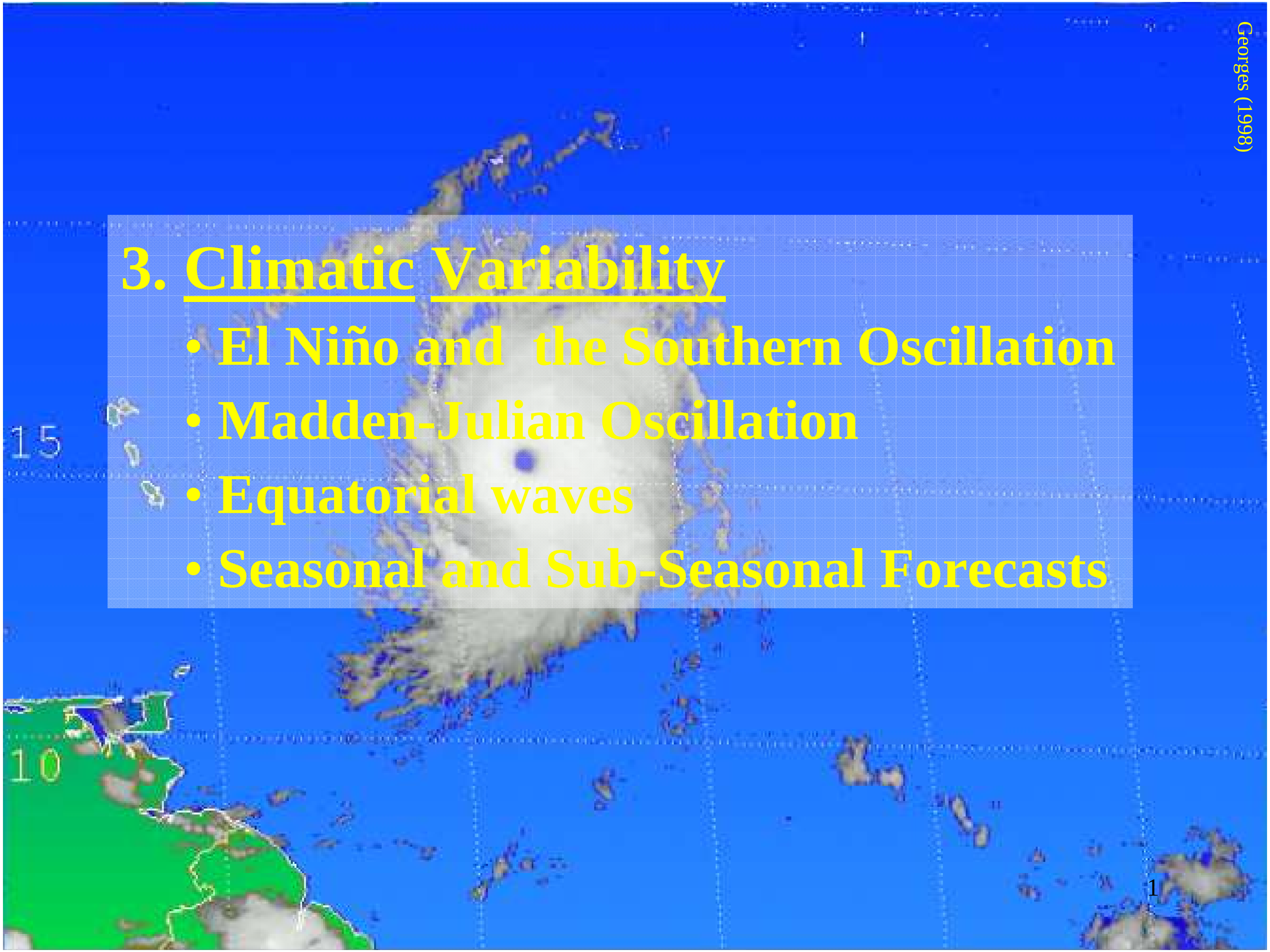
# 3. Climatic Variability

- El Niño and  the Southern Oscillation
- Madden-Julian Oscillation
- Equatorial waves
- Seasonal and Sub-Seasonal Forecasts



# ENVIRONMENTAL CONDITIONS FOR TROPICAL CYCLONES TO FORM AND GROW

- Ocean surface waters warmer than 26°C ;
- An unstable atmosphere to allow convection to develop ;
- Relatively moist layers in the mid-troposphere ;
- A minimum distance of 5-10° from the equator;
- A pre-existing disturbance near the Earth's surface with sufficient cyclonic vorticity and convergence ;
- Low values of vertical wind shear between the surface and the upper troposphere .

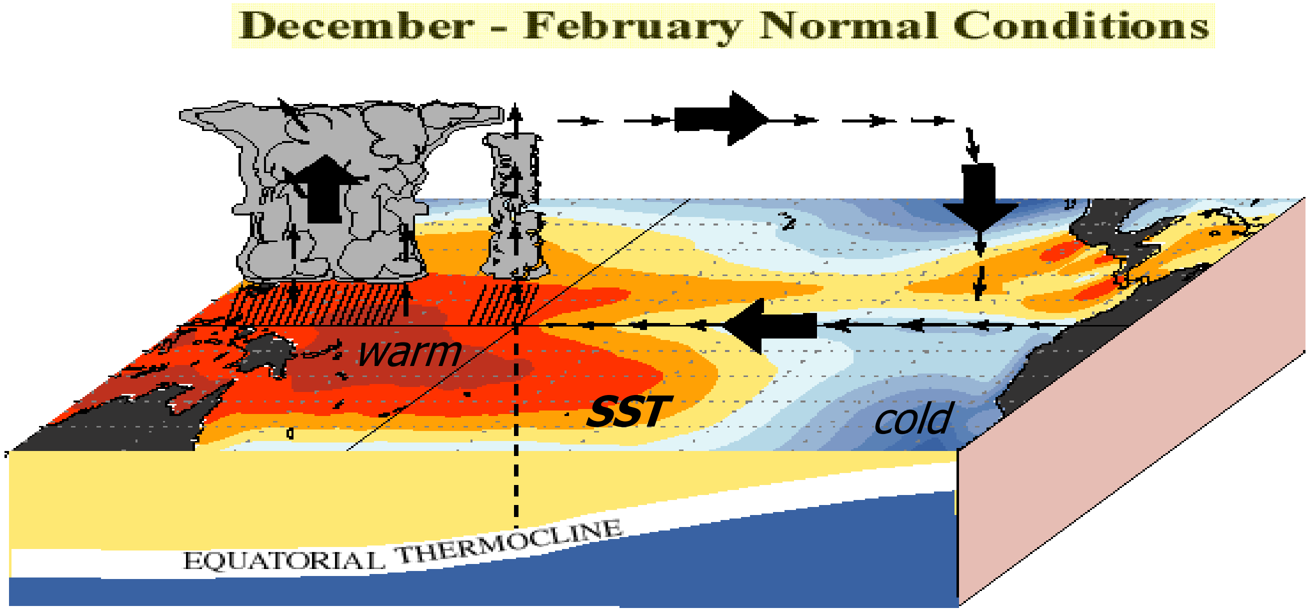
# VARIATIONS IN THESE CONDITIONS AFFECT TROPICAL CYCLONE ACTIVITY

- Seasonal variations in tropical cyclone activity depend on changes in one or more of the six parameters
  (*e.g. N Indian : no TCs during the monsoon due to increased wind shear*)

- Variations in these parameters (both before and during the tropical cyclone season) can be used to understand and, in some cases, predict seasonal tropical cyclone activity.

- ENSO (El Niño – Southern Oscillation) is the primary driver of interannual variability of tropical cyclone activity.

# « NORMAL » ATMOSPHERIC AND OCEANIC CONDITIONS OVER THE PACIFIC OCEAN (1)

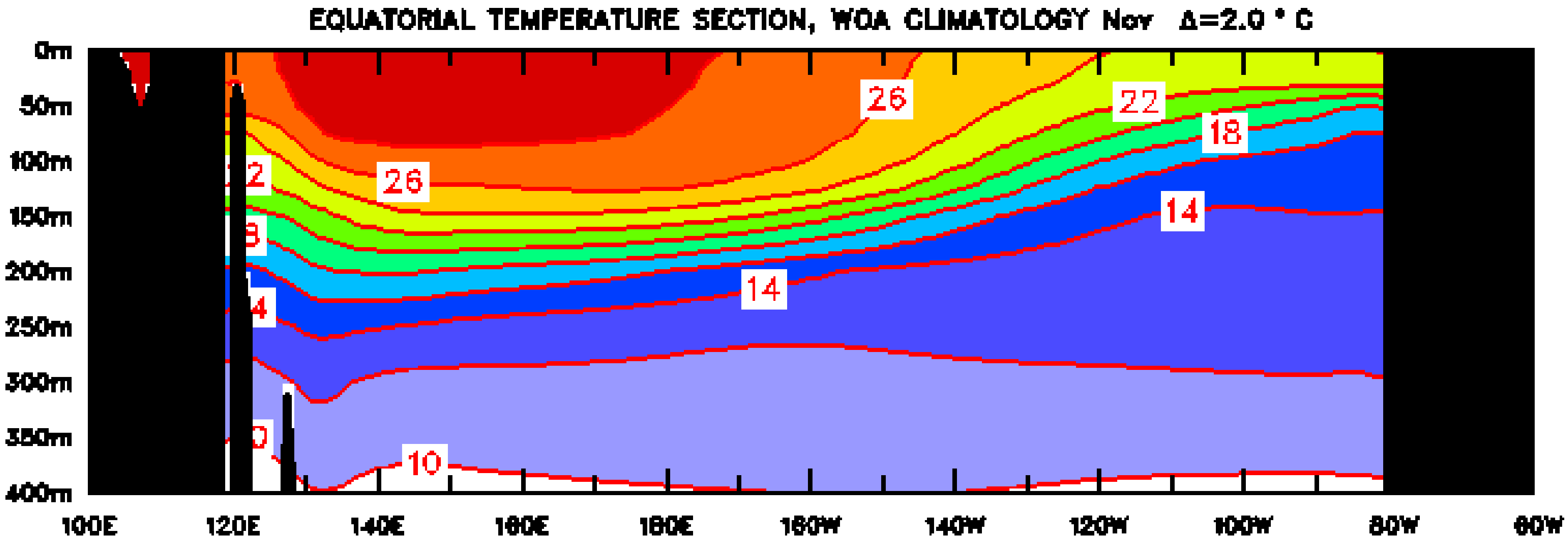



This distribution of SST and precipitation results from easterly (trade) winds in the lower troposphere and westerly winds aloft.

Over the equatorial western Pacific, a low pressure zone is associated with mean upward motions. High surface pressure et mean downward motions prevail to the east.

This « Zonal Walker Cell » represents the « normal » atmospheric circulation over the tropical and equatorial Pacific ocean.

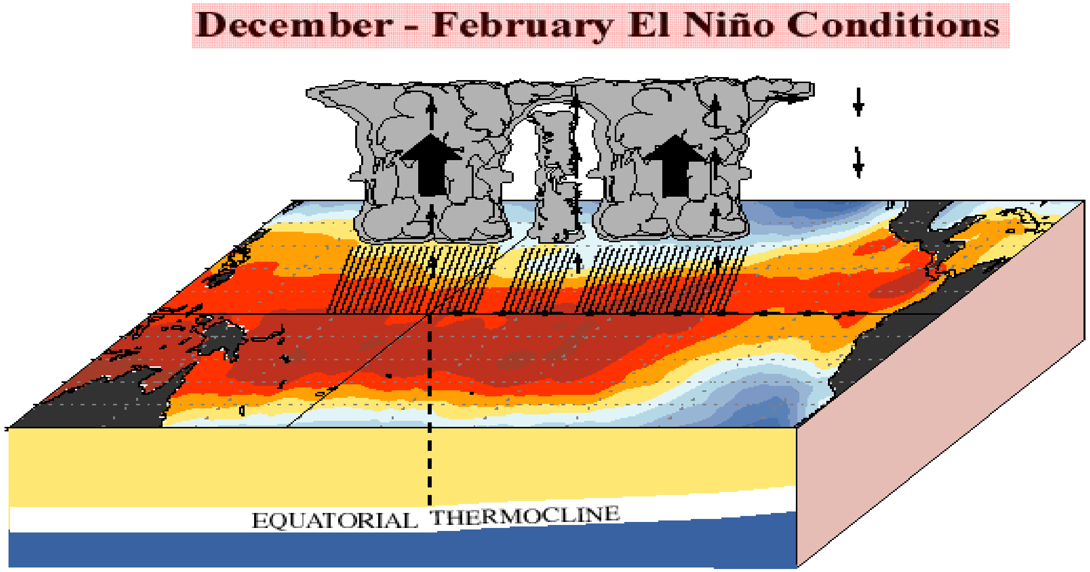
# « NORMAL » ATMOSPHERIC AND OCEANIC CONDITIONS OVER THE PACIFIC OCEAN (2)



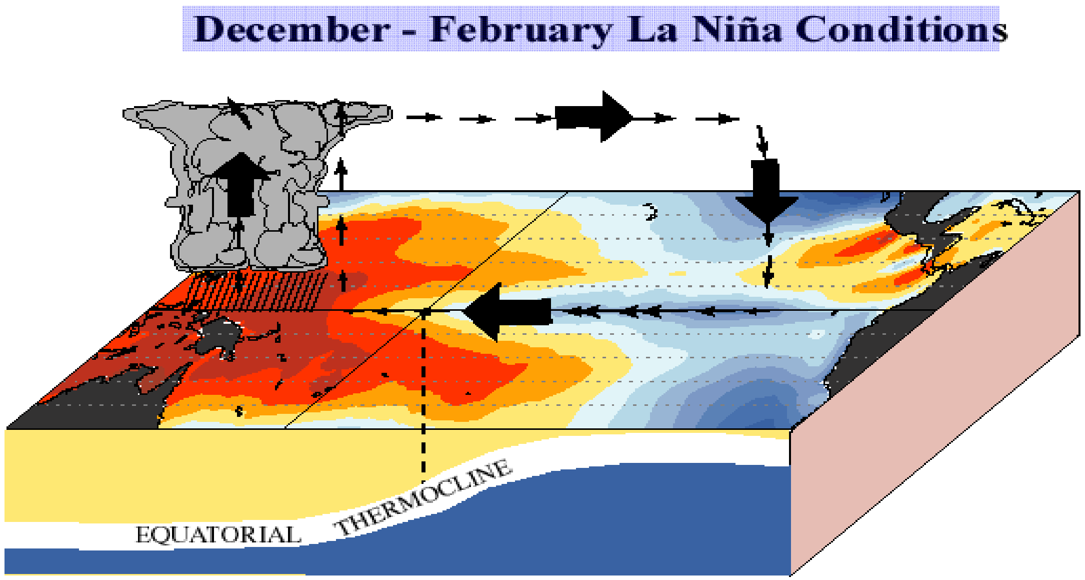

The thermal structure of equatorial and tropical Pacific reveals une deep warm *(SST > 27°C)* layer to the west, and a cooler *(SST<23°C)* and thinner mixed layer to the east.

Between the upper mixed layer and the deep water below, the thermocline, varies in depth from west (150-200m) to east (50-100m).

# « PERTURBED » ATMOSPHERIC AND OCEANIC CONDITIONS OVER THE PACIFIC OCEAN

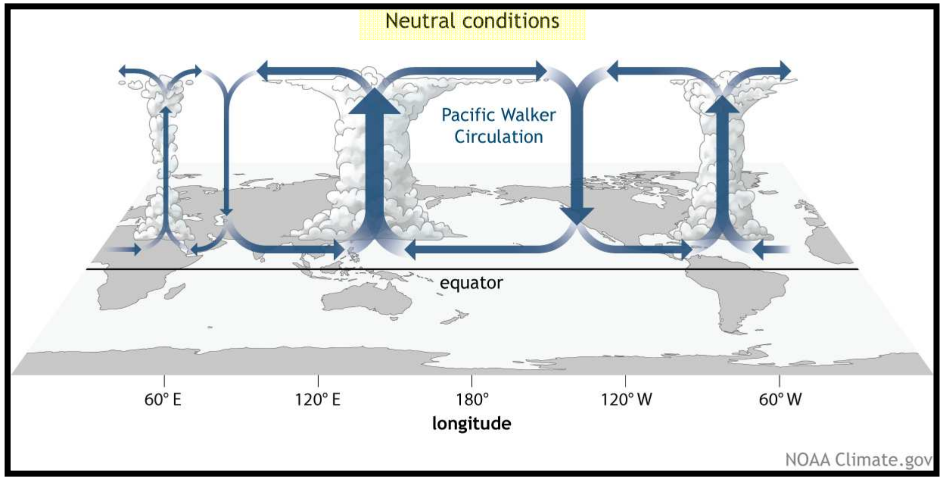


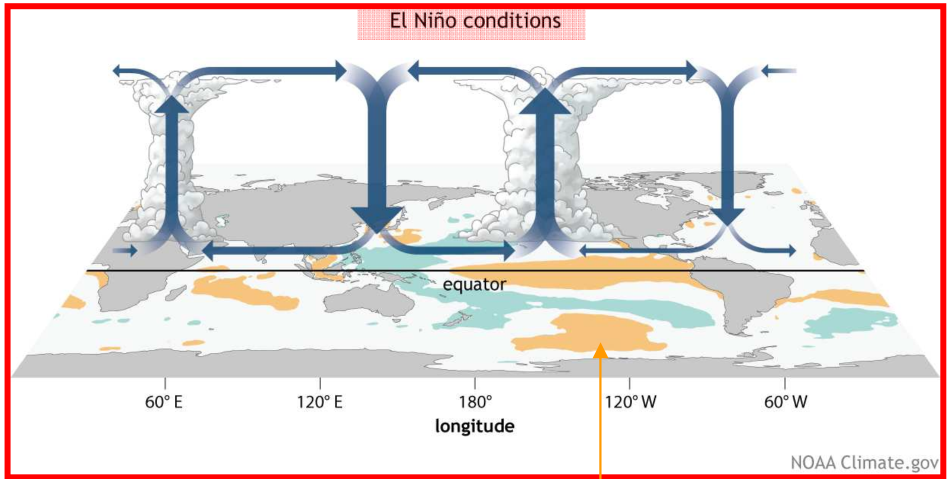

**El Niño :** The low-level easterly trade winds and the upper-tropospheric westerly winds are weaker, in relation with a less intense Walker Circulation.

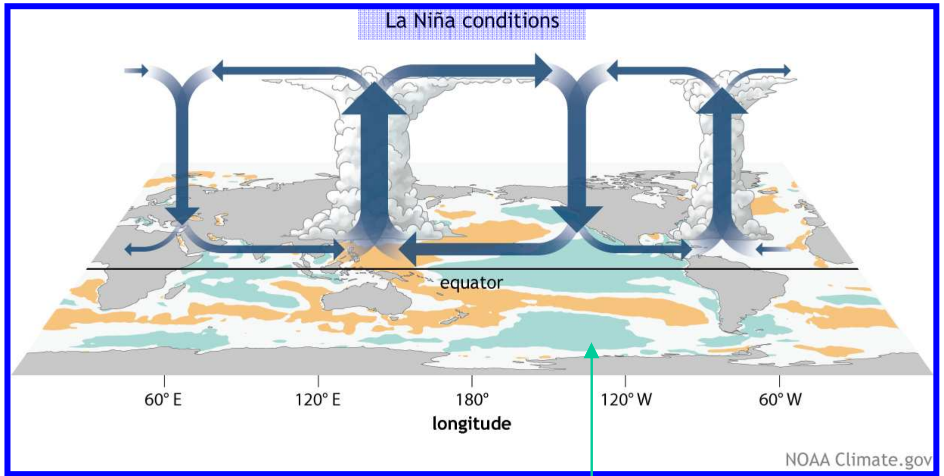



**La Niña :** The low-level easterly trade winds and the upper-tropospheric westerly winds are stronger, in relation with a more intense Walker Circulation.

# « PERTURBED » WALKER CIRCULATION



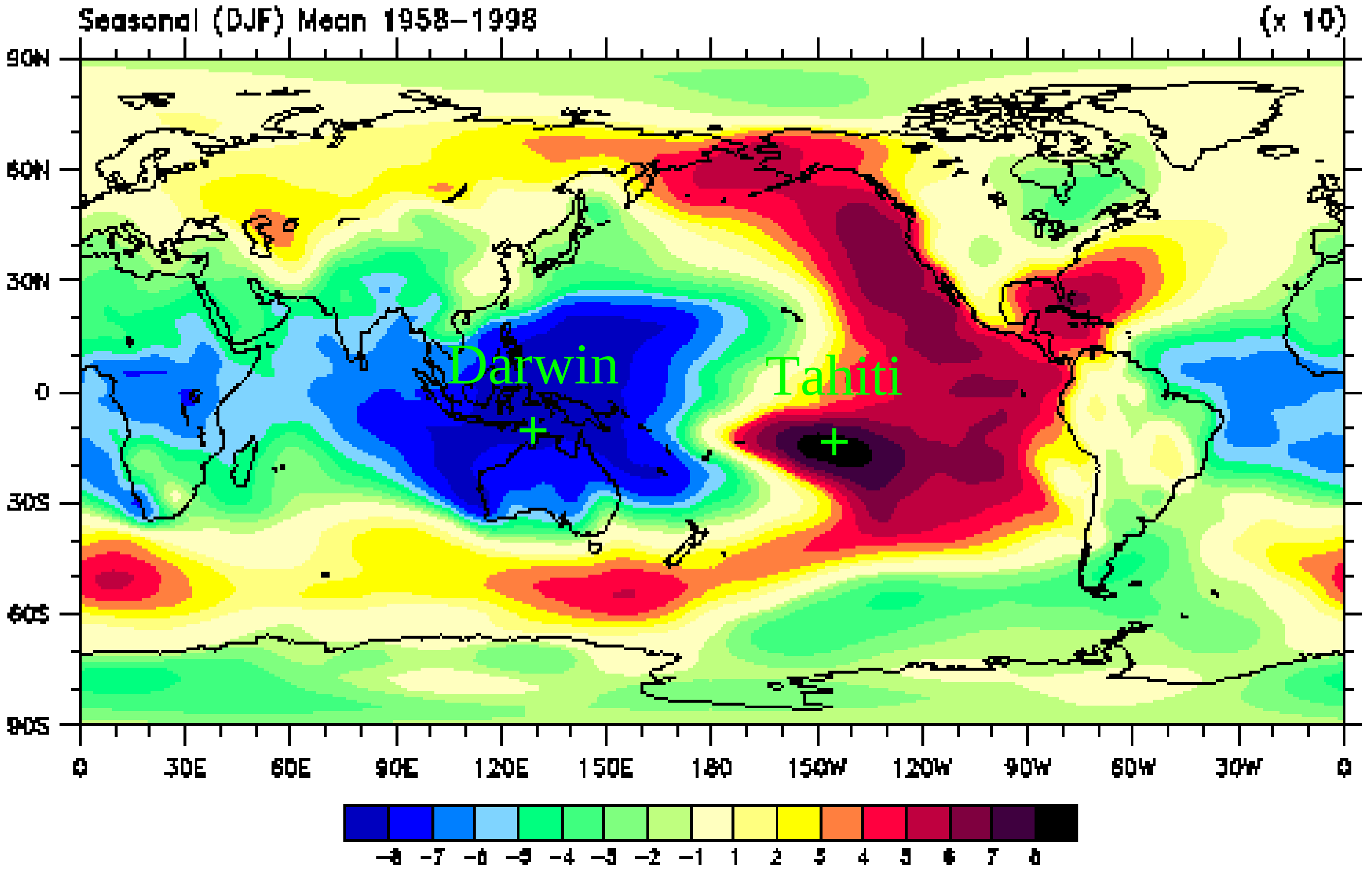




$\Delta SST > 0$

$\Delta SST > 0$

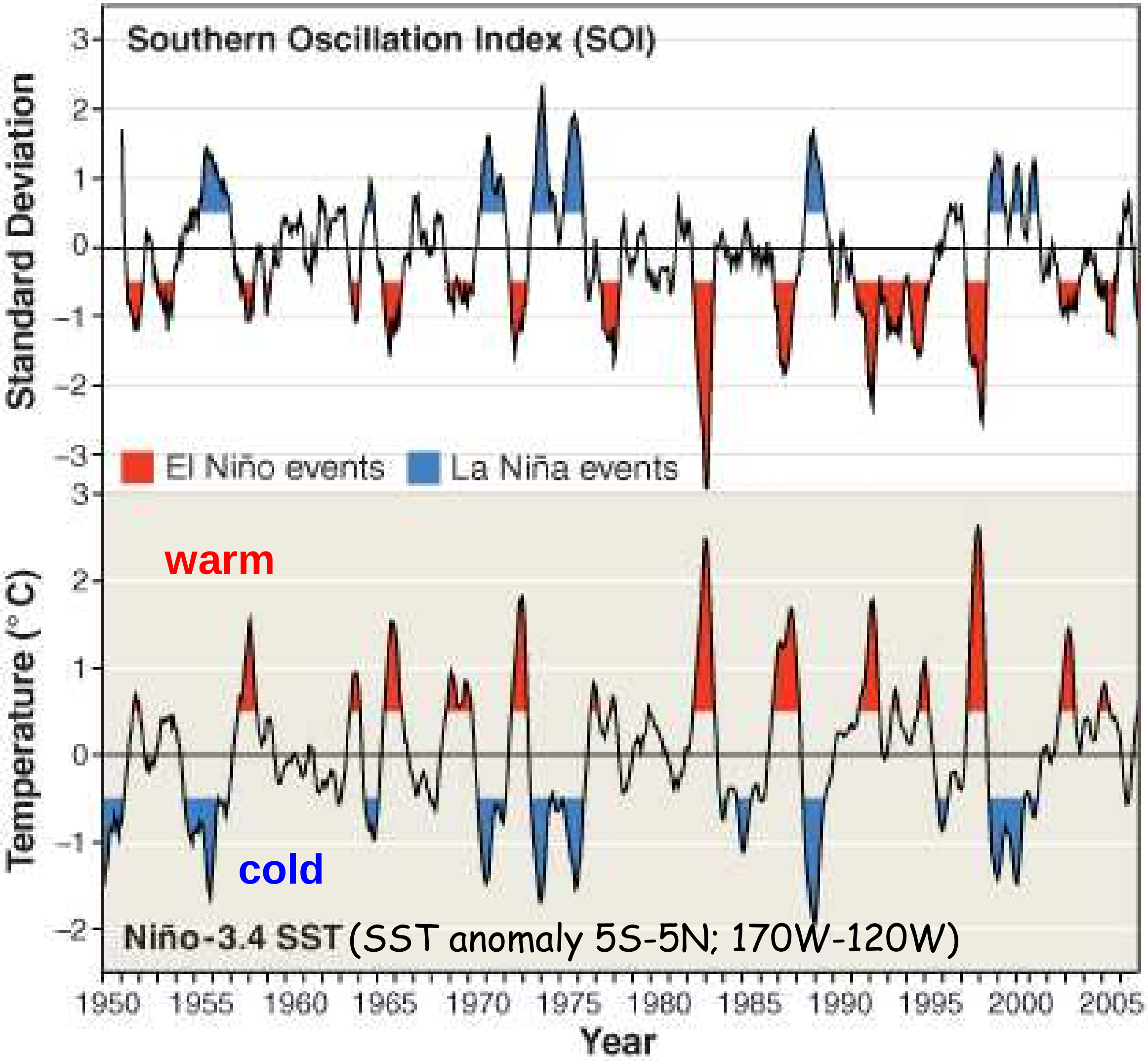
# THE GLOBAL INFLUENCE OF ENSO




The map of <u>global correlations of sea-level pressure (SLP) with Tahiti</u> *(Central Pacific : 17° 52' S - 149° 56' W)* reveals the very large atmospheric influence zone of ENSO.

<u>Darwin</u> *(N Australia, 12° 28' S - 130° 51' E)* can be considered as the opposite pole to Tahiti.

# SOUTHERN OSCILLATION INDEX




The SOI « *Southern Oscillation Index* » is the normalized difference in SLP between Tahiti and Darwin.

High pressure at Darwin and low pressure at Tahiti correspond to El Niño (warm) events (SOI<0), the opposite pressure conditions (SOI>0) correspond to La Niña (cold) events.

# THE INFLUENCE OF ENSO ON TROPICAL CYCLONE ACTIVITY

The state of ENSO has been related to TC numbers in many regions of the world.

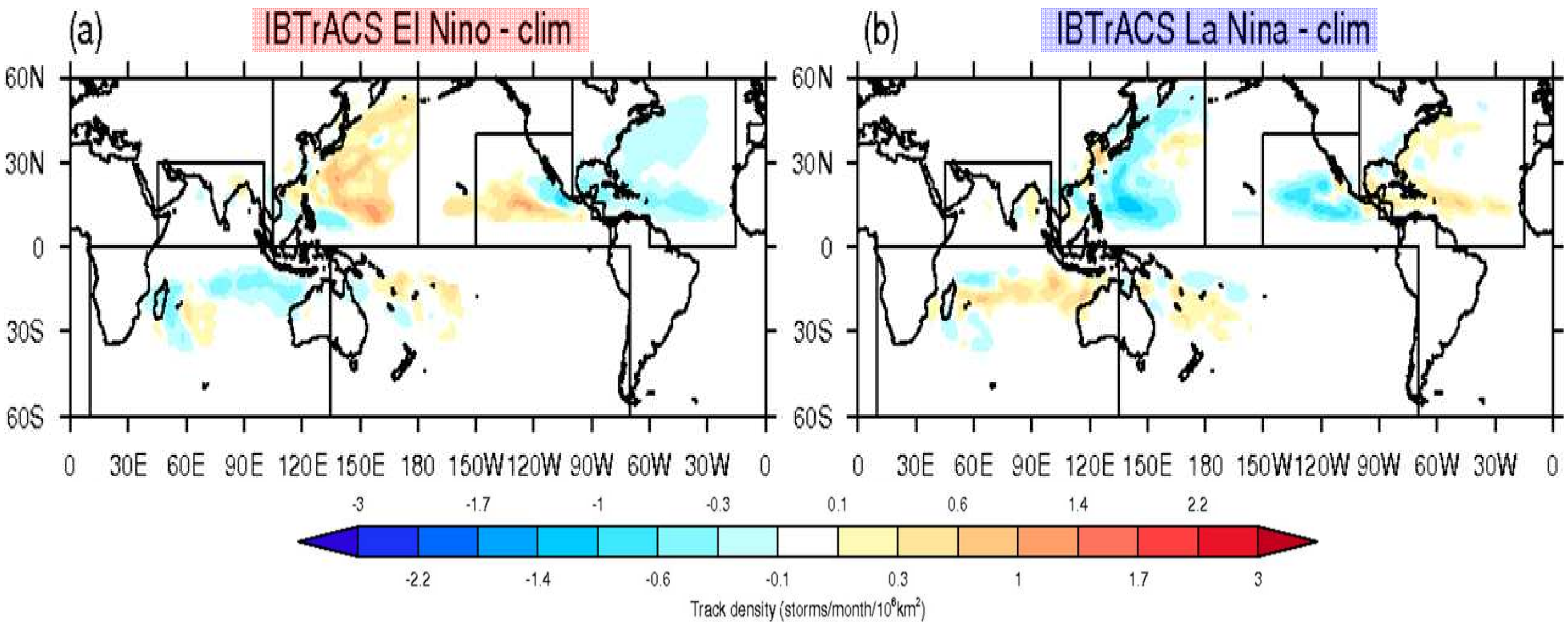
Coherent relationships between cyclone occurrence and the phase of ENSO have been found, although the dynamical reasons for the modulation appear to be quite different in the various cyclone basins of the world.

The different factors are the SST, the SLP, the tropospheric wind and humidity.

The influence of ENSO can appear through shifts in the location of cyclogenesis, and in cyclone frequency and intensity.

# TROPICAL CYCLONES VARIABILITY
# ENSO / Global

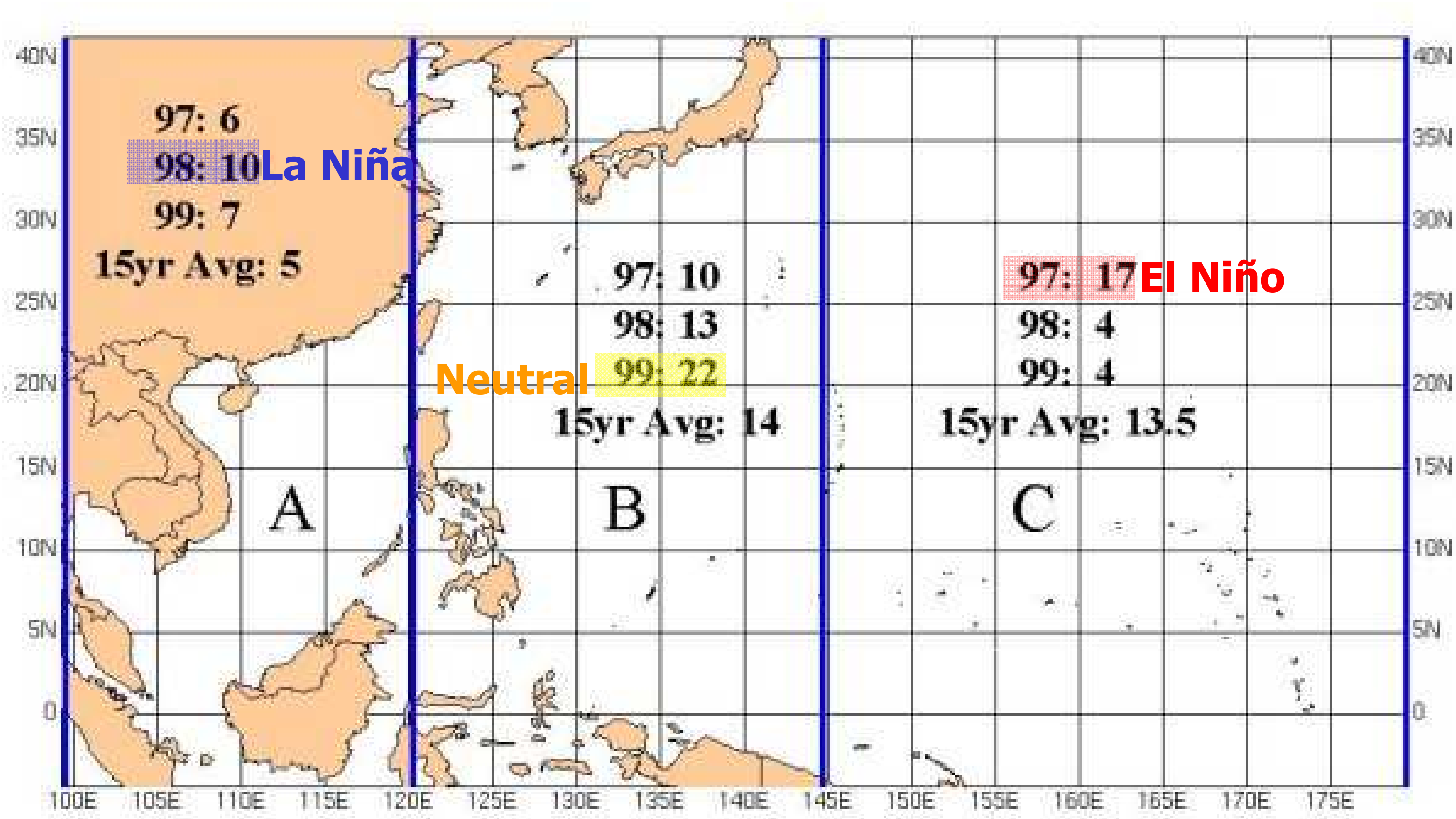
**Bell *et al.* 2014:** *J. Climate*, **27**, 6404–6422




*Tropical cyclone track density (storm transits / month / $10^6$ km$^2$)*
*from IBTrACS during May–November in the Northern Hemisphere and October–May in the Southern Hemisphere*
*(a) El Niño years minus 1979–2010 climatology,*
*(b) La Niña years minus 1979–2010 climatology.*

# TROPICAL CYCLONES VARIABILITY
# ENSO / western North Pacific (1)

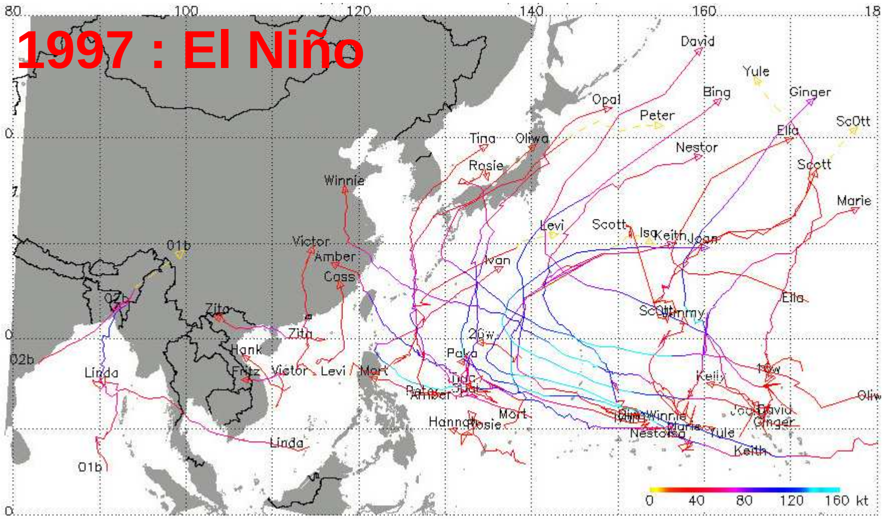
**Chu 2004 :** « *ENSO and tropical cyclone activity. Hurricanes and Typhoons : Past, Present, and Potential* ». R.J. Murnane and K.B. Liu, Eds., Columbia Univ. Press, 297-332

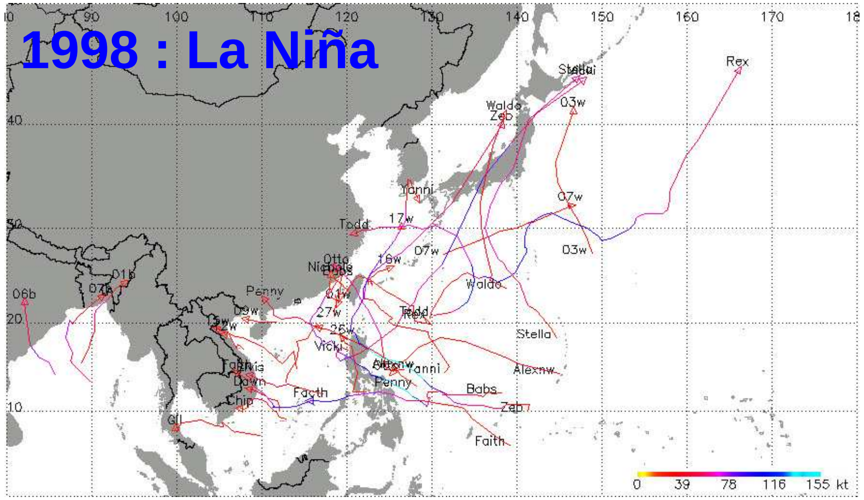



The tropical cyclogenesis zone shifts eastward (westward) during ENSO warm / El Niño (cold / La Niña) years.

# TROPICAL CYCLONES VARIABILITY
# ENSO / western North Pacific (2)

During El Niño years, the eastward and equatorward shift in origin location allow TCs to maintain a longer lifespan while tracking westward over open water. Interactions with transient midlatitude synoptic systems result in more recurved trajectories toward NE Asia.

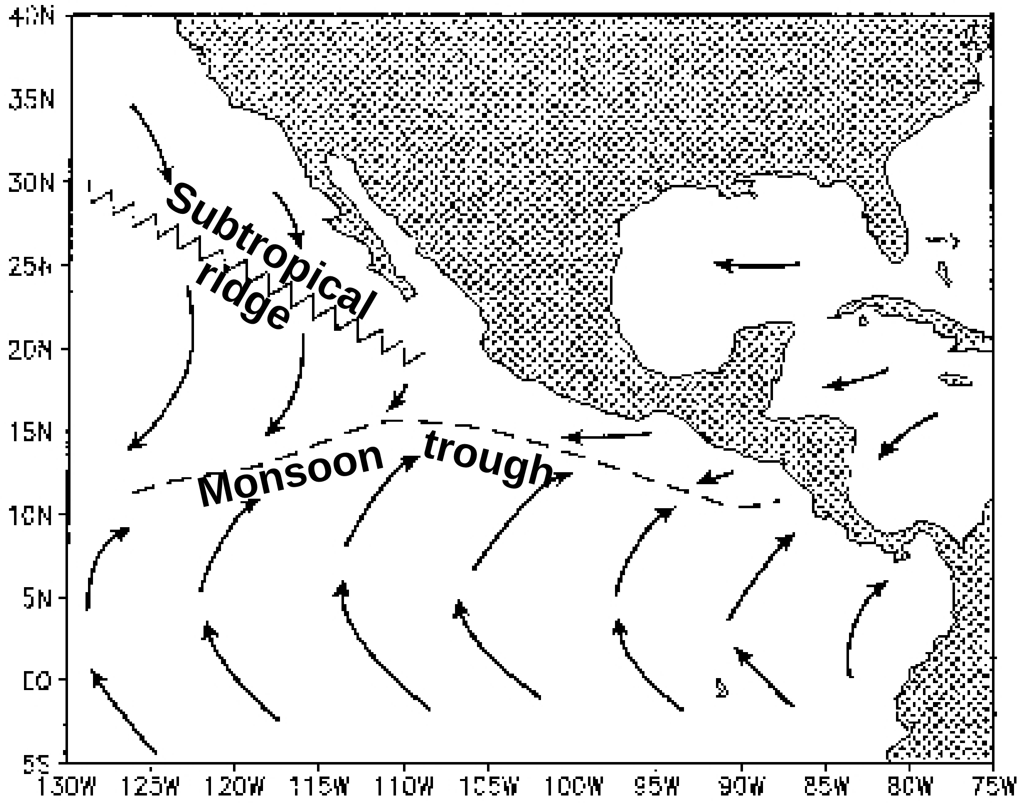



During La Niña years, the monsoon trough is short and confined in the western extreme of N Pacific. Landfalls are more common in the SE Asia shores.

# TROPICAL CYCLONES VARIABILITY
# ENSO / eastern North Pacific (1)

A majority of storms form along the axis of the <u>monsoon trough</u>, but TCs might also be triggered by <u>tropical Easterly Waves</u> from West Africa and the Atlantic.




Schematic showing the long-term mean surface circulation in August in the eastern North Pacific. The monsoon trough axis is denoted by a broken line, and the ridge axis by a zigzag line. Wind directions are indicated by arrows.

!! when TCs are <u>active in the eN Pacific</u>, they tend to be <u>suppressed over the Atlantic</u> and vice versa !!

# TROPICAL CYCLONES VARIABILITY
# ENSO / eastern North Pacific (2)

There is no obvious impact of ENSO on the overall TC frequency in the eN Pacific.

If only intense storms (Saffir-Simpson category ≥3) are considered, the ratio during El Niño to La Niña years is about 1.7.

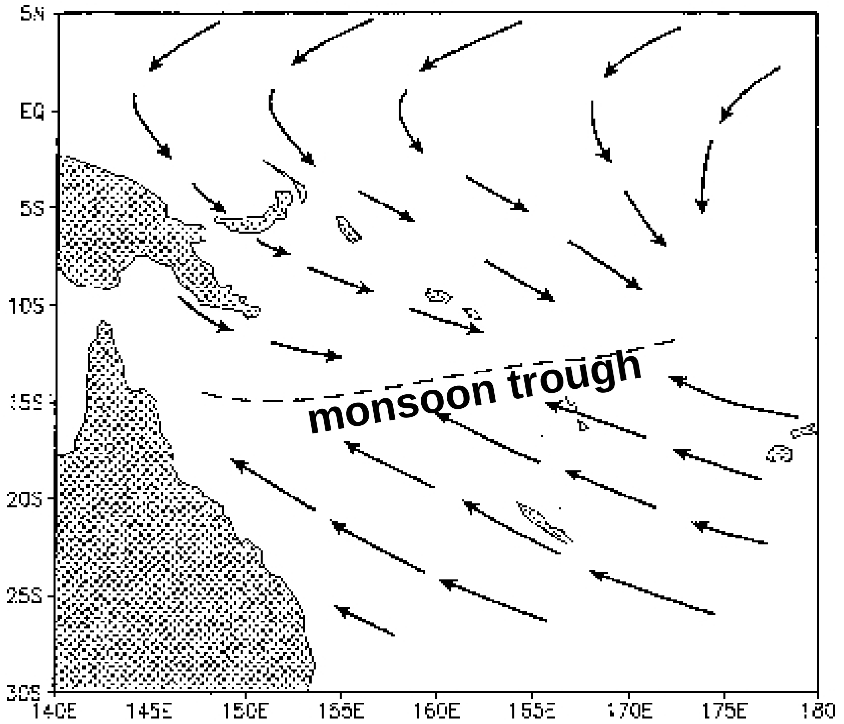


TC tracks expand westward during El Niño years, and retreat eastward during La Niña.

# TROPICAL CYCLONES VARIABILITY
# ENSO / western South Pacific (1)

There is a <u>strong correlation between the SOI and TC days</u> in the **Australian region (105°E – 155°E).**

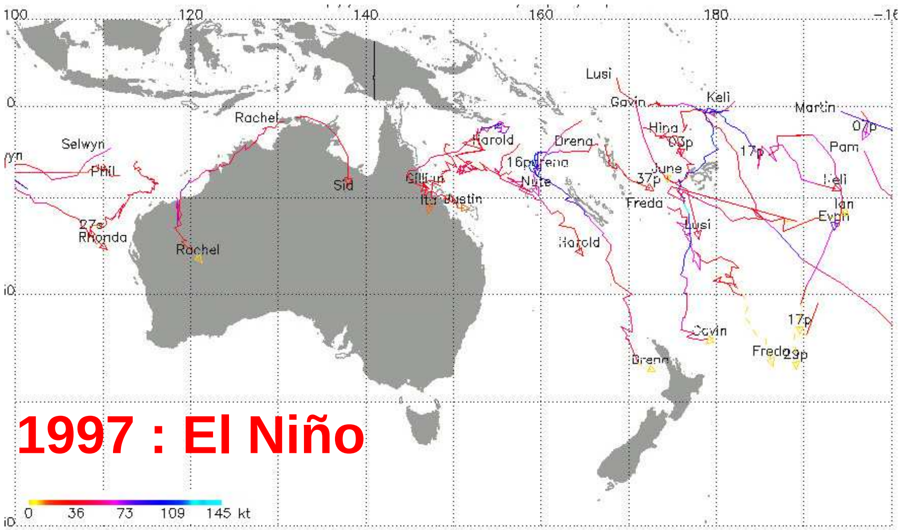
<u>Higher SLP</u>, <u>cooling of ocean surface</u>, and the <u>sinking branch of the Walker circulation</u> during El Niño years combine to produce <u>unfavourable conditions</u> for TC formation.

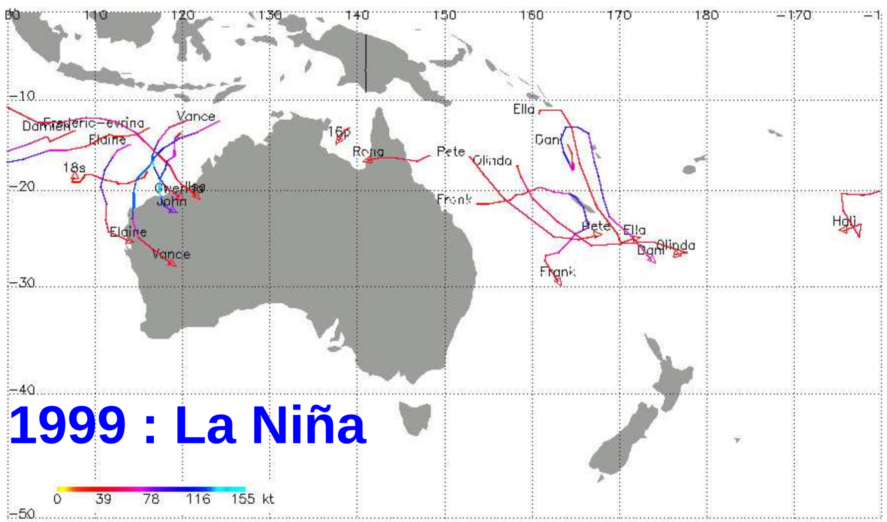



Schematic showing the long-term mean surface circulation in February in the southwestern Pacific. The monsoon trough axis is indicated by a broken line. Wind directions are indicated by arrows.

In the **wS Pacific (>155°E)**, the <u>eastern end of the monsoon trough</u> is usually near 175°E, but it can <u>extend as far east</u> as 140°W during El Niño years.

# TROPICAL CYCLONES VARIABILITY
# ENSO / western South Pacific (2)

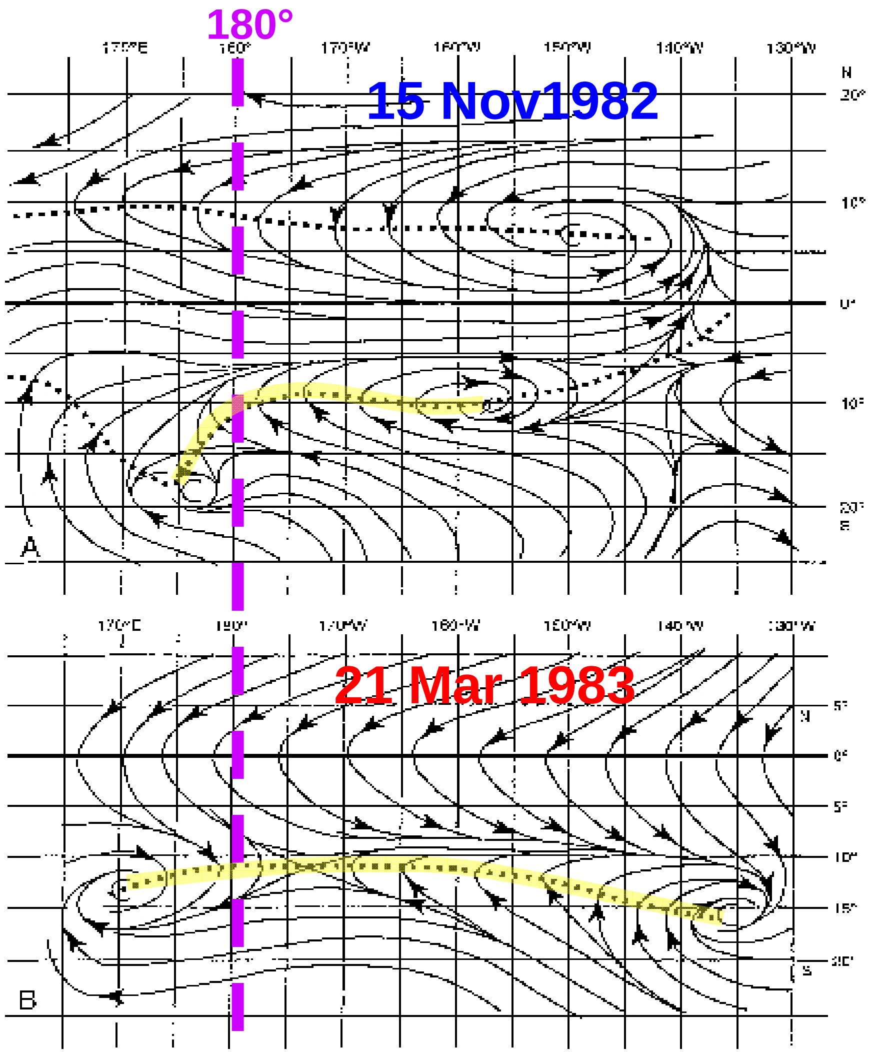



During El Niño years, the median location of TC genesis points is about 20° eastward from the climatological mean.

During La Niña years, TCs form more closer to Australia with a higher risk of landfall.

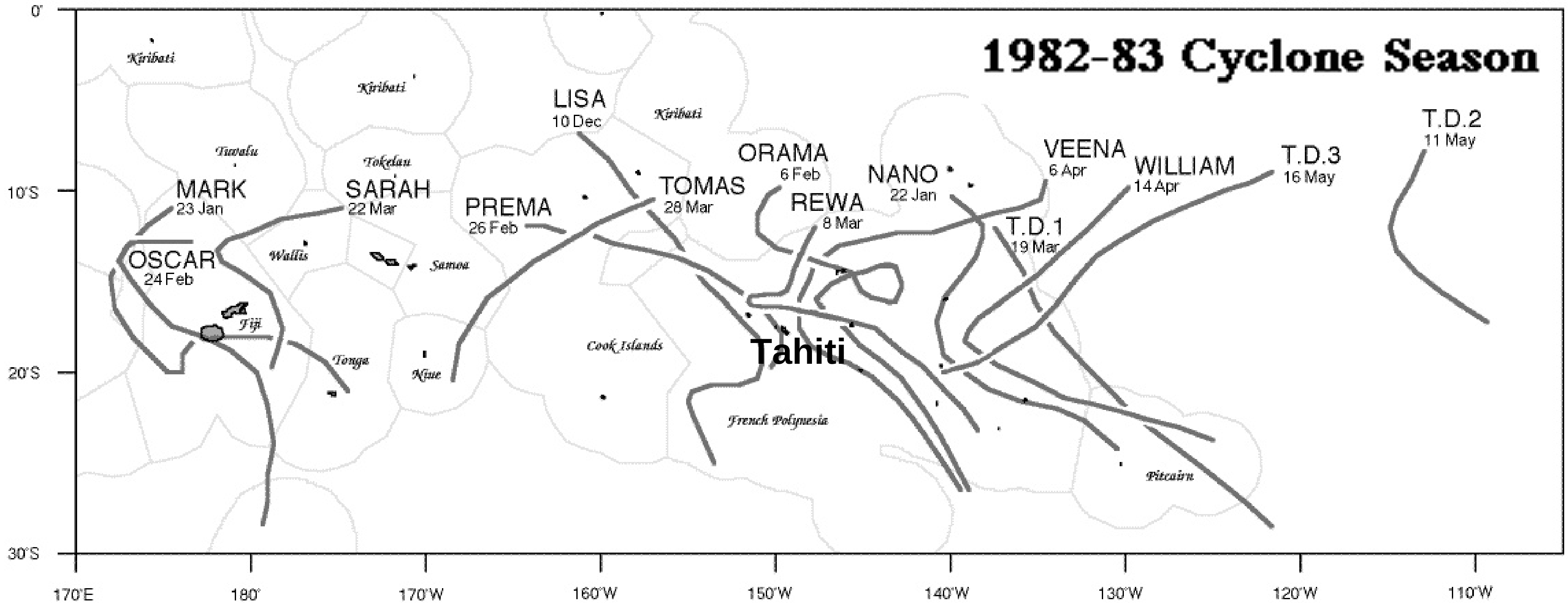
# TROPICAL CYCLONES VARIABILITY
# ENSO / western South Pacific (3)




Surface streamline analyses for (A) November 15, 1982, and (B) March 21, 1983. The trough lines are indicated by dots. Note that in (A) the equatorial westerlies in the central Pacific are embedded between the double trough, one in each hemisphere, and that the tropical depression near Penryhn in the South Pacific (~158°W) is indicated. In (B), westerlies lie between the trough (dotted line) and the equator. Note the trough extends as far east as 135°W (adapted from Sadler, 1983, with permission).

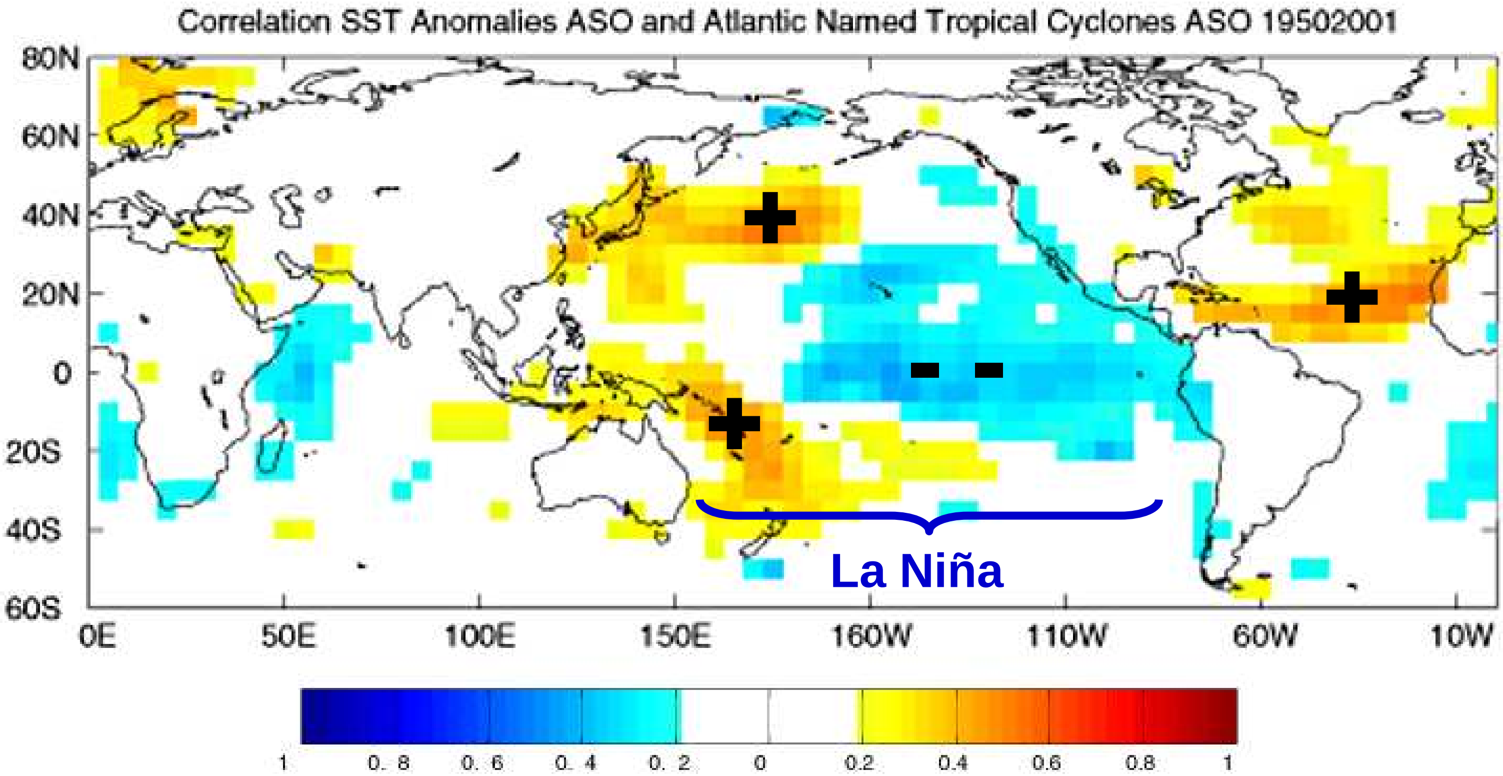
During the very strong 1982-1983 El Niño, the South Pacific trough extended almost 20° of longitude (≈ 2000 km) east of its mean climatological position.

# TROPICAL CYCLONES VARIABILITY
# ENSO / western South Pacific (4)



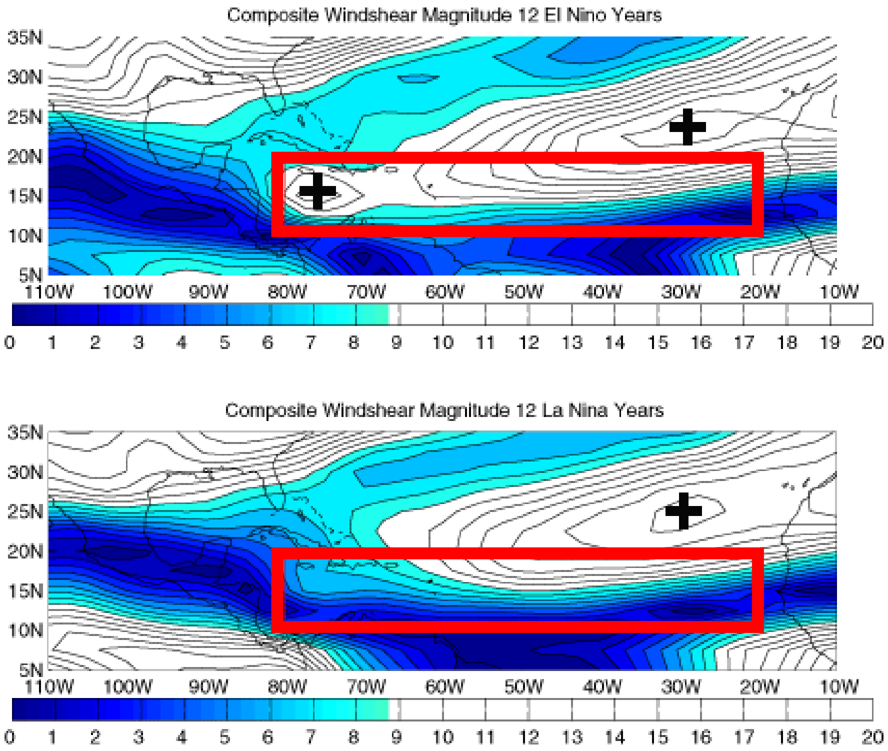

During the very strong <u>1982-1983 El Niño</u>, anomalous conditions caused <u>TCs to occur in French Polynesia</u> (up to 110°W !) that is not generally regarded as a cyclone-prone area (due to strong vertical wind shear).

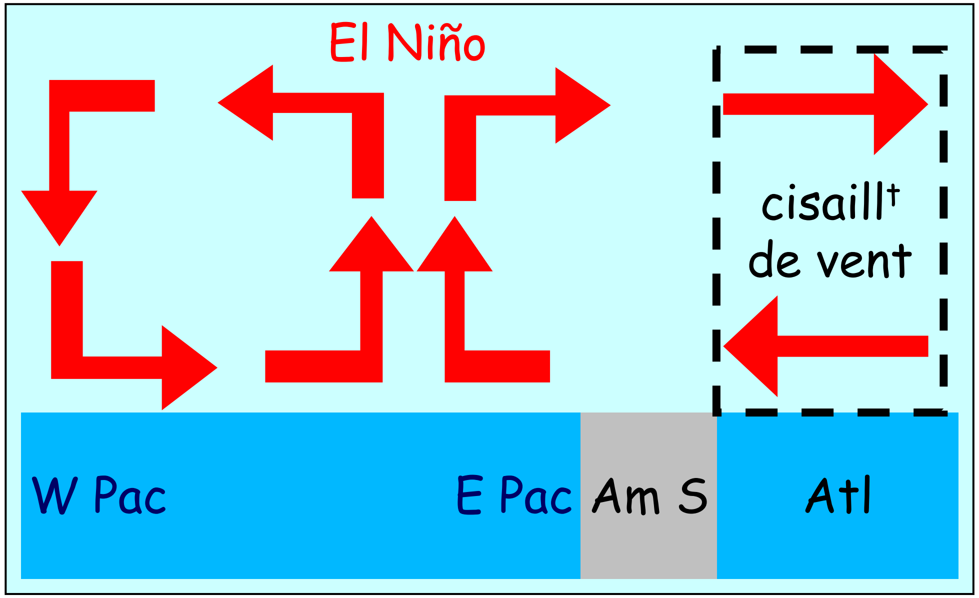
# TROPICAL CYCLONES VARIABILITY
# ENSO / Atlantic (1)




There are <u>more storms</u> over the Atlantic during La Niña years than during El Niño years

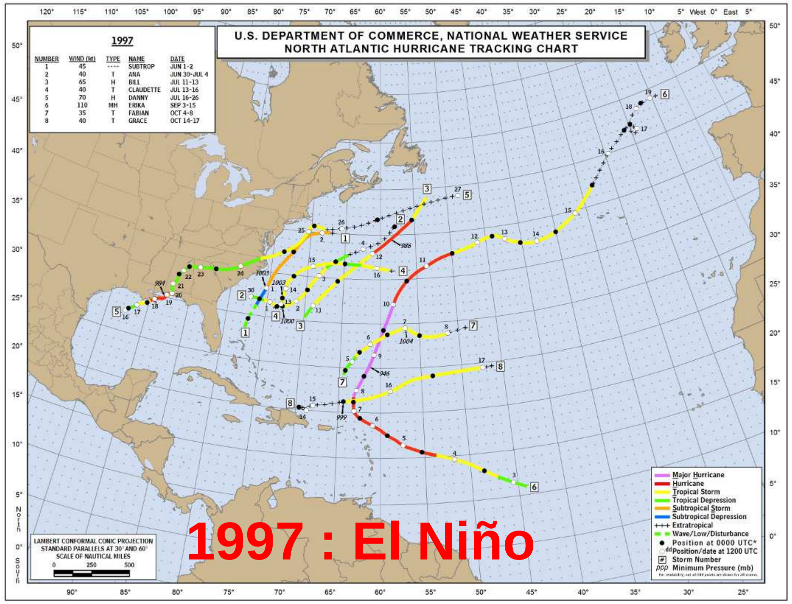
# TROPICAL CYCLONES VARIABILITY
# ENSO / Atlantic (2)



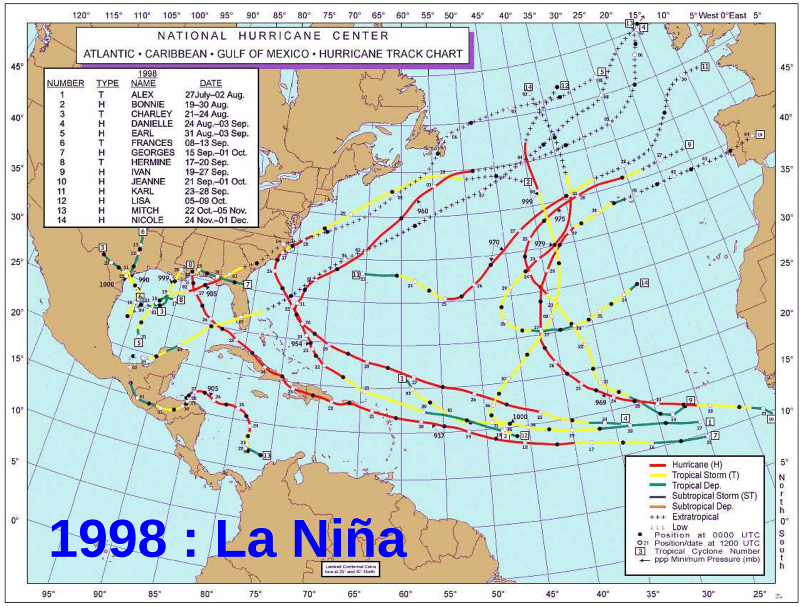

<u>Changes in the vertical wind shear</u>
are the most important environmental factor
in modulating the TC activity over the Atlantic.

# TROPICAL CYCLONES VARIABILITY
# ENSO / Atlantic (3)

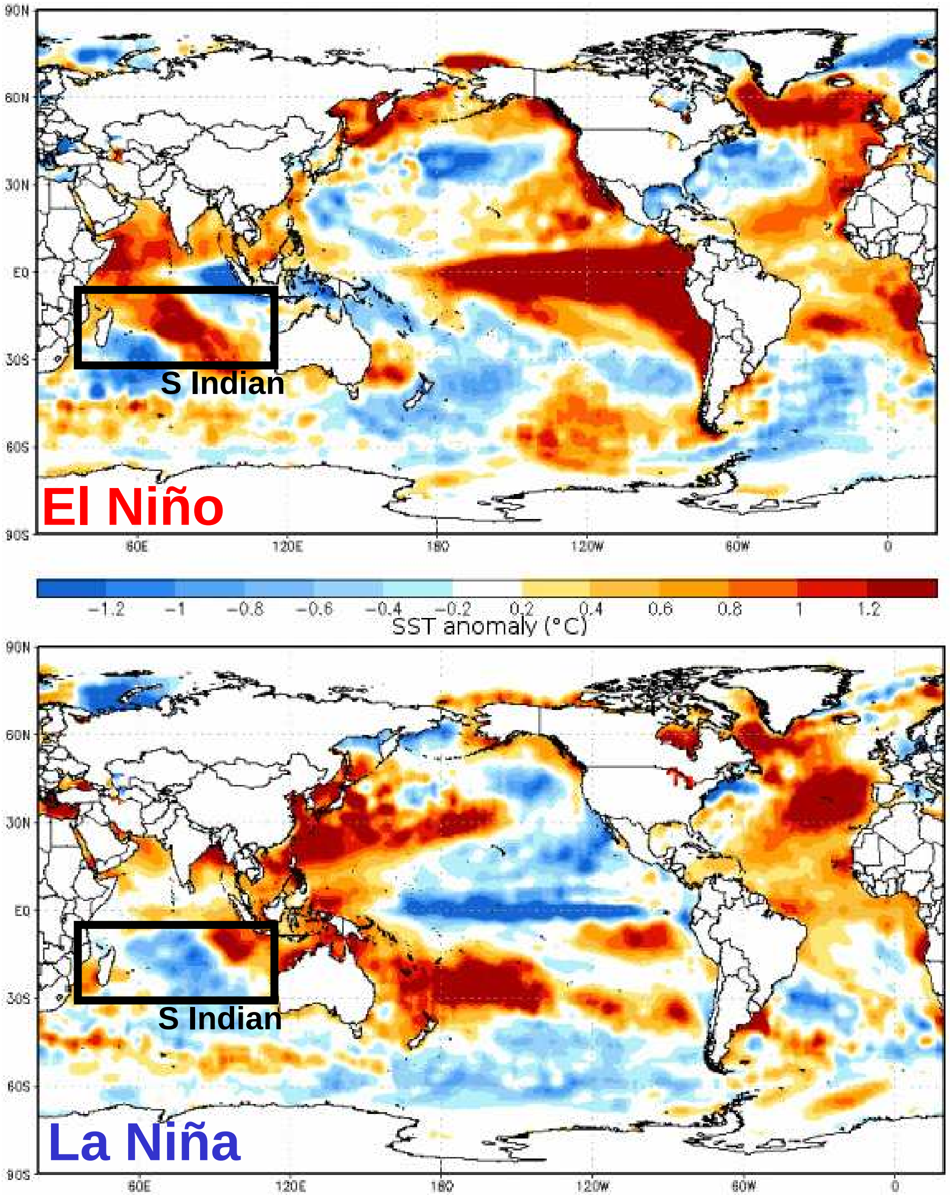



During “El Niño”, the warm pool and tropical convection shift eastward to the NE Pacific. The <u>enhanced upper-level divergent outflows</u> from the Walker circulation cause <u>subsidence</u> and upper-level westerly winds <u>intensifying the vertical wind shear</u>, over the Caribbean and tropical Altantic.

“La Niña” has a profound impact on hurricane <u>number</u>, <u>lifetime</u>, <u>intensity</u> and <u>landfall probability</u>. There is a <u>20:1 ratio in median damage per year</u> during the opposite phases (3 billion USD in La Niña vs. 150 million USD in El Niño.



# TROPICAL CYCLONES VARIABILITY
# ENSO / South Indian (1)

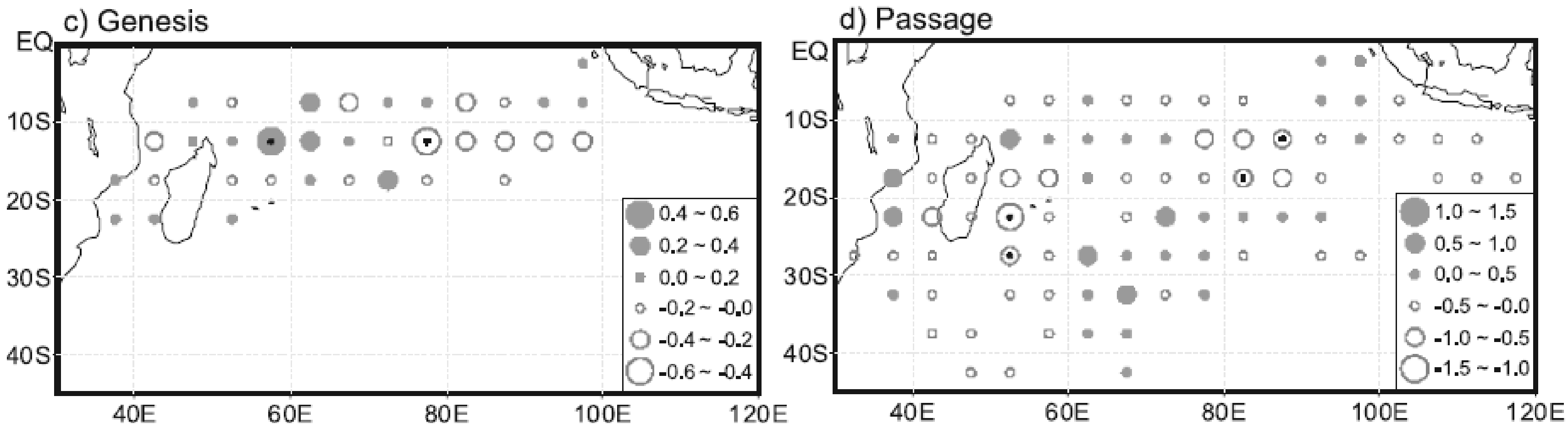



Conflicting influences of ENSO-related SST and upper-level westerlies anomalies.
No statistically significant changes in TC numbers during El Niño or La Niño seasons.

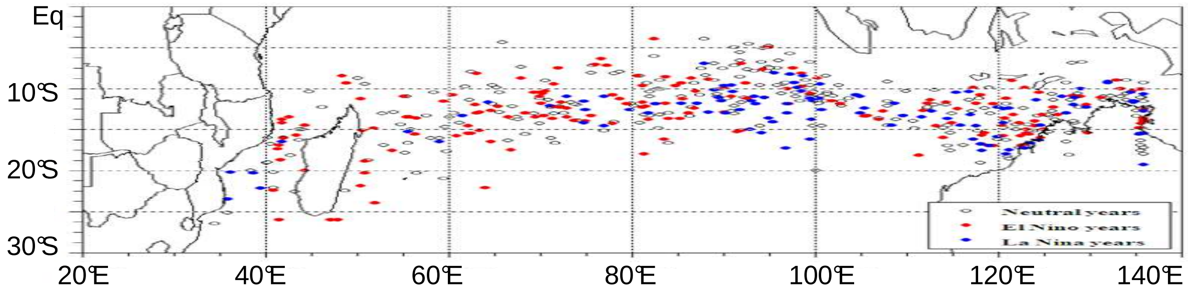
# TROPICAL CYCLONES VARIABILITY
# ENSO / South Indian (2)

**Ho *et al.* 2006** : *J. Geophys. Res.*, <u>111</u>, D22101

El Nino minus La Nina




**Kuleshov *et al.* 2006** : *Ann. Geophys.*, <u>27</u>, 2523-2538

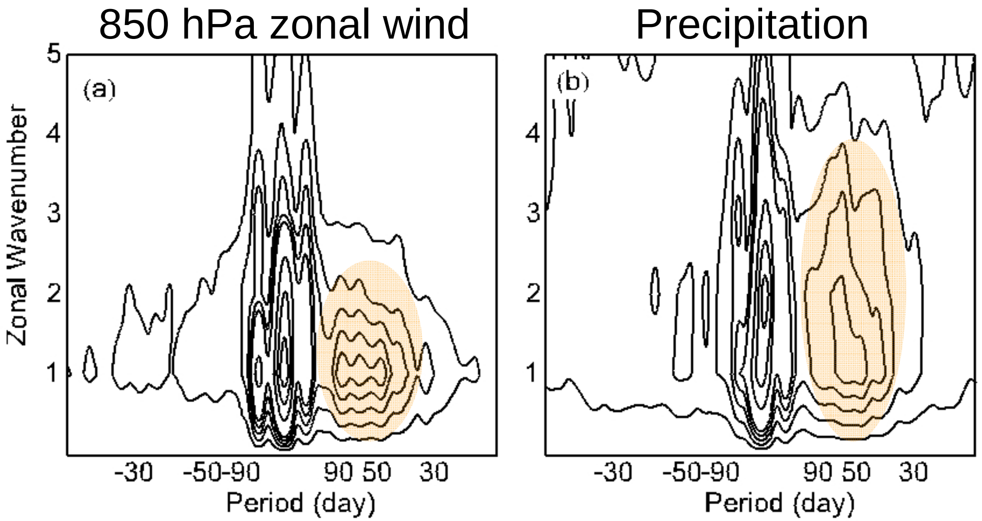



The <u>formation area</u> for tropical cyclones in the south Indian ocean tends to shift west in El Niño compared to La Niña seasons

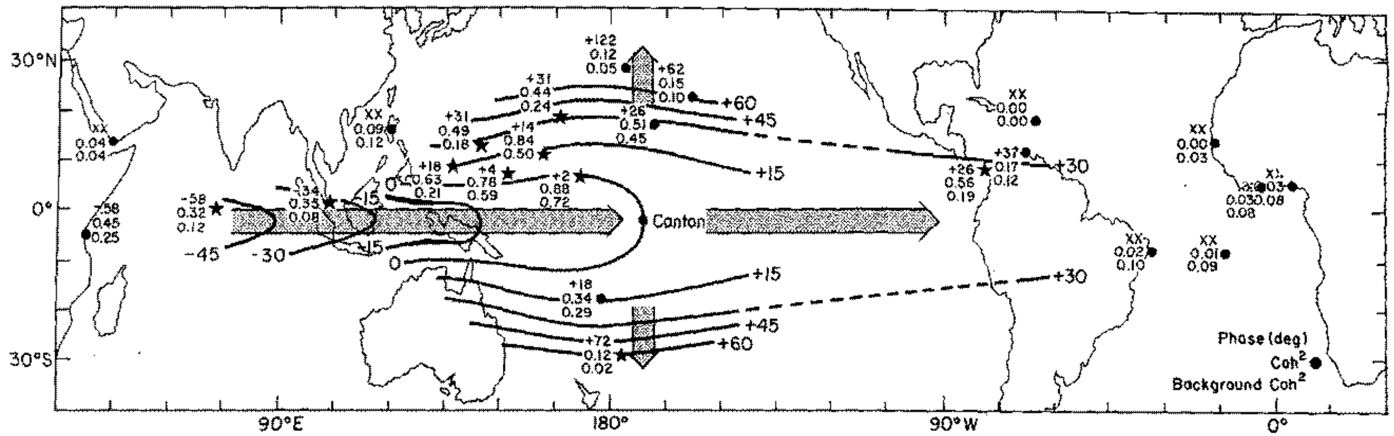
(*changes in low-level vorticity, mid tropospheric humidity, wind shear ?*)

# Madden-Julian Oscillation – MJO (1)

**Madden & Julian 1972** : *J. Atmos. Sci.*, 29, 1109-1123 + 1994 : *Mon. Wea. Rev.*, 122, 814-837
**Zhang 2005** : *Rev. Geophys.*, 43, 1-36

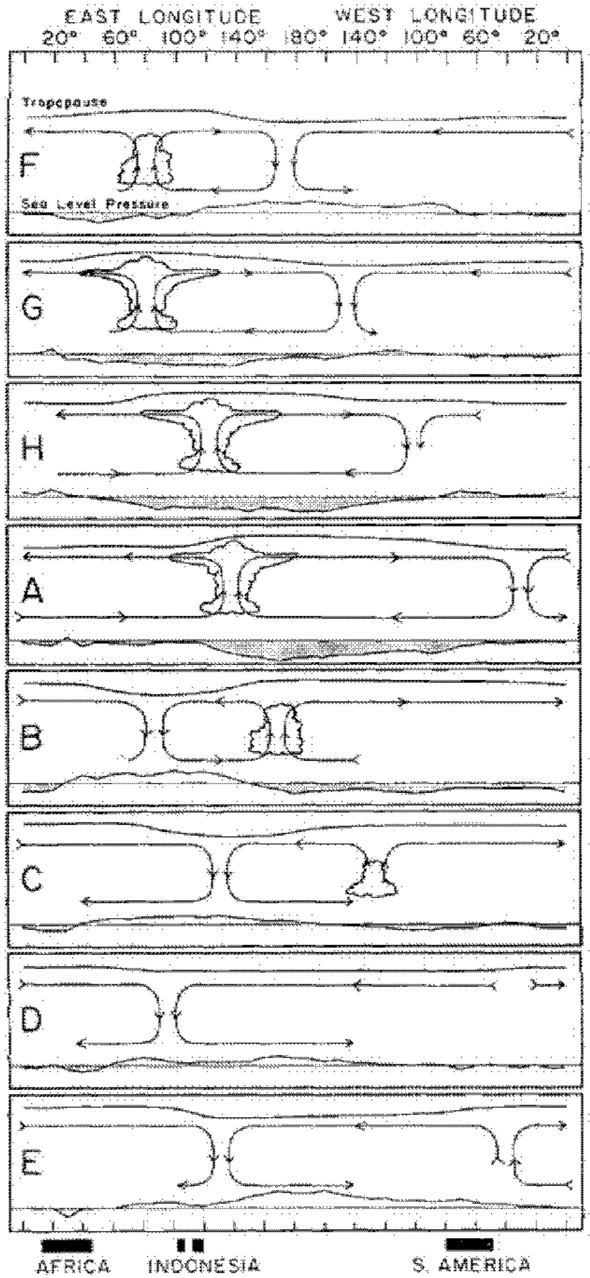



Time-space power spectra of (a) 850 hPa zonal wind (NCEP/NCAR reanalysis) and (b) precipitation [*Xie and Arkin*, 1997] for 1979 through 1998, averaged over 20°N–20°S and 60°–180°E. Positive (negative) periods correspond to eastward (westward) propagating power. Data resolutions for the spectra are pentad in time and 10° in longitude.



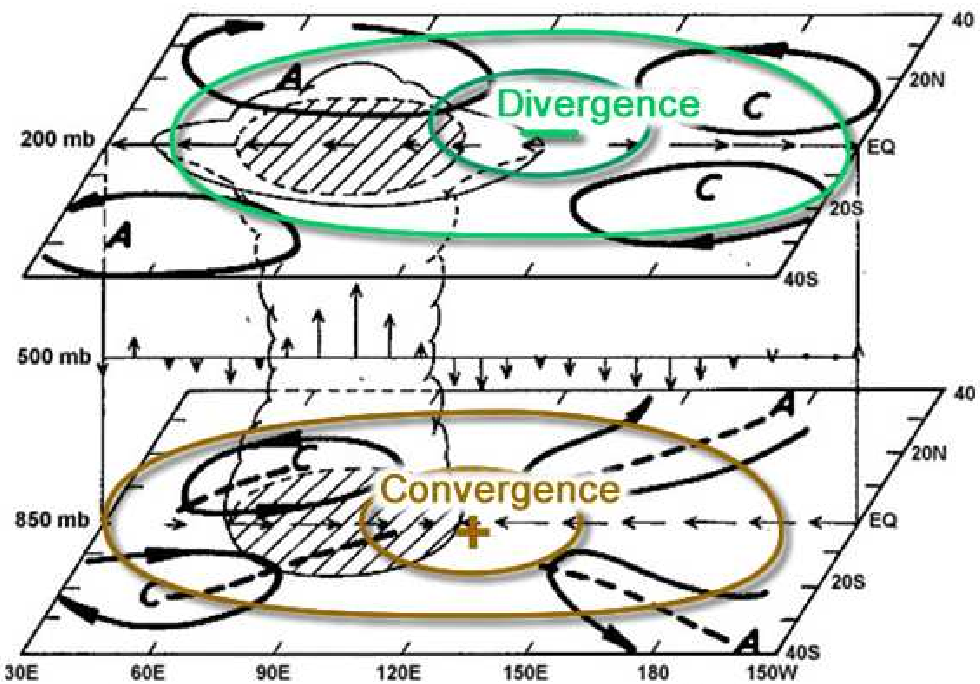

Mean phase angles (deg), coherence squares, and background coherence squares for approximately the 36–50-day period range of cross spectra between surface pressures at all stations and those at Canton. The plotting model is given in the lower right-hand corner. Positive phase angle means Canton time series leads. Stars indicate stations where coherence squares exceed a smooth background at the 95% level. Mean coherence squares at Shemya (52.8°N, 174.1°E) and Campbell Island (52.6°S, 169.2°E) (not shown) are 0.08 and 0.02, respectively. Both are below their average background coherence squares. Values at Dar es Salaam (0.8°S, 39.3°E) are from a cross spectrum with Nauru. The arrows indicate propagation direction (adapted from Madden and Julian 1972).

# Madden-Julian Oscillation – MJO (2)



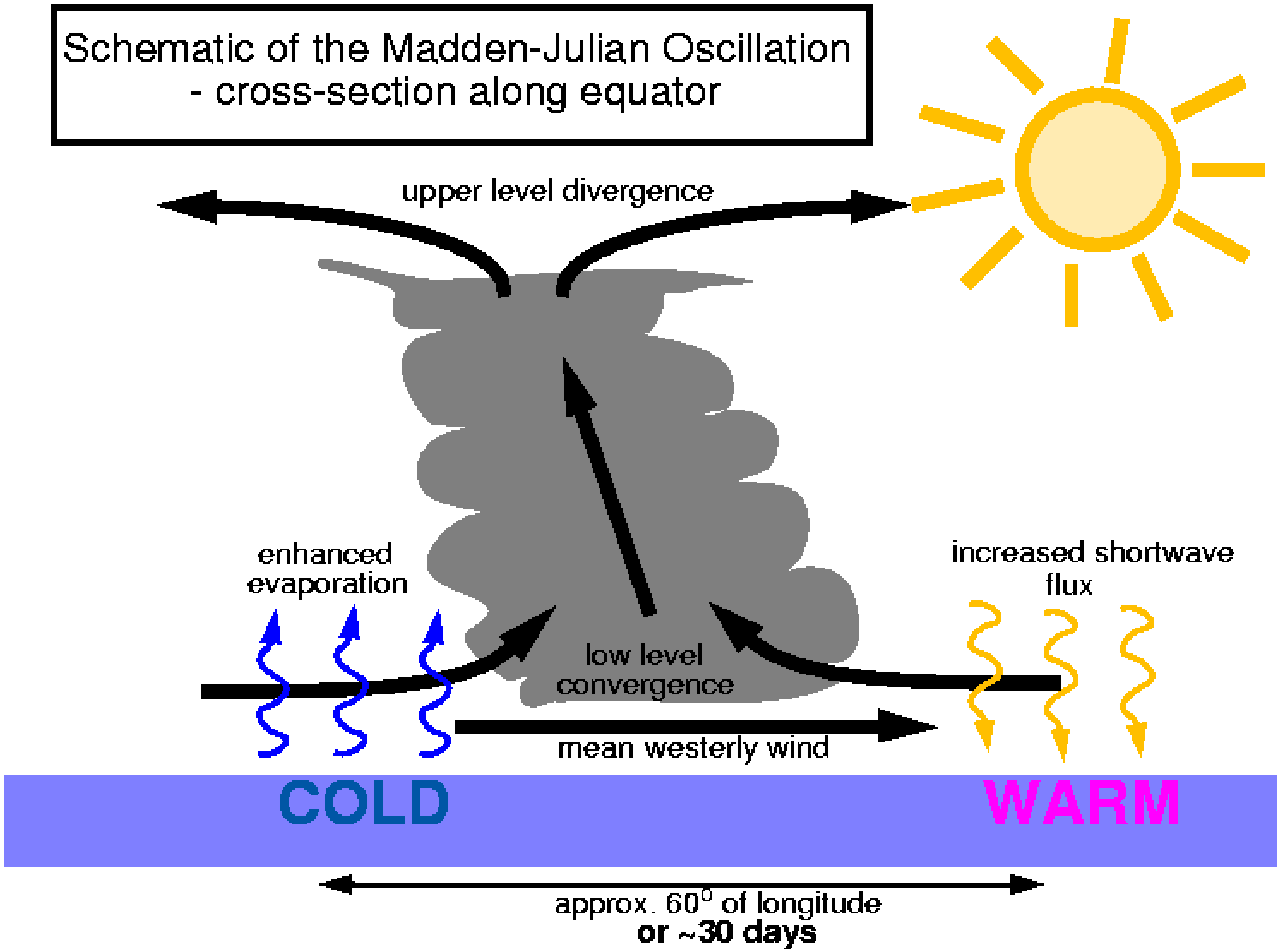

Longitude-height schematic diagram along the equator illustrating the fundamental large-scale features of the Madden-Julian Oscillation (MJO) through its life cycle (from top to bottom). Cloud symbols represent the convective center, arrows indicate the zonal circulation, and curves above and below the circulation represent perturbations in the upper tropospheric and sea level pressure.

Schematic Depiction of the Large-scale Wind Structure of the MJO



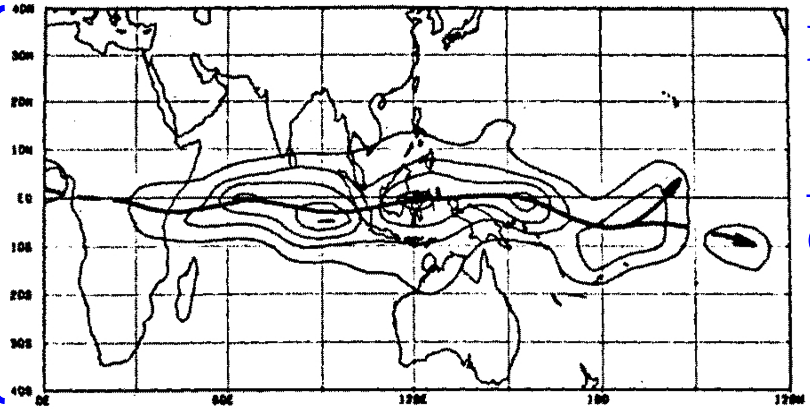

Schematic depiction of the large-scale wind structure of the MJO. The cloud symbol indicates the convective center. Arrows represent anomalous winds at 850 and 200 hPa and the vertical motions at 500 hPa. "A" and "C" mark the anticyclonic and cyclonic circulation centers, respectively. Dashed lines mark troughs and ridges. From *Rui and Wang* [1990].

# Madden-Julian Oscillation – MJO (3)



# Madden-Julian Oscillation – MJO (4)

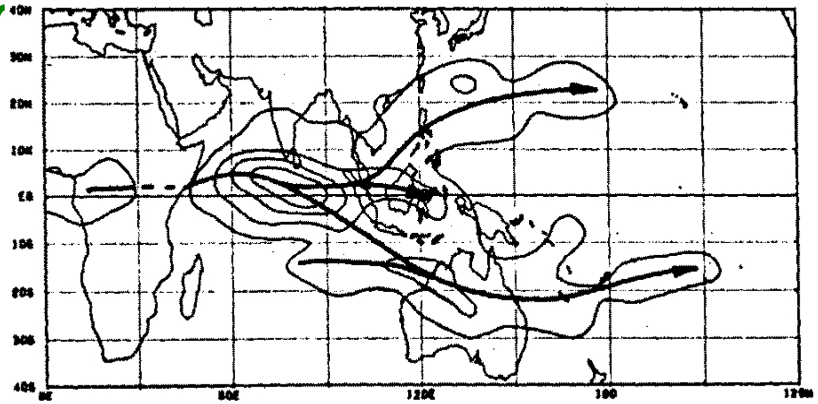
**« Strict » MJO**



**Boreal winter / Austral summer :**

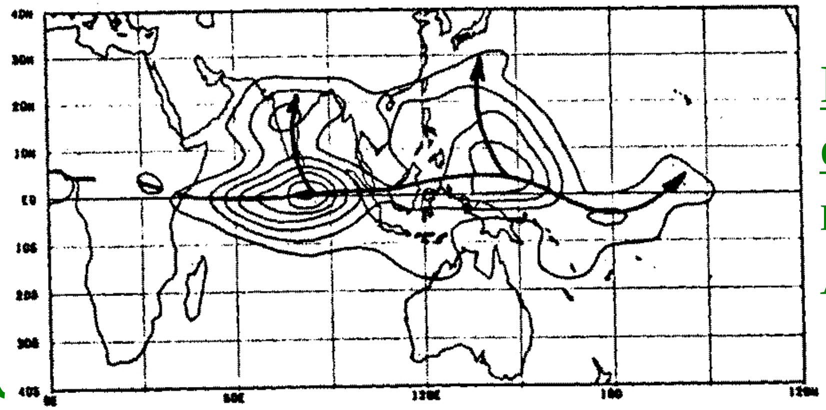
Strickly eastward-moving cloud complexes

**Boreal Summer Intra-Seasonal Oscillation (BSISO)**



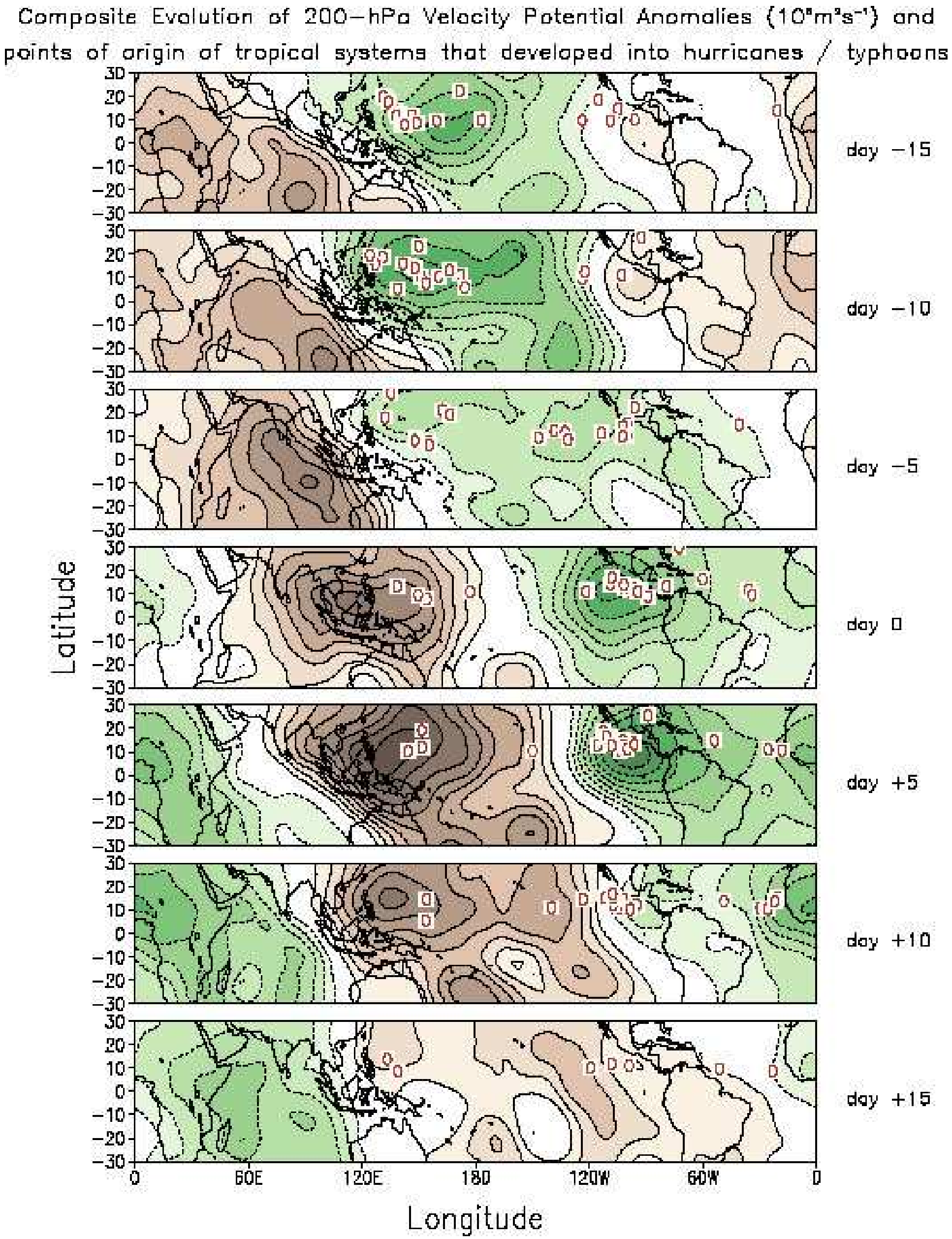
**Boreal Summer :**

Eastward complexes that split either to the north over to the south over the Indian ocean



Eastward complexes that are connected with cloud systems that move northward into southern Asia

# TROPICAL CYCLONES VARIABILITY : MJO



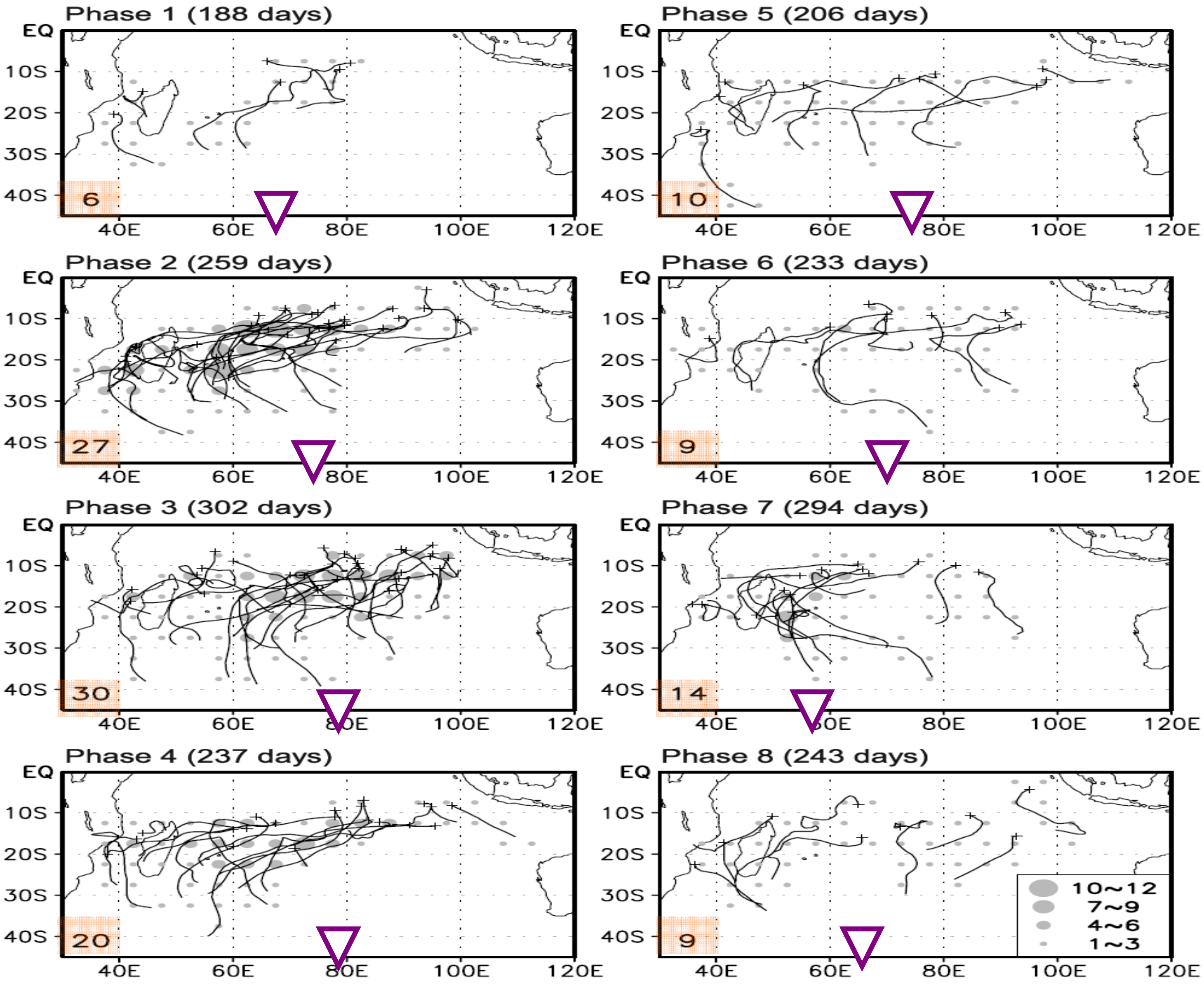

**Higgins & Shi 2001 :** *J. Climate*, 14, 403-417

*The points of origin of tropical cyclones that developed into hurricanes / typhoons ar shown as open circles.*
*The green (brown) shading roughly corresponds to regions where convection is favored (suppressed) as represented by 200-hPa velocity potential anomalies.*

The MJO produce a strong modulation of TC activity, in relation with associated variations in low- and upper-level winds, vertical wind shear, atmospheric humidity and temperature, organized convection, SST, …

# TROPICAL CYCLONES VARIABILITY
# MJO / South Indian

**Ho et al. 2006 :**
*J. Geophys. Res.*, 111,
D22101

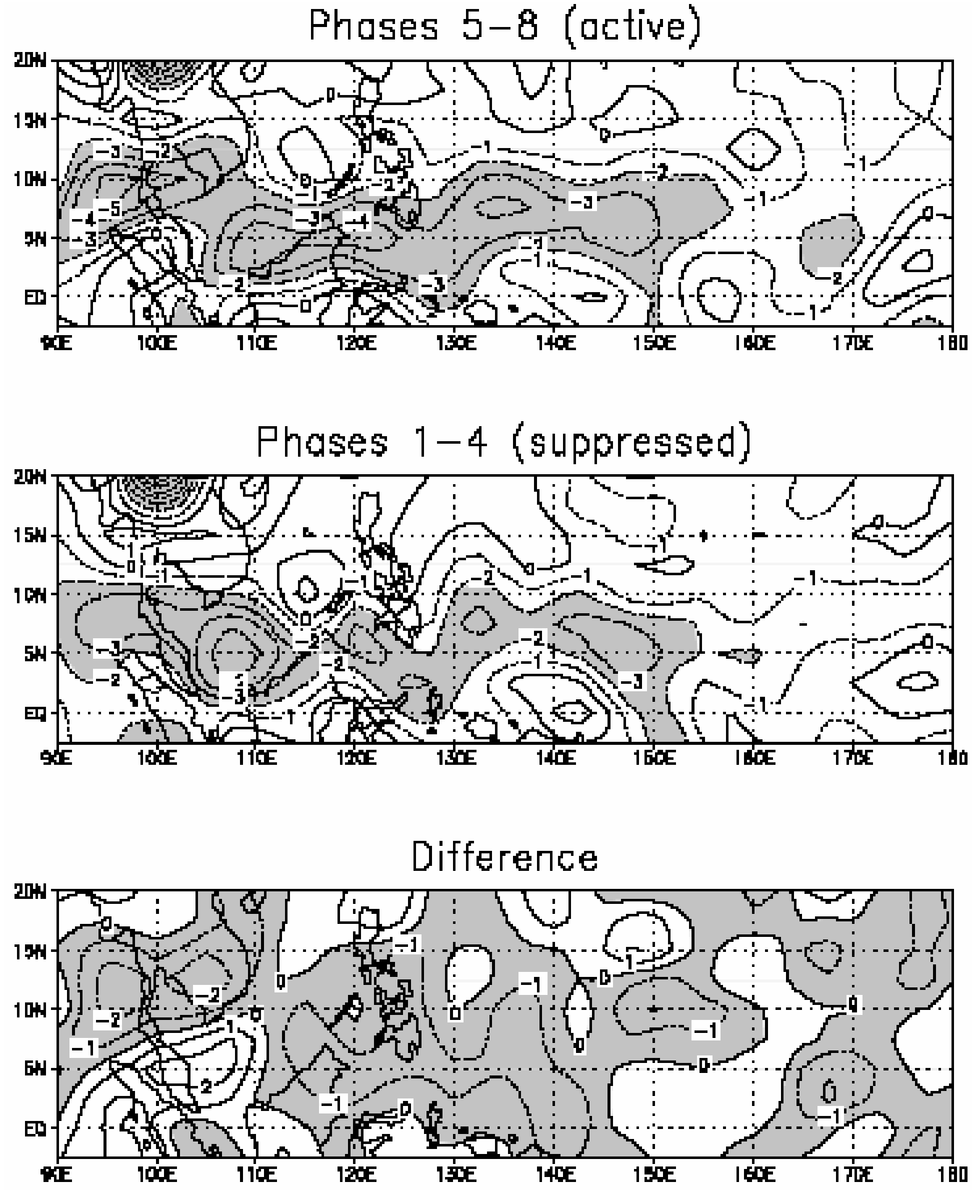



Genesis and track of TCs for each MJO phase.

*The inverted triangles are the median of genesis longitudes.*

*TC genesis numbers are shown in the bottom left corner for the corresponding MJO phase.*

# TROPICAL CYCLONES VARIABILITY
# MJO / western North Pacific



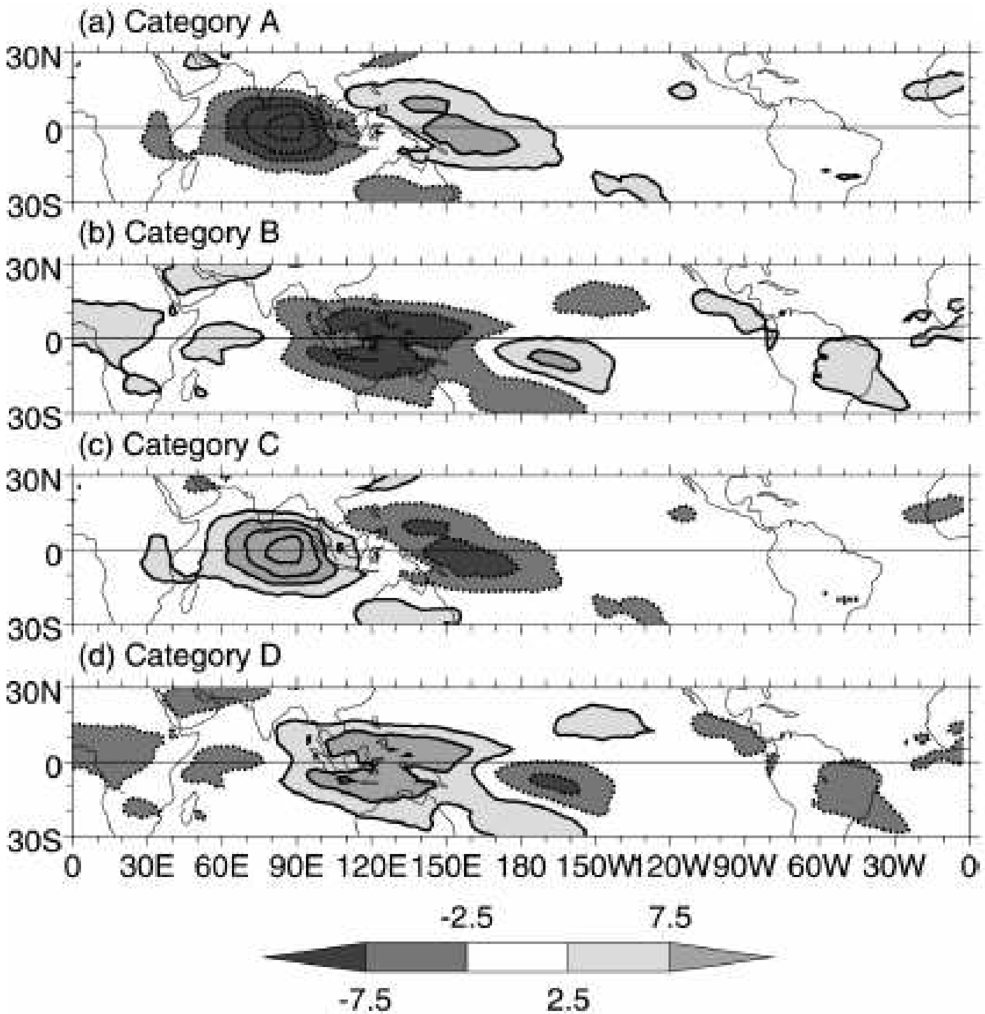

**Sobel & Maloney 2000 :**
*Geophys. Res. Lett.*,
27, 1739-1742

Convergence is larger in the active MJO phase than during the suppressed phase by about 1 x $10^{-6}$ $s^{-1}$.
The tongue of large convergence also shifts slightly northward in the active phase.
NW Pacific tropical cyclones are more frequent during the active phase, because of the existence of a larger number of precursor depressions.

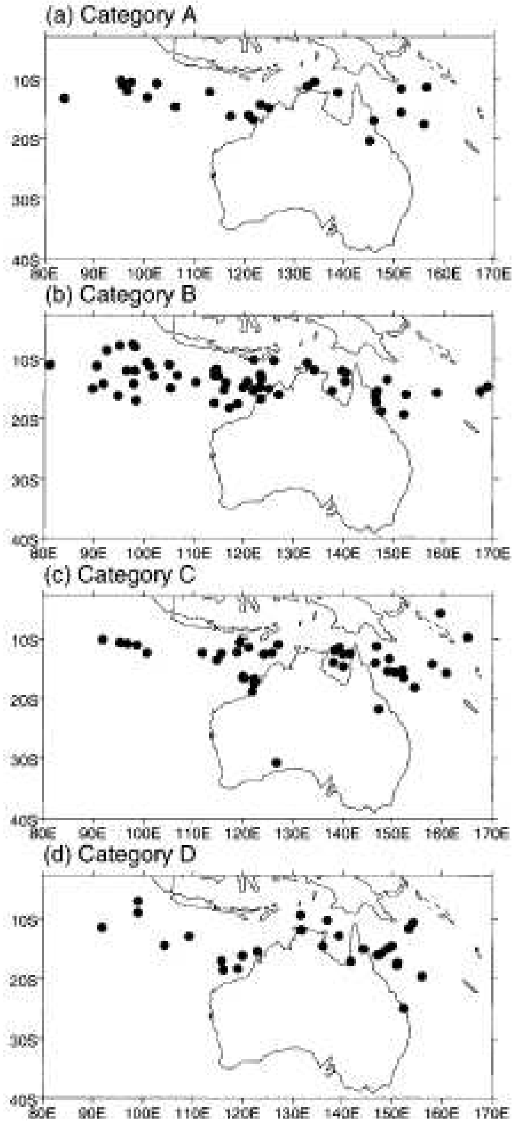
*Group velocity divergence at 850 hPa composited over the active (top) and suppressed (middle) phase of the MJO, in units of $10^{-6}$ $s^{-1}$.*

# TROPICAL CYCLONES VARIABILITY
# MJO / Australian basin

**Hall et al. 2001 :** *Mon. Wea. Rev.*, <u>129</u>, 2970–2982




*Anomaly maps of OLR for MJO category*




*TC genesis locations for MJO category*

# TROPICAL CYCLONES VARIABILITY
# MJO / eastern North Pacific

**Maloney & Hartmann 2000 :** *Science* , 287 , 2002-2004

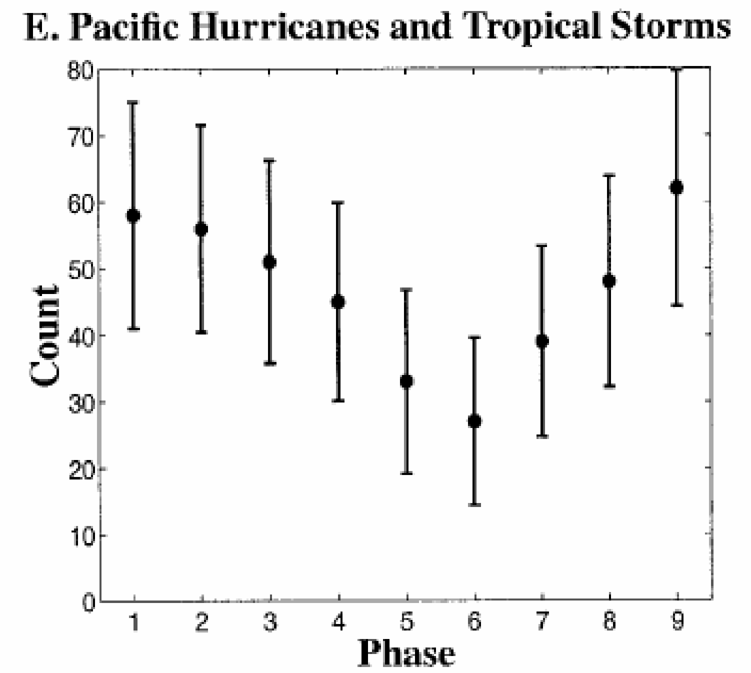



FIG. 10. Number of hurricanes and tropical storms as a function of MJO phase for the eastern Pacific Ocean hurricane region during May–Nov 1979–95. Error bars represent 95% confidence limits.

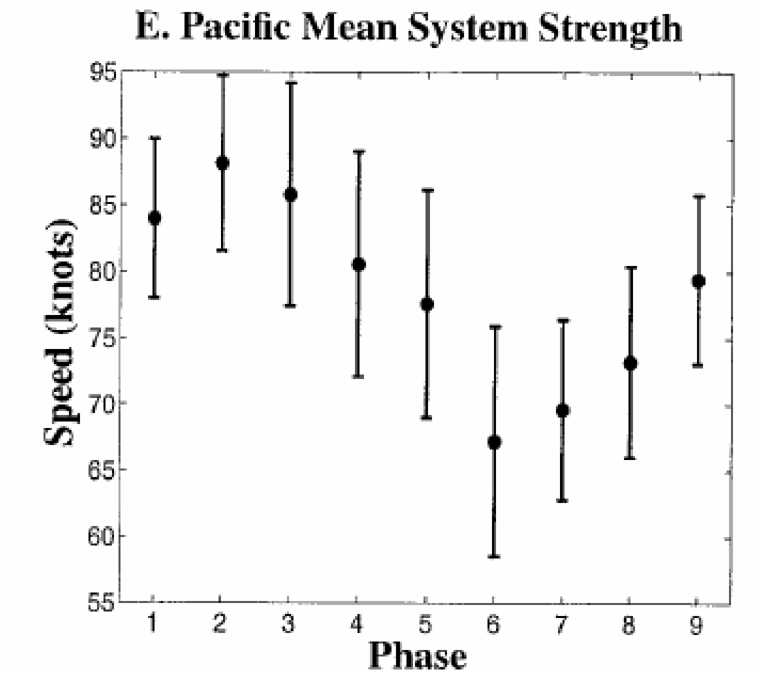
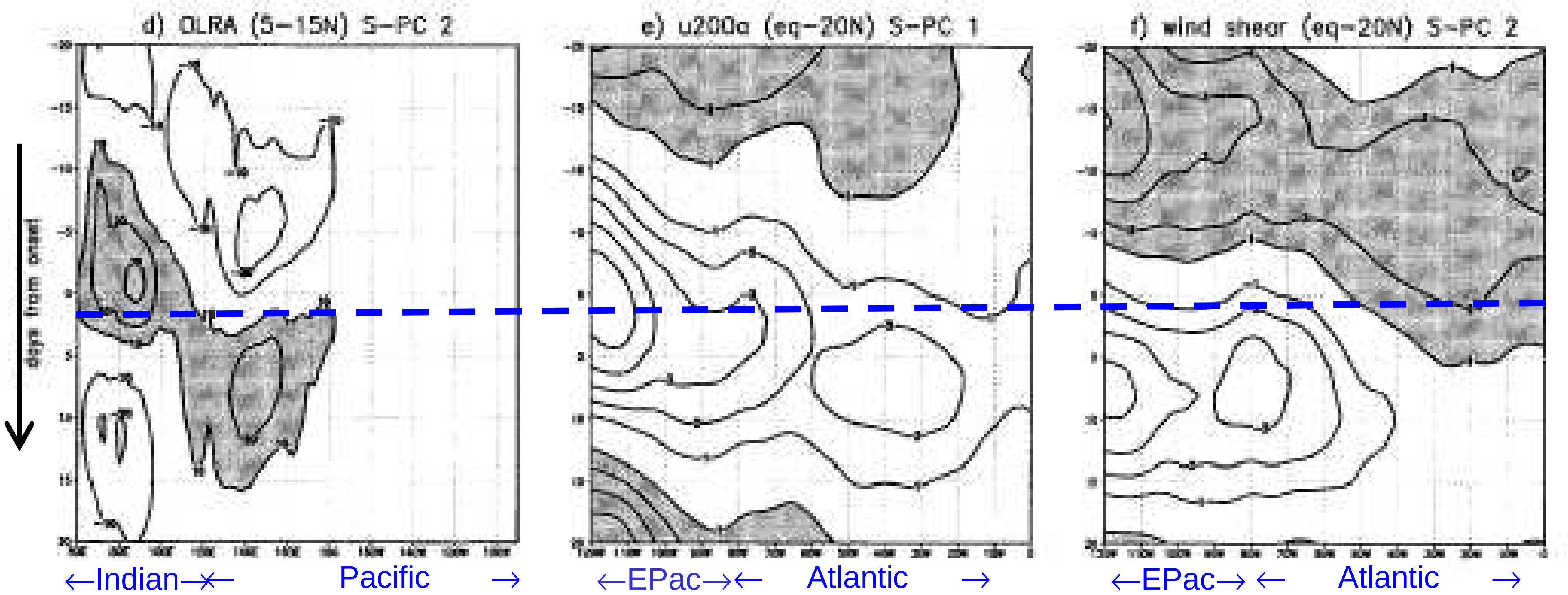



FIG. 11. Average strength (kt) of hurricanes and tropical storms as a function of MJO phase for the eastern Pacific Ocean hurricane region during May–Nov 1979–95. Error bars represent 95% confidence limits.

Over twice the number of named tropical systems exist in Phases 1 and 2. A pronounced cycle in system strength is also seen during the progression through the phases.

# TROPICAL CYCLONES VARIABILITY
# MJO / Atlantic (1)

**Mo 2000 :** Mon. Wea. Rev., <u>128</u>, 4097–4107

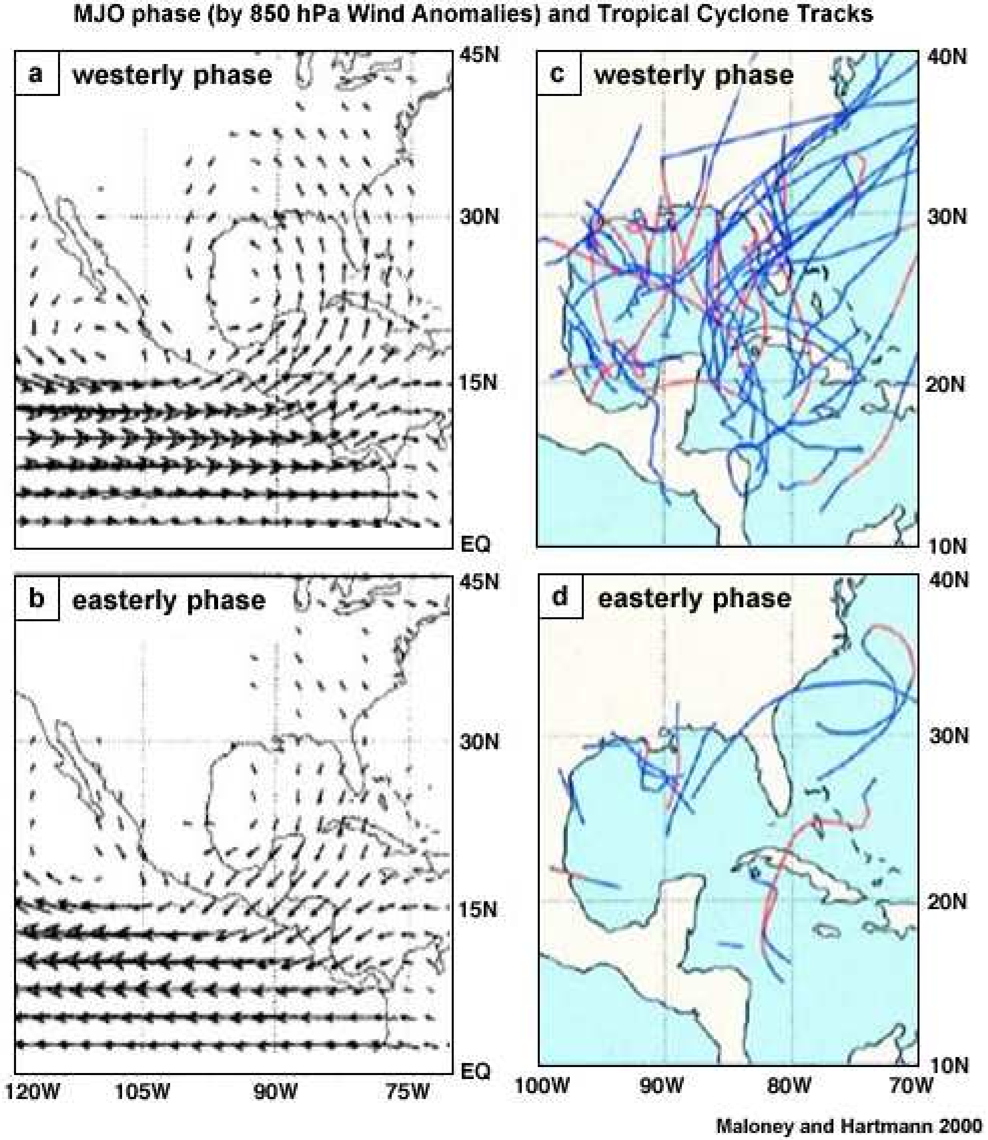



Tropical cyclones in the Atlantic are <u>more likely to occur when convection over the Indian Ocean is enhanced</u>.

The response of the <u>wind shear in the Main Development Region</u> (5-15°N ; 30-120°W) is <u>remotely forced</u> by MJO from the eastern hemisphere.

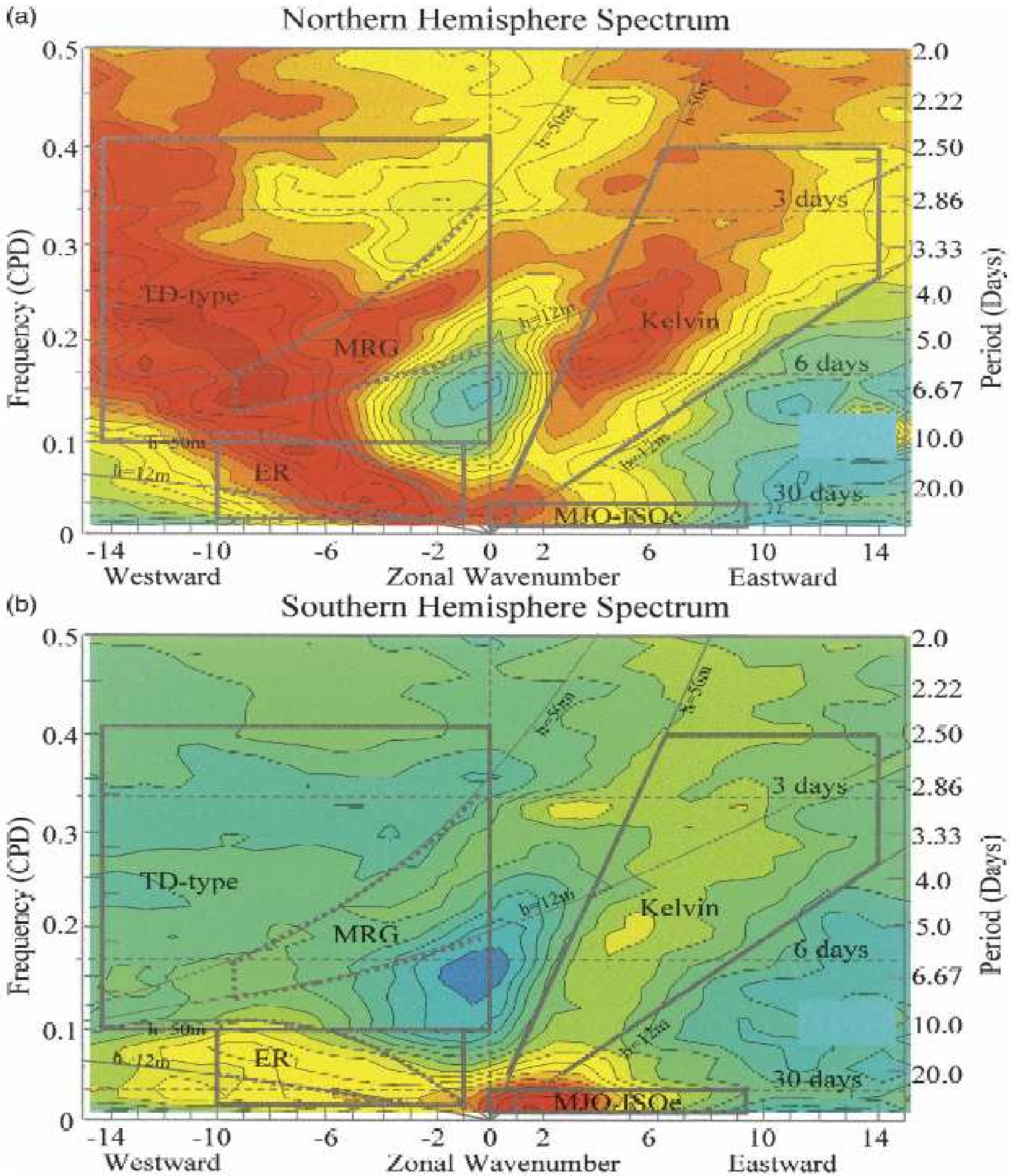
# TROPICAL CYCLONES VARIABILITY
# MJO / Atlantic (2)

**Maloney & Hartmann 2000 :** *Science* , 287 , 2002-2004



# TROPICAL CYCLONES VARIABILITY

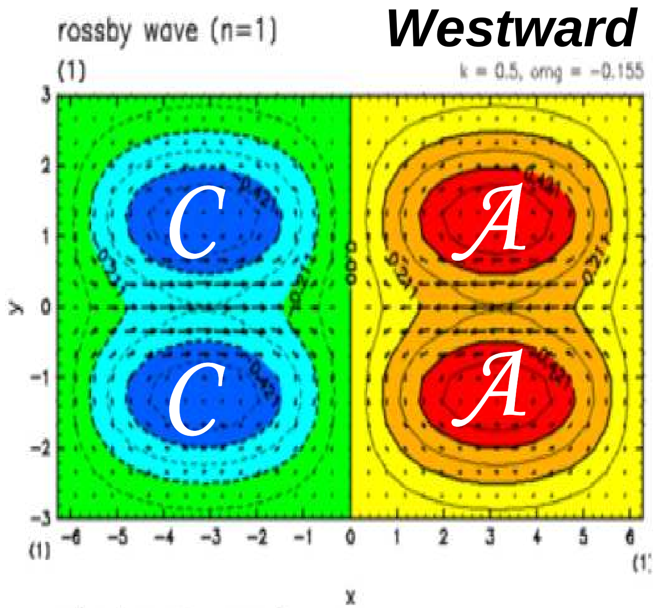
# Convectively coupled equatorial waves (1)

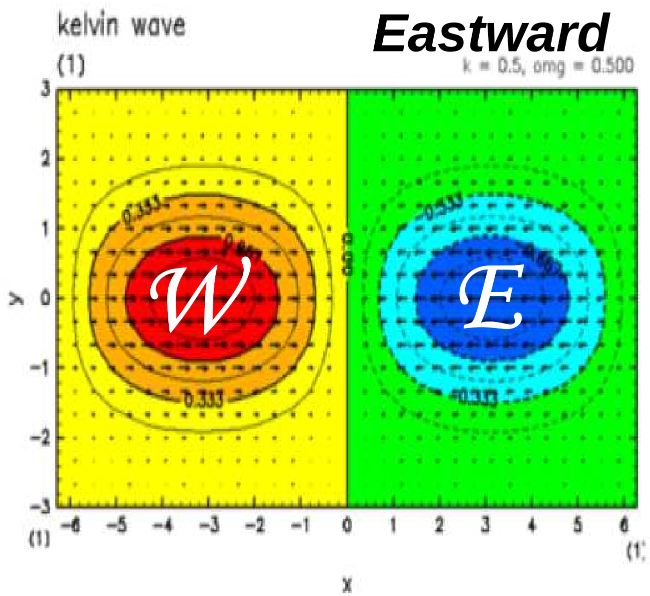


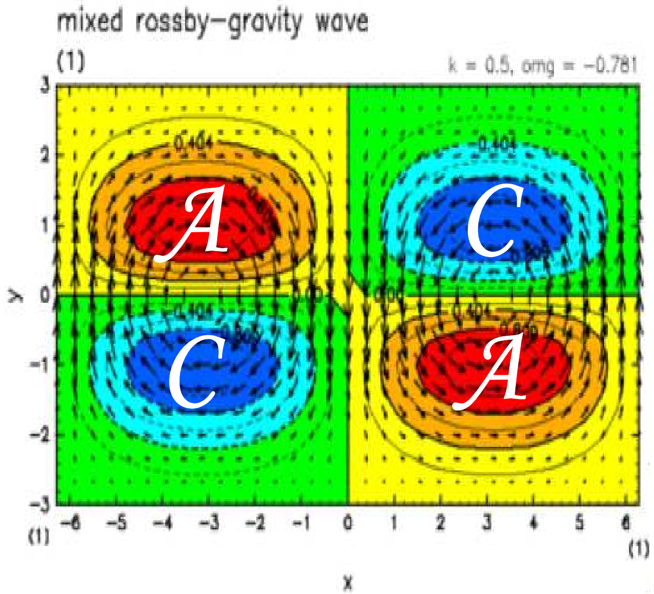

**Frank & Roundy 2006 :**
*Mon. Wea. Rev.*, 134, 2397-2417

The MJO is by far the most active wave type in the Southern Hemisphere. Higher-frequency tropical waves are all much more prominent in the Northern Hemisphere.

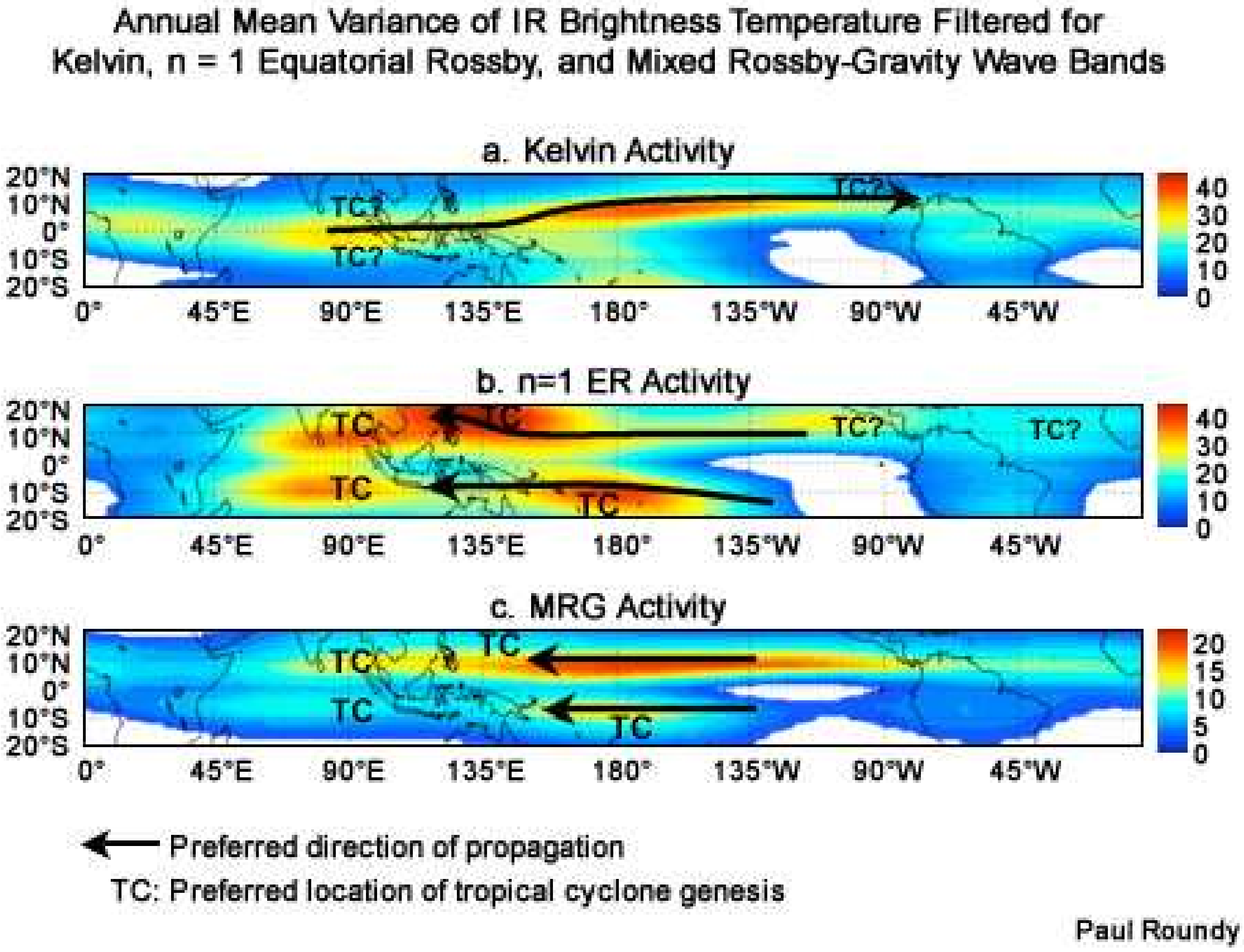
# TROPICAL CYCLONES VARIABILITY
# Convectively coupled equatorial waves (2)



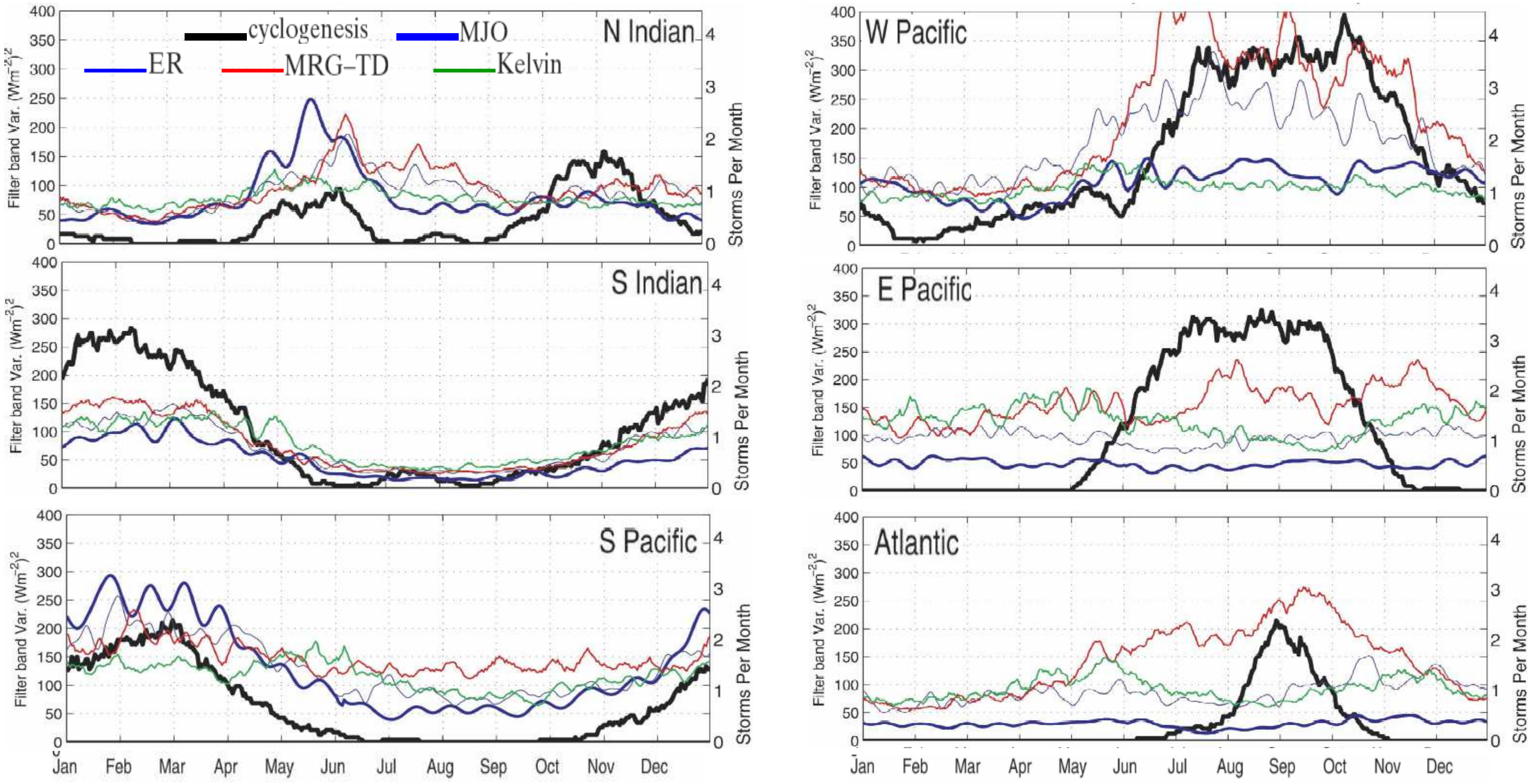



# TROPICAL CYCLONES VARIABILITY
# Convectively coupled equatorial waves (3)



# TROPICAL CYCLONES VARIABILITY
# Convectively coupled equatorial waves (4)

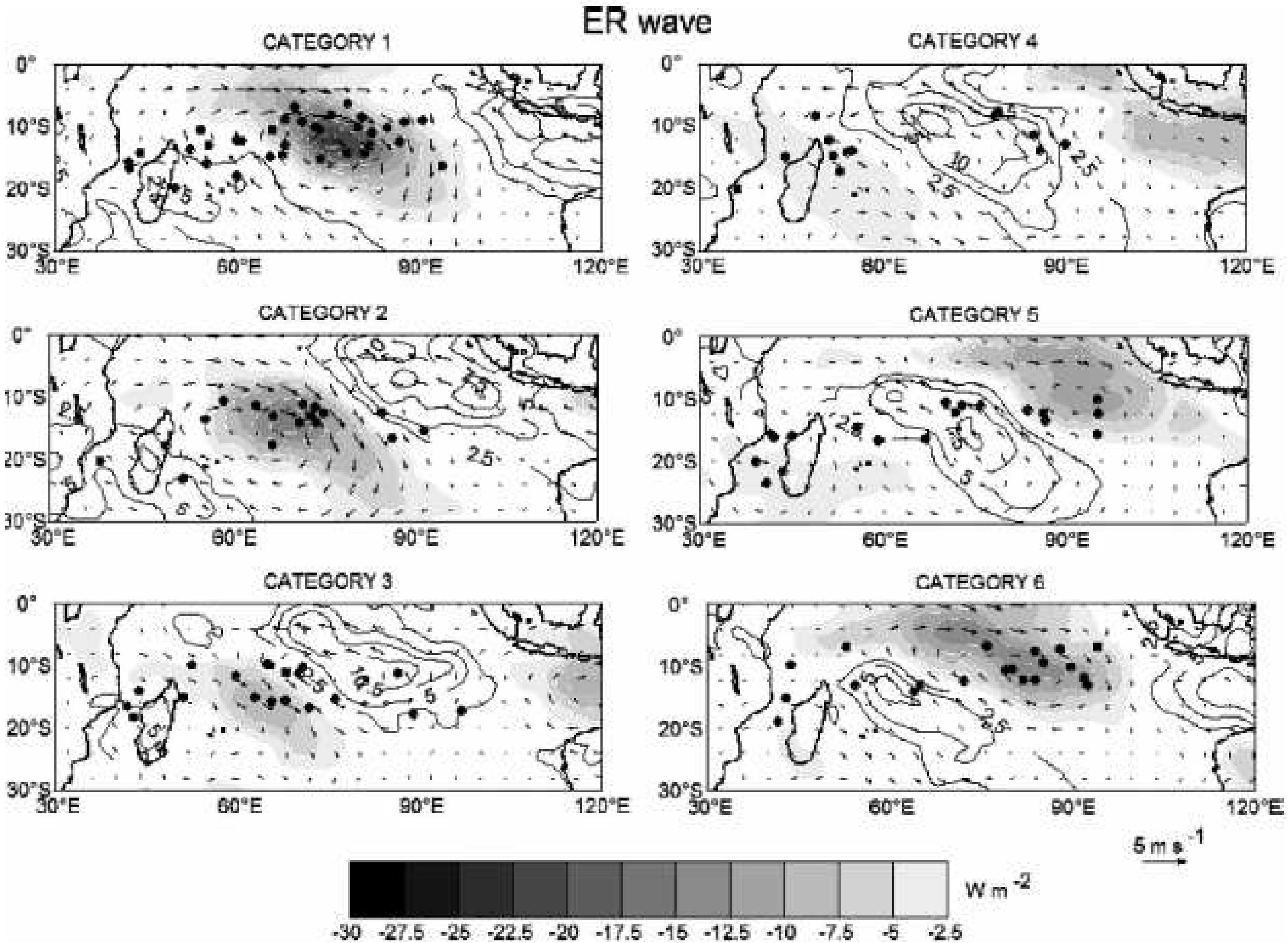



Comparing Figs. 2 and 4 it is clear that the low-frequency MJO band and ER band variances that dominate the Southern Hemisphere spectrum are strongly seasonal, and they vary in phase with the cyclone season in the two Southern Ocean basins and for the first peak of the North Indian season. Activity in the Kelvin band tends to follow the same pattern, though the cycles are somewhat less distinct than for the MJO and ER bands.

All of the wave types (except the MJO) are more active in the Northern than in the Southern Hemisphere. This is particularly true for the MRG–TD-type band, which varies strongly and in phase with the cyclone season in the North Atlantic and the northwest Pacific.

# TROPICAL CYCLONES VARIABILITY
# Equatorial Rossby waves / S Indian (1)

Bessafi & Wheeler 2006: *Mon. Wea. Rev.*, 134, 638-656

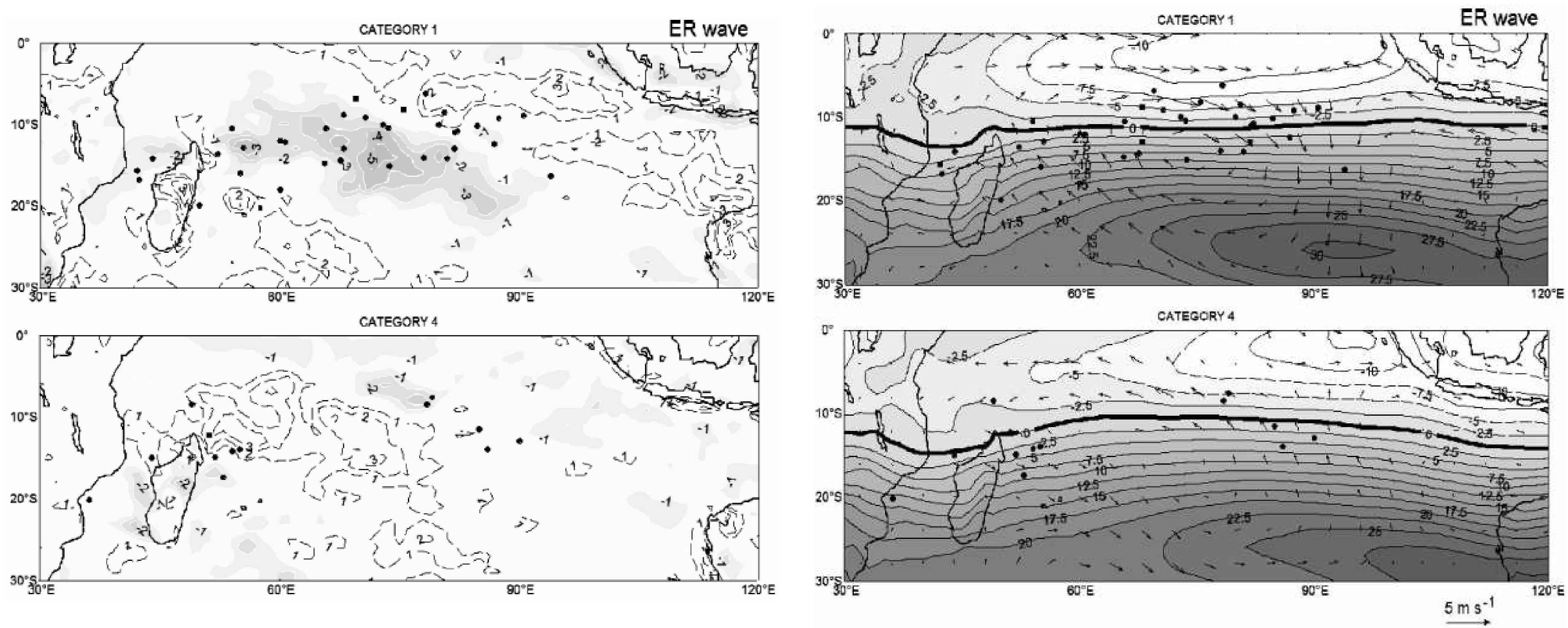



*Composite 850-hPa wind (vectors) and OLR anomalies (<0 : shading, >0 : contours) for **each category of the ER-wave**.*

*Dots represent the TC genesis location for each category*

# TROPICAL CYCLONES VARIABILITY
# Equatorial Rossby waves / S Indian (2)

*850-hPa vorticity anomaly & TC genesis* *850-hPa wind anomaly & wind shear*




The large modulation of TC genesis in the SW Indian ocean by the ER-waves is attributable to the large variation of the low-level vorticity and coincidence with enhanced convection.

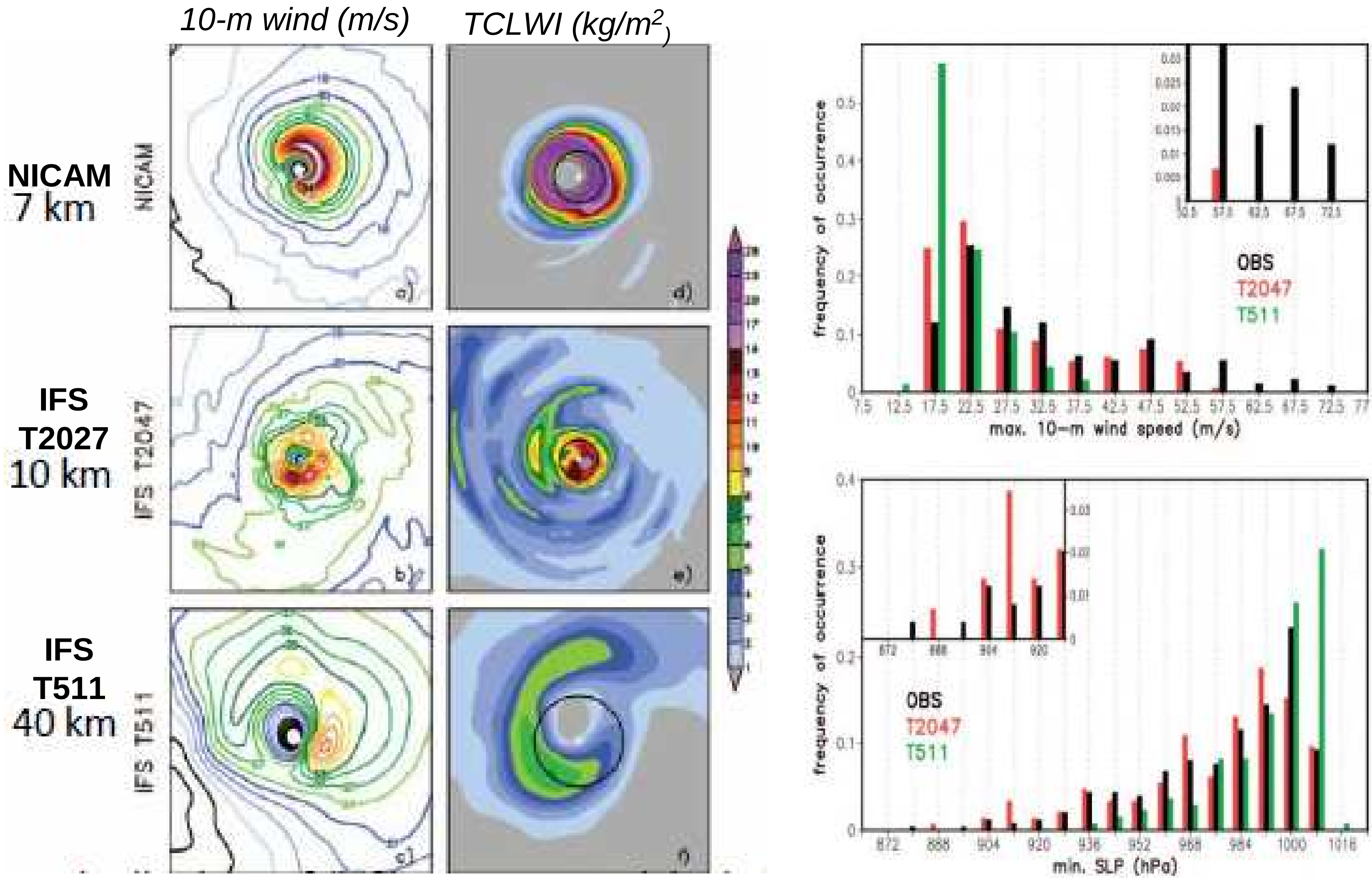
The smaller changes in vertical wind shear appears less important.

# TROPICAL CYCLONES VARIABILITY

- TC genesis in the different basins has a clear modulation signal by large-scale atmospheric variability.
- Intraseasonal and interannual disturbances have some predictability. These time scales are relevant for extending the current TC predictability.
- Future high resolution (convection permitting) global (non-hydrostatic) models will promote realistic process-resolving intraseasonal simulations.

# Project ATHENA : High Spatial Resolution in Global Climate Models

**Kinter *et al.* 2013 :** *Bull. Amer. Meteor. Soc.*, 94, 231–245



# TROPICAL CYCLONES SEASONAL FORECAST

**<u>GOAL</u> :** (TS+TC) number and days, TC number and days, Cat-3+ number and days, accumulated cyclone energy ( ACE = $\int V_{max}{}^2 dt$ ), per season

**<u>STATISTICAL METHODS</u> :**

- predictors = large-scale parameters related to TC activity few months later (e.g. ENSO, SST, wind shear, SLP, atmospheric circulation, convective activity, … ) ;
- regression equations based on climatology
- analog seasons
- CSU, NOAA, TSR, Cuban Institute of Meteorology, BoM, Shangai Typhoon Institute

**<u>DYNAMICAL METHODS</u> :**

- seasonal forecasting systems (up to 6 months)
- predictors and regression
- track the « TC-like vortices »

# TROPICAL CYCLONES SEASONAL FORECAST :
# CSU / Tropical Meteorology Project → Atlantic

| Forecast Parameter and 1981-2010 Median (in parentheses) | 4 April 2012 | Update 1 June 2012 | Update 3 Aug 2012 | Observed 2012 Total | % of 1981-2010 Median |
|---|---|---|---|---|---|
| Named Storms (NS) (12.0) | 10 | 13 | 14 | 19 | 158% |
| Named Storm Days (NSD) (60.1) | 40 | 50 | 52 | 99.50 | 166% |
| Hurricanes (H) (6.5) | 4 | 5 | 6 | 10 | 154% |
| Hurricane Days (HD) (21.3) | 16 | 18 | 20 | 26.00 | 122% |
| Major Hurricanes (MH) (2.0) | 2 | 2 | 2 | 1 | 50% |
| Major Hurricane Days (MHD) (3.9) | 3 | 4 | 5 | 0.25 | 6% |
| Accumulated Cyclone Energy (ACE) (92) | 70 | 80 | 99 | 129 | 140% |
| Net Tropical Cyclone Activity (NTC) (103%) | 75 | 90 | 105 | 121 | 117% |

The **2012 Atlantic hurricane season** was quite unusual, with near record-high numbers of named storms and named storm days observed. Conversely, the season was associated with a negligible amount of major hurricane activity.

This year's seasonal forecasts were somewhat of an under-prediction.

# TROPICAL CYCLONES SEASONAL FORECAST :
# CSU / Tropical Meteorology Project → Atlantic

| Forecast Parameter and 1981-2010 Median (in parentheses) | 10 April 2013 | Update 3 June 2013 | Update 2 Aug 2013 | Observed 2013 Total | % of 1981-2010 Median |
|---|---|---|---|---|---|
| Named Storms (NS) (12.0) | 18 | 18 | 18 | 13 | 108% |
| Named Storm Days (NSD) (60.1) | 95 | 95 | 84.25 | 35.75 | 59% |
| Hurricanes (H) (6.5) | 9 | 9 | 8 | 2 | 31% |
| Hurricane Days (HD) (21.3) | 40 | 40 | 35 | 3.75 | 18% |
| Major Hurricanes (MH) (2.0) | 4 | 4 | 3 | 0 | 0% |
| Major Hurricane Days (MHD) (3.9) | 9 | 9 | 7 | 0 | 0% |
| Accumulated Cyclone Energy (ACE) (92) | 165 | 165 | 142 | 30 | 32% |
| Net Tropical Cyclone Activity (NTC) (103%) | 175 | 175 | 150 | 43 | 42% |

While many of the large-scale conditions associated with active seasons were present (e.g., anomalously warm tropical Atlantic, absence of El Niño conditions, anomalously low tropical Atlantic sea level pressures), very dry mid-level air combined with mid-level subsidence and stable lapse rates to significantly suppress the **2013 Atlantic hurricane season**.