

A satellite view of Earth from space, showing a large tropical cyclone with a distinct eye and spiral cloud bands. The Earth's curvature is visible on the left side. In the top right corner, a portion of a satellite is visible, including a large white parabolic dish antenna and other instruments.

El Niño and Intense Tropical Cyclones

Roles of basin-to-basin frequency changes in the poleward shifts of the maximum intensity location in tropical cyclones

16 February 2016

Moon et al. (2015, Nature), Jin et al. (2014, Nature)
Moon et al. (2015, ERL), Kossin et al. (Nature)

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BRIEF COMMUNICATIONS ARISING

El Niño and intense tropical cyclones

ARISING FROM F.-F. Jin, J. Boucharel & I.-I. Lin *Nature* **516**, 82–85 (2014); doi:10.1038/nature13958

The El Niño/Southern Oscillation (ENSO) influences global climate as well as extreme weather events such as floods, droughts, and tropical cyclones, leading to large societal impacts globally^{1–3}. Jin *et al.*⁴

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NATURE | BRIEF COMMUNICATION ARISING

El Niño and intense tropical cyclones

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[Affiliations](#) | [Contributions](#)*Nature* **526**, E4–E5 (29 October 2015) | doi:10.1038/nature15546

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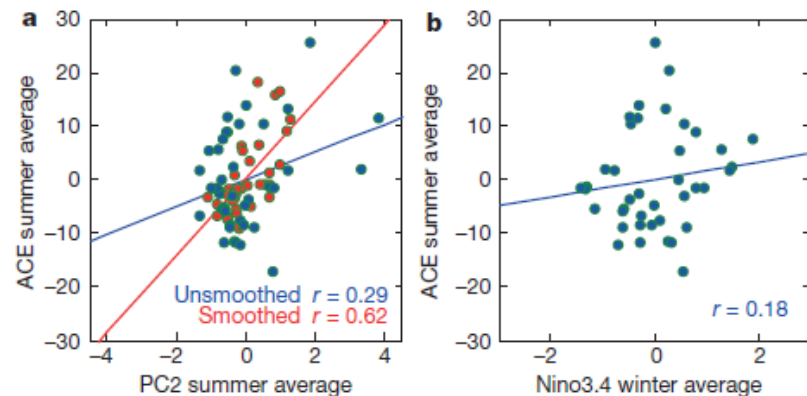


Figure 1 | Relationships of subsurface ocean heat delivered by El Niño (PC2) and the ENSO signal (Niño3.4) with tropical cyclone activity in the eastern North Pacific. **a**, Scatter plot of ACE against PC2 with smoothed (red) and unsmoothed (blue) data. **b**, Scatter plot of ACE against the Niño3.4 index. ACE and PC2 are averaged over the boreal summer and autumn (June to November) and Niño3.4 is averaged over the ENSO peak period (December to February) before the summer tropical cyclone season. Linear regressions (straight lines) and correlation coefficients r are shown. All data sets are detrended, and are unsmoothed except for the smoothing discussed above. For consistent comparisons with ref. 4, we used the same analysis period (1970–2009), methods, and data as in ref. 4, except for the smoothing. The subsurface ocean heat over the upper 105 m (T105) represents all the existing subsurface ocean conditions in the eastern North Pacific, whereas PC2 explains only 56% of the T105 variations through a process delivered by El Niño. Therefore, PC2 is the index explaining the relationship between subsurface ocean heat delivered by El Niño and tropical cyclone activity in ref. 4, although T105 is more closely related to tropical cyclone activity than PC2.

Eastern Pacific tropical cyclones intensified by El Niño delivery of subsurface ocean heat

F.-F. Jin^{1,3}, J. Boucharel¹ & I.-I. Lin²

The El Niño Southern Oscillation (ENSO) creates strong variations in sea surface temperature in the eastern equatorial Pacific, leading to major climatic and societal impacts^{1,2}. In particular, ENSO influences the yearly variations of tropical cyclone (TC) activities in both the Pacific and Atlantic basins through atmospheric dynamical factors such as vertical wind shear and stability^{3–6}. Until recently, however, the direct ocean thermal control of ENSO on TCs has not been taken into consideration because of an apparent mismatch in both timing and location: ENSO peaks in winter and its surface warming occurs mostly along the Equator, a region without TC activity. Here we show that El Niño—the warm phase of an ENSO cycle—effectively discharges heat into the eastern North Pacific basin two to three seasons after its wintertime peak, leading to intensified TCs. This basin is characterized by abundant TC activity and is the second most active TC region in the world^{5–7}. As a result of the time involved in ocean transport, El Niño's equatorial subsurface 'heat reservoir', built up in boreal winter, appears in the eastern North Pacific several months later during peak TC season (boreal summer and autumn). By means of this delayed ocean transport mechanism, ENSO provides an additional heat supply favourable for the formation of strong hurricanes. This thermal control on intense TC variability has significant implications for seasonal predictions and long-term projections of TC activity over the eastern North Pacific.

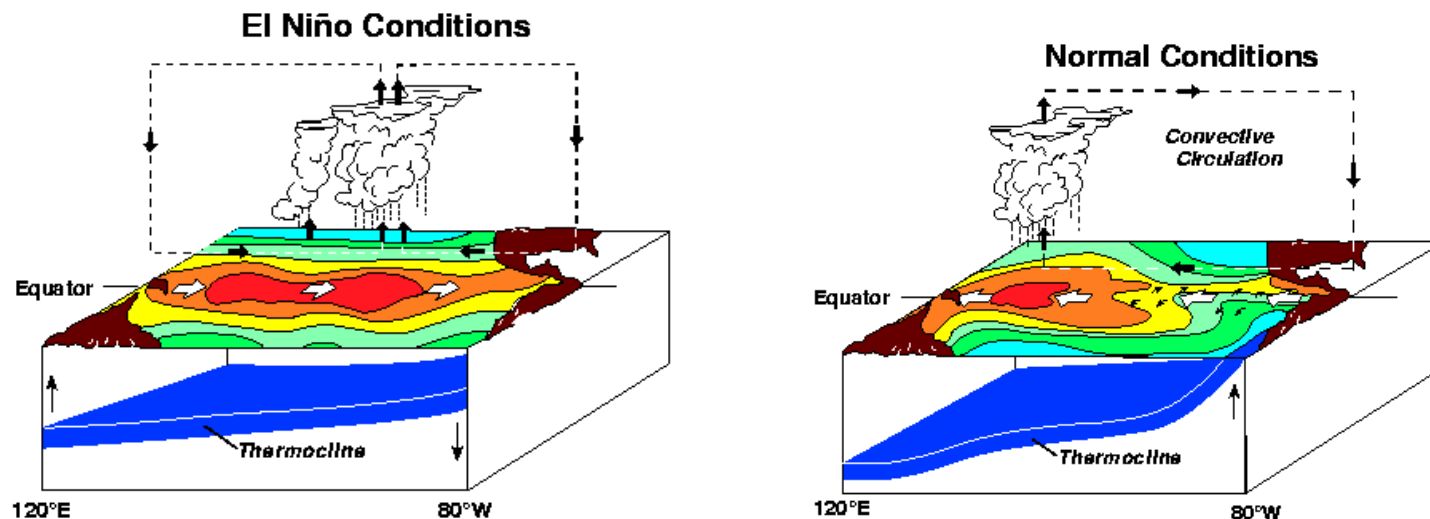
environment is projected to promote an increase in these extreme events^{7,10,11}.

ENSO modulates TC activity in this region^{9,12–16}. Changes in anomalies in sea surface temperature (SST) induced by ENSO can alter atmospheric conditions, such as atmospheric stability, vertical wind shear and relative humidity^{4,5,12–14}. A recent study suggests that the strength of the cross-equatorial pressure gradient in the eastern Pacific determines the latitudinal position and intensity of the mean Intertropical Convergence Zone and its subsequent sub-weekly variability, which is responsible for the amplification of deep convection and the formation of tropical depressions¹⁶. Although previous research^{13–15} has suggested that ENSO SST and thermocline depth affect TC interannual variability over this region statistically, the physical linkage between ENSO, ocean subsurface heat and TC activity has not been established.

So far, the potential thermal impact of ENSO heat discharge on TC activity in this region has been overlooked despite the well established findings from two lines of research: first, the equatorial upper ocean heat is discharged into off-equatorial regions in the main thermocline underneath the surface as an aftermath of El Niño events^{17–19}; and second, strong TCs are capable of pumping up water from more than 100 m below the surface^{20,21}. Here we combine oceanic subsurface conditions from ORA-S3 (the reanalysis from the European Centre for Medium Range Weather Forecast)²² and TC data derived from the best track archives

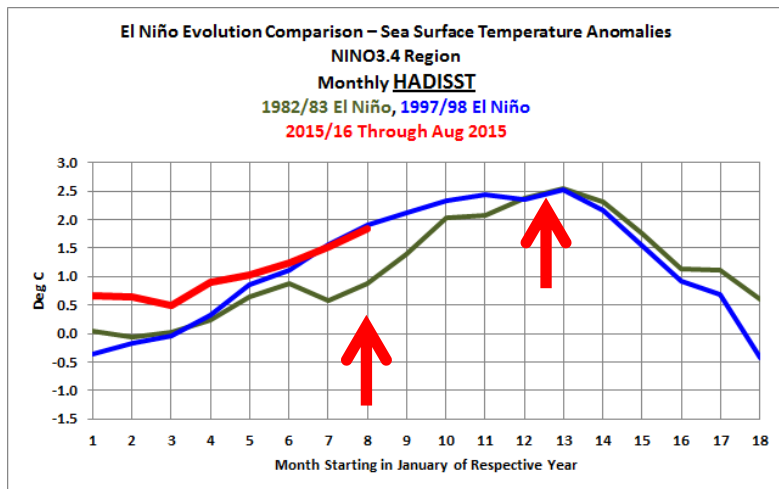
ENSO and Tropical Cyclones

- ✓ The El Niño Southern Oscillation (**ENSO**) creates strong variations in **sea surface temperature** in the **eastern equatorial Pacific**, leading to **major climatic and societal impacts**
- ✓ In particular, ENSO influences the yearly variations of **tropical cyclone (TC)** activities in both **the Pacific and Atlantic basins** through atmospheric dynamical factors such as **vertical wind shear and stability**.
- ✓ Until recently, however, the **direct ocean thermal control of ENSO on TCs** has not been taken into consideration because of an **apparent mismatch in both timing and location**



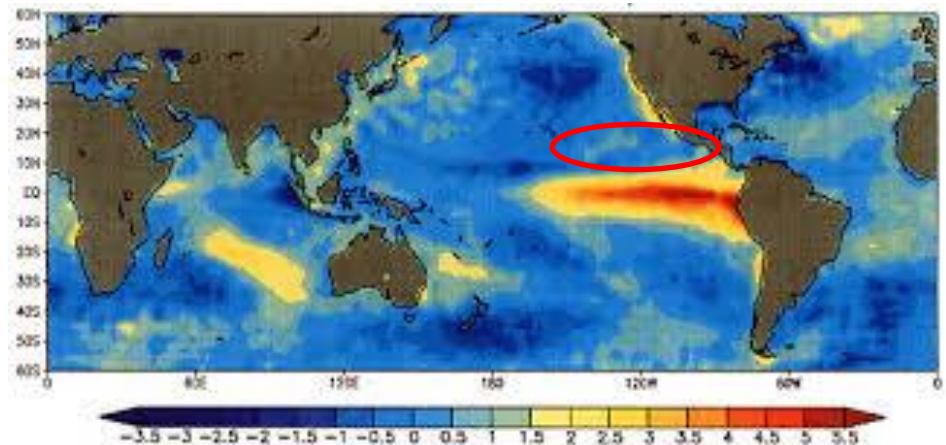
ENSO and Tropical Cyclones

- ✓ ENSO peaks in winter and its surface warming occurs mostly along the Equator, a region without TC activity.
- ✓ El Niño effectively discharges heat into the eastern North Pacific basin (ENP) after its wintertime peak through the subsurface, leading to intensified TCs several months later (during peak TC season).
- ✓ By means of this delayed ocean transport mechanism, ENSO provides an additional heat supply favorable for the formation of strong hurricanes, which has significant implications for seasonal predictions and long-term projections of TC activity over the ENP.



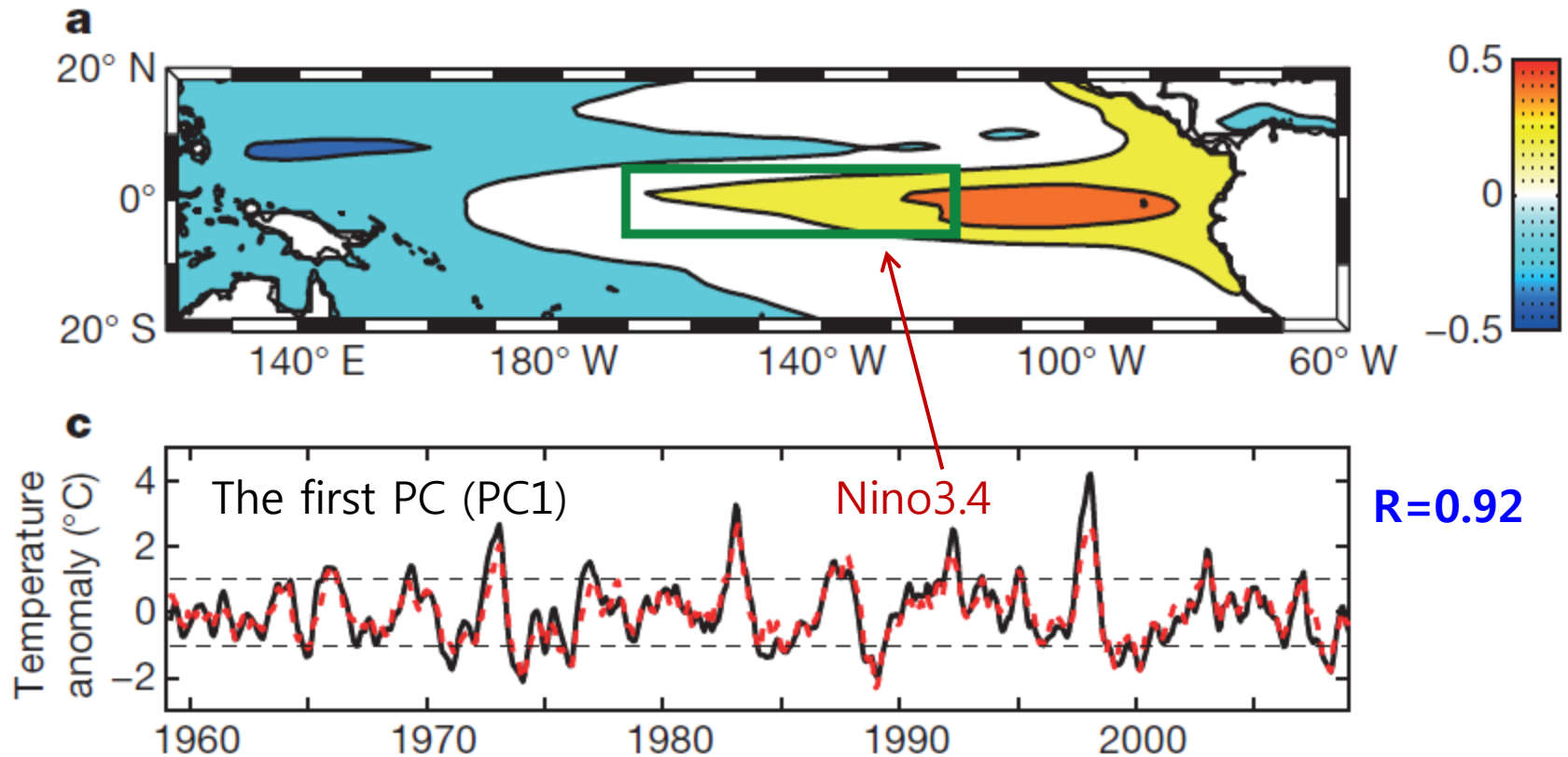
Reference Period for Anomalies = 1981-2010

Bob Tisdale



EOF Decomposition of T105 anomalies

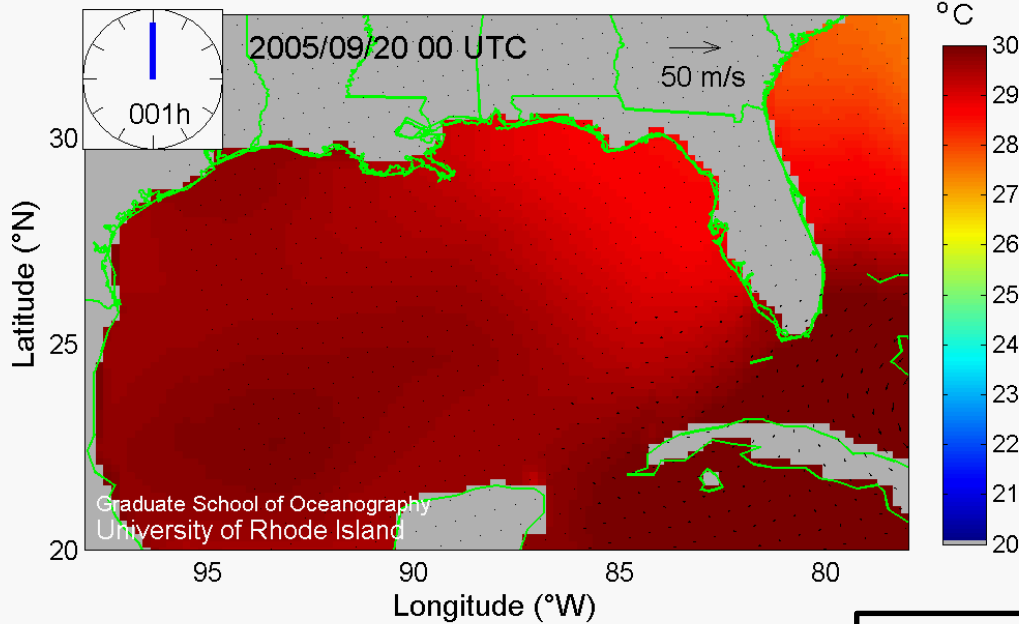
The spatial patterns of the first EOF modes (46.8%)



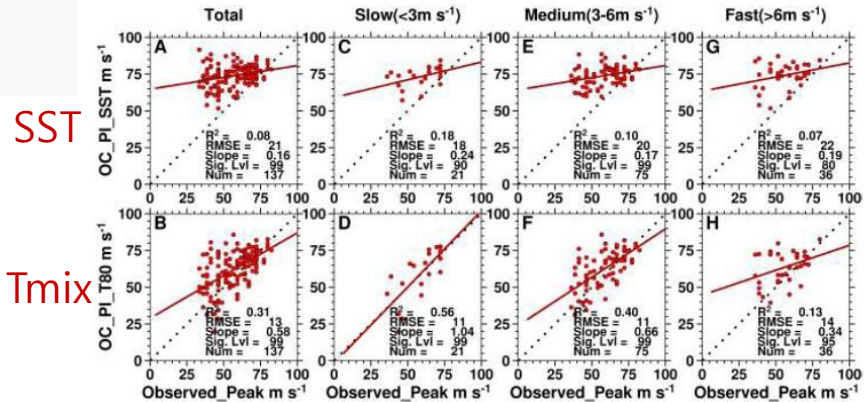
- ✓ ORA-S3 (the 3-D ocean temperature reanalysis data from the ECMWF)
- ✓ T105 (temperatures averaged between 5 and 105m)

Vertically-mixed Temperature (T_{mix})

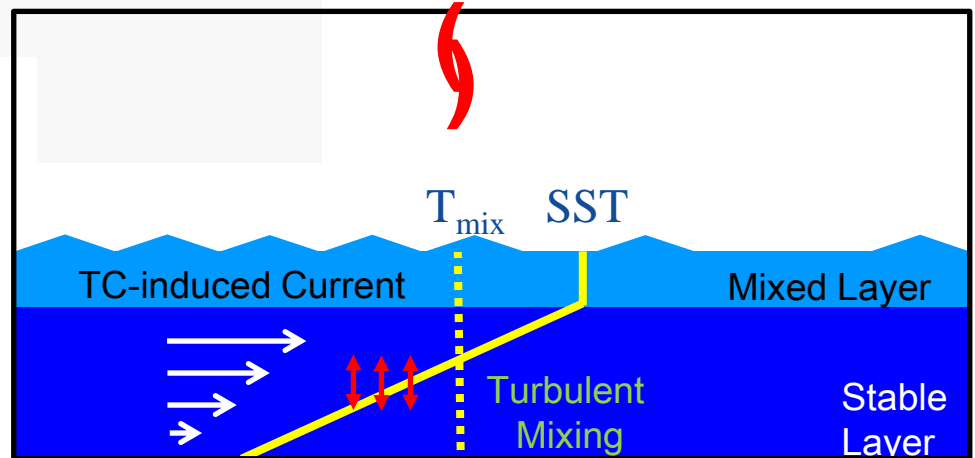
Sea Surface Temperature : Hurricane Rita



✓ TC feels mixed temperature, rather than SST

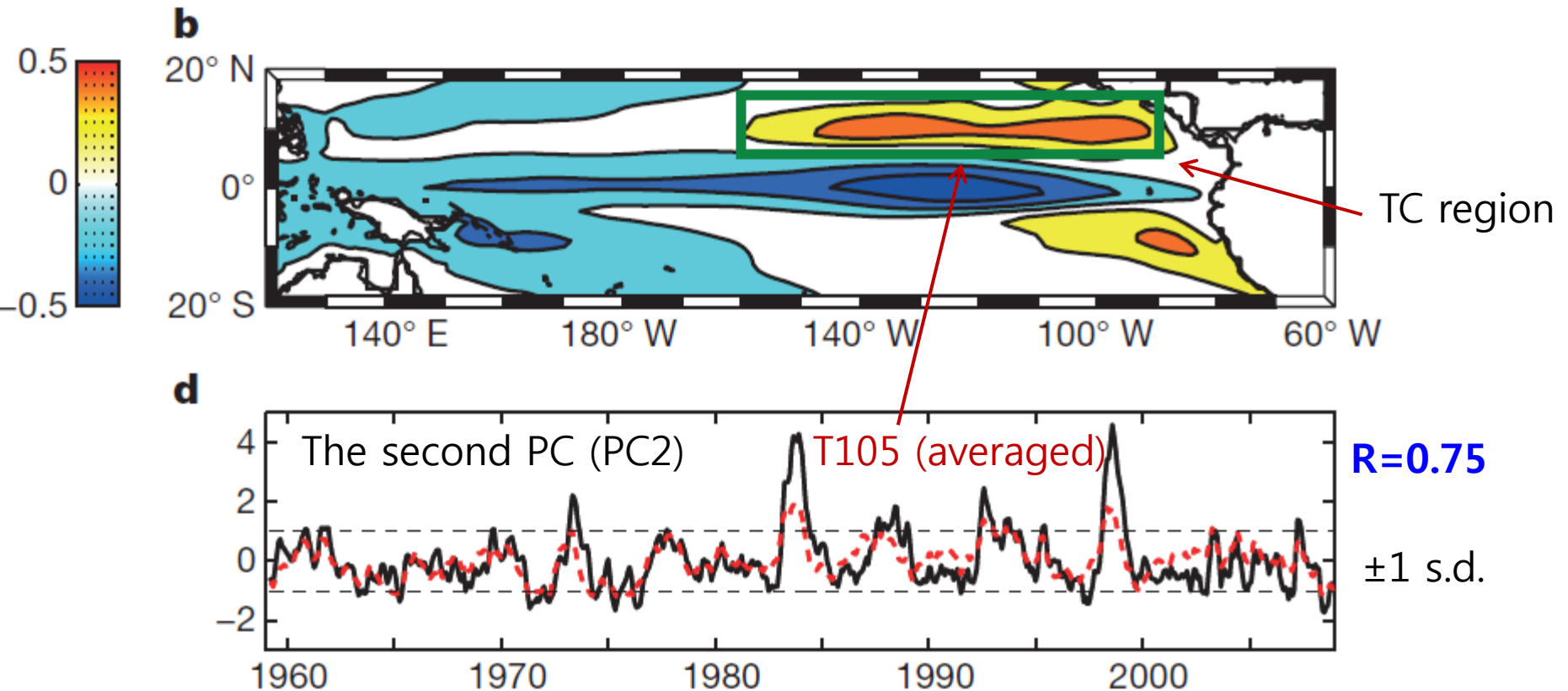


Lin et al. (2013)



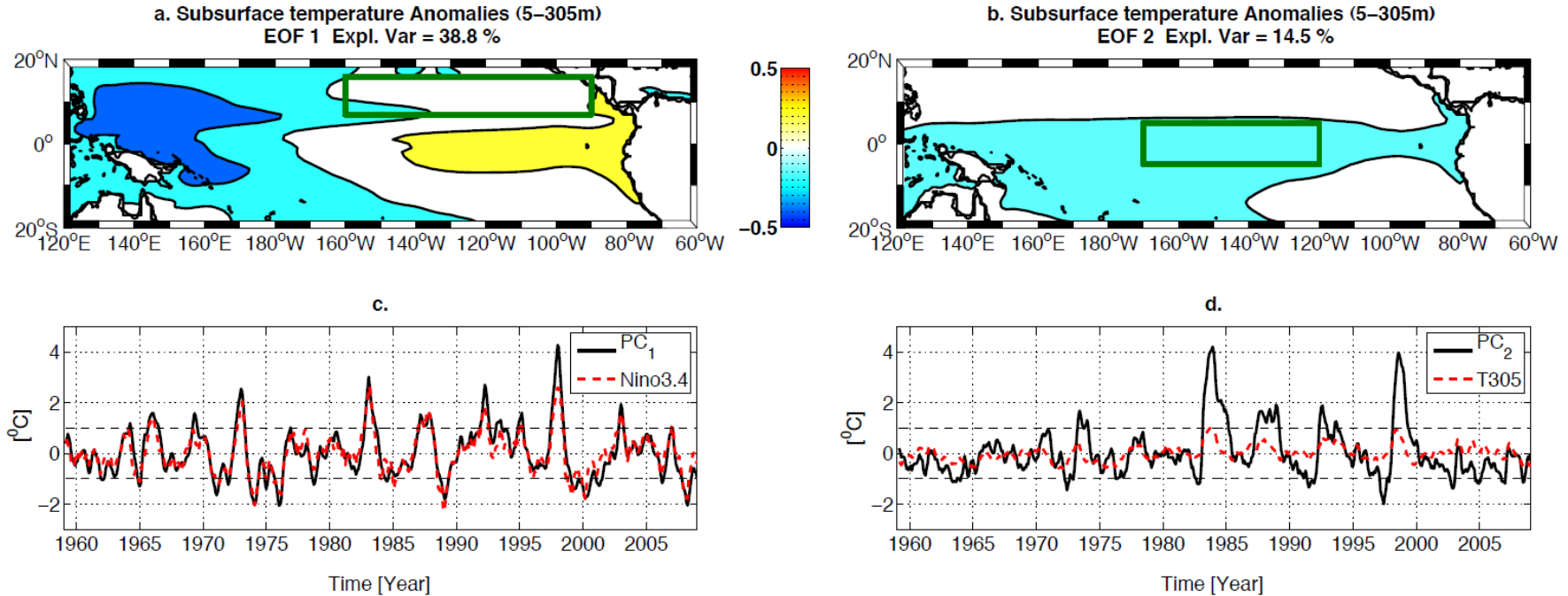
EOF Decomposition of T105 anomalies

The spatial patterns of the second EOF modes (11.7%)



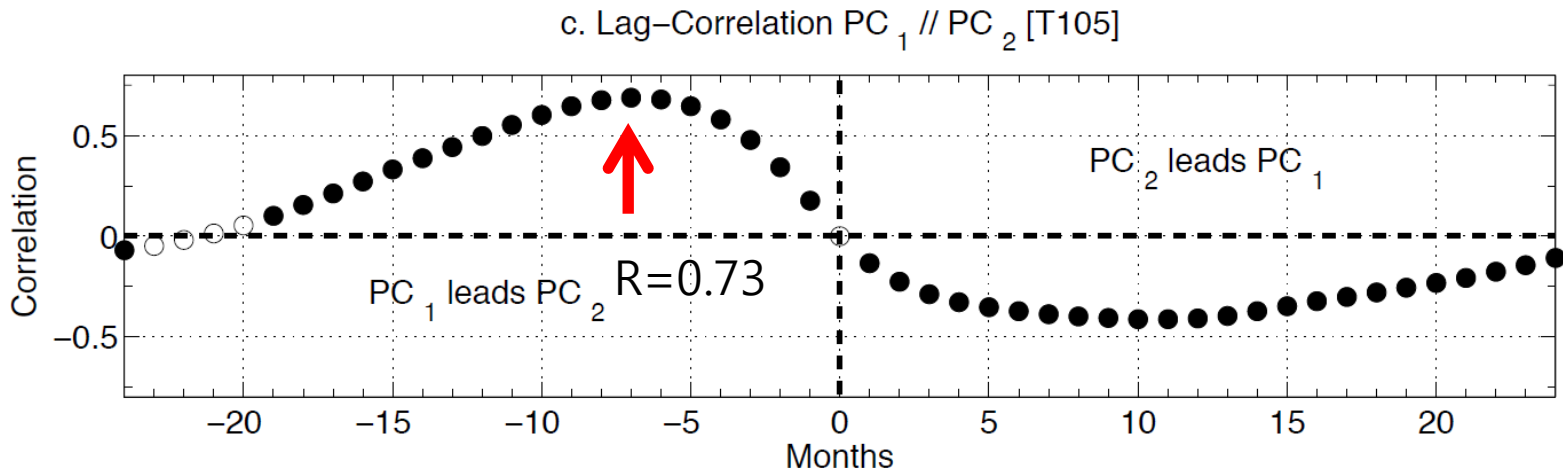
- ✓ PC2: the **subsurface off-equatorial heat redistribution** associated with ENSO, which is highly correlated with **the warm water volume** (i.e., T105)
- ✓ This specific fraction of the upper subsurface temperature serves as the best **potential heat reservoir fuelling the overlying TC activity**

Missed in earlier studies of ENSO



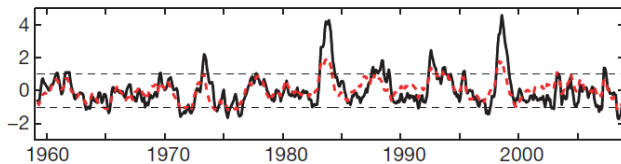
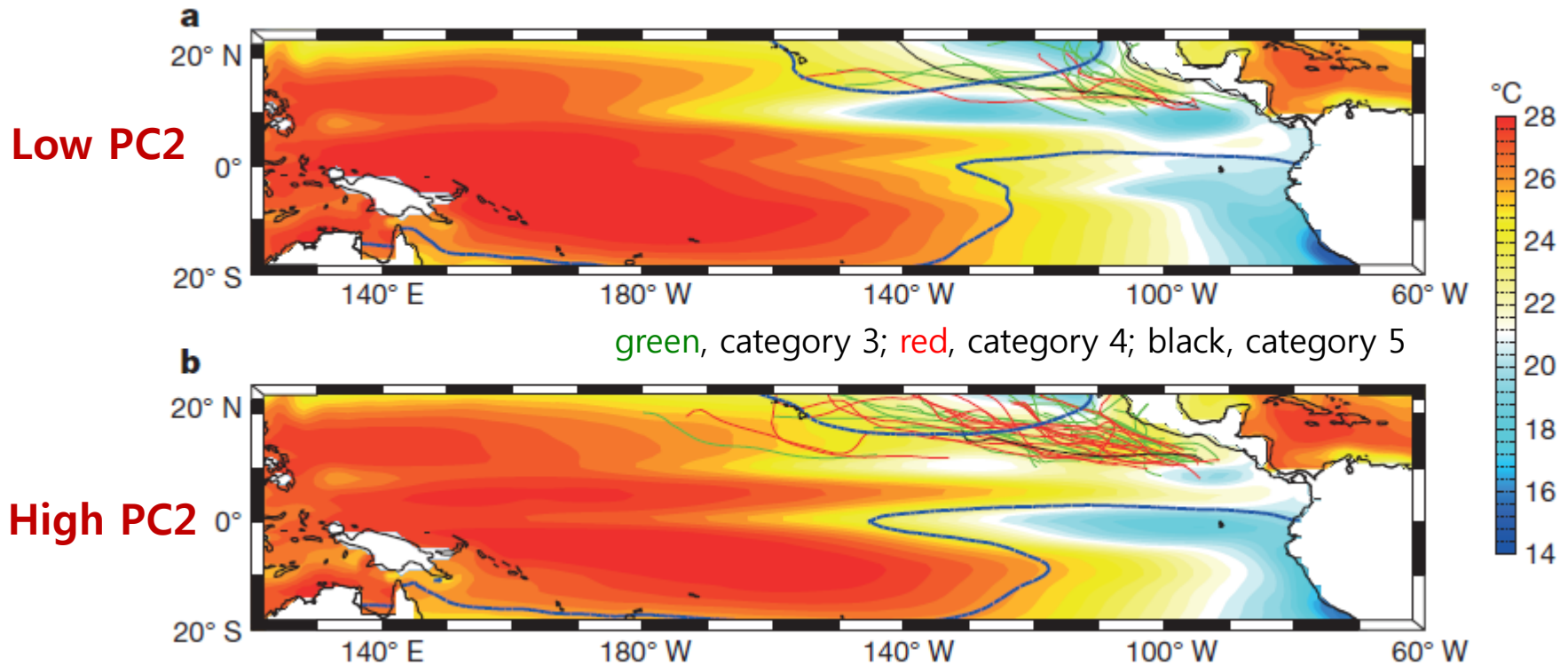
- ✓ **The ocean heat content** is typically calculated as the ocean Temperature averaged within the **top 300m**
- ✓ **T105 is much more relevant** in capturing the ENSO discharge occurring in the eastern tropical Pacific, which is a highly stratified oceanic region characterized by a shallow thermocline

Lag-Correlation between PC1 and PC2



- ✓ The second PC (PC2) lags the first by about **7–8months** (lag correlation of 0.73)
- ✓ El Nino events usually peak around Christmas time; warm T105 anomalies discharged from the Equator as the aftermath of El Nino events will therefore **peak during the following boreal summer and autumn**, just **in time for the active hurricane season** in the Northern Hemisphere.

TC activity for periods of high and low PC2



PC2 time series is respectively above and below one standard deviation

- ✓ There is a clear tendency towards increased occurrences of intense TCs during anomalously warm T105 periods (high PC2) in the central to ENP

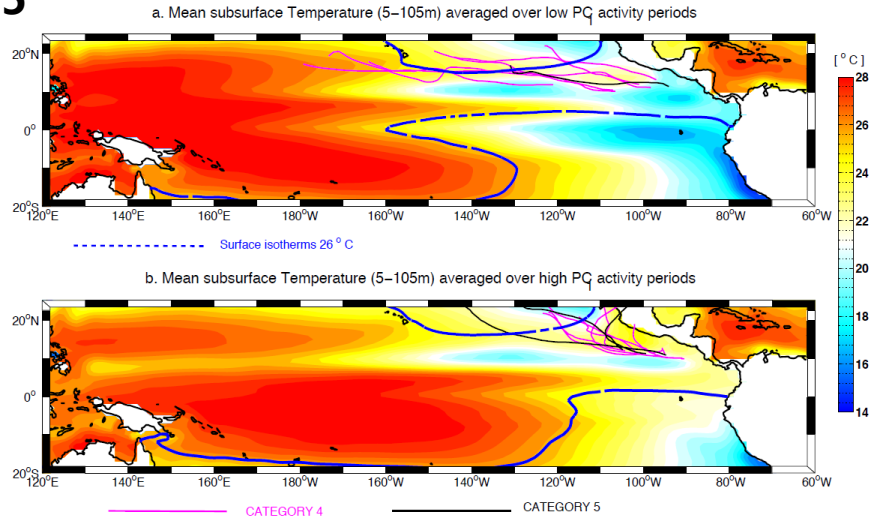
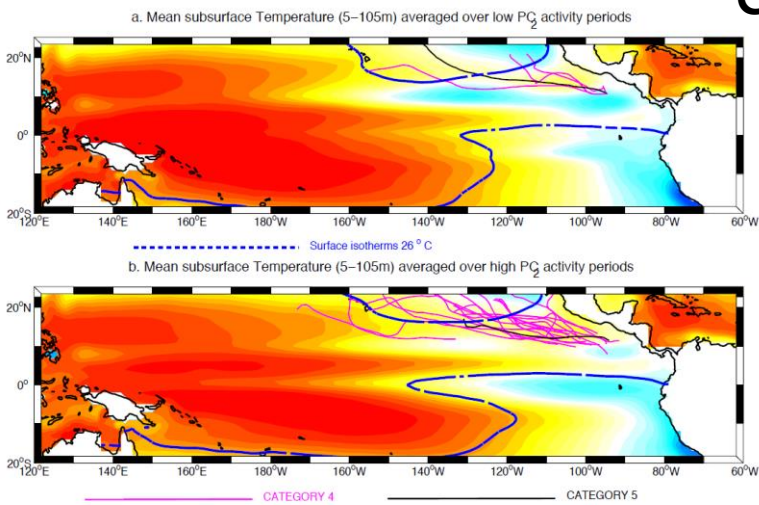
TC activity for periods of high and low PC2

Tropical Cyclone count	HIGH T105 activity		LOW T105 activity	
	$PC2 > std(PC2)$	$PC1 > std(PC1)$	$PC2 < -std(PC2)$	$PC1 < -std(PC1)$
Total Number	117	101	67	71
TD + TS	46	46	27	28
Cat1	24	16	16	19
Cat2	8	12	8	12
Cat3	21	17	12	5
Cat4	17	7	3	6
Cat5	1	3	1	1
Cat4 + Cat5	18	10	4	7

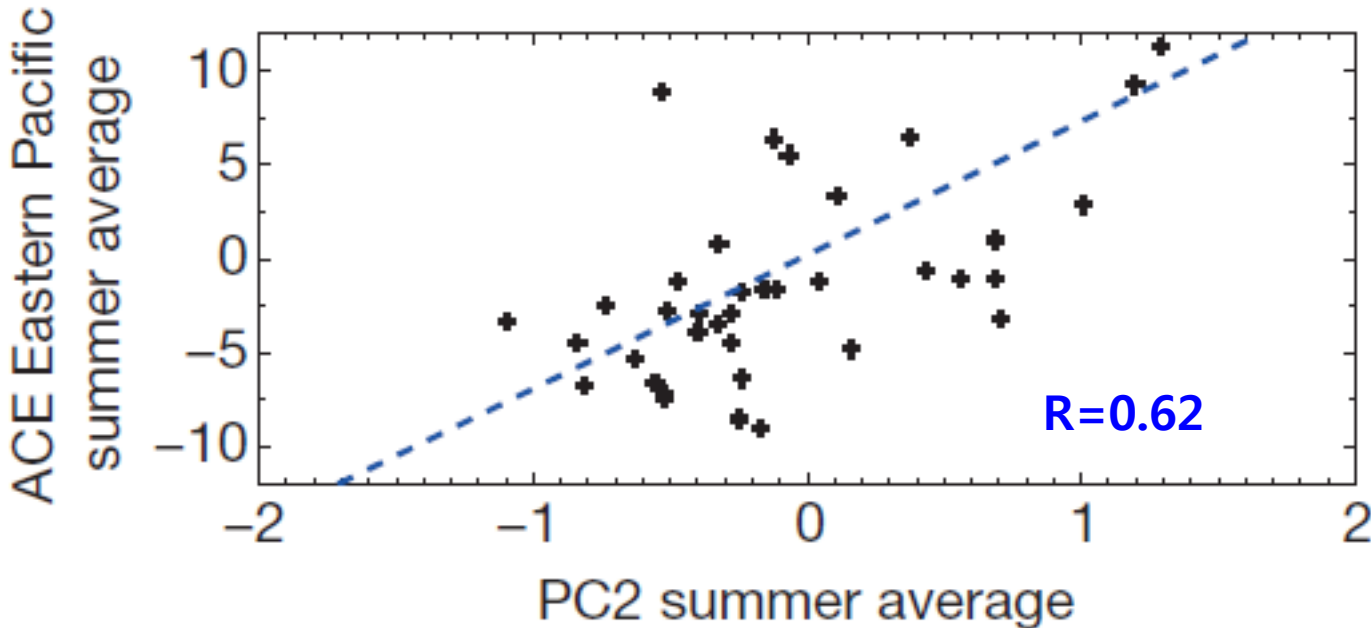
PC2

Cat. 4+5

PC1



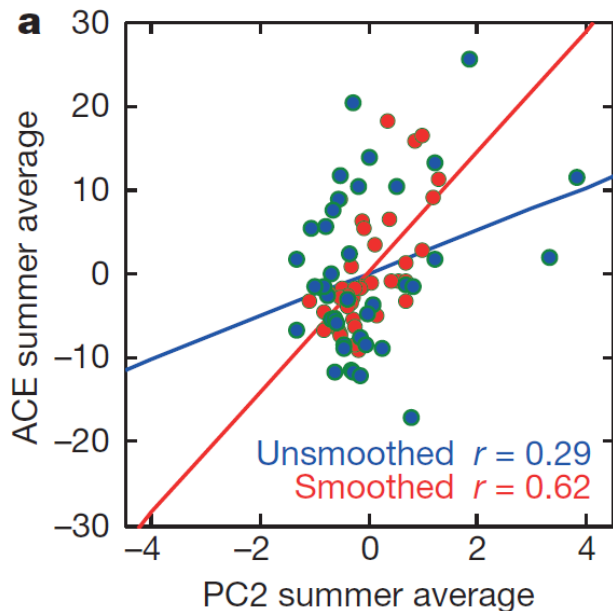
TC activity (ACE) & PC2 summer average



- ✓ TC activity is measured by the accumulated cyclone energy index (ACE) in the central to eastern North Pacific
- ✓ Subsurface thermal conditions and TC activity in the north Eastern Pacific are highly correlated

Problem 1

Correlation between TC activity (ACE) & PC2 summer average

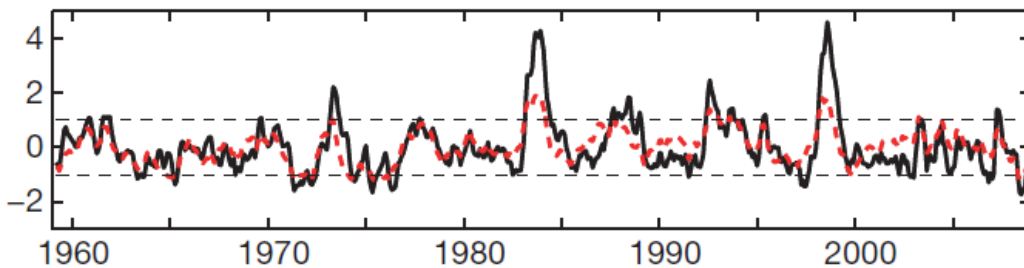


- ✓ We cannot reproduce the high correlation
- ✓ The reason : They used the data smoothing (three-year moving average) used in their correlation analysis
- ✓ The smoothing increased correlations artificially from 0.29 to 0.62
- ✓ Three-year smoothing is a suitable technique when the physical variations being examined are multiannual.
- ✓ However, the use of smoothing is not appropriate in this case because they examined interannual variations of tropical cyclone activity, focusing on interseasonal connections between wintertime ENSO and summertime tropical cyclones.

Problem 2

The way of comparing tropical cyclone activity between high and low subsurface heat content (PC2 active) periods.

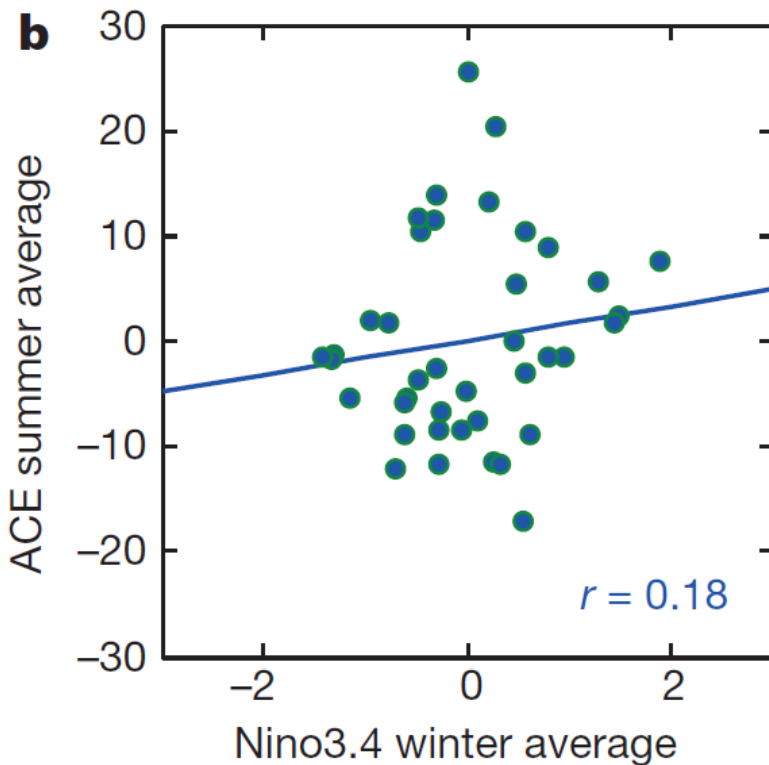
Periods	Total number of selected months	Monthly-mean TC numbers for Cat3+4+5 (Number of selected months)						Summer-mean intense TC numbers
		J	J	A	S	O	N	
High PC2	43	0.50 (8)	1.38 (8)	1.14 (7)	1.43 (7)	0.86 (7)	0.00 (6)	5.30
Low PC2	25	0.25 (8)	1.14 (7)	1.00 (2)	1.00 (2)	1.00 (2)	0.00 (4)	4.39
Climatology		0.31	0.86	0.90	0.75	0.43	0.00	3.25
Confidence Level in difference between two periods [%]		67%	27%	8%	31%	16%	0%	67%



- ✓ unequal sampling : 43 vs. 25
21 vs. 6
- ✓ Total number is compared
- ✓ Difference is not significant in monthly-based pair comparison

Problem 3

Limitation in the seasonal prediction of tropical cyclone activity

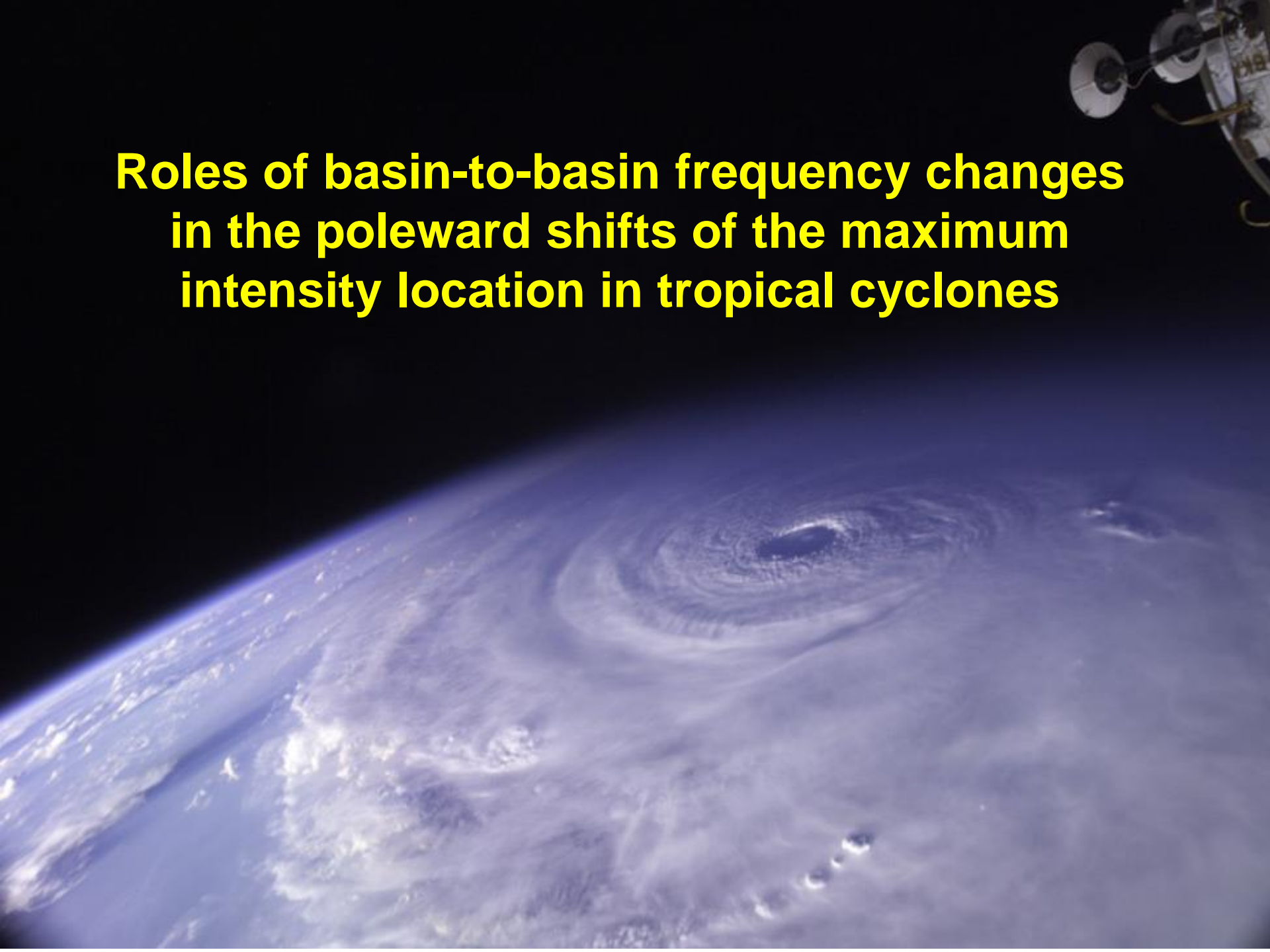


- ✓ Jin et al. (2014) argued that observed **ENSO signals (the Nino index) in the winter are good indicators** of tropical cyclone activity during the subsequent summer in the eastern North Pacific.
- ✓ However, the correlation between the Nino index in the winter and ACE during the subsequent summer is very low, which implies that the subsurface ocean heat delivered by El Nino has **very little contribution (~3%)** to the total variations of tropical cyclone activity in the subsequent summer.
- ✓ Consequently, the theory of Jin et al. (2014) has **limitations in practical seasonal tropical cyclone prediction.**

Conclusions

- ✓ In spite of these concerns, we agree that the delivery of subsurface ocean heat for **specific big El Nino events (cold tongue El Nino)** have an influence on tropical cyclone activity in the eastern North Pacific.
- ✓ In these cases, there is no doubt that ocean thermal control can be used as **a predictor for seasonal prediction** of tropical cyclones in the eastern North Pacific.
- ✓ However, Claims of Jin et al. (2014) for a direct connection between the subsurface ocean thermal control delivered by El Nino and tropical cyclone activity are premature for **general ENSO events**.
- ✓ The connections are not robust enough to apply for the seasonal prediction for **all types of ENSO events**.
- ✓ An analysis classified according to **the types of ENSO (El Nino or La Nina; cold tongue or warm pool El Nino)** will be required to improve the correlations and reliability of prediction.

**Roles of basin-to-basin frequency changes
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Roles of interbasin frequency changes in the poleward shifts of the maximum intensity location of tropical cyclones

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Keywords: tropical cyclone, poleward migration, maximum intensity location, frequency change

Supplementary material for this article is available [online](#)

Abstract

An observed poleward migration in the average latitude at which tropical cyclones (TCs) achieved their lifetime-maximum intensities (LMIs) was previously explained by changes in the mean meridional environments favorable to storm development linked to tropical expansion and anthropogenic warming. We show that the poleward migration is greatly influenced by basin-to-basin changes in TC frequency associated with multi-decadal variability, particularly for the Northern Hemisphere (NH). The contribution of the frequency changes to the poleward migration is

The poleward migration of the location of tropical cyclone maximum intensity

James P. Kossin¹, Kerry A. Emanuel² & Gabriel A. Vecchi³

Temporally inconsistent and potentially unreliable global historical data hinder the detection of trends in tropical cyclone activity^{1–3}. This limits our confidence in evaluating proposed linkages between observed trends in tropical cyclones and in the environment^{4,5}. Here we mitigate this difficulty by focusing on a metric that is comparatively insensitive to past data uncertainty, and identify a pronounced poleward migration in the average latitude at which tropical cyclones have achieved their lifetime-maximum intensity over the past 30 years. The poleward trends are evident in the global historical data in both the Northern and the Southern hemispheres, with rates of 53 and 62 kilometres per decade, respectively, and are statistically significant. When considered together, the trends in each hemisphere depict a global-average migration of tropical cyclone activity away from the tropics at a rate of about one degree of latitude per decade, which lies within the range of estimates of the observed expansion of the tropics over the same period⁶. The global migration remains evident and statistically significant under a formal data homogenization procedure³, and is unlikely to be a data artefact. The migration away from the tropics is apparently linked to marked changes in the mean meridional structure of environmental vertical wind shear and potential intensity, and can plausibly be linked to tropical expansion, which is thought to have anthropogenic contributions⁶.

Inconsistencies in the historical global ‘best-track’ data can introduce

Here we consider the 31-yr period 1982–2012. In this period, the global best-track data are considered most complete and at their highest quality in each basin⁹, and storm position is well monitored globally by geostationary satellites. This period also encompasses a recent satellite-based global tropical cyclone intensity reanalysis³, and is the interval over which the atmospheric reanalysis products^{12–14} that provide information on the environmental changes that affect tropical cyclones are most reliable.

When the annual-mean latitude of LMI is calculated from the best-track data in the Northern and Southern hemispheres over this period (Fig. 1a, b, red lines), there are clear and statistically significant poleward trends in both hemispheres of 53 and 62 km per decade, respectively (Table 1). The positive contribution to these hemispheric trends from each ocean basin except that of the North Indian Ocean (Table 1 and Extended Data Fig. 1) suggests that the migration away from the tropics is a global phenomenon, although there are large regional differences in the trend amplitudes and their statistical power. These differences are probably due, in part, to regional differences in interannual to multidecadal variability¹⁵. The largest contribution to the Northern Hemisphere trend is from the western North Pacific Ocean, which is also the most active basin in terms of annual tropical cyclone frequency. By contrast, the North Indian Ocean has the lowest mean annual frequency, and the small equatorward trend there has a much lesser effect on the hemispheric trend. The North Atlantic Ocean and eastern North Pacific

Uncertainties in TC best track data

- ✓ **Inconsistencies in the historical global 'best-track' data** can introduce substantial **uncertainty** into global-mean measures of TC activity.
- ✓ Since the introduction of **geostationary weather satellites** in the mid to late **1970s**, measures of TC frequency are generally considered to be **accurate**
- ✓ There is **no observed trend** in **global frequency** since that time.
- ✓ Comparatively, measures of **TC intensity** are considered to be **highly uncertain** in the global data.
- ✓ Consequently, **storm duration** is also **uncertain** because identifying the moment when a **cyclone forms** (cyclogenesis) requires accuracy in intensity estimates
- ✓ Similar uncertainty exists in identifying a **cyclone's demise** (cyclolysis).
- ✓ Same uncertainties : power dissipation (**PDI**) and accumulated cyclone energy (**ACE**), which are combinations of **frequency, duration and intensity**.

2. Storm position at the time of LMI

- ✓ But measurements of a **storm's position** taken around the time that it reaches its **lifetime-maximum intensity (LMI)** are much **less uncertain**.
- ✓ By this time in a storm's evolution, it is **more likely** to have been **detected** and to be **under close observation**.
- ✓ Measurements of **storm position at the time of LMI** are also **less sensitive** to
 - (i) inaccuracy in **measurements of intensity**,
 - (ii) interregional differences in **wind-averaging techniques**, because determining the **absolute LMI** is not critical it is necessary only to know that the **intensity has peaked**.
 - (iii) **temporal heterogeneity** in the historical best-track intensity record. It is this heterogeneity that has presented substantial challenges to **trend detection** in TC metrics that require **absolute measures of intensity**.

Main conclusion : Identify a pronounced **poleward migration** in the average latitude at which TCs have achieved their LMI over the past 30 years

Data

1. TC Data

1. Best-track data : the International Best Track Archive for Climate Stewardship (**IBTrACS**) v03r05
 2. The homogenized intensity data were taken from the **Advanced Dvorak Technique** Hurricane Satellite (**ADT-HURSAT**) data set.
- ✓ **Analysis period** : 31 years (**1982–2012**), most complete and at their highest quality in each basin, and storm position is well monitored globally by geostationary satellites.
 - ✓ This period : **a recent satellite-based global tropical cyclone intensity reanalysis, most reliable atmospheric reanalysis products** that provide information on the environmental changes that affect tropical cyclones.

2. Atmospheric Reanalysis Data

- ✓ NCEP/NCAR
- ✓ ERA Interim
- ✓ MERRA.

Method

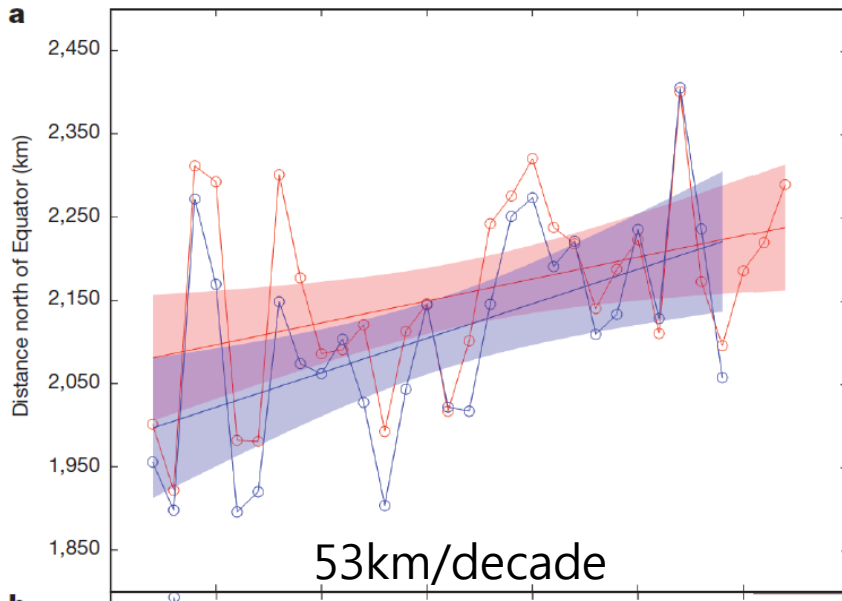
- ✓ **ENSO variability** was removed from the LMI latitude time series by regressing the individual series from the N. and S. hemispheres onto the Nino-3.4 index averaged over the most active periods of TC activity (August–October in the north and January–March in the south), and analysing the residuals.
- ✓ All analysis: done after **detrending**
- ✓ Change points detection: **the Student t and Mann–Whitney statistics** to test for significance at 95% confidence
- ✓ **Vertical wind shear** : the magnitude of the vector difference of the respective horizontal wind velocities at the 250- and 850-hPa pressure levels.
- ✓ **Potential intensity** : the theoretical limit of the strength of a tropical cyclone. It is computed using the following formula

$$V^2 = \frac{SST - T_0}{T_0} \frac{C_k}{C_D} (k^+ - k)$$

Emanuel (1999)

Trends in position of annual-mean LMI

Northern hemisphere (NH)



Southern hemisphere (SH)

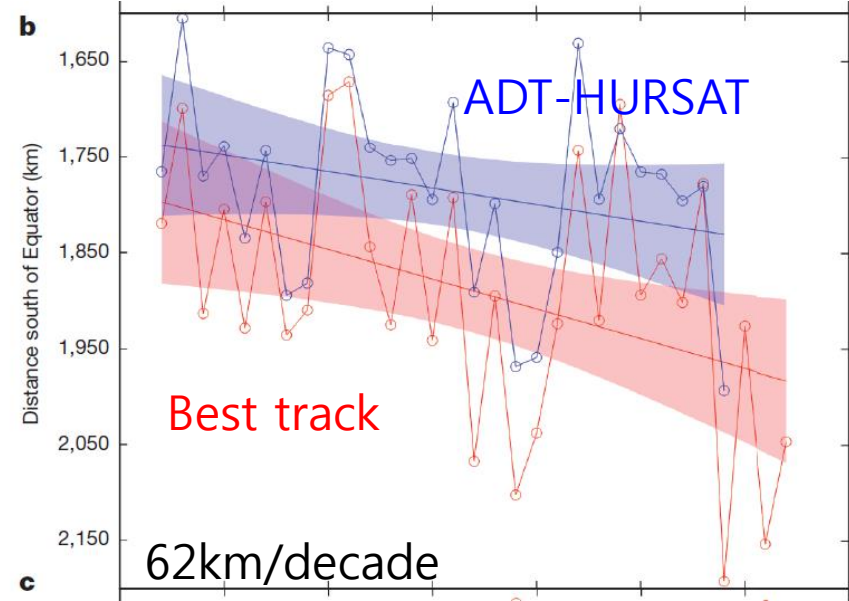


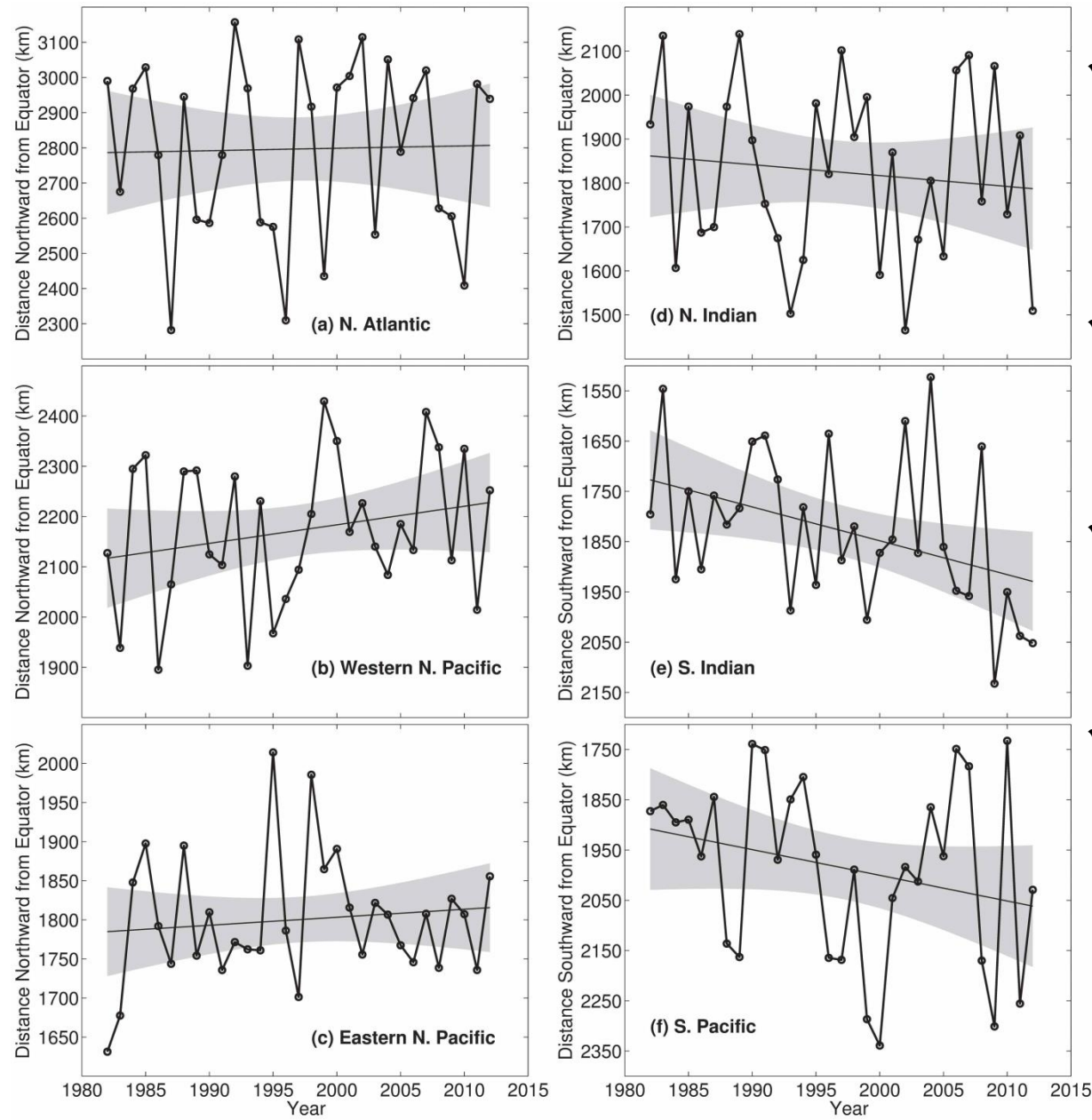
Table 1 | Linear trends, by region, of annual-mean latitude of LMI

	NHEM	SHEM	NATL	WPAC	EPAC	NIO	SIO	SPAC	Global
Best track	+53 ± 43	+62 ± 48	+7 ± 98	+37 ± 55	+10 ± 32	-25 ± 78	+67 ± 55	+51 ± 68	+115 ± 70
ADT-HURSAT	+83 ± 50	+35 ± 44	-12 ± 126	+105 ± 71	+34 ± 30	+10 ± 106	+30 ± 52	+54 ± 79	+118 ± 70

Trends are deduced from the best-track and ADT-HURSAT data sets. The slope (kilometres per decade) and the 95% two-sided confidence bounds are shown. Positive slopes represent poleward migration. NHEM, Northern Hemisphere; SHEM, Southern Hemisphere; NATL, North Atlantic; WPAC, western Pacific; EPAC, eastern Pacific; NIO, North Indian Ocean; SIO, South Indian Ocean; SPAC, South Pacific.

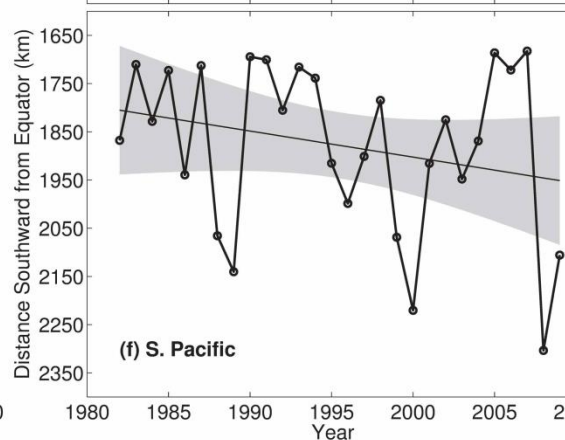
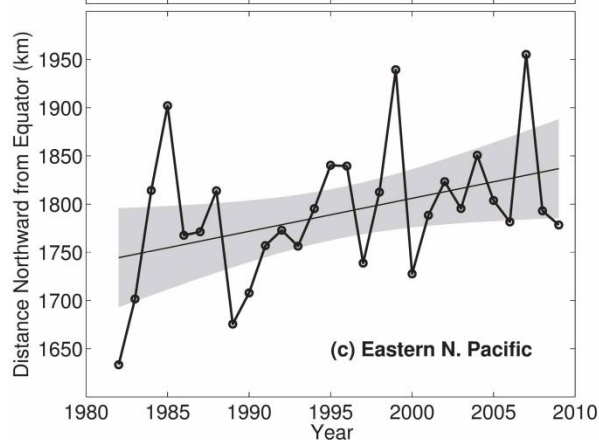
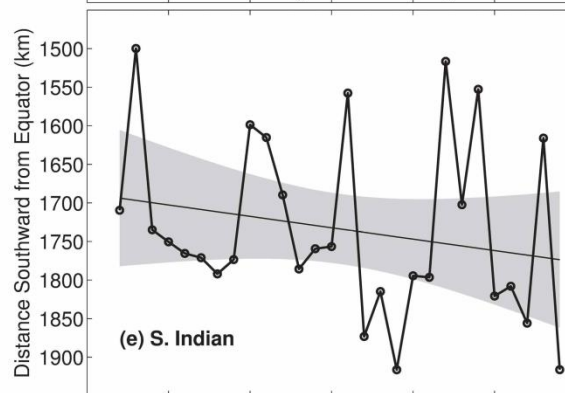
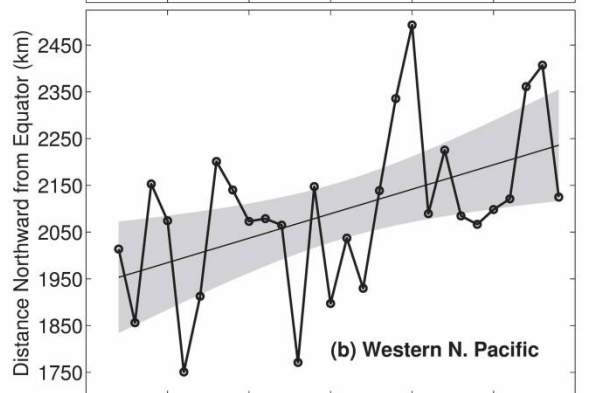
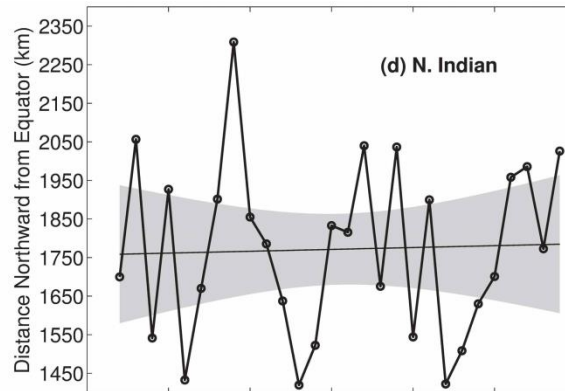
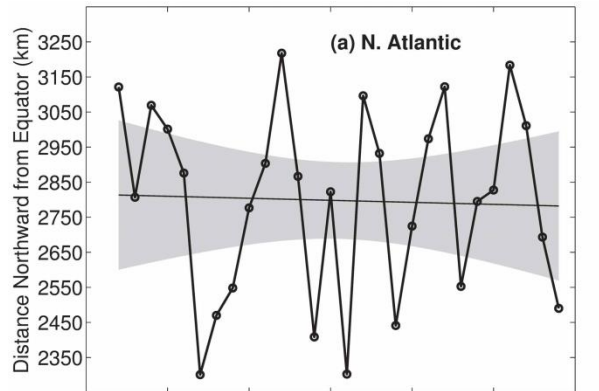
- ✓ Statistically significant poleward trends in both hemispheres of **53 and 62km per decade**. The positive contribution to these hemispheric trends from each ocean basin except that of the North Indian Ocean suggests that the migration away from the tropics is a **global phenomenon**

Trends in individual basins (Best track)



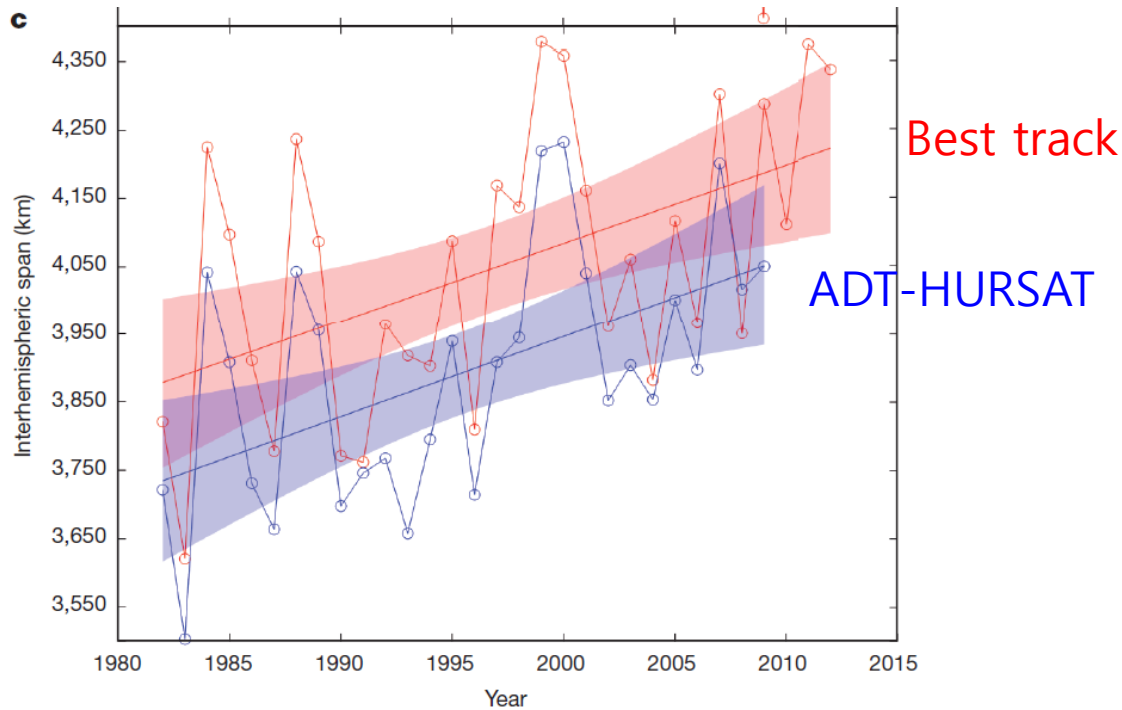
- ✓ The largest contribution to the N Hemisphere trend : the western North Pacific Ocean
- ✓ the North Indian Ocean : the small equatorward trend
- ✓ The N Atlantic Ocean and eastern N Pacific : small poleward trends
- ✓ The S. Hemisphere : both the S. Pacific and the S. Indian Ocean regions contribute substantially to the poleward trend.

Trends in individual basins (ADT-HURSAT)



- ✓ The largest contribution to the N Hemisphere trend : the western North Pacific Ocean and the eastern N Pacific
- ✓ The N Atlantic Ocean and : small equatorward trends
- ✓ N Indian Ocean : no trend in that region
- ✓ The S. Hemisphere : both the S. Pacific and the S. Indian Ocean regions contribute substantially to the poleward trend.

Trends in interhemispheric Span



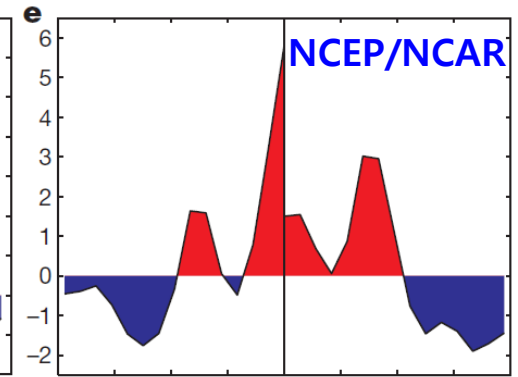
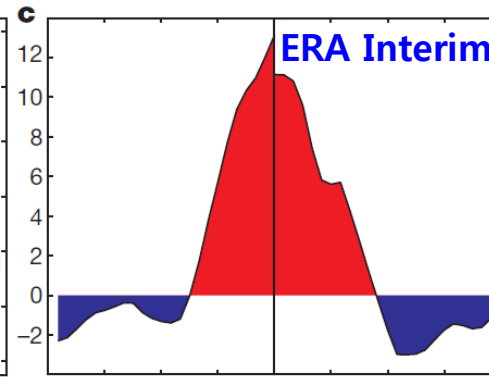
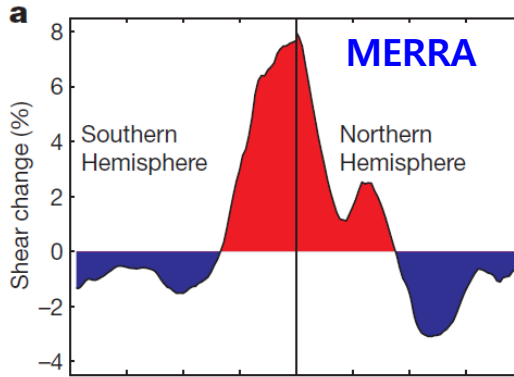
- ✓ When both hemispheres are considered together they depict a **global migration away from the deep tropics**
- ✓ **Best-track** : 115 km per decade
- ✓ **ADT-HURSAT** : 118 km per decade
- ✓ In this global view, both are statistically significant.

What caused the poleward migration?

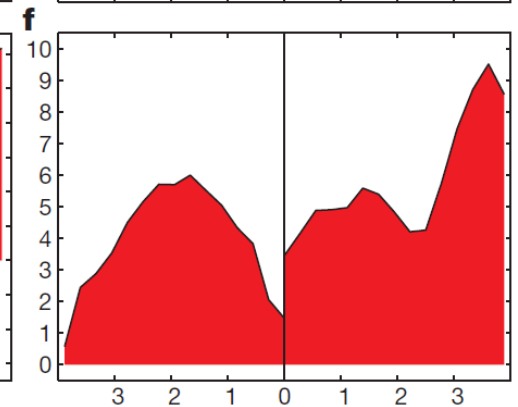
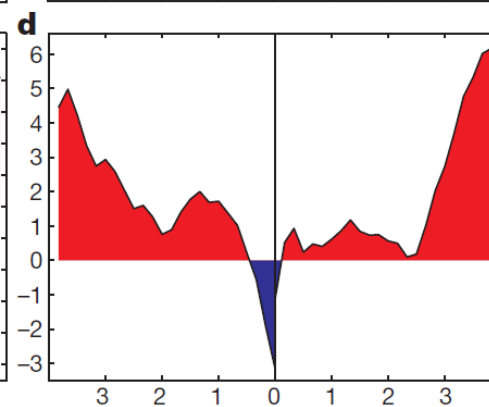
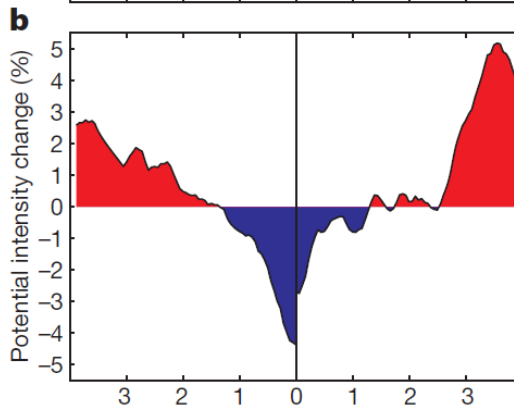
- ✓ Although regional differences are evident, the migration of the mean latitude of LMI away from the deep tropics is observed in both hemispheres, which indicates that this is a **global phenomenon**.
- ✓ Known major factors controlling tropical cyclone evolution are the environmental **vertical wind shear** and the **potential intensity**.
- ✓ **Potential intensity** : the thermodynamically based maximum tropical cyclone intensity that the environment will support, all other factors being optimal.
- ✓ **Vertical wind shear** : one of the key factors that inhibit a storm from achieving this maximum.
- ✓ **Greater shear and lesser potential intensity** each inhibits genesis and intensification, and vice versa,

Vertical wind shear & Potential intensity

vertical
wind shear



Potential
intensity



Meridional distance from Equator (10^3 km)

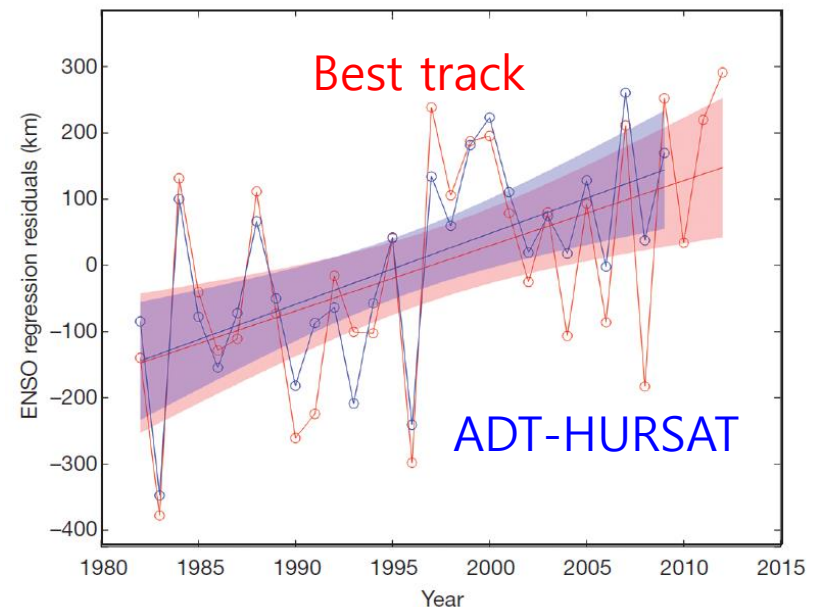
Meridional distance from Equator (10^3 km)

Meridional distance from Equator (10^3 km)

- ✓ **Deep tropics** : Decreased potential intensity, increased shear
- ✓ **Higher latitudes** : Increased potential intensity, decreased shear
- ✓ The changes in mean potential intensity are **not as consistent** among the different reanalysis products, particularly in the tropics, which is probably a result of spurious differences in upper tropospheric temperatures.
- ✓ This is plausibly linked to a poleward migration of the latitude of LMI

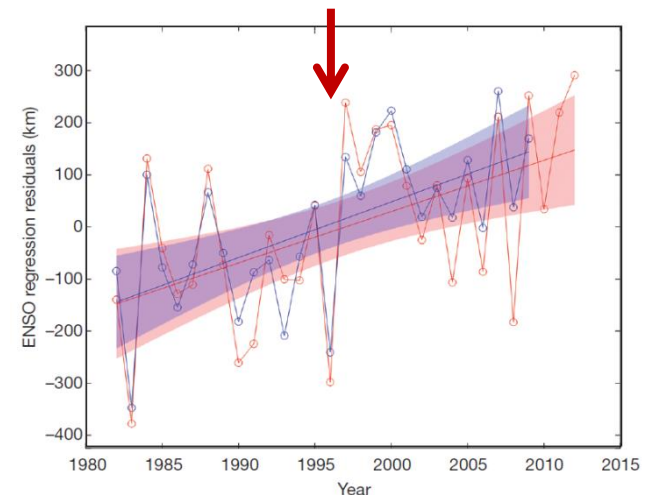
Effect of ENSO

- ✓ **Shifts in tropical cyclone tracks** in most regions have also been linked to phase changes in **El Nino/Southern Oscillation (ENSO)**, which can potentially contribute to the poleward trends in LMI identified here.
- ✓ To test this, we **decrease the contribution of ENSO** by regressing the LMI latitude time series onto an index of ENSO variability.
- ✓ When this is done, the amplitude of the interhemispheric migration rates is found to **decrease only slightly** in both the best-track and the ADT-HURSAT data, and the statistical power of the trends in fact increases.
- ✓ This makes it **unlikely** that natural ENSO variability has a role in the observed multi-decadal poleward migration of LMI, although it plays a substantial part in its inter-annual variability.



Link to tropical expansion

- ✓ The potential for contributions from **natural variability occurring on decadal or longer timescales** still exists, but quantifying this is difficult using relatively short observation records.
- ✓ Propose : there is a linkage between the poleward migration of LMI and the **observed expansion of the tropics**.
- ✓ **The rate of expansion since 1979** varies considerably among existing studies, but **the rate of LMI migration** identified here **falls well within this range**.
- ✓ The forcing mechanisms of the expansion : at present uncertain but are generally thought to have **anthropogenic contributions**.
- ✓ The expansion of the tropics exhibits a **step change in the late 1990s**.
- ✓ Change-point analysis : a **significant change point in 1996**, providing further support for a linkage between the two independently observed phenomena.



Conclusions

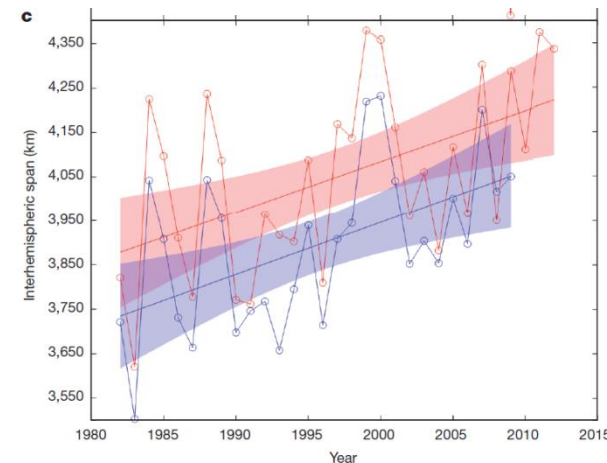
- ✓ **The poleward trends are evident** in the global historical data in both the N. and the S. hemispheres, with **rates of 53 and 62 km per decade**, respectively, and are statistically significant.
- ✓ When considered together, the trends in each hemisphere depict a global average migration of tropical cyclone activity away from the tropics at a rate of about **one degree of latitude per decade**, which **lies within the range of estimates of the observed expansion of the tropics** over the same period.
- ✓ The global migration remains evident and statistically significant under a **formal data homogenization procedure**, and is unlikely to be a data artefact.
- ✓ The migration away from the tropics is apparently linked to marked changes in the mean meridional structure of **environmental vertical wind shear and potential intensity**
- ✓ This can plausibly be linked to tropical expansion, which is thought to have **anthropogenic contributions**.

Importances

- ✓ If these environmental changes continue, a concurrent **continued poleward migration (??)** of the latitude where tropical cyclones achieve their LMI would have potentially profound consequences for life and property.
- ✓ Any related changes in positions where storms make landfall will have obvious effects on **coastal residents and infrastructure**.
- ✓ Increasing hazard exposure and mortality risk from TC may be compounded in **coastal cities outside the tropics, while being offset at lower latitudes**.
- ✓ Tropical cyclones also have an important role in maintaining **regional water resources**, and a poleward migration of storm tracks could **threaten potable water supplies** in some regions while **increasing flooding** events in others.
- ✓ Given these motivating factors, further study of the poleward migration of tropical cyclone LMI identified here, and its **potential link to the observed expansion of the tropics**, is warranted.

Arising Issues

- ✓ Despite the pronounced and statistically significant global and hemispheric mean trends in poleward migration, **the trends in each basin are mostly insignificant**, even showing **an opposite, equatorward trend in some basins**
- ✓ For example, the **North Atlantic**, which has seen a marked increase in TC activity since the mid-1990s, shows almost **no poleward trend** on the basis of historical 'best-track' data over the past 30 years
- ✓ Moreover, when KEV used a state-of-the-art data set of TC intensity (ADT-HURSAT), **an equatorward trend** is found for the North Atlantic.
- ✓ The large discrepancy between the regional and global (or hemispheric) trends raises the question as to **how a statistically significant global mean trend can occur without significant trends in most basins.**
- ✓ **Purpose of study** : Perform a **quantitative analysis** to **identify the contributions to the trends** and attempt to determine whether the observed poleward trend of the LMI latitudes **will continue** or not



Trends in individual basins

Best track

ADT-HURSAT

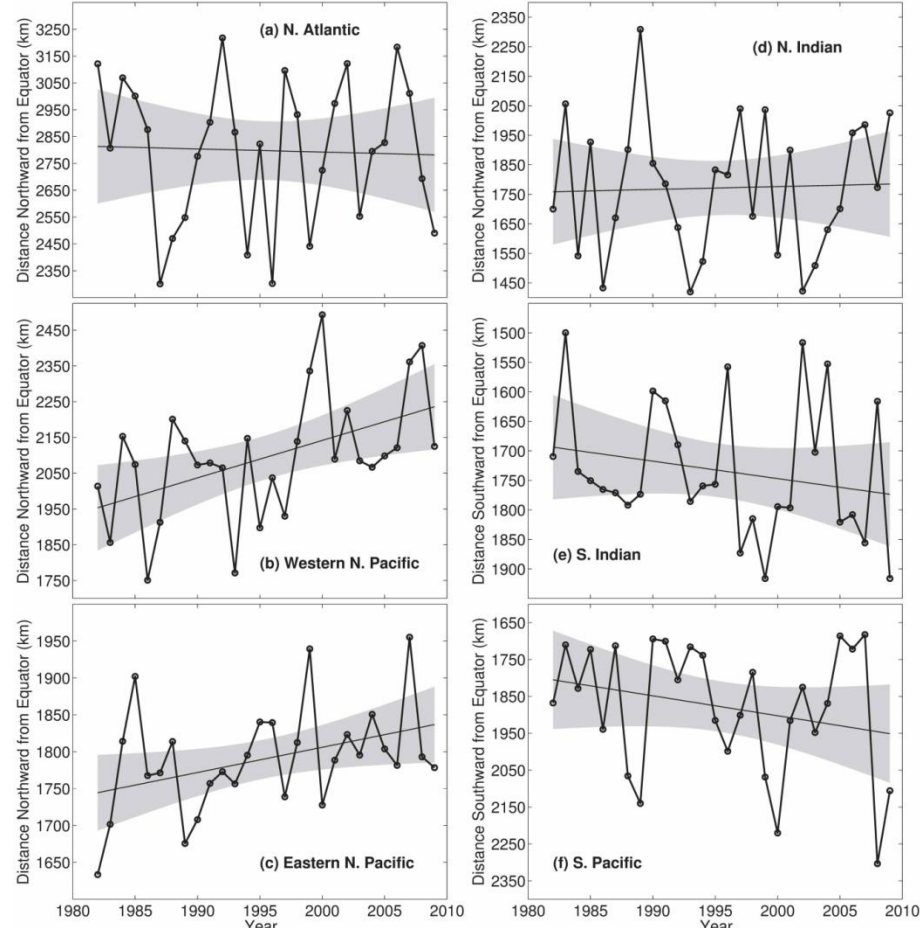
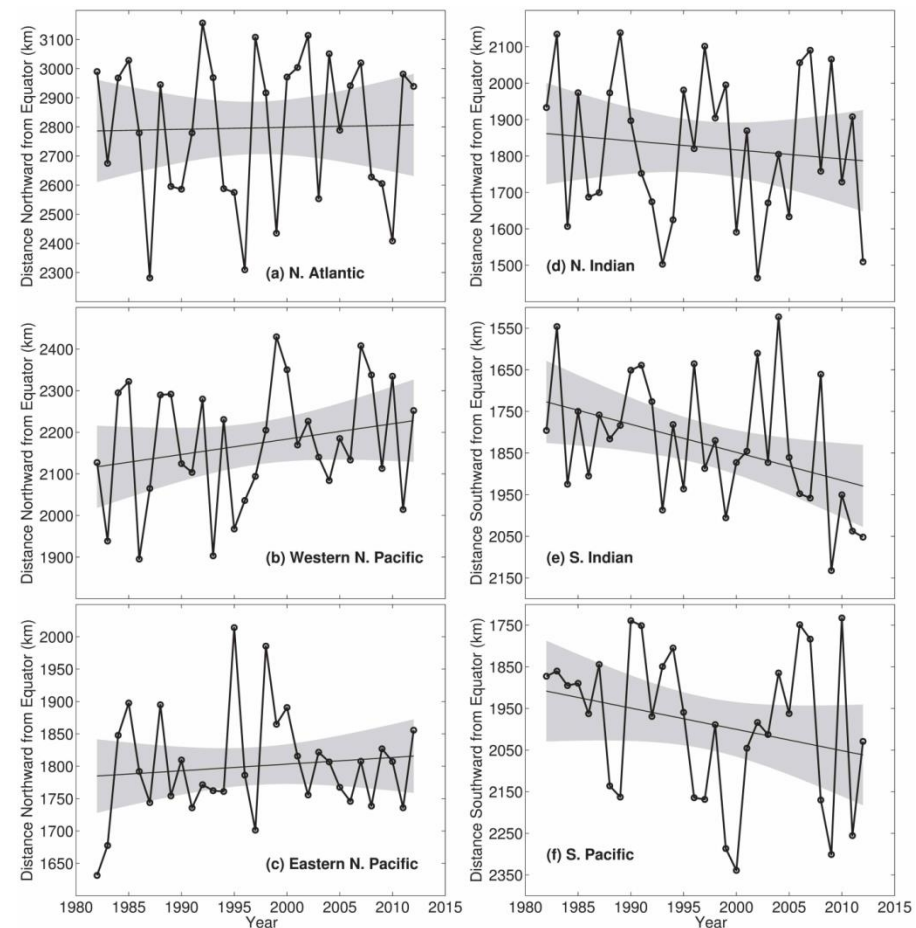


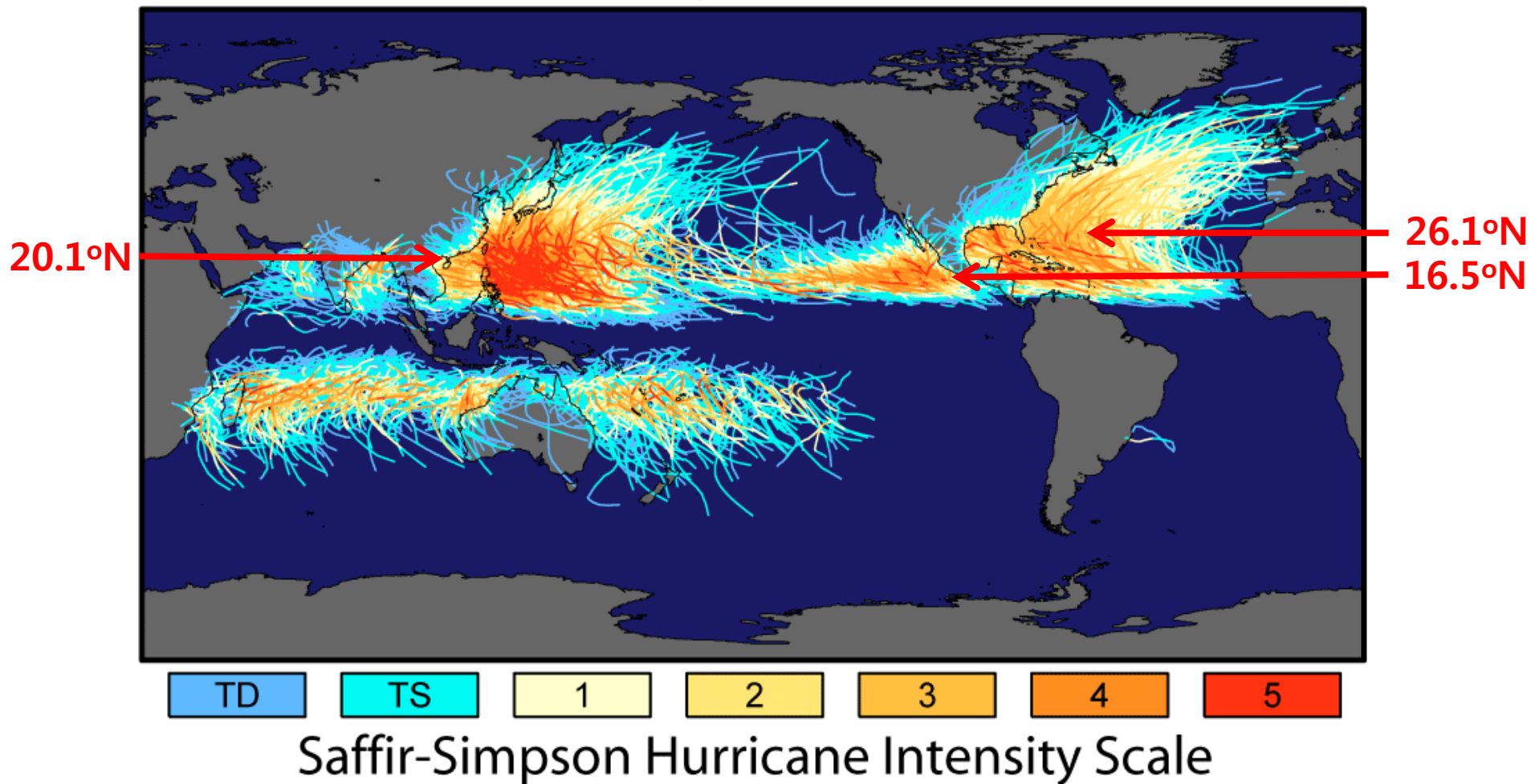
Table 1 | Linear trends, by region, of annual-mean latitude of LMI

	NHEM	SHEM	NATL	WPAC	EPAC	NIO	SIO	SPAC	Global
Best track	+53 ± 43	+62 ± 48	+7 ± 98	+37 ± 55	+10 ± 32	-25 ± 78	+67 ± 55	+51 ± 68	+115 ± 70
ADT-HURSAT	+83 ± 50	+35 ± 44	-12 ± 126	+105 ± 71	+34 ± 30	+10 ± 106	+30 ± 52	+54 ± 79	+118 ± 70

Trends are deduced from the best-track and ADT-HURSAT data sets. The slope (kilometres per decade) and the 95% two-sided confidence bounds are shown. Positive slopes represent poleward migration. NHEM, Northern Hemisphere; SHEM, Southern Hemisphere; NATL, North Atlantic; WPAC, western Pacific; EPAC, eastern Pacific; NIO, North Indian Ocean; SIO, South Indian Ocean; SPAC, South Pacific.

Trends in individual basins ()

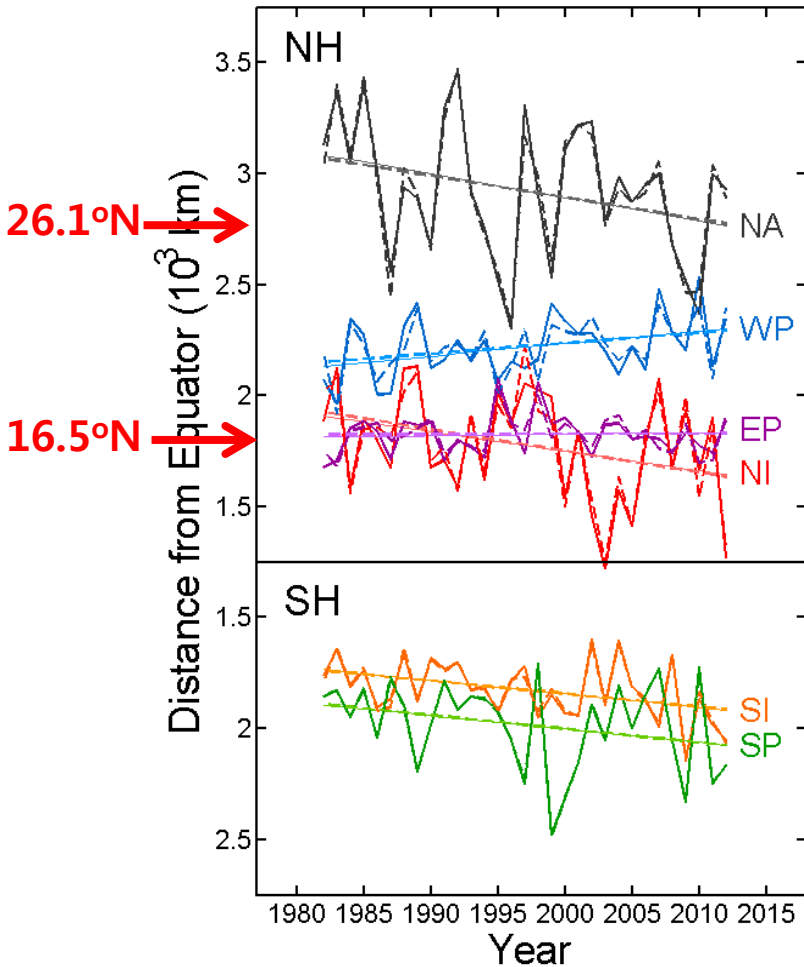
Tracks and Intensity of All Tropical Storms



Trends in individual basins

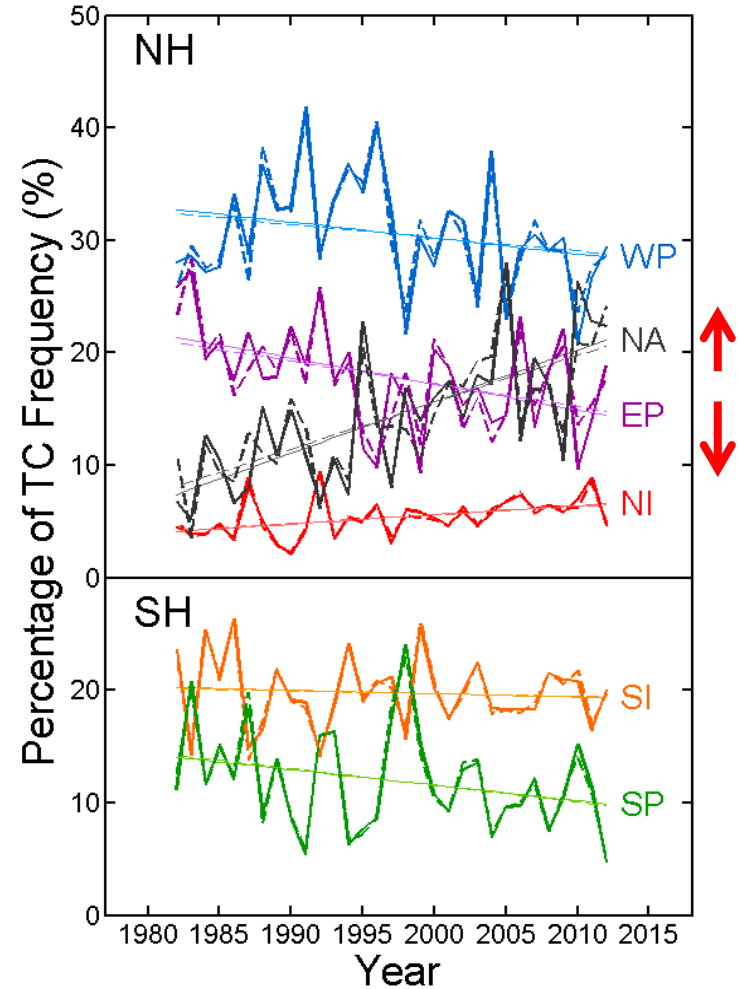
Annual-mean latitude of LMI

(a)



Percentages of TC frequency to the total global TC frequency and their linear trends

(b)



Linear trends in LMI & Frequency

	WP	NA	EP	NI	SI	SP	NH	SH	GLB	IH
Linear trend of LMI latitude [km decade ⁻¹]	47.2 (93%)	-97.7 (88%)	1.4 (1%)	-97.3 (94%)	58.3 (97%)	61.3 (82%)	51.6 (97%)	55.3 (96%)	57.6 (99%)	106.9 (99%)
Clim.-mean latitude of LMI	20.1°N	26.1°N	16.5°N	15.9°N	16.5°S	18.0°S	20.1°N	17.0°S	19.1	-
Linear trend of frequency percentage [% decade ⁻¹]	-1.2 (72%)	4.2 (99%)	-2.0 (97%)	0.8 (99%)	-0.2 (16%)	-1.5 (80%)	1.7 (87%)	-1.7 (87%)	-	-
Clim.-mean frequency percentage [%]	30.6	14.4	17.9	5.4	19.8	12.0	68.2	31.8	-	-
Linear trends by frequency contribution [km decade ⁻¹]	-2.7	30.7	6.7	-1.8	2.0	2.0	32.9	4.0	36.9	

Methods : Decomposition

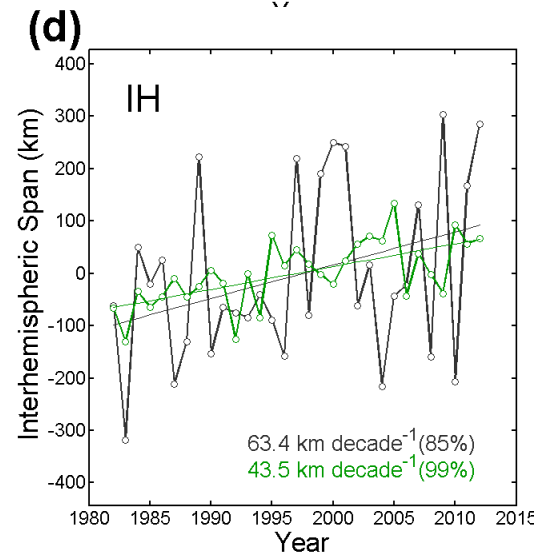
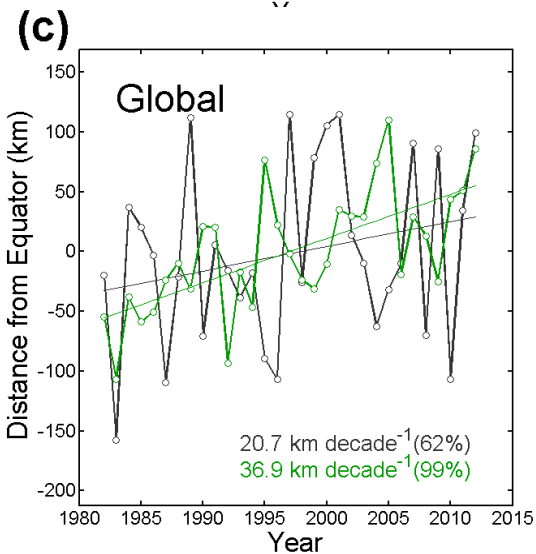
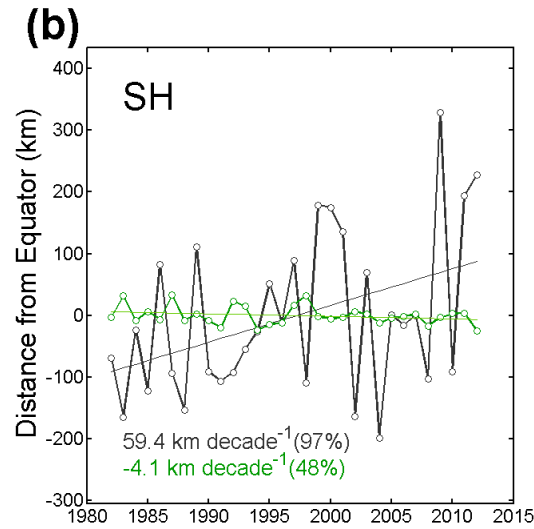
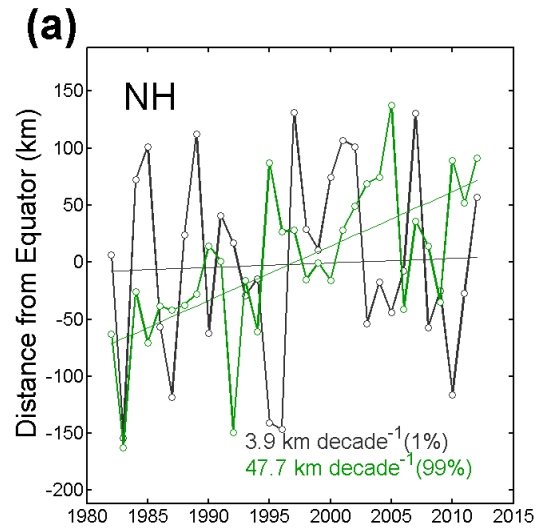
- ✓ The annual global-mean latitude of LMI is determined by sum of multiplying the annual mean LMI latitude (\overline{LLAT}_i) by the ratio of annual TC frequency (N_i) for each basin to the total global TC frequency ($NGLB_i$) in all basins.
- ✓ Here the annual-mean latitude of LMI (\overline{LLAT}_i) can be divided into two components: **climatological mean LMI latitude** (\overline{LLAT}_{clim_i}) and **anomaly** ($\Delta\overline{LLAT}_i$) from the mean value at each basin

$$LLAT = \sum_{i=1}^{N_{basin}} \left(\overline{LLAT}_i \times \frac{N_i}{NGLB_i} \right) = \underbrace{\sum_{i=1}^{N_{basin}} \left(\overline{LLAT}_{clim_i} \times \frac{N_i}{NGLB_i} \right)}_{\text{frequency contribution}} + \underbrace{\sum_{i=1}^{N_{basin}} \left(\Delta\overline{LLAT}_i \times \frac{N_i}{NGLB_i} \right)}_{\text{Pure migration contribution}} \quad (1)$$

N_{basin} is the total number of ocean basins for the globe.

- ✓ Assume that the annual-mean latitude of LMI at each basin is not changing (i.e., climatological basin-mean LMI latitude) → **the trend by changes in the relative annual TC frequency from each basin (frequency contribution)**.
- ✓ Recalculate it using the anomaly from the climatological basin-mean value → the trend by the pure poleward migration of LMI latitude at each basin (**pure migration contribution**)

Comparisons of contributions



frequency contribution (green)

pure migration contribution (black)

✓ NH : mainly determined by the frequency contribution

✓ SH : mostly controlled by the pure migration contribution

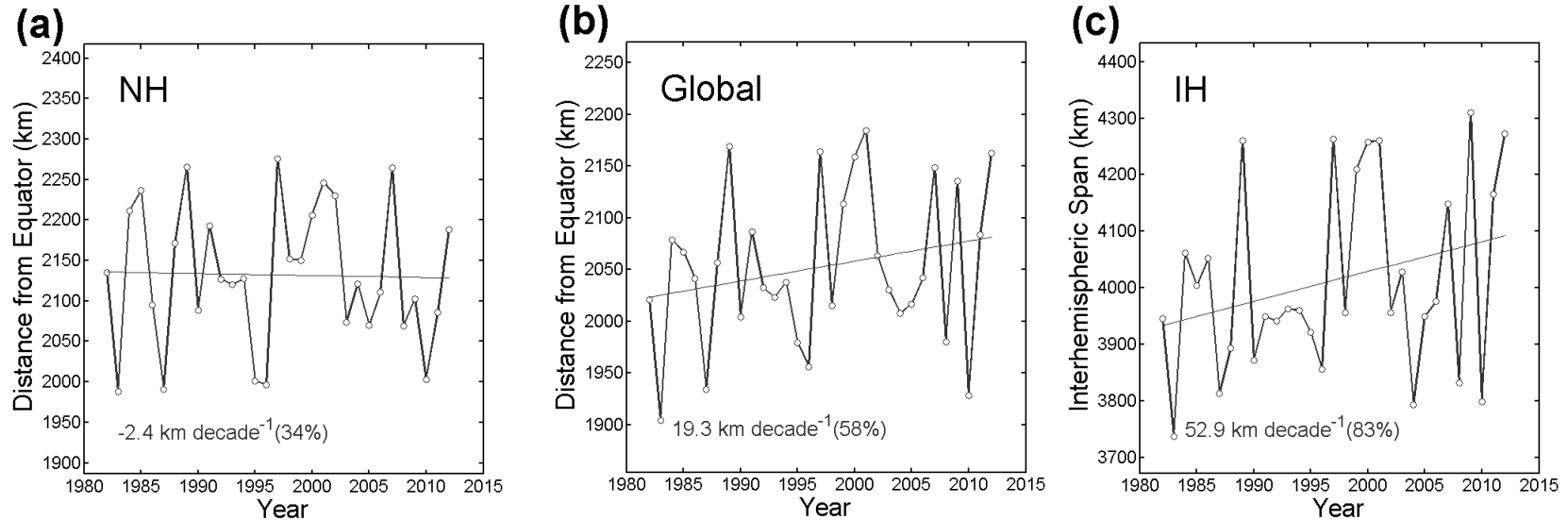
✓ In the NH, 92.4% (47.7 km per decade) of the poleward trend of 51.6 km per decade is a result of the frequency contribution and only 7.6% (3.9 km per decade) is from the pure poleward migration contribution within each basin.

✓ In the SH, 59.5 km per decade is from the pure migration contribution and -4.1 km per decade is from the frequency contribution.

Comparisons of contributions

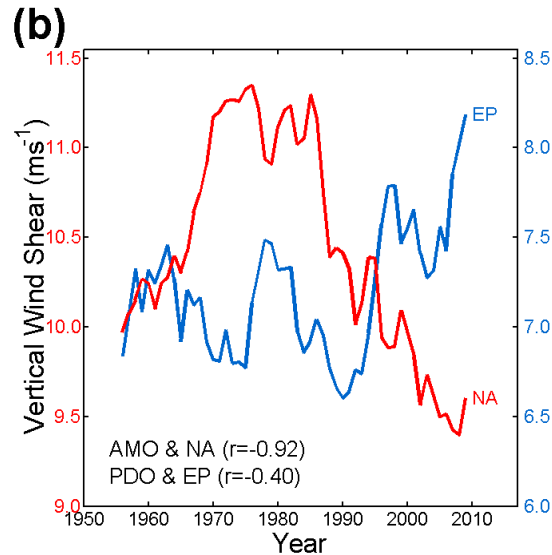
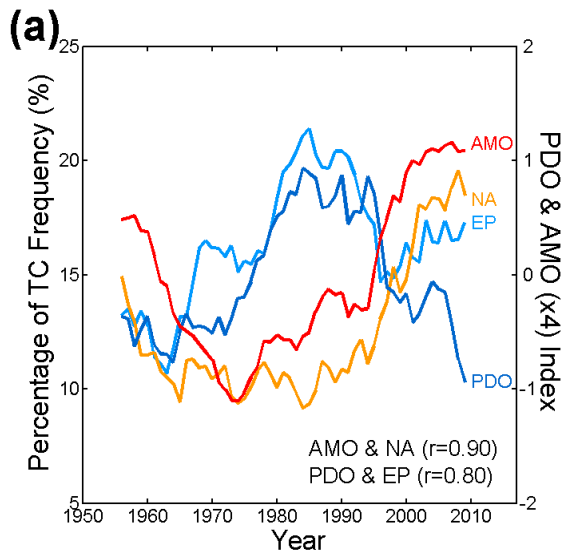
- ✓ In terms of the global average and the interhemispheric span (IS), the frequency contribution influences the poleward trends more than the pure migration contribution since the NH accounts for the majority (68%) of the global TC frequency.
- ✓ Actually, a statistically significant poleward trend of LMI migration with 99% confidence can be produced by using only the frequency contribution for both the global average and interhemispheric span, but not by only the pure migration contribution

Role of frequency change in NA and EP



- ✓ The frequency changes in the NA and the EP are leading most of the frequency contribution shown in the global mean trend.
- ✓ Based on these results, if we simply adjust the climatological mean LMI latitudes for the two basins (NA: 26.1°N , EP: 16.5°N) to the global-mean (19.1°) or NH-mean (20.1°N) LMI latitude and keep the annual variability to remove the frequency contributions from the two basins, the poleward trend of annual-mean LMI latitude is no longer statistically significant for the NH, globe, or interhemispheric span.
- ✓ These results suggest that an increasing trend of the relative annual-mean TC frequency in the NA where the climatological mean LMI latitude is the highest and a decreasing trend of the frequency in the EP where the mean LMI latitude is very low is the main reason for the poleward trend of LMI latitude in the NH, which also influences global and interhemispheric span trends.

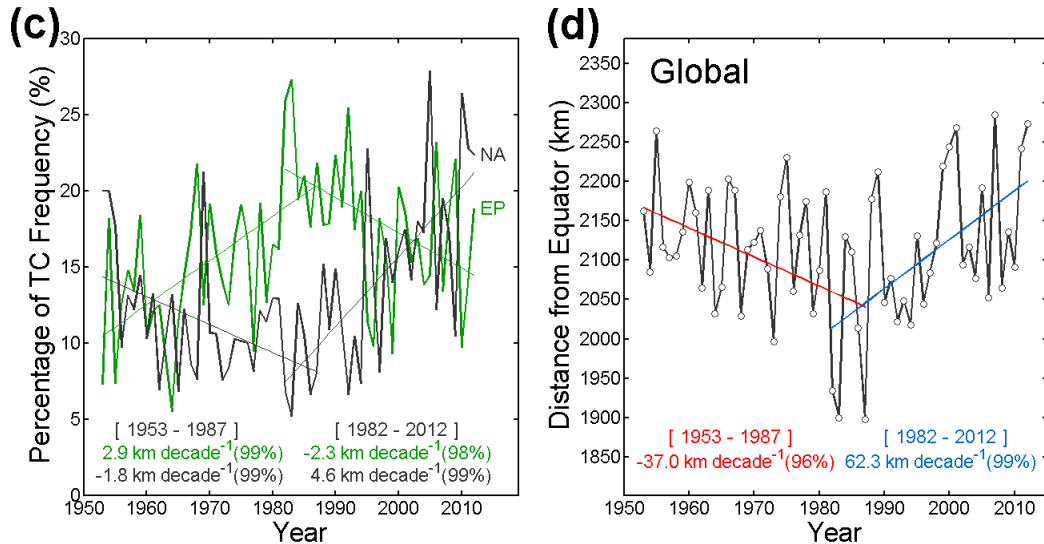
Link to AMO & PDO



- ✓ The TC frequencies in the NA and EP are well known to be linked to not only interannual ENSO variability but also to decadal or longer climate variability such as the AMO and PDO

- ✓ Using an extended data set (1953-2012), the multidecadal variations of TC frequency in the NA (FRQ_NA) and the EP (FRQ_EA) are found to be highly correlated with the AMO ($r=0.9$, AMO & FRQ_NA, where r denotes the correlation coefficient) and the PDO ($r=0.8$, PDO & FRQ_EA), respectively, which are both significant with 99% confidence.
- ✓ It is also shown that the AMO and PDO are linked to variations of the vertical wind shear (VWS) over the main TC development regions of the NA (VWS_NA) and EP (VWS_EP), respectively (Fig. 4b), which is a major index related to TC genesis.

Multidecadal Variability



✓ These linkages imply that the poleward migration of the global LMI location observed during the last 30 years, at least in the NH, can be explained as a phase of such multidecadal variability.

- ✓ The close relationship between the frequency in the NA/EP and the migration of LMI latitude is also found in the earlier data although the data quality of the period could be an issue.
- ✓ During the earlier period (1953-1987), the frequency trends in the NA and the EP are opposite to those during the last 30 years and the resulting trend of the global-mean LMI latitude is also reversed.
- ✓ This suggests that if the frequency trends in the two ocean basins are reversed, as found in earlier TC records, the poleward trend could be changed to an opposite, equatorward, trend in the future.

Conclusions

- ✓ A quantitative analysis of historical global TC track data reveals that the observed poleward migration of LMI latitude is largely influenced by basin-to-basin changes in TC frequency.
- ✓ Particularly for the NH which accounts for the majority of global TC frequency, 92% of the poleward trend is a result of the frequency changes.
- ✓ The linear trend analysis reveals that the recent increasing and decreasing trends of TC frequency in the NA and EP, respectively, with very high and low climatological mean LMI latitudes (NA=26.1°N, EP=16.5°N) play a key role in the poleward migration in the NH.
- ✓ The frequency contribution well illustrates how the global and hemispheric poleward trends become statistically significant in spite of the insignificant trends observed in all basins of the NH.
- ✓ Due to the dominance of the frequency control in the LMI latitudes in the NH, we could even produce a statistically significant global poleward trend only using the basin-to-basin frequency changes without any migration in all basins.

Conclusions

- ✓ The SH is mainly controlled by the migrations related to the mean meridional environmental changes in each basin.
- ✓ Additional analyses show that the TC frequencies and VWS (a major index related to TC genesis) in the NA and EP are highly correlated with decadal or longer climate variability such as the AMO and PDO.
- ✓ These imply that the poleward migration of the global LMI location observed during the last 30 years could be changed to an opposite trend in the future if the phase of the multidecadal variability in the NH is reversed.

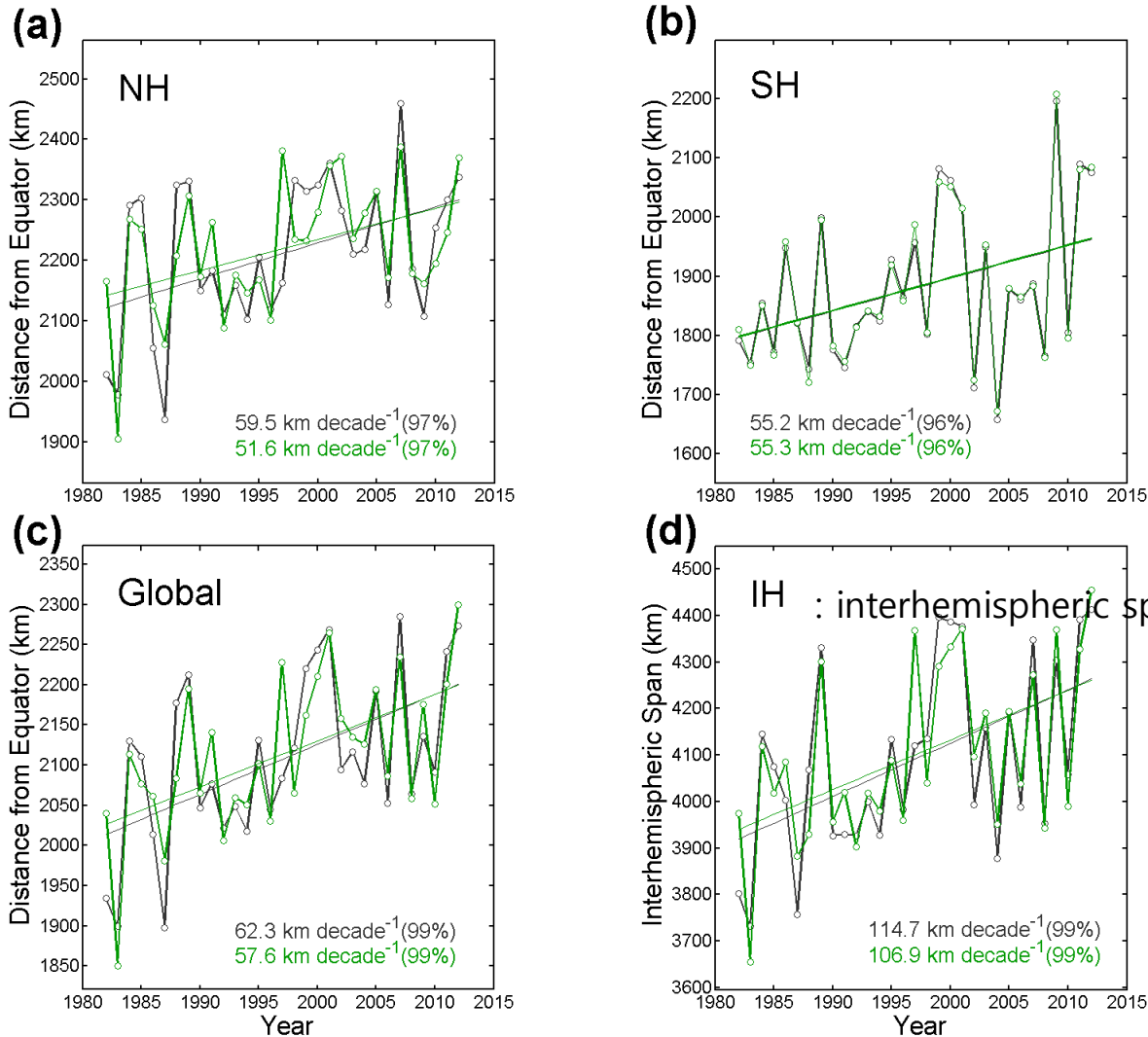


Thank you for Attention!

Data & Methods

- ✓ Global best track data were obtained from the International Best Track Archive for Climate Stewardship (IBTrACS, version v03r05) over the 31-year period 1982–2012
- ✓ We use IBTrACS-ALL data in which the best track data were provided by all agencies and dataset sources,
- ✓ When a storm has overlapping data from multiple sources, we use the source with the greatest reported LMI as in KEV.
- ✓ In storms that achieve their LMI more than once, the latitude of LMI is taken at the first occurrence.
- ✓ **The calculation has been done for TCs that are of at least tropical storm**
- ✓ For TCs passing the International Date Line in the Pacific, the ocean basin to which the TC belongs is determined according to the location where the storm reached its LMI.
- ✓ Significance tests on linear trends are conducted using the Mann-Kendall trend test [*Mann, 1945; Kendall, 1970*].

Trends after reduction of ENSO



Black : After reducing the ENSO contribution

Green : raw data with ENSO

✓ All statistically significant with 95% confidence and similar to those of KEV

- ✓ Poleward trends : 52, 55, 58 and 107 km/decade in the NH, SH, global, and IH
- ✓ Without reducing the ENSO contribution : 60, 55, 62 and 115 km per decade
- ✓ ENSO plays only a minor role in the long-term hemispheric and global trends

Discrepancy between global and individual basins

- ✓ Compared to the hemispheric or global mean trends, significant trends in the annual-mean latitude of LMI are **not found in all individual ocean basins** except the South Indian Ocean where the trend is significant with 95% confidence
- ✓ In particular, in the NH that accounts for 68% of global TC frequency, **negative contributions** are found from the North Atlantic and the North Indian Ocean.
- ✓ The discrepancy in the annual-mean trends between the NH (or global) and the individual basins is a result of the contribution of the temporal variations **in the relative annual frequency of storms from each basin** where climatological mean LMI latitude is greatly different
- ✓ The trends in the percentage of the annual TC frequency for each basin to the total annual global TC frequency are clear and statistically significant in all basins of the NH except the western North Pacific.

Discussions

- ✓ The present analysis has been done mainly for TCs that are of at least tropical storm (TS) strength with maximum wind speeds (MWS) of more than 17 m s^{-1} , which is different from KEV who used two datasets for analysis of LMI latitude: the global best track data and a globally homogenized record of intensity taken from the Advanced Dvorak Technique Hurricane Satellite (ADT-HURSAT) data set.
- ✓ The two datasets are very different, particularly in the TC intensities used. The former includes tropical depressions (TD) with MWS of less than 17 m s^{-1} ; the latter is limited to only TCs with intensities of at least hurricane or typhoon strength (MWS of more than 33 m s^{-1}).
- ✓ In general, it is more difficult to estimate the intensity of TDs mainly because TDs have no eye, do not typically have the organization or the spiral shape of more intense storms, and live for a short period [*Kossin et al.*, 2013].
- ✓ For these reasons, RSMC-Tokyo regional center under the World Meteorological Organization (WMO), which takes the responsibility of producing TC best tracks in the western North Pacific, does not provide intensity information for TDs.

Discussions

- ✓ The ADT-HURSAT data are also limited to only TCs with MWS of more than 33 m s^{-1} to reduce potential errors in the ADT analysis.
- ✓ Although we provide results of additional analyses including TDs (see Figs. S2, S3; Table S1) which are shown to be consistent with the present conclusions, we believe that it is prudent to exclude TDs in the present analysis due to accuracy issues [*Landsea et al.*, 2010].
- ✓ For ADT-HURSAT records, limitations still exist in determining the accurate time of LMI since they were produced without using various observational data from aircraft, buoys, weather stations, and other observational platforms.
- ✓ Limiting the sample to only intense TCs with a maximum intensity 33 m s^{-1} may also lead to making basin-based analysis difficult due to a reduction of sampling number.

Discussions

- ✓ In the extended TC data going back to the 1950s before satellite imagery, the low latitude TCs over the open ocean might have been missed preferentially compared to higher latitude ones closer to the North America and Asia continents, as the latter would have been more completely observed.
- ✓ This may contribute to some of the trends toward lower latitudes of LMI positions from the 1950s to around 1980 in Fig. 4d.
- ✓ However, considering that the limitations in TC observations could exist in both the NA and EP during the period, we cannot deny the possibility that the earlier equatorward trend of LMI position in Fig. 4d is real as a result of the clear long-term opposite trends of both TC frequency and VWS (a crucial index related to TC genesis) between the two basins (Fig. 4c & 4d).

Discussions

- ✓ The global trends in the annual mean latitude of LMI are a result of both intra-basin and inter-basin changes.
- ✓ The climatological mean latitude of LMI varies by basin (see, for example, Extended Data Fig. 1) such that, in addition to meridional shifts within each basin, changes in the relative annual frequency of storms from each basin can also contribute to the global trends in the latitude of LMI.
- ✓ To quantify this contribution, the LMI latitude of every storm was normalized by the respective basin-mean LMI latitude, and the analysis of Fig. 1c was repeated.
- ✓ When this was performed, the trend in the best-track data decreased from 115 ± 70 to 78 ± 66 km per decade and the trend in the ADT-HURSAT data decreased from 118 ± 70 to 92 ± 65 km per decade.
- ✓ Thus, both factors contribute, but the intra-basin poleward migration of LMI dominates the trends.