# Attribution of Recent Increases in Atlantic Hurricane Activity

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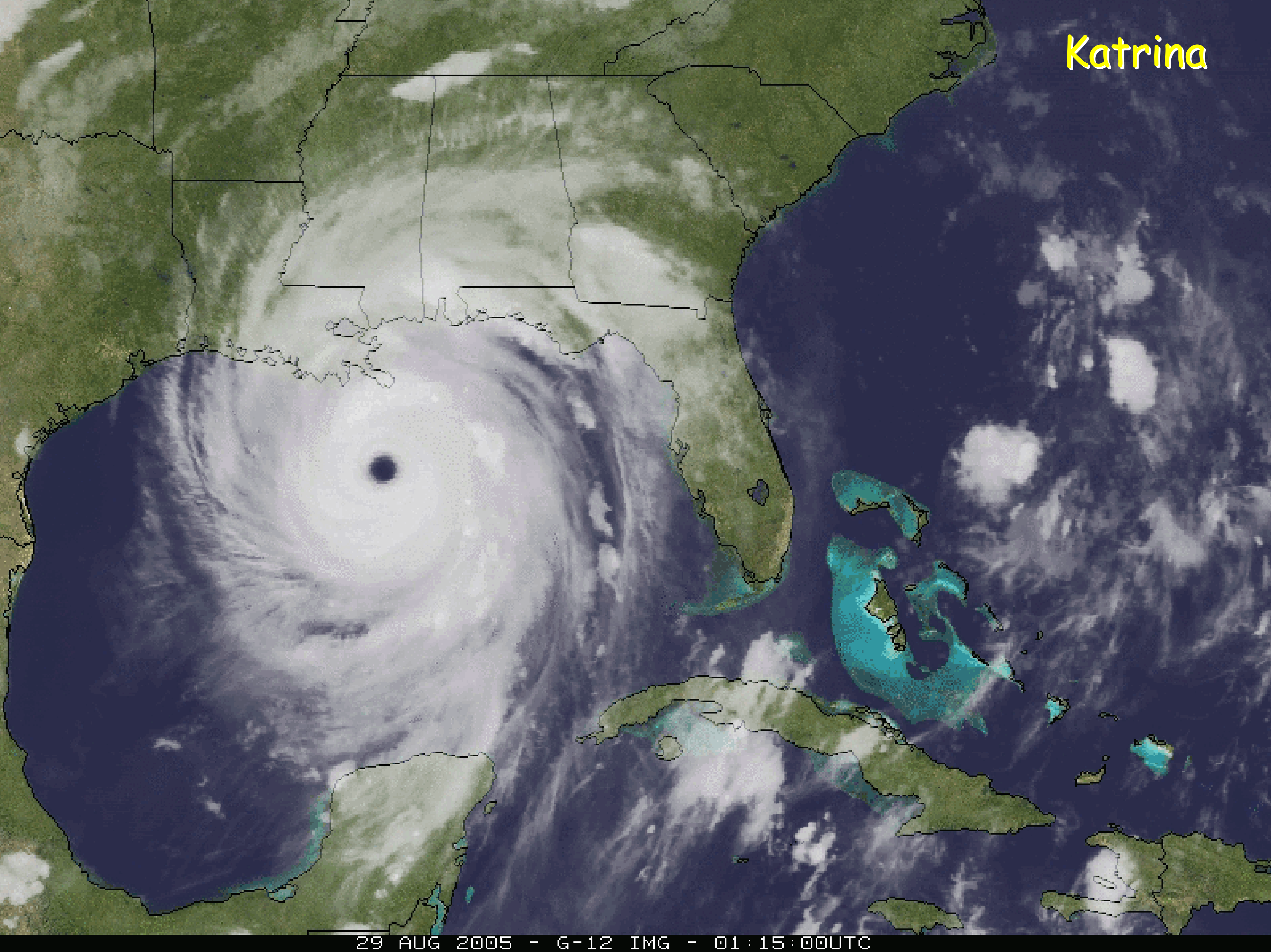
# Issues for detection and attribution of changes in hurricanes

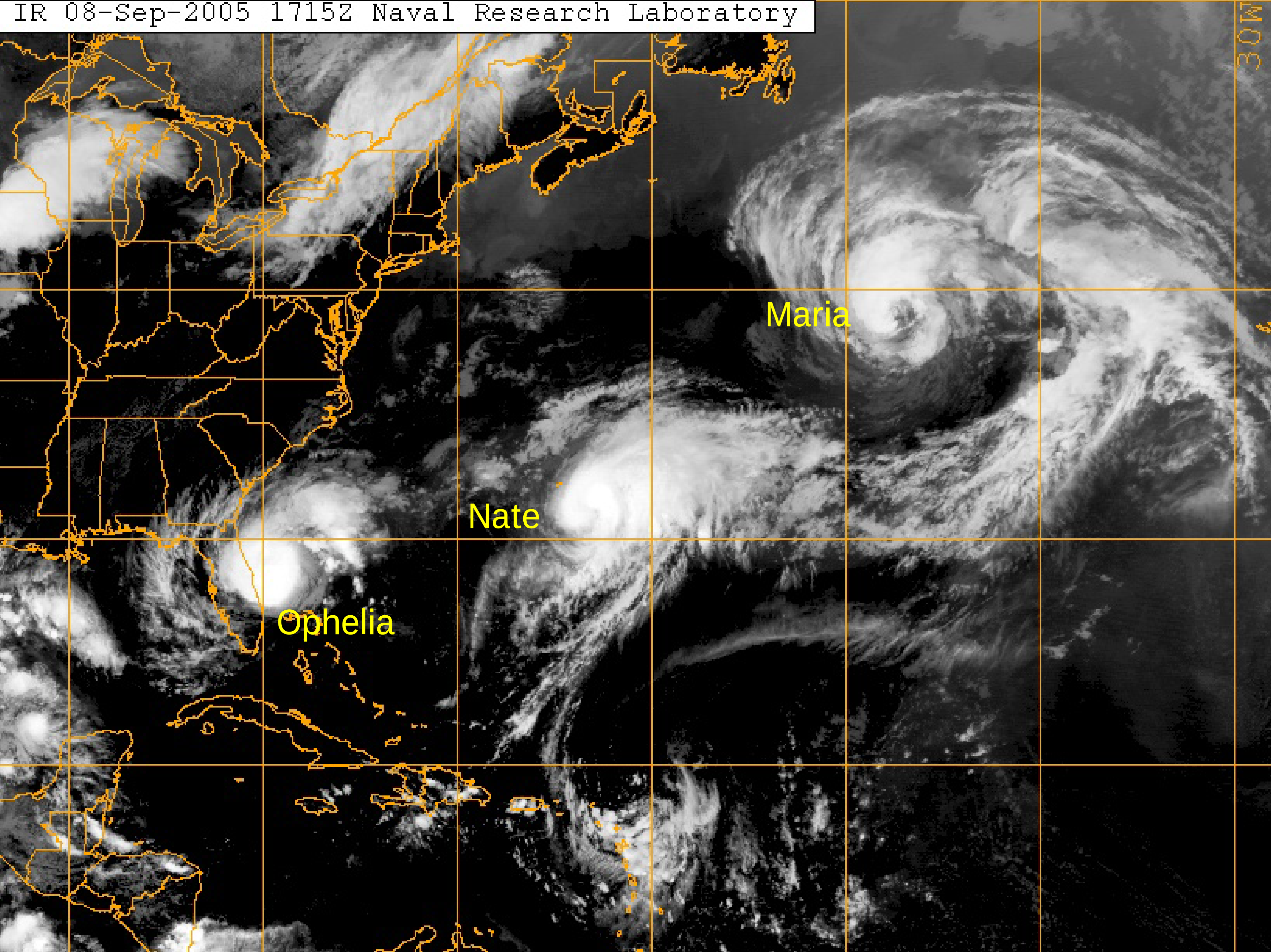
- What has happened?
- How good is the observational record?
- How should hurricanes change as climate changes?
- Are models adequate?
- What is the role of global warming?
- What is the role of natural variability?
- What do models reveal?

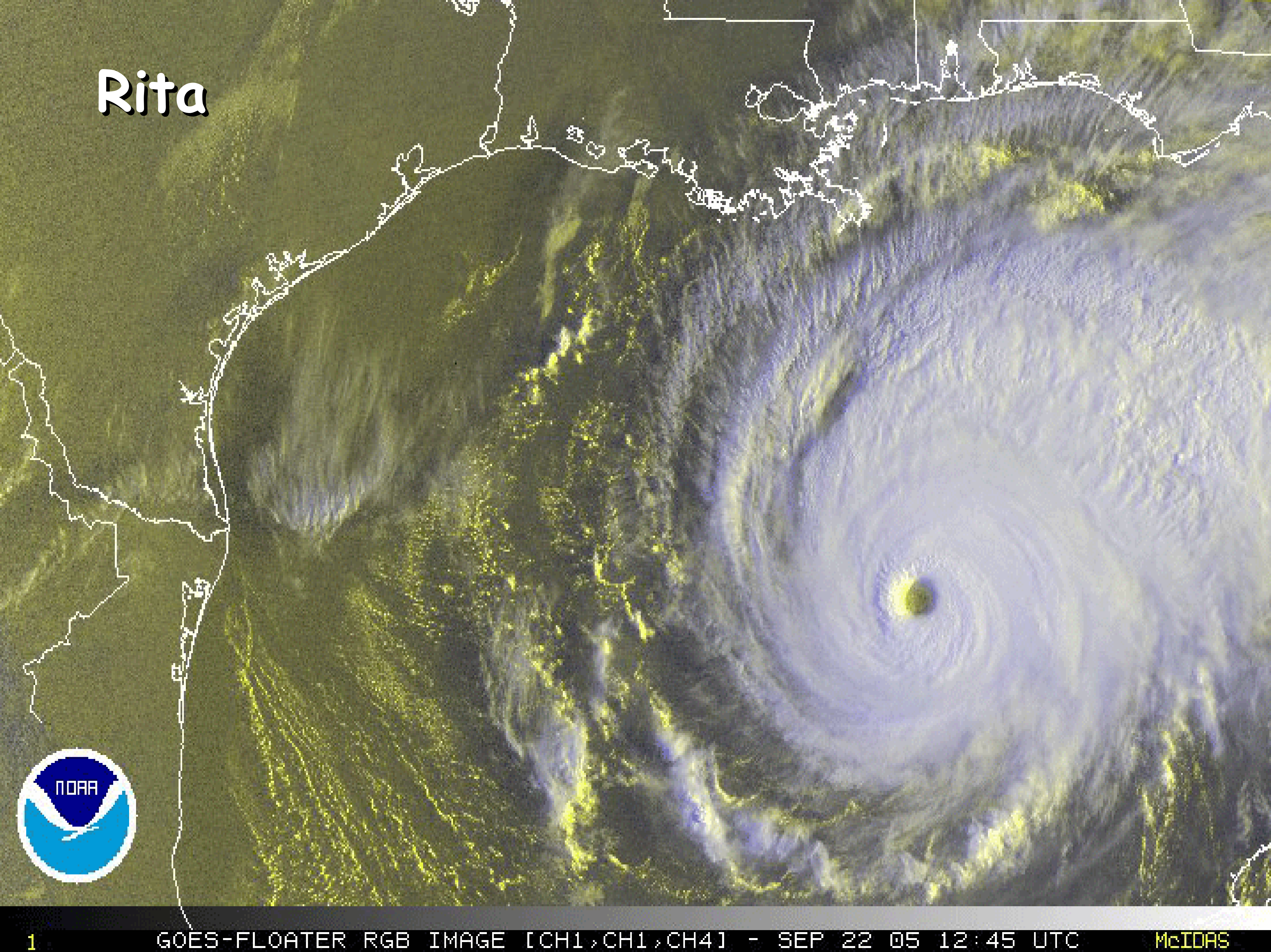

Image courtesy of MODIS Rapid Response Project at NASA/GSFC
Ivan
15 Sept 2004
1850 UTC


Katrina
29 AUG 2005 - G-12 IMG - 01:15:00UTC

# Katrina's aftermath

Refugees in USA Aug 31 ⇒


IR 08-Sep-2005 1715Z Naval Research Laboratory
30W
Maria
Nate
Ophelia

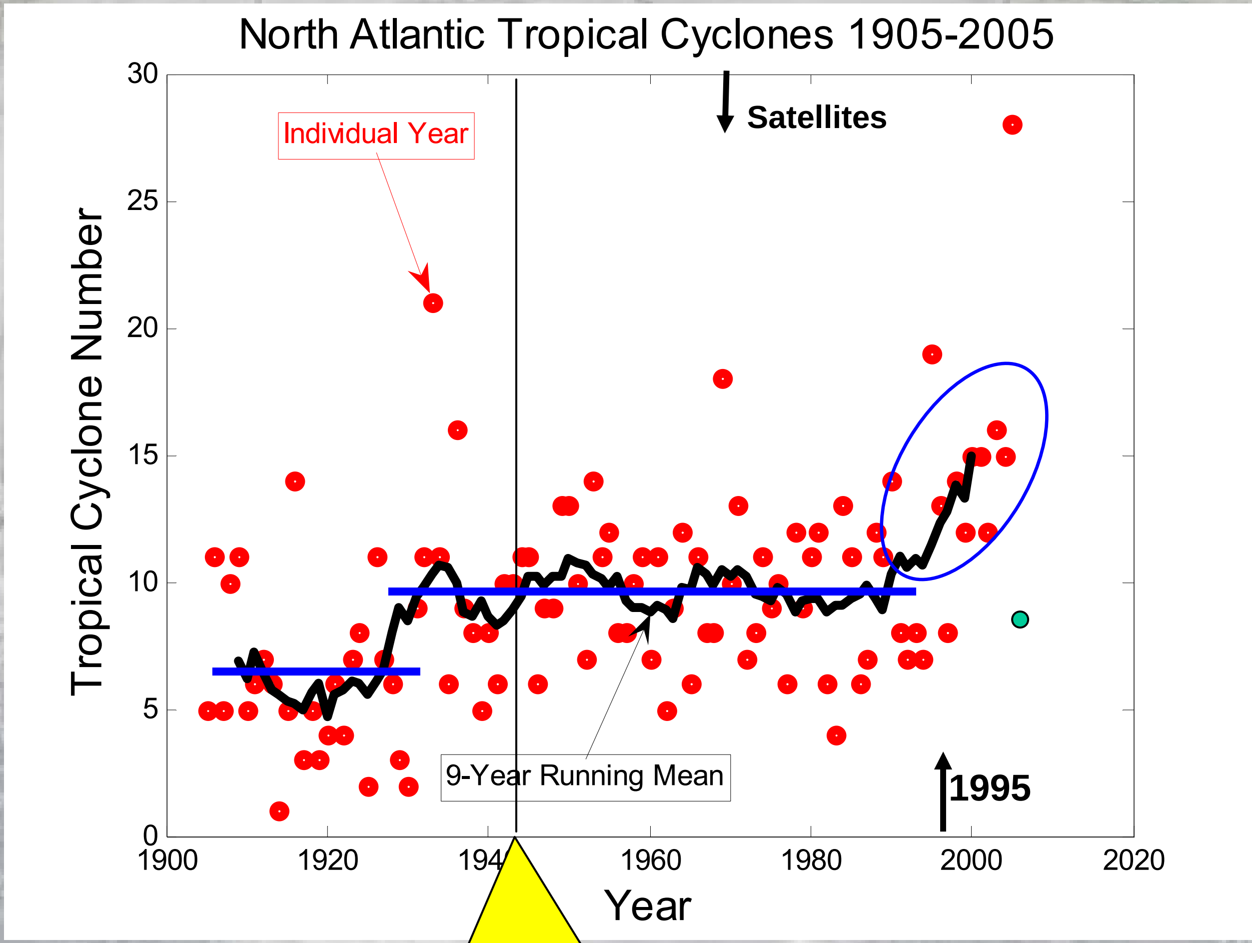

Rita
NOAA
1 GOES-FLOATER RGB IMAGE [CH1,CH1,CH4] - SEP 22 05 12:45 UTC McIDAS

Hurricane Wilma:  21 October 2005

# North Atlantic Hurricanes 2005
# A record breaking year:

- Strongest Gulf hurricane month of July (Dennis)
- Most named storms (27*: normal 10)
- Most hurricanes (15: normal 6 1970-2004)
- First ever V, W, $\alpha$, $\beta$, $\gamma$, $\delta$, $\varepsilon$, $\zeta$
- 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

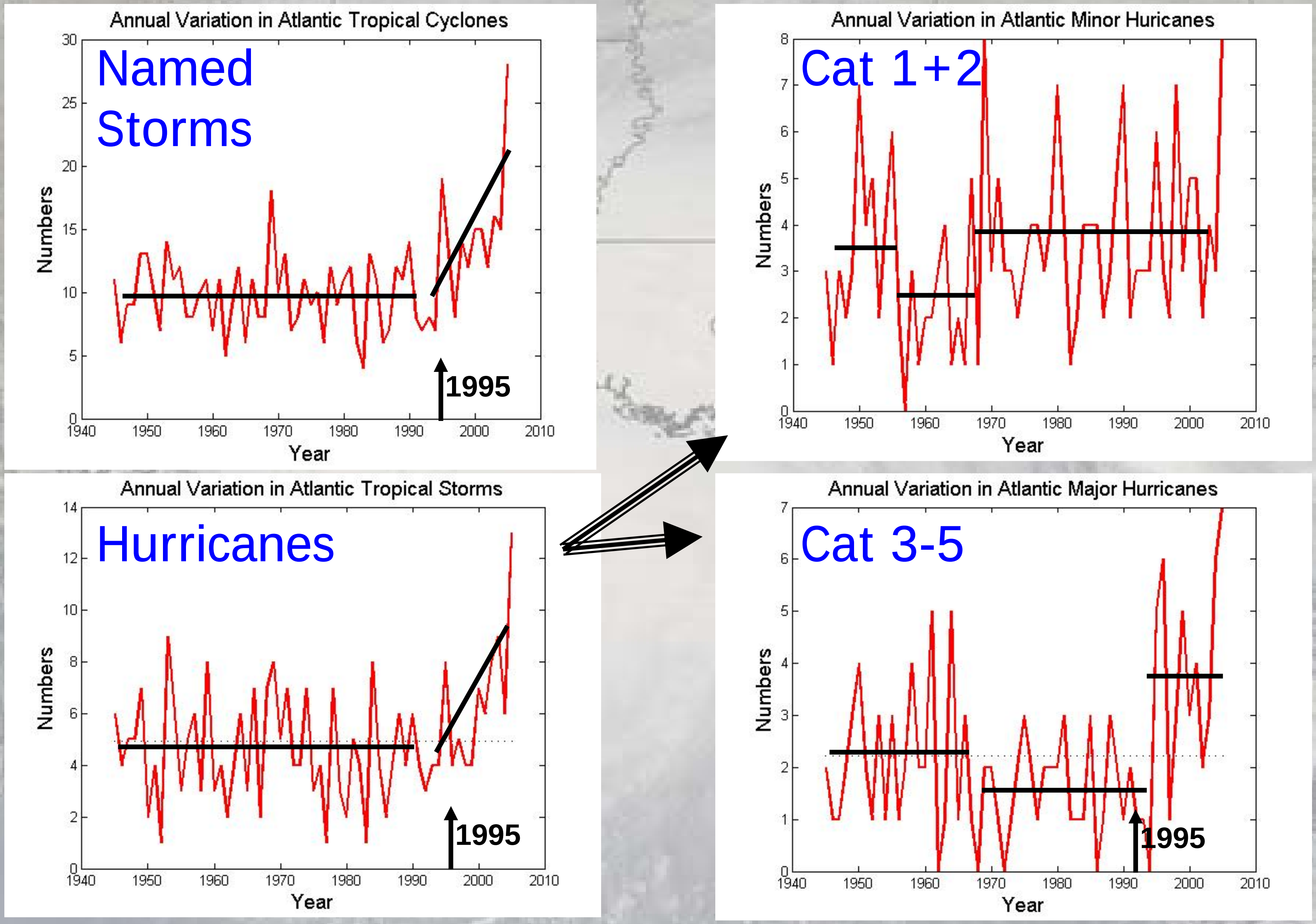
# Atlantic Tropical Cyclone Trends




Start of aircraft surveillance

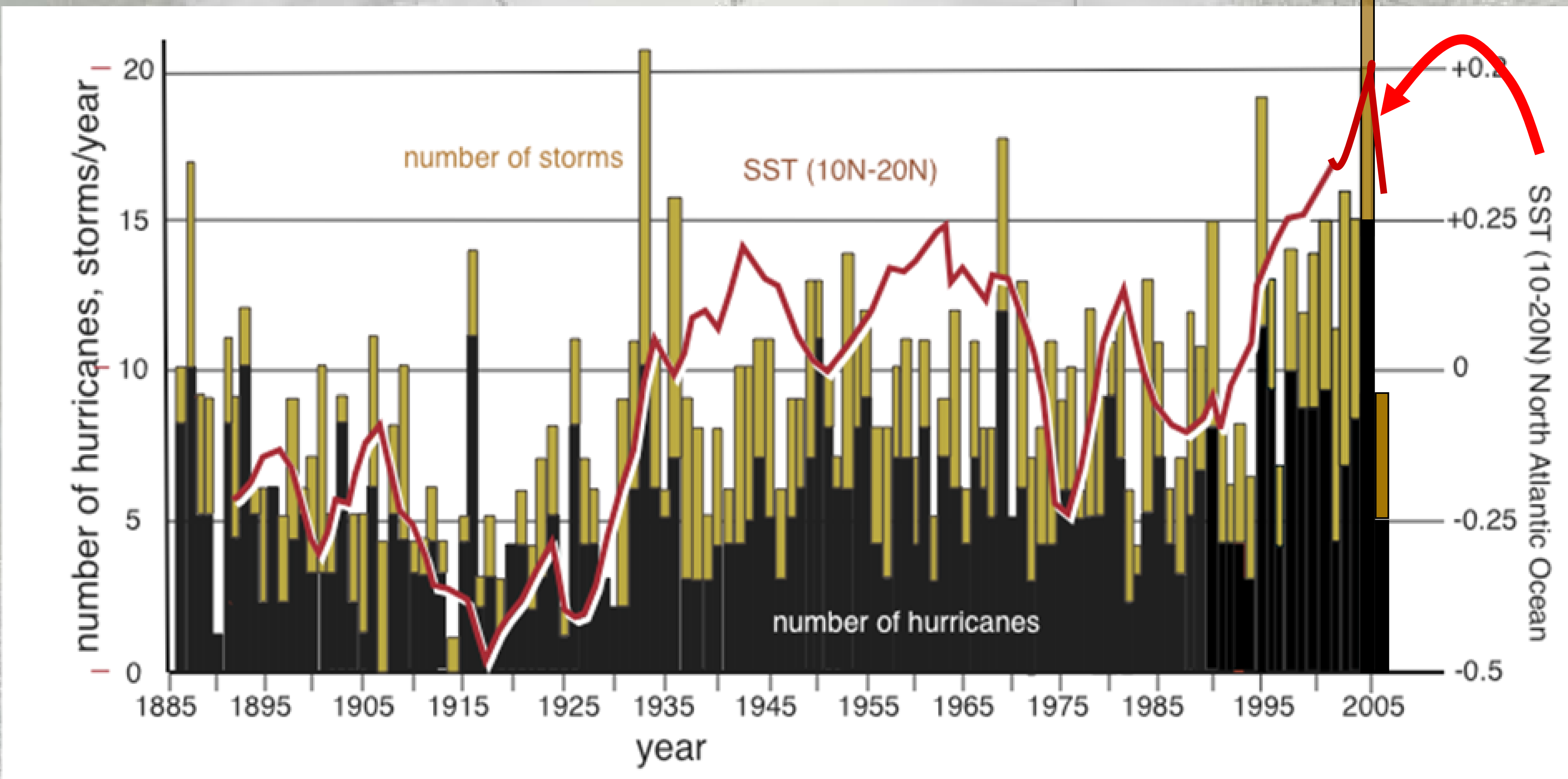
Greg Holland

# Atlantic Hurricane Trends




Greg Holland

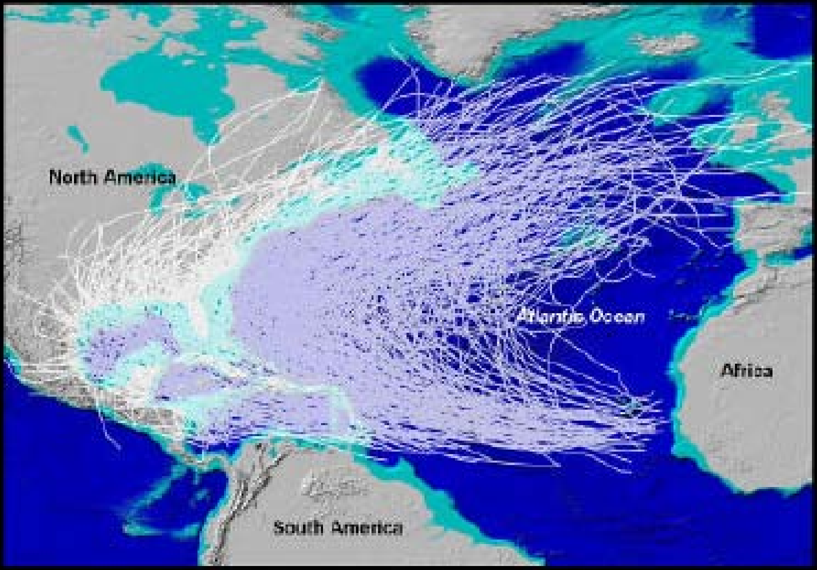
# Changes in hurricane frequency in the North Atlantic Ocean



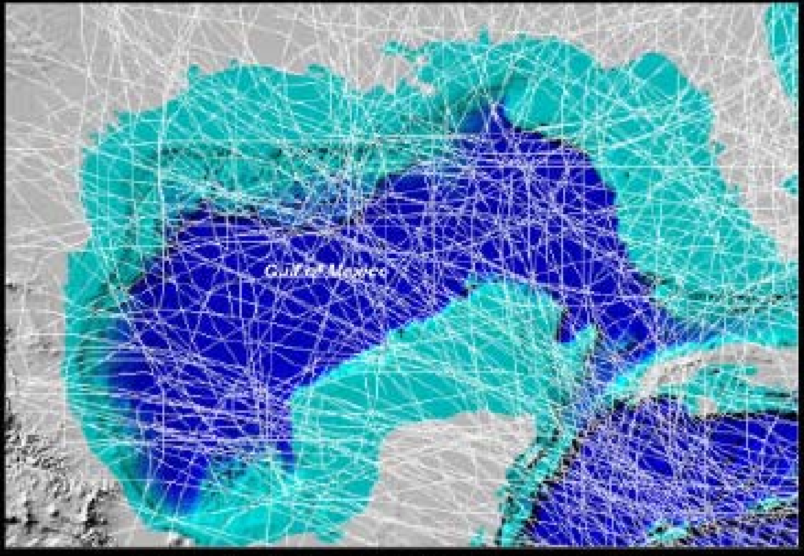
# Issues on changing damage from hurricanes

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.



North Atlantic Hurricane 'Tracks' 1886-1996 from NOAA NHC



Gulf of Mexico Hurricane 'Tracks' 1886-1996 from NOAA NHC

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:

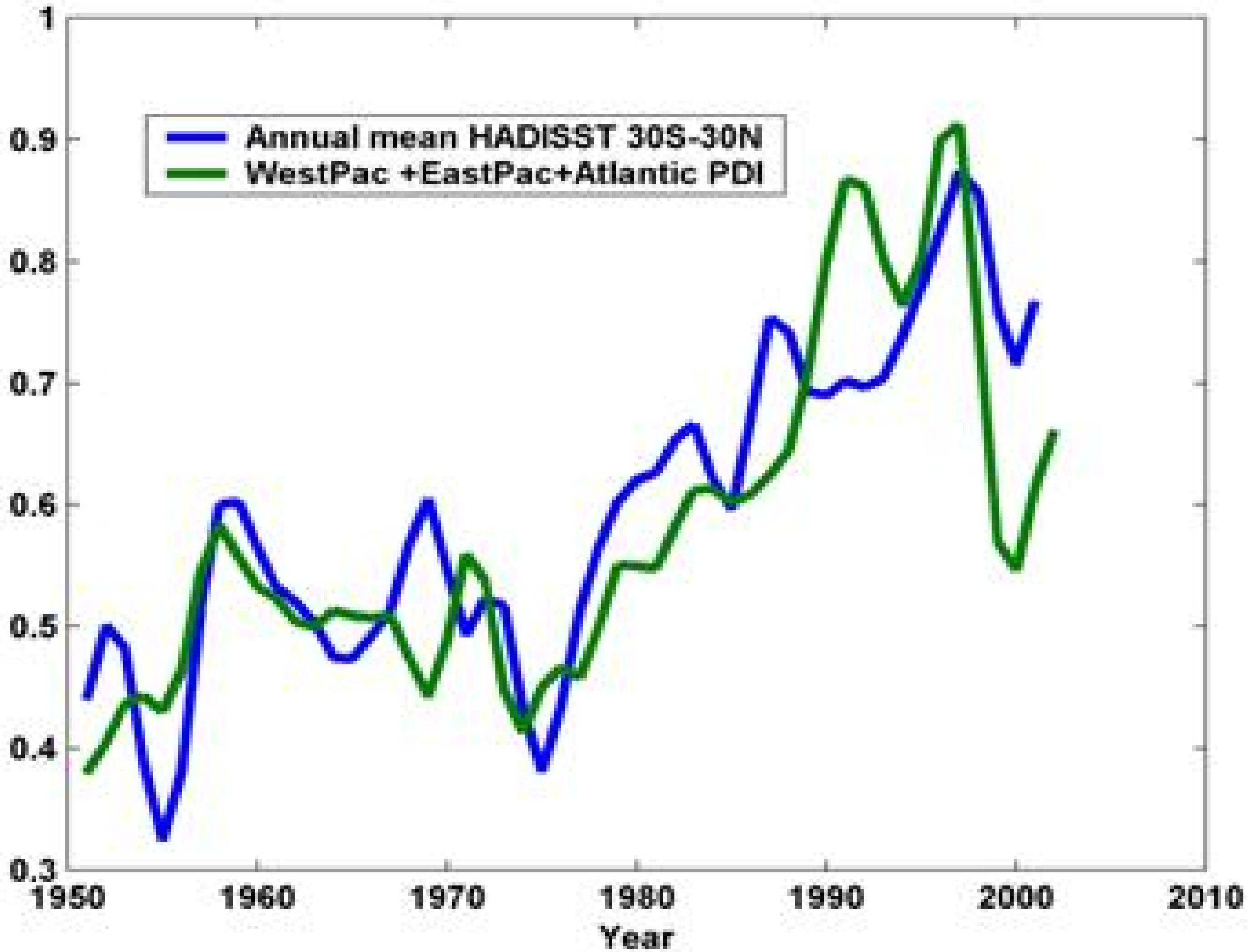
$$Power\ dissipation = 2\pi \int_0^{\tau} \int_0^{r_0} C_D \rho |\mathbf{V}|^3\ r dr dt.$$

**Simplified "Power Dissipation Index" (Emanuel 2005):**

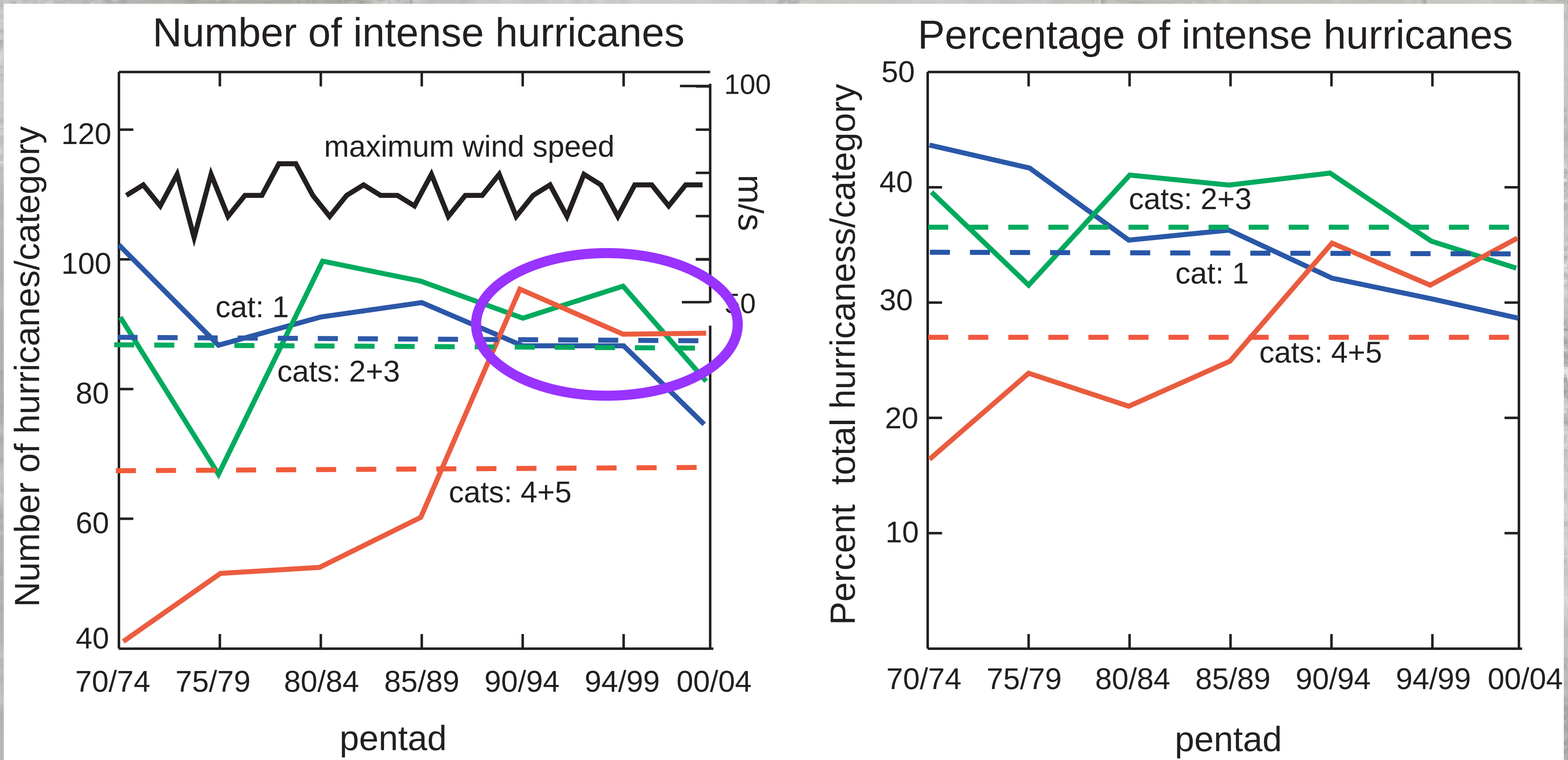
$$PDI \equiv \int_0^{\tau} V_{max}^3 dt$$

Courtesy: K. Emanuel

# Atlantic + western North Pacific




Courtesy: K. Emanuel
Revised

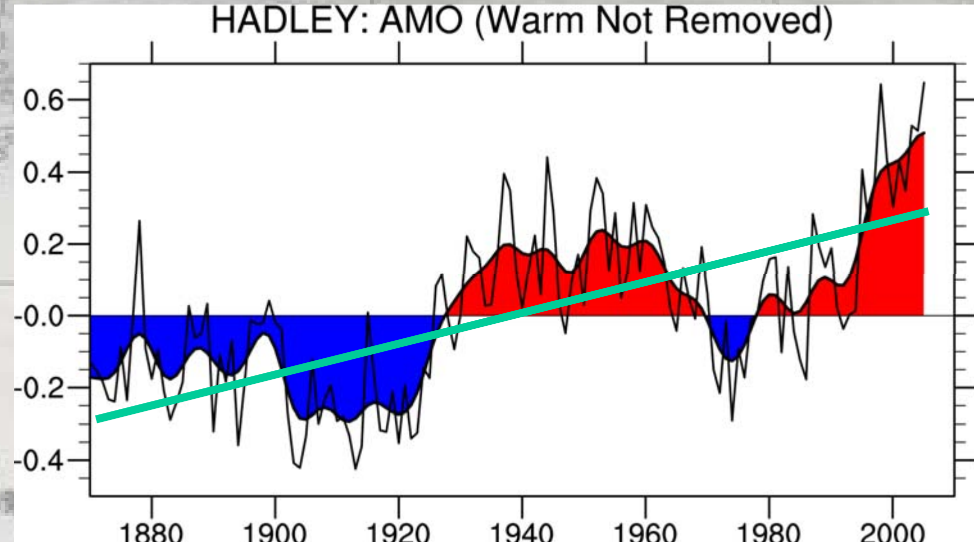



A large increase is seen in the number and proportion of hurricanes reaching categories 4 and 5. The largest increase occurs in the North Pacific, the Indian and Southwest Pacific oceans, and smallest increase in the North Atlantic Ocean.

From Webster et al (2005)

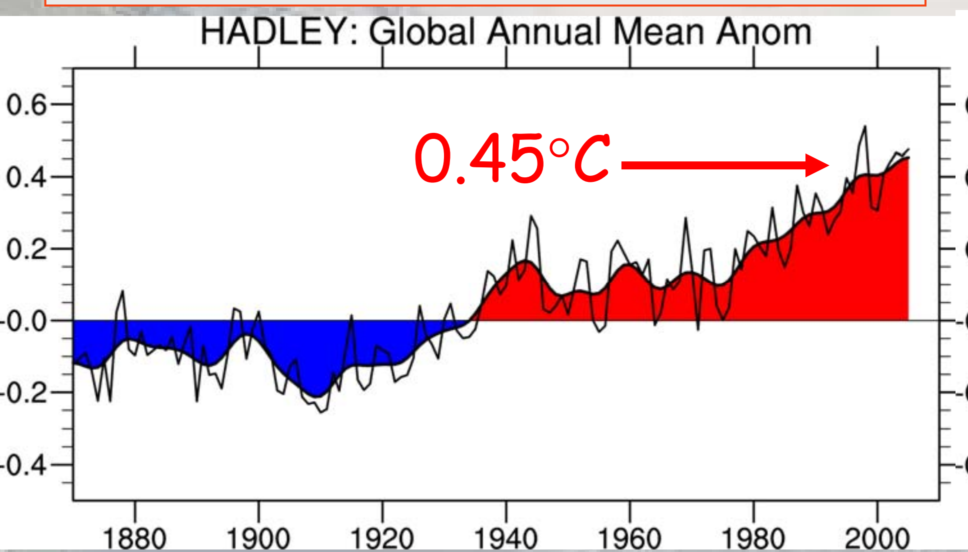
# The Atlantic Multi-decadal Oscillation

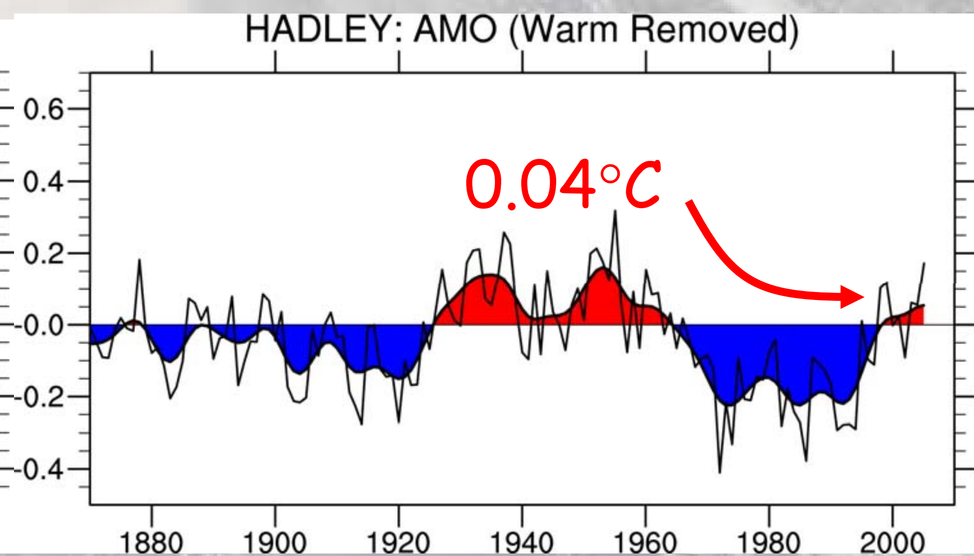
AMO index defined by Enfield et al. (2001) as mean SST north of equator in Atlantic: then take 10 year running mean.
Base period 1901-70.

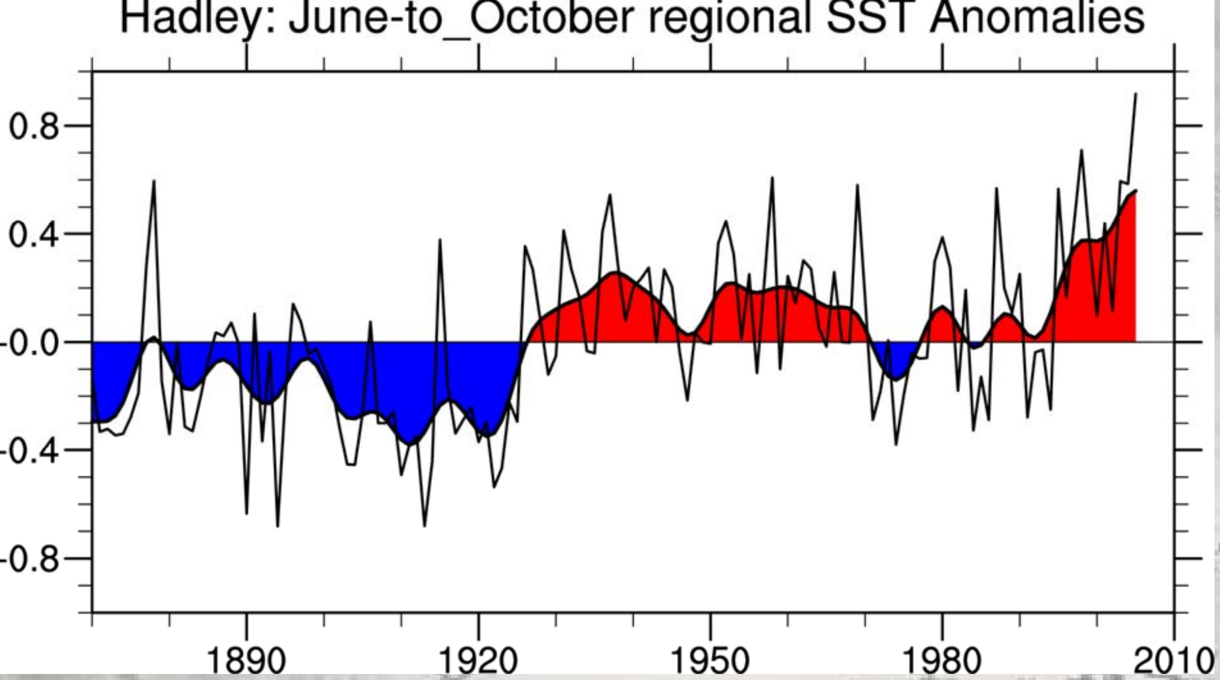



But what about global SST warming?

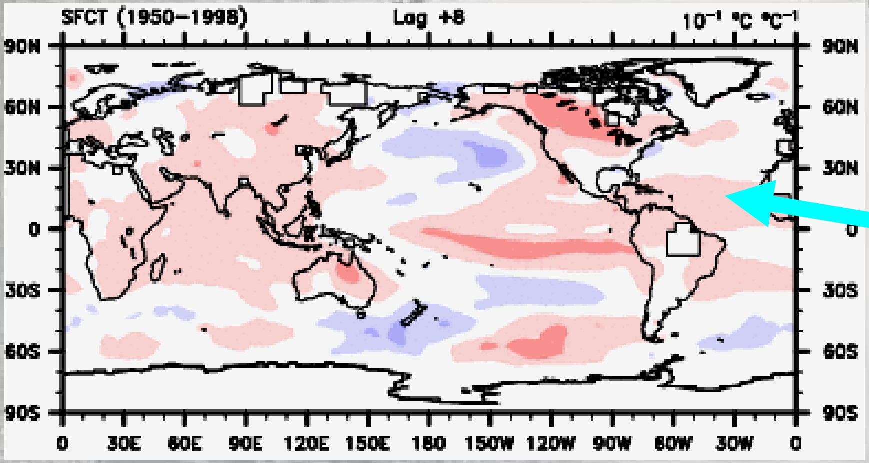
More definitive AMO index





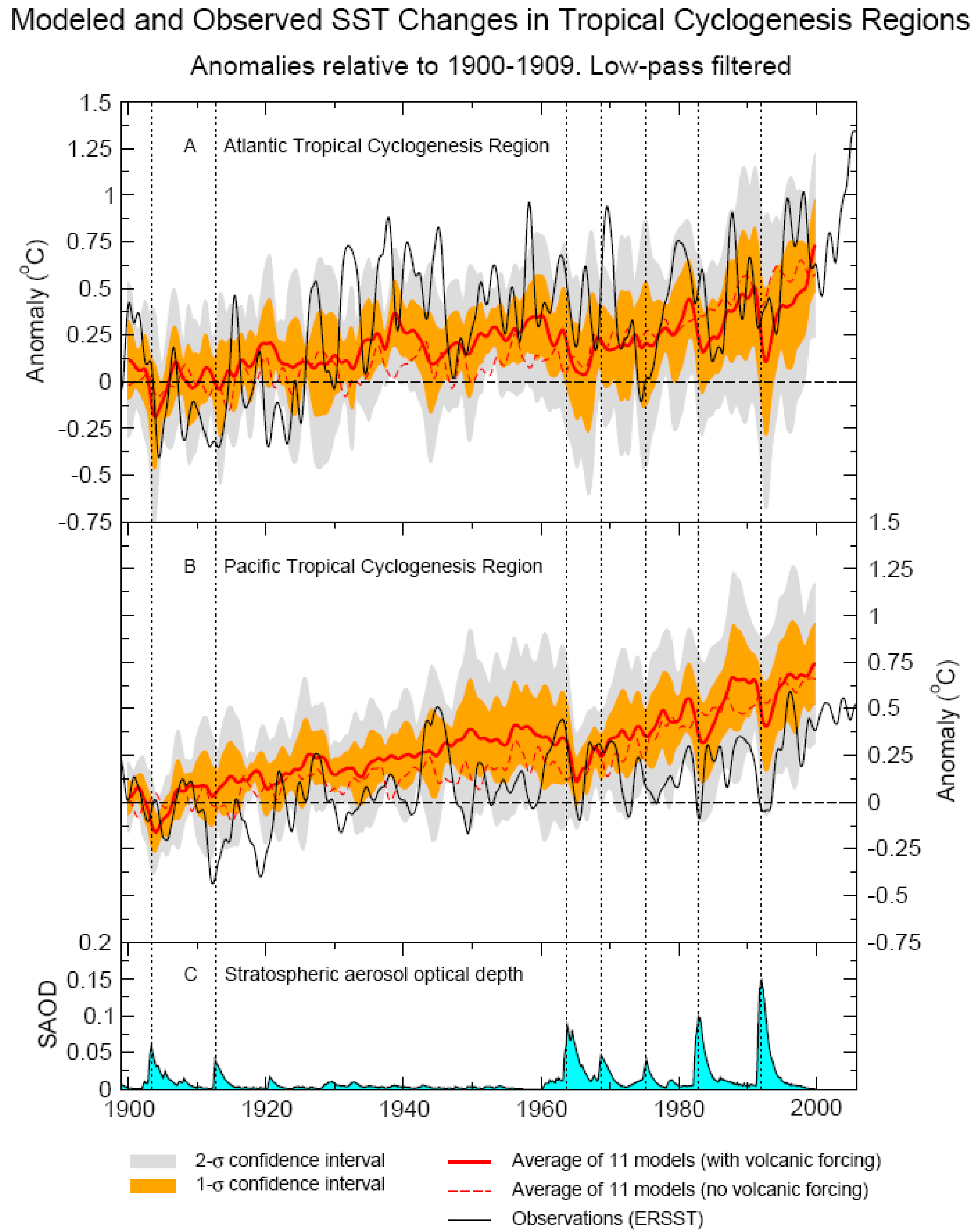

Atlantic SSTs
10-20°N 0.92°C
above 1901-70
normal.
<u>All time record.</u>
Due to weak trades
and reduced LH
fluxes.




Dec 2004 Nino3.4 0.9°C
Regression with Nino3.4
8 months later: 0.2°C in
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

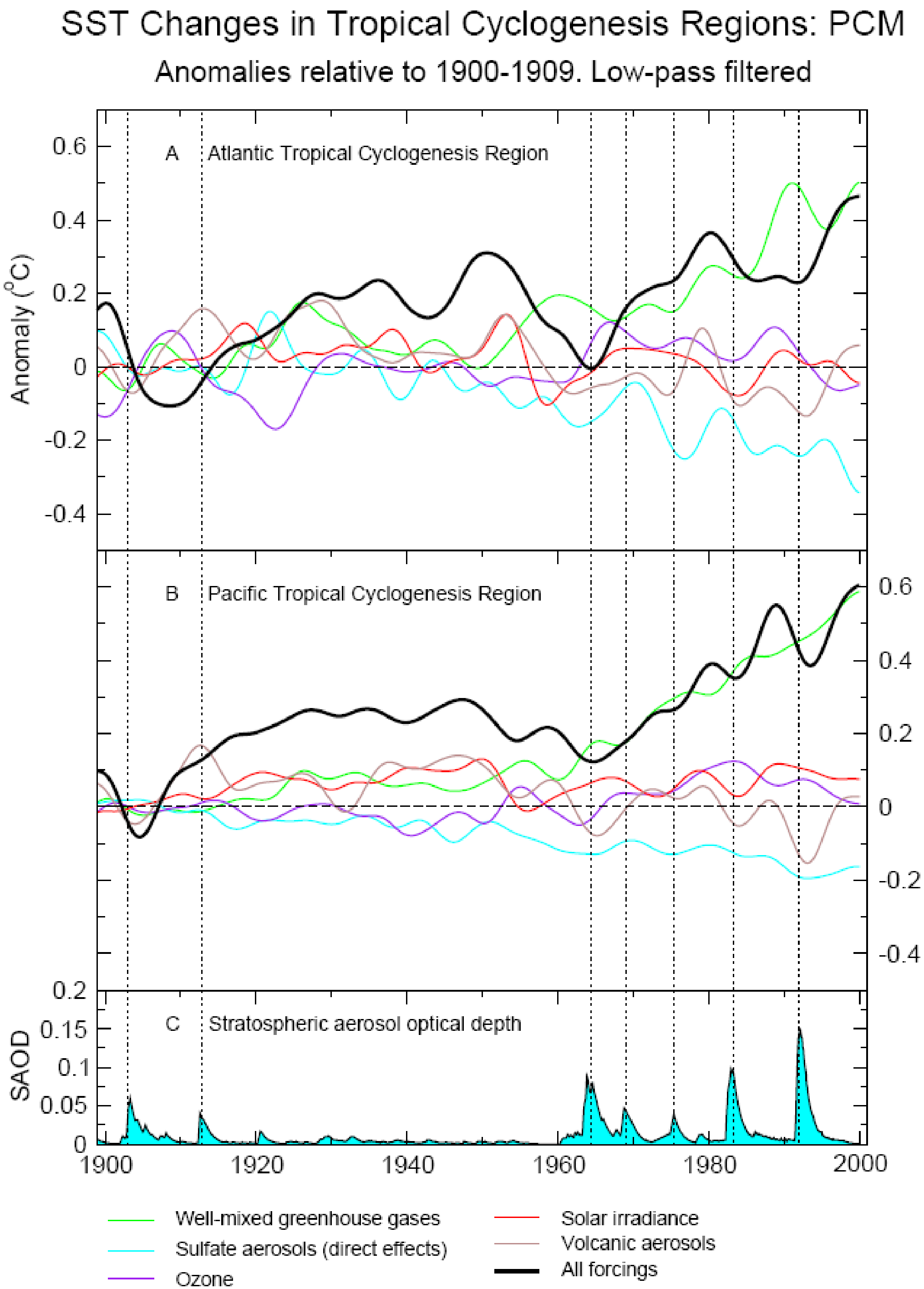



**Monthly SST anomalies for (A) Atlantic and (B) Pacific tropical cyclogenesis regions:**
**Observed (black)**
**and 22 climate models.**

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?**

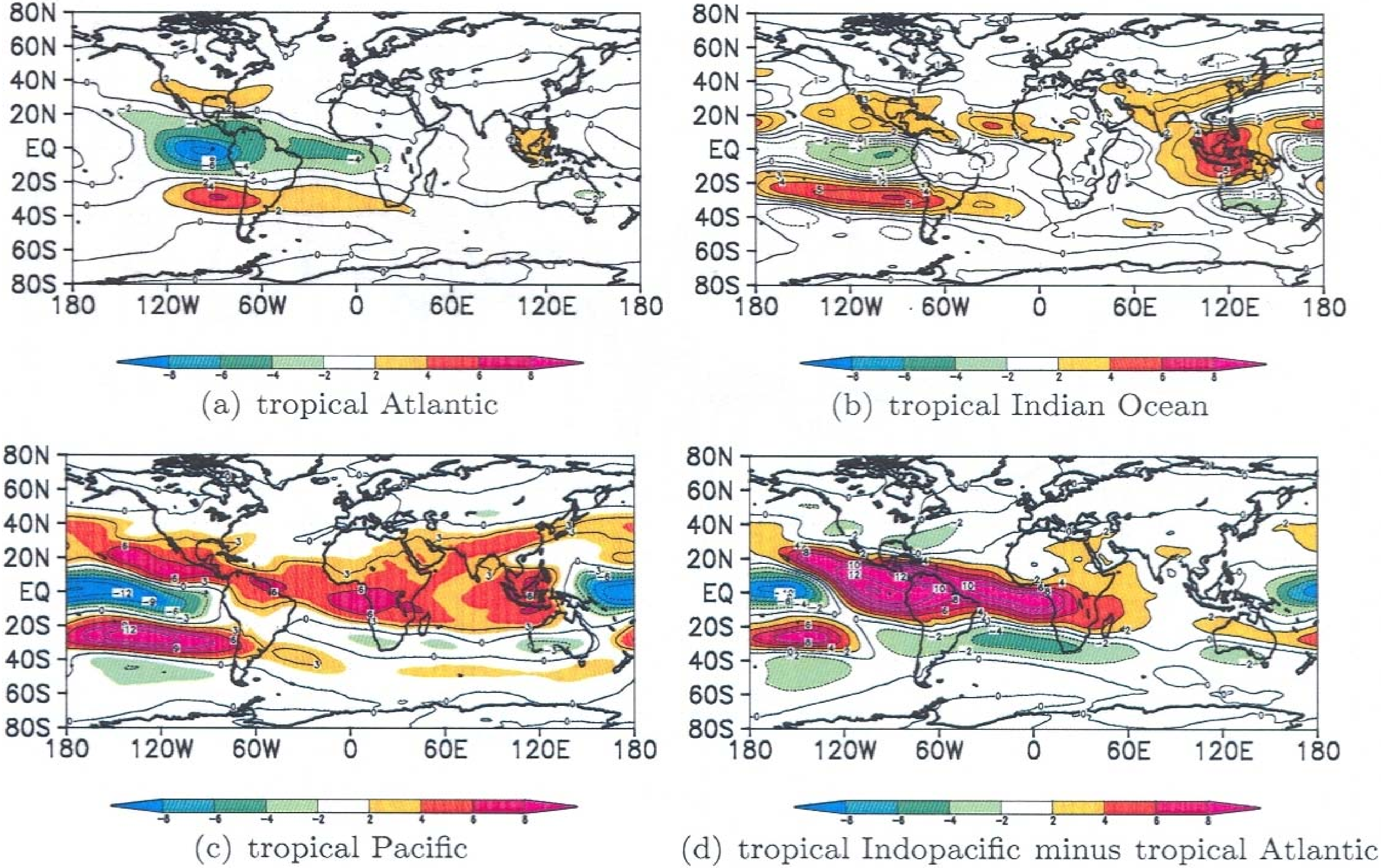



**Models show signal to noise of natural variability is large: trend can only arise from increased GHGs:**

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




(a) tropical Atlantic

(b) tropical Indian Ocean

(c) tropical Pacific

(d) tropical Indopacific minus tropical Atlantic

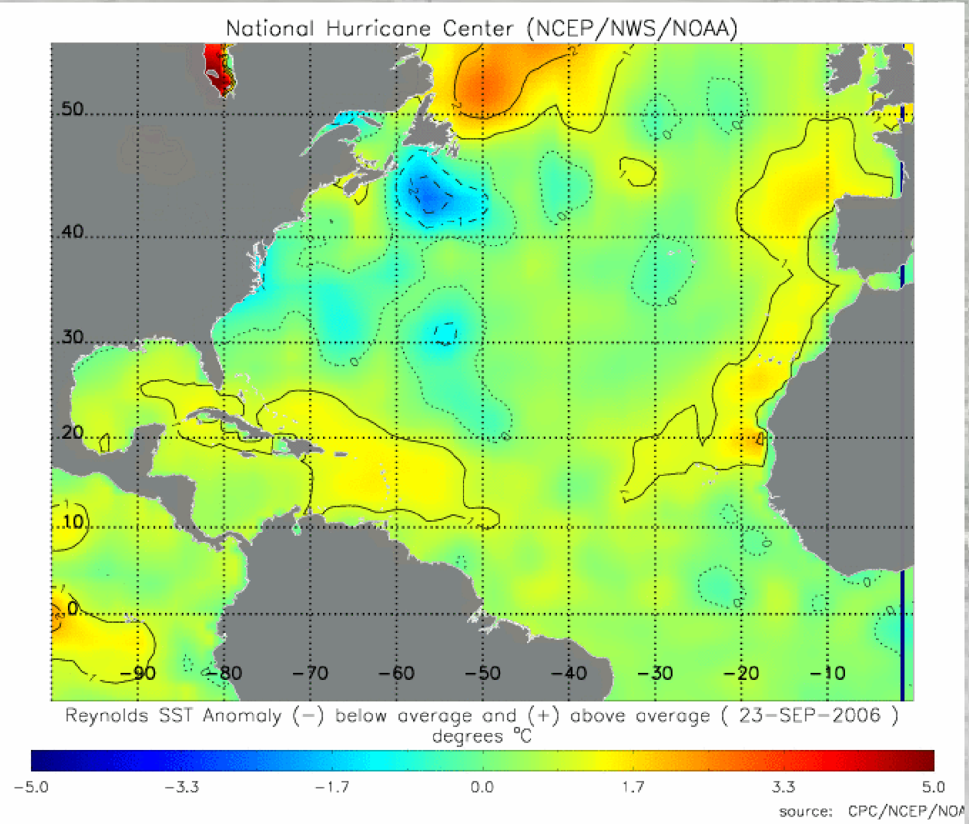
Linear regression maps of T106 ECHAM5 AGCM simulated Atlantic TC vertical wind shear (200 -850 hPa) for regions given for 1870-2003. Color gives statistical significance (T-test). Biggest effect is from Pacific.

Latif et al 2006 GRL (see Aiyyer and Thorncroft 2006 JCl 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.

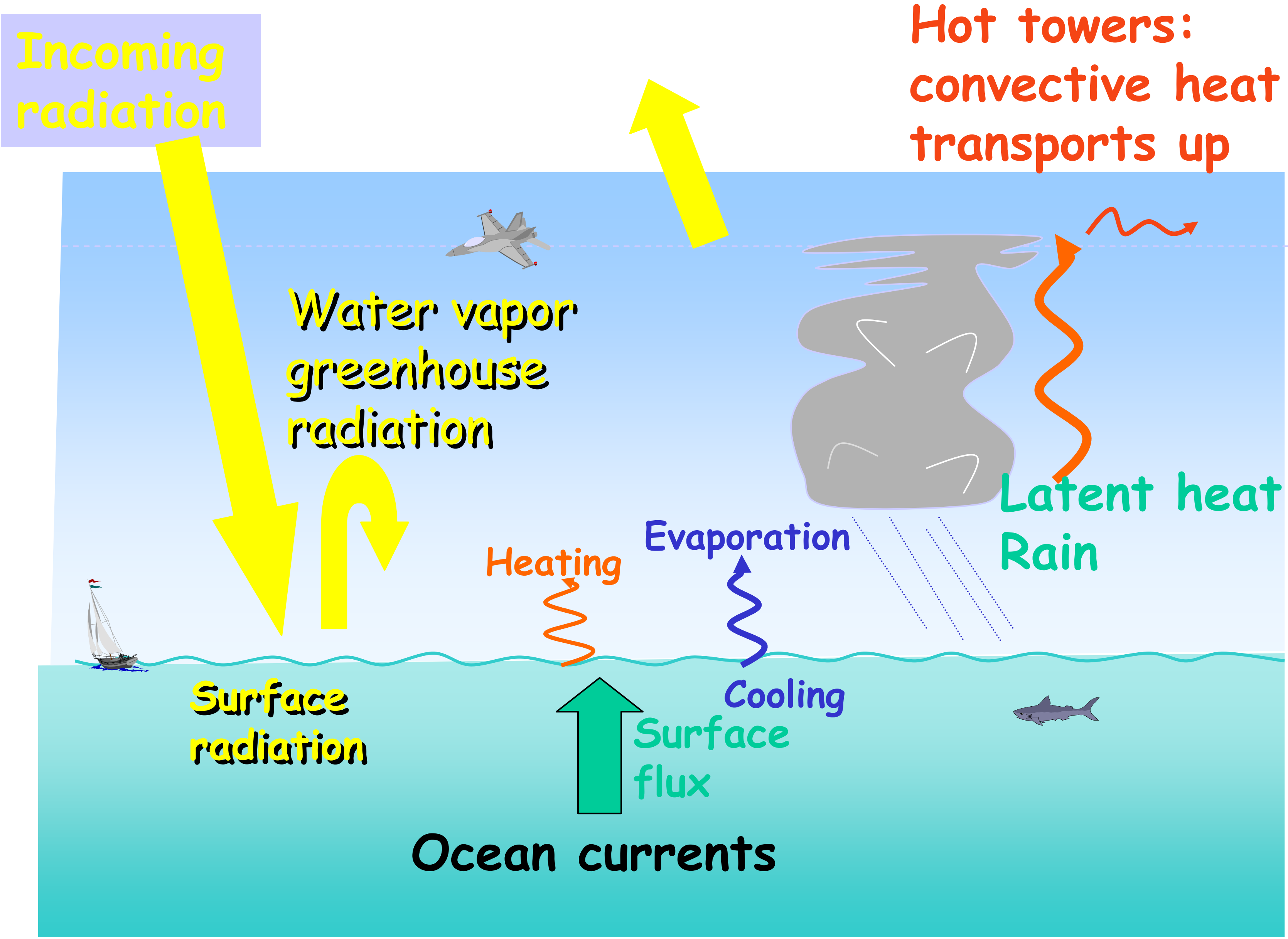



Foltz and McPhaden, GRL 2006 show how the weak NE tradewinds, anomalous latent heat fluxes and solar radiation contributed to the record breaking SSTs in summer 2005

## 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

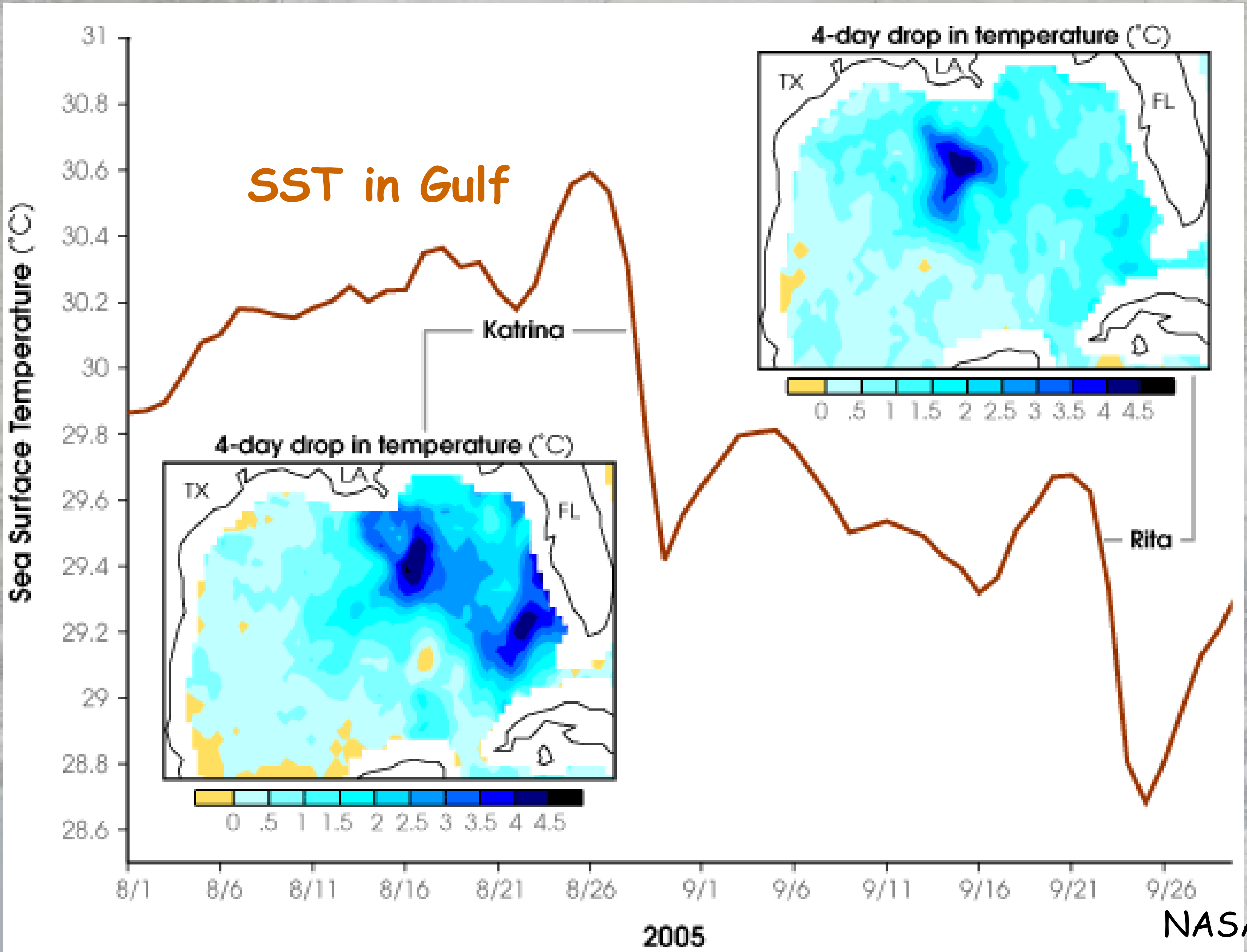


## In the tropics, heat from the sun is apt to build up:

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




NASA

# 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?

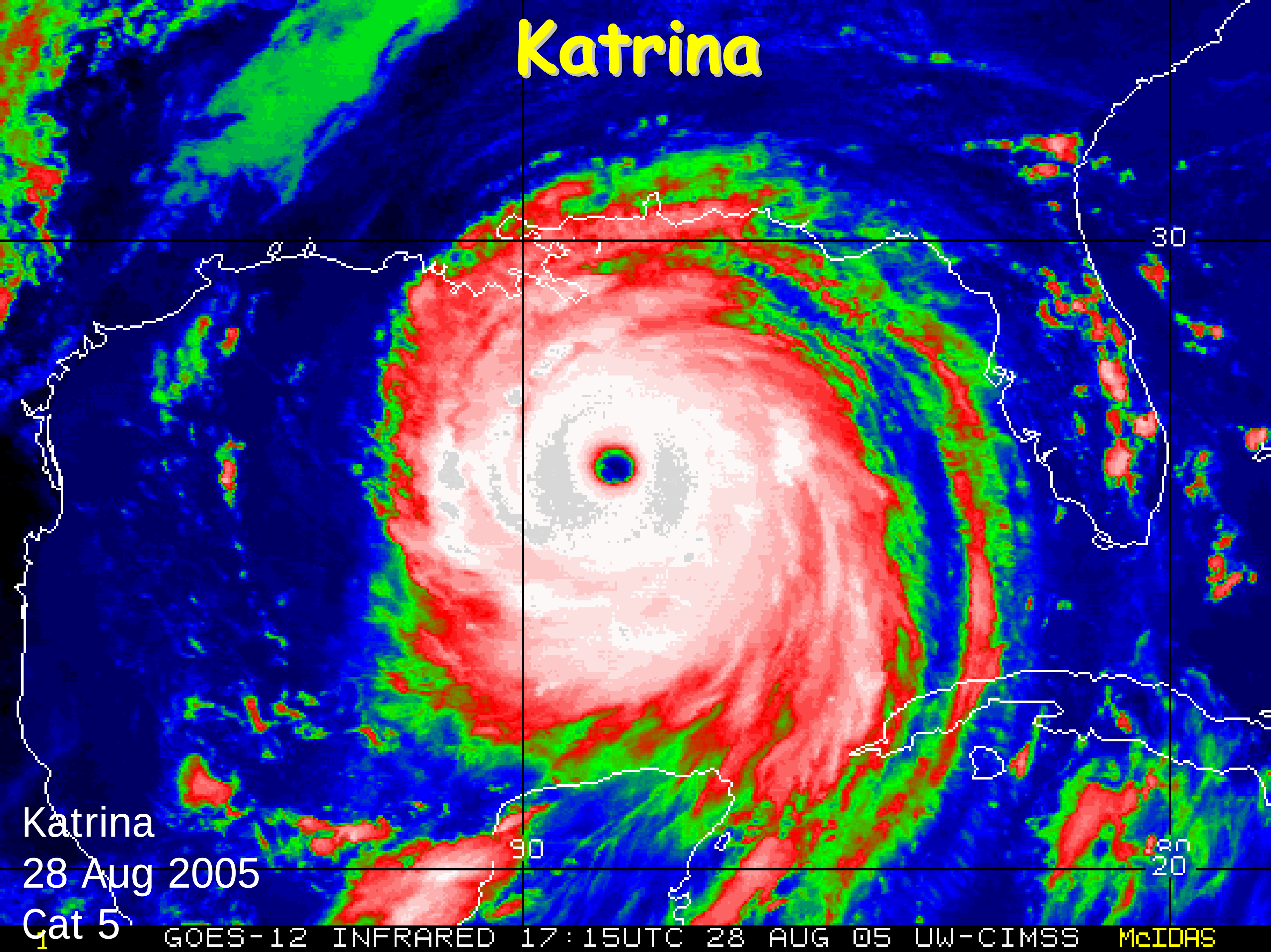
# Hypothesis on effects from global warming

**Water vapor over oceans increases ~7% per K SST**

- To first order, surface latent heat fluxes also increase by at least this amount as $E \approx \rho C V q_s(Ts)(1-RH) \sim q_s(Ts)$
- Convergence in boundary layer also should go up proportionately. [$q\Uparrow$, $\omega\Uparrow$, $v_r\Uparrow$ **and** $v_r.q\Uparrow$ **squared**]
- Could also increase intensity: V
- Other feedbacks (friction, sea spray, stability etc)

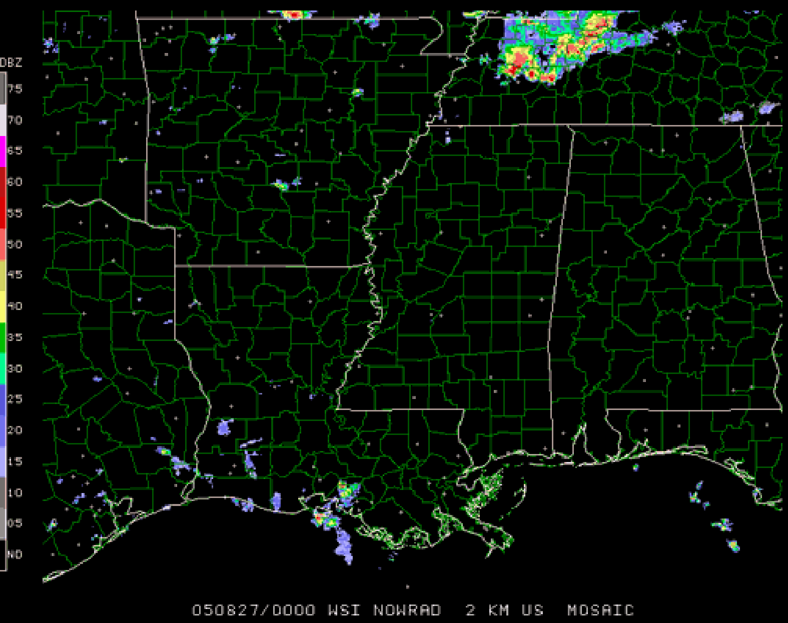
Hence estimated rainfall, latent heating and water vapor in the storms should increased $1.07^2 = 1.14$ or 14%. [7 to 21% error bars] per K.

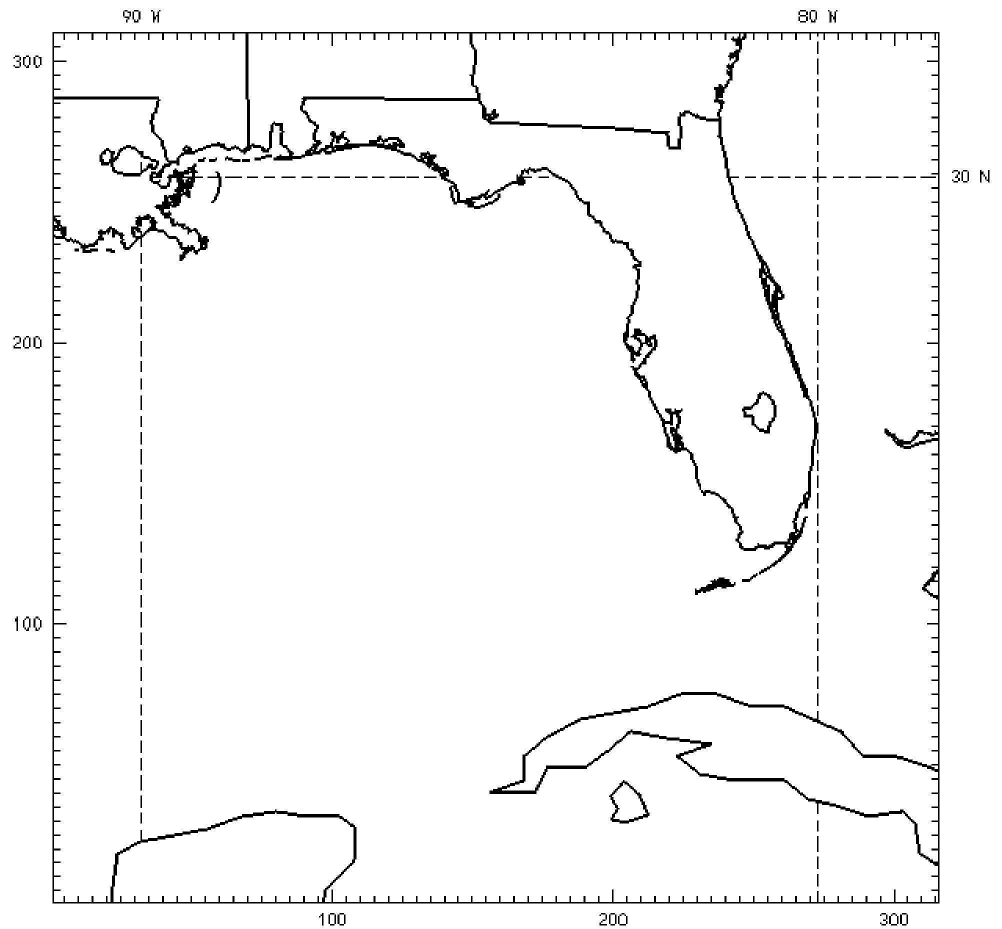
**For observed 0.5K increase in SST this means increases in rainfall and latent heat release in storms by order 7%.**


Katrina
30
90
20
Katrina
28 Aug 2005
Cat 5
GOES-12 INFRARED 17:15UTC 28 AUG 05 UW-CIMSS McIDAS

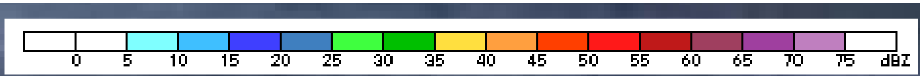
# Hurricane Katrina
# WRF Moving grid

27 Aug 2005 00 Z




Mobile Radar

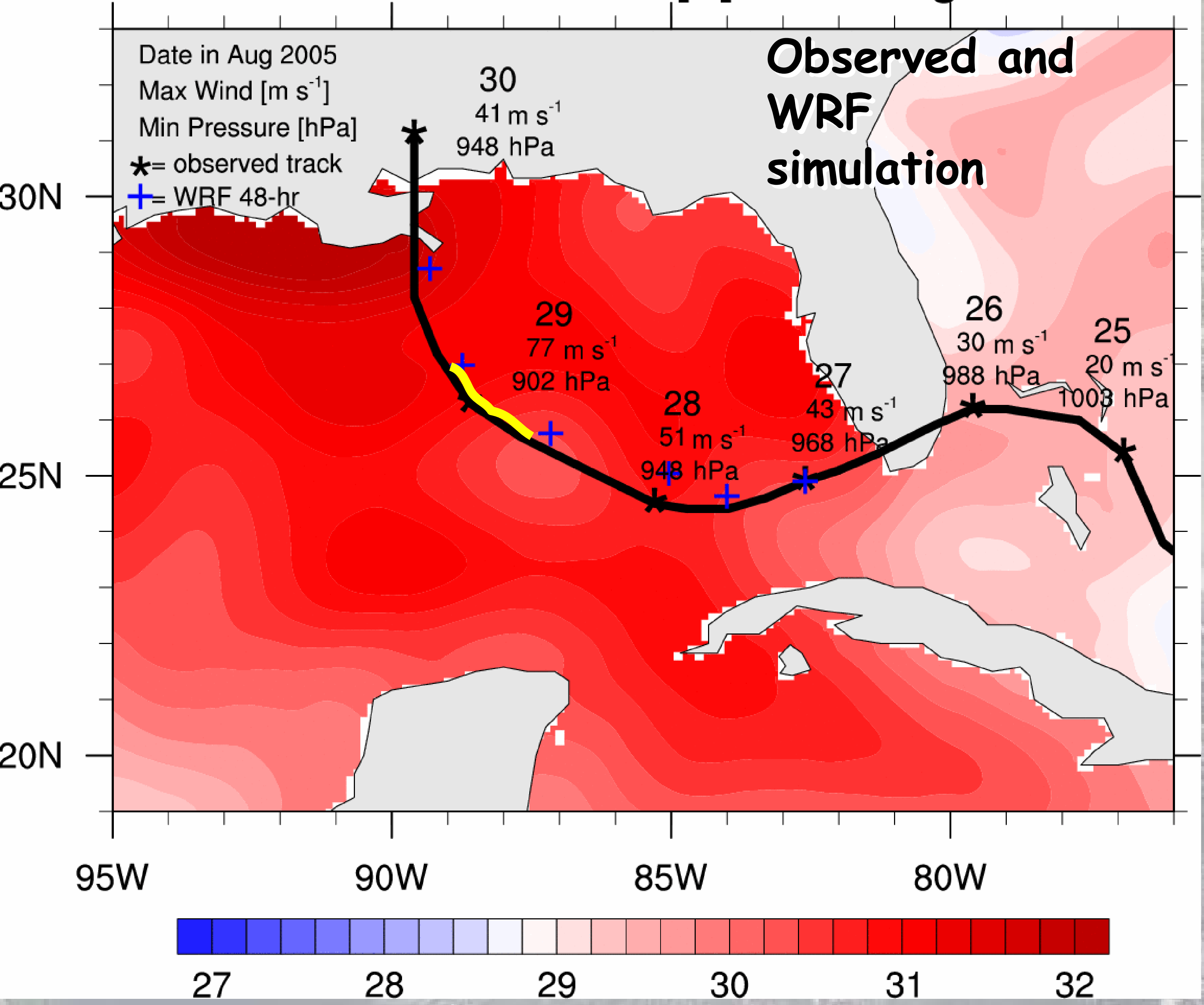


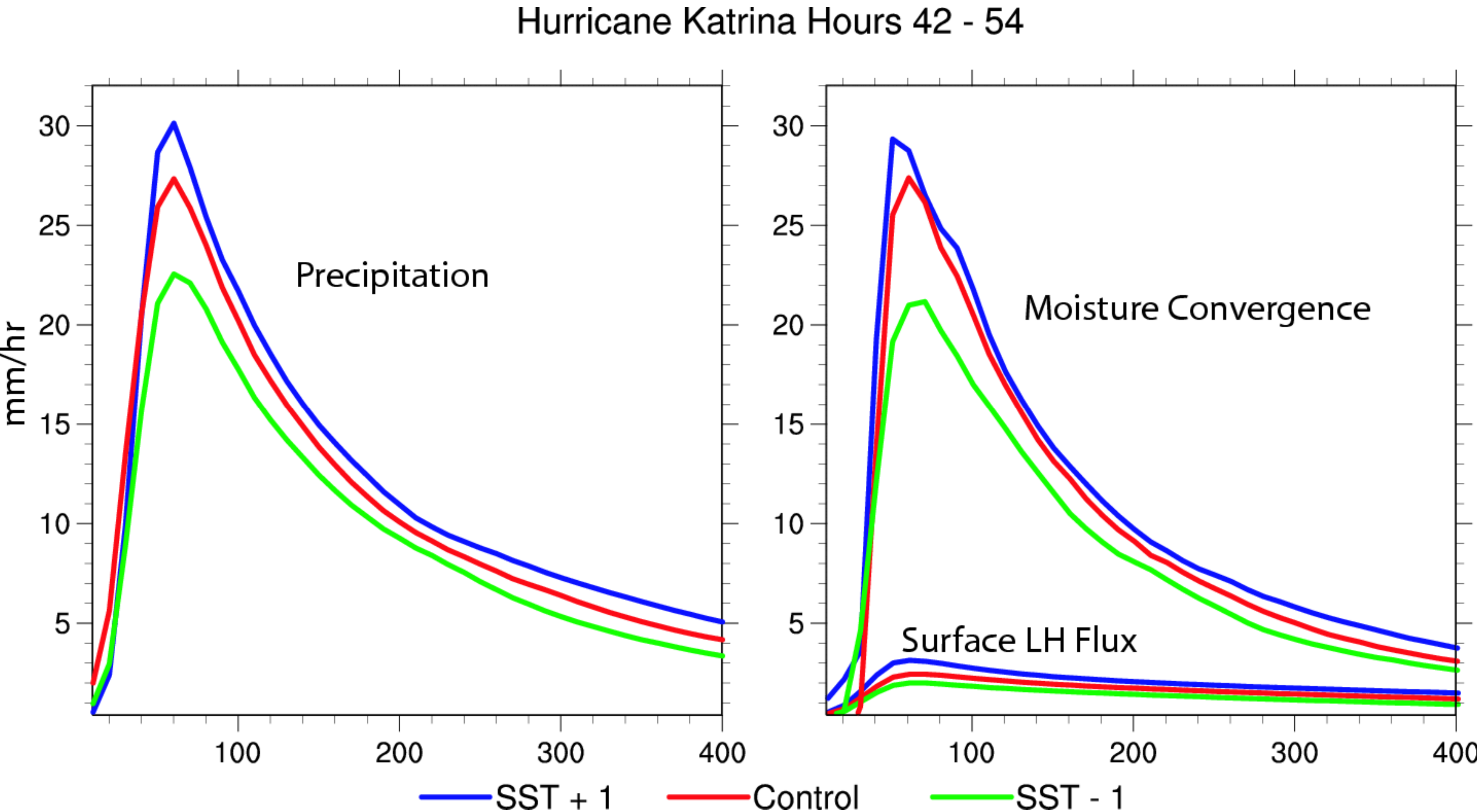
# Katrina experiments

- 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

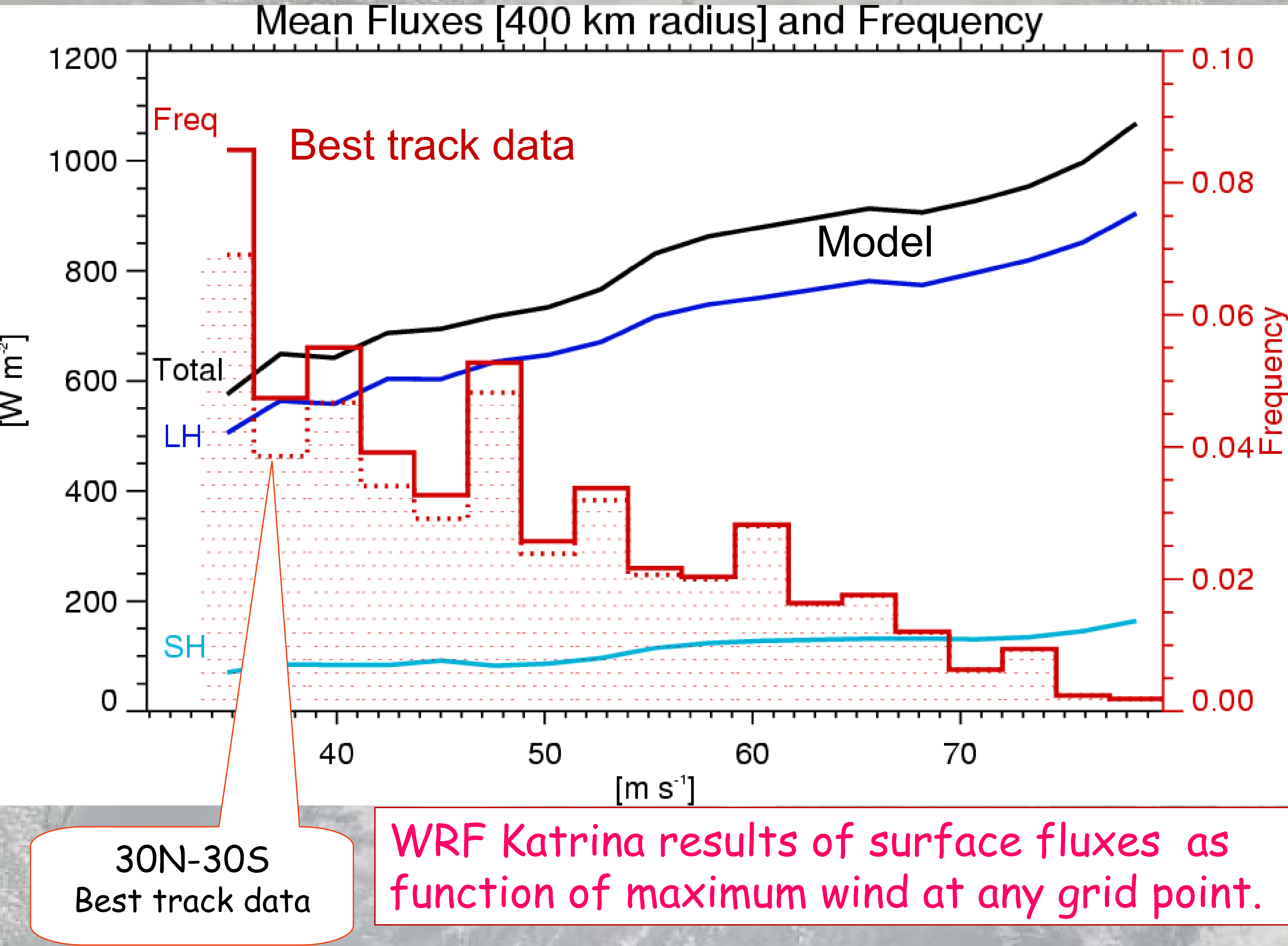
  - Max winds 58 m/s (-1) go to 70 m/s (+1)
  - Order 10% per C

# Hurricane Katrina SST [C]: 25-30 Aug 2005

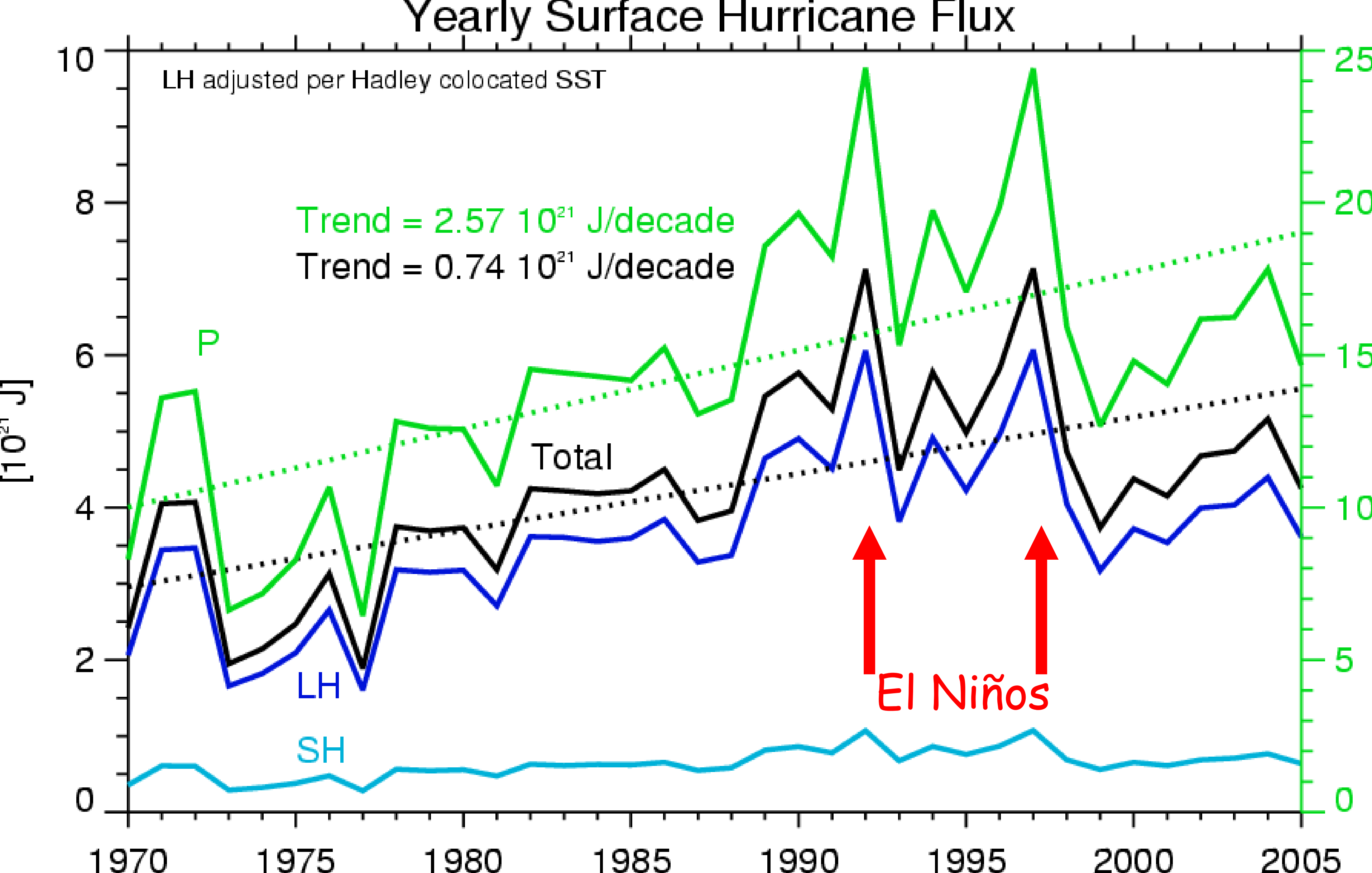





- Precipitation is dominated by moisture convergence
- Surface flux of moisture is essential: amounts to >1500 $Wm^{-2}$.
- Substantial increases with increasing SSTs: rain increased by 19%/K inside 400 km.




WRF Katrina results of surface fluxes as function of maximum wind at any grid point.




For 1990-2005: over 0-400 km radius ($5\times10^{11}$ $m^2$), ocean cooling is 0.52, 0.58, 1.84$\times10^{22}$ J/yr, or 0.16, 0.185, 0.58 PW.

## TC flux climatology

**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?