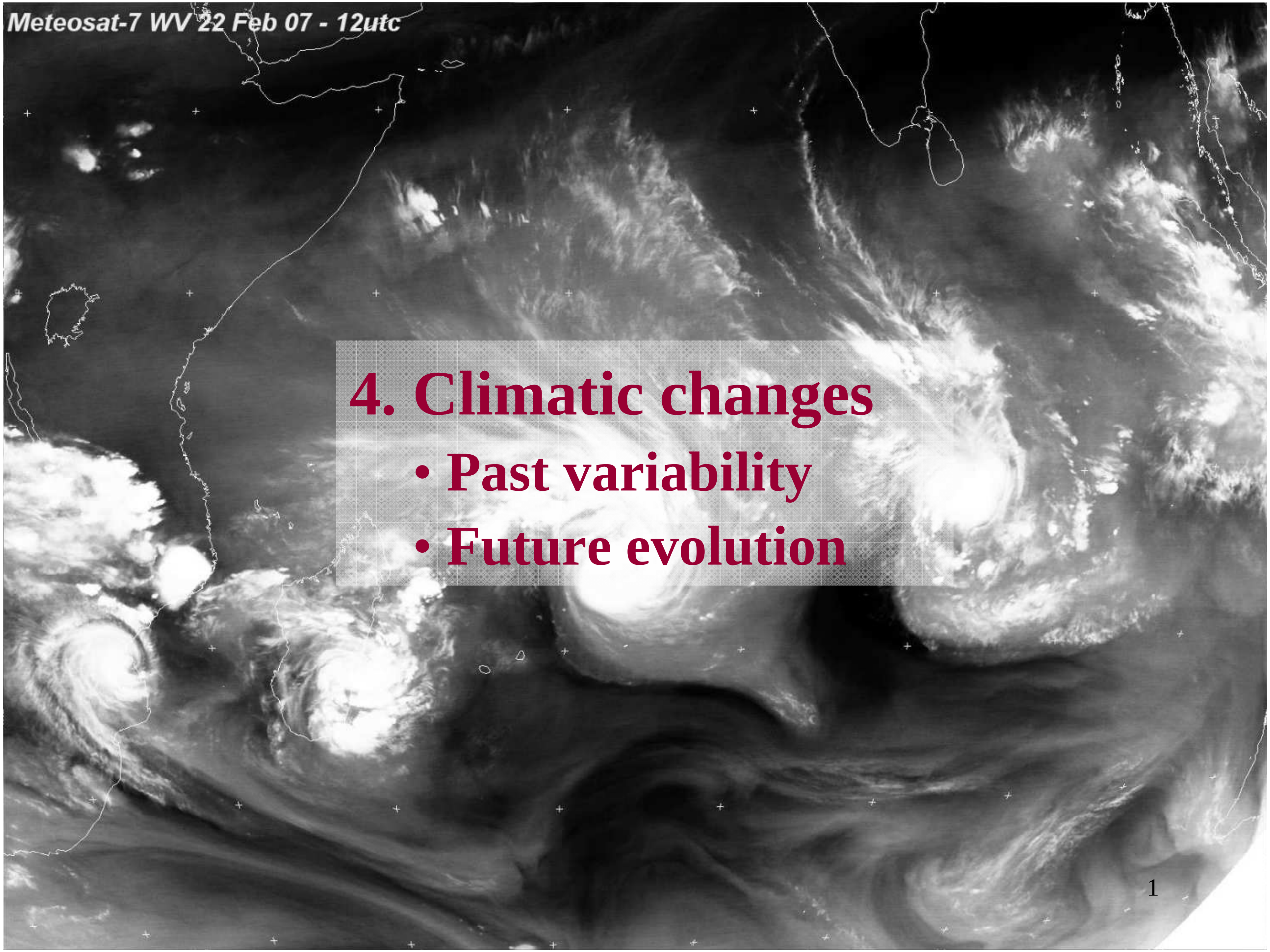


4. Climatic changes

- **Past variability**
- **Future evolution**

TROPICAL CYCLONES and CLIMATE

- How TCs have varied during the instrumental record ?

- How will TC activity vary in the future ?

CURRENT CLIMATE :
how TCs have varied during the instrumental record (1)

Understanding tropical cyclone variability on interannual to interdecadal timescales is hampered by the relatively short period over which accurate records are available :

>1850 : Land and ship observations

>1945 : Radiosonde network & aircraft reconnaissance

(N Atlantic and NW Pacific until 1987 only)

>1965 : Meteorological satellites (polar-orbiting, VIS & IR)

>1975 : Meteorological satellites (geostationnay, VIS & IR)

>1990 : Meteorological satellites (polar-orbiting, MW, scatt.)

Changes in the TC databases due to observational platform improvements (and sometimes degradations) can often be mistaken as true variations in TC activity.

IBTrACS (the *International Best Track Archive for Climate Stewardship*, **Knapp *et al.* 2010 :** *Bull. Amer. Meteor. Soc.*, 91, 363–376) collects the TC best-track data from all available RSMCs (*Regional Specialized Meteorological Centers*) and other agencies, combines them into one product, and disseminates in easily used formats.

CURRENT CLIMATE :
how TCs have varied during the instrumental record (2)

For the North Atlantic basin (incl. Gulf of Mexico & Caribbean Sea), aircraft reconnaissance data provide a nearly complete record back to the mid-1940s.

The North-Western Pacific basin also has had extensive aircraft surveillance giving valid records going back to at least the late 1950s, until 1987.

Thus, it is difficult to make analyses of trends and of the physical mechanisms responsible for the TC variability on a global basis.

Because of this limitation, most studies on long-term changes in tropical cyclone activity have focused upon the N Atlantic and NW Pacific.

CURRENT CLIMATE : how TCs have varied during the instrumental record (3)

For the other basins (N& S Indian, SW & NE Pacific), reliable estimates of TCs only exist for the satellite era (>1970).

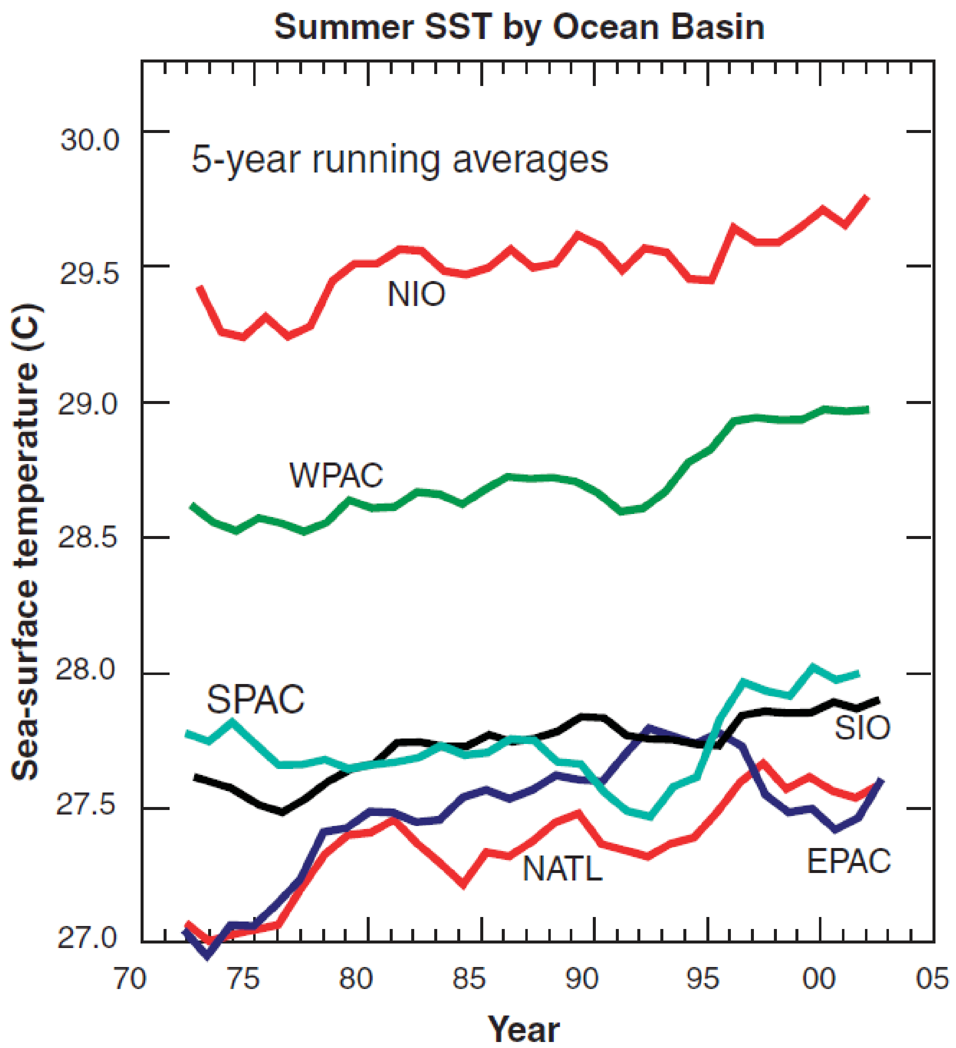
! Geostationay satellite coverage over the Indian ocean started in 1998 !

Before the early 1980s, the Dvorak Technique [**Dvorak 1975 :** *Mon. Wea. Rev.*, 103, 420-430], a method which utilizes satellite imagery to assign an intensity to TCs, was only applicable to visible images and therefore could not be used at night.

Since 1984, improved technology has allowed the technique to be applied to both infrared and visible imagery [**Dvorak 1984 :** *NOAA Technical Report NESDIS 11*]. More accurate estimates of real-time intensity and evolution have become available.

The quality and resolution of satellite imagery has continued to improve over time.

CURRENT CLIMATE :
how TCs have varied during the instrumental record (4)



Webster *et al.* 2005 :
Science, 309, 1844-1846

Tropical ocean SSTs have increased by approximately 0.5°C between 1970 and 2004

CURRENT CLIMATE :
how TCs have varied during the instrumental record (5)

<u>None of the time series</u> (global number of storms, number of storm days) <u>shows a trend</u> that is statistically different from zero over the period.

There is a <u>substantial decadal-scale oscillation</u> in the number of TCs and the number of TC days.

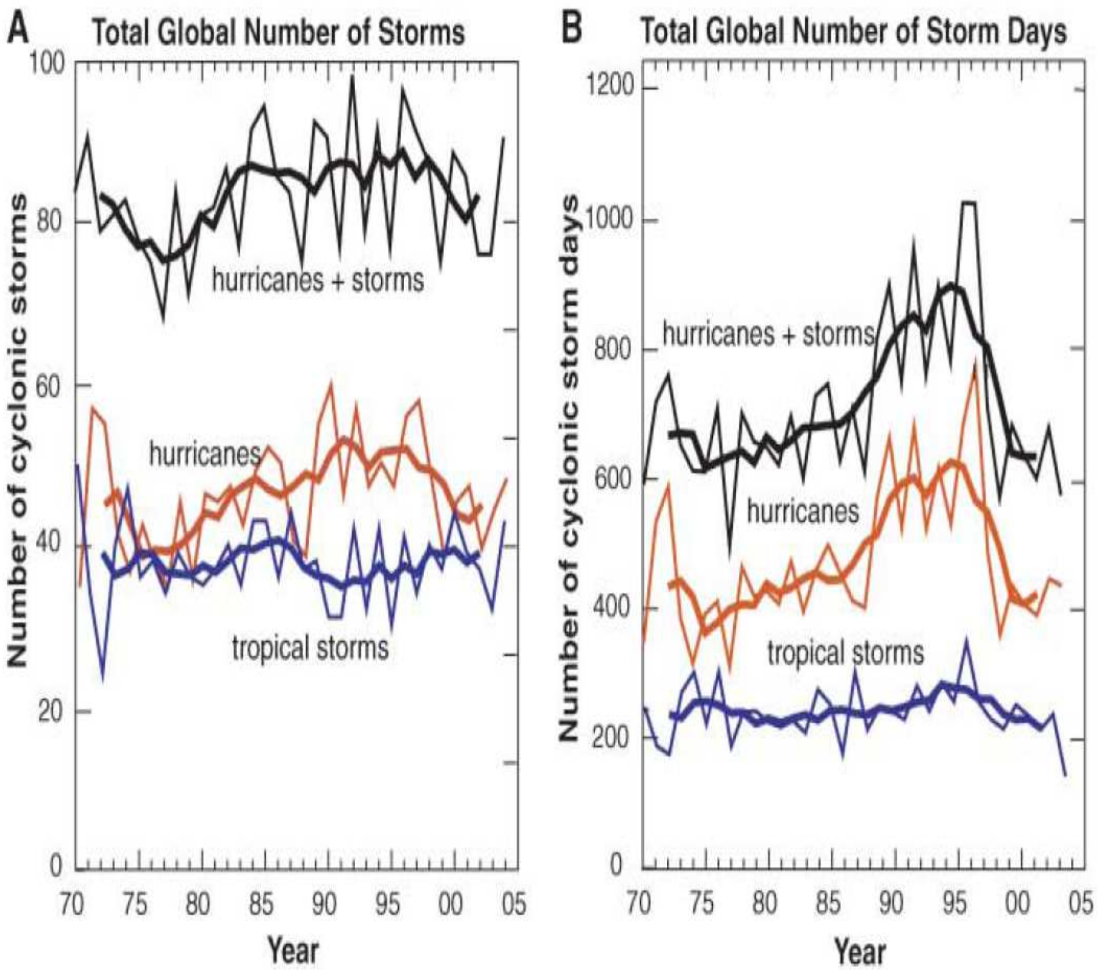


Fig. 2. Global time series for 1970–2004 of (**A**) number of storms and (**B**) number of storm days for tropical cyclones (hurricanes plus tropical storms; black curves), hurricanes (red curves), and tropical storms (blue curves). Contours indicate the year-by-year variability, and the bold curves show the 5-year running average.

CURRENT CLIMATE :
how TCs have varied during the instrumental record (6)

In each basin time series, the annual frequency and duration of TCs also exhibit overall trends for the 35-yr period that are not statistically different from zero.

The exception is the Atlantic ocean which possesses an increasing trend in frequency and duration.

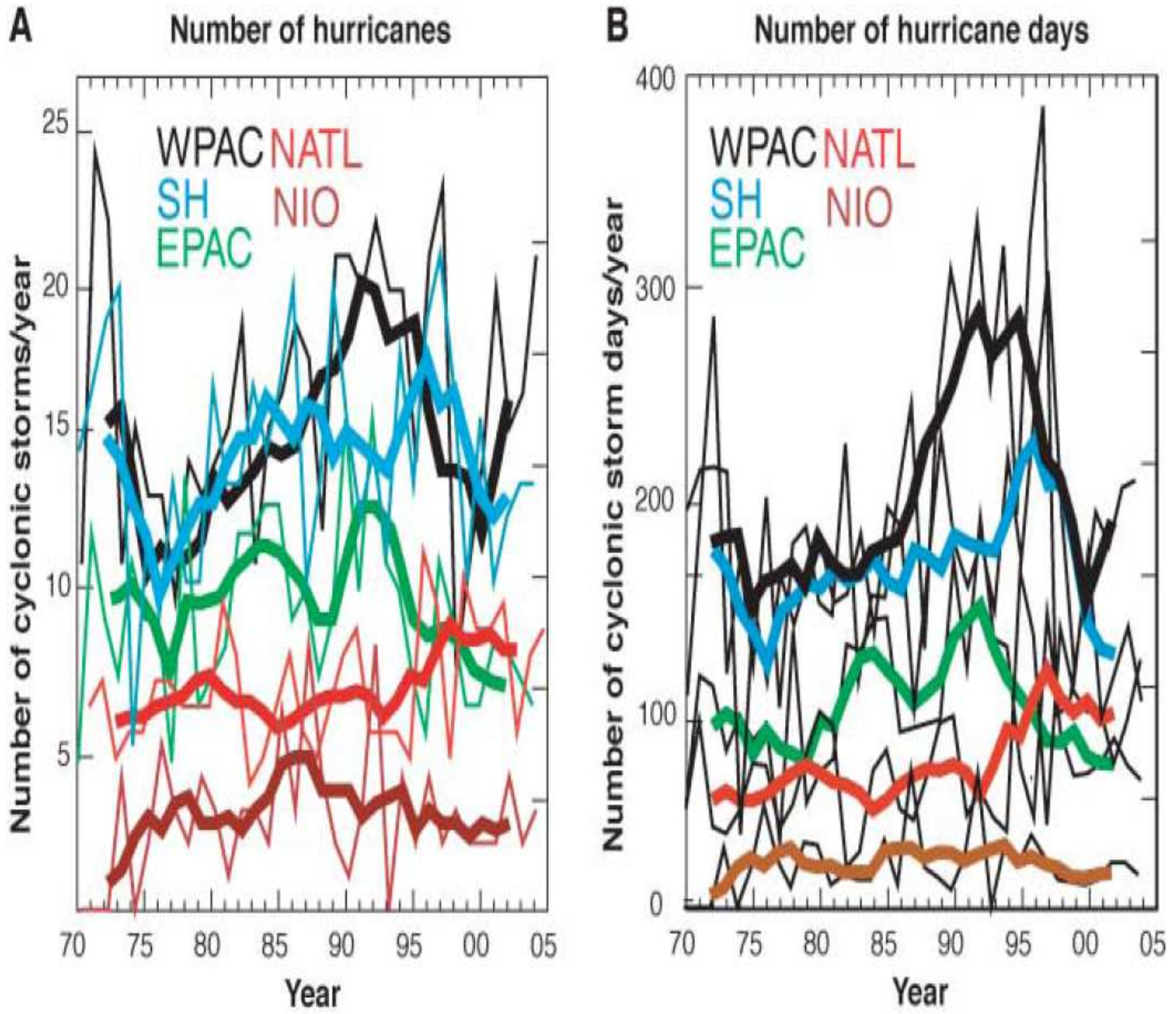


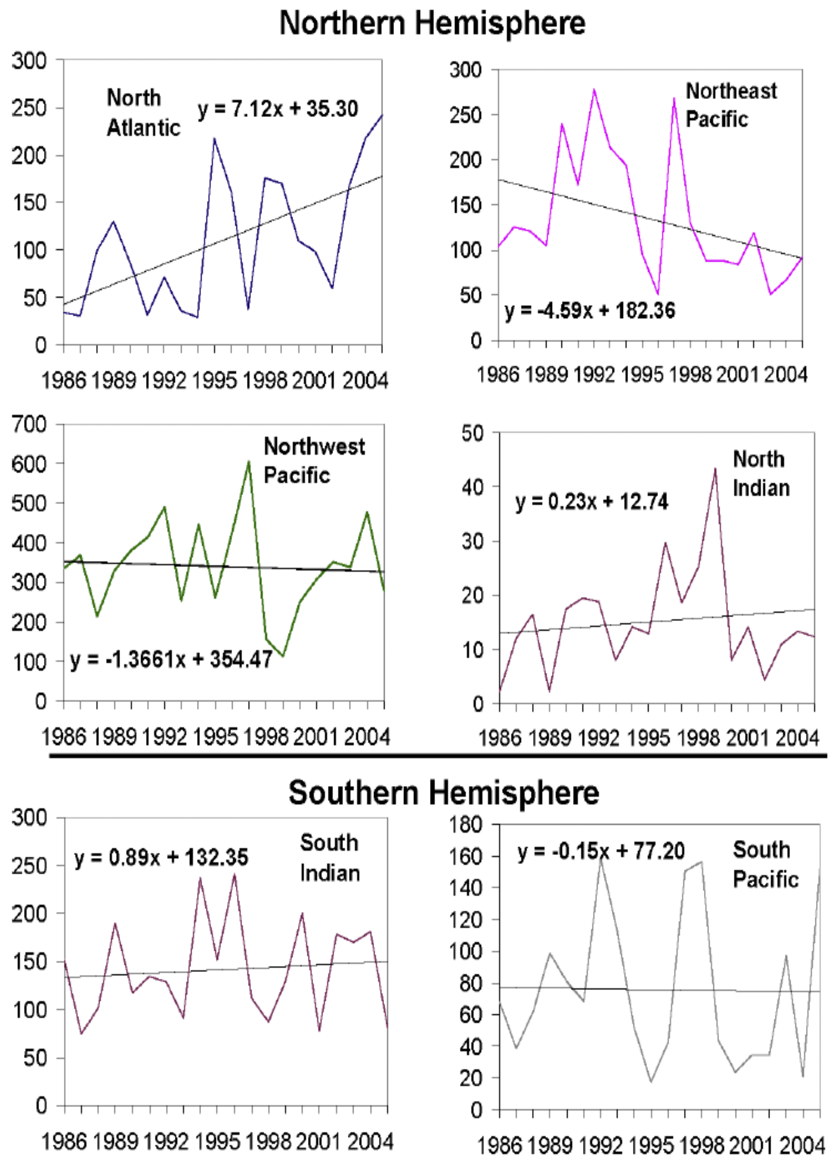
Fig. 3. Regional time series for 1970–2004 for the NATL, WPAC, EPAC, NIO, and Southern Hemisphere (SIO plus SPAC) for (**A**) total number of hurricanes and (**B**) total number of hurricane days. Thin lines indicate the year-by-year statistics. Heavy lines show the 5-year running averages.

CURRENT CLIMATE :
how TCs have varied during the instrumental record (7)

Klotzbach 2006 :
GRL, 33, L10805

Accumulated Cyclone Energy (ACE) is the sum of the maximum 1-min surface wind speed squared for all periods when the storm is at least of TS strength (≥17 m s^{-1}). ACE is proportional to total kinetic energy generated by the storms.

The largest trends are a large increase in the N Atlantic and a noticeable decrease in the NE Pacific. The trends in all other basins are quite small.



CURRENT CLIMATE :

how TCs have varied during the instrumental record (8)

Webster *et al.* 2005 :
Science, 309, 1844-1846

The number of CAT-1,2,3 TCs has decreased, but CAT-4,5 storms has almost doubled in number and in proportion, in all the ocean basins.

This trend is correlated with SST increase, consistent with climate simulations that a doubling of CO_2 may increase the frequency of the most intense TCs.

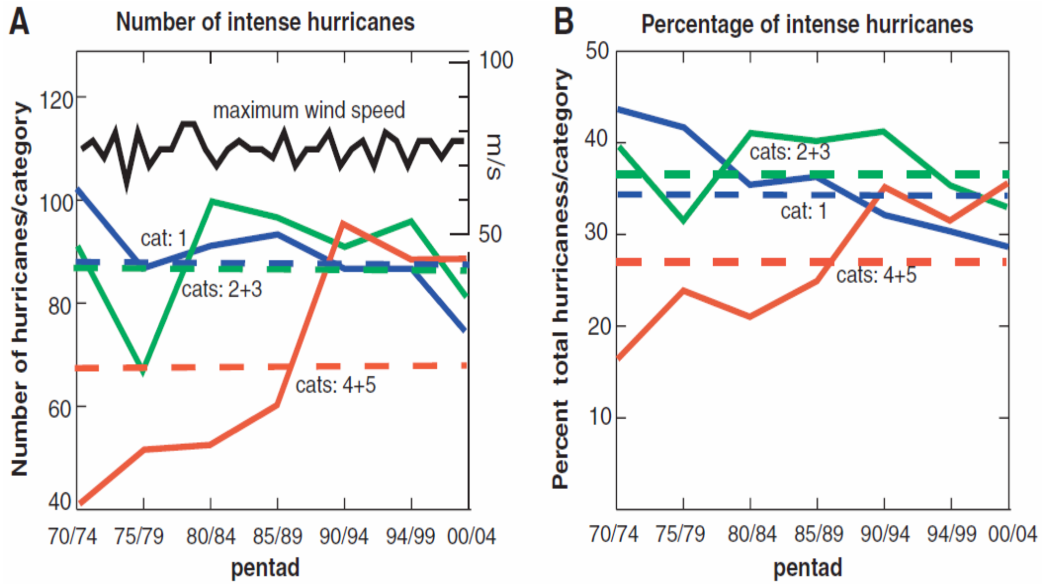


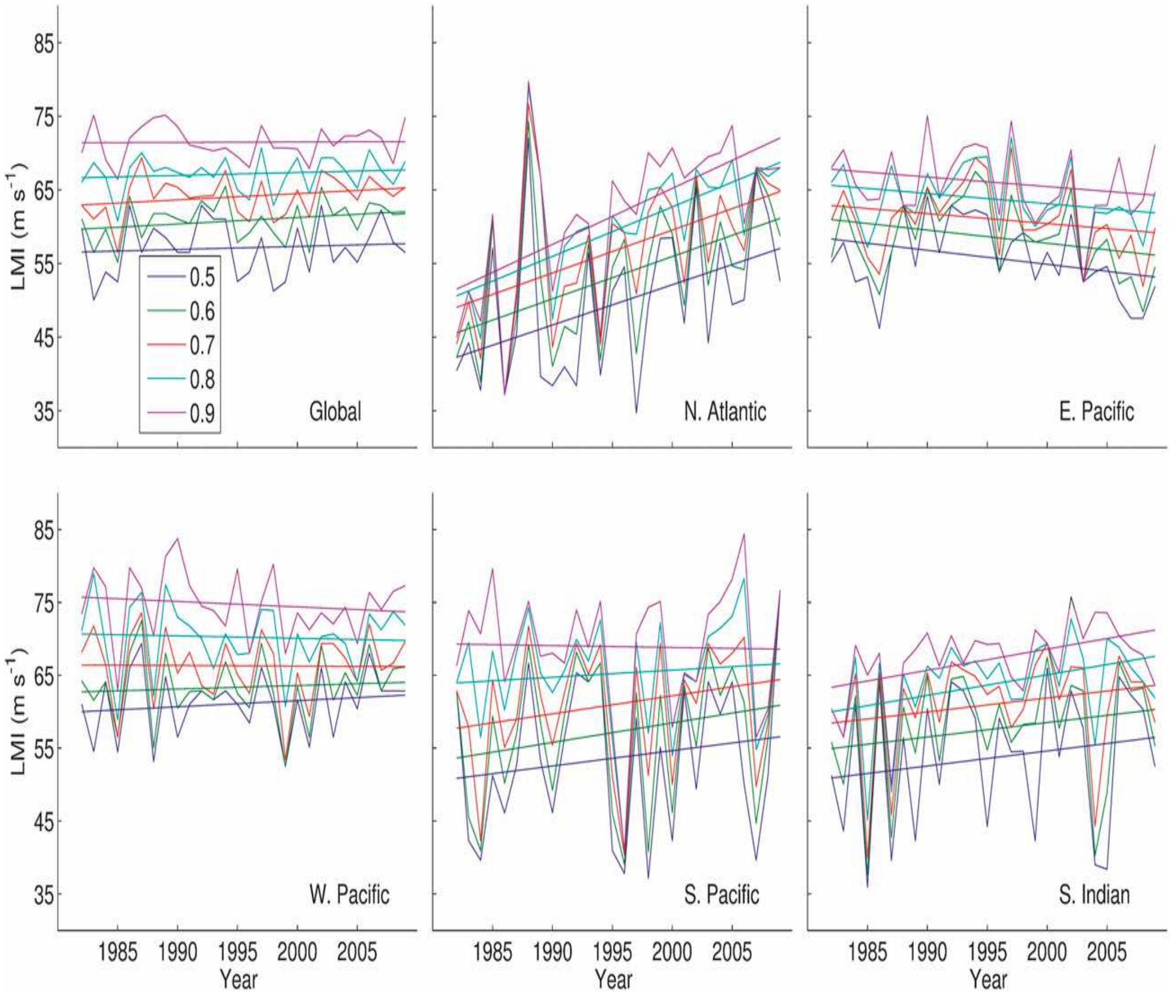
Fig. 4. Intensity of hurricanes according to the Saffir-Simpson scale (categories 1 to 5). (**A**) The total number of category 1 storms (blue curve), the sum of categories 2 and 3 (green), and the sum of categories 4 and 5 (red) in 5-year periods. The bold curve is the maximum hurricane wind speed observed globally (measured in meters per second). The horizontal dashed lines show the 1970–2004 average numbers in each category. (**B**) Same as (A), except for the percent of the total number of hurricanes in each category class. Dashed lines show average percentages in each category over the 1970–2004 period.

CURRENT CLIMATE :
how TCs have varied during the instrumental record (9)

Kossin *et al.* 2013 :
J. Climate, 26, 9960-9976

Increasing, but weak, trends are found in the global data, indicating a subtle shift of LMI (*Lifetime Maximum Intensity*) toward stronger storms.

In the North Atlantic, very strong positive trends are found, while negative trends are found from the eastern Pacific region. No clear trend is seen in the western Pacific. Contrarily, both the South Pacific and south Indian Ocean exhibit positive trends at most quantiles.



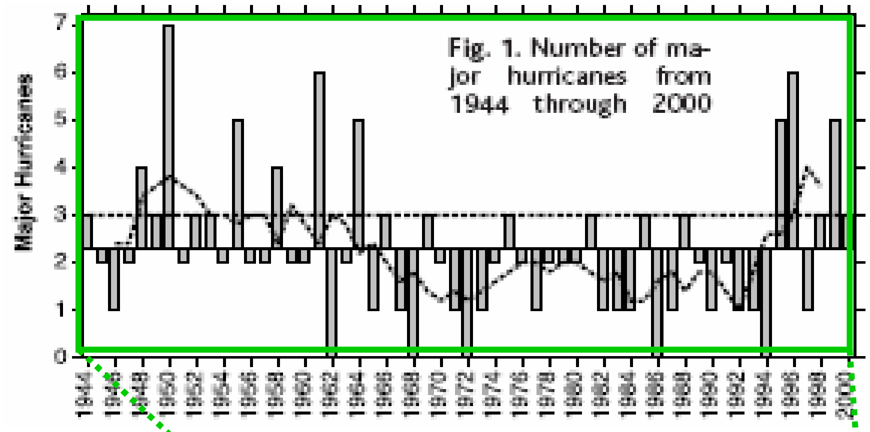
CURRENT CLIMATE :

how TCs have varied during the instrumental record (10)

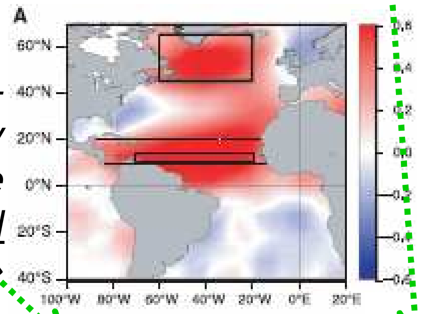
Goldenberg et al. 2001 :
Science, 293, 474-479

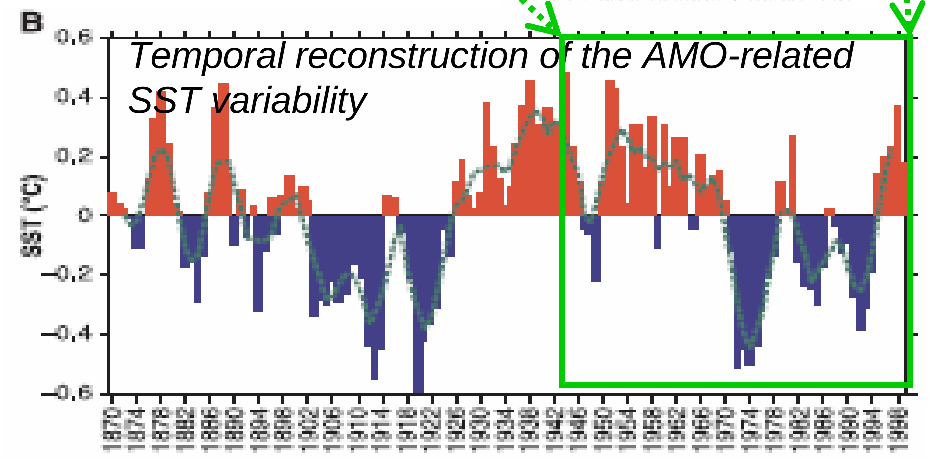
Non-ENSO SST variability is dominated by the "Atlantic Multidecadal Oscillation". Its positive phase has warm SSTs in the N Atlantic from 0° to 30°N and from 40° to 70°N. The time series for the AMO and major hurricanes show similar shapes :

- 1945-1970 : AMO>0, large TC activity
- 1970-1995 : AMO<0, weak TC activity
- 1995-present : AMO>0, large TC activity.



First rotated EOF of non-ENSO global SST variability for 1870-2000, known as the « Atlantic Multidecadal Oscillation »

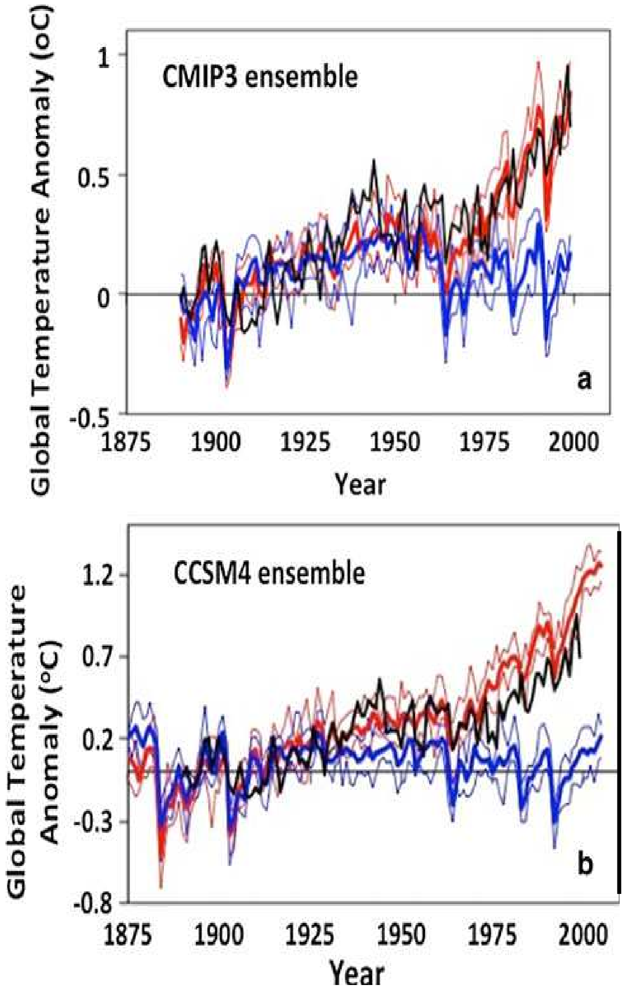


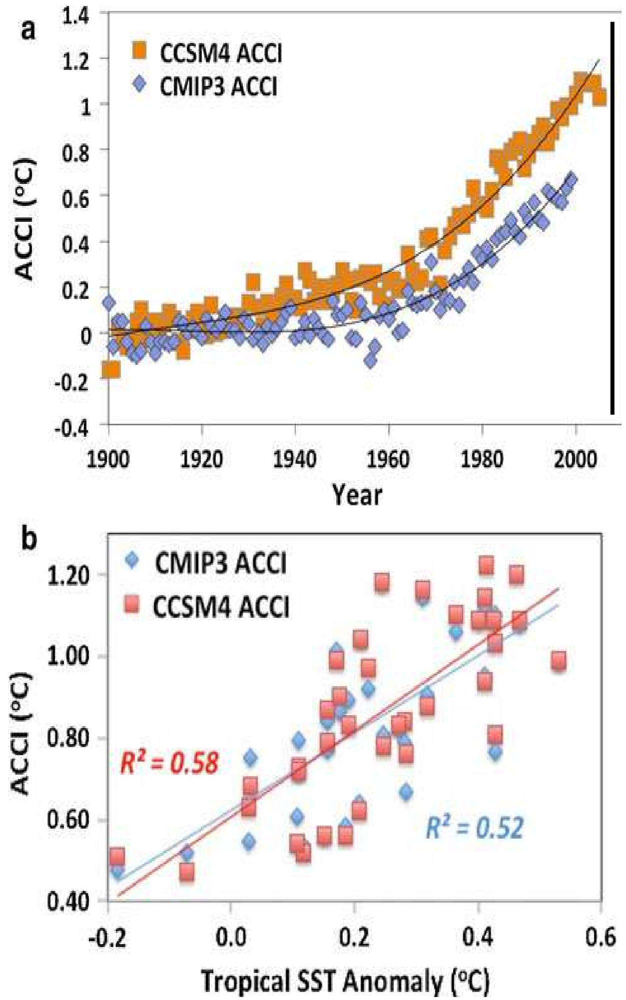


CURRENT CLIMATE :
how TCs have varied during the instrumental record (11)

Holland and Bruyère 2014 :
Clim. Dyn., 42, 617–627

Ensemble simulations of annual-mean global surface temperature *with (red)* *and* *without (blue)* *anthropogenic gas forcing, together with the observed global surface temperatures (black);*



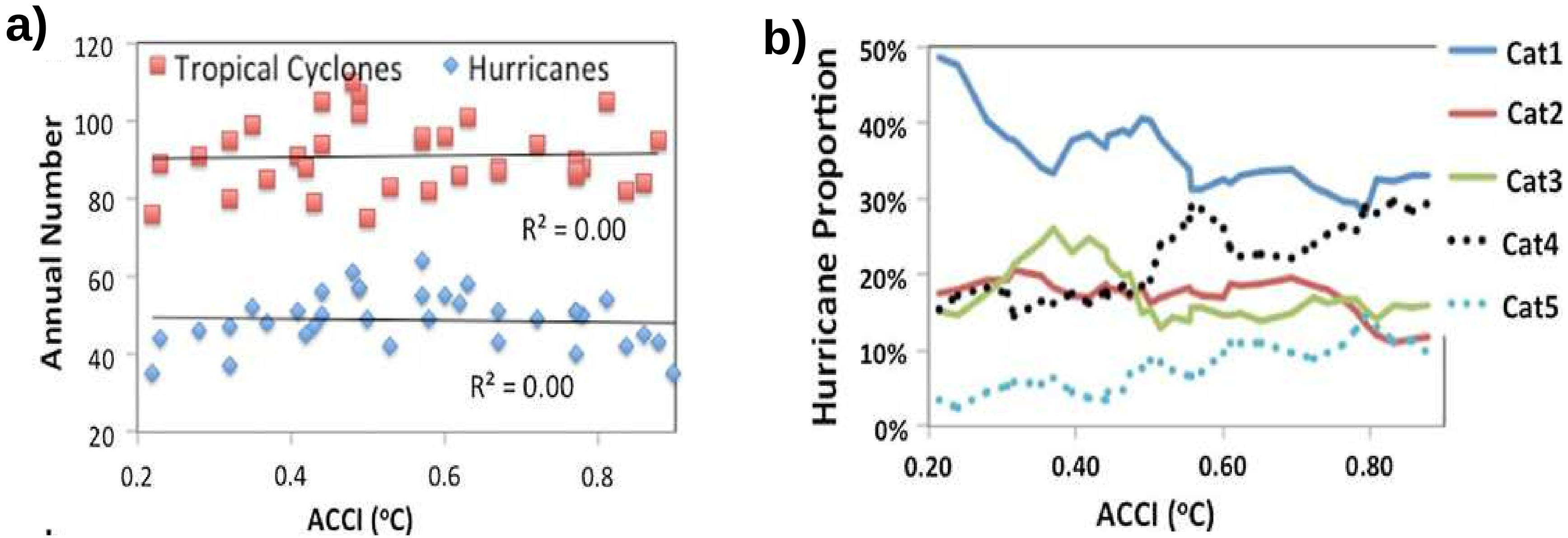


ACCI (Anthropogenic Climate Change Index) *calculated from the differences between the ensemble annual means*

Relationship between the ACCI and annual global tropical SST anomalies

CURRENT CLIMATE :
how TCs have varied during the instrumental record (11)

Holland and Bruyère 2014 :
Clim. Dyn., 42, 617–627



ACCI influence on:

a) *annual frequency of global tropical cyclones and hurricanes;*

b) *hurricane proportions in each of the Saffir–Simpson hurricane categories*

CURRENT CLIMATE :
how TCs have varied during the instrumental record (12)

Global :

[**Holland and Bruyère 2014 :** *Clim. Dyn.*, 42, 617-627]

No anthropogenic signal in annual global tropical cyclone numbers

The proportion of Cat-4 and 5 storms has increased at ≈ 25–30 % per °C

Similar decrease in Cat-1 and 2 storms proportions

Western North Pacific :

[**Lee *et al.* 2012 :** *Trop. Cycl. Res. Rev.*, 1, 213-220 + 277-299]

[**Ying *et al.* 2012 :** *Trop. Cycl. Res. Rev.*, 1, 231-241]

Pronounced inter-decadal variations

Results highly dependent on which best track data set is used

Consensus trends indicate fewer but stronger storms since 1984

Decreasing occurrence in South China sea, increasing along East coast of China

North Atlantic :

[**Landsea *et al.* 2010 :** *J. Climate*, 23, 2508-2519]

[**Kossin *et al.* 2013 :** *J. Climate*, 26, 9960-9976]

Data homogeneity issues

Increase in TC activity since 1970

External forcings (AMM/AMO, aerosols, upper tropospheric T, …) partly responsible

CURRENT CLIMATE :
how TCs have varied during the instrumental record (13)

North Indian :

[**Niyas *et al.* 2009 :** *Meteor. Monogr.*., 3, 35 pp.]

[**Singh *et al.* 2010 :** *Indian Ocean Trop. Cycl. and Clim. Change*, 51-54]

[**Evan *et al.* 2011 :** *Nature*, 479, 94-97]

1961-2008 : decreasing TC activity in Arabian Sea and Bay of Bengal

Increasing trend for th most intense TCs

Reduced wind shear as a major cause, but not certain

Larger impacts attributed to coastal developments

South Indian and South Pacific :

[**Kuleshov *et al.* 2010 :** *J. Geophys. Res.*, 115, D01101]

[**Callaghan and Power 2011 :** *Clim. Dyn.*, 37, 647-662]

Decreasing TC activity in N Australia (*non significant after including 2010-2011*)

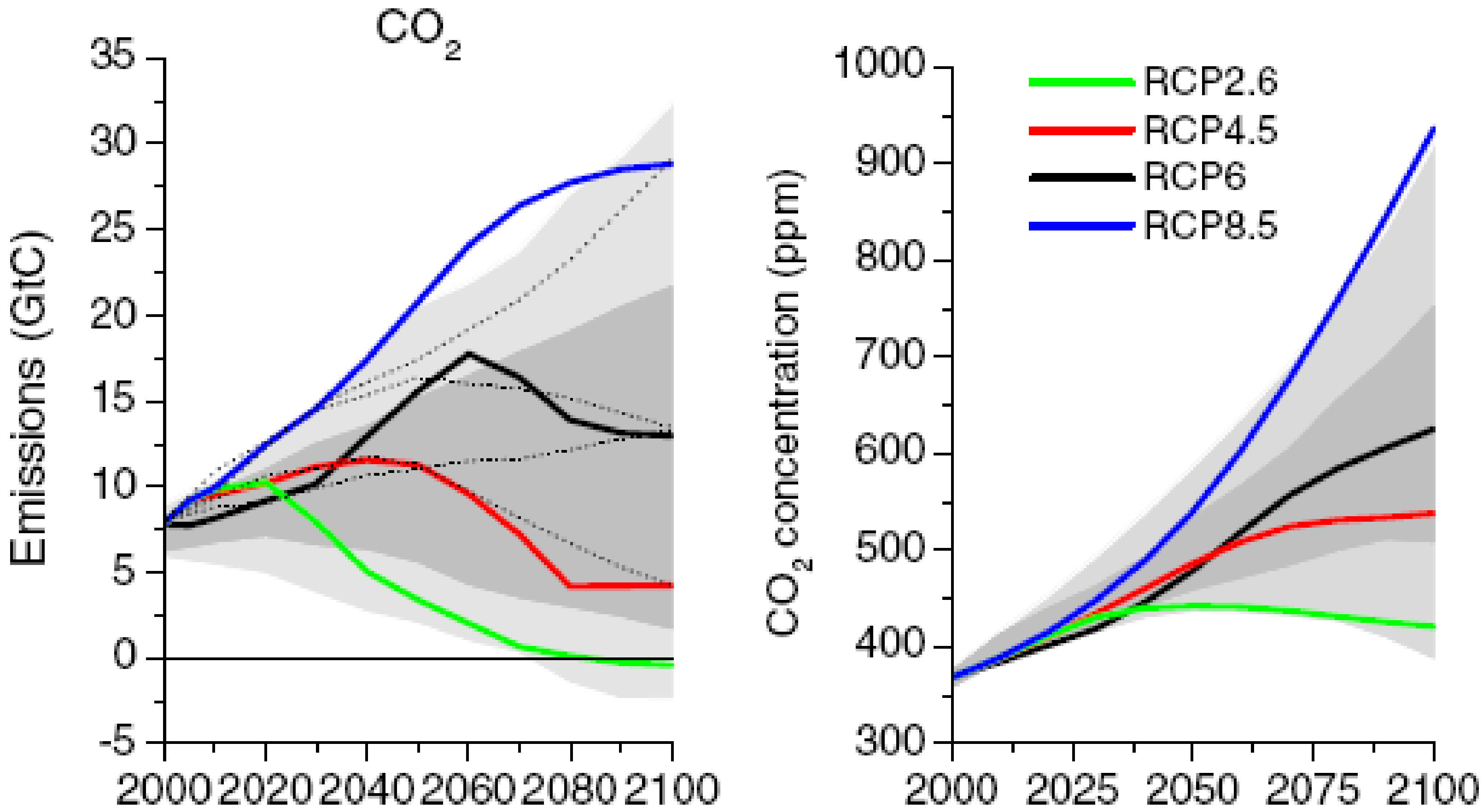
No trend in the total number of TCs in the Southern Hemisphere

Positive trend in <950 hPa storms in South Indian (*but changes in data quality*)

FUTURE CLIMATE :
how TCs will vary in the future ?

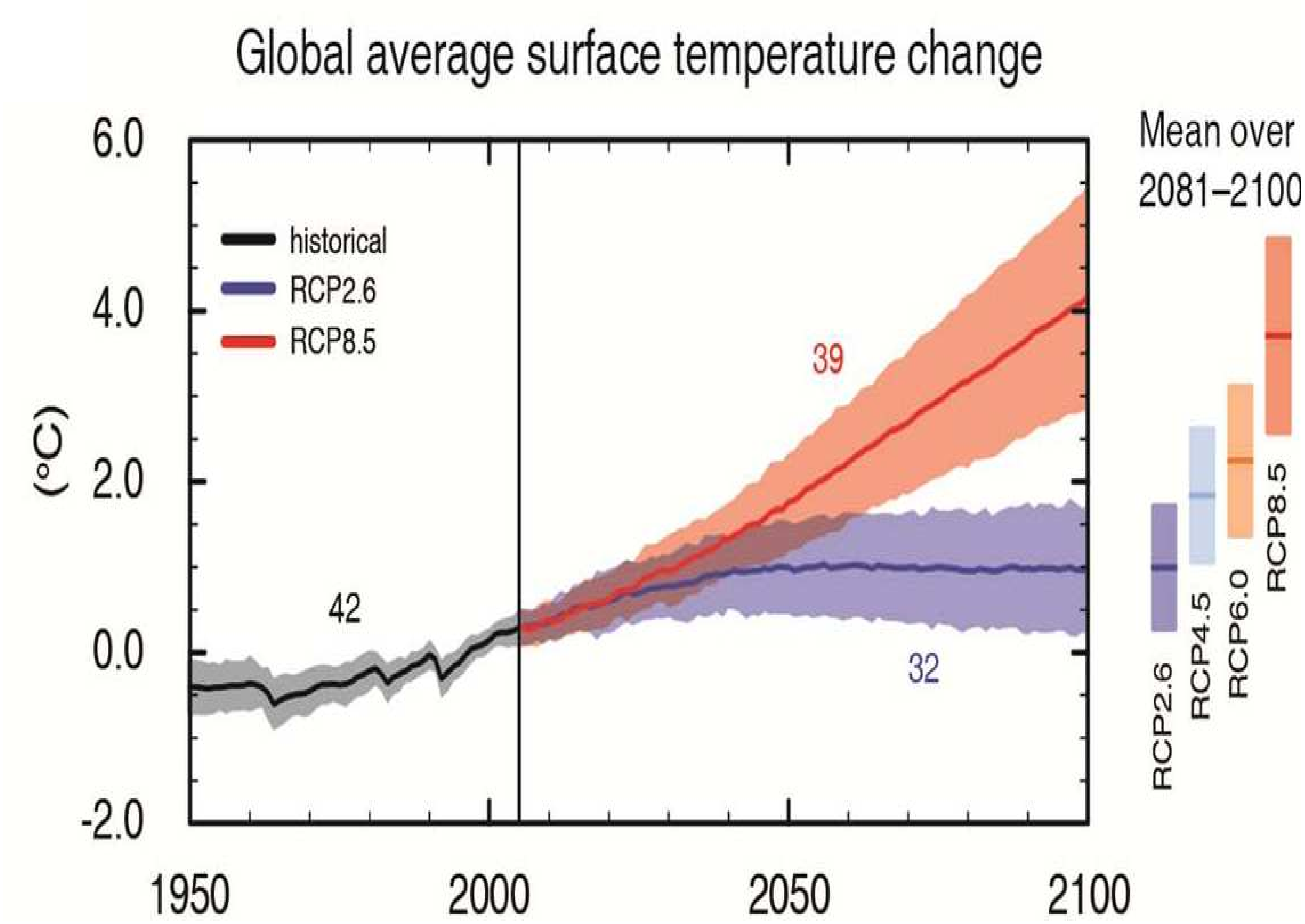
« Climate Change and Tropical Cyclones »
J. McBride & K. Walsh , 2014
8th WMO Int. Workshop on Tropical Cyclones
+
« Hurricanes and Climate:
The U.S. CLIVAR Working Group on Hurricanes »
K. Walsh *et al.*, 2015
Bull. Amer. Meteor. Soc., 96, 997–1017
+
« Tropical cyclone and climate change : A review »
T.R. Knutson *et al.*, 2010
in *"Global Perspectives on Tropical Cyclones: From Science to Mitigation"*
World Scientific Publishing Co.

FUTURE CLIMATE :
characteristics of global warming (1)



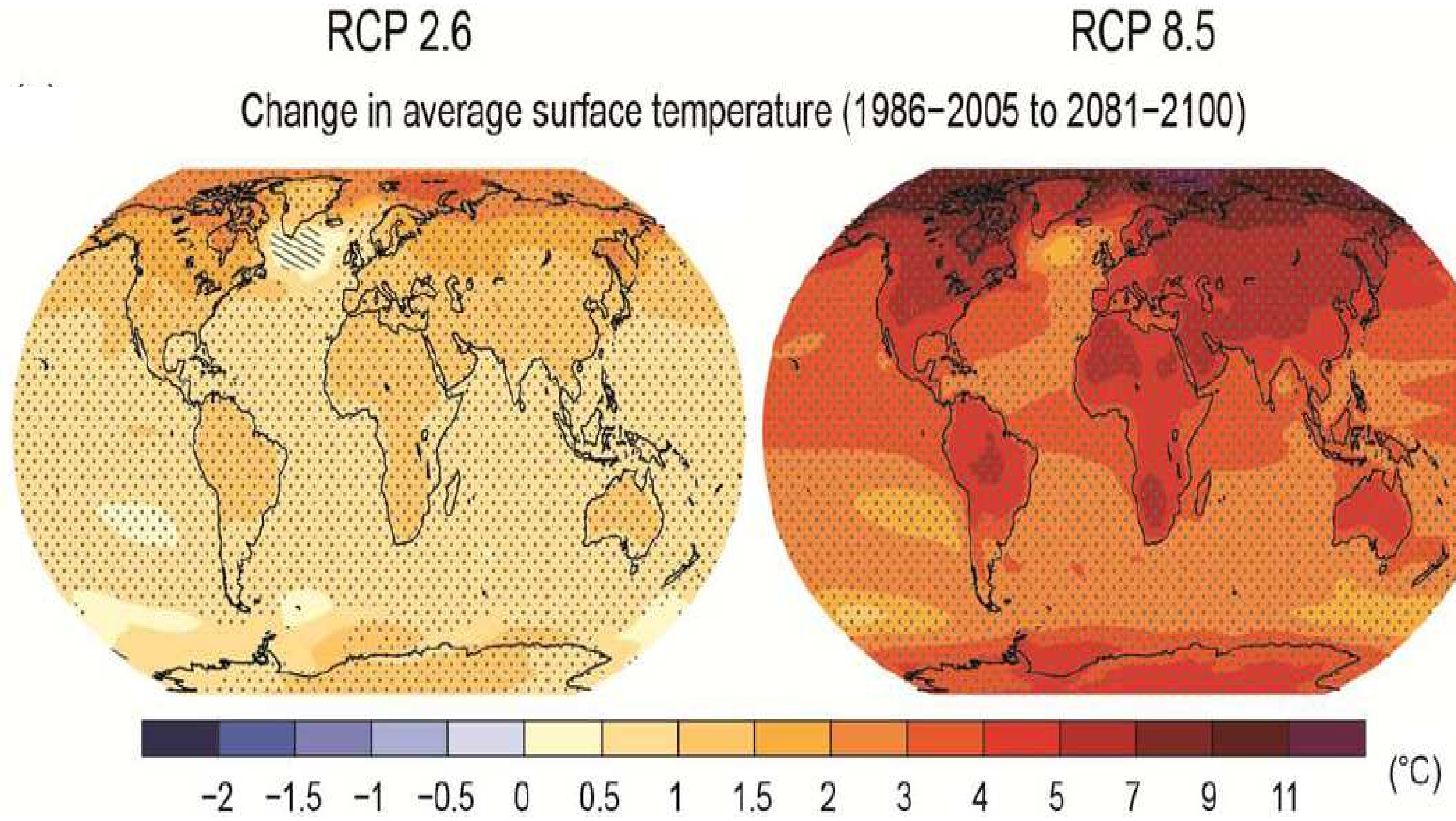
IPCC 5th Assessment Report (2013) : different « Representative Concentration Pathways (RCPs) » or socio-economic pathways translate into greenhouse gases emission and concentration scenarios.

FUTURE CLIMATE :
characteristics of global warming (2)

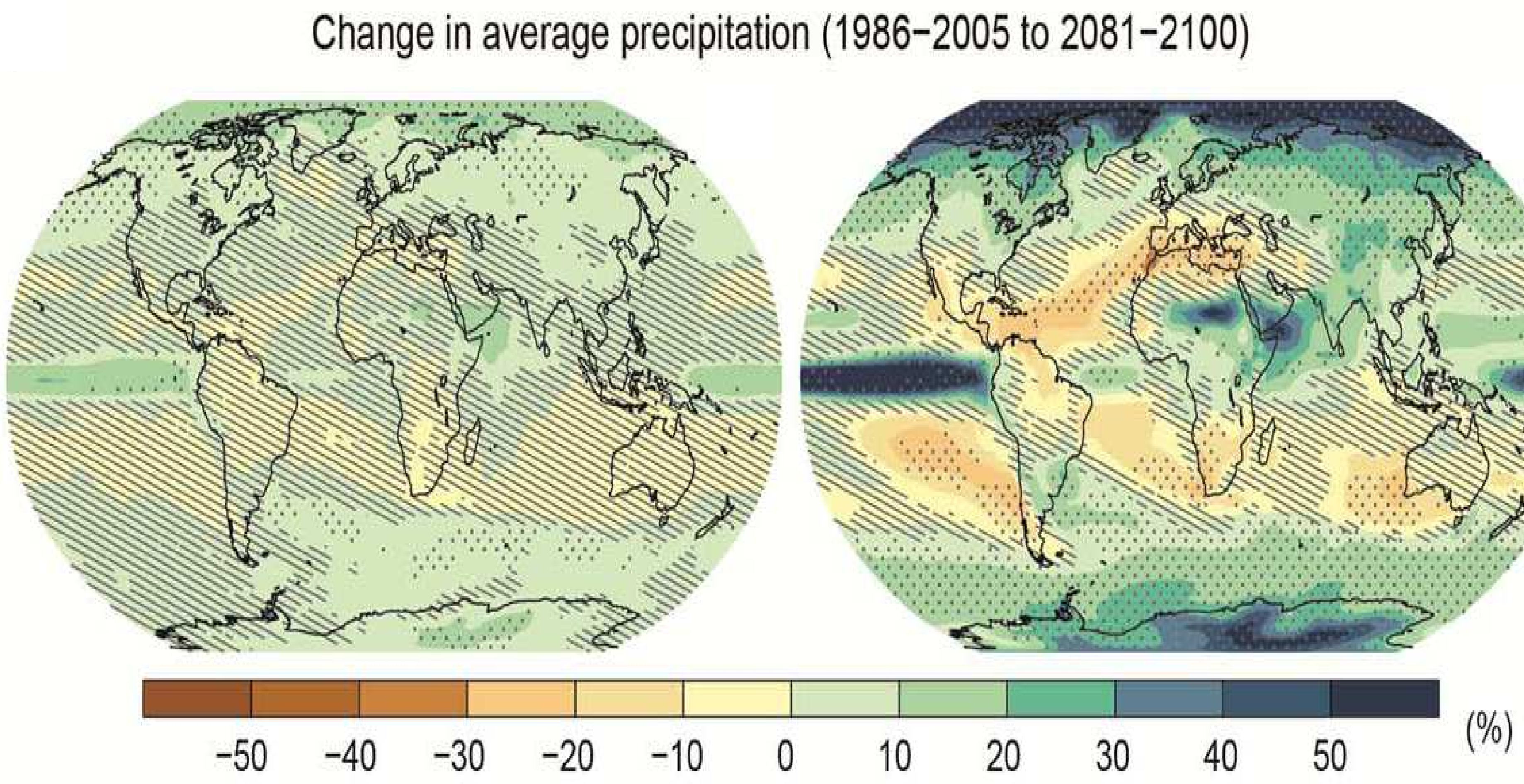


IPCC 5th Assessment Report (2013) : surface temperature increases during the 21st century are likely to be larger than historical increases …

FUTURE CLIMATE :
characteristics of global warming (3)



FUTURE CLIMATE :
characteristics of global warming (4)



FUTURE CLIMATE :
how TCs will vary with global warming (1) ?

- **Frequency ?**
- **Intensity ?**
- **Precipitation ?**
- **Area affected ?**
- **Impact ?**

FUTURE CLIMATE :
how TCs will vary with global warming (2) ?

Different methods are used to estimate future TCs behaviours from (Coupled or Atmospheric) Global Climate Models (GCM) :

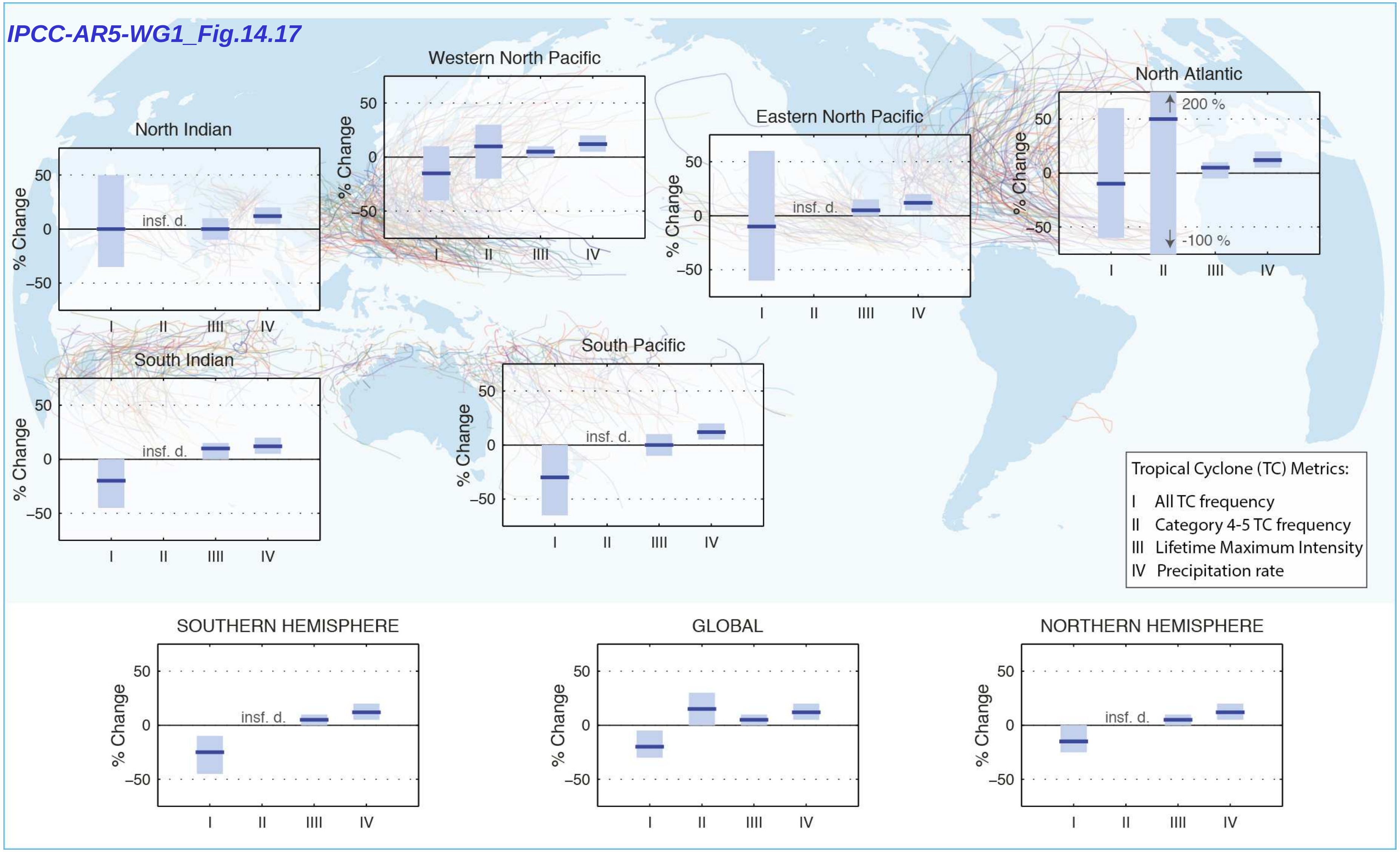
- Use GCM directly :
  - Estimate TC counts, wind speeds, precipitation
- Nested high-resolution experiments :
  - Downscaling
  - Case studies, regional characteristics, intensity, …
- Infer TC behaviour from large-scale GCM variables :
  - Frequency : Gray & al genesis parameter
  - Intensity : Emanuel – Holland potential intensity

FUTURE CLIMATE : how TCs will vary with global warming (3) ?

- TC frequency simulations are highly dependent on the ability of Climate Models to adequately simulate the changes in large-scale conditions that affect TC development (SST anomalies, convective instability, relative humidity profile, wind shear, …).

- The convergence of results obtained from different models provide some confidence in global and hemispheric projections of TC frequency changes.

FUTURE CLIMATE :
how TCs will vary with global warming (4) ?



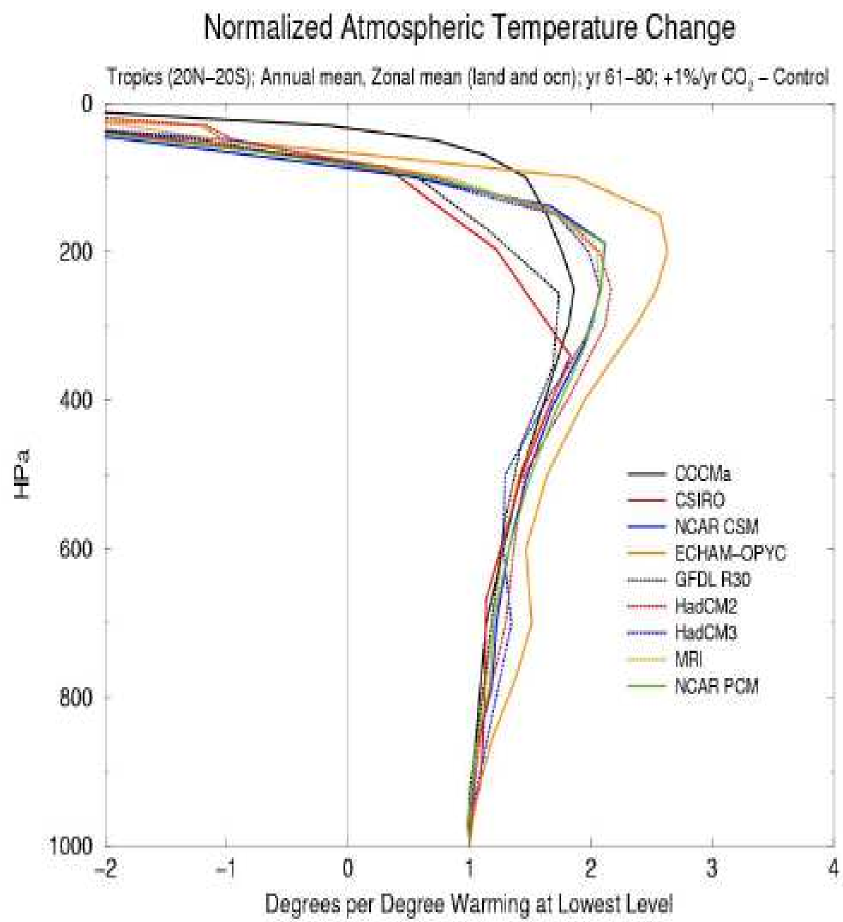
FUTURE CLIMATE :
how TCs will vary with global warming (5) ?
Frequency

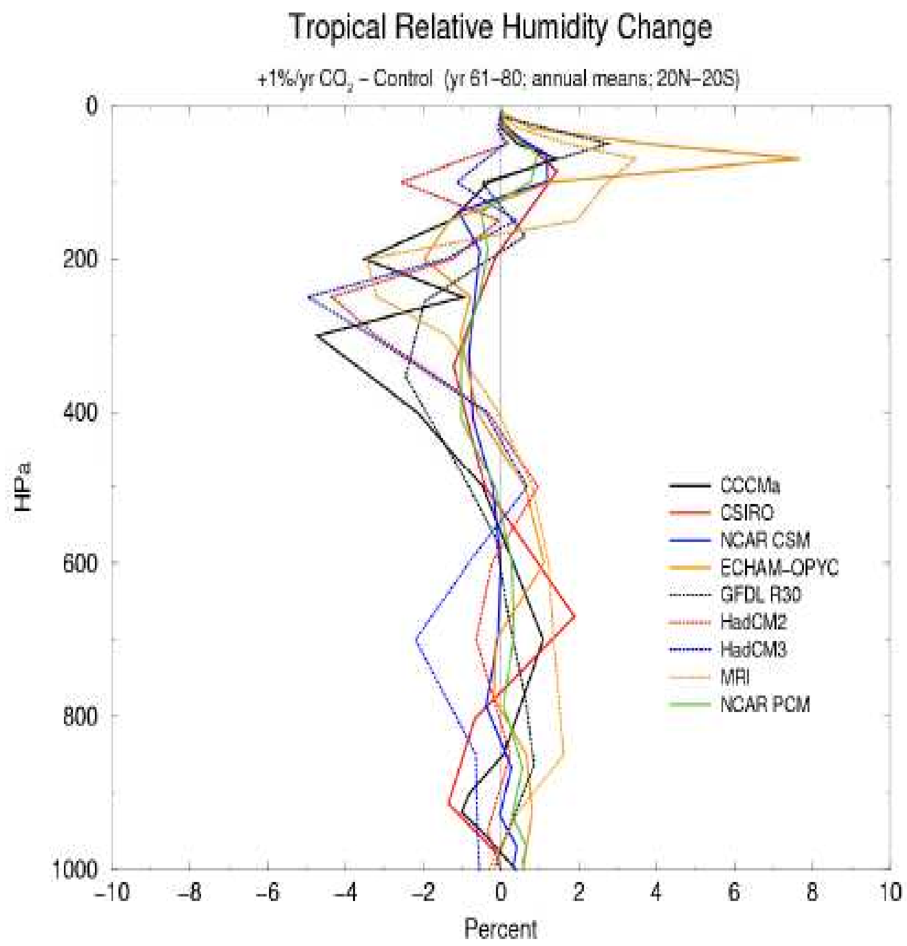
- It is likely that global mean TC frequency will either decrease or remain unchanged owing to global warming.
- For the late 21st century, model projections indicate decrease ranging from 0 to -40% globally.
- Disagreements between models for regional distributions.

- This may be due to weakening of tropical circulation with weaker convective instability and larger saturation deficit in the middle to upper troposphere.
- The threshold for TC formation rises roughly along with the tropical mean SST.

- The more robust decrease in the southern Hemisphere (-10 to -40% vs. 0 to -30%) may be due to smaller increase in SST (compared to northern Hemiphere), as well as areas of increased vertical wind shear.

FUTURE CLIMATE :
how TCs will vary with global warming (6) ?





All climate models show increasing static stability in the Tropics with <u>enhanced warming in the tropical upper troposphere</u>, and relatively <u>little change in the lower tropospheric humidity</u>.

FUTURE CLIMATE :
how TCs will vary with global warming (7) ?
Intensity

- All of the highest resolution models (≤50 km horizontal grid spacing), which reproduce reasonably corrext intensity distribution for past and present conditions, show evidence for some increase of intensity.

- There is a clear tendency among these models at higher resolution to project an increase in the frequency of the strongest tropical cyclones, although this may not occur in all basins.

- Globally, the proportion of Cat-4,5 storms may increase by 0-25%.
- For individual basins, projections based on different models vary by ±15% or more.

FUTURE CLIMATE :
how TCs will vary with global warming (8) ?
Rainfall

- As the atmosphere warms in relation with increasing content of greenhouse gases, the integrated water vapour column will increase (*Clausius-Clapeyron : relative humidity increases by ~7% per °C warming*)

- This should increase rainfall rates in systems (such as TCs) where moisture convergence is an important component of the water budget.
- For TCs, an increase in storm-wind intensity would amplify this phenomenon, through enhanced ocean-to-atmosphere moisture flux.

- The increase of TC-related rainfall rates is a robust projection in model simulations.
- The range of projections for the late 21st century is +5 to +20% globally.

FUTURE CLIMATE :
how TCs will vary with global warming (9) ?
Rainfall

- However, model resolution and parameterized physical processes near the storm center (<100 km) place a level of uncertainty on such projections that is not easily quantified !
- Annually averaged rainfall from TCs could decrease if the impact of decreased frequency of storms exceeds that of increased rainfall rated in individual (stronger) storms !

FUTURE CLIMATE :
how TCs will vary with global warming (10) ?
Affected area and Impact

- Confidence in projection of changes in TC genesis location, tracks, duration and aereas of impact is low.
- Existing models projections do not show dramatic changes in these features.

- The vulnerability of coastal regions to TC storm-surge flooding is expected to increase with global-warming related sea-level rise and coastal developments.
- This vulnerability will also depend on future storm characteristics.

- GCM projections for the expansion of the tropics indicate some potential for some poleward shift of the averaged latitude of ET transition.

FUTURE CLIMATE :
Progress summary and outlook

- **Substantial progresses** have been achieved during the last decade :
    - Links between climate and potential intensity
    - More credible simulations of present-day climatology
    - Ability to predict interannual variability of TC

- **Some issues are not yet satisfying :**
    - When will the climate change signal dominate natural variability ?
    - Sensivity of atmospheric GCM to the regional details of forcing SST
    - No climate theory can predict the formation of TCs (location, rate)
    - TC genesis indices, trained in present climate, might not be adapted to the future warmer world
    - Differences between TC tracking methods in GCM

FUTURE CLIMATE : Recommendations

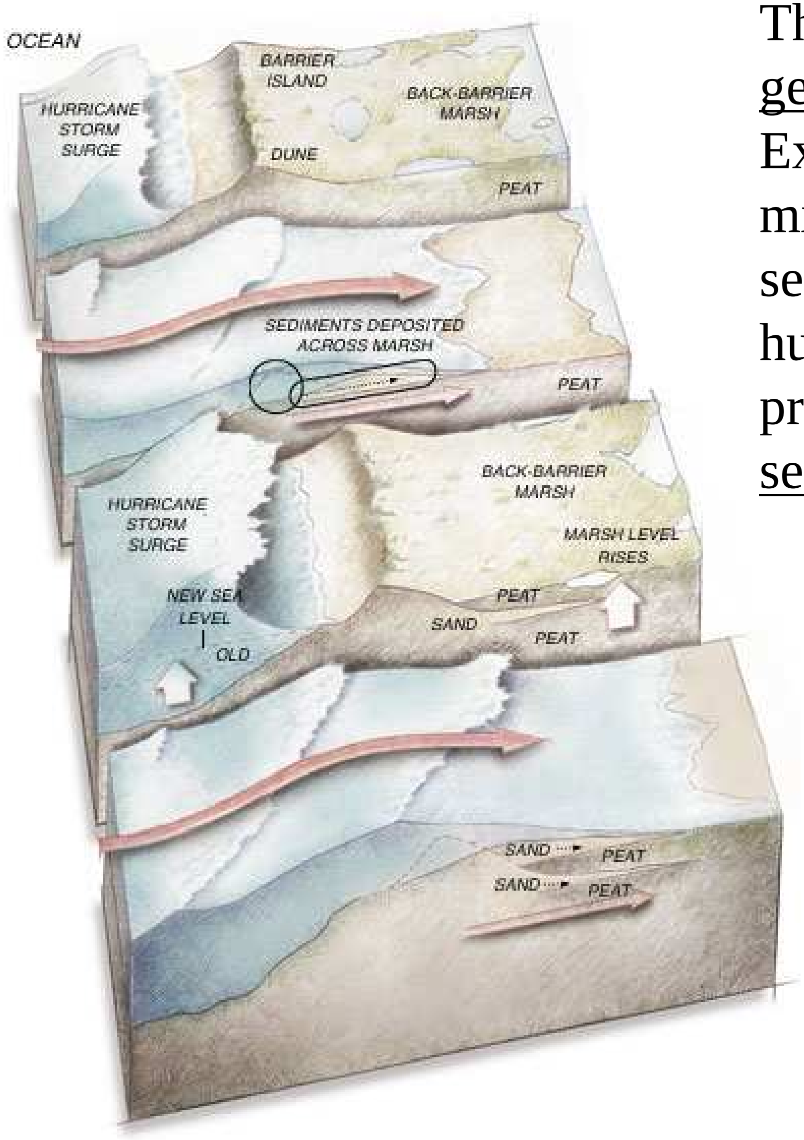
- **Improved TC databases :** beyond IBTrACS, creating a homogeneous climate record over all basins continues to be a challenge, especially for intensity data.
  Satellite-derived datasets, beyond Dvorak method, should help to estimate the evolution of storm structure and intensity.

- **Numerical models :** higher horizontal resolution, improved physics (convection, air-sea interaction, aerosols, …), coupled models will provide more realistic simulations of TC activity in future climate.
  More accurate information about drivers of TC variability.
  Common diagnostics, tracking methods and Genesis Potential Indices would facilitate comparisons between models.

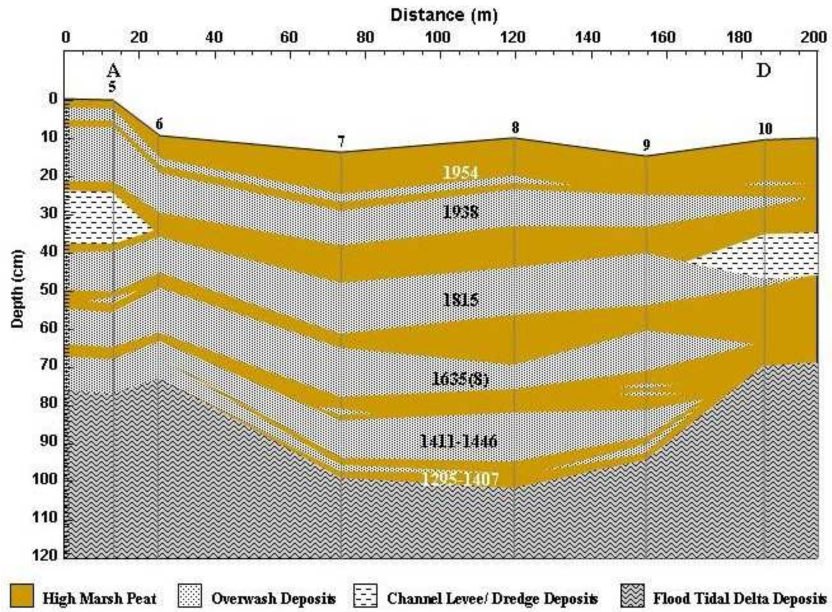
- **Regional characteristics :** natural (intra-seasonal to multi-decadal) variability vs. anthropic global warming ; details of projected SST changes in the tropics and related dynamical influences ; storm surge, sea level rise and densely populated areas (coastal cities, deltas)

PALEOTEMPESTOLOGY
TCs of forgotten path (1)

Frappier *et al.* 2007
Tellus, 59A, 529-537



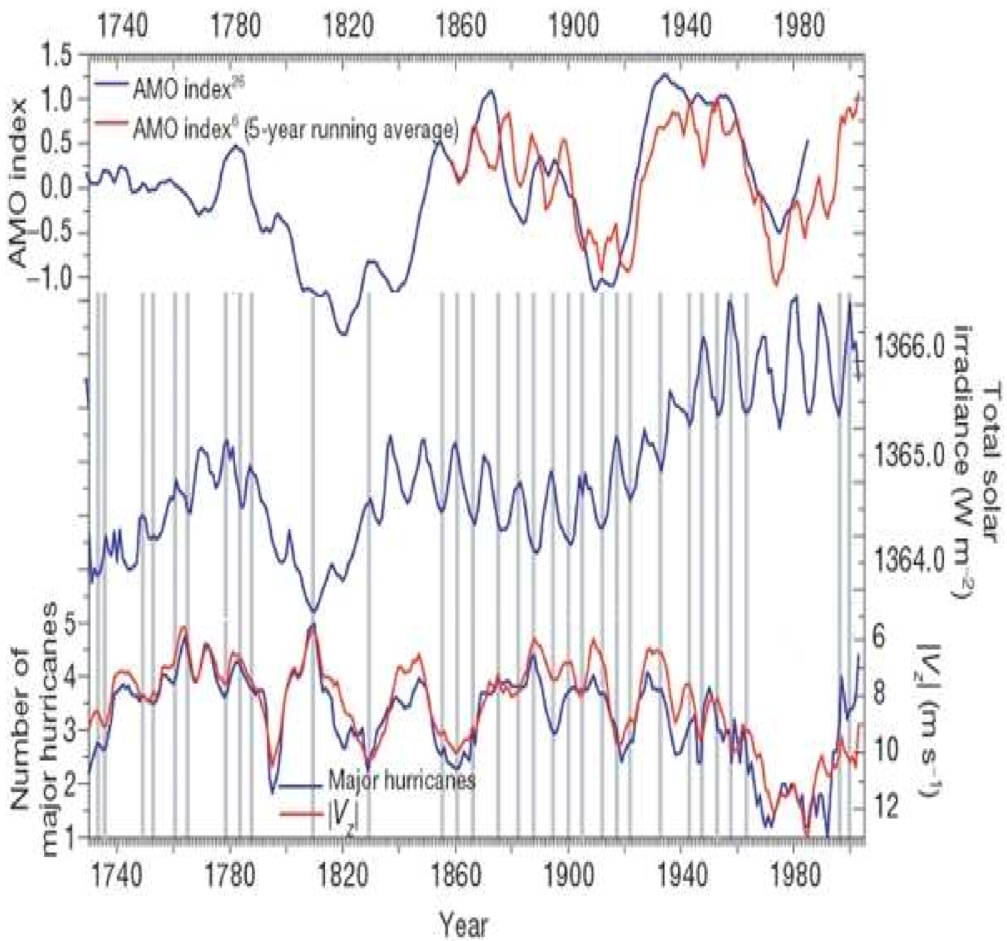
This is the study of past TC activity by means of geological proxies.
Examples of proxies include overwash deposits, microfossils, wave-generated or flood-generated sedimentary structures, oxygen isotopic ratios of hurricane rainfall in shallow-water corals, … preserved in the sediments of marine or lagoonal sediments.



PALEOTEMPESTOLOGY : TCs of forgotten path (2)

Nyberg *et al.* 2007 :
Nature, 447, 698-701

Low Atlantic hurricane activity in the 1970s and 1980s compared to the past 270 years

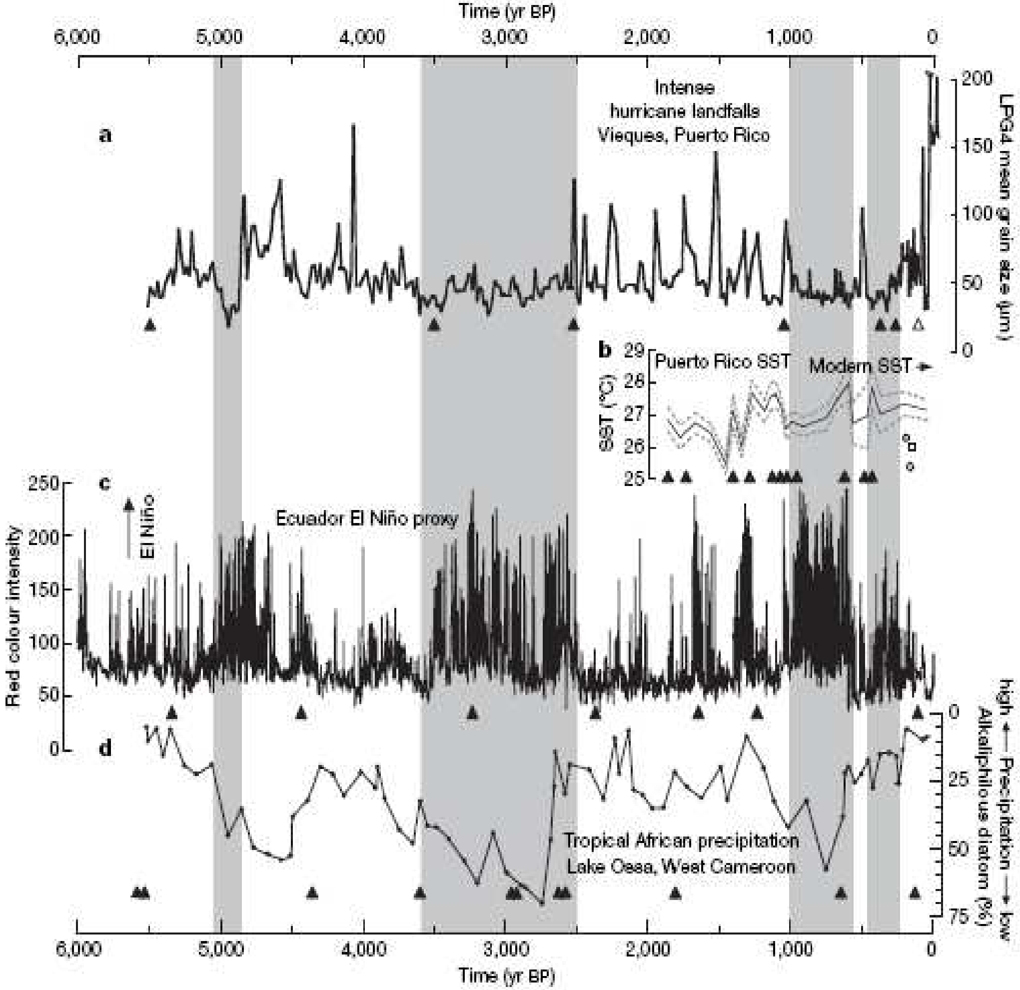


Frequency of major Atlantic hurricanes over the past 270 years from proxy records of vertical wind shear & sea surface temperature (corals & marine sediment core) : *Reduced major hurricane activity coincides with a lower Atlantic Multi-decennal Oscallition (AMO) index around 1820-1830, 1910-1920, 1970-1990. Enhanced activity coincides with a high index around 1750-1790, 1870-1900 and 1930-1960. Peaks and trends of high activity concurred with lower Total Solar Irradiance, and vice versa.*

PALEOTEMPESTOLOGY : TCs of forgotten path (3)

Intense hurricane activity over the past 5,000 years controlled by El Niño and the West African monsoon

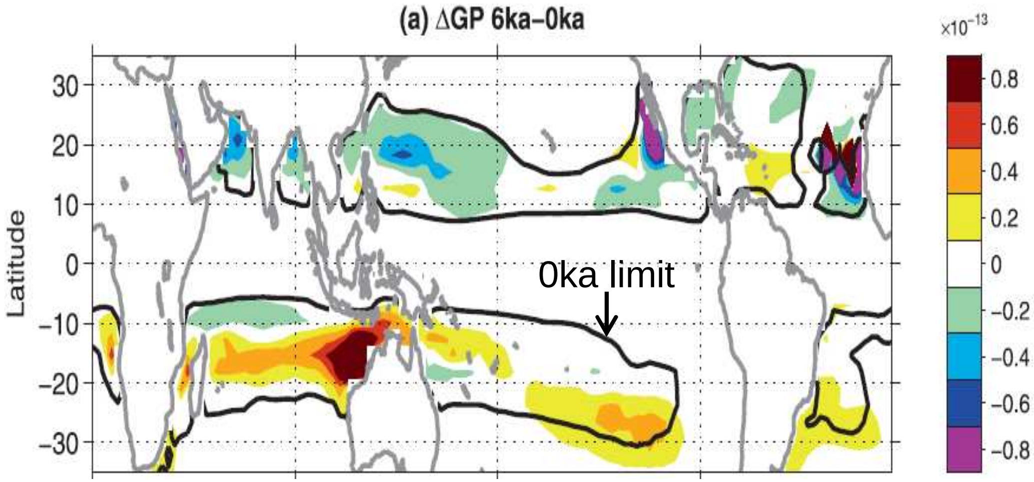
Donnelly & Woodruff 2007 :
Nature, 447, 465-468



Comparison of the intense hurricane record from a lagoon on the Puerto Rican island of Vieques with other climate records :

The results suggest that, in addition to fluctutations in tropical Atlantic SST, changes in atmospheric dynamics tied to ENSO & the West African monsoon also act to modulate intense hurricane activity on centenial and millenial timescales.

PALEOTEMPESTOLOGY : TCs of forgotten path (4)



Difference in storm-season ensemble mean genesis potential between 6ka and 0ka

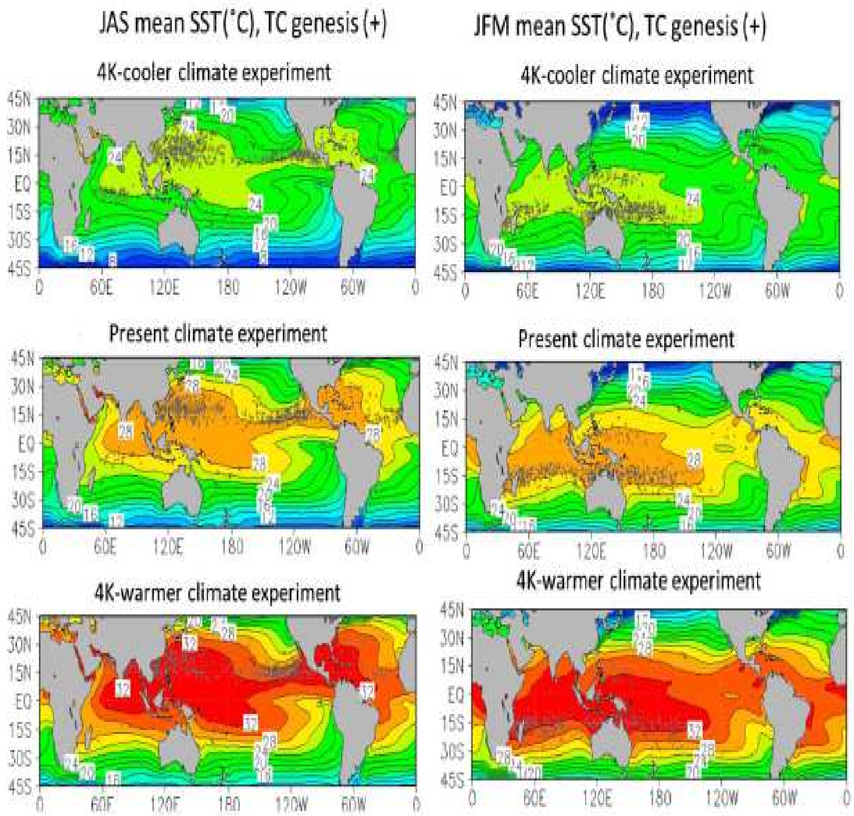
$$\mathrm{GP} = \frac{a[\min(|\eta|, 4\times 10^{-5})]^3[\max(V_{\mathrm{PI}} - 35, 0)]^2}{\chi^{4/3}[25 + V_{\mathrm{shear}}]^4}$$

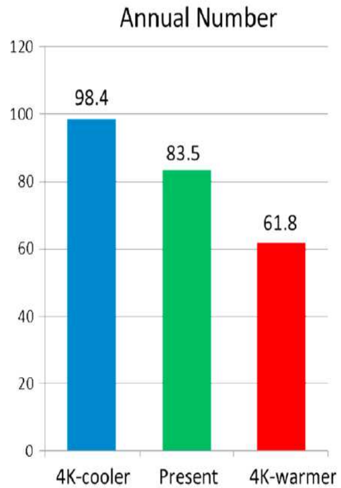
Genesis Potential Index

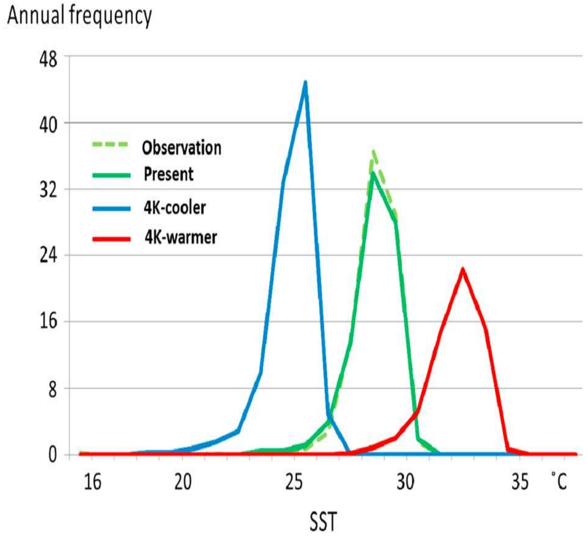
Korty *et al.* 2012 :
J. Climate, 25, 8196-8211

Mid-Holocene (-6 ky BP) :

- There was substantially more TOA solar radiation during the Northern Hemisphere TC season than there is today, and less TCs than today would develop.
- The Southern Hemisphere, which received much less solar radiation, displays slightly more favorable conditions for TC genesis and intensity during the MH than in the preindustrial era control.







PALEOTEMPESTOLOGY
: TCs of forgotten path (5)

Sugi *et al.* 2015 :
Geophys. Res. Lett., 42, 6780-6784

4K-cooler/warmer climate compared to the present :

The global TC frequency significantly increases in the 4K-cooler climate compared to the present climate.

This is consistent with a significant decrease in TC frequency in the 4K-warmer climate.

For the mechanism of TC frequency reduction in a warmer climate, upward mass flux hypothesis and saturation deficit hypothesis have been proposed.