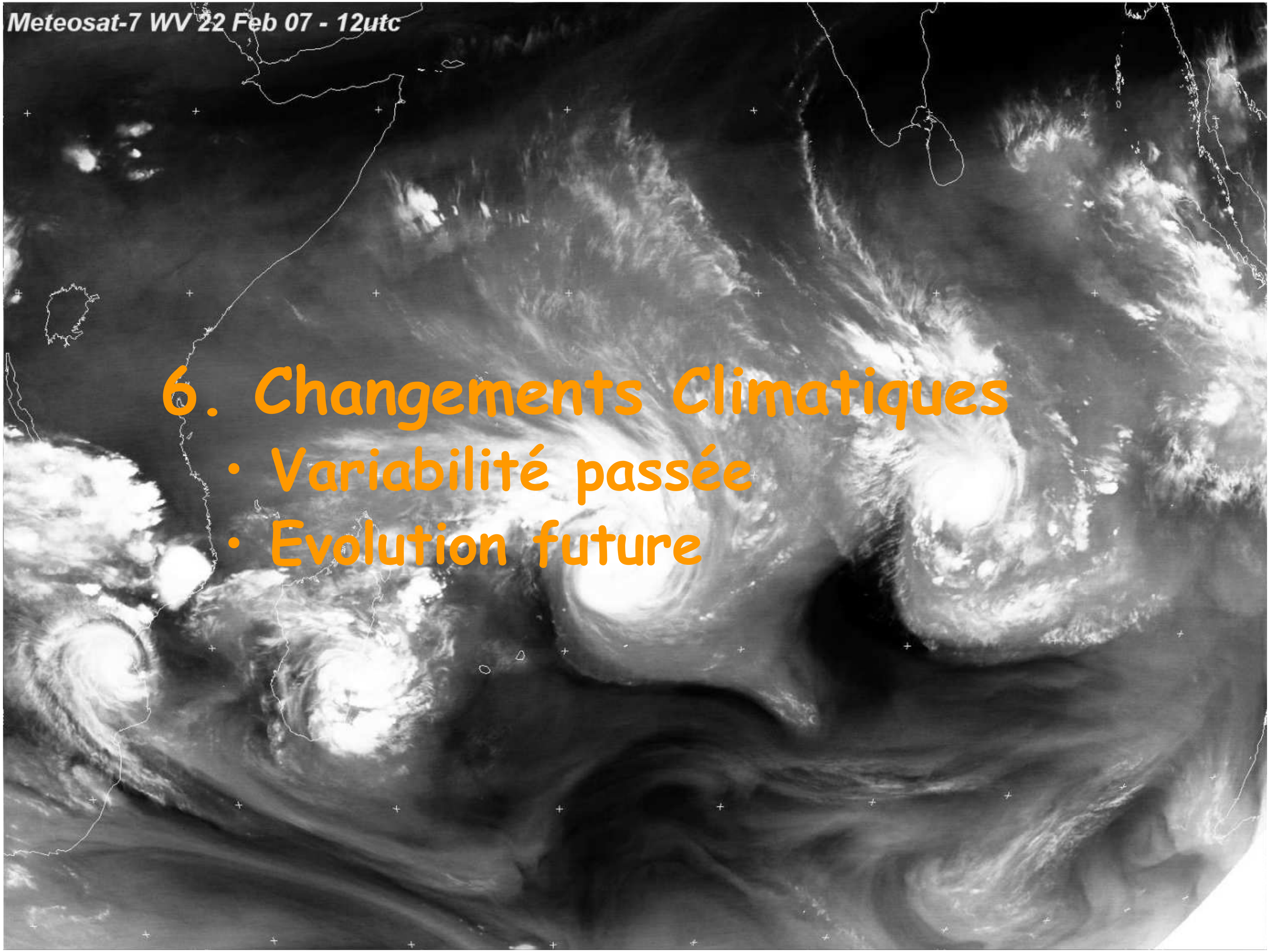


6. Changements Climatiques

- Variabilité passée
- Evolution future

Tropical cyclone and climate change

- 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

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.

Current Climate : how TCs have varied during the instrumental record

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

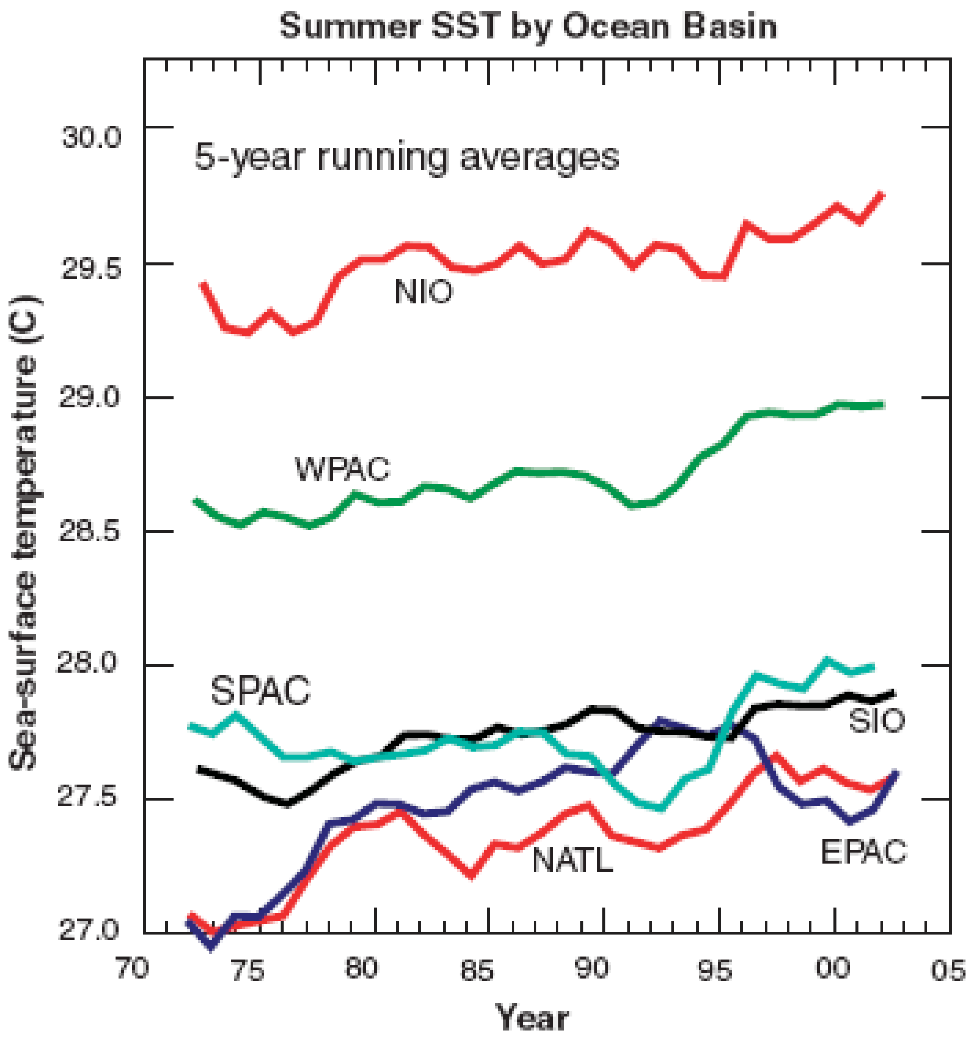
For the remaining basins (N, SW & SE Indian, SW& NE Pacific), reliable estimates of TCs only exist for the satellite era (>1970).

Before the early 1980s, the Dvorak Technique [*Dvorak, 1975*], a method which utilizes satellite imagery to assign an intensity to TCs, was only applicable to visible satellite imagery 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*], and more accurate estimates of real-time intensity 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



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

Current Climate : how TCs have varied during the instrumental record

Webster et al., 2005
[Science, 309, 1844-1846]

TS+TC activity was tabulated using estimates of the locations and intensities produced by the international warning centers from 1970-2004.

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

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

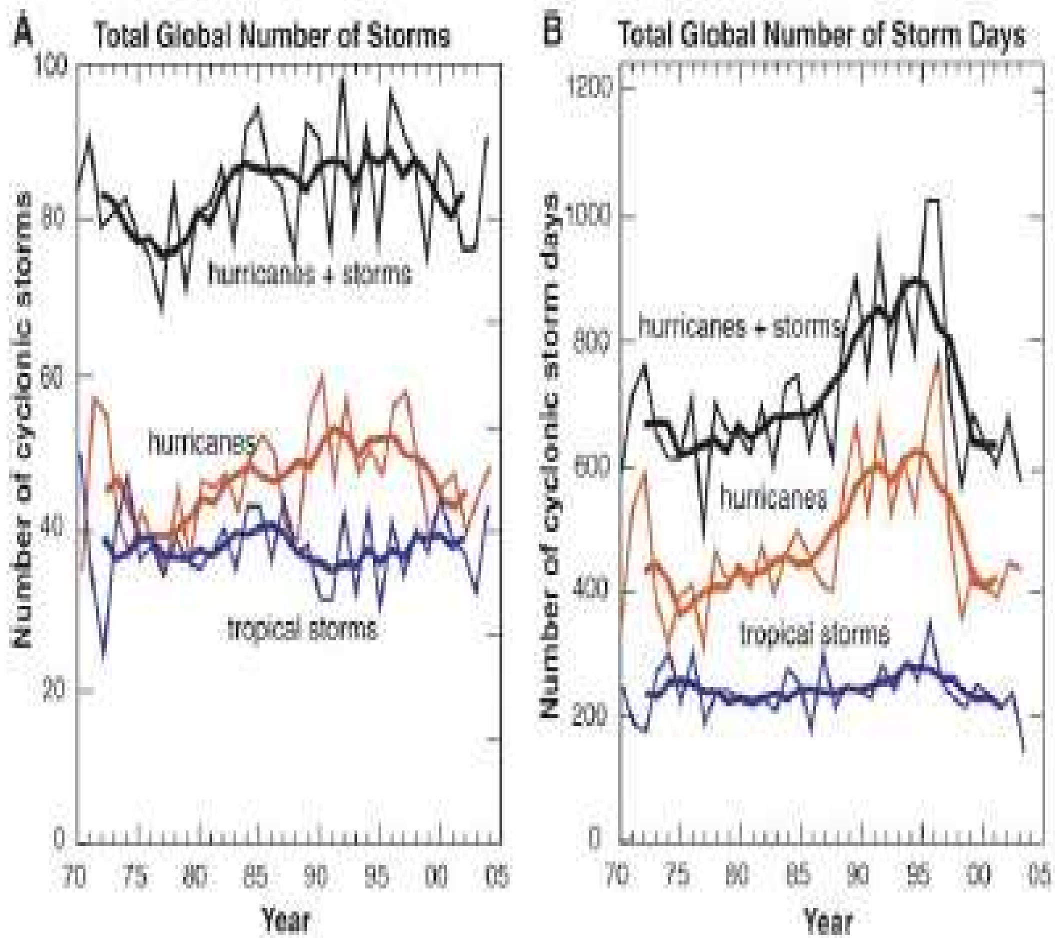


Fig. 2. Global time series for 1970–2004 of (A) number of storms and (B) number of storm days for tropical cyclones (hurricanes plus tropical storms; black curves), hurricanes (red curves), and tropical storms (blue curves). Contours indicate the year-by-year variability, and the bold curves show the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

Current Climate : how TCs have varied during the instrumental record

Webster et al. (2005)

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 N Atlantic ocean which possesses an increasing trend in frequency and duration.

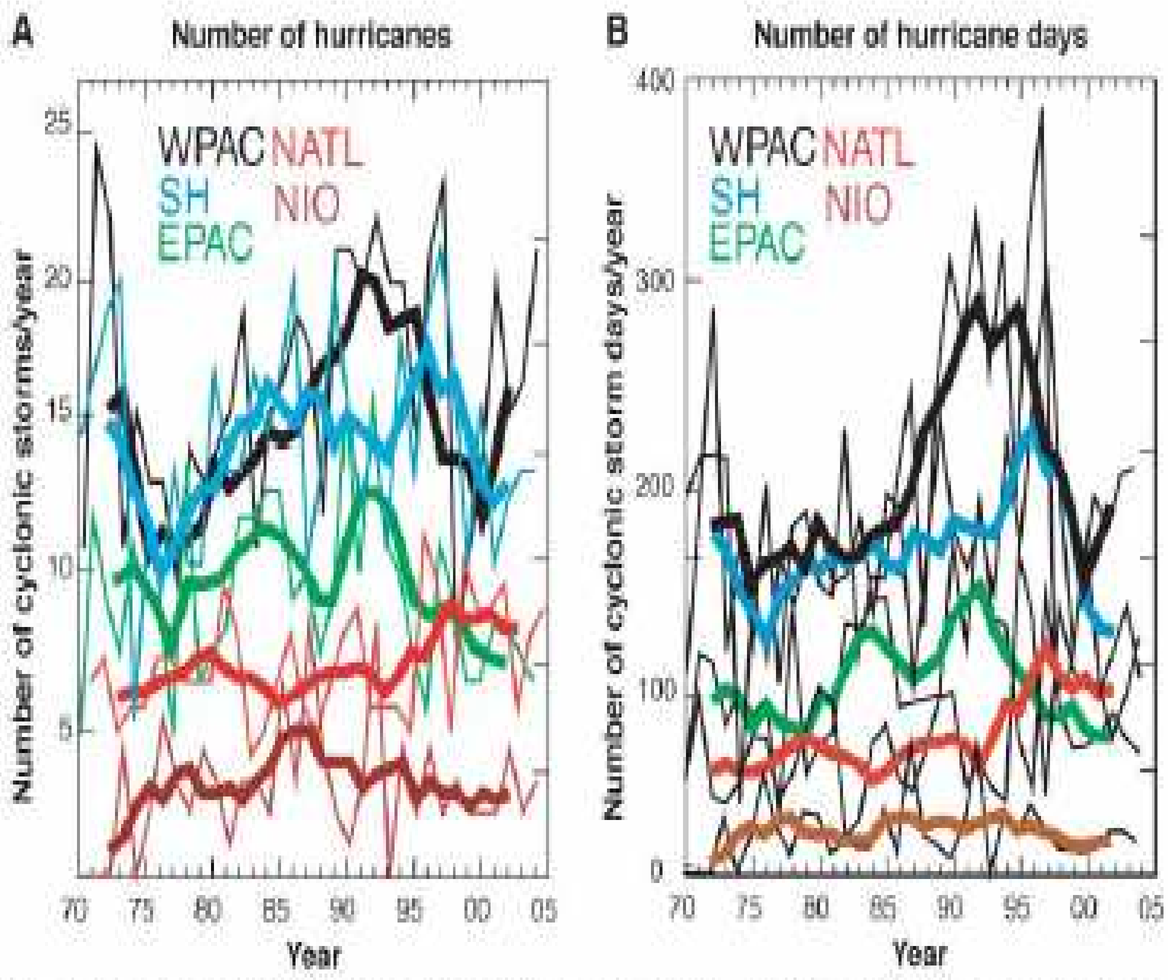
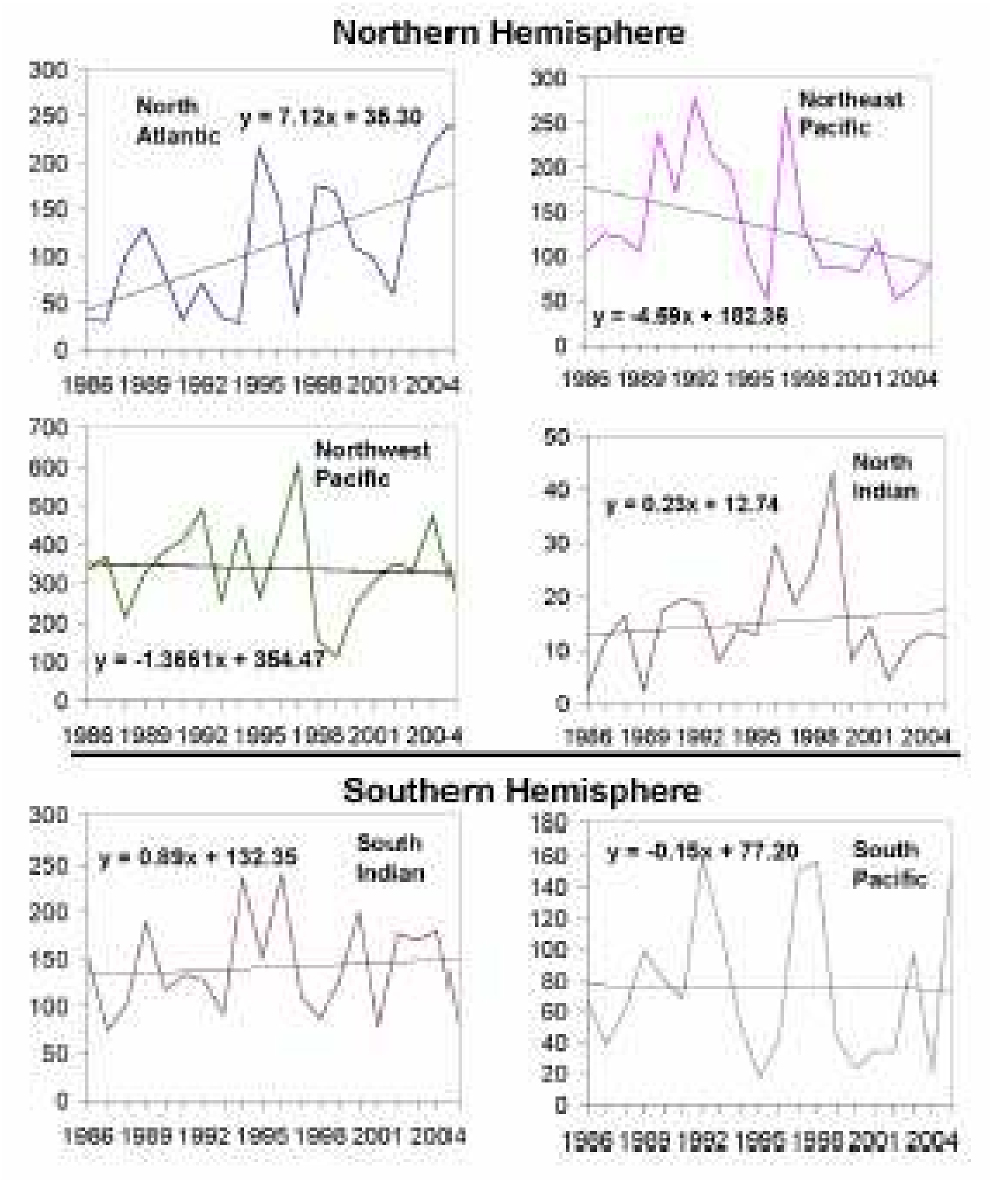


Fig. 3. Regional time series for 1970–2004 for the NATL, WPAC, EPAC, NIO, and Southern Hemisphere (SIO plus SPAC) for (A) total number of hurricanes and (B) total number of hurricane days. Thin lines indicate the year-by-year statistics. Heavy lines show the 5-year running averages.

Current Climate : how TCs have varied during the instrumental record

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 the kinetic energy generated by a storm. 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

Webster et al. (2005)
Emanuel, 2005
[Nature, 436, 686-688]

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.

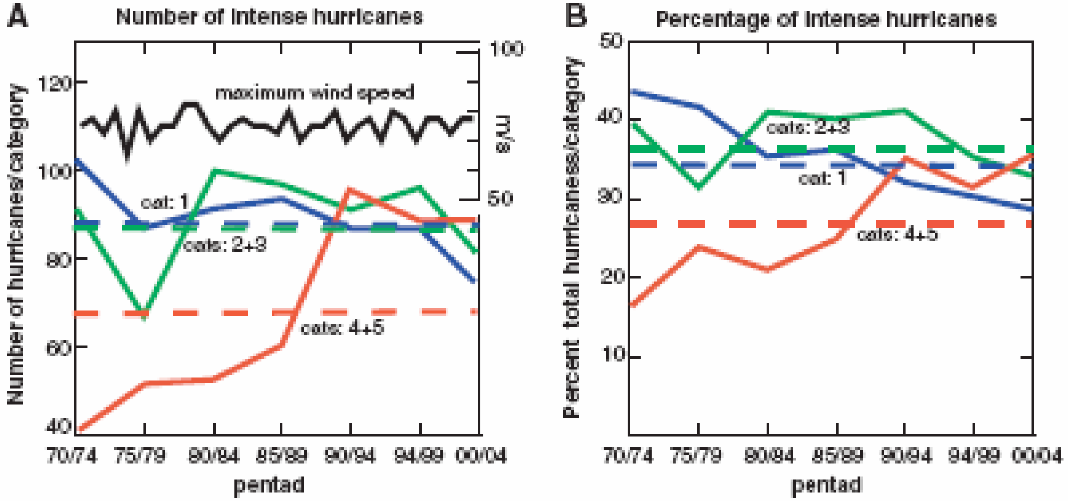


Fig. 4. Intensity of hurricanes according to the Saffir-Simpson scale (categories 1 to 5). (A) The total number of category 1 storms (blue curve), the sum of categories 2 and 3 (green), and the sum of categories 4 and 5 (red) in 5-year periods. The bold curve is the maximum hurricane wind speed observed 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.

Table 1. Change in the number and percentage of hurricanes in categories 4 and 5 for the 15-year periods 1975–1989 and 1990–2004 for the different ocean basins.

Basin	Period 1975–1989 Number	Percentage	1990–2004 Number	Percentage
East Pacific Ocean	36	25	49	35
West Pacific Ocean	85	25	116	41
North Atlantic	16	20	25	25
Southwestern Pacific	10	12	22	28
North Indian	1	8	7	25
South Indian	23	18	50	34

Current Climate : how TCs have varied during the instrumental record

Klotzbach (2006)

N Hemisphere CAT-4,5 storms have remained virtually the same between 1986-1995 and 1996-2005, and a modest increase has been observed in the S Hemisphere.

There is a statistically significant relationship between SST and ACE, as well as SST and CAT-4,5 storms, for both the N Atlantic and the NE Pacific (25-30% variance explained). Correlation for the other 4 TC basins is actually slightly negative.

Table 2. Category 4–5 Hurricanes by Ten-Year Periods (1986–1995, 1996–2005) for Individual TC Basins, the North Atlantic and the Northeast Pacific, the Northern Hemisphere, the Southern Hemisphere, and the Globe

Basin	1986–1995	1996–2005	Ratio (1996–2005/ 1986–1995)
North Atlantic	10	25	250%
Northeast Pacific	37	23	62%
N. Atlantic + NE Pacific	47	48	102%
Northwest Pacific	75	76	101%
North Indian	3	4	133%
South Indian	26	36	138%
South Pacific	13	16	123%
Northern Hemisphere	125	128	102%
Southern Hemisphere	39	52	133%
Global	164	180	110%

Table 3. Correlations Between ACE and SSTs and Category 4–5 Hurricanes and SSTs for All TC Basins[a]

Basin	Correlation with ACE	Correlation with Cat. 4–5 Hurricanes
North Atlantic	**0.57**	**0.39**
Northeast Pacific	**0.58**	**0.59**
Northwest Pacific	−0.28	−0.11
North Indian	−0.07	−0.29
South Indian	−0.32	−0.18
South Pacific	−0.38	−0.20

Current Climate : how TCs have varied during the instrumental record

Trenberth & Shea, 2006
[GRL, 33, L12074]
Mann & Emanuel, 2006
[Eos, 87, 233-241]

Multiple regression model to the SST anomalies for the tropical N Atlantic :

$T_{TNA} = T_{Global} + T_{ENSO} + T_{AMO} + \varepsilon$

- About 0.45°C of the SSTA in the N Atlantic is common to global SST and is thus linked to global warming.
- Additional 0.2°C stemmed from effects of ENSO.
- A revised AMO index accounts between 0.1 and 0.2°C.

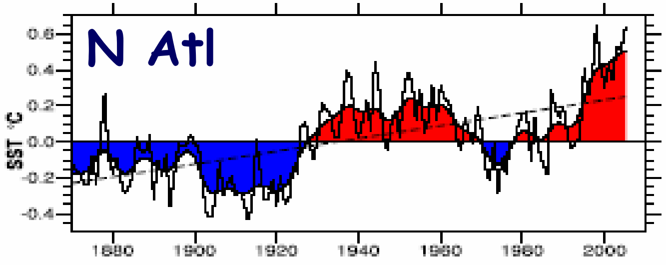


Figure 1. Annual SST anomalies averaged over the North Atlantic (0 to 60°N, 0 to 80°W) for 1870–2005, relative to 1901 to 1970 (°C).

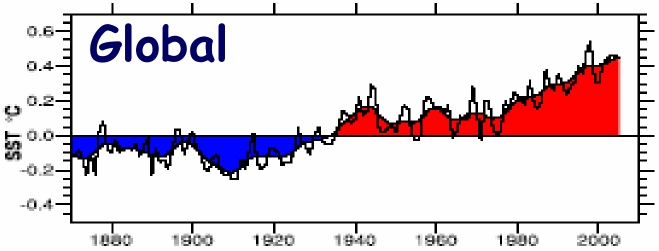


Figure 2. Annual SST anomalies averaged over the global oceans 60°N to 60°S for 1870–2005, relative to 1901 to 1970 (°C). The heavy line with fill is the low-pass filter.

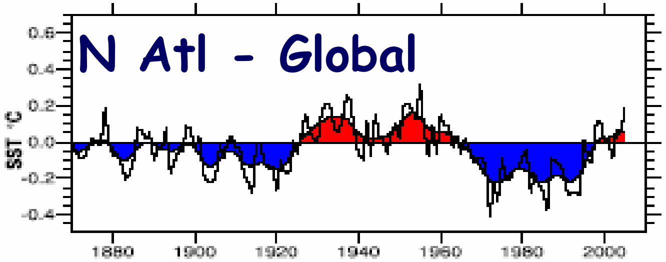


Figure 3. Annual SST anomalies averaged over the North Atlantic (0 to 60°N, 0 to 80°W) for 1870–2005, relative to 1901 to 1970 (°C) but with the global mean SST (Figure 2) removed. The heavy line with fill from the low-pass filter depicts the revised AMO.

Current Climate : how TCs have varied during the instrumental record

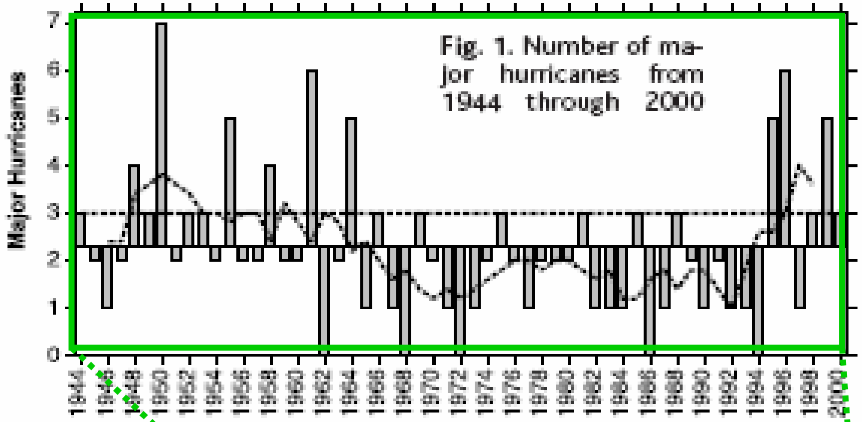
Goldenberg et al., 2001

[Science, 293, 474-479]

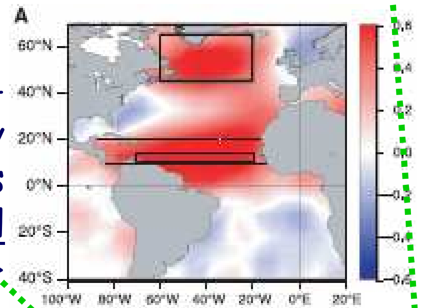
Non-ENSO SST variability is dominated by the "Atlantic Multidecadal Oscillation". Its positive phase has warm SSTs in the N Atlantic from 0° to 30°N and from 40° to 70°N.

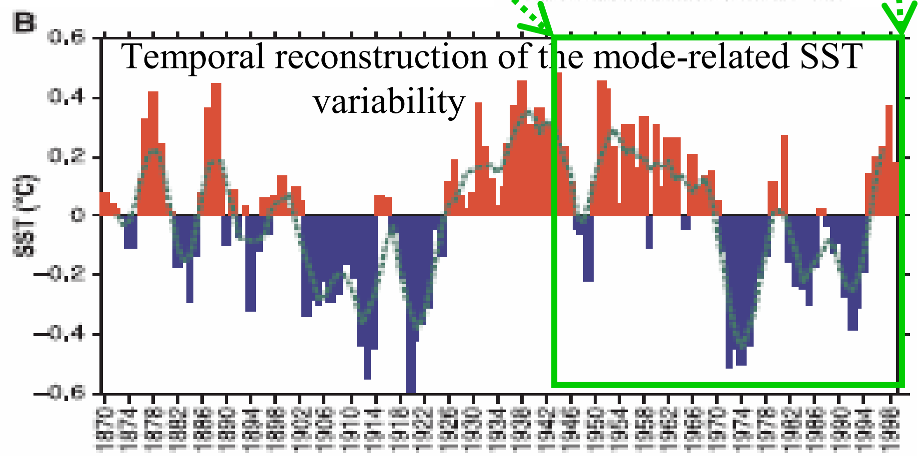
The time series for the AMO and major hurricanes show similar shapes, with :

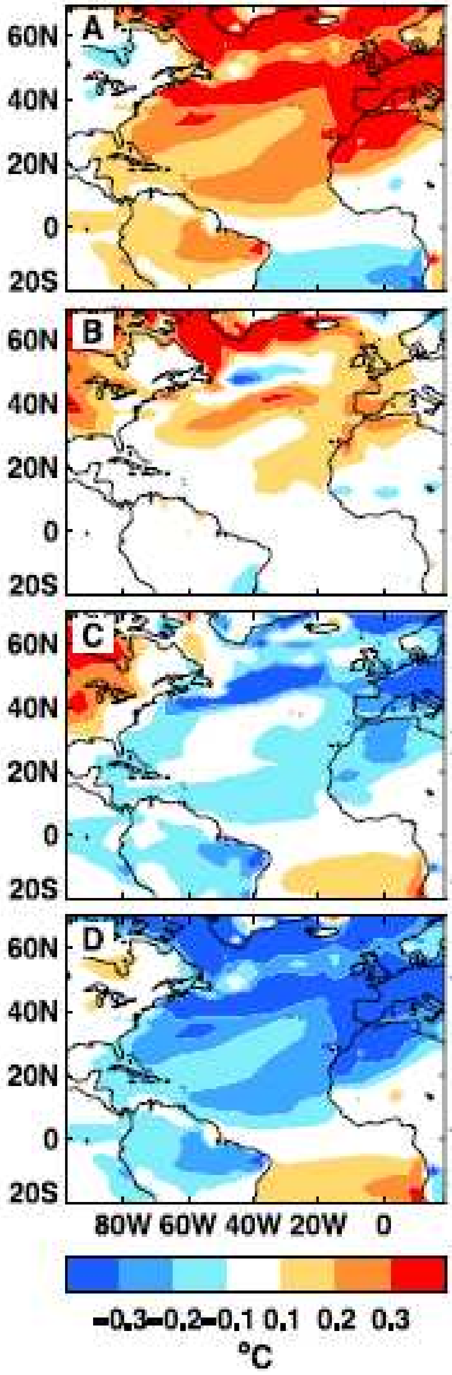
- 1945-1970 : positive AMO, large TC activity ;
- 1970-1995 : negative AMO, weak TC activity ;
- 1995-present *(2020?)* : positive AMO, large TC activity.



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





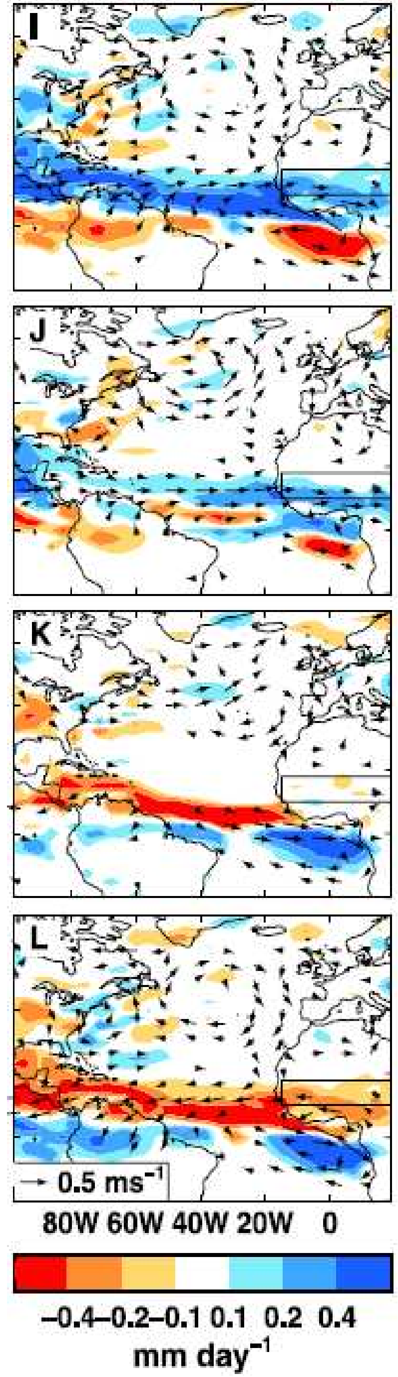


Knight et al., 2006
[GRL, <u>33</u>, L17706]

A 1400-yr simulation of the HadCM3 climate model produces a realistic long-lived AMO as part of its internal climate variability in the North Atlantic region for model years 400 to 900

(←) <u>surface air temperature</u>

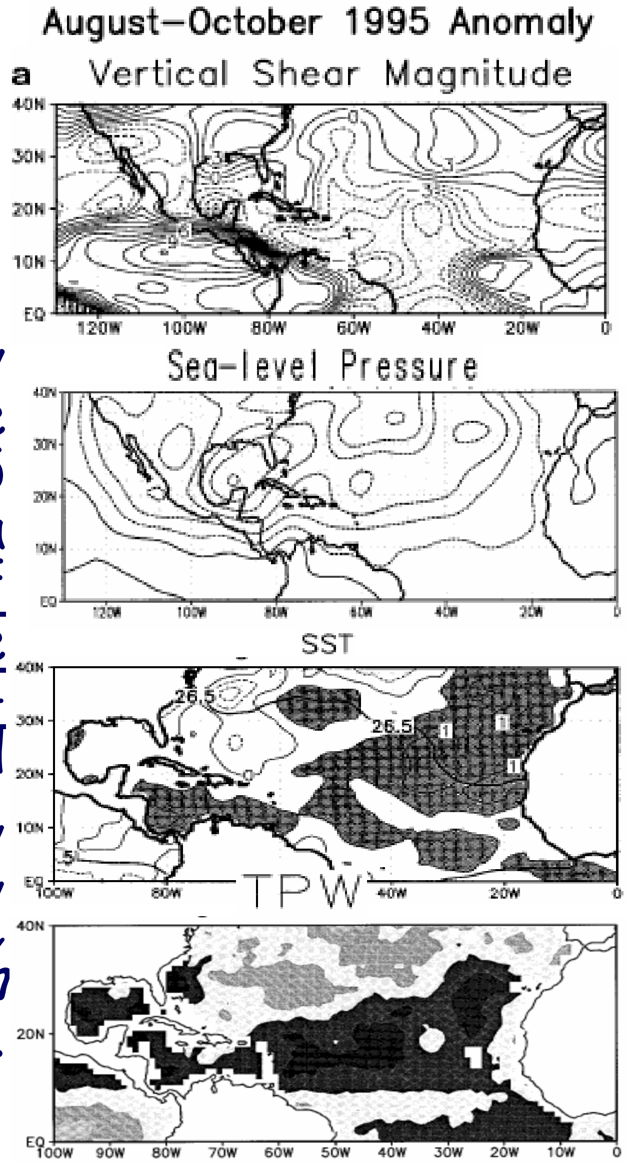
decadal mean <u>precipitation</u> + 850 hPa <u>wind anomalies</u> (→)

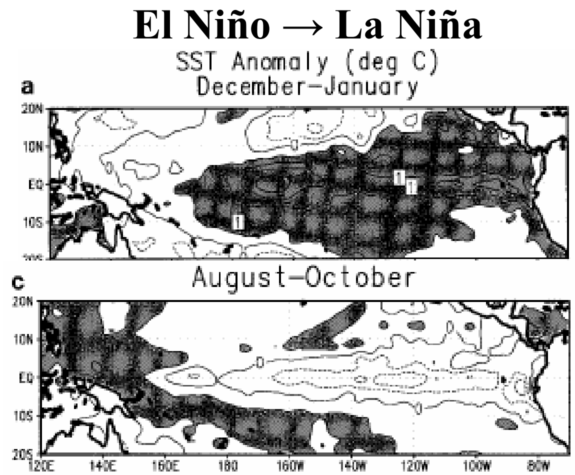


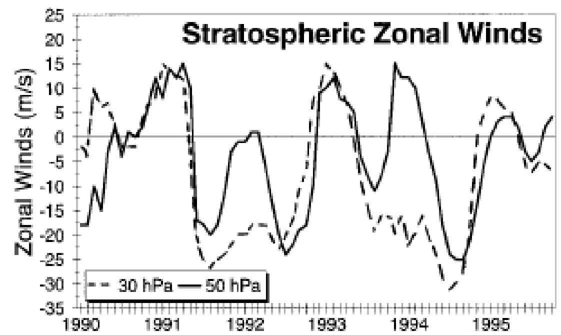
Current Climate : how TCs have varied during the instrumental record

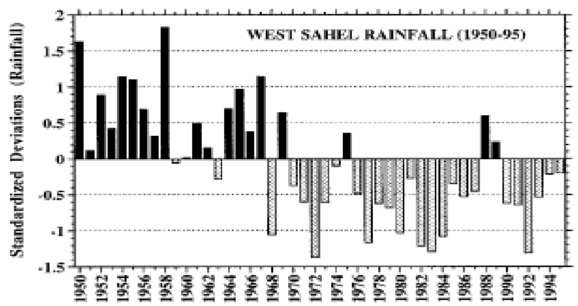
Landsea et al., 1999
[Climatic Change, 42, 89-129]

The sharply increased hurricane activity during 1995 is attributed to a juxtaposition of virtually all the favorable large-scale features (wind shear, SLP, SST, precipitable water, ENSO, *QBO*, *W African monsoon*).







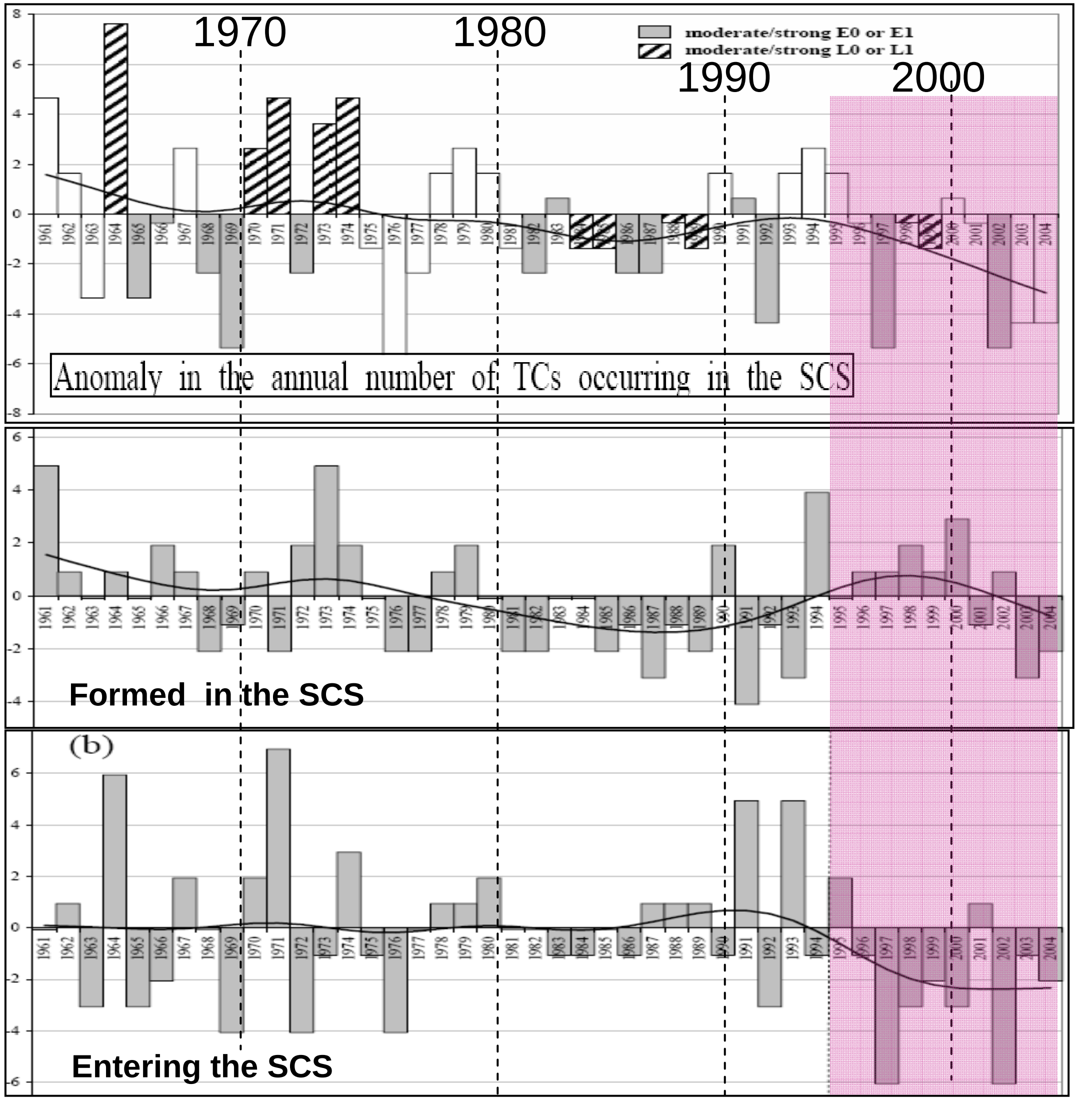


Current Climate : how TCs have varied during the instrumental record

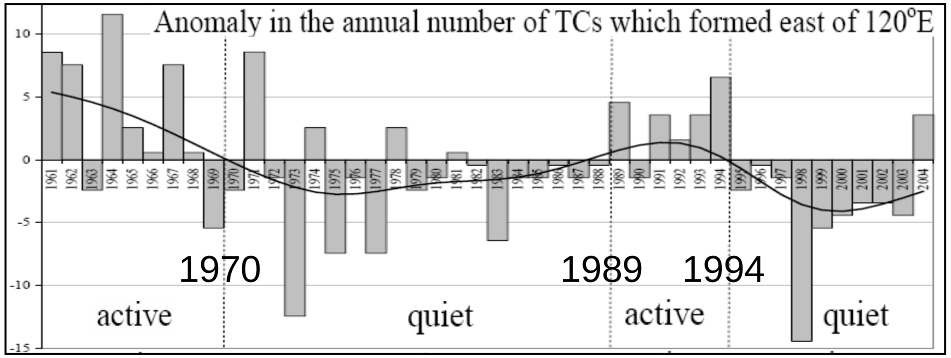
Wu et al., 2006
[EOS, 87, 537-538]

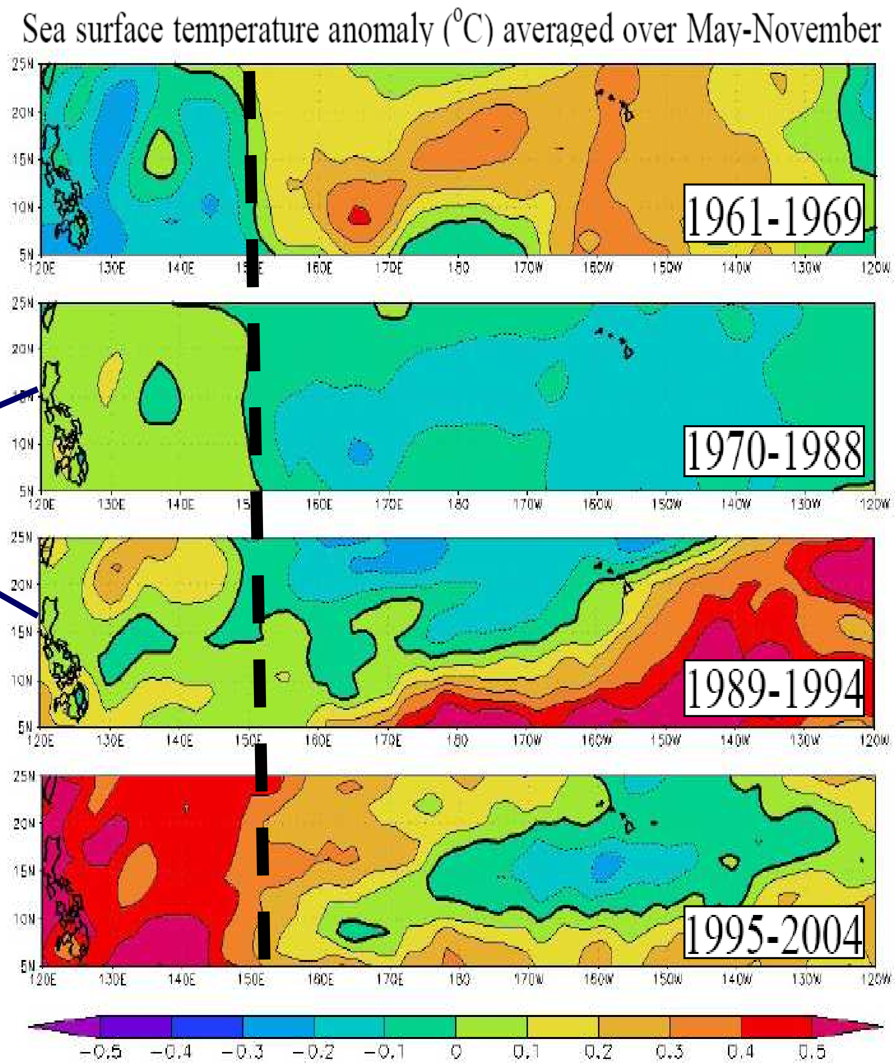
TCs occurring in the **South China Sea (SCS : 10-25N , 105-120E)** result from :

- TCs forming in the SCS;
- TCs forming E of 120°E, then entering the SCS
- The rapid drop of TCs in SCS since the mid-1990 is mainly due to a decrease of the second category



Current Climate : how TCs have varied during the instrumental record





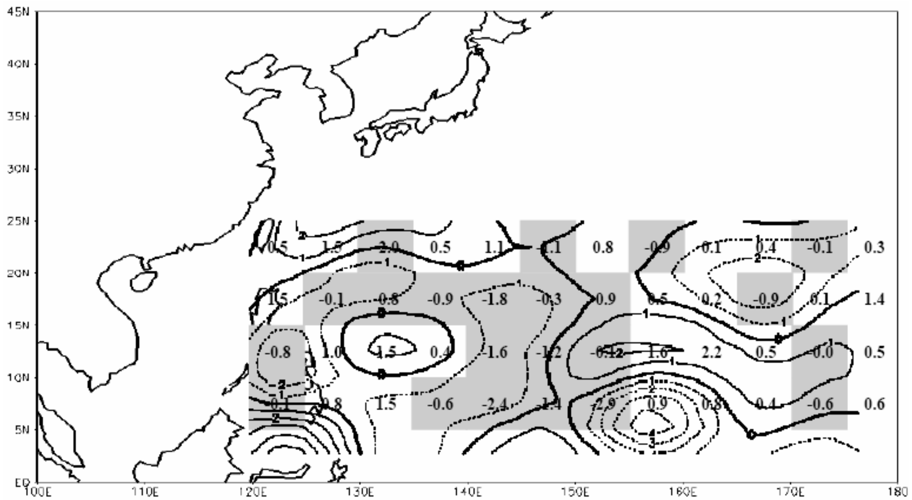
Quiet phases

$SSTA_{W\ of\ 155°E} > 0$, $SSTA_{E\ of\ 155°E} < 0$

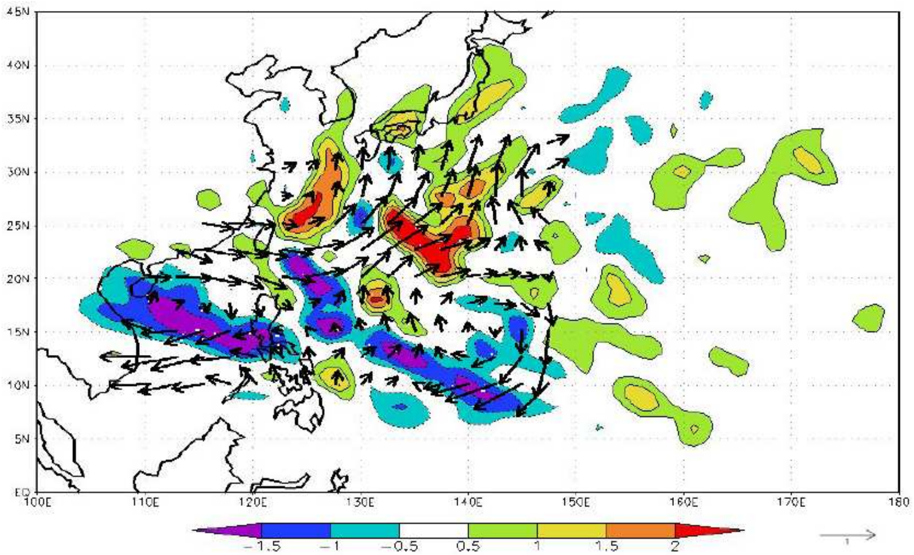
[≈ La Niña]

→ Perturbed Walker circulation with low-level anticyclonic & upper-level cyclonic circulations = unfavourable conditions for tropical cyclogenesis at 120-155 °E

Current Climate : how TCs have varied during the instrumental record



Grey : fewer TCs formation in 1995-2004
Contours : low-level vorticity anomaly (10^{-6} s^{-1})

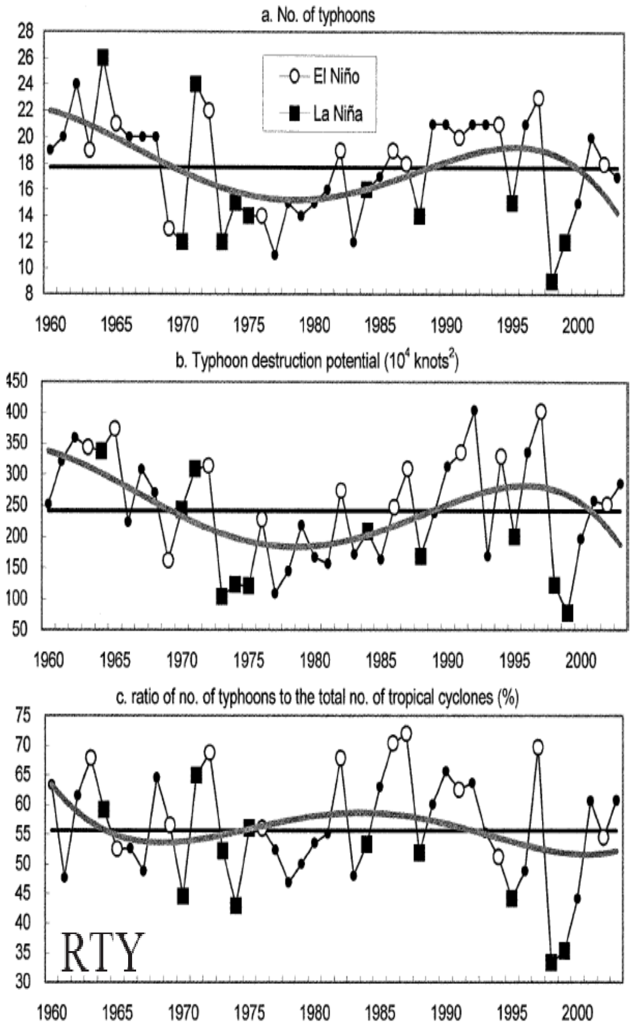


Contours : Anomaly in TC track density
Arrows : Anomaly of the 500 hPa flow

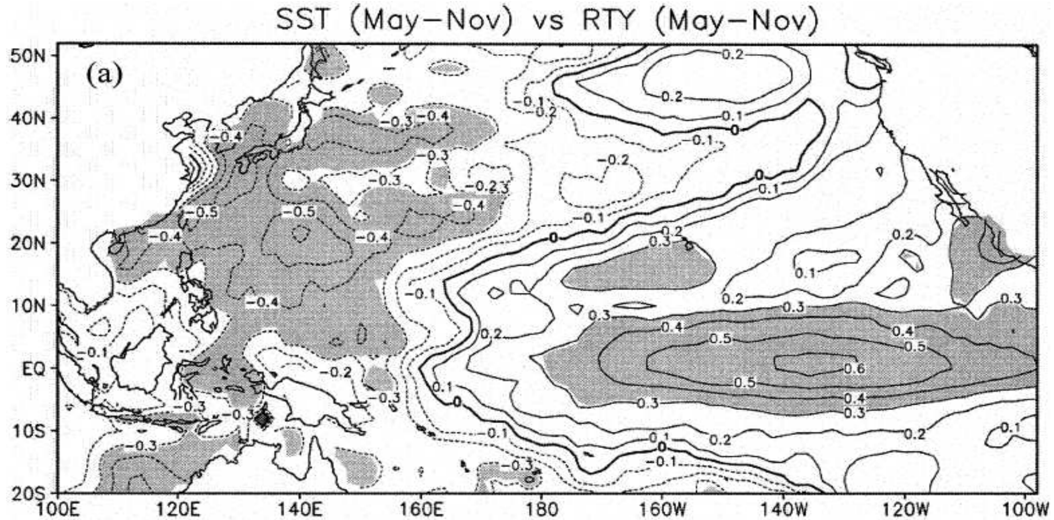
Fewer TCs forming E of 120°E move towards and enter the SCS, in relation with the anomalous mid-tropospheric flow. Instead, most of them are steered towards Japan.

Current Climate : how TCs have varied during the instrumental record

Western North Pacific Typhoon Activity



Spatial distribution of correlation coefficients between RTY and SST in the period May–Nov



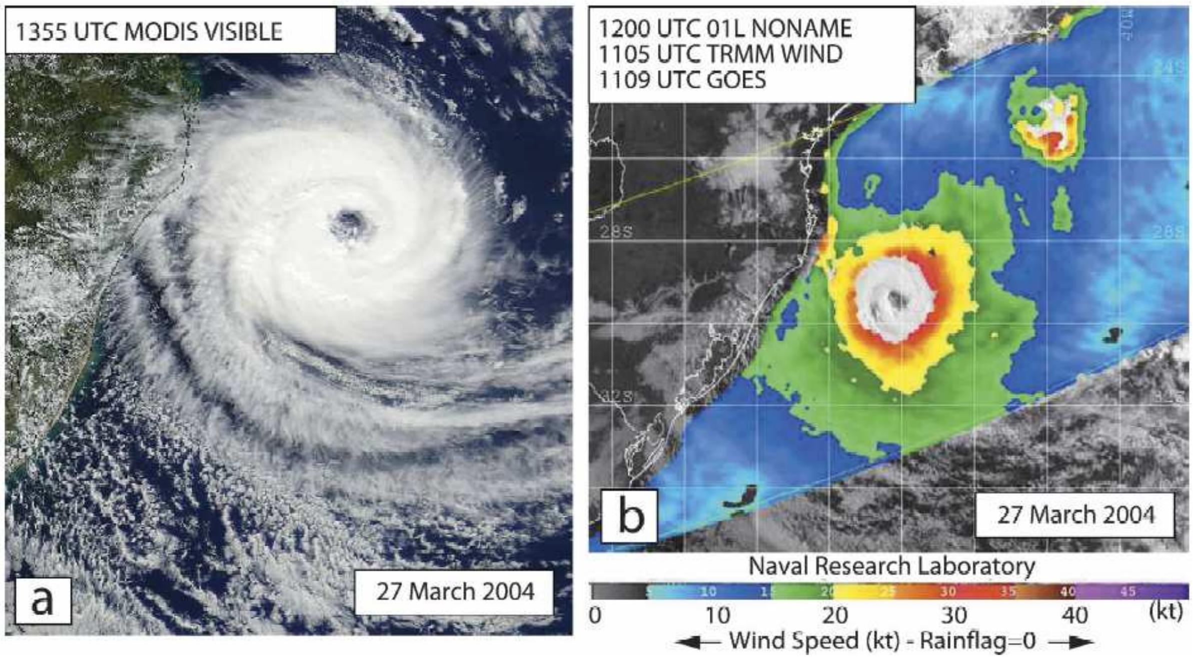
Chan & Liu 2004 *[J. Climate, 17, 4590-460]*

- The average typhoon activity in NW Pacific shows <u>no significant relationship with local SST</u>, but increases when the <u>SST over the equatorial E Pacific is above normal</u> (i.e. El Niño years) ;
- The <u>interannual variations of typhoon activity is mostly controlled by large-scale ENSO-related dynamic and thermodynamic factors</u> (low-level vorticity, wind shear, moist static energy, …)

Current Climate : how TCs have varied during the instrumental record

Pezza & Simmonds, 2006 *[8th ICSHMO]*
Mc Taggart-Cowan et al., 2006 *[Mon. Wea. Rev., 134, 3029–3053]*

In March 2004, the first-ever reported TC in the South Atlantic hit southern Brazil. Catarina initiated as an Extra-Tropical Cyclone in a frontal system, undergoing Tropical Transition two days later under persistent low vertical wind shear over near-average SST.
The trend towards an increasingly positive phase of the "Southern Annular Mode" in global warming scenarios could favor similar conditions.



« Statement on Tropical Cyclones and Climate Change »

[6th WMO Int.Workshop on Tropical Cyclones, 2006]

+

« Tropical cyclones and climate change »

Knutson *et al.*, 2010

[*Nature Geosci.*, 3, 157-163]

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« Tropical cyclone and climate change : A review »

Knutson *et al.*, 2010

[in *"Global Perspectives on Tropical Cyclones: From Science to Mitigation"*, World Scientific Publishing Co.]

+

« TC activity on climate timescales »

Knutson *et al.*, 2010

[*7th WMO Int. Workshop on Tropical Cyclones*]

Detection & attribution : Tropical cyclone frequency

- In terms of global tropical cyclone frequency, it was concluded that there was no significant change in global tropical storm or hurricane numbers from 1970 to 2004, nor any significant change in hurricane numbers for any individual basin over that period, except for the Atlantic.

- Thus, considering available observational studies, and after accounting for potential errors arising from past changes in observing capabilities, it remains uncertain whether past changes in tropical cyclone frequency have exceeded the variability expected through natural causes.

Detection & attribution : Tropical cyclone intensity

- A substantial global increase in the number of the most severe tropical cyclones has been reported from 1975 to 2004. Other studies contested this finding, based on concerns about data quality and the short record-length relative to multidecadal variability.

- The short time period of the data does not allow any definitive statements regarding separation of anthropogenic changes from natural decadal variability or the existence of longer-term trends and possible links to greenhouse warming.

Detection & attribution : Tropical cyclone rainfall

- Atmospheric moisture content has increased in recent decades in many regions. This should increase rainfall rates in systems (such as tropical cyclones) where moisture convergence is an important component of the water-vapour budget.

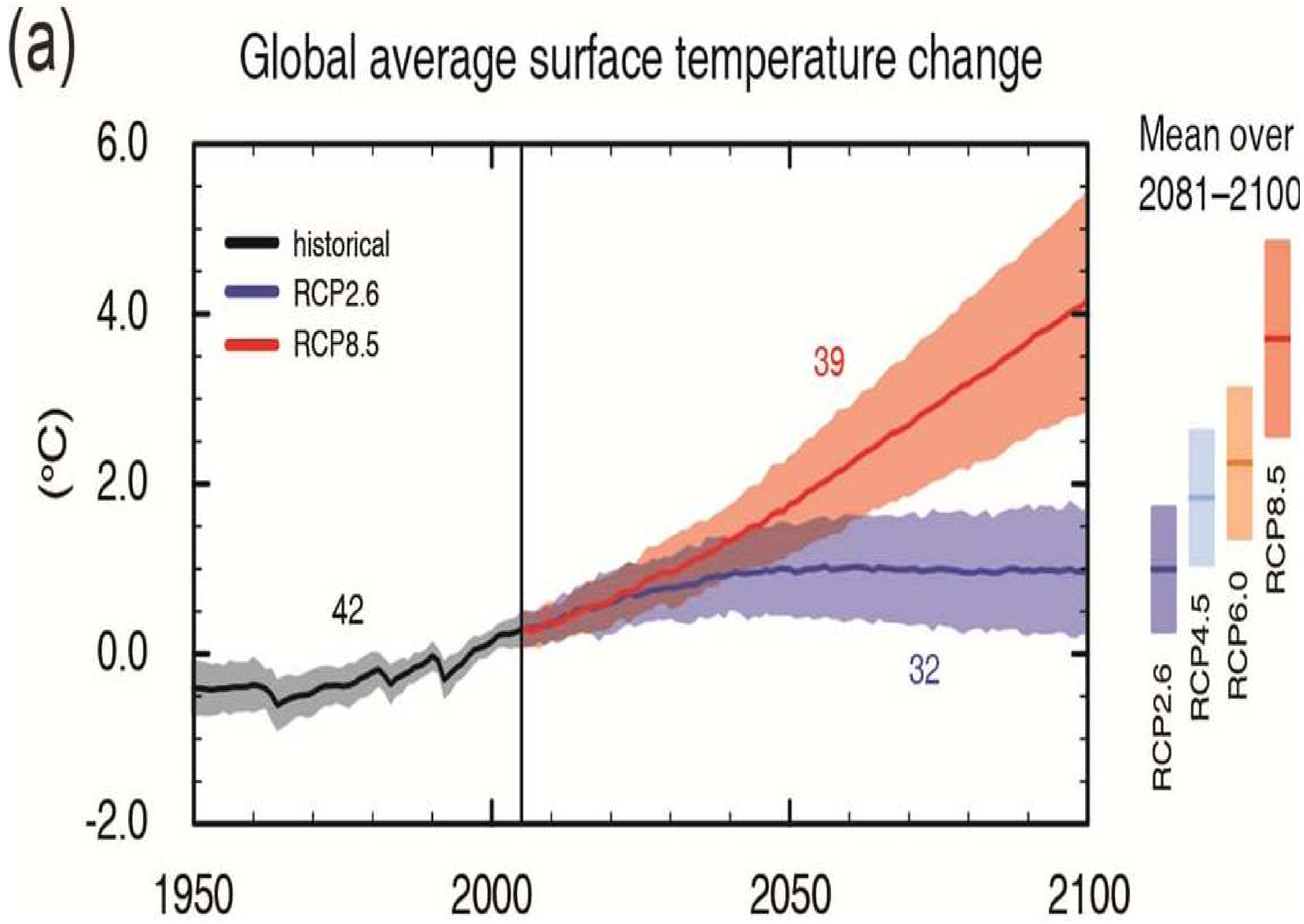
- Satellite-based studies report an increase in the occurrence of heavy-rain events, generally in the tropics during 1979–2003, and also an increase during warm periods of interannual variability. A number of studies of land-based precipitation data have identified increasing trends in the frequency of very heavy precipitation events.

- None of these studies isolate tropical cyclone precipitation rates.

Detection & attribution :
Tropical cyclone genesis, track, duration

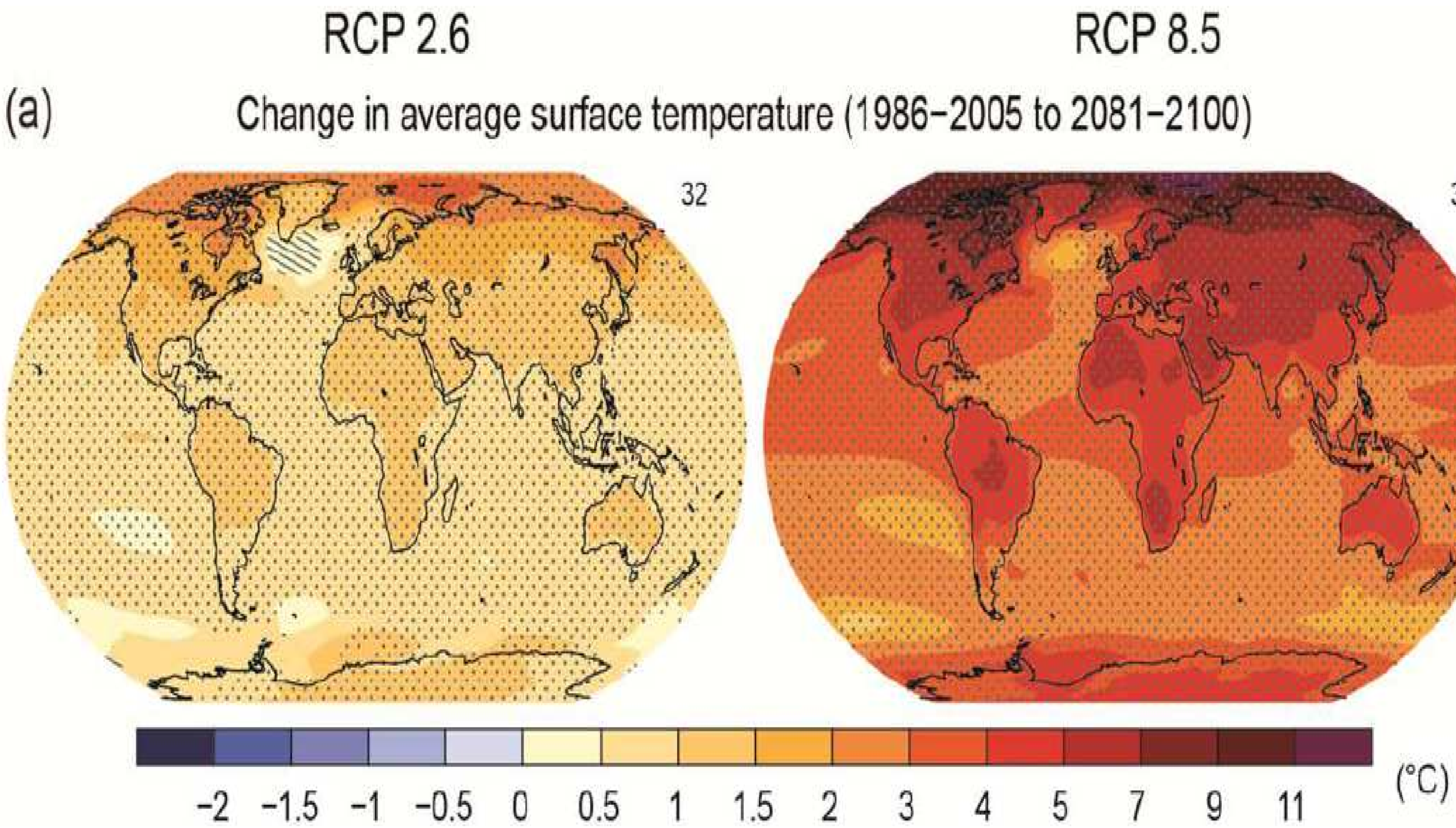
- There is no conclusive evidence that any observed changes in tropical cyclone genesis, tracks, and duration exceed the variability expected from natural causes.
- At least some of the increase in the eastern Atlantic and in short-lived systems are likely attributable to observing-system change, rather than climate change.
- Sea level has risen globally by about 0.17 m during the twentieth century. There also has been marked degradation of coastal wetlands. However, no detectable increase in storm-surge flooding from tropical cyclones has been established.

<u>Future Climate</u> : how TCs will vary ?

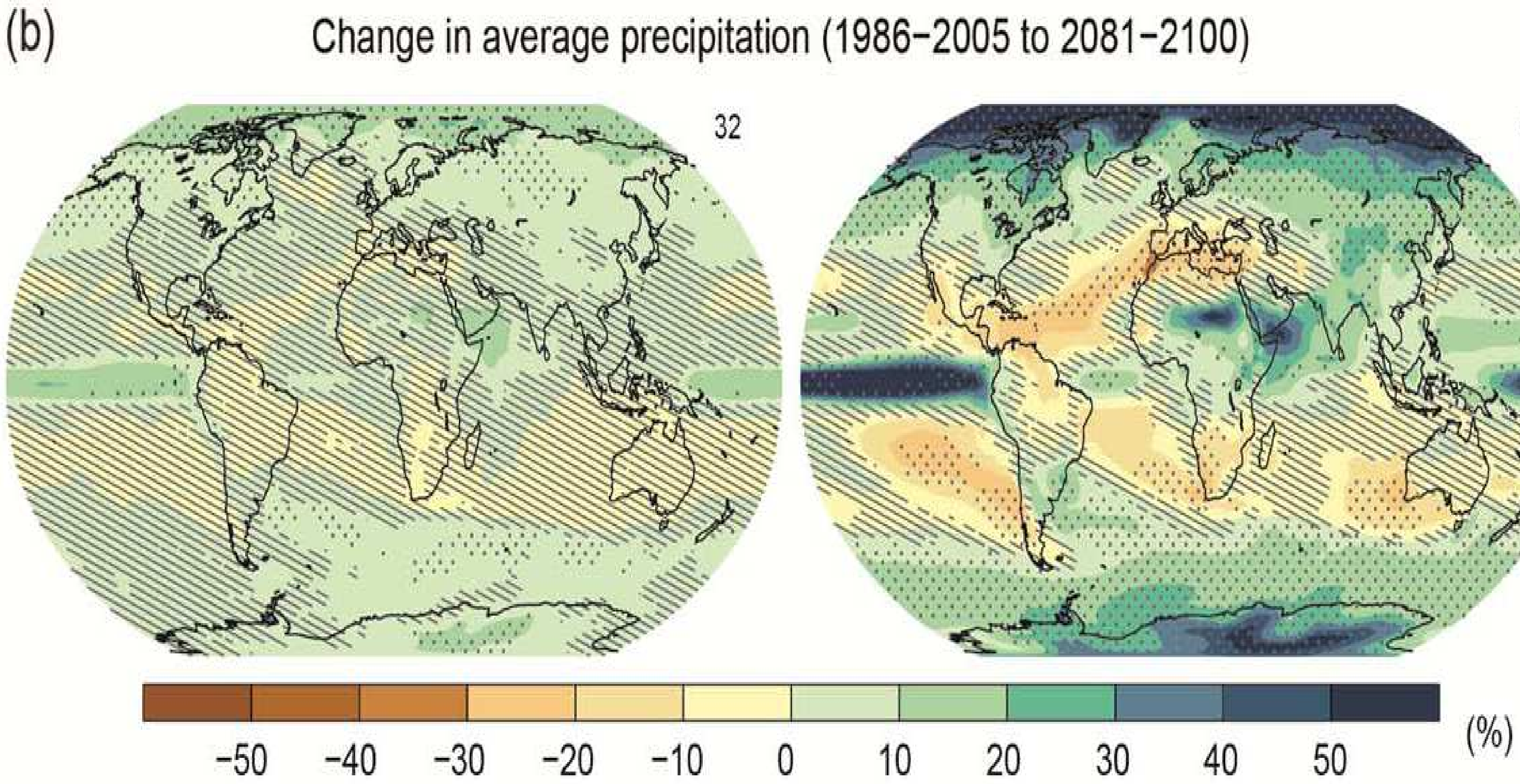


IPCC 5th Assessment Report (2013) : surface temperature increases during the 21st century are likely to be larger than historical increases …

Future Climate : how TCs will vary ?



Future Climate : how TCs will vary ?



Future Climate : how TCs will vary ?

How will TCs change in relation with this global warming :

- frequency ?
- intensity ?
- precipitation ?
- area affected ?

Future Climate : how TCs will vary ?

Modeling methods used to simulate future TCs behaviours :

- Use Global Climate Models (GCM) directly :
  - estimate TC counts, wind speeds, precipitation

- Infer TC behaviour from large-scale GCM variables :
  - Frequency : Gray's genesis parameters*
  - Intensity : Emanuel – Holland Potential Intensity

- Nested high-resolution experiments :
  - downscaling
  - case studies, regional characteristics, intensity, …

Tropical cyclone frequency : Projection

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

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

Tropical cyclone frequency : Projection

	Global	N Hem	S Hem	N Atl	NW Pac	NE Pac	N Indian	S Ind	SW Pac
Sugi *et al.* 2002	66	72	61	161	34	33	109	43	69
Tsutsui 2002	102			86	111	91	116	124	99
McDonald *et al.* 2005	94	97	90	70	70	180	142	110	82
Oouchi *et al.* 2006	70	72	68	134	62	66	48	72	57
Begtsson *et al.* 2007		81		87	72	107	49		
Emanuel 2008	93	102	87	104	106	95	93	88	85

Ratio (%) of number of tropical storms in global warming experiment to number in control

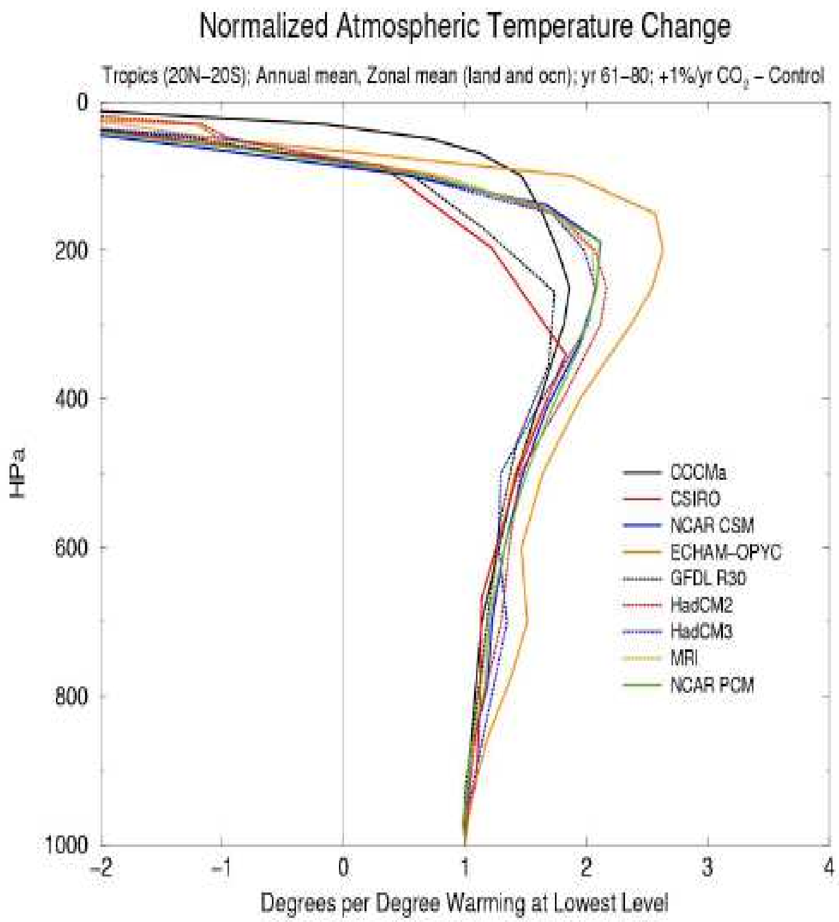
Tropical cyclone frequency : Projection

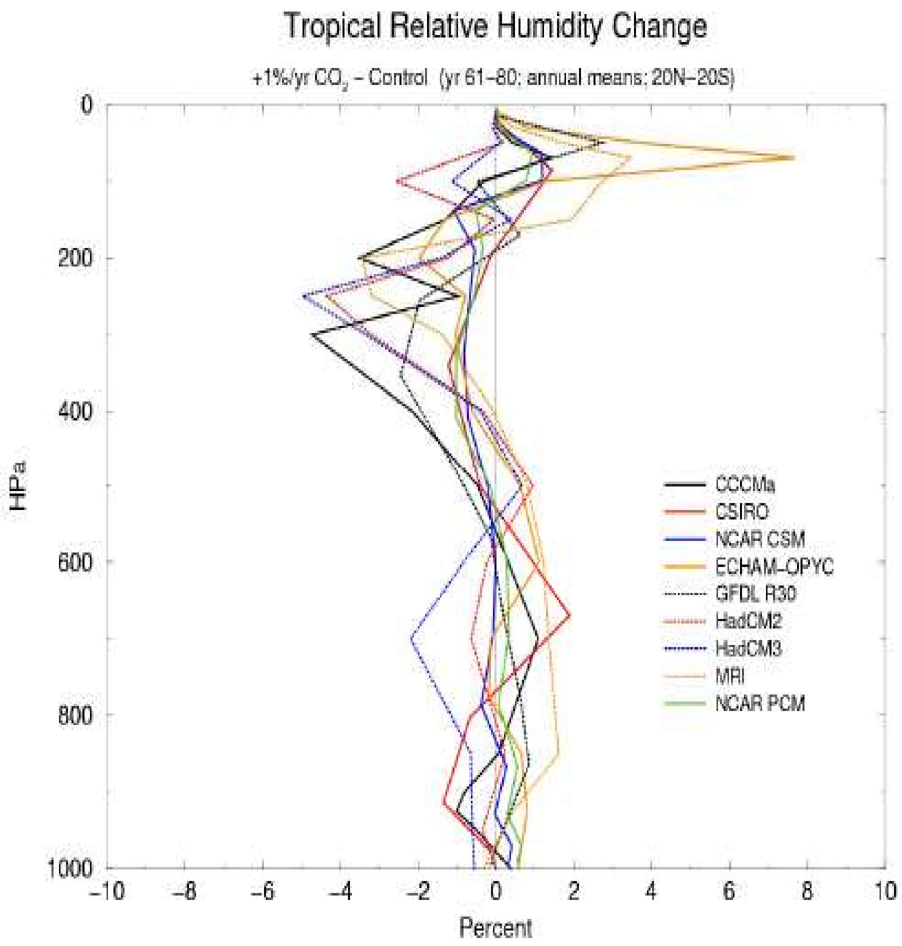
- It is likely that global mean TC frequency will either decrease or remain unchanged owing to global warming
- For the late 21st century, model projections indicate decrease ranging from -6 to -34% globally.

- 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 S Hem may be due to smaller increase in SST (compared to N Hem) as well as areas of increased vertical wind shear.

Tropical cyclone frequency : Projection





All climate models show enhanced warming in the tropical upper troposphere, and relatively little change in the lower tropospheric humidity.

Tropical cyclone intensity : Projection

- All of the highest resolution models (≤50 km horizontal grid spacing) show evidence for some increase of intensity.

- Globally, the mean maximum wind speed may increase by +2 to +11% (equivalent to -3 to -21% central pressure fall).
- For some individual basins, projection based on single models vary over a range of the order of ±15% or more.

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

Tropical cyclone intensity : Projection

! The model-projected changes result from a competition between the opposite influences of decreasing overall storm frequency and increasing intensity of the strongest storms !

! The future characteristics of intense TCs (Safir-Simpson Cat 3-4-5, Dvorak >5) deserve particular attention, as these relatively infrequent storms have historically accounted for a large proportion of damages !

<u>Tropical cyclone rainfall</u> : Projection

- <u>As the atmosphere warms</u> in relation with increasing content of greenhouse gases, <u>the integrated water vapour column will increase</u> (Clausius-Clapeyron : $\partial q_s / \partial T > 0$)

- This should <u>increase rainfall rates</u> in systems (such as TCs) <u>where moisture convergence is an important component</u> of the water budget.
- For TCs, an <u>increase in storm-wind intensity would amplify</u> this phenomenon.

- The <u>increase of TC-related rainfall rates is a robust projection in model simulations</u>.
- The range of projections for the late 21st century is <u>+3 to +37</u> globally.

Tropical cyclone rainfall : Projection

- The larger sensitivity is reported for the inner (r<200 km) region of the storms, with typical projected change of about +20%.

! However, model resolution and parameterized physical processes near the storm center 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 storms !

TC genesis, track, duration & surge : Projection

- 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.

- GCCM projections for the expansion of the (sub)tropics indicate some potential for a poleward shift of the averaged latitude of transition, but no modelling studies have focussed on this issue.

TC role on climate : Projection

- TCs, through wind-induced mixing of tropical ocean waters and subsequent re-heating of the cold wakes, make a potentially important contribution to the meridional heat transport by the ocean.

- In the future, increased TC activity would increase the poleward heat transport through this mechanism so the warming of the low latitudes would be moderated and, in turn, this would moderate any projected increase of TC frequency or intensity …

Progress summary and outlook

- During the last decade, substantial progresses have been achieved :
  - New analyses of global data on TC duration and intensity
  - Higher resolution global modelling
  - Improved statistical & dynamical downscaling tools

→ We cannot now conclusively indentify anthropogenetic signals on past TC data

→ Human influence on future TC activity could arise from several mechanisms (SST, sea-level rise, circulation changes, …)

→ Global TC frequency is likely to either decrease or remain essentially the same

→ A future increase in the globally averaged frequency for the strongest TCs is more likely than not

Recommended future research

- Data homogeneity in TC databases : high quality, global analysis of TCs from about 1970 for all basins

- Data homogeneity for TC-related variables : global analysis at higher horizontal resolution

→ More reliable evaluations of seasonal variability, geographical distribution of genesis and occurrence frequency, track climatology and storm structure

Recommended future research

- GCCM : aerosol forcing, internal vs. natural (intra-seasonal to multi-decadal) variability, climate sensitivity, details of projected SST warning in the tropics and related dynamical influences

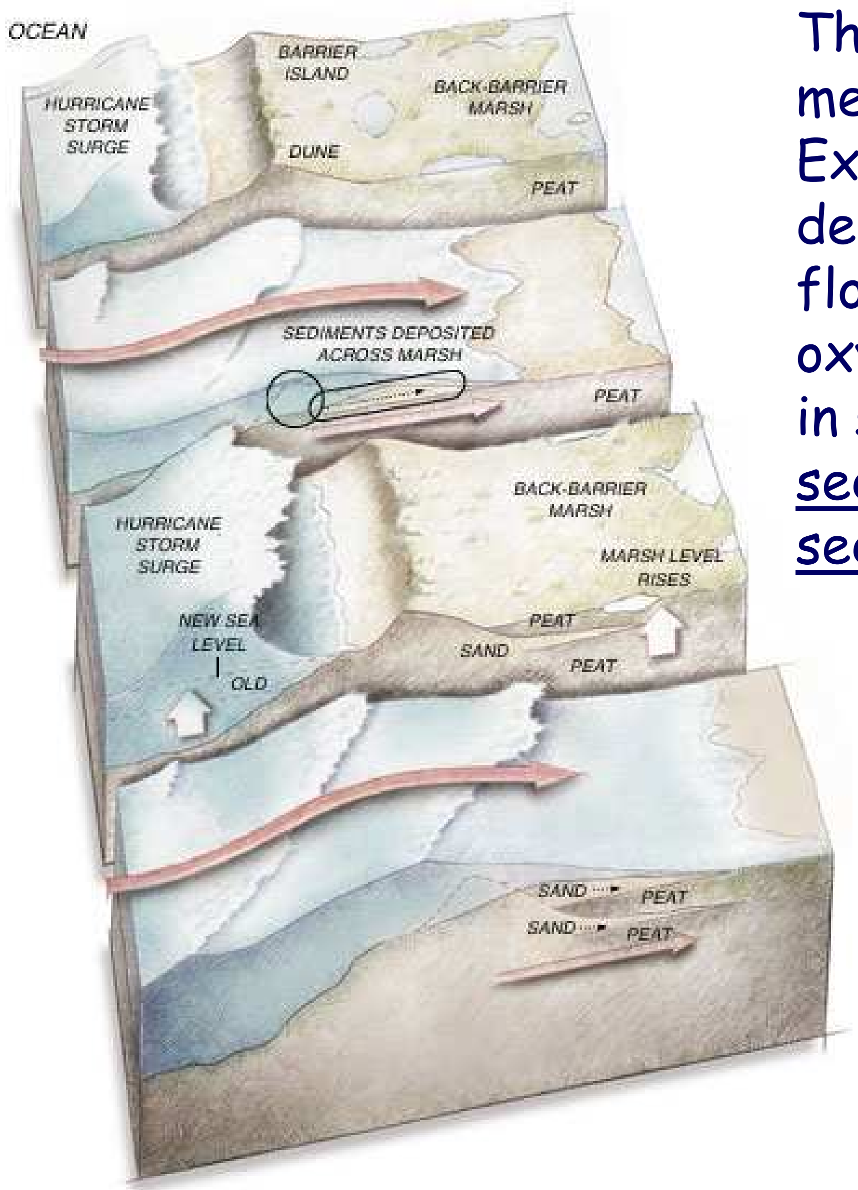
- High-resolution models : nested models have different climatology, 1-km resolution may be needed to resolve the inner region of TCs

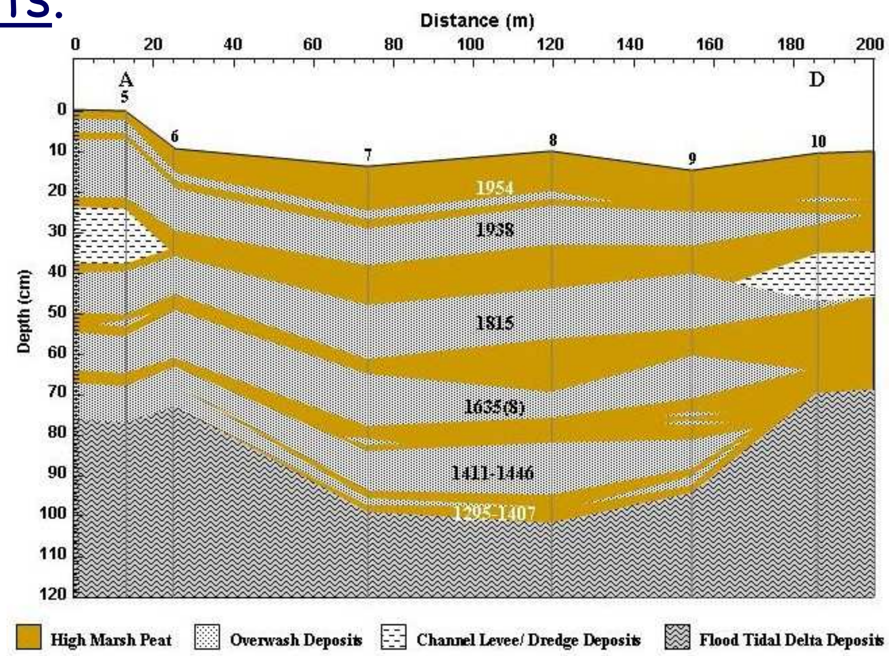
- Empirical modeling from large-scale variables : (intra-seasonal to multi-decadal) variability of genesis parameters in the past and the future, potential intensity taken into account both thermodynamics and dynamics.

Paleotempestology

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.

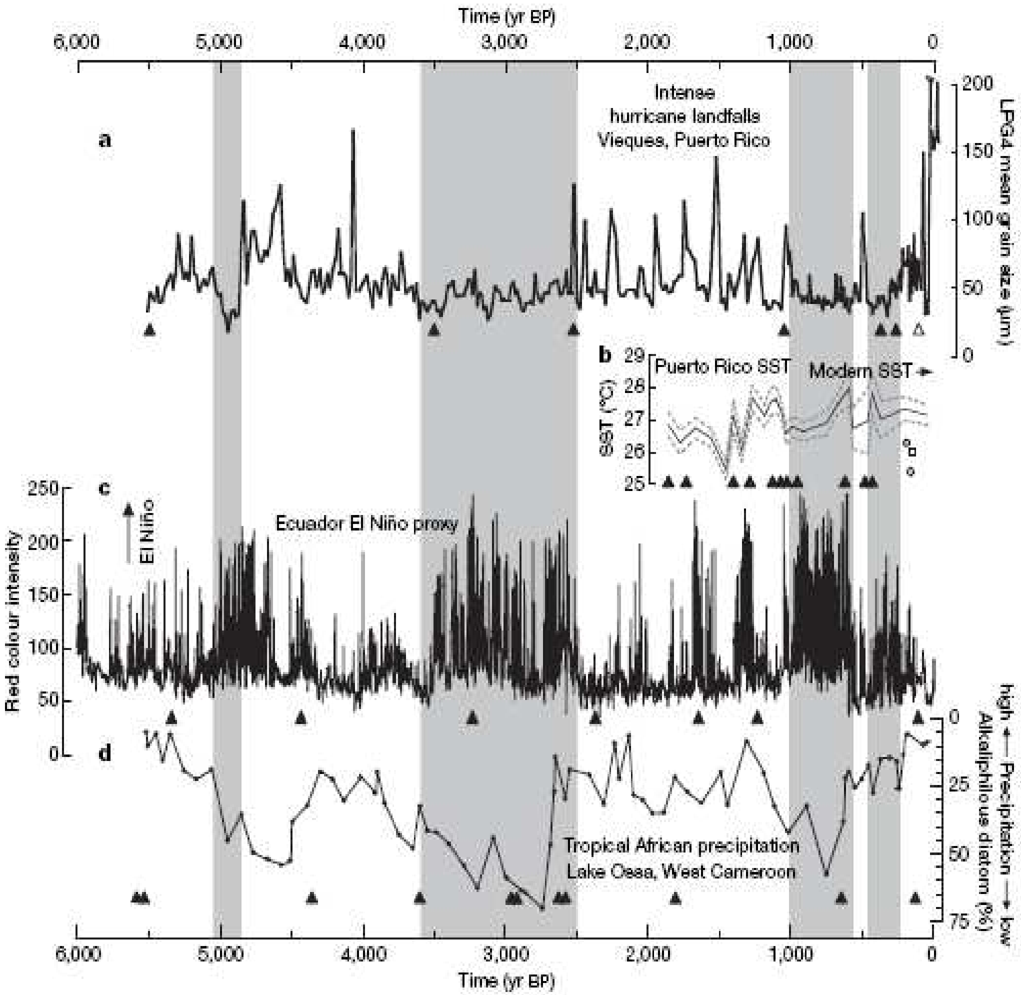




Paleotempestology

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

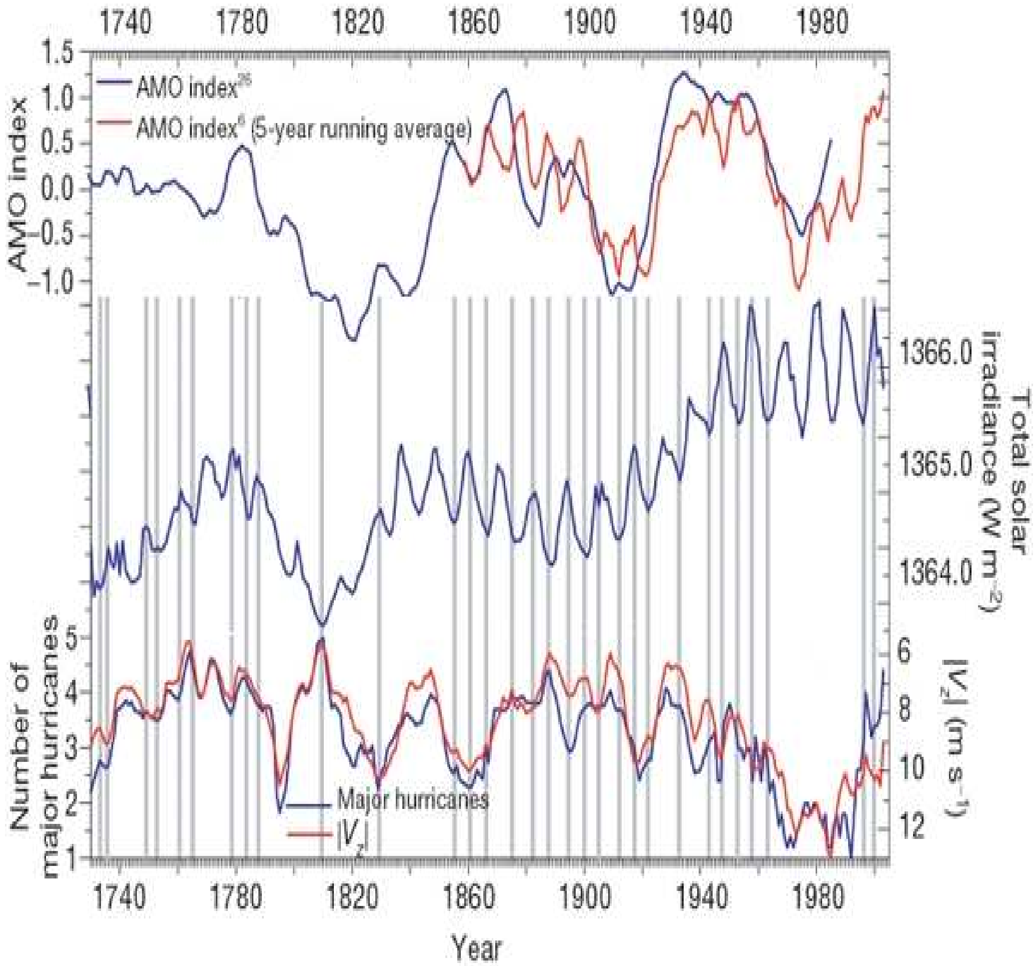


Comparison of the <u>intense hurricane record from a lagoon on the Perto Rican island of Vieques</u> with other climate records :

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

Paleotempestology

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



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

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.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