)
- High water vapor content
- Weak wind shear (or vortex comes apart)
- Weak static stability
- Pre-existing disturbance

Large variability year to year in individual basins.
El Niño means more action in Pacific, suppression in Atlantic
Large decadal variability in Atlantic
Better measure of tropical cyclone activity:

Power dissipation = \( 2\pi \int_0^\tau \int_0^{r_0} C_D \rho |V|^3 r \, dr \, dt \).

Simplified “Power Dissipation Index” (Emanuel 2005):

\[ PDI \equiv \int_0^\tau V_{max}^3 \, dt \]
Atlantic + western North Pacific

Courtesy: K. Emanuel
Revised
A large increase is seen in the number and proportion of hurricanes reaching categories 4 and 5. The largest increase occurs in the North Pacific, the Indian and Southwest Pacific oceans, and smallest increase in the North Atlantic Ocean.

From Webster et al (2005)
The Atlantic Multi-decadal Oscillation

AMO index defined by Enfield et al. (2001) as mean SST north of equator in Atlantic: then take 10 year running mean. Base period 1901-70.

But what about global SST warming?

More definitive AMO index

HADLEY: AMO (Warm Not Removed)

HADLEY: Global Annual Mean Anom

HADLEY: AMO (Warm Removed)
Atlantic SSTs in the range 10-20°N were 0.92°C above the 1901-70 normal, setting a new all-time record. This was due to weak trades and reduced LH fluxes.

Dec 2004 Nino3.4 was 0.9°C. Regression with Nino3.4 8 months later showed a 0.2°C increase in the Tropical Atlantic.

Global warming: 0.45°C
2004-05 El Niño: 0.2°C
AMO: <0.1°C

Trenberth et al 2002
Trenberth and Shea 2006
Modeled and Observed SST Changes in Tropical Cyclogenesis Regions

Monthly SST anomalies for (A) Atlantic and (B) Pacific tropical cyclogenesis regions: Observed (black) and 22 climate models. Model data are smoothed: 2 groups: with and without volcanic forcing (V and No-V) and end in 1999. The yellow and grey envelopes are 1 and 2 confidence intervals for the V averages.

Santer et al 2006

Is the variability realistic? Do the models simulate observed?
Models show signal to noise of natural variability is large: trend can only arise from increased GHGs:

Contribution of different external forcings to SST changes in the Atlantic (A) and Pacific (B) tropical cyclogenesis regions.

Results are from a 20CEN run and from single-forcing experiments performed with the Parallel Climate Model (PCM). Each result is the low-pass filtered average of a four-member ensemble.

Santer et al. 2006
Linear regression maps of T106 ECHAM5 AGCM simulated Atlantic TC vertical wind shear (200 -850 hPa) for regions given for 1870-2003. Color gives statistical significance (T-test). Biggest effect is from Pacific.

Latif et al 2006 GRL (see Aiyyer and Thorncroft 2006 JCI for obs)
What about 2006?

- La Nina in 2005-06 winter (vs El Nino 2004-05)
- Jan 2005: light winds, sunny
- Jan 2006: much stronger than normal winds
- SSTs below normal in west Atlantic earlier; warmed midway thru season
- Developing El Nino in Pacific
- Unfavorable conditions for TCs in Atlantic: wind shear etc.

Foltz and McPhaden, GRL 2006 show how the weak NE tradewinds, anomalous latent heat fluxes and solar radiation contributed to the record breaking SSTs in summer 2005
In the tropics, heat from the sun goes into the ocean and is apt to build up: Where does the heat go?

1) Surface heat cannot radiate to space owing to optically thick water vapor.

2) Heat goes from the ocean into the atmosphere largely through evaporation that is greatly enhanced in tropical storms. It moistens the atmosphere (latent energy) and cools the ocean.

3) Heat and moisture are transported to higher latitudes by extratropical cyclones and anticyclones (cold and warm fronts) mainly in winter.

4) Heat is transported upwards: in convection, especially thunderstorms, tropical storms, hurricanes and other disturbances. Energy and moisture from the surface is moved upwards, typically producing rain, drying the atmosphere, but heating it, and stabilizing the atmosphere against further convection.
Tropical ocean heat balance

- Incoming radiation
- Surface radiation
- Water vapor greenhouse radiation
- Heating
- Evaporation
- Cooling
- Ocean currents
- Surface flux
- Hot towers: convective heat transports up
- Latent heat
- Rain
In the tropics, heat from the sun is apt to build up:

4) There is a competition between individual thunderstorms and organized convection to transport heat upwards in the general atmospheric circulation.

5) Tropical storms are much more effective at cooling the ocean.
Cold wake from Katrina and Rita in Gulf of Mexico

SST in Gulf
Hypothesis:

Hurricanes play a key role in climate, but are not in models and are not parameterized.

Prospects are for more intense storms, heavier rainfalls and flooding, and coastal damage, but perhaps lower tropical ocean temperatures?
Hypothesis on effects from global warming

Water vapor over oceans increases \( \sim 7\% \) per K SST
- To first order, surface latent heat fluxes also increase by at least this amount as \( E \approx \rho CV q_s(Ts)(1-RH) \sim q_s(Ts) \)
- Convergence in boundary layer also should go up proportionately. \([q\uparrow, \omega\uparrow, v_r\uparrow \text{ and } v_r.q\uparrow \text{ squared}]\)
- Could also increase intensity: \( V \)
- Other feedbacks (friction, sea spray, stability etc)

Hence estimated rainfall, latent heating and water vapor in the storms should increased \( 1.07^2 = 1.14 \) or 14%. \([7 \text{ to } 21\% \text{ error bars}]\) per K.

For observed 0.5K increase in SST this means increases in rainfall and latent heat release in storms by order 7%.
Katrina experiments

- Given good track forecasts of Katrina, as well as the diagnostics of the energy and water budgets, we rerun the forecast simulations with SSTs changed by +1°C and -1°C.
- The control run has the central pressure 892 mb vs observed 902 mb:
  - +1°C: 870 mb: -22 mb
  - -1°C: 910 mb: +18 mb
- Max winds 58 m/s (-1) go to 70 m/s (+1)
- Order 10% per C
Precipitation is dominated by moisture convergence.
Surface flux of moisture is essential: amounts to >1500 Wm$^{-2}$.
Substantial increases with increasing SSTs: rain increased by 19%/K inside 400 km.
WRF Katrina results of surface fluxes as function of maximum wind at any grid point.
For 1990-2005: over 0-400 km radius ($5 \times 10^{11}$ m$^2$), ocean cooling is 0.52, 0.58, $1.84 \times 10^{22}$ J/yr, or 0.16, 0.185, 0.58 PW.
The results suggest an evaporative, total enthalpy, precipitation ocean cooling of: 0.16, 0.185, 0.58 PW over a year.

Over the tropical ocean 20°N to 20°S the LH is equivalent to 1.5 W m\(^{-2}\), or 1.1 °C/year over a 10 m layer.

Globally this is 0.36 and 1.13 W m\(^{-2}\) vs CO\(_2\) radiative forcing 1.5 W m\(^{-2}\).

It matters!
And it is not included in climate models.
Implications for climate models

1) In models, the thunderstorms and convection are not resolved and are dealt with by “sub-grid” scale parameterization.

2) However, most (all?) climate models have premature onset of convection, as seen in the diurnal cycle over land, and feature convection too often and with insufficient intensity. (cf Lin et al. 2006 J Cl)

3) This characteristic likely means that sub-grid scale convection is overdone at the expense of organized convection (MJO, tropical storms, etc; see Lin et al. 2006, JC).

4) Hence models likely under-predict changes in hurricanes.

5) Hurricanes are missing in models: SSTs may get too warm: increased TCs keep SSTs cooler.
Research questions for detection and attribution of changes in hurricanes

- Need to reprocess the satellite record.
- Need measures of activity: size, duration, intensity, rainfall, track, ACE, PDI etc
- How is TC environment changing and why?
- Models must improve in simulation of natural variability: ENSO, AMO, PDO
- Need to improve climate models: Resolution, precipitation (frequency, intensity, amount), atmospheric stability, convection (sub-grid scales), tropical transients (storms, MJO, easterly waves)
- Coupled problem: must have ocean model
- How to parameterize effects of hurricanes?