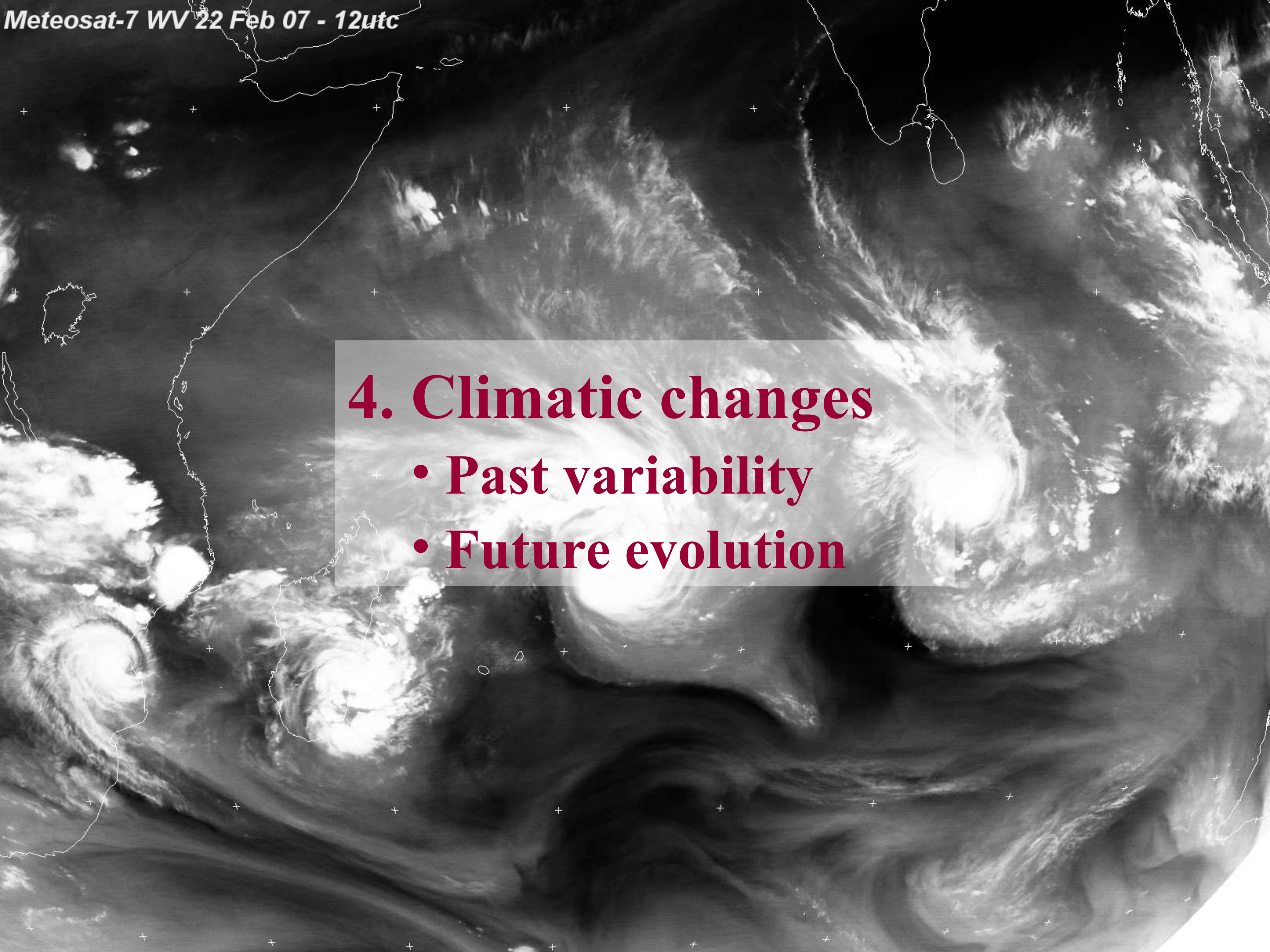


4. Climatic changes

- Past variability
- Future evolution

TROPICAL CYCLONES and CLIMATE

- How TCs have varied during recent and distant past ?
- 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

(North Atlantic and western North Pacific until 1987 only)

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

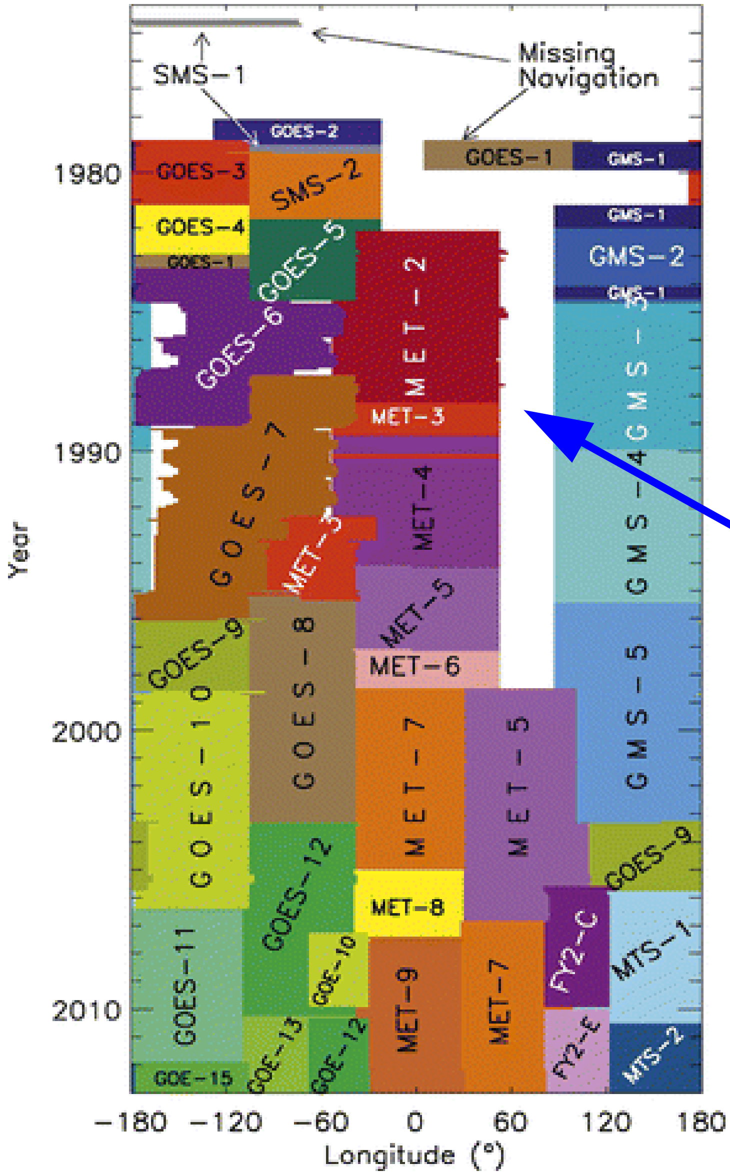
>1975 : Meteorological satellites (geostationnay, VIS & IR)

>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)



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

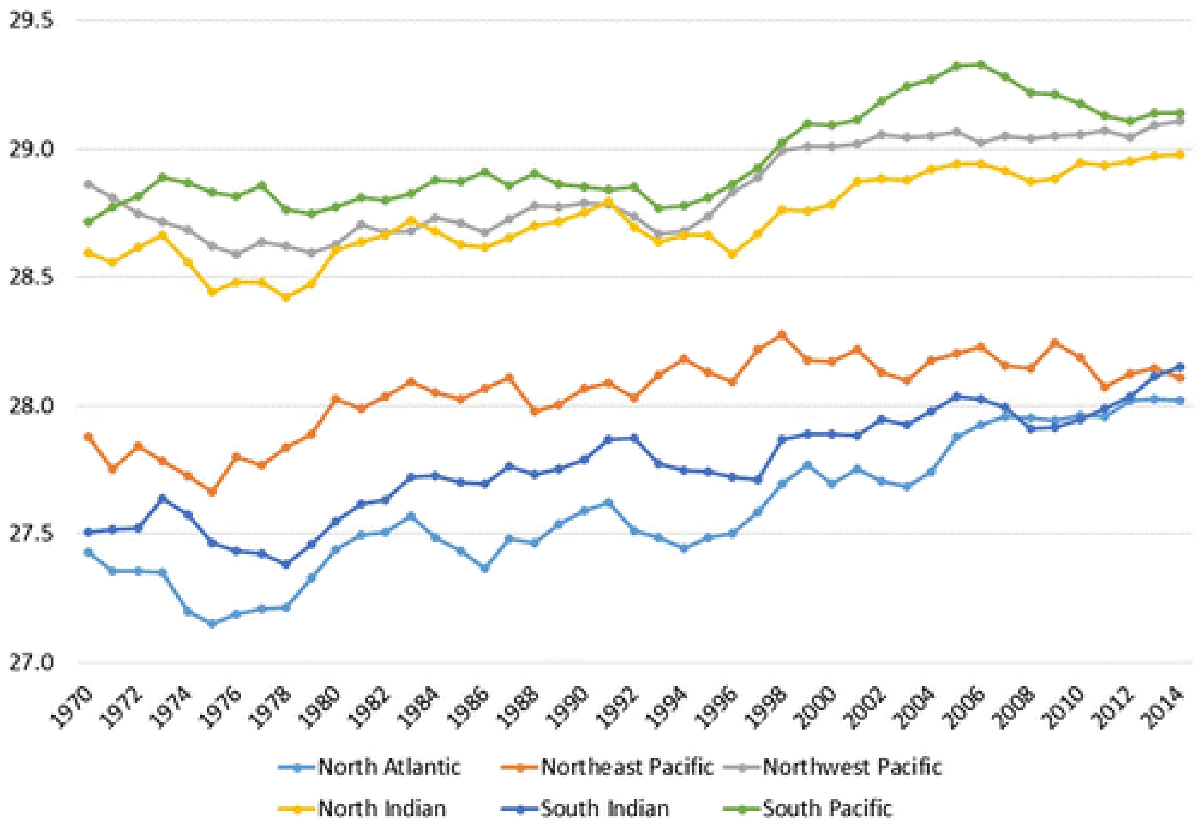
Global meteorological geostationary satellite coverage over the past ~40 years.

Gap in the N and S Indian ocean until 1998 ...

The Dvorak Technique [**Dvorak 1975 :** *Mon. Wea. Rev.*, 103, 420-430 & **1984 :** *NOAA Technical Report NESDIS 11*] utilizes VIS & IR satellite imagery to assign an intensity to TCs.

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

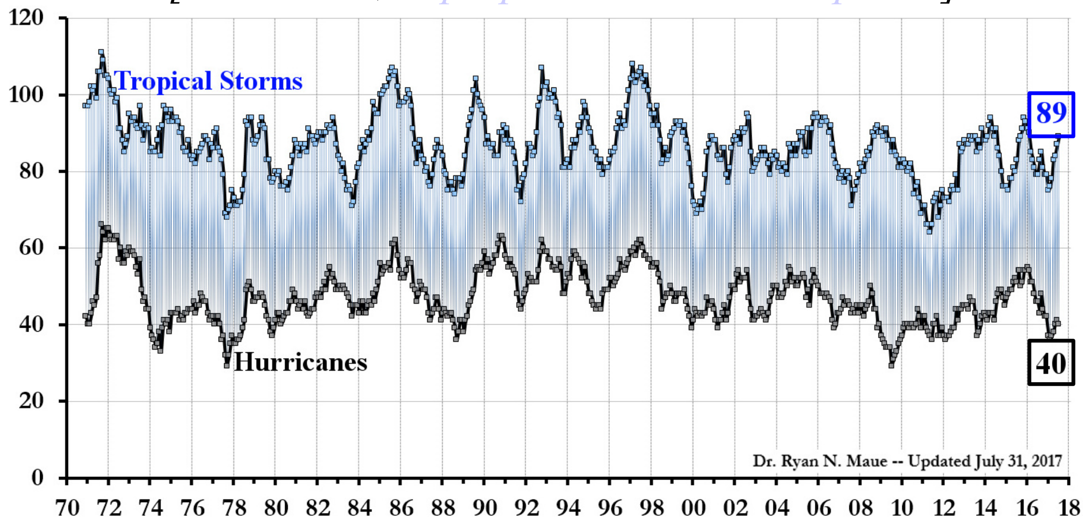
Klotzbah and Landsea 2015 :
J. Clim., 28, 7621-7629



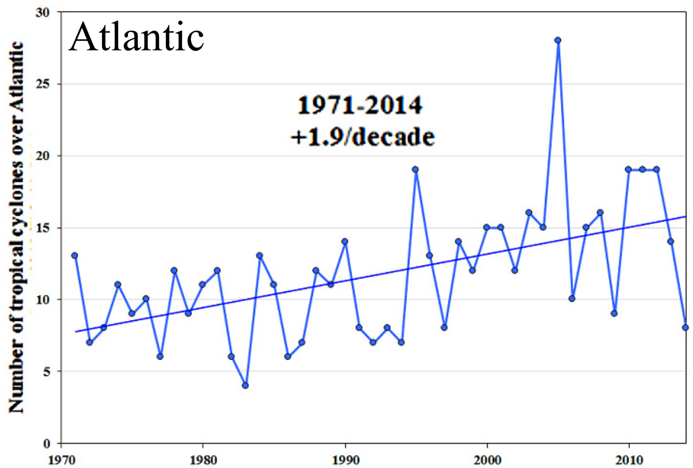
Tropical ocean SSTs have increased by ≈0.5°C between 1970 and 2014

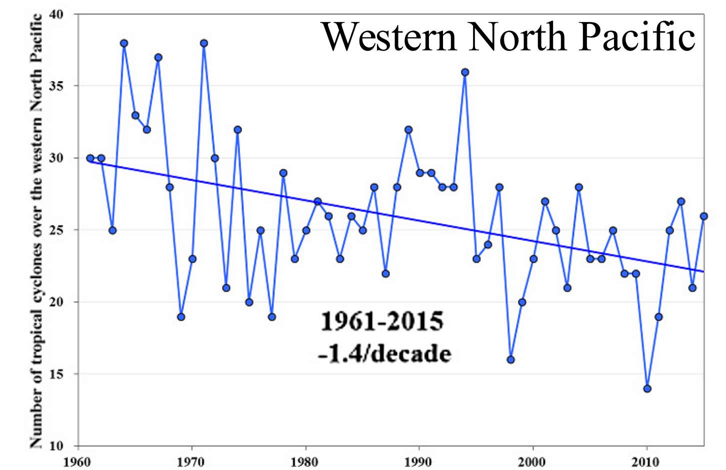
CURRENT CLIMATE :
how TCs have varied during the instrumental record (4)

[R.M Maue, http://policlimate.com/tropical/]



The top time series is the number of TCs that reach at least tropical storm strength (maximum lifetime wind speed > 17 m/s). The bottom time series is the number of hurricane strength (> 33 m/s) TCs.

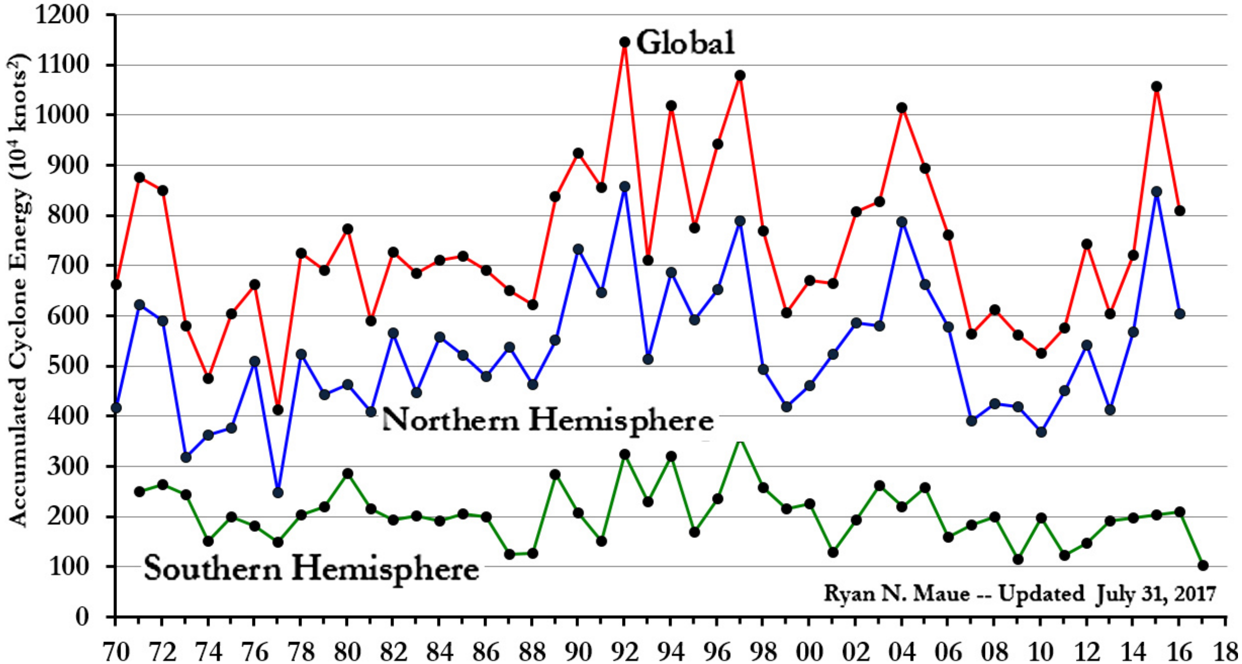




[http://gb.weather.gov.hk/climate_change/obs_global_tc_e.htm]

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

[R.M Maue, http://policlimate.com/tropical/]



Accumulated cyclone energy, or **"ACE"**, is used to express the activity and destructive potential of individual tropical cyclones and entire tropical cyclone seasons.

ACE is calculated as the <u>sum of the square of the wind speed every 6 hours</u>, and is then <u>mutiplied by a factor of 10^{-4}</u> for usability.

The <u>ACE of a season</u> is the <u>sum of the ACE for each storm</u> and takes into account the number, strength, and duration of all the tropical storms in the season.

The caveat to using ACE as a measure of the activity of a season is that <u>it does not take the size of the hurricane or tropical storm into account</u>.

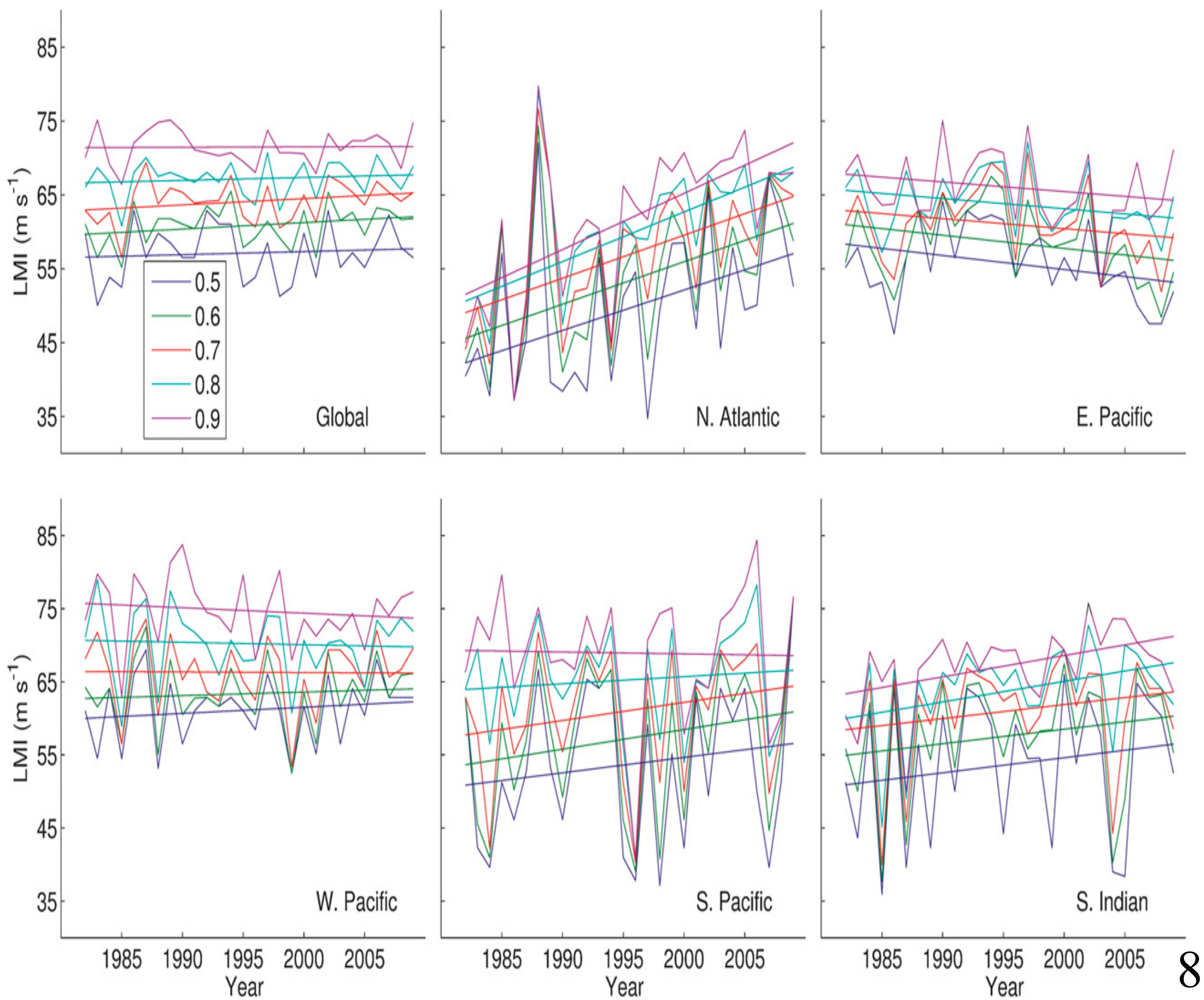
CURRENT CLIMATE :
how TCs have varied during the instrumental record (6)

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

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

Quantiles (0.5 to 0.9) of LMI



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

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.

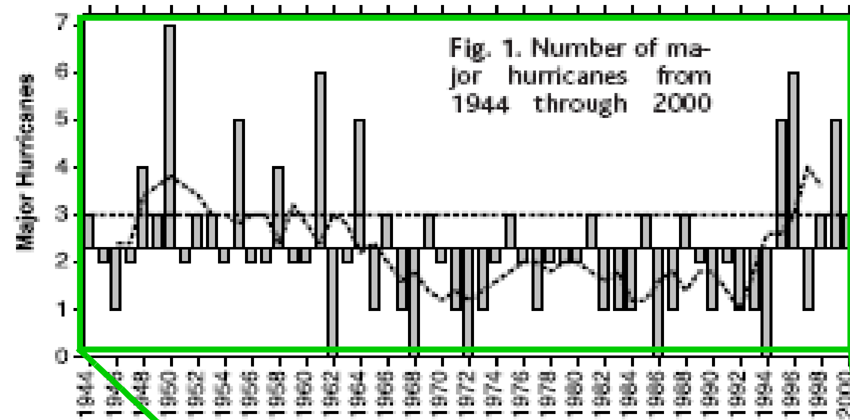
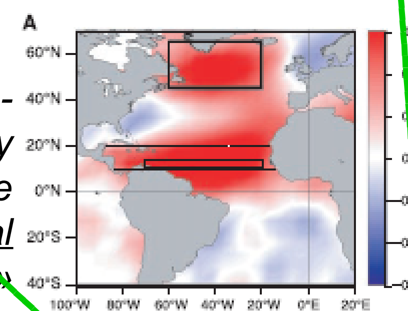
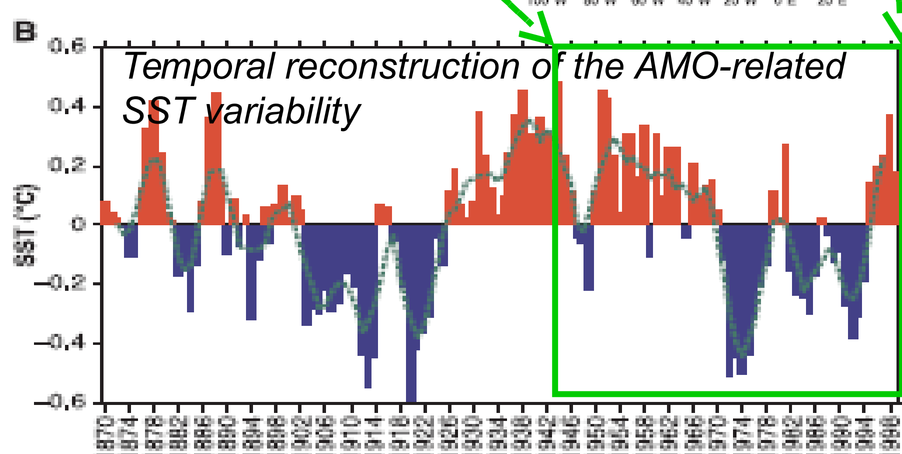


Fig. 1. Number of major hurricanes from 1944 through 2000



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

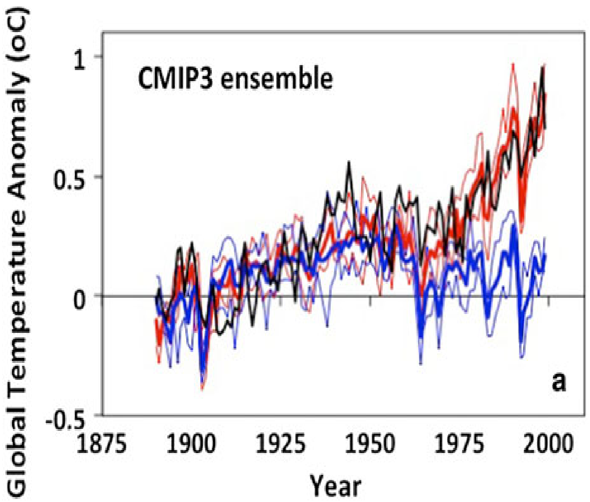


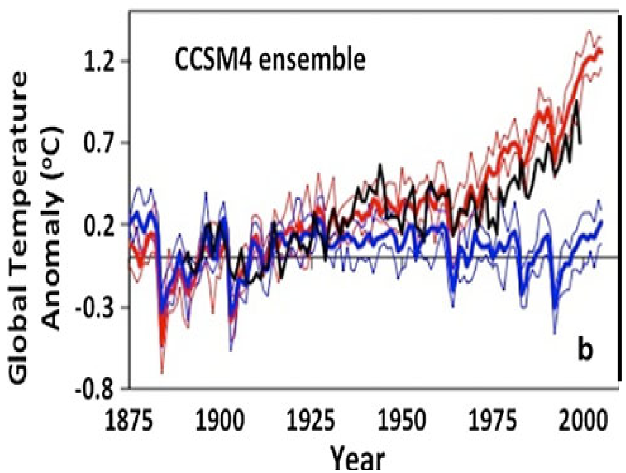
Temporal reconstruction of the AMO-related SST variability

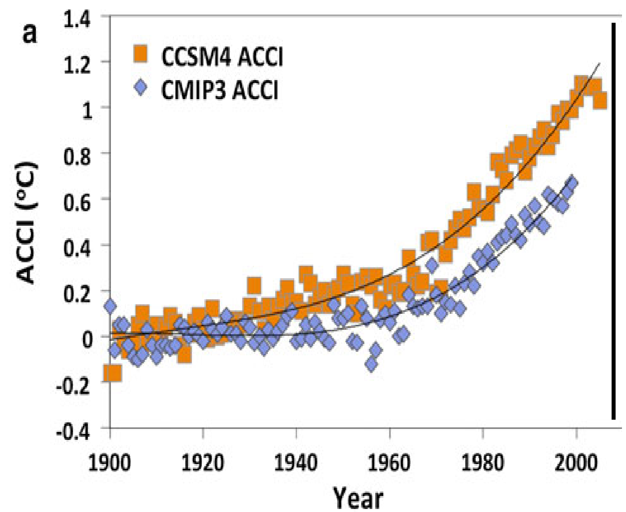
CURRENT CLIMATE :
how TCs have varied during the instrumental record (8)

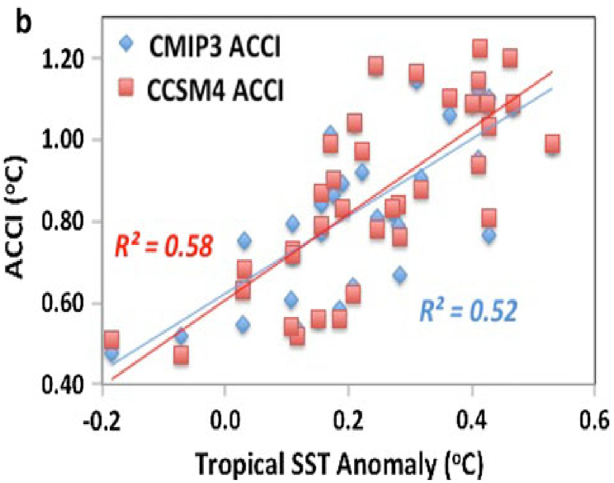
Holland and Bruyère 2014 :
Clim. Dyn., 42, 617–627

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







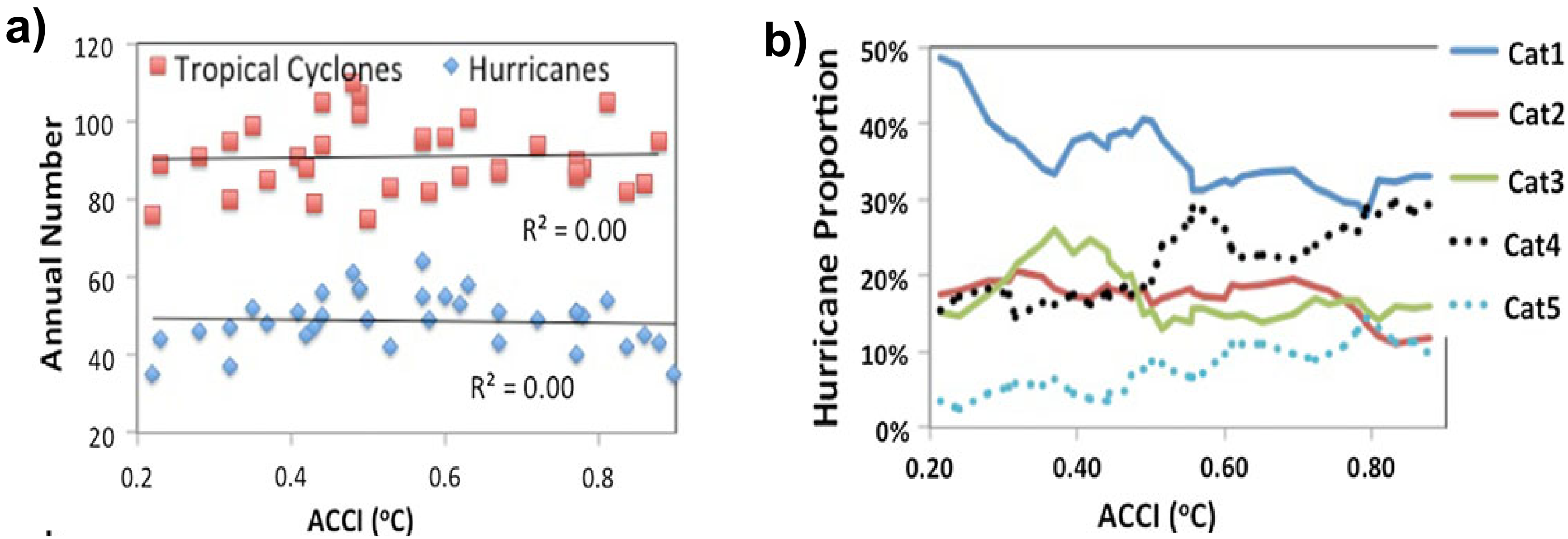


ACCI (Anthropogenic Climate Change Index) calculated from the differences between the annual means ***« with »*** **-** ***« without »***

Relationship between the *ACCI* and *annual global tropical SST anomalies*

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

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



No change in global cyclone frequency or average intenstity

Substantial increase in the proportion of the most intense cyclones

CURRENT CLIMATE :
how TCs have varied during the instrumental record (10)

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 by ≈ 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 the most intense TCs
Reduced wind shear as a major cause (air pollution?), but not certain
Larger impacts attributed to coastal developments

South Indian and South Pacific :

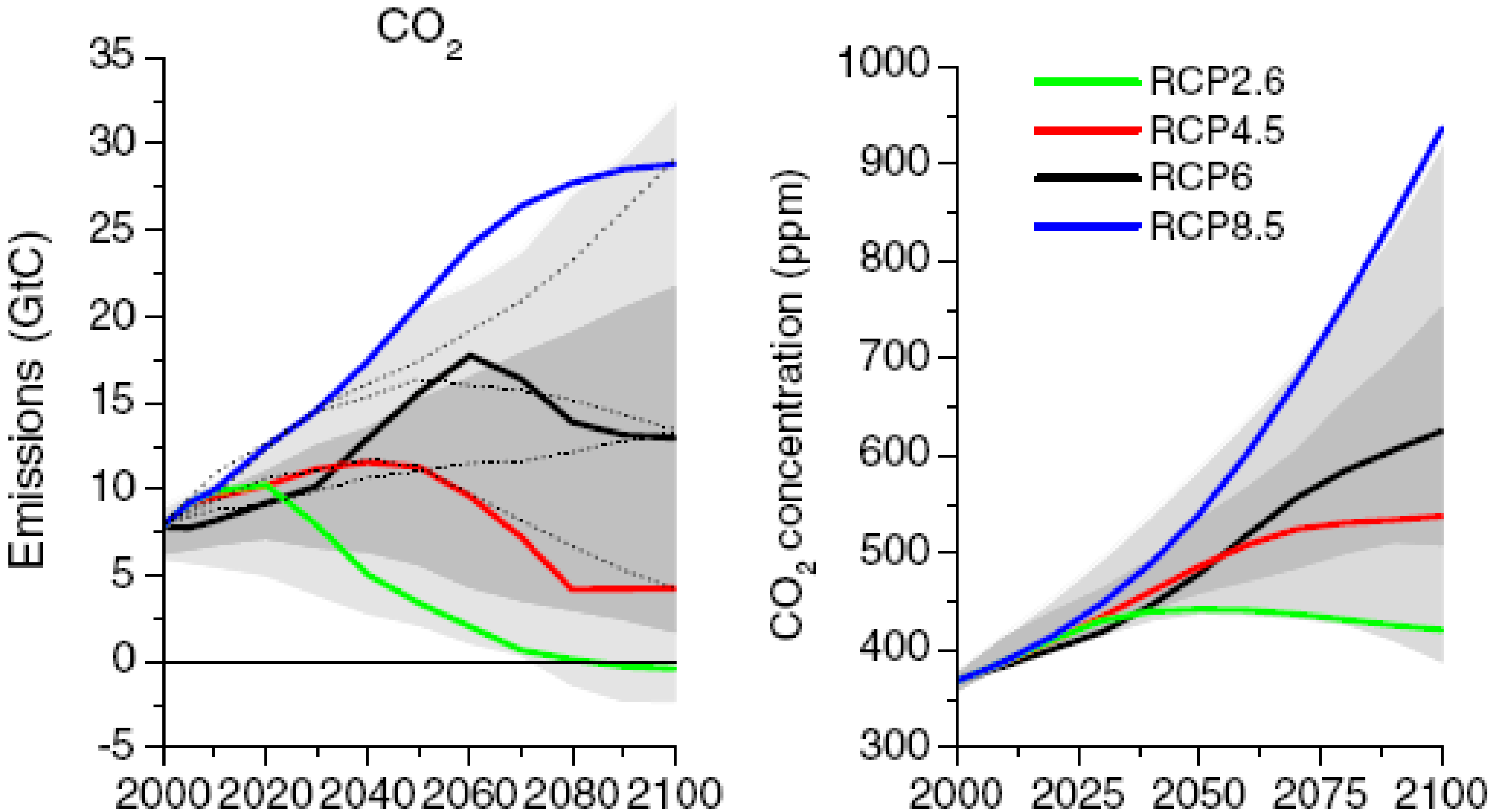
[**Kuleshov *et al.* 2010 :** *J. Geophys. Res.*, 115, D01101]
[**Callaghan and Power 2011 :** *Clim. Dyn.*, 37, 647-662]

Decreasing TC activity in N Australia (*non significant after including 2010+*)
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 ?

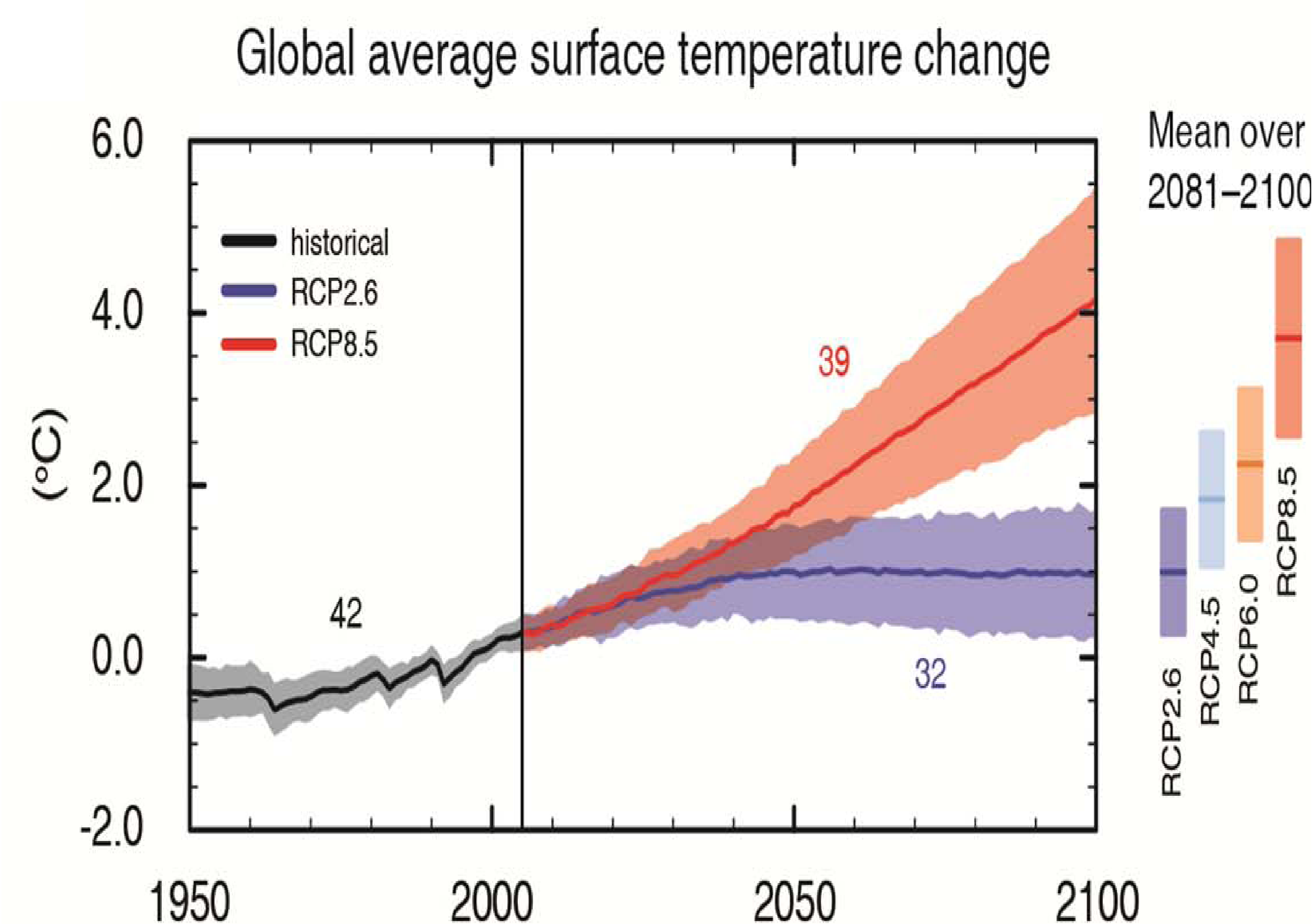
« Tropical Cyclones and Climate Change »
K.J.E. Walsh *et al.* , 2015
WIREs Clim. Change, 7, 65-89
(from *IWTC-8*, Jeju, Republic of Korea, 2-10 December 2014)
+
« Hurricanes and Climate:
The U.S. CLIVAR Working Group on Hurricanes »
K.J.E. Walsh *et al.*, 2015
Bull. Amer. Meteor. Soc., 96, 997–1017
+
« Climate Phenomena and their Relevance
for Future Regional Climate Change. 14.6.1 : Tropical Cyclones »
J.H. Christensen *et al.*, 2013
in *"Climate Change 2013: The Physical Science Basis ;*
IPCC Working Group I Contribution to AR5"
Cambridge University Press

FUTURE CLIMATE : characteristics of global warming (1)



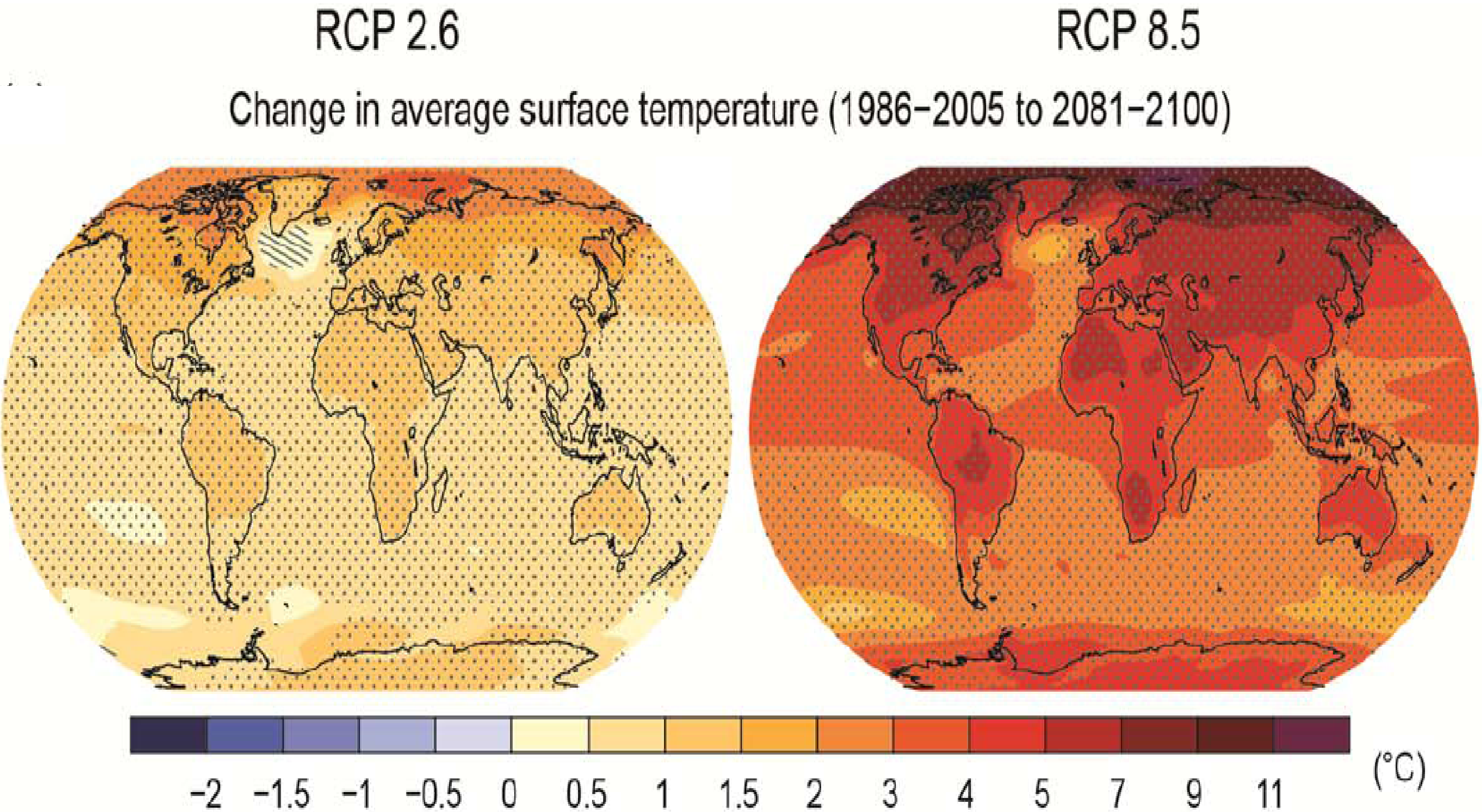
IPCC 5th Assessment Report (2013) : different « Representative Concentration Pathways (RCPs) » or socio-economic pathways translate into greenhouse gases emission and concentration scenarios.

FUTURE CLIMATE :
characteristics of global warming (2)

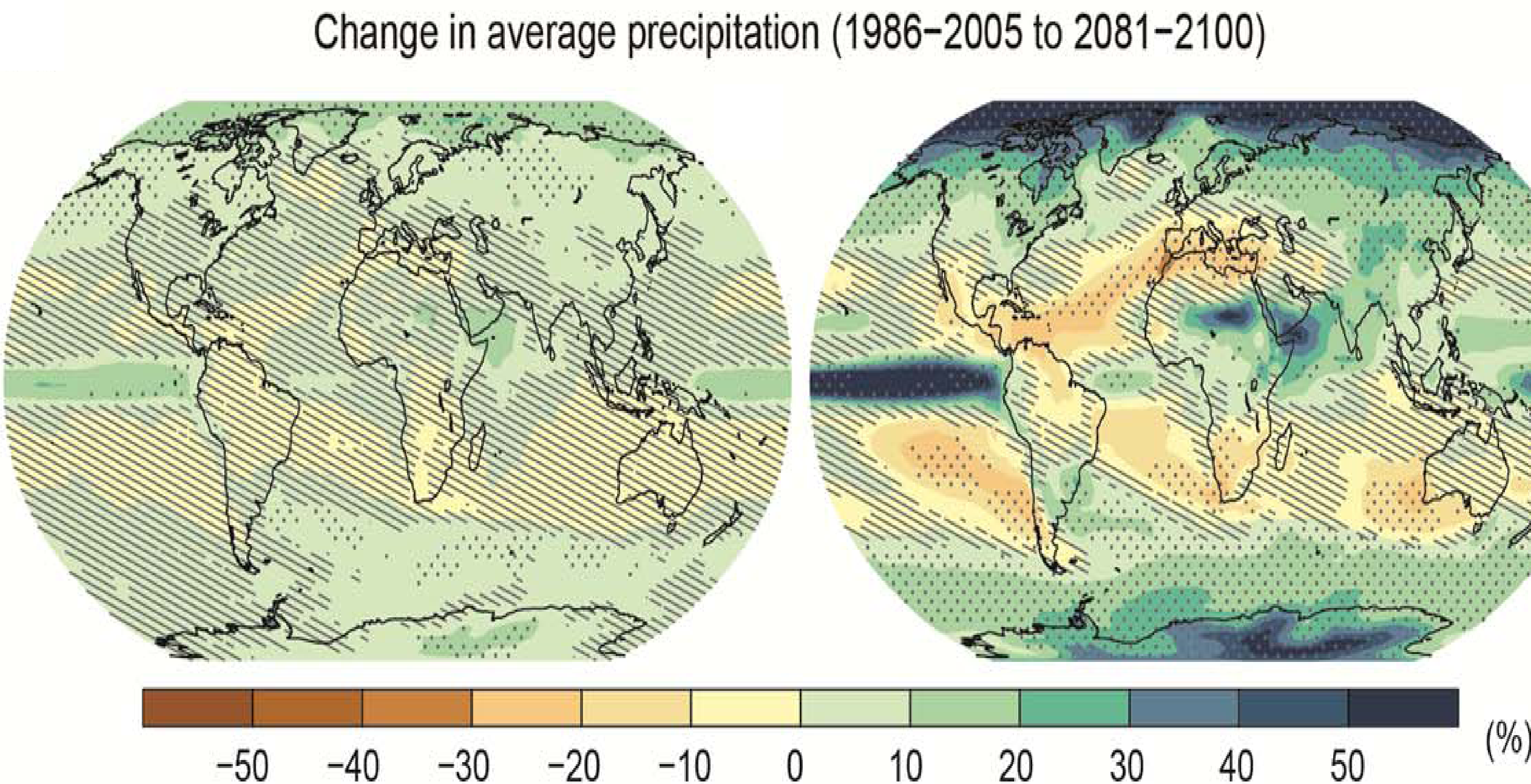


IPCC 5th Assessment Report (2013) : surface temperature increases during the 21st century are likely to be larger than historical increases …

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, …

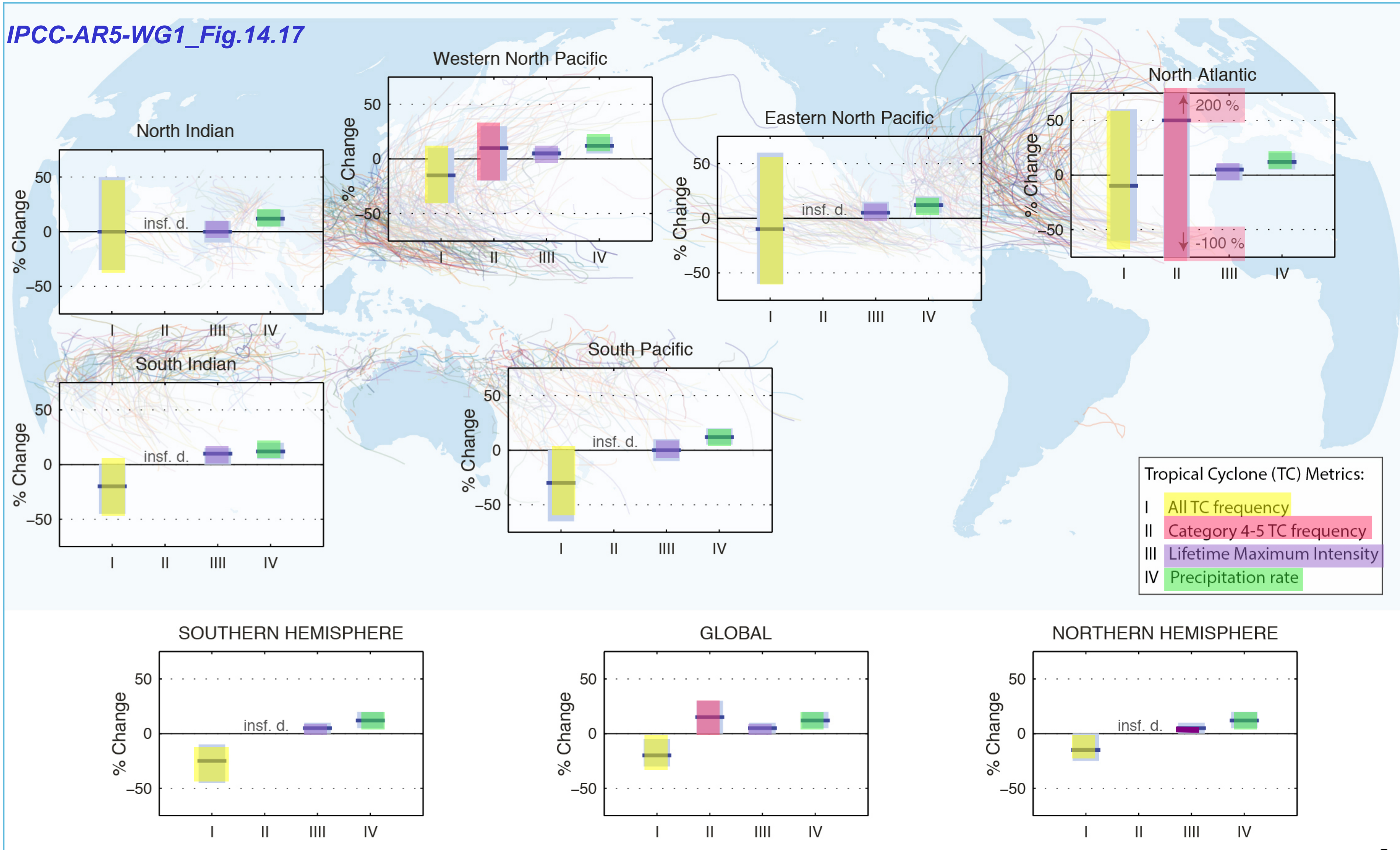
- Infer TC behaviour from large-scale GCM variables :
  - Frequency : Gray & al genesis parameter
  - Intensity : Emanuel – Holland potential intensity

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

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

- The <u>convergence of results obtained from different models provide some confidence</u> 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) ?

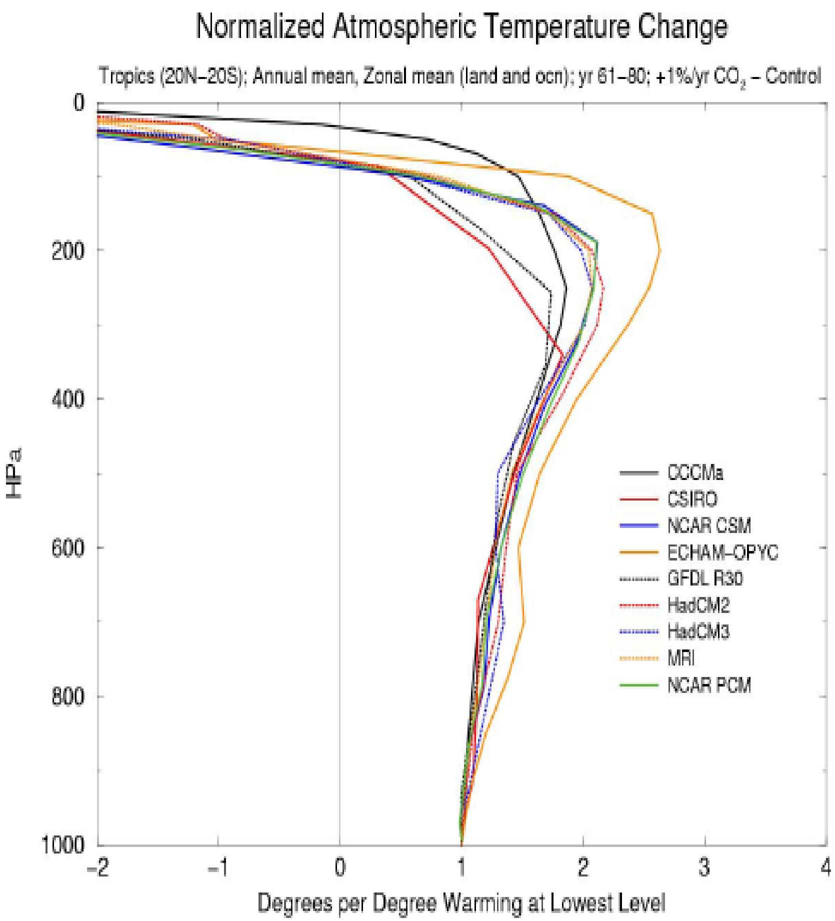
Frequency

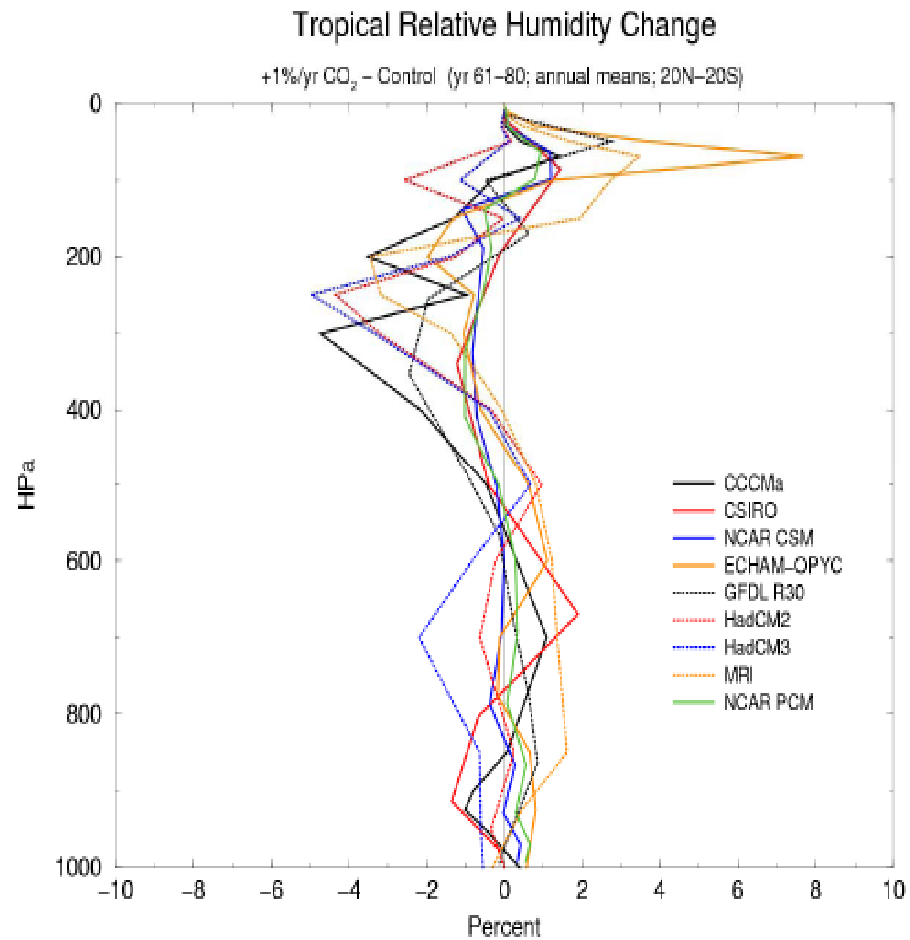
- It is likely that global mean TC frequency will either decrease or remain unchanged owing to global warming.
- For the late 21st century, model projections indicate decrease ranging from 0 to -40% globally.
- There are substantial disagreements between models for regional distributions.

- 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 enhanced warming in the tropical upper troposphere, and relatively little change in the lower tropospheric humidity.

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 correct intensity distribution for past and present conditions, show evidence for some increase of intensity.

- There is a 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.

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

- The vulnerability of coastal regions to TC storm-surge flooding is expected to increase with global-warming related sea-level rise and coastal developments with increased population at risk.

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

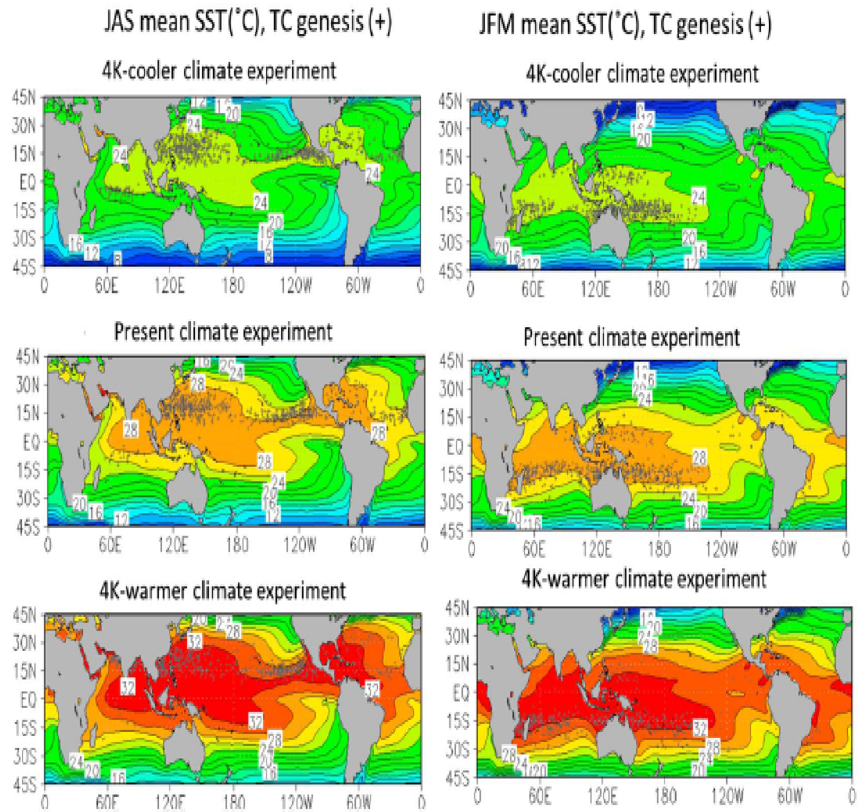
- **Some issues are not yet satisfying :**
  - When will the climate change signal dominate natural variability ?
  - Sensivity of atmospheric GCM to the regional details of forcing SST
  - No climate theory can predict the formation of TCs (location, rate)
  - TC genesis indices, trained in present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

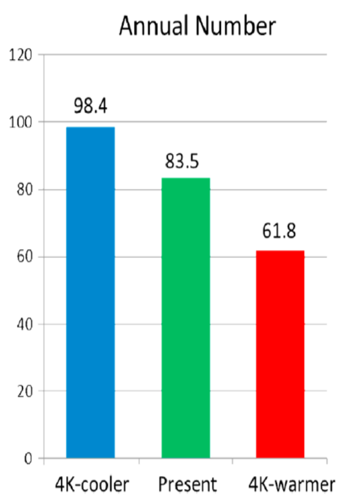
FUTURE CLIMATE : Recommendations

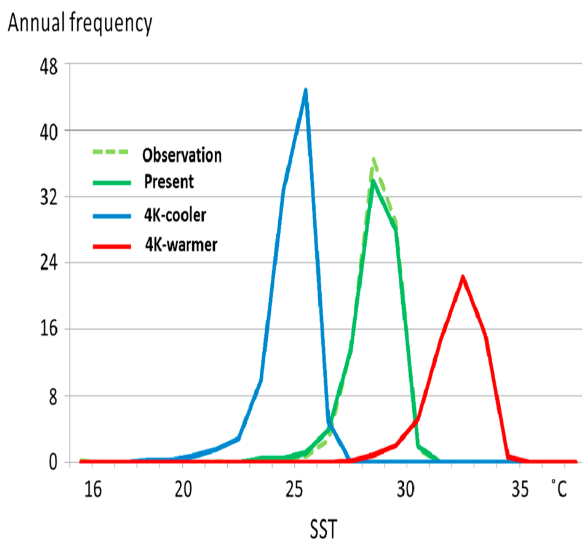
- **<u>Improved TC databases</u> :** beyond IBTrACS, creating a homogeneous long-term climate record over all basins continues to be a challenge, especially for intensity data.
  Satellite-derived datasets, beyond Dvorak method, should help to estimate the evolution of storm structure and intensity.

- **<u>Numerical models</u> :** higher horizontal resolution, improved physics (convection, air-sea interaction, aerosols, …), coupled models will provide more realistic simulations of TC activity and variability in future climate.
  Common diagnostics and tracking methods would facilitate comparisons between models.

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







TCs in other climates

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
- This is consistent with a significant decrease in TC frequency in the 4K-warmer climate.
- Changes in upward mass flux and saturation deficit could explain the reduction of TC frequency in a warmer climate