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 – pattern of SST change key:
  - 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.
  - Uncertainty in past and future changes in T(p) impacts interpretation of past, and perhaps TC prediction.

- 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…

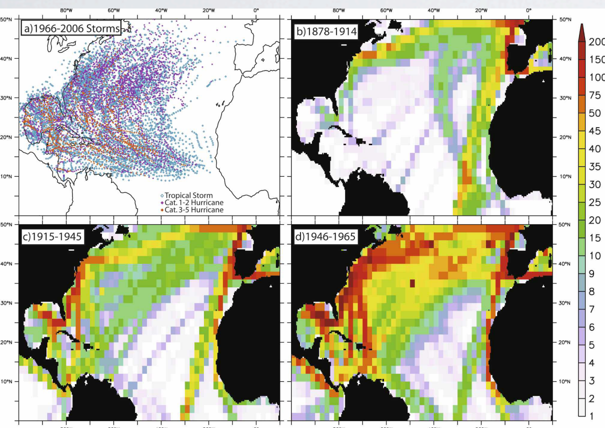
- High-resolution coupled and atmospheric models enable the next generation of hurricane prediction and projection.

Outline

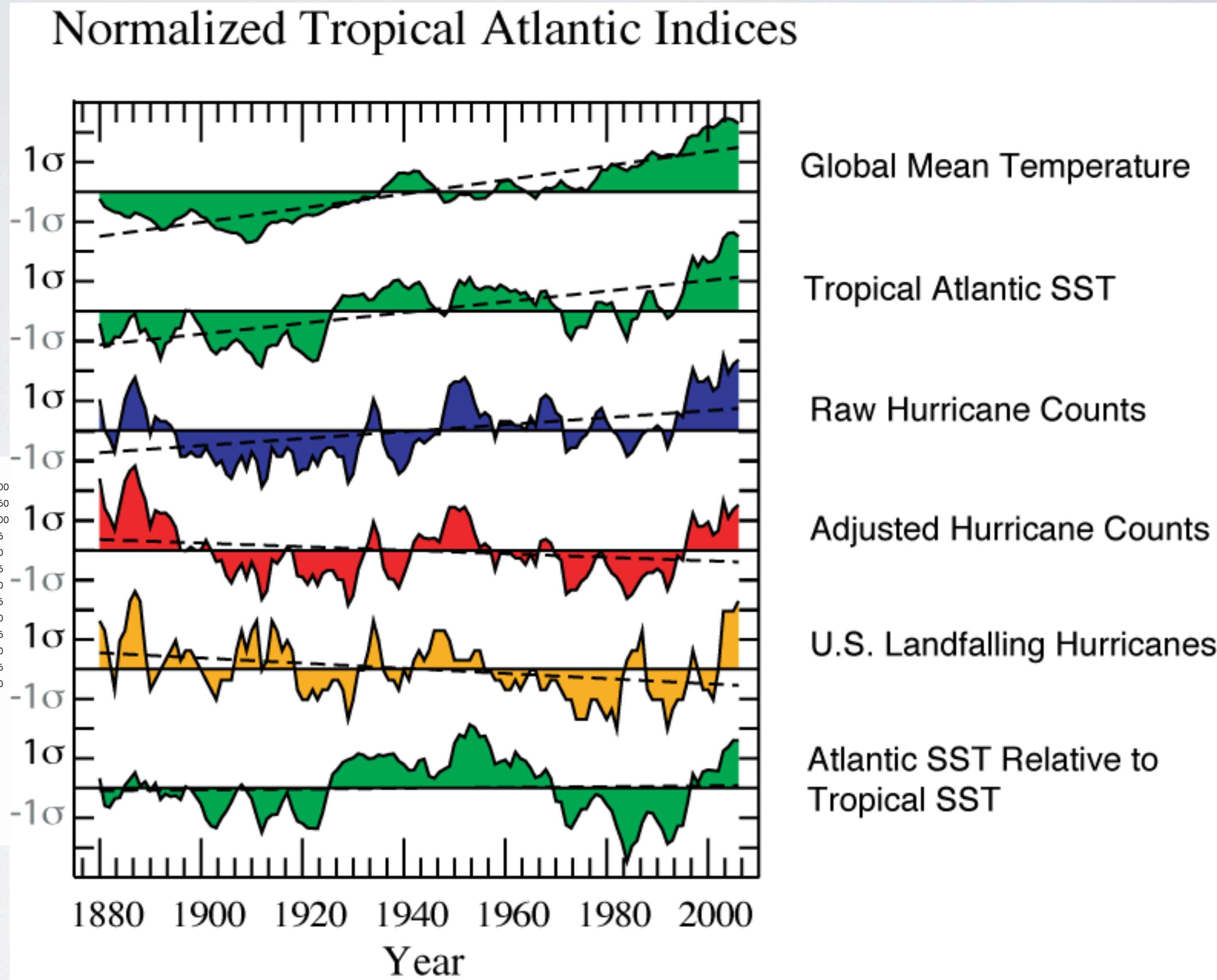
- Historical hurricane records
- Projecting decadal to centennial hurricane activity
  - Issues regarding non-moist-adiabatic warming
- Predicting multi-year hurricane activity

Historical Hurricane Records

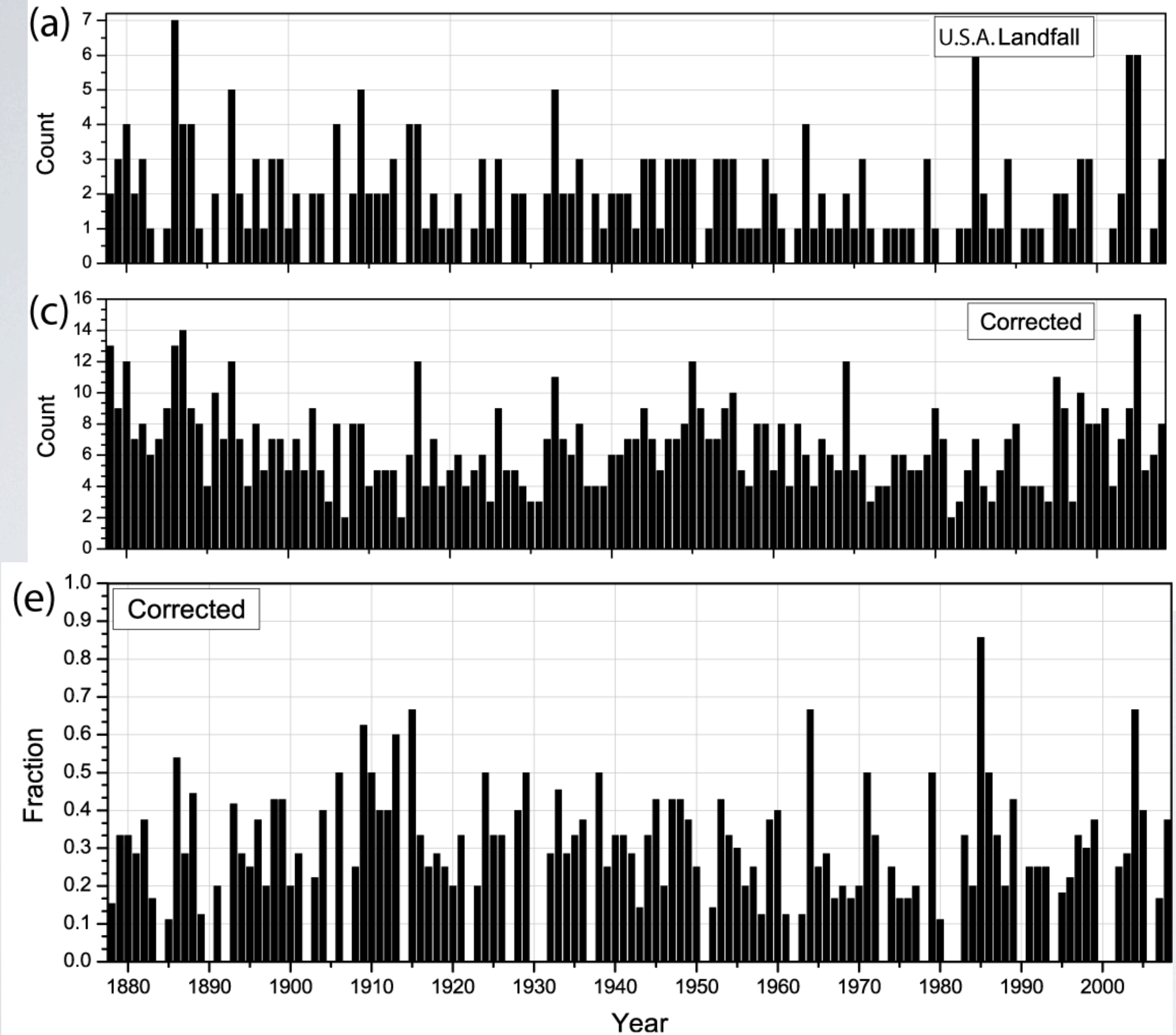
Adjustments to storm counts based on ship/storm track locations and density



Vecchi and Knutson (2008, J. Clim.)
Landsea et al. (2009, J. Clim.)
Vecchi and Knutson (2011, J. Clim.)
Villarini et al. (2011, J. Clim.)



Seasonal hurricane counts



U.S. Landfalling Hurricanes

Basinwide Hurricanes

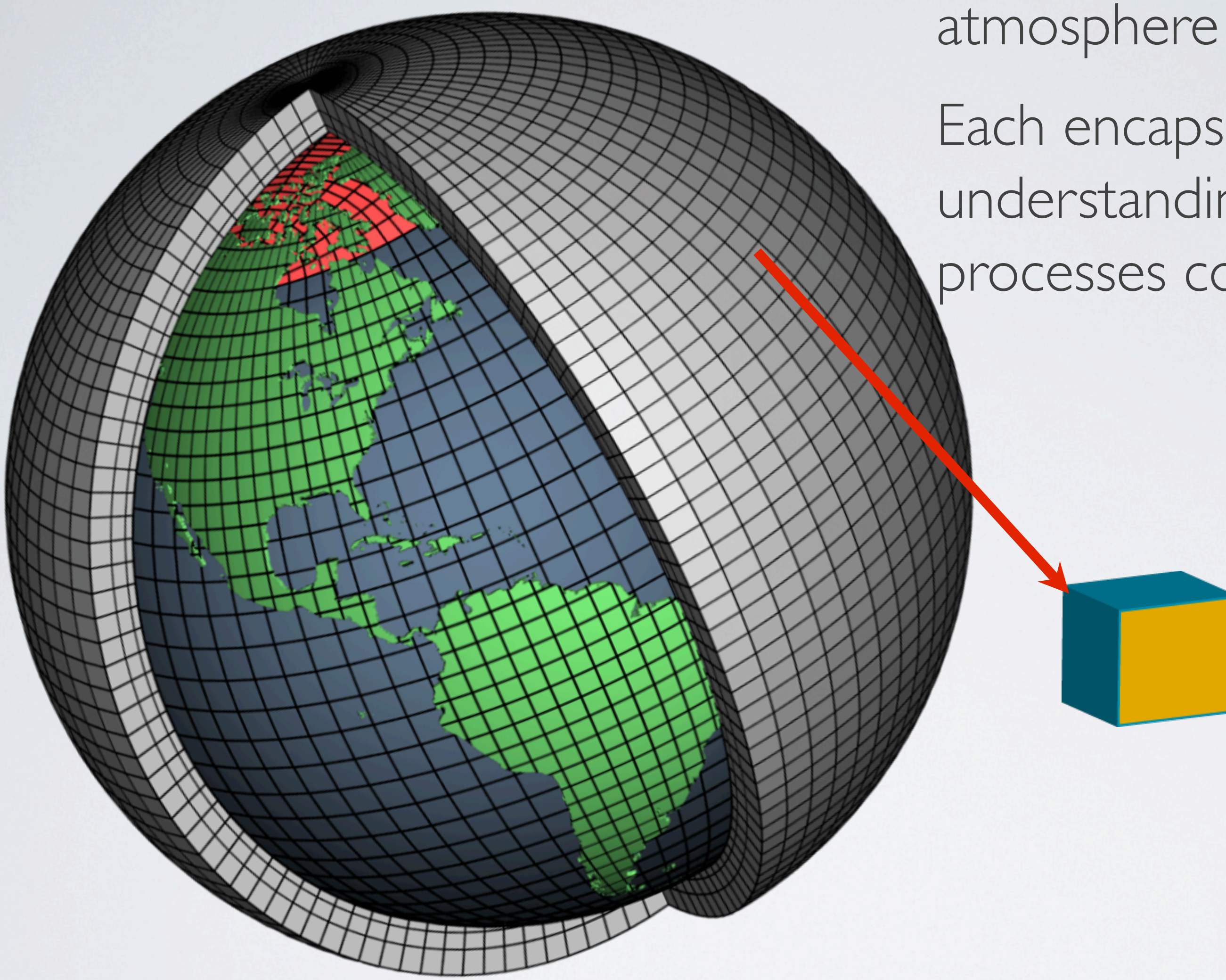
Fraction of Basinwide Hurricanes Making U.S. Landfall

Vecchi and Knutson (2011, J. Clim.); Villarini et al. (2012, J. Clim.)

Multi-decadal projections of TC activity

Models have land, ocean, atmosphere and ice components.

Each encapsulates our best understanding of underlying processes controlling its evolution.



In each grid cell:

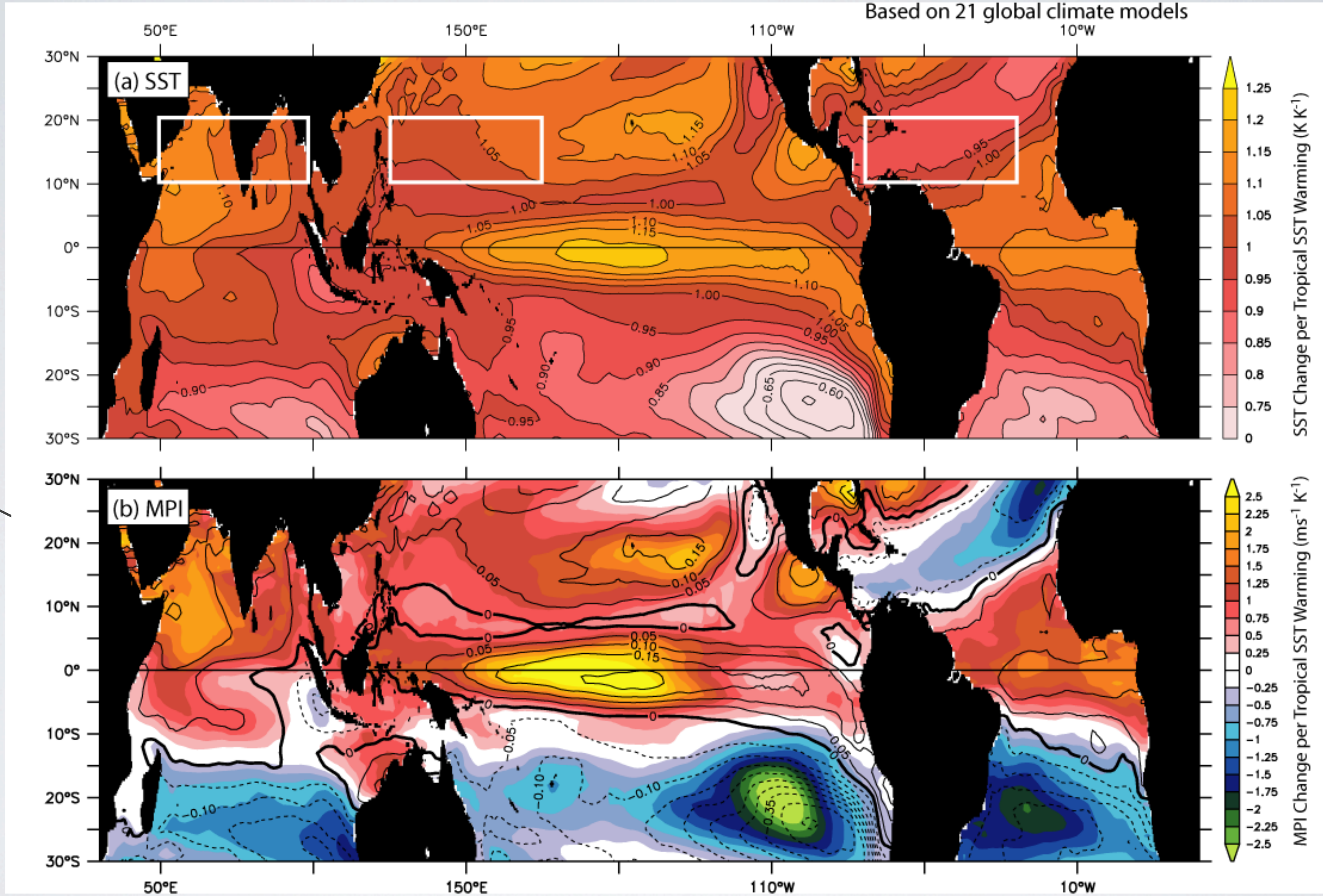
- ⋆conserve momentum (F=m ·a)
- ⋆account for changes in mass and composition
- ⋆conserve energy (radiation, latent, etc...)

"Force" with solar radiation, structure of continents and atmospheric composition (e.g., CO_2)

GCM Projections of 21st Century Changes in Large-Scale Environment

Surface Temp.

Tropical Cyclone Potential Intensity



Contour: relative SST=local minus tropical-mean

Vecchi and Soden (2007, Nature)

Why "relative SST"$=T_{local}-T_{trop}$?

$$PI \propto \frac{T_s - T_o}{T_o}(k^* - k)\Big|_{r_{\max}}$$

Surface warming -> PI increase
Warming aloft -> PI decrease

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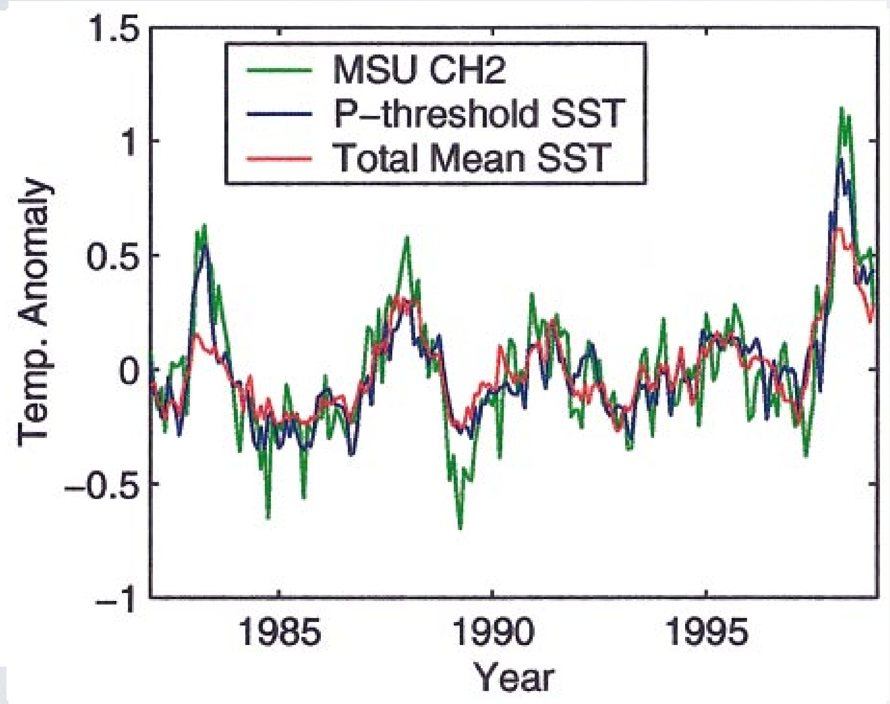

Sobel et al. (2002, J. Clim.)
see also Sobel and Bretherton (2000, J. Clim.)

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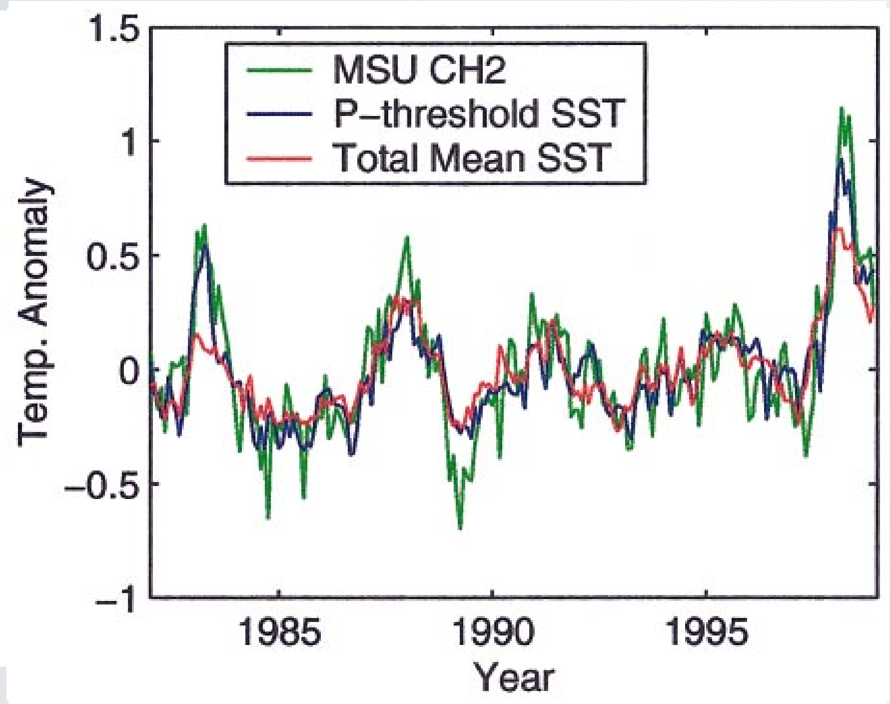

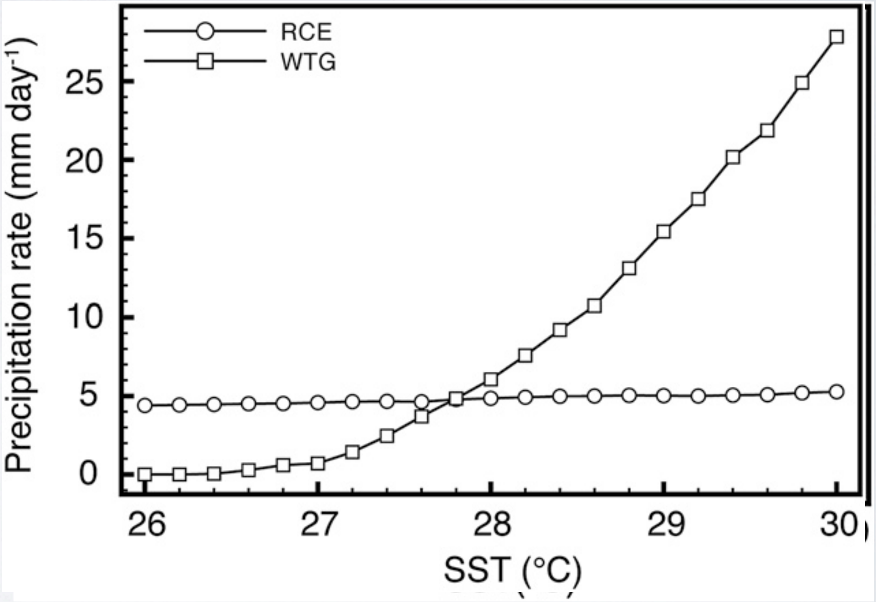

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Ramsay and Sobel (2011, J. Clim.)

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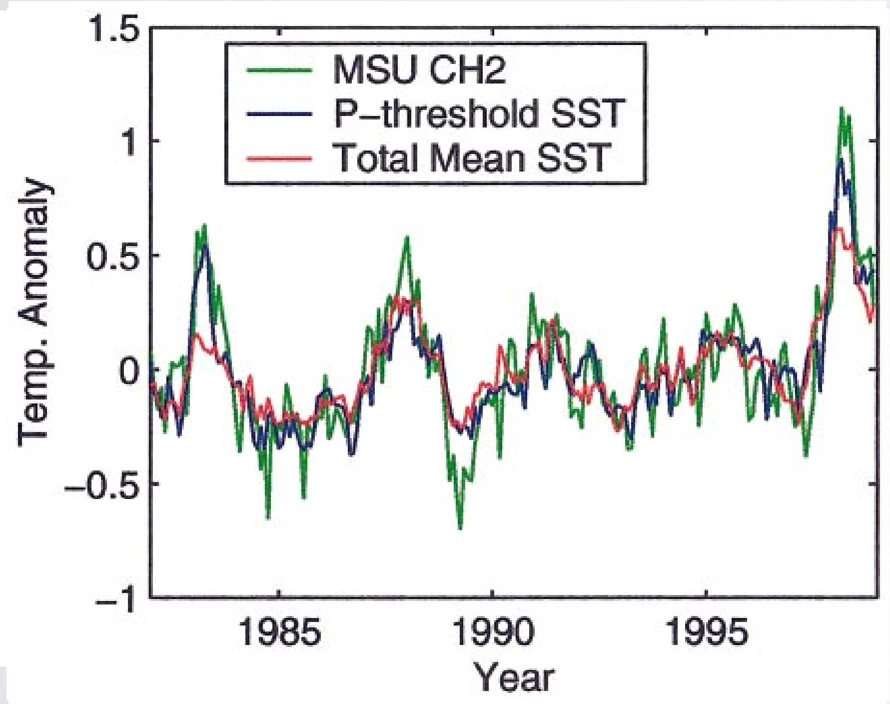
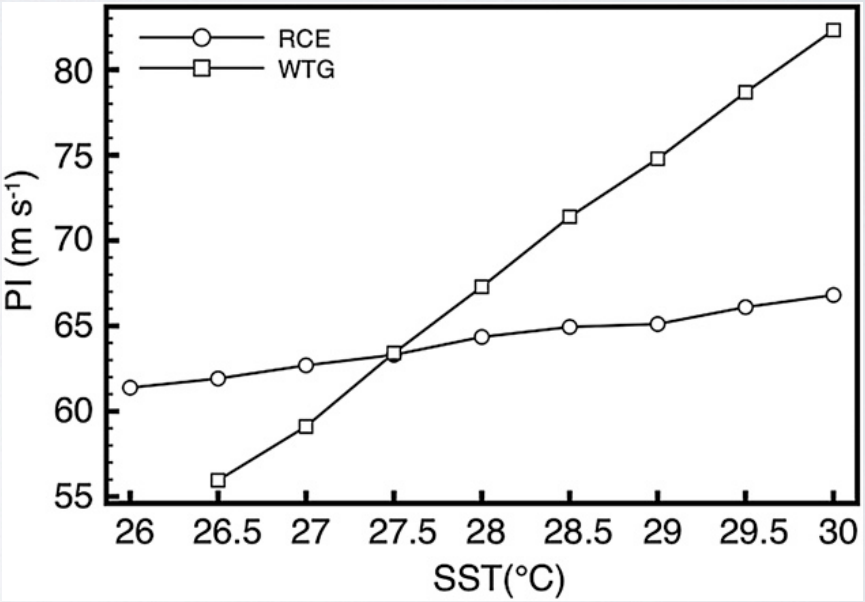
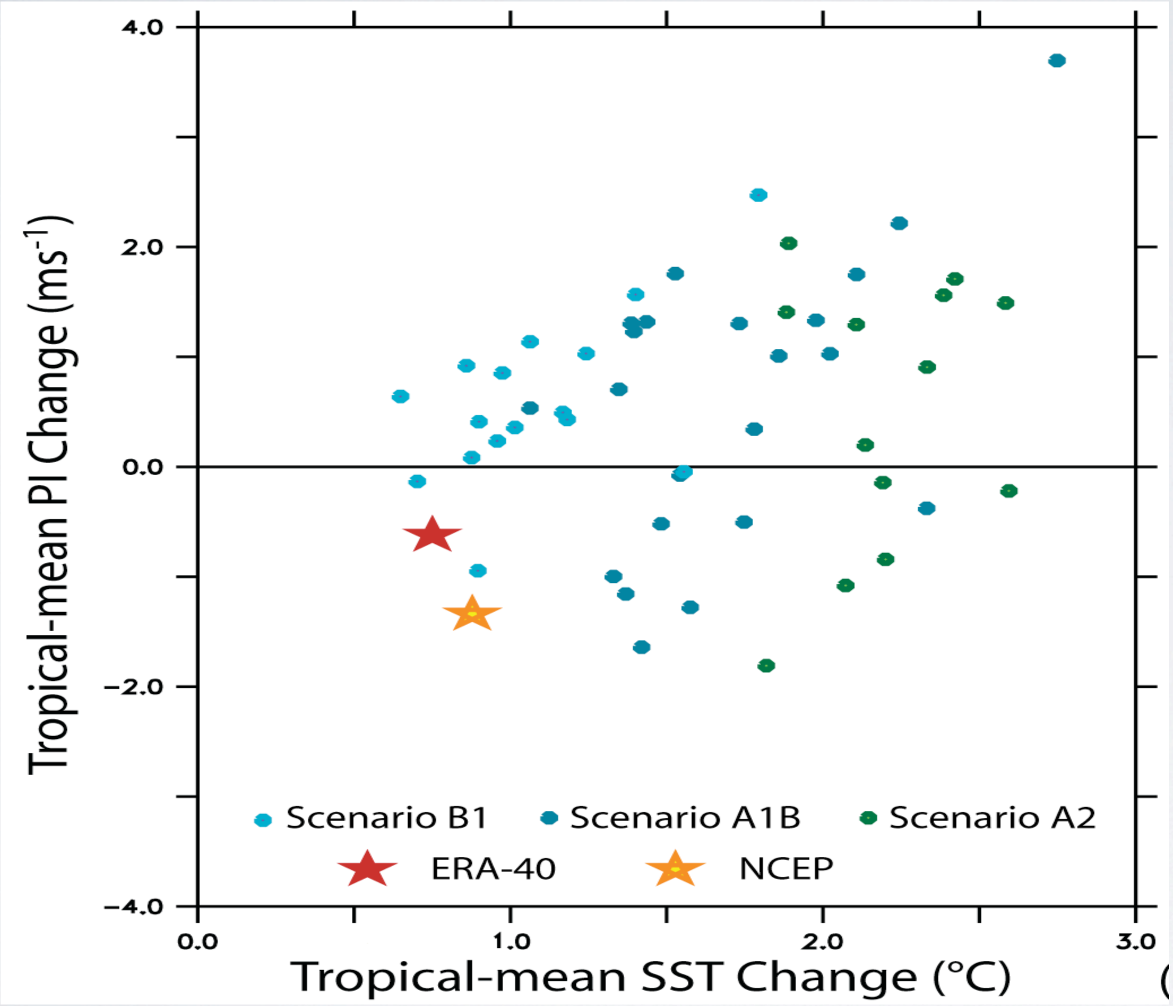




Sobel et al. (2002, J. Clim.)
see also Sobel and Bretherton (2000, J. Clim.)

Ramsay and Sobel (2011, J. Clim.)

What about tropical-mean PI change?



Vecchi and Soden (2007, Nature)

Not well constrained by SST changes.

Related to vertical structure of temperature change.

Why "relative SST"$=T_{local}-T_{trop}$?

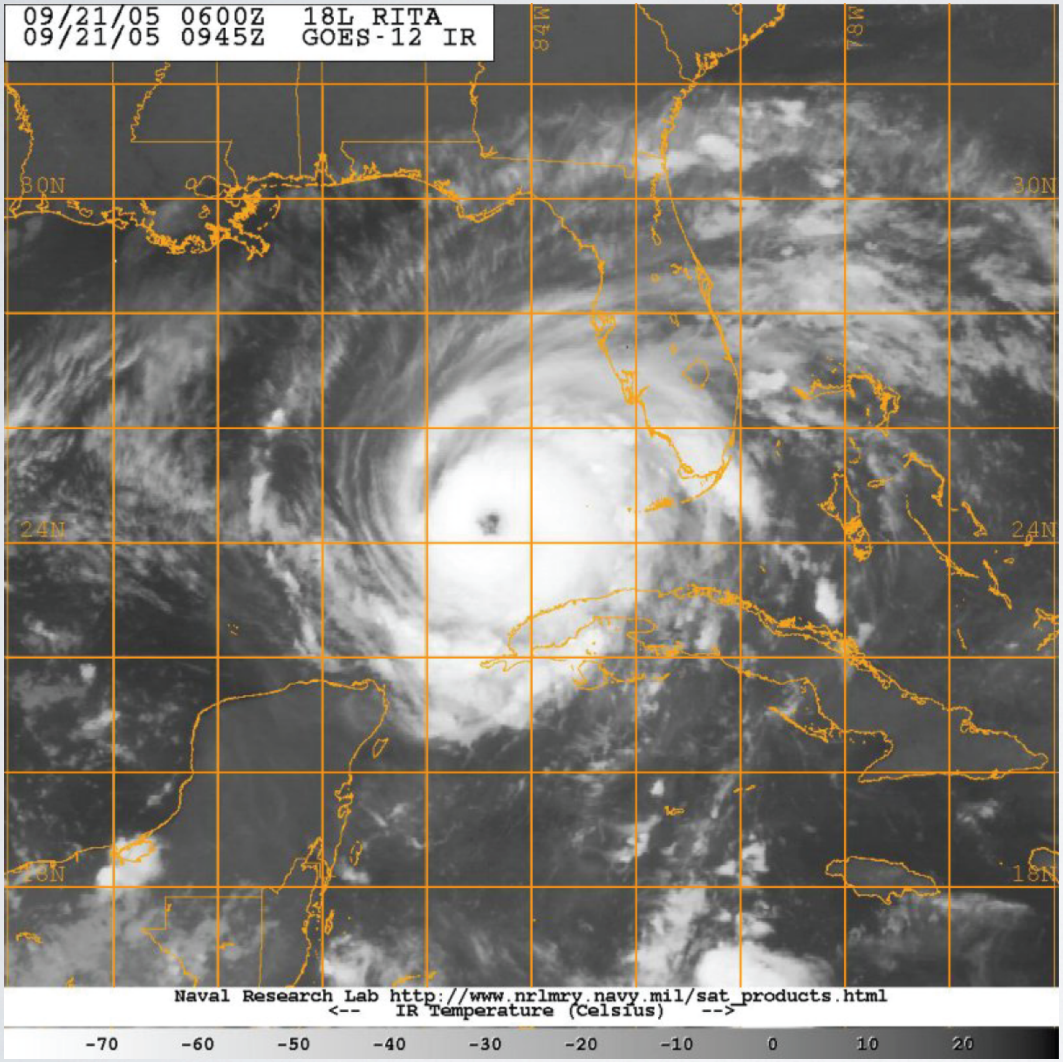
$$PI \propto \frac{T_s - T_o}{T_o}(k^* - k)\Big|_{r_{\max}}$$

If warming something like moist adiabatic*, then relative SST (through impact of tropical-SST on upper troposphere) can be an OK proxy for PI changes.

Also through stability, relative SST in Atlantic can be good proxy for other cyclone-relevant quantities (w_{500}, rh_{700}, shear, etc.)

*Will come back to this.

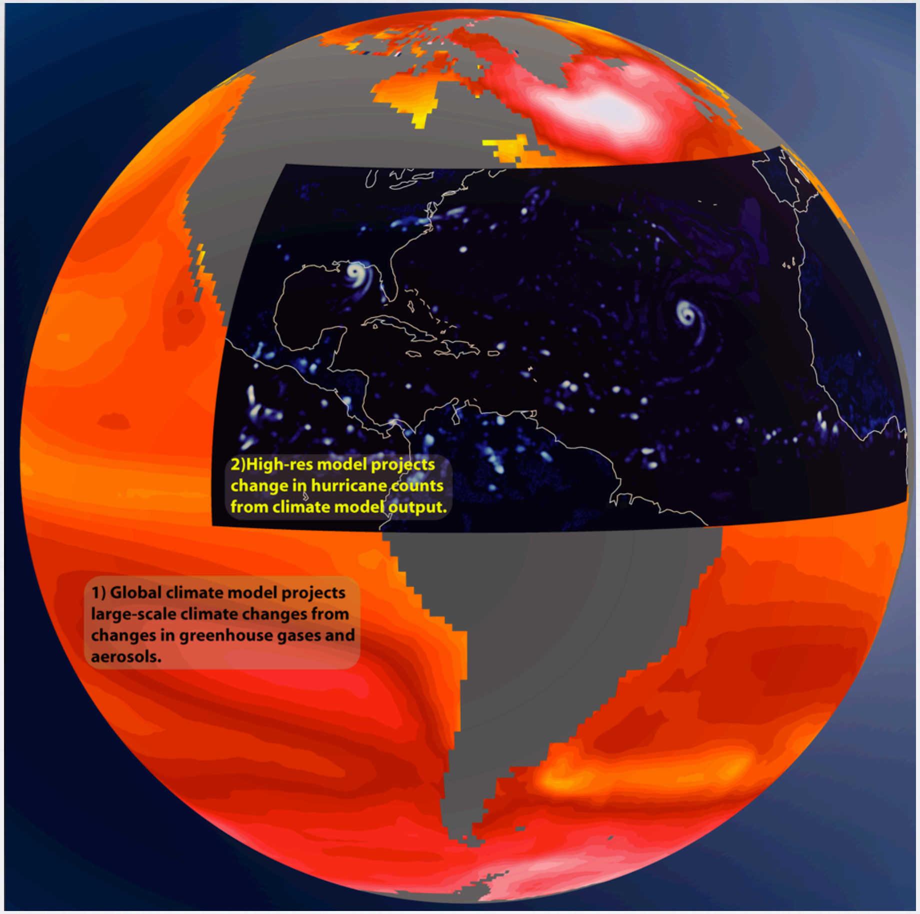
But, current computing power limits ability of coupled global climate models to represent hurricanes



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

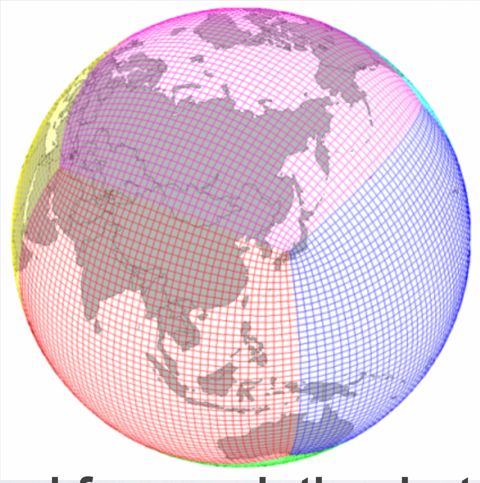


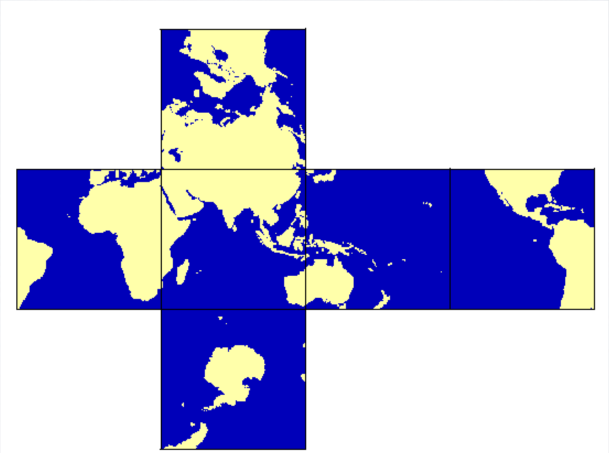
Global Climate Models -> High-resolution Model

Large-scale TS Frequency

The GFDL High-Resolution Atmosphere Model (HiRAM)

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



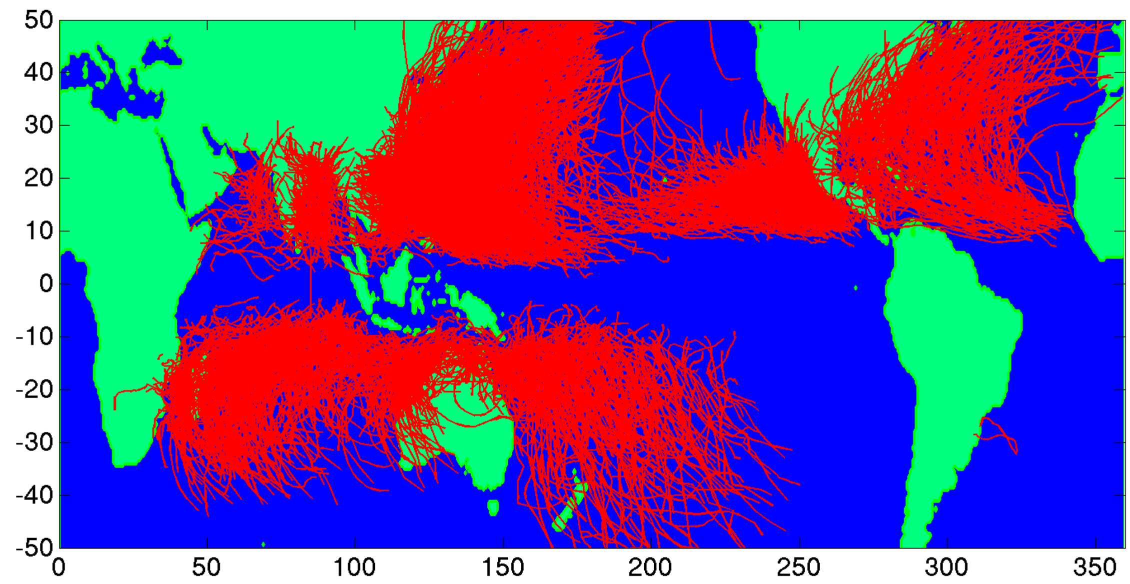


- Designed for resolution between 1– 100 km, capable of direct cloud simulation
- A PDF based 6-category cloud micro-physics with finite-volume vertical sub-grid reconstruction allowing vertically & horizontally sub-grid cloud formation
- A "non-intrusive" shallow convective parameterization (Bretherton scheme modified by Zhao *et al.* 2009)
- Options to couple with ocean and wave models

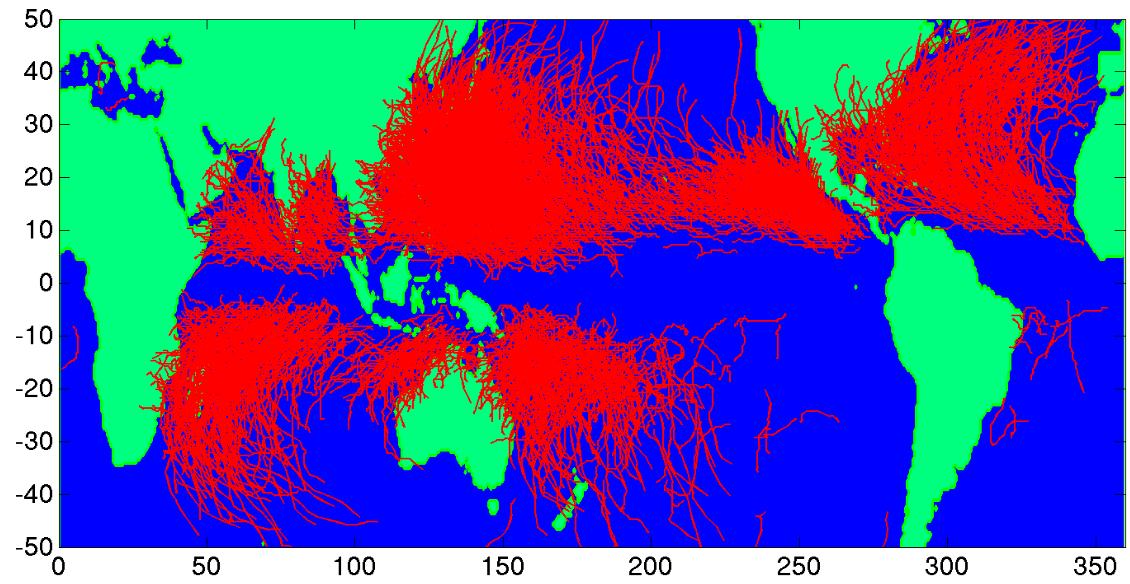
Slide: S-J Lin

Geographical distribution of TC tracks (1981-2009)

Observation

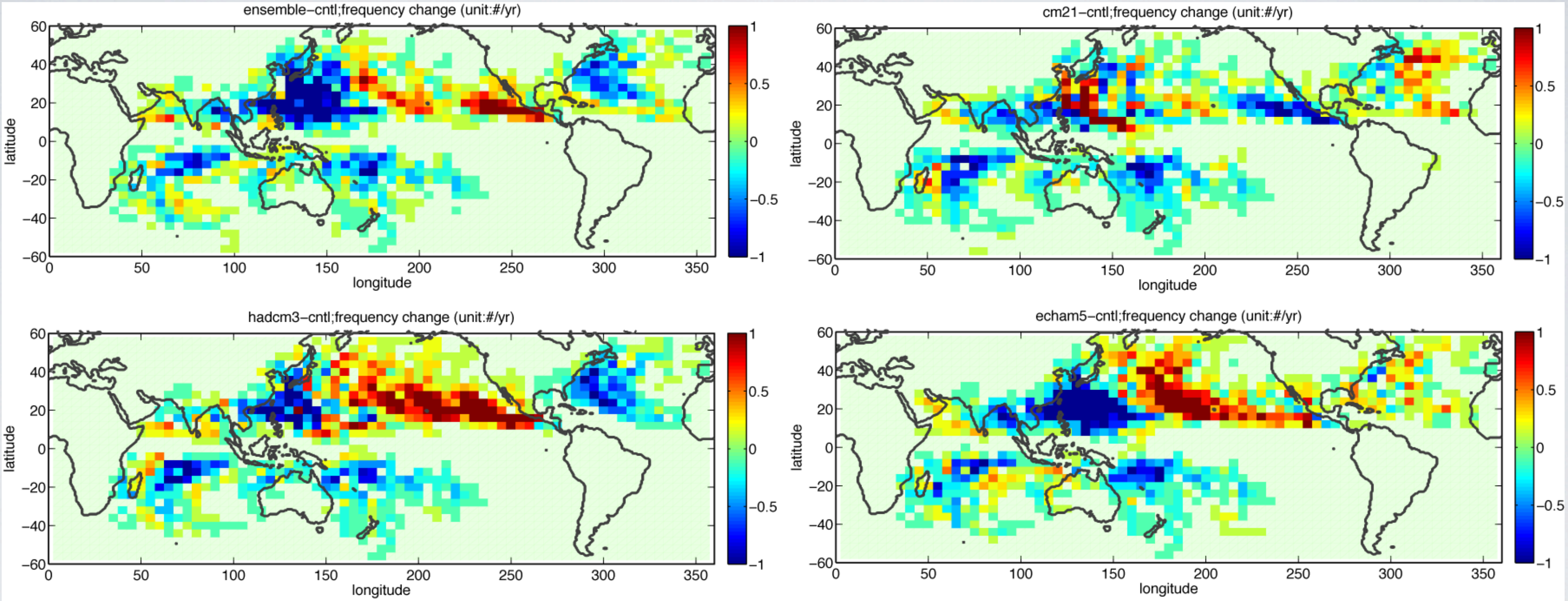


HiRAM-C180 AMIP simulation



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

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

Regional increase/decrease much larger than global-mean.

Pattern depends on details of ocean temperature change.

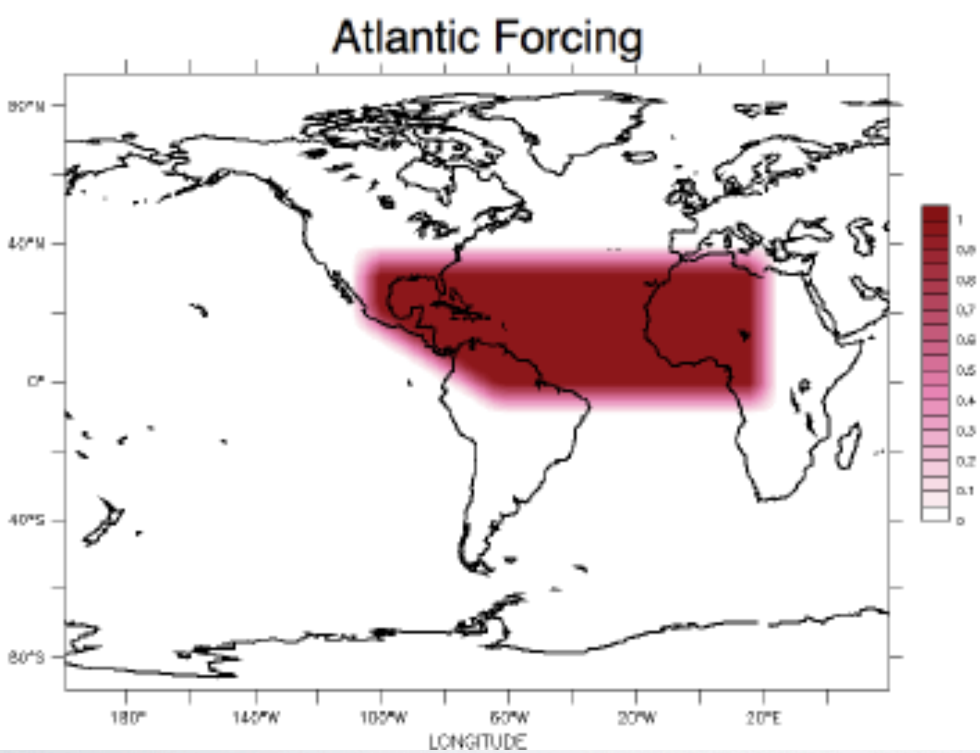
Sensitivity of response seen in many studies

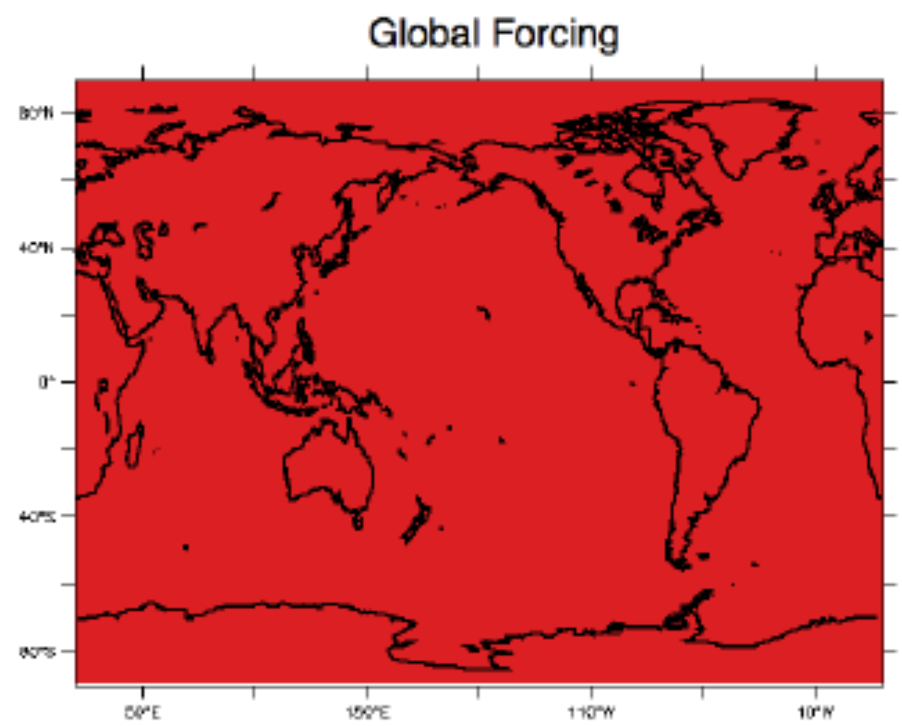
e.g., Emanuel et al. 2008, Knutson et al. 2008, Sugi et al. 2010, Villarini et al. 2011, Knutson et al. 2013, etc.

Idealized Forcing Experiments

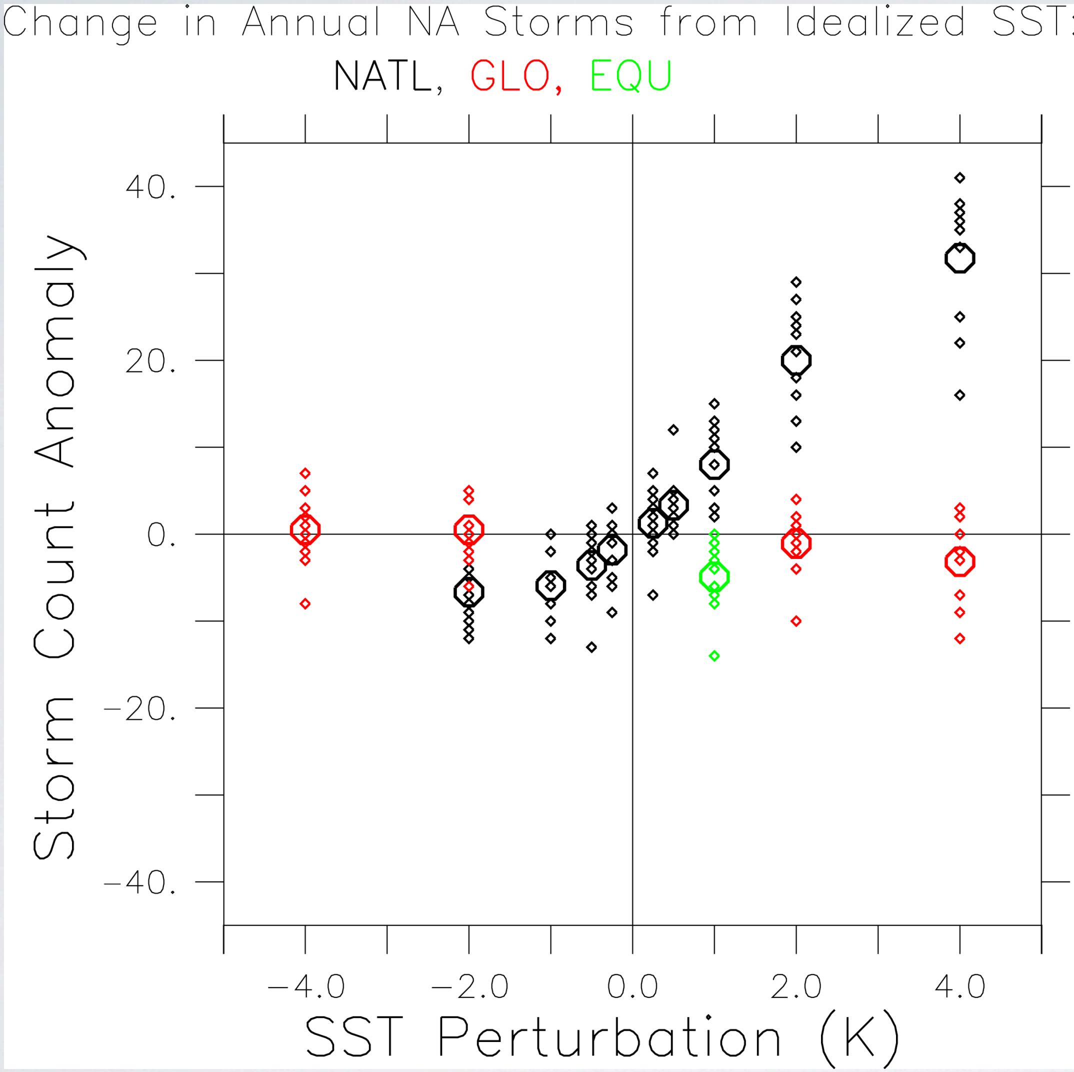
If local SST the dominant control, as opposed to relative SST:

- Similar Atlantic Response to Atlantic and Uniform F’ cing
- Little Pacific Response to Atlantic compared to Uniform





North Atlantic Response to Idealized SST



Atlantic Forcing

Uniform Forcing

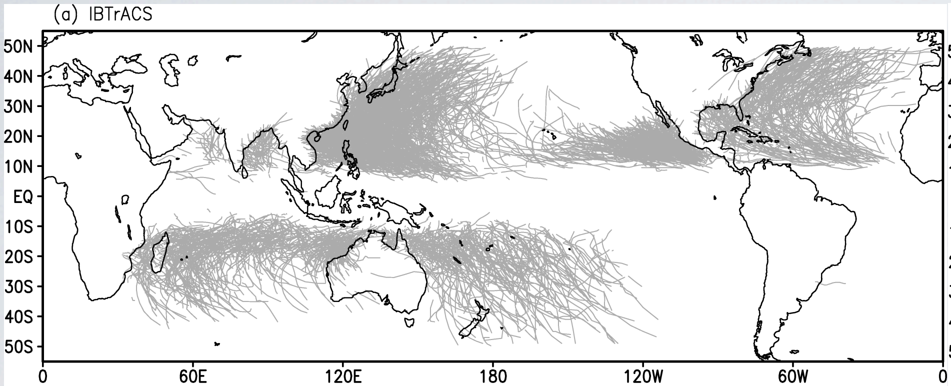
Near-equatorial Forcing

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

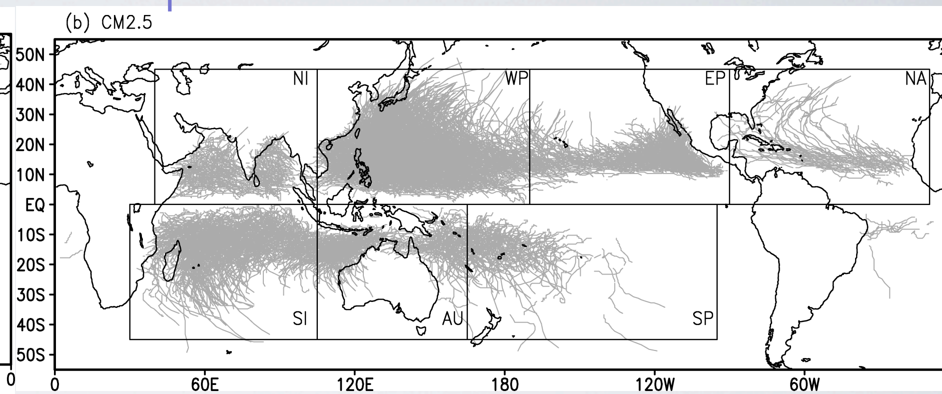
Vecchi et al (2013, in prep.)

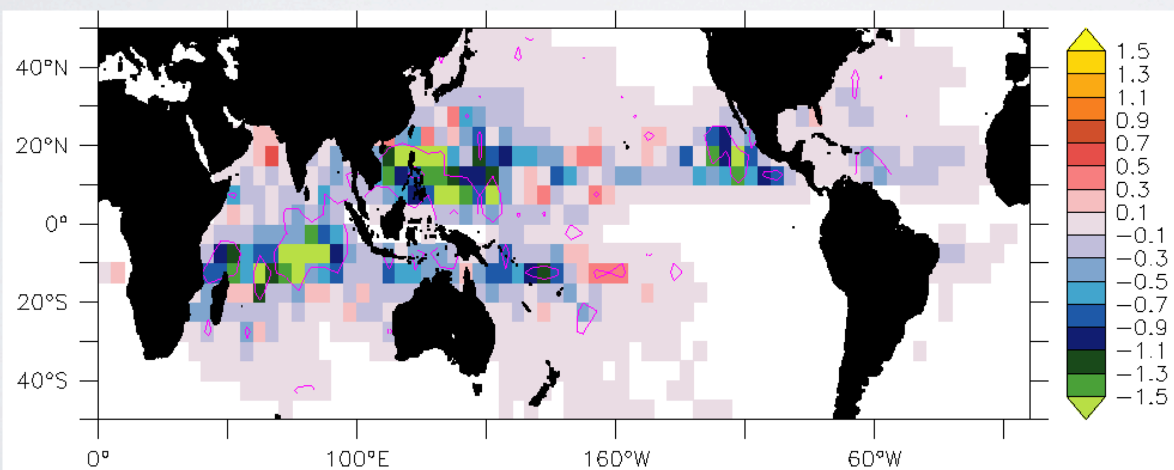
Response of TCs in high-resolution global coupled model (GFDL CM2.5, *Delworth et al. 2012, J. Climate; Kim et al. 2013 in prep.*)

Observed Tracks



Coupled Model Tracks





More storms

Fewer storms

CM2.5 Tropical storm density response to CO_2 doubling

Use homogenized data and high-res models to build statistical models for exploration and projections

$$Rate = e^{a+bSST_{ATL}-cSST_{TRO}}$$

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

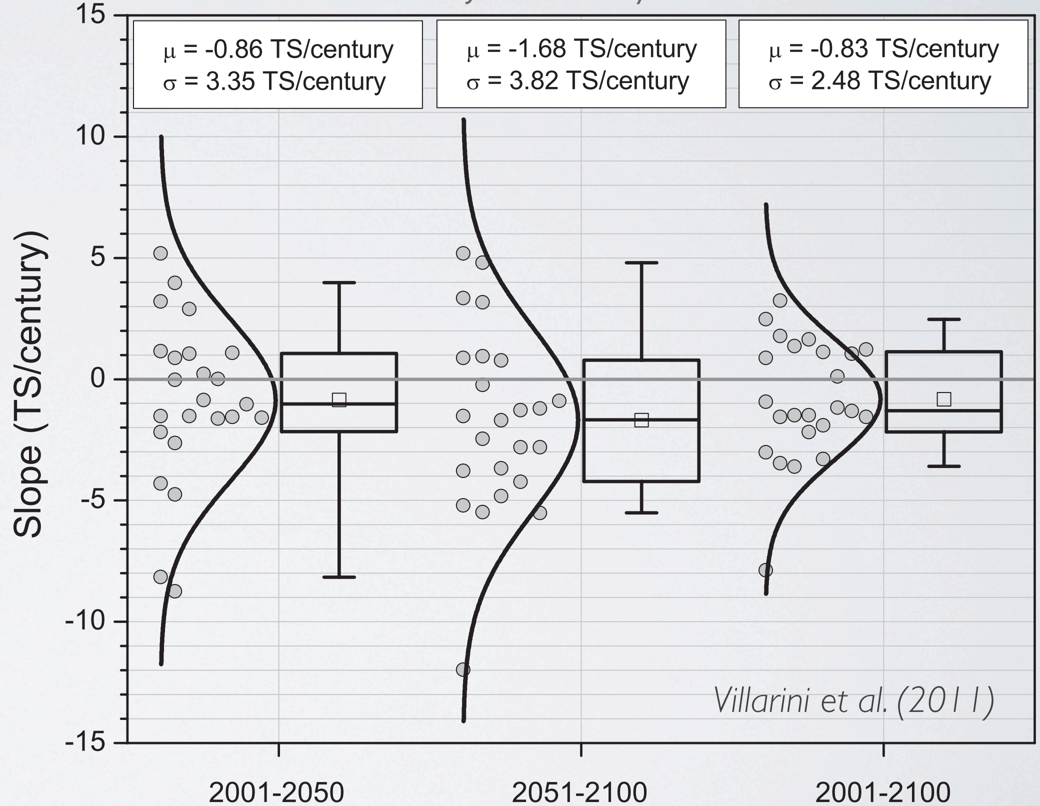
Use two predictors:

- Tropical Atlantic SST (positive)
- Tropical-mean SST (negative)

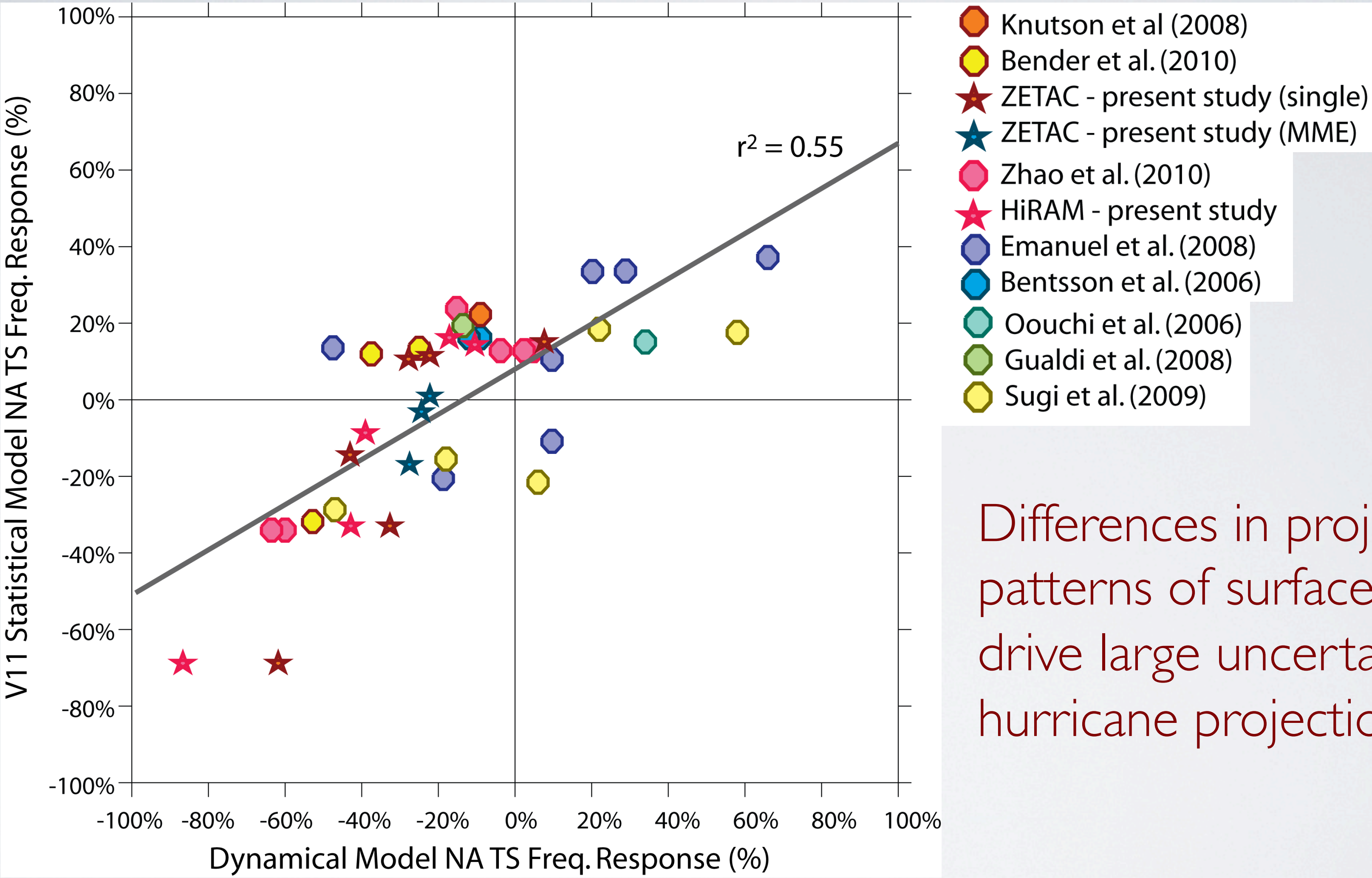
Consistent with high-res dynamical models, understanding on controls to hurricanes & "cheap".

Knutson et al. (2008) Swanson (2008), Vecchi et al. (2008), Zhao et al. (2009, 2010), Villarini et al. (2010, 2011.a.,.c), Villarini and Vecchi (2011)

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

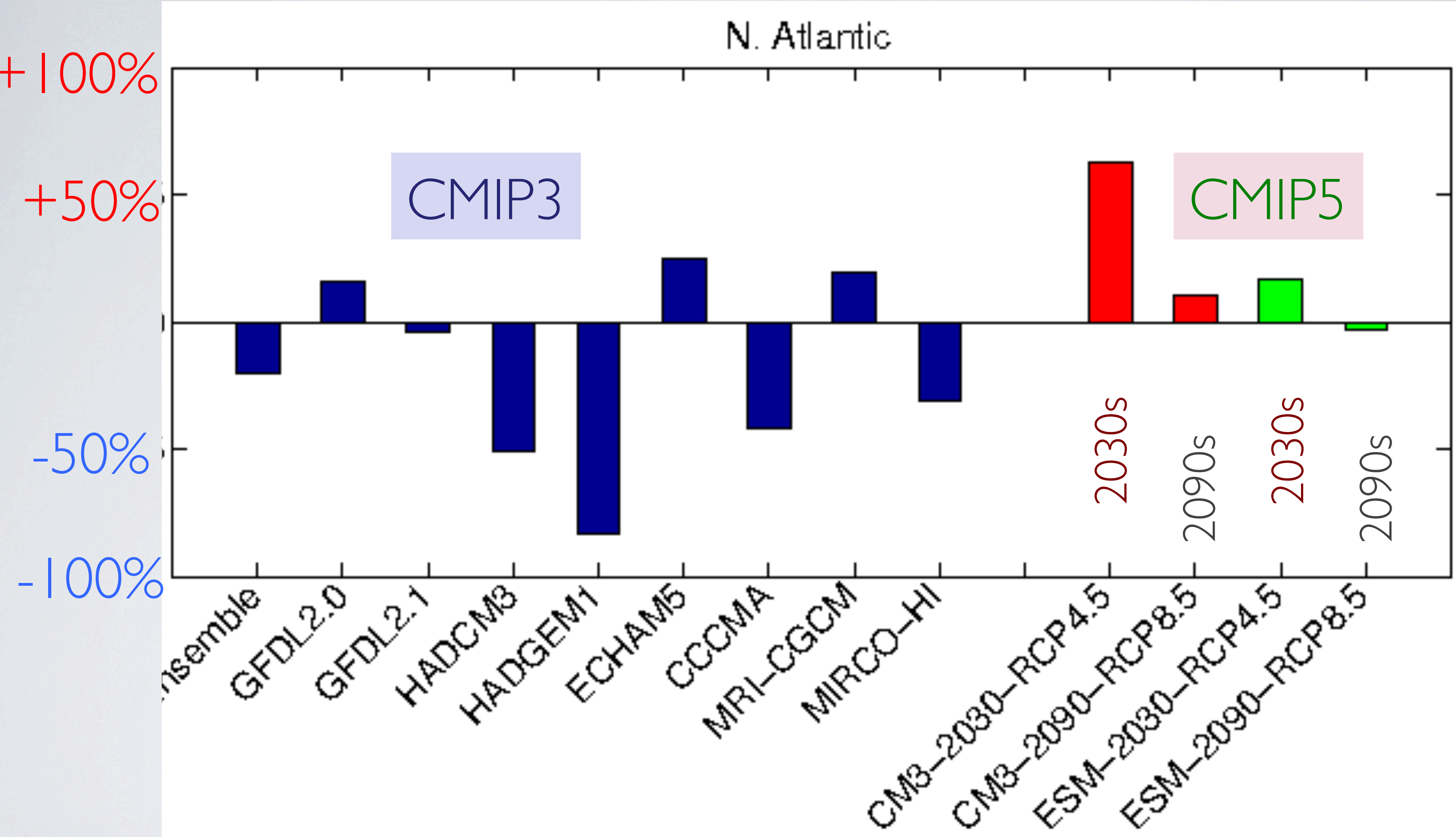


Differences in projected patterns of surface warming drive large uncertainties in hurricane projections

$$Rate = e^{a+bSST_{ATL}-cSST_{TRO}}$$

Knutson et al. (2013, J. Clim.)
See also Villarini et al. (2011, J. Clim.)
Vecchi et al. (2008, Science)

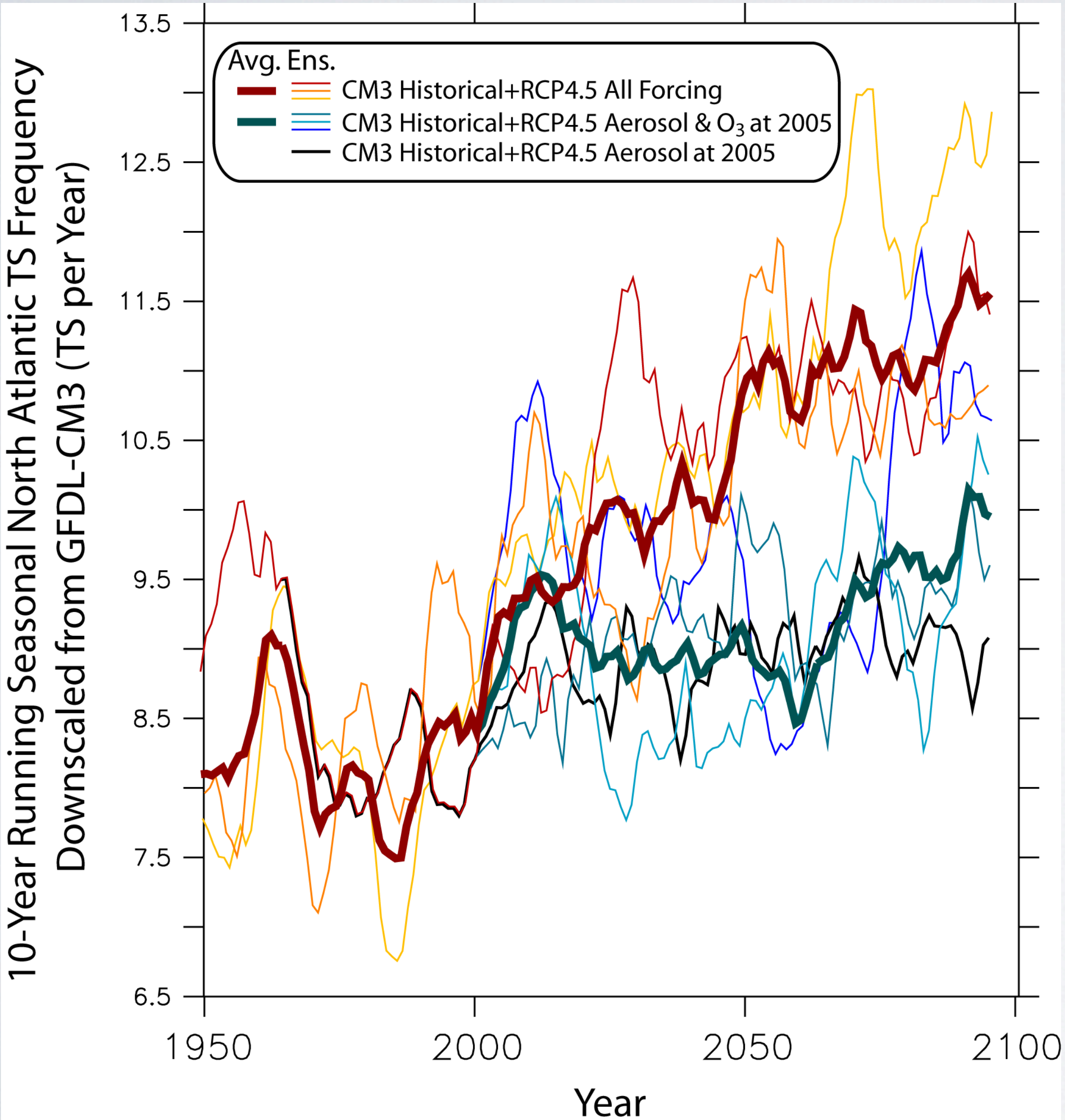
Dynamical Projections of Atl. Hurricanes for end of 21st Century



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)



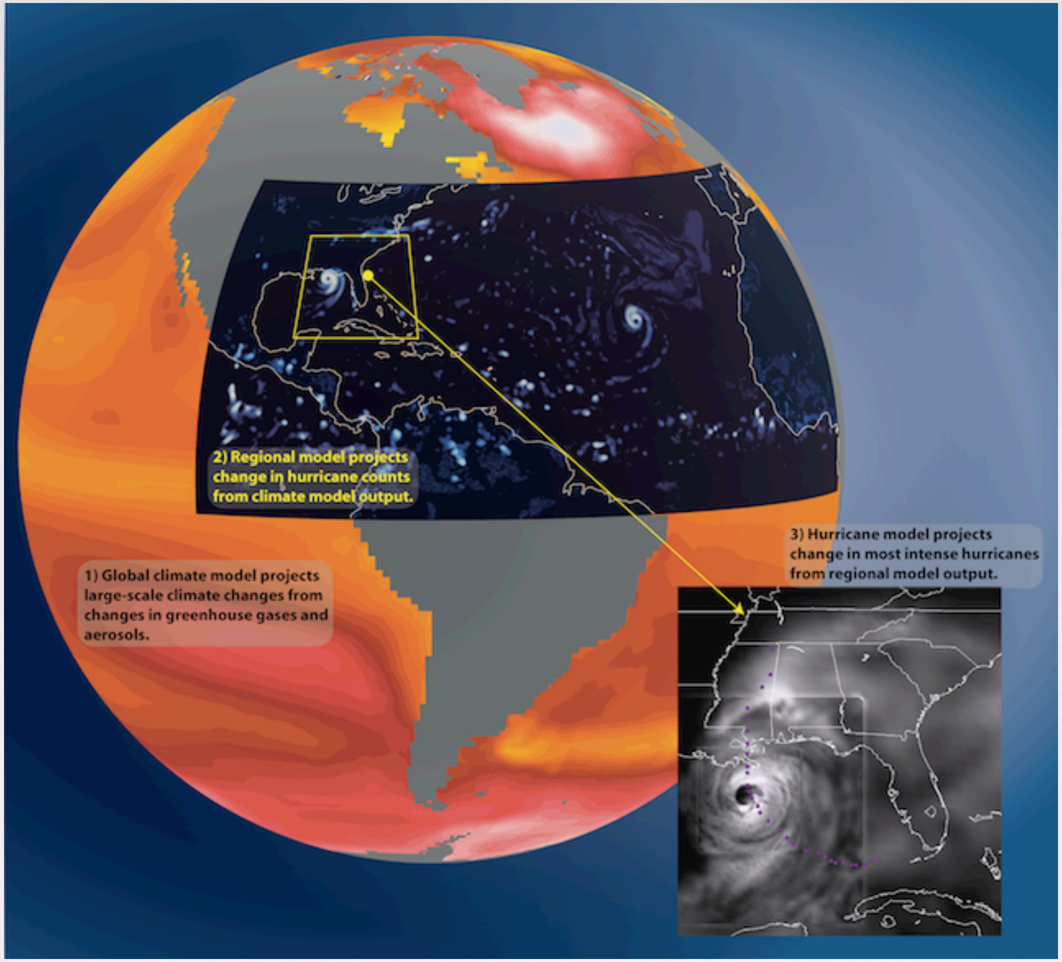
All Forcing

No future aerosol or O_3

No future aerosol

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

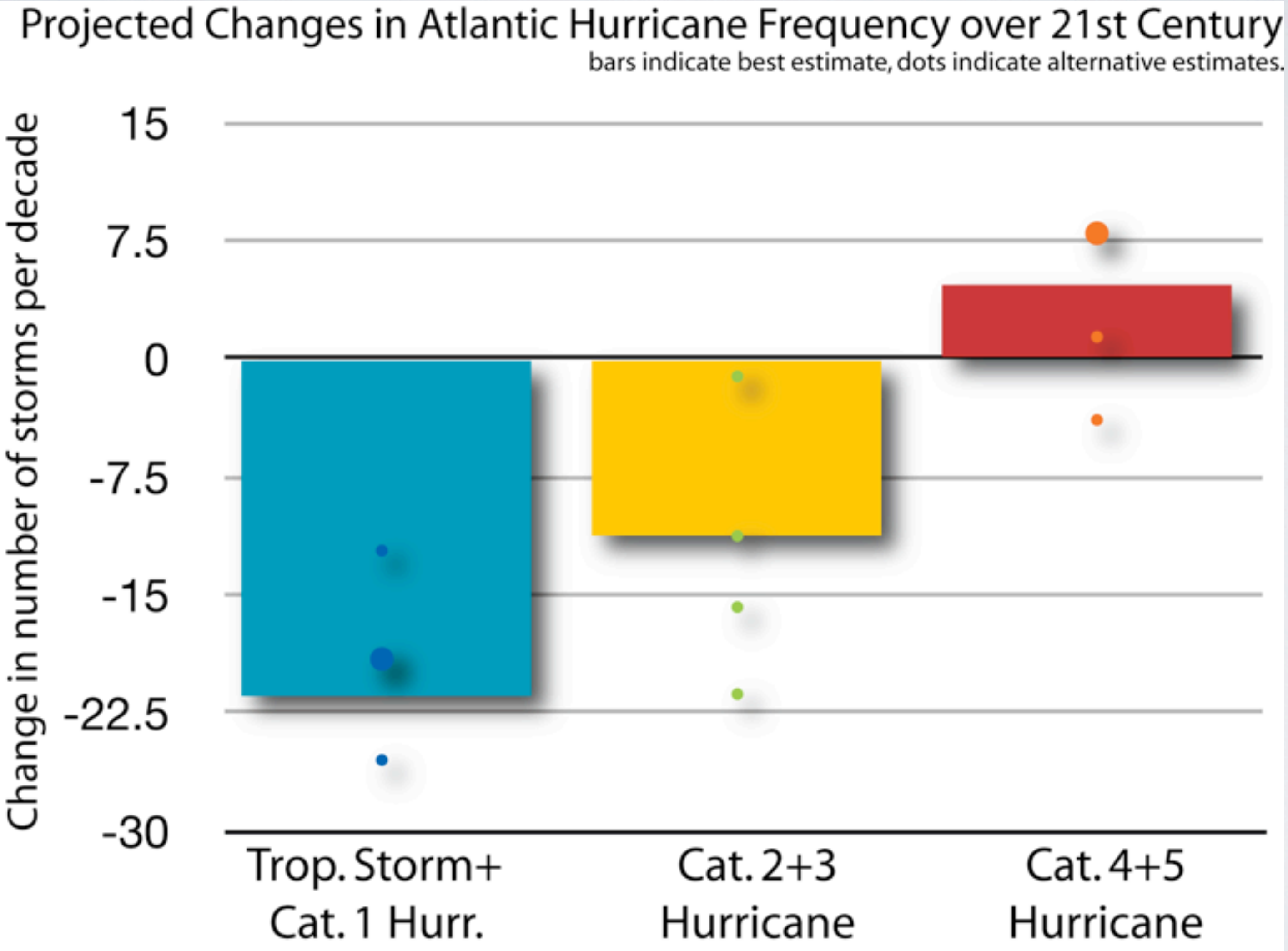
Multi-decadal projections



Global Climate Models -> High-Res Model -> Hurricane model

Large-scale TS Frequency Intensity

Dynamical double downscaling for Atlantic: Overall frequency decrease projected, but more of the strongest storms



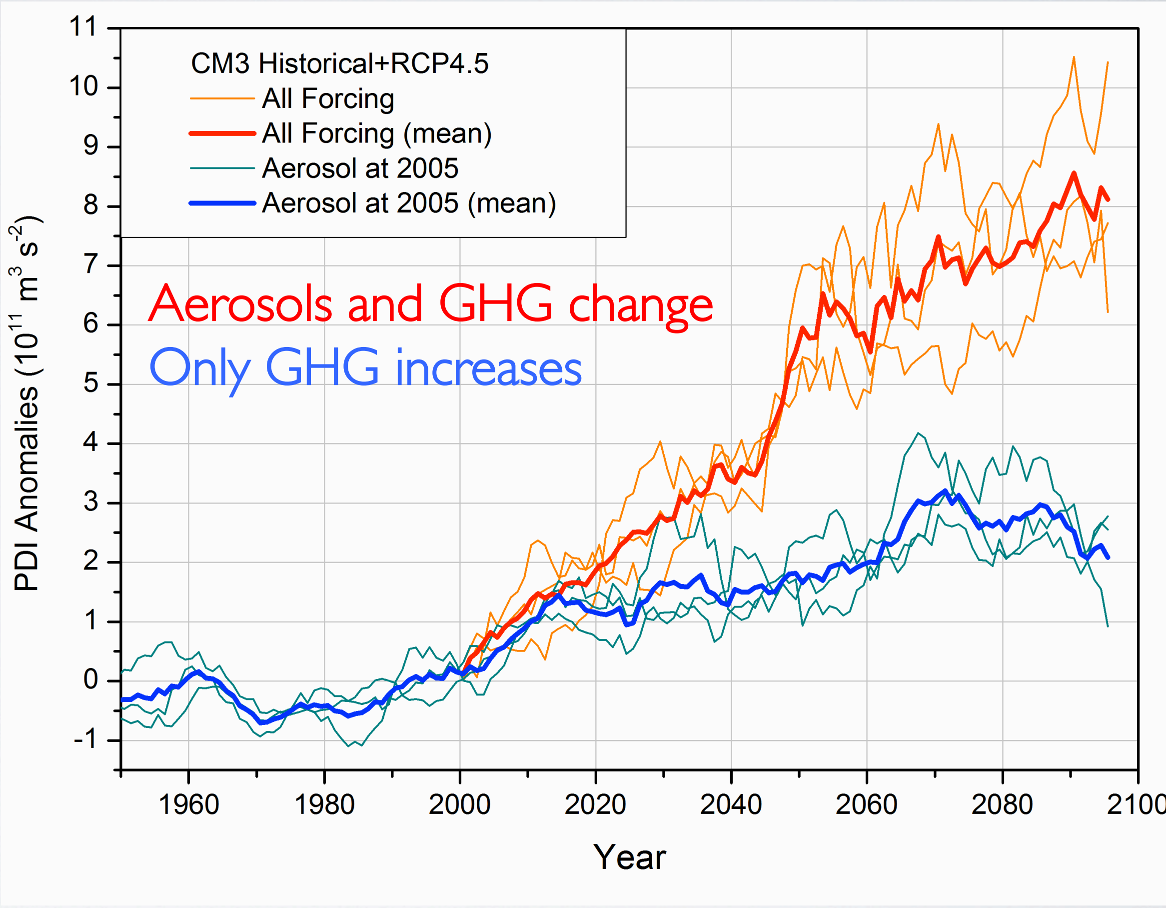
Adapted from Bender et al (2010, Science)

see also Knutson et al. (2008, Nature Geosci.); Knutson et al. (2013, J. Clim., in press)

Projections of changes in atmospheric aerosols contribute to projected increases in Atlantic hurricane intensity

Power Dissipation Index

$$PDI = \sum_{storms} U_{max}^3$$



Villarini and Vecchi (2013.b, J. Climate)
See also Knutson et al. (2013, J. Climate)

Historical aerosol forcing may have masked century-scale greenhouse-induced intensification in Atlantic

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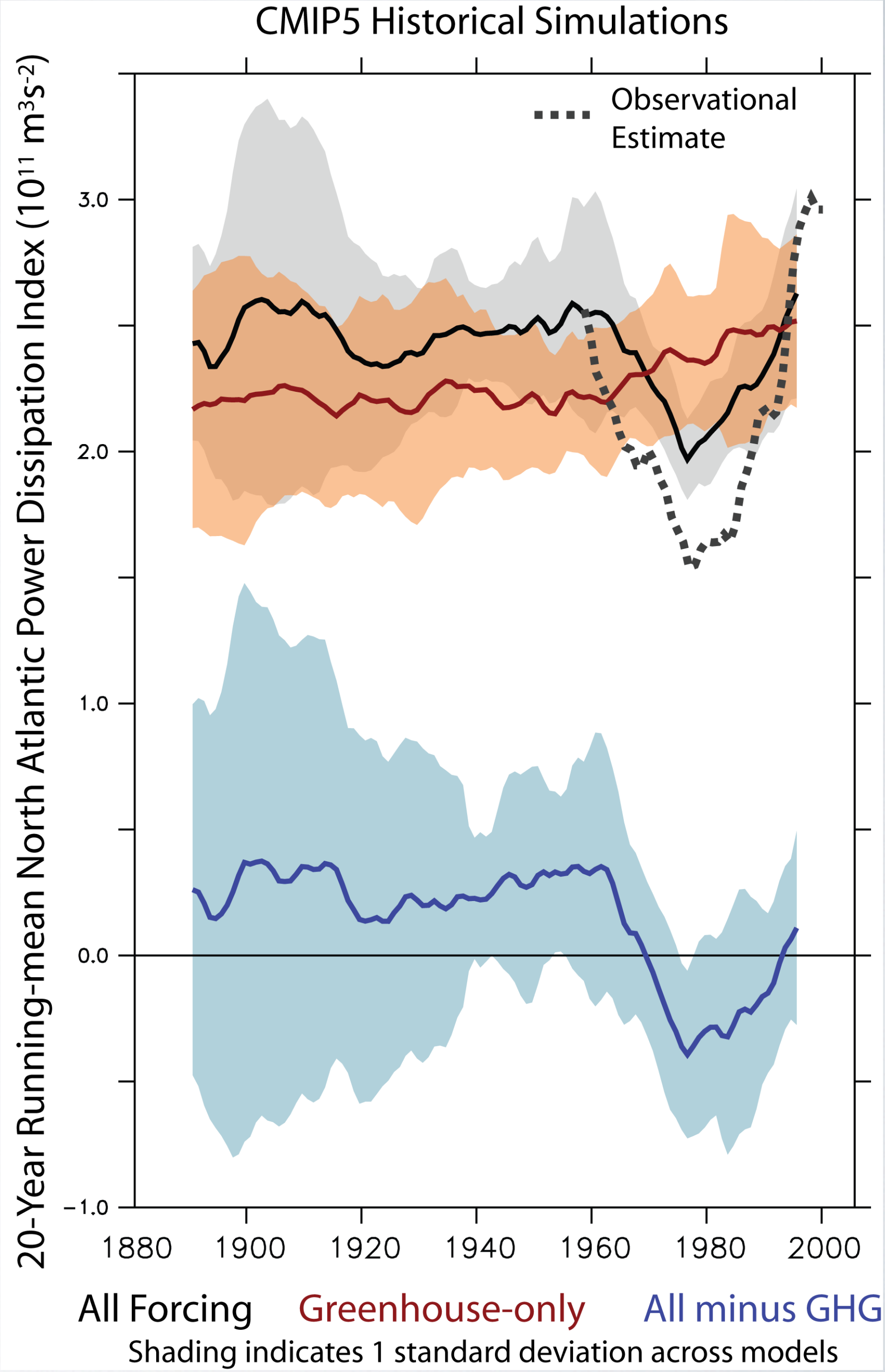


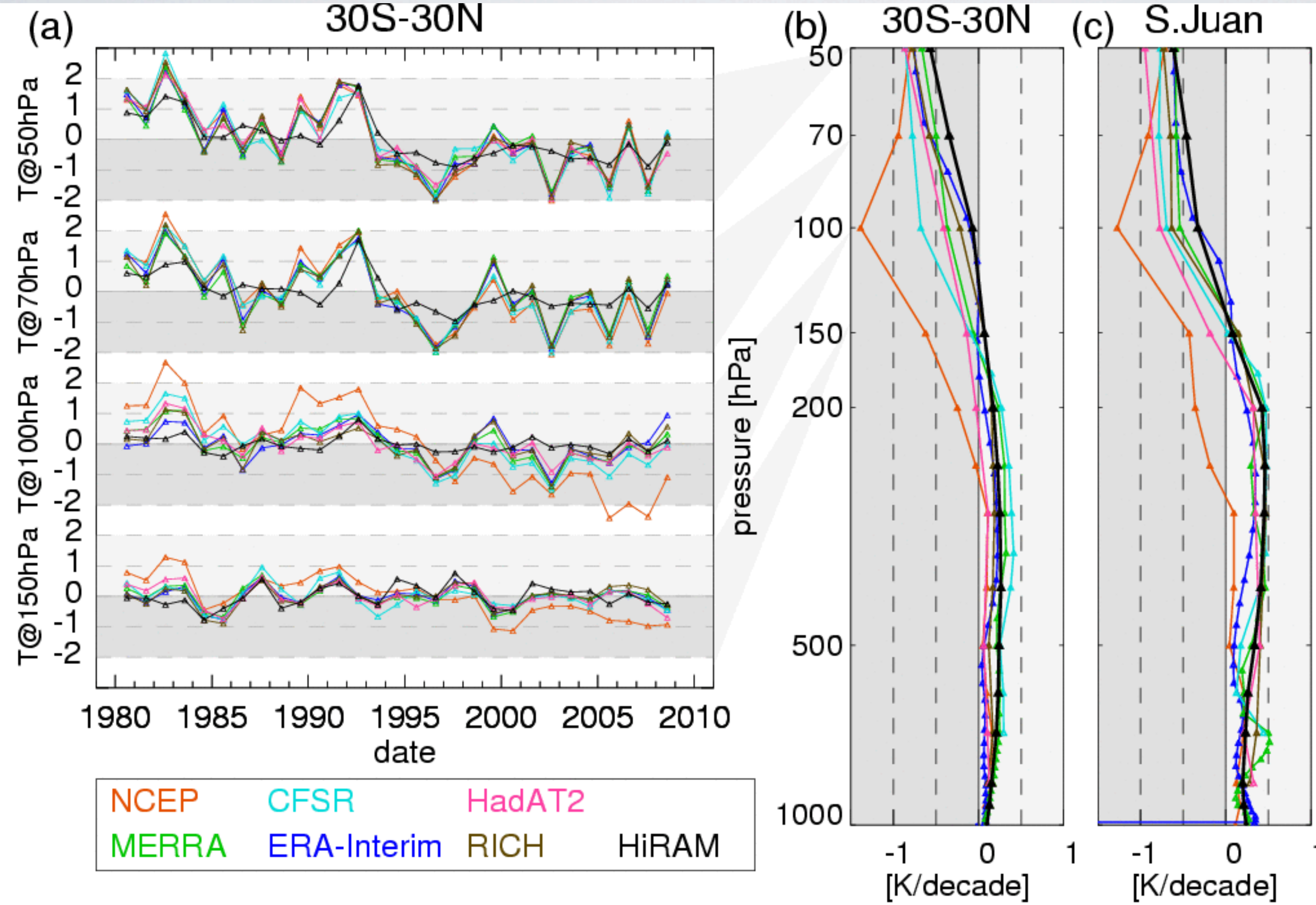
Villarini and Vecchi (2013.b, J. Climate)

Issues regarding non-moist-adiabatic warming

If warming something like moist adiabatic, then relative SST (through impact of tropical-SST on upper troposphere) can be an OK proxy for PI, circulation, humidity, shear, precip…changes.

What about non-moist adiabatic warming?
Estimates of past atmospheric ΔT

Reanalyses Radiosonde-only AGCM

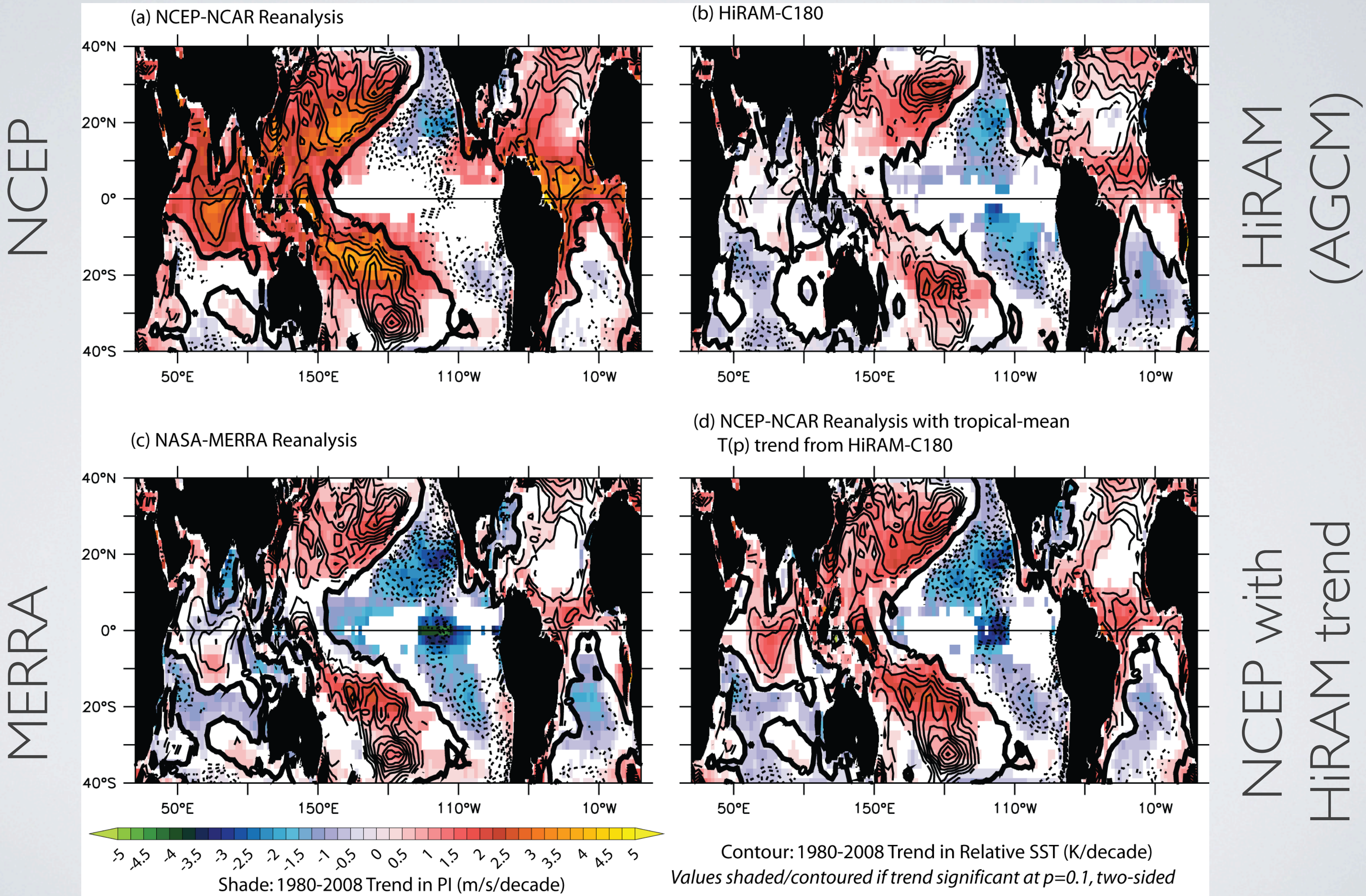


NCEP used in Knutson et al. (2008) and Emanuel et al. (2008)

HiRAM used in Zhao et al. (2009)

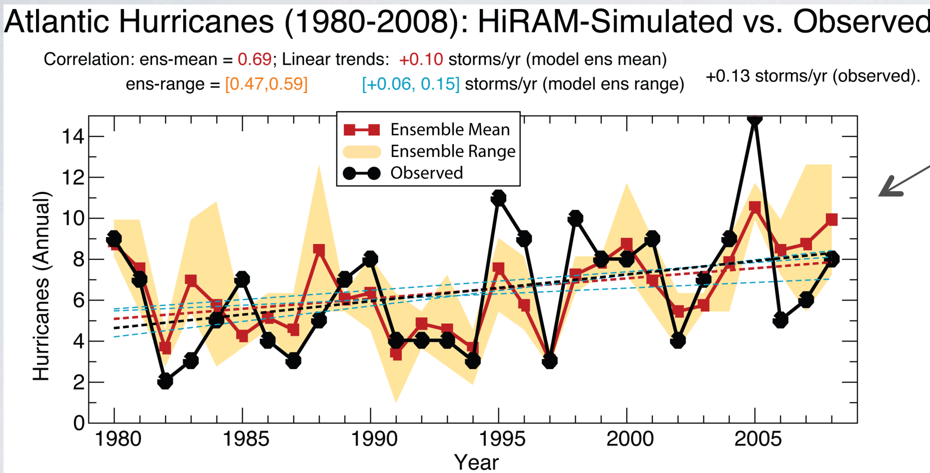
Vecchi et al. (2013.b, J. Climate, in press)

Differences in vertical structure of ΔT lead to differences in ΔPI Largely from TTL and Upper Troposphere



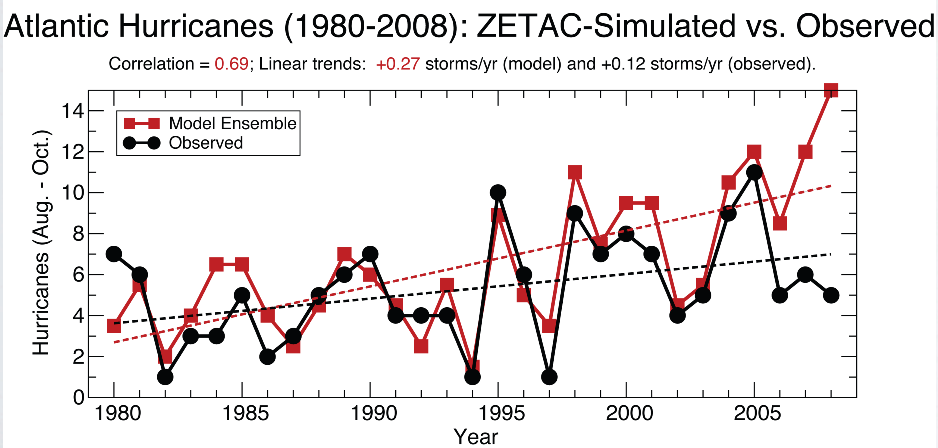
Vecchi et al. (2013.b, J. Climate, in press)

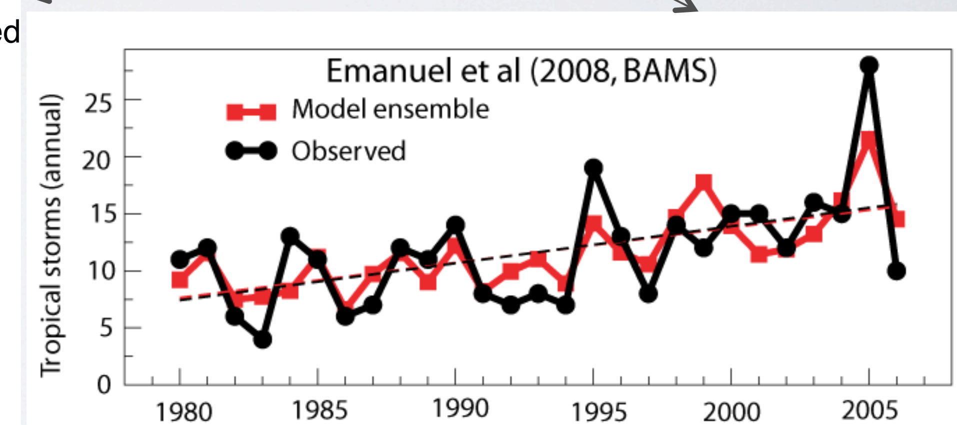
Different TC downscaling studies assume/simulate different ΔT(p) in historical simulation: get similar correlation



Simulates ~adiabatic warming

Use NCEP (assume UT/TTL cooling)

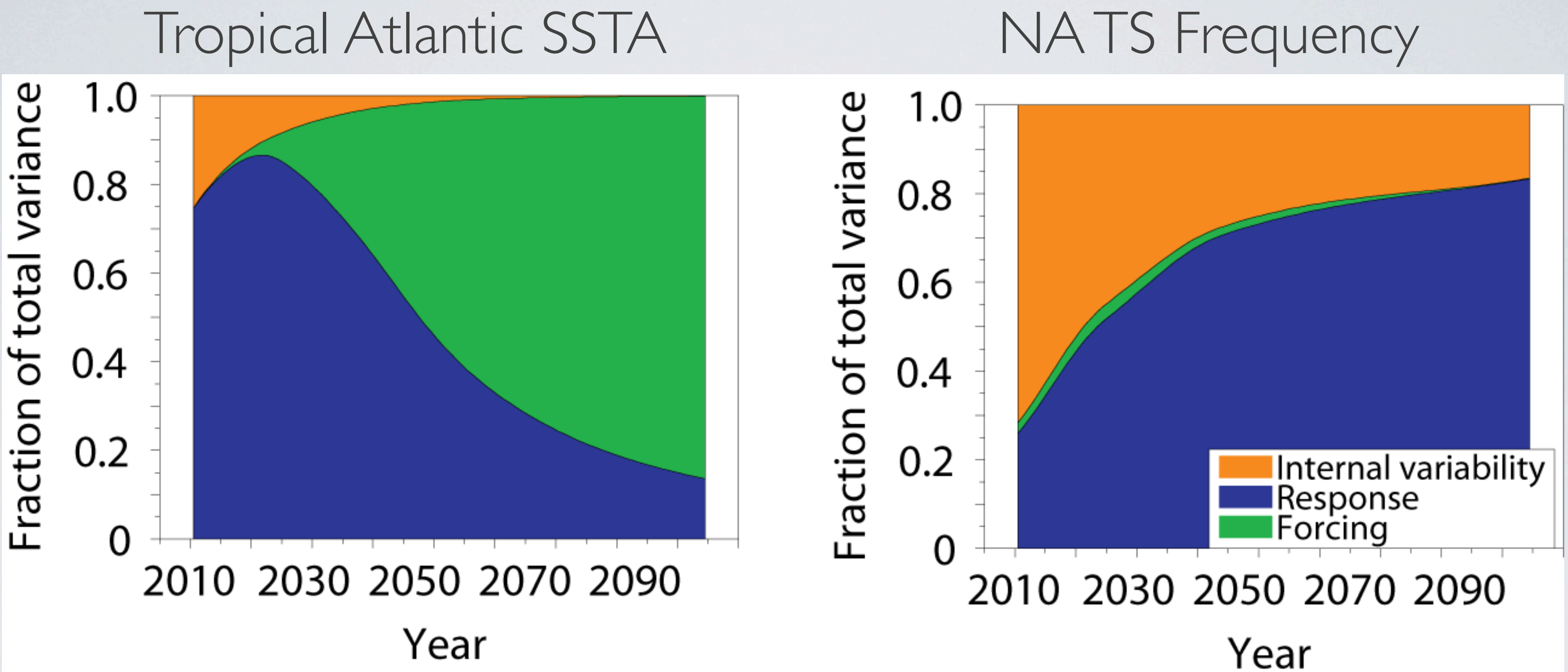




Vecchi et al. (2013.b, J. Climate, in press)

Multi-year hurricane prediction

Key uncertainty sources to projections of decadal TS activity



Villarini et al. (2011), Villarini and Vecchi (2012)

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?"

Sources of & Limitations on climate predictability

years to decade

hours to a year

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

Many decades
to centuries

Climatology

Climate response to forcing

(e.g., CO_2, aerosols, sun, volcanoes)

need good models and estimates of forcing

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

Merge multiple tools and understanding to build experimental long-lead hurricane forecast system: skill from as early as October of year before

April & onward forecasts fed to NOAA Seasonal Outlook Team

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

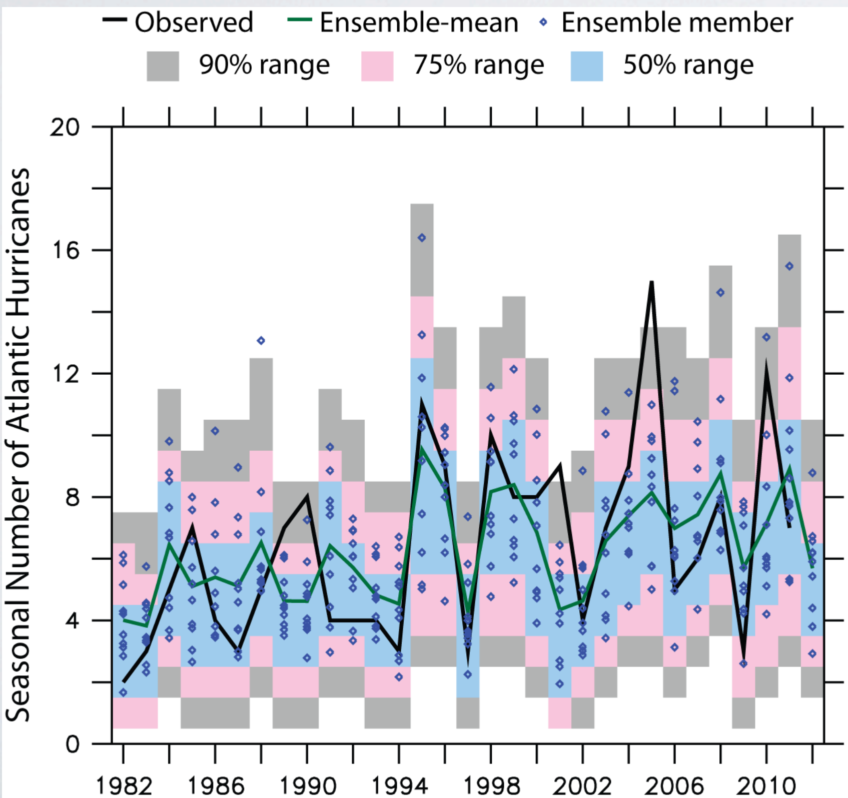
Build statistical model of the response of hurricanes in HiRAM

Use initialized coupled model to forecast future values of SST

Apply Stat model to Predicted SST

Make Prediction of Full PDF of Hurricane Activity

Initialized January: r=0.66



HyHuFS

http://gfdl.noaa.gov/HyHuFS

Vecchi et al. (2011); Villarini and Vecchi (2013.b)

Experimental decadal predictions

Hybrid system: statistical hurricanes, dynamical decadal climate forecasts

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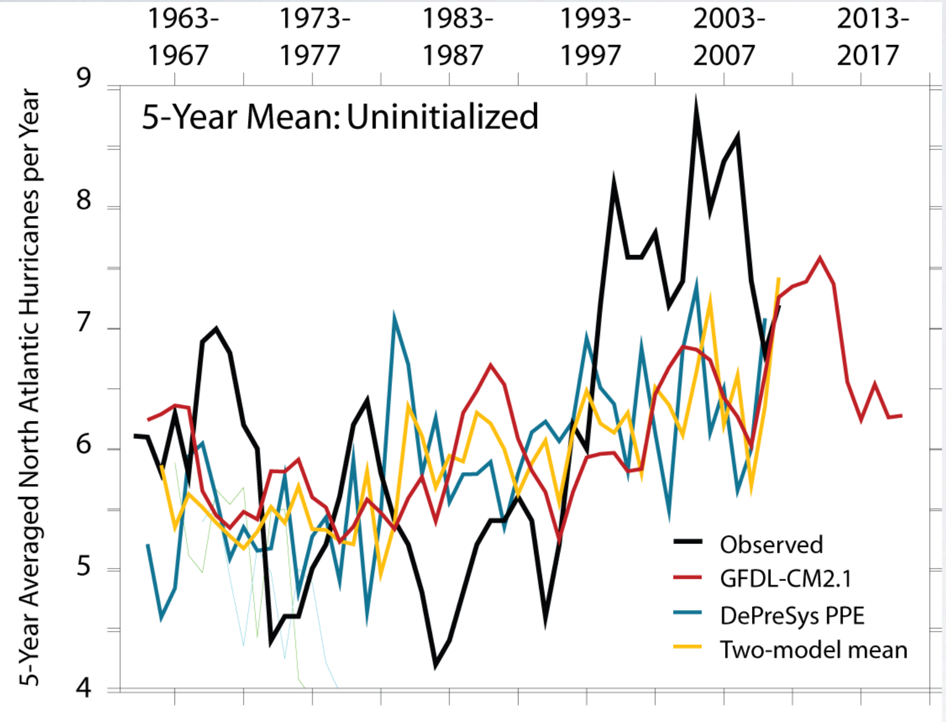

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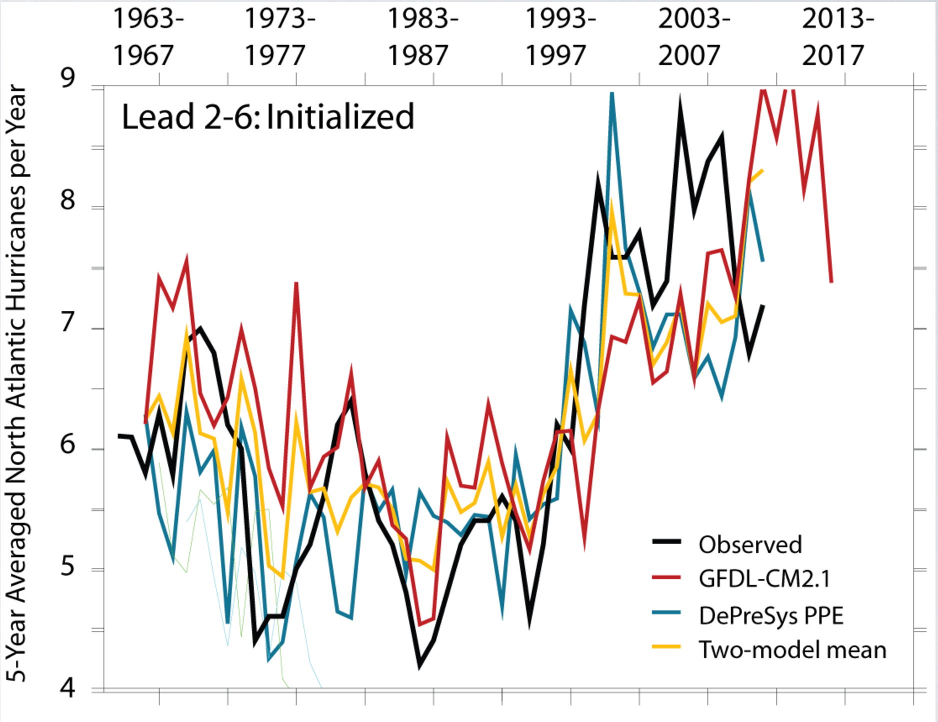

- Retrospective predictions encouraging.
- However, small sample size limits confidence
- Skill arises more from recognizing 1994-1995 shift than actually predicting it.
- This is for basinwide North Atlantic Hurricane frequency only.

EXPERIMENTAL: NOT OFFICIAL FORECAST

Vecchi et al. (2013.a, J. Clim. in press), see also Smith et al. (2010, Science)

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Hybrid system: statistical hurricanes, dynamical decadal climate forecasts

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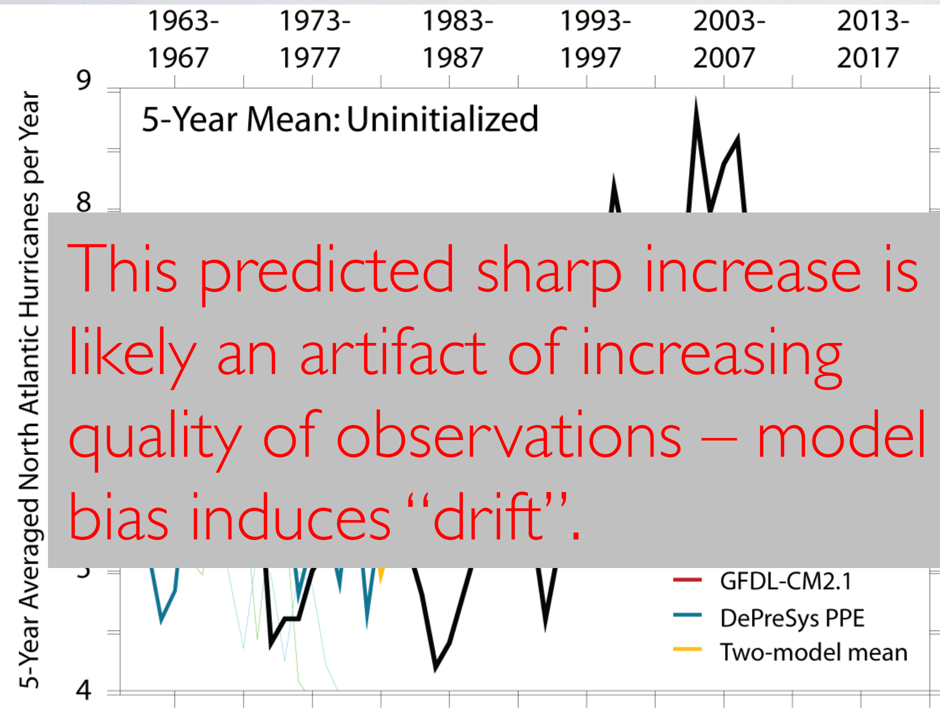

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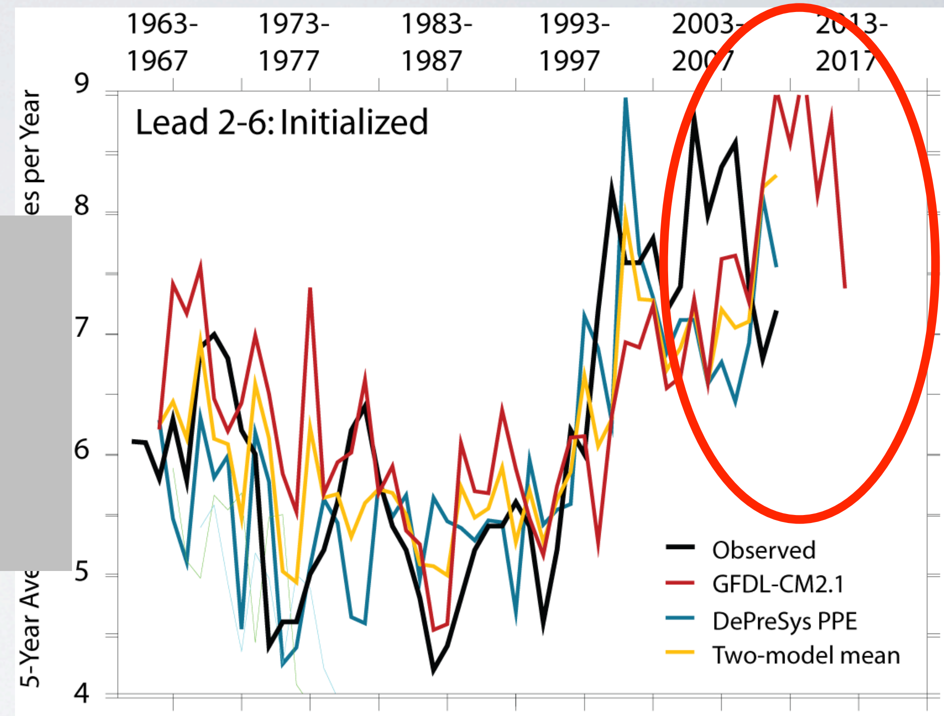

This predicted sharp increase is likely an artifact of increasing quality of observations – model bias induces "drift".

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EXPERIMENTAL: NOT OFFICIAL FORECAST

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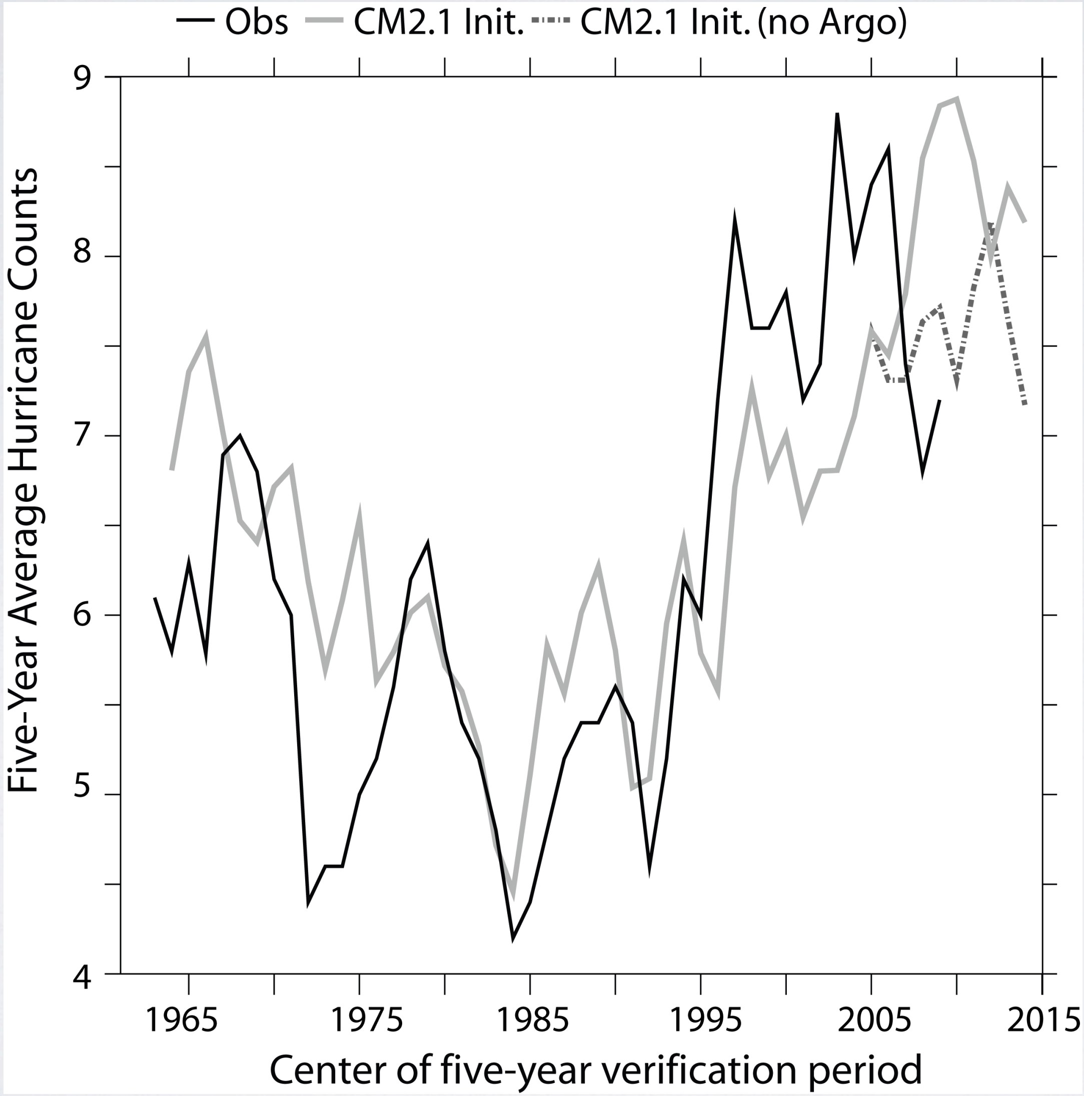
Removing observational inhomogeneity removes post-2004 upswing: need stable, sustained observations



Vecchi et al. (2013.a, J. Climate in press)

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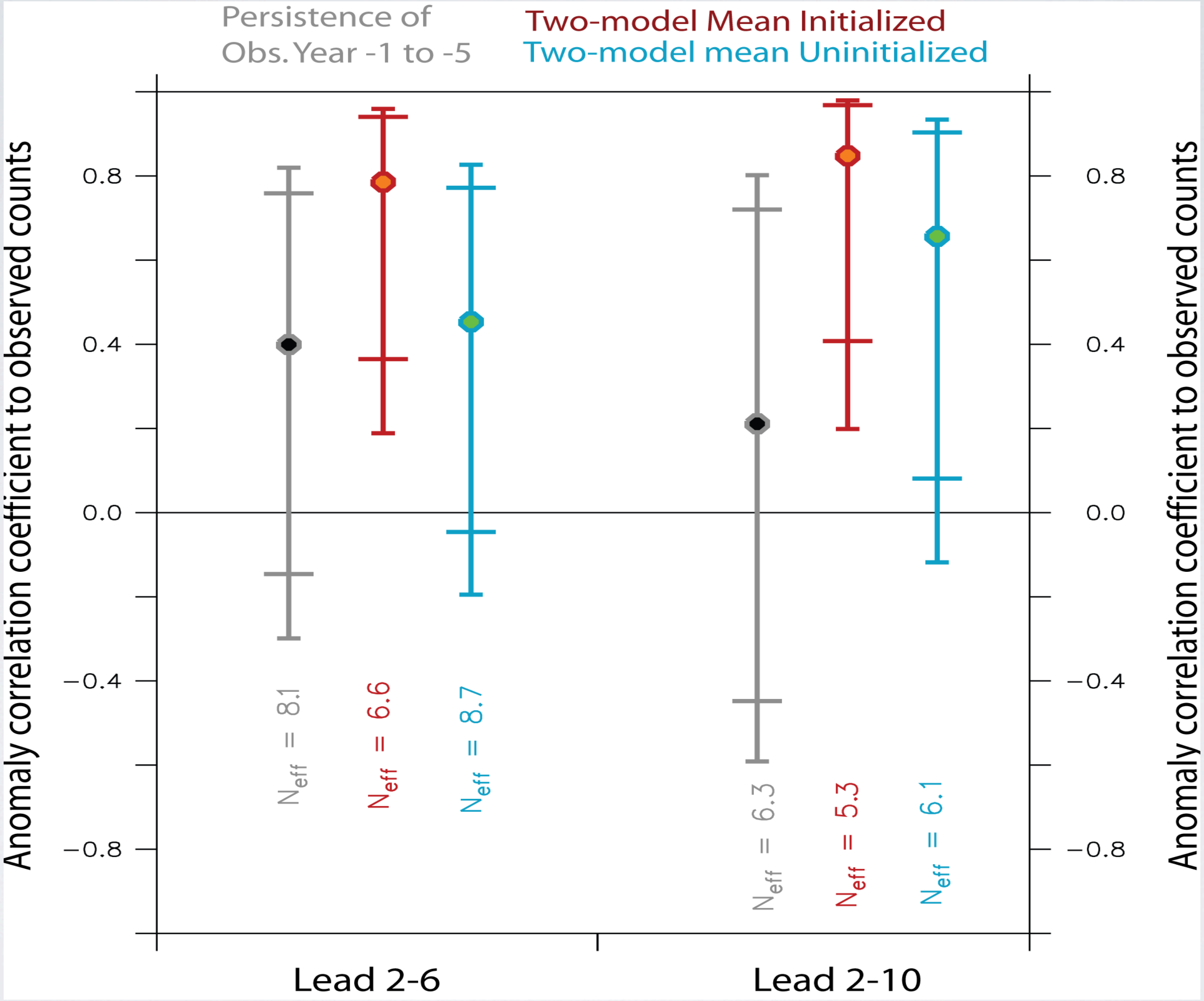
80% &
90% C.I.s



Vecchi et al. (2013.a, J. Climate in press); Msadek et al. (2013, submitted)

Summary

- Premature to conclude we have seen hurricane change due to CO_2

- Models allow estimates of future activity – pattern of SST change key:
  - 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.
  - Uncertainty in past and future changes in T(p) impacts interpretation of past, and perhaps TC prediction.

- 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.

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