How can we predict future changes in tropical storm frequency and intensity?
A review

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How does Climate Change affect tropical cyclone activity?

- Changes (trends) of environmental factors that are known to influence TC activity:
  - Tropospheric atmospheric temperature
  - Sea surface temperature
  - Tropospheric water vapor
  - Atmospheric circulation
- Issues:
  - Sensitivity to changes
  - Interactions, feedbacks
  - Regional responses
  - Interactions with climate modes: ENSO, AMO, AMM

Theory - frequency

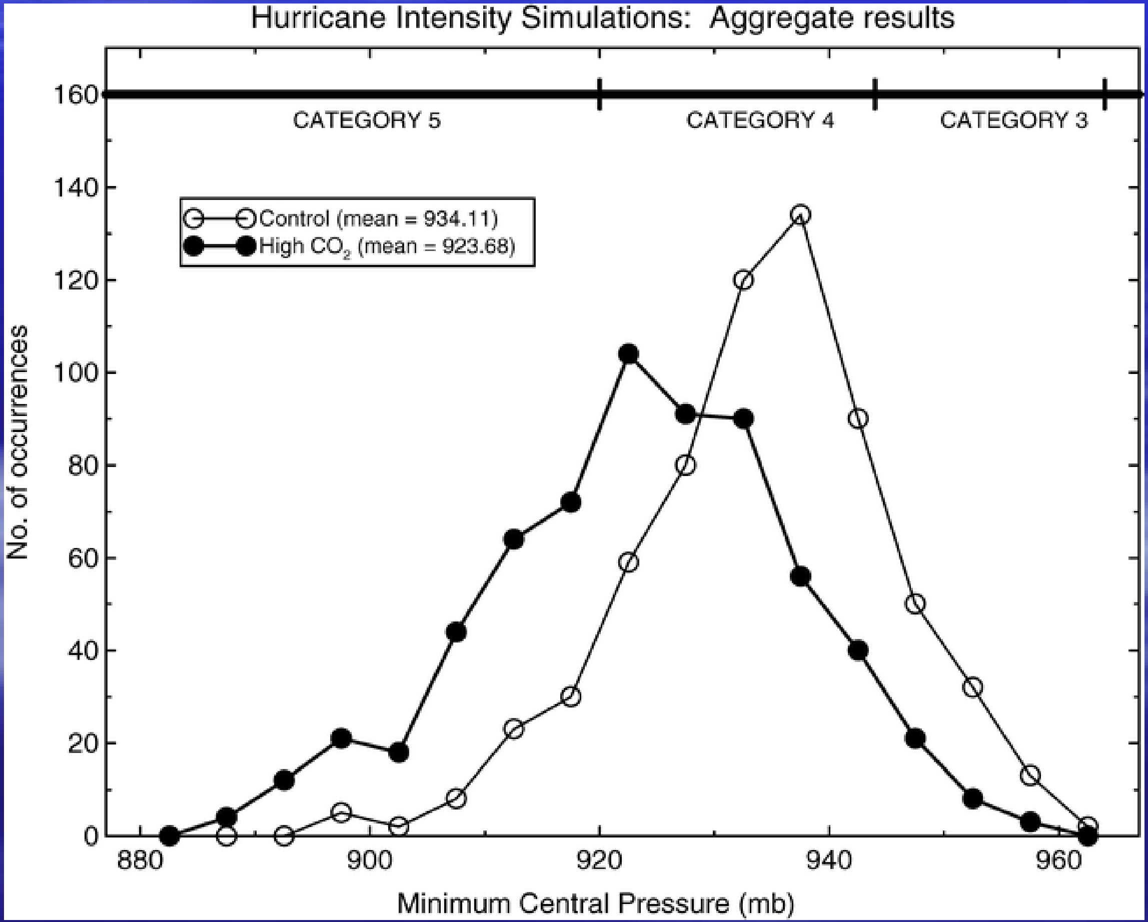
- No comprehensive theory for tropical cyclone genesis yet.
- Marsupial paradigm: formation and development of a proto-vortex within a tropical wave (Dunkerton et al. 2008).
- No clear guidance TC frequency with climate change
- Development of empirical genesis indices: relate frequency to large-scale conditions

Intensity theory

- Potential intensity (PI) theory of hurricanes (Emanuel 1985) - analogous to a Carnot cycle.
- Alternative PI: Holland (1997).
- Under high CO_2 conditions: increased Potential Intensity and future TC intensities (Emanuel 1987).
- Criticisms of details of Emanuel's PI theory:
  - Persing and Montgomery (2003): thermodynamic assumptions.
  - Smith, Montgomery and Vogl (2008): momentum budget on the boundary layer
  - Bryan and Rotunno, in press (2009): balanced flow assumptions.

Idealized models : TC intensity

- Knutson and Tuleya (2004): idealized hurricane model forced by climatologies of different global model scenarios under increased CO_2.

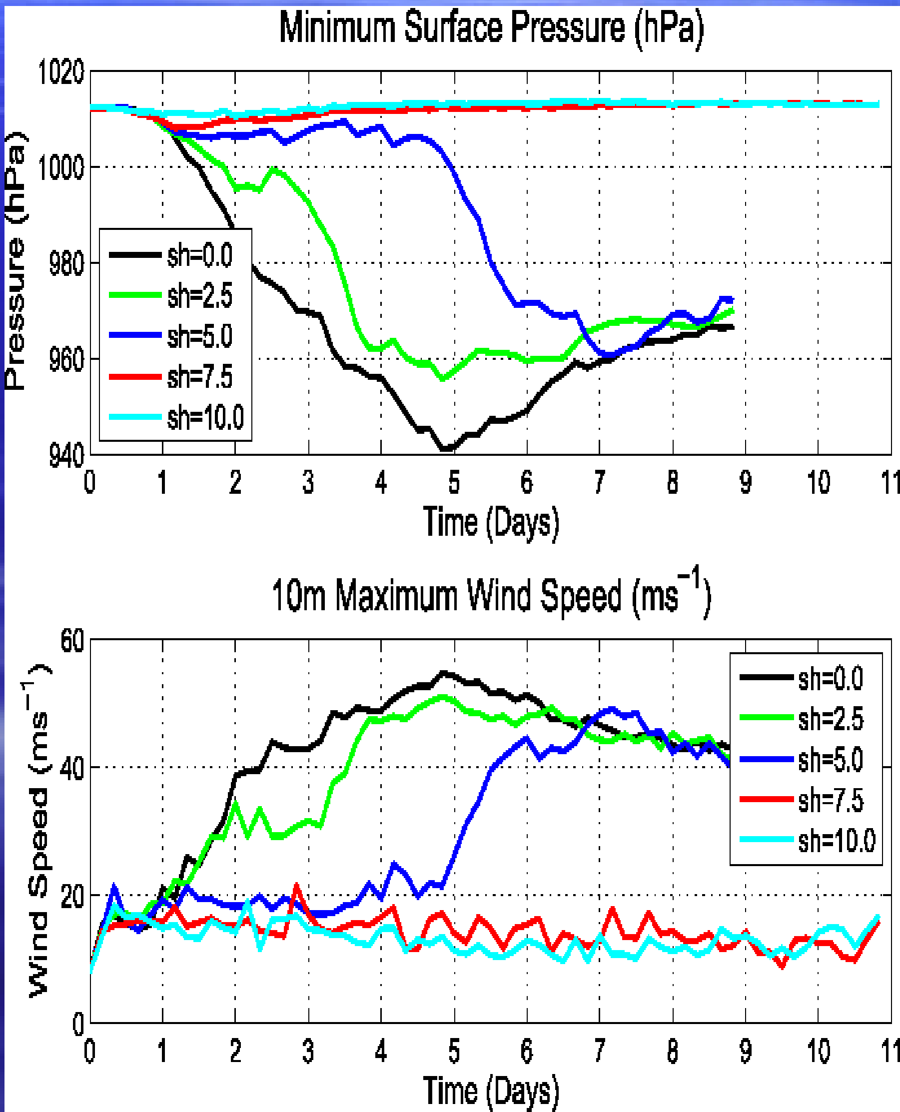


Wind speed sensitivity to warming:
~ 3.3% per degree Celsius

Idealized models (2)

Nolan and Rappin (2008):

Model TCs have higher sensitivity to vertical shear under warmer SST conditions.



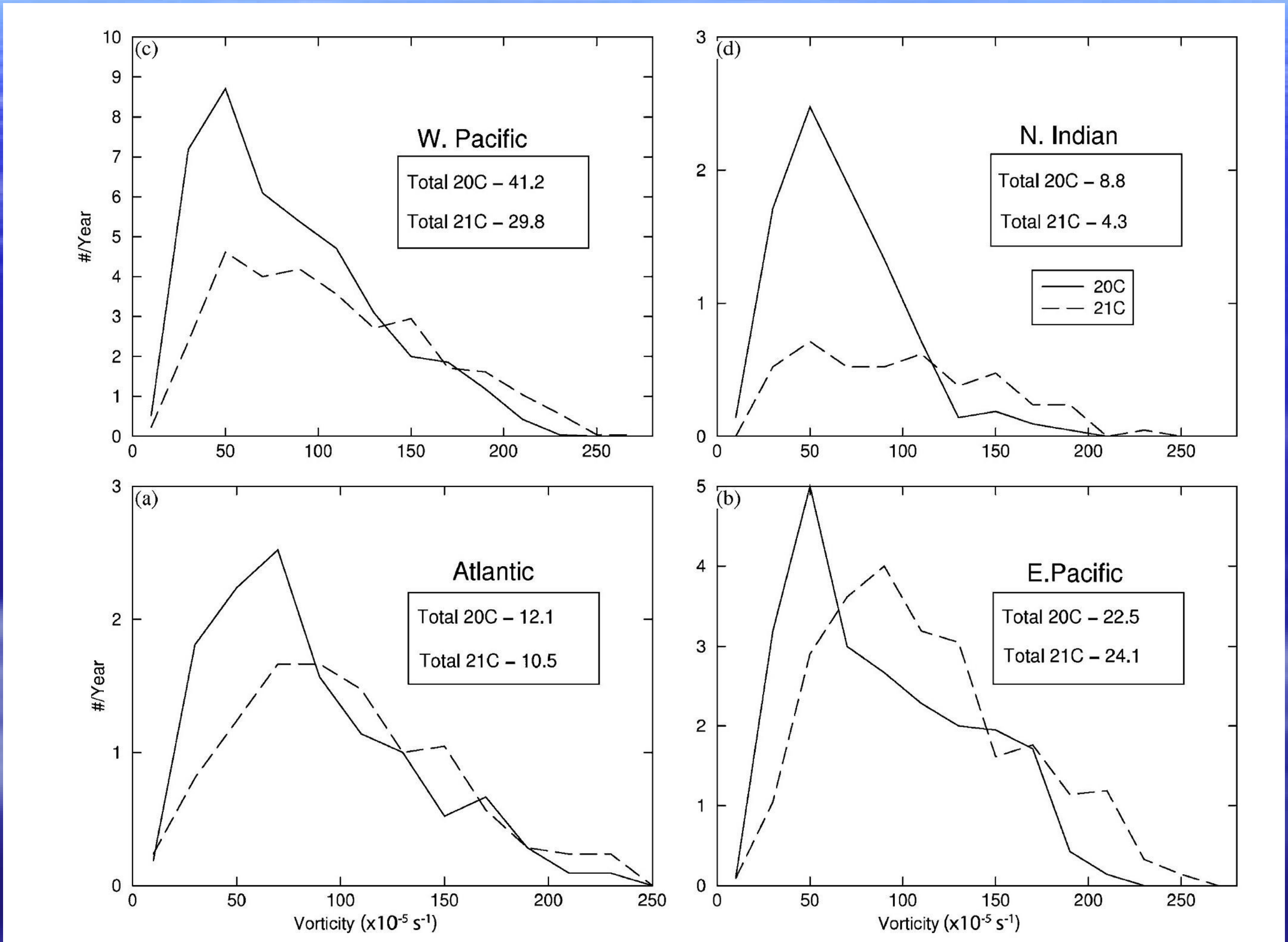
Issues – Idealized models

- Idealized setting (e.g. idealized boundary, forcing, radiative equilibrium, uniform flow) could miss some important effects of CC.
- No ocean coupling
- Effects of CC on frequency – not properly considered.
- Initial weak vortex is present as initial condition.

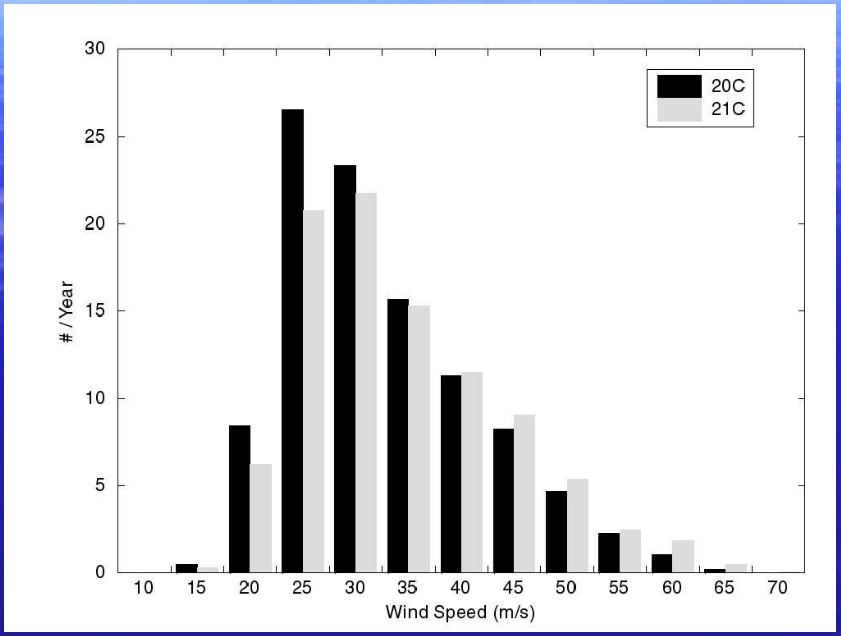
TCs in Global Climate Models

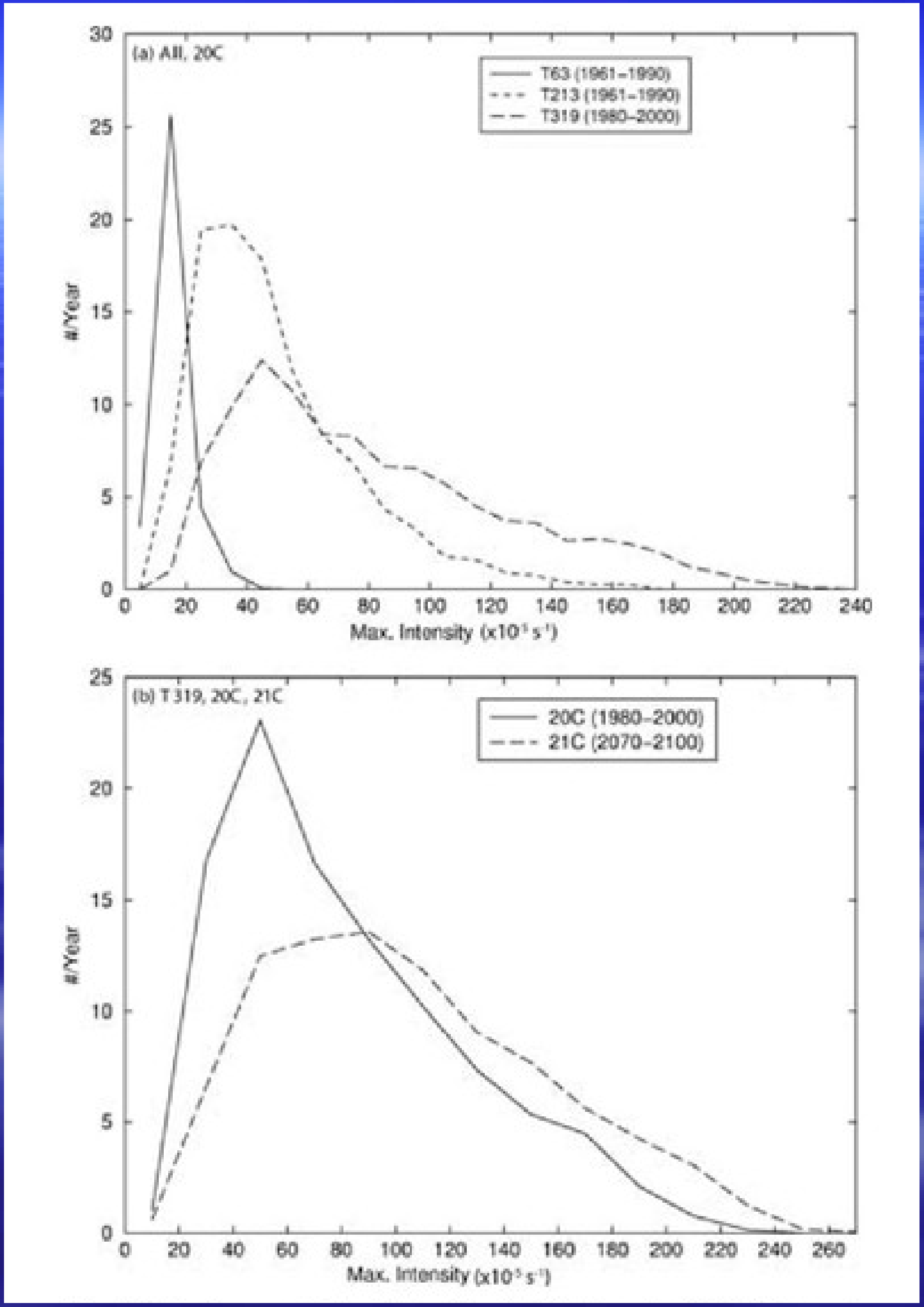
- Detect and track vortices with properties similar to observed TCs.
- First study by Manabe et al. (1970).
- Global models used in seasonal forecasts of TC activity: ECMWF, IRI.
- First study analyzing TC activity changes under climate change conditions using global models: Bengtsson et al. 1996

TCs in Global Climate Models (1):



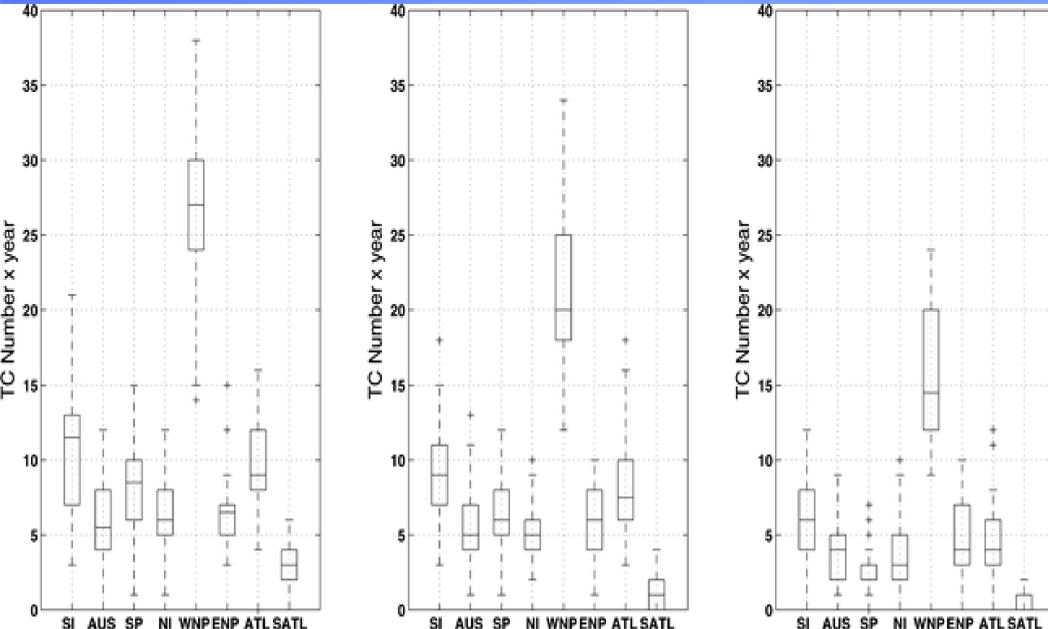
Bengtsson et al. 2007





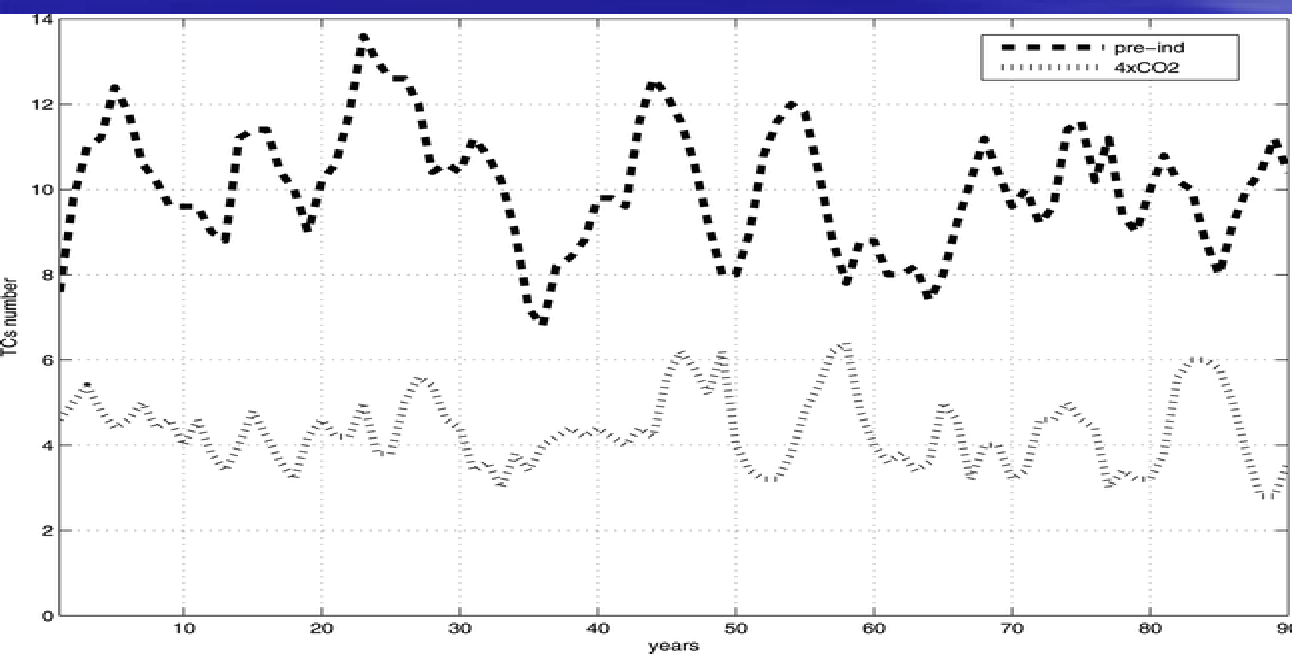
Bengtsson et al. 2007

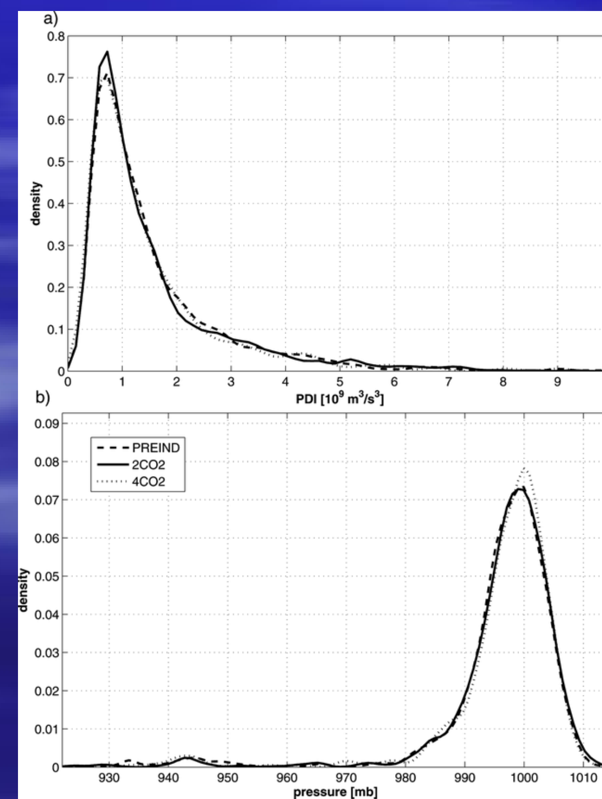
TCs in Global Climate Models (2):



Gualdi et al 2008:

Fully ocean-atmosphere coupled model





Issues - Climate Models

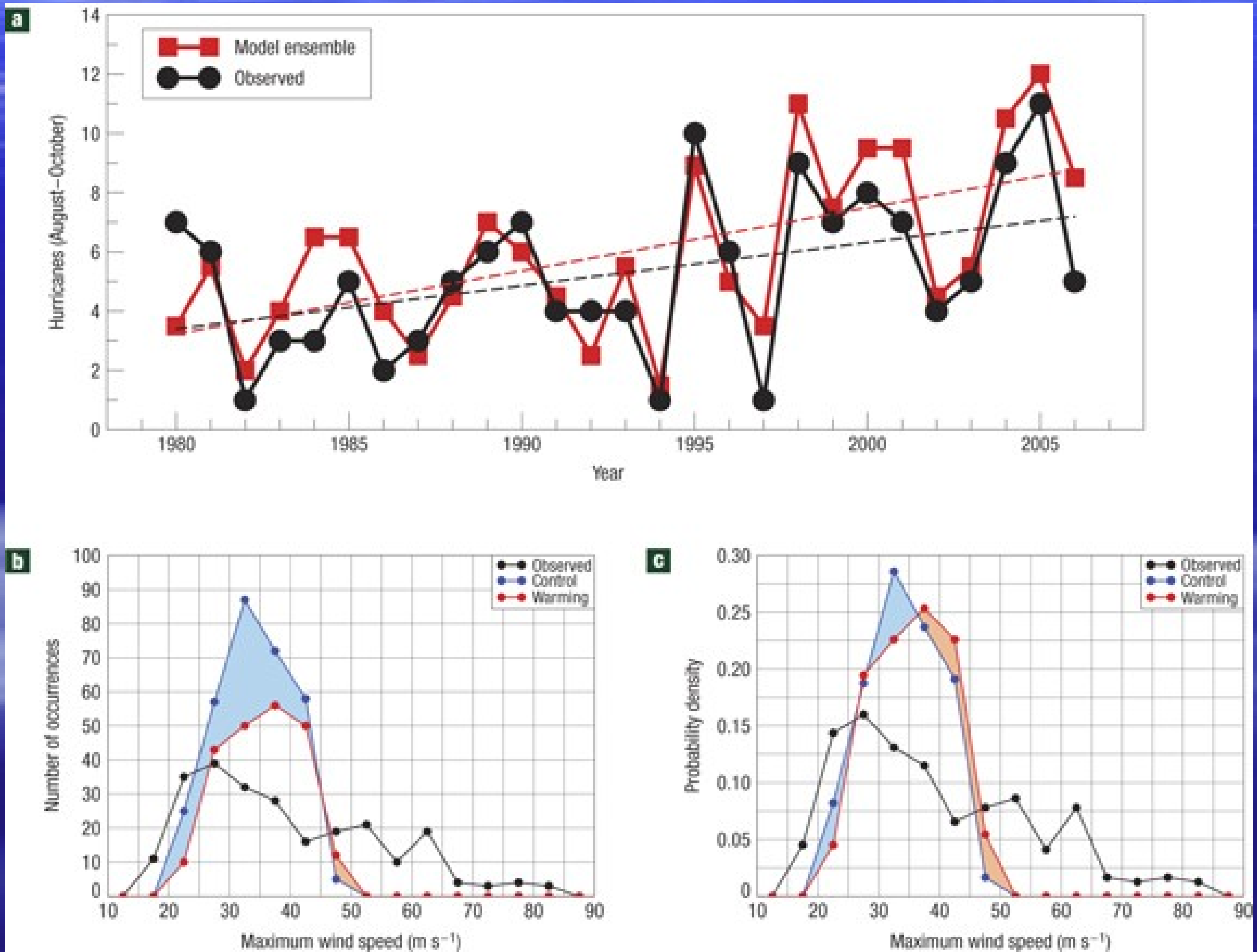
- Future climate change forcing scenarios
- Magnitude of climate change in various fields
- Model physics
- Different regional responses in the models (e.g. SST)
- Different model sensitivities to CC
- ENSO projections in the future (more El Niños vs. more La Niñas)

Issues – Global Models

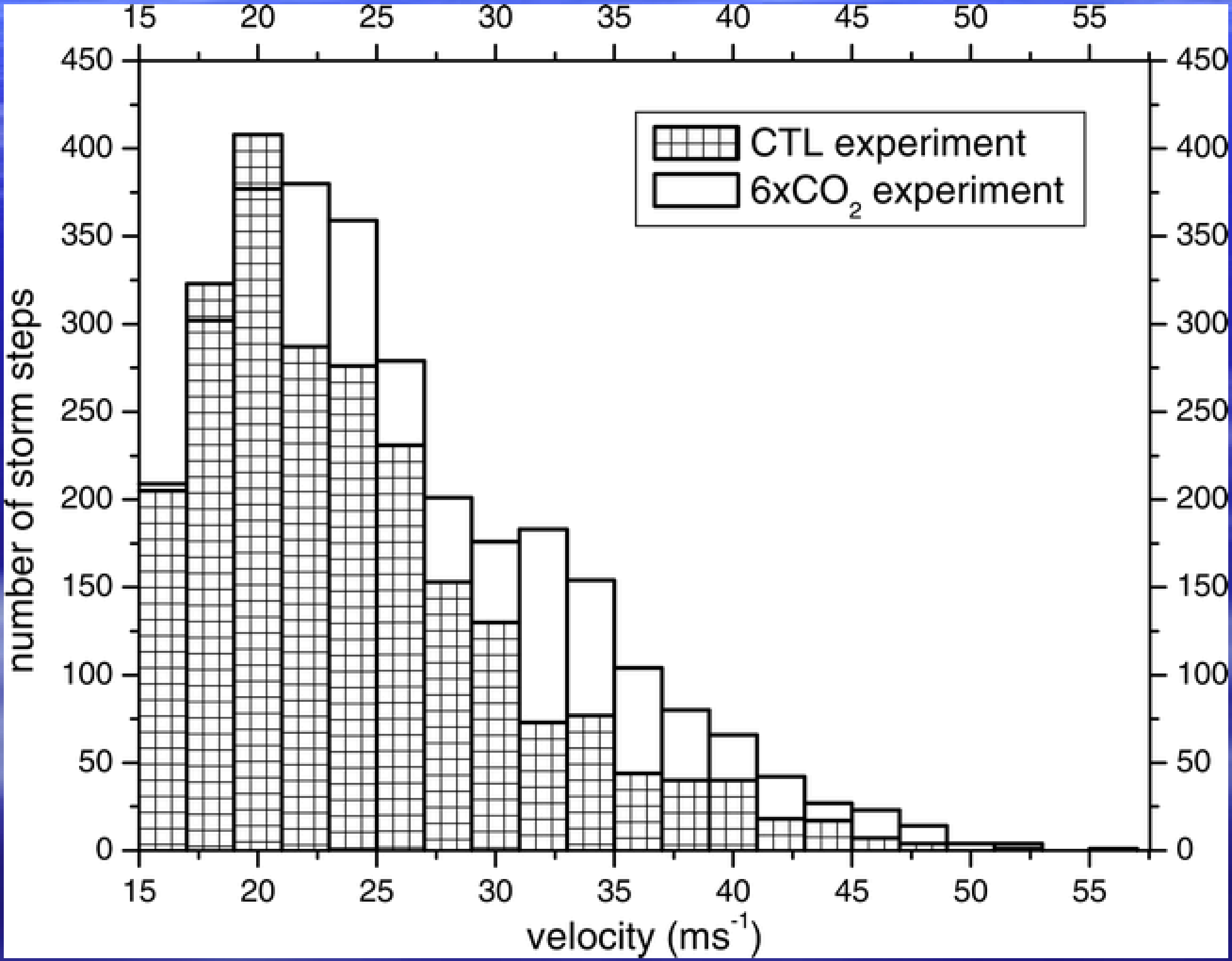
- TCs are infrequent events: necessary many years of model simulation to test significant changes compared to natural variability.
- Definition of TCs vary among groups, which makes comparison difficult.
  - TCMIP project: model intercomparison project for TCs in climate models.
- Error in model TC climatology and interannual variability e.g. tracks, intensity.
- Model biases will affect TC activity
- Few models can reproduce the MJO – TC relationship well (e.g. ECMWF – Vitart, GRL in press)
- Model resolution

TCs in Regional Climate Models (1):

Knutson et al. 2008: Downscaling in the Atlantic



TCs in Regional Climate Models (2)



Stowasser et al 2007.

Downscaling over the Western North Pacific

Number ~ constant, but regional changes

Increase in intensity

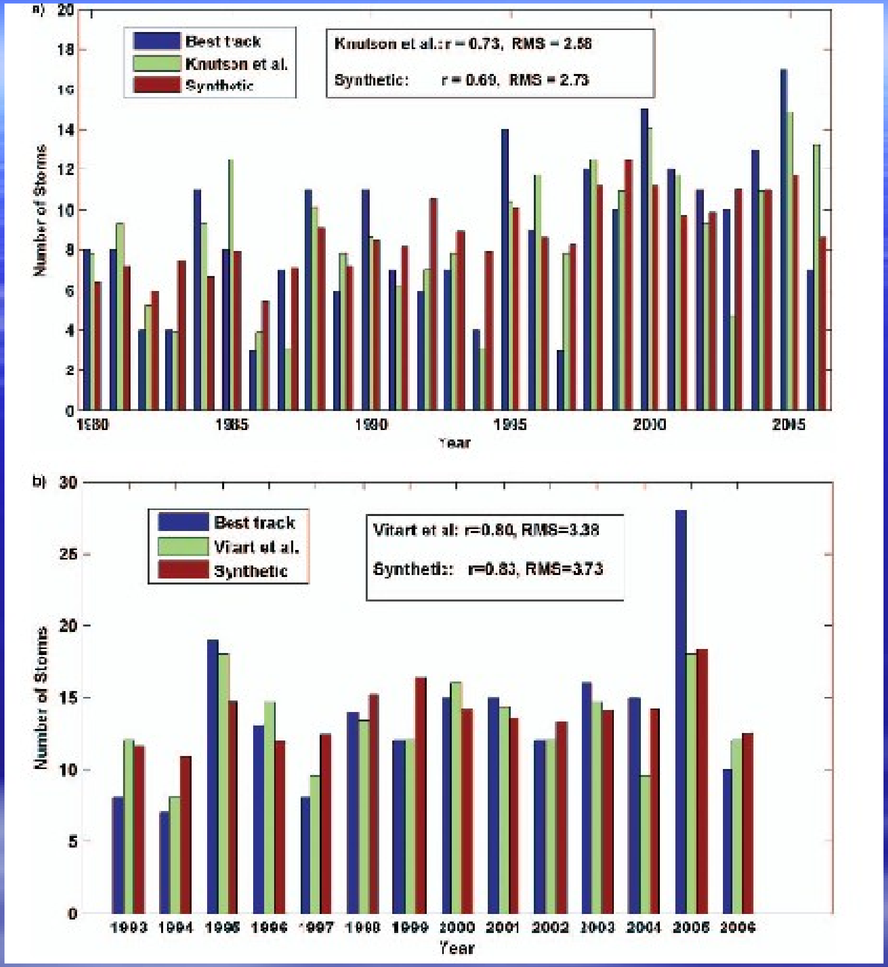
Issues - Regional Models

- Similar issues as global models
- RCM climatologies and sensitivites can be different from forcing global model
- Domain choice can affect result of simulation (Landman, Seth and Camargo 2005).
- Skill does not automatically increase - seasonal time scales (Camargo et al. 2007).

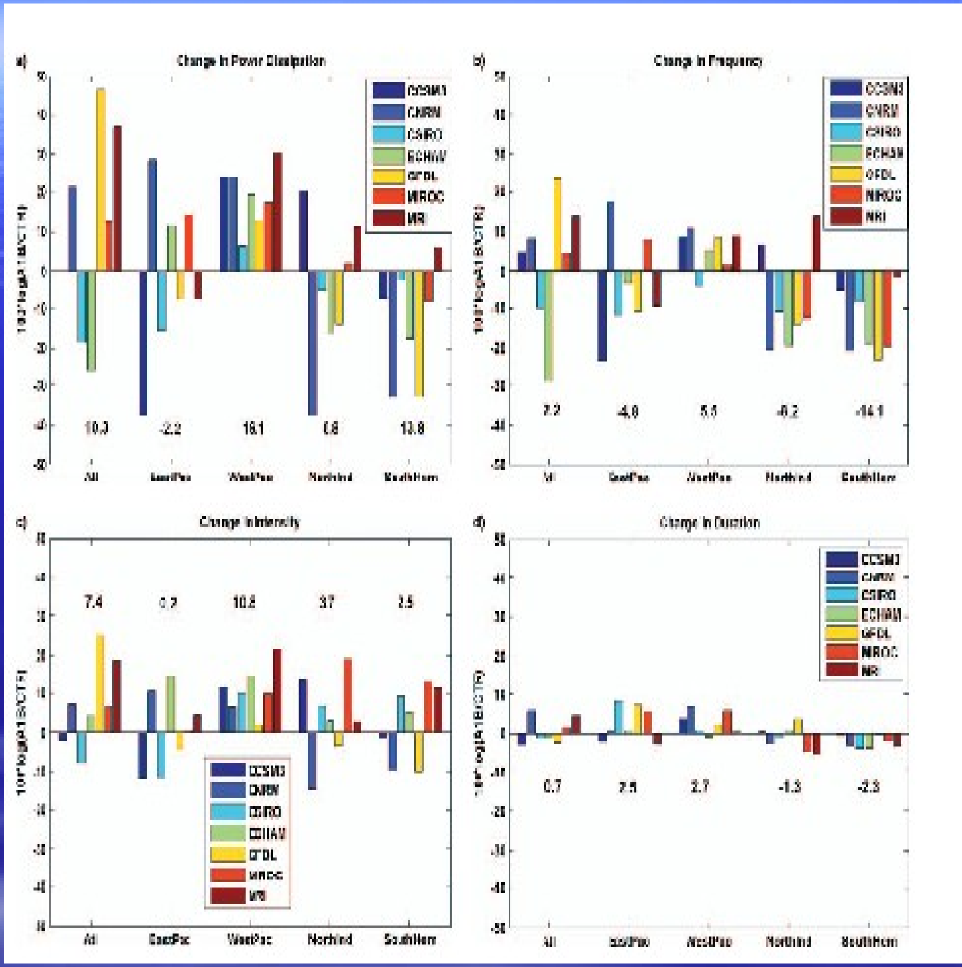
Statistical - Dynamical Downscaling

- Developed by Kerry Emanuel’s group
- Infers TC activity from large-scale circulation of models and reanalysis.
- Mixture of statistical models:
  - Random seeding for TC genesis
  - Markov model for TC tracks (based on historical TC tracks)
- and dynamical model:
  - Hurricane model for TC intensity

Current TC activity - Atlantic



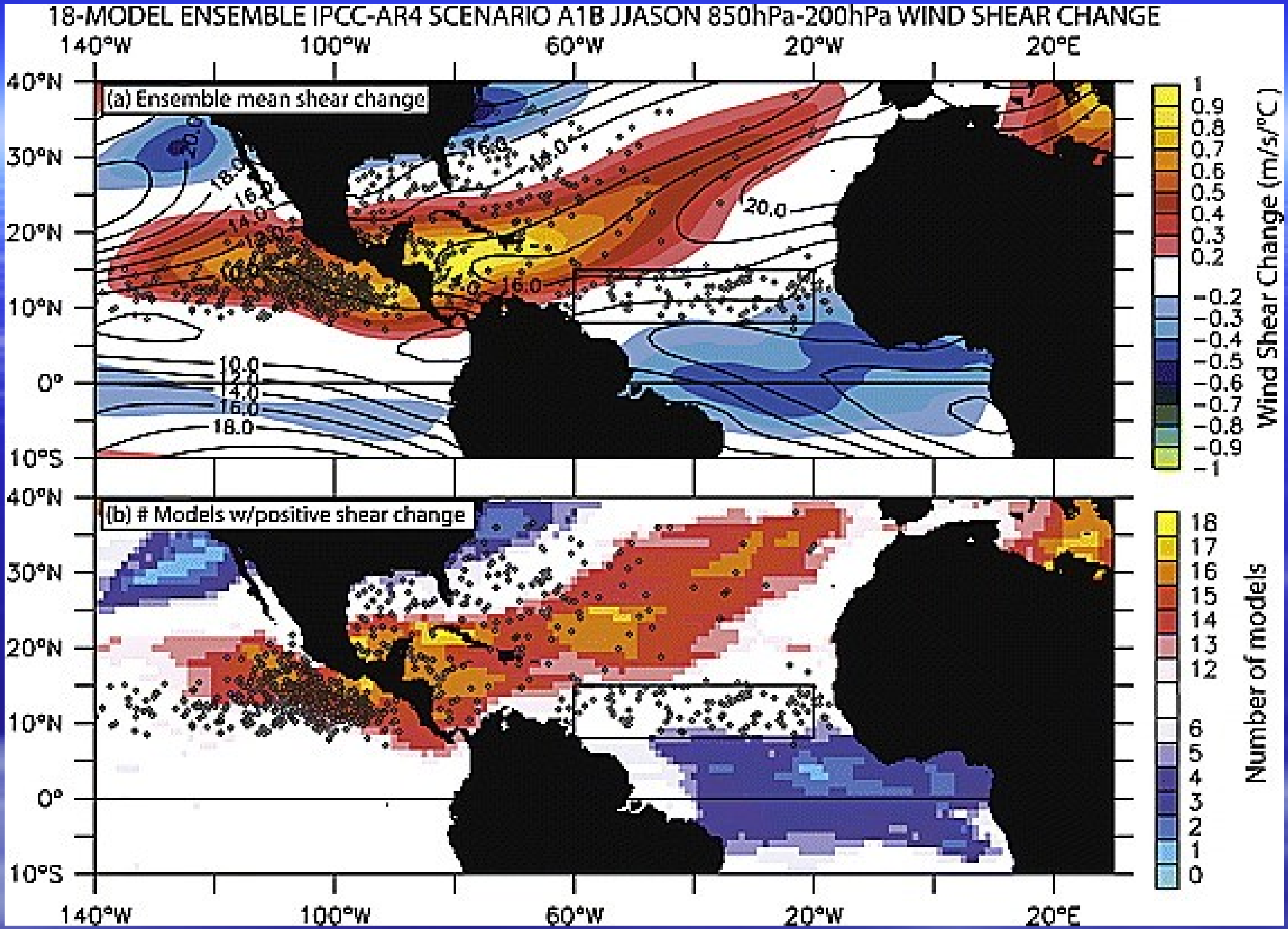
Future TC activity



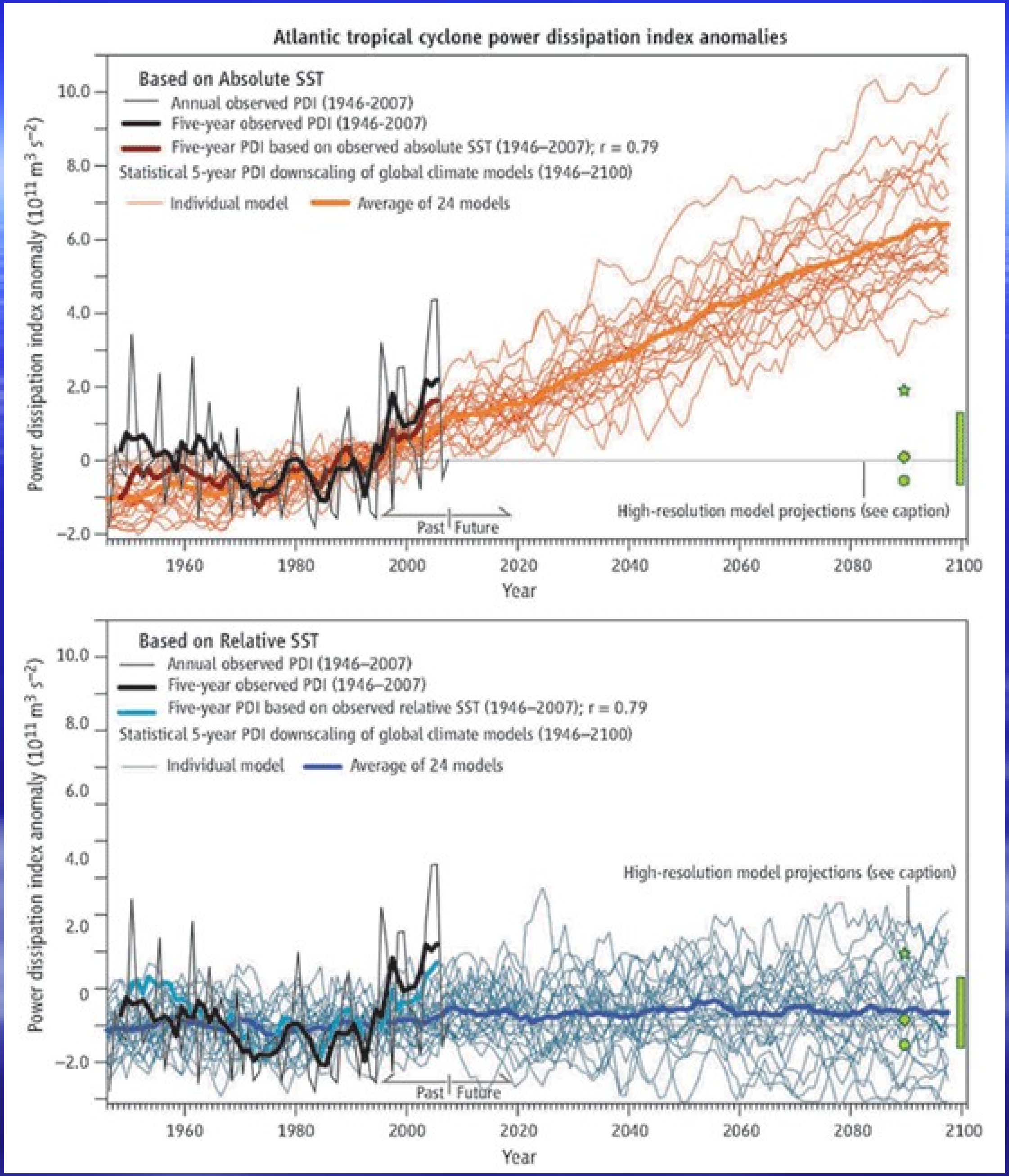
Emanuel et al. 2008

Large-scale variables

- Best feature of climate models: large-scale climate.
- Use environmental variables that are known to affect TC activity to infer future TC activity.
- Possible variables:
  - SST and relative SST
  - Vertical shear
  - Potential Intensity
- OR a combination of variables



Vecchi and Soden, 2006



Vecchi et al. 2008

Genesis indices

- Gray (1979) – 1st index for genesis based on large-scale quantities related to TC activity
- Application of Genesis index to TC – CC problem:
  - Usage of a SST threshold (Gray) is a problem
  - Many alternative indices proposed
  - e.g. Royer et al. 1998: convective precipitation
  - Applications to CC problem for various models

Emanuel's Genesis Potential Index

Refinement of Gray's tropical cyclone genesis index using monthly Reanalysis data:

$$GP = |10^5 \eta|^{3/2} (\square/50)^3 (V_{pot}/70)^3 (1+0.1V_{shear})^{-2}$$

η = absolute vorticity at 850hPa (s^{-1})

$\square$ = relative humidity at 700hPa (%)

V_{pot} = potential intensity (m/s)

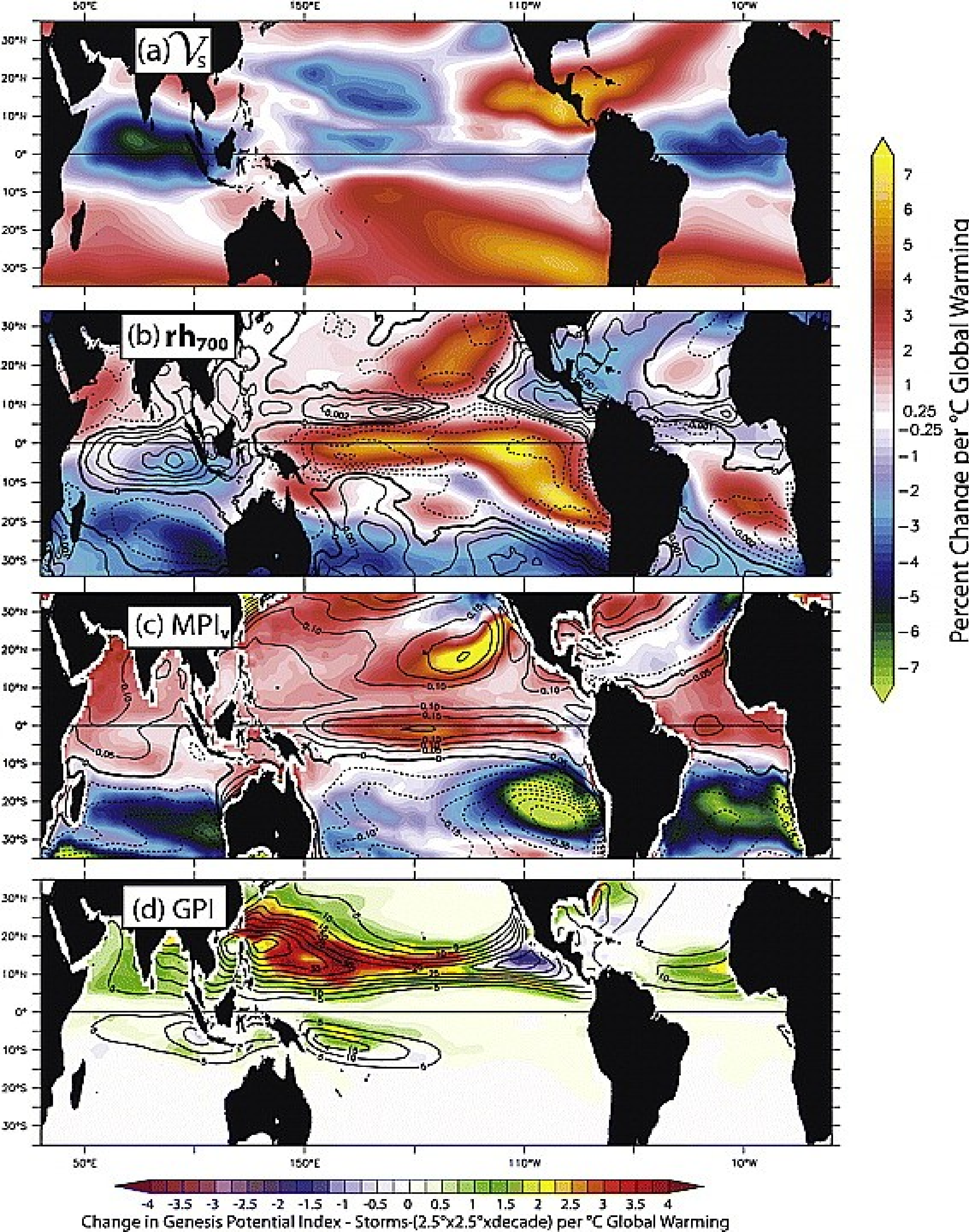
V_{shear} = magnitude of the vertical wind shear between 200 and 850hPa (m/s).

Emanuel and Nolan, 26th AMS Conf. Hurricanes & Tropical Meteorology, 2004.

Camargo, Emanuel and Sobel, J. Climate 2007.

Emanuel's GPI:

- Reproduces current TC climatology
- Reproduces TC response to ENSO (Camargo et al. 2007)
- Can reproduce well the MJO modulation of TC activity (Camargo et al. 2009)



Vecchi and Soden, 2006

Issues – large-scale variables

- Analysis of the environment only, not of TC activity per se.
- Interactions and feedbacks between various variables
- Detailed regional patterns are important and vary among models
- There is no “perfect” empirical index

Summary

- Various methods are used to infer future TC activity.
- All methods have positive aspects and some drawbacks.
- Ultimately a combination of these methods with robust significant results – best option.
- Standard definitions for TCs and diagnostics for model variables should improve comparisons.