Dominant Role of Subtropical Pacific Warming on the Extreme 2015 Eastern Pacific Hurricane Season

Murakami et al. (2017, J. Climate)

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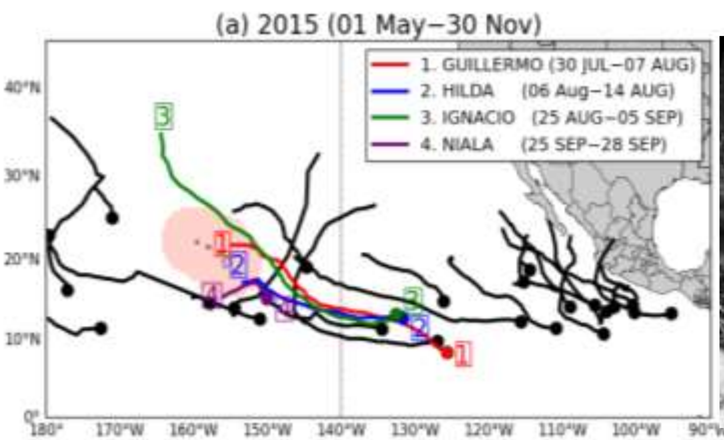
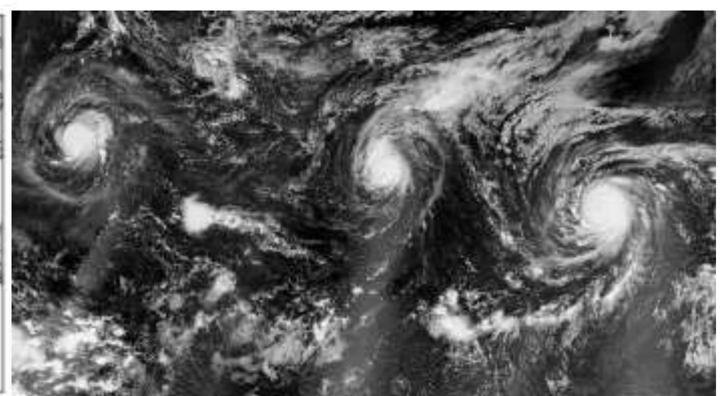
GFDL/Princeton AOS

Active 2015 Tropical Cyclone (TC) Year in the Eastern Pacific Ocean (EPO)

- 27 tropical storms formed (historical record since 1966)
- 15 hurricanes (historical record since 1966)
- 4 Hawaiian hurricanes (2nd most frequent since 1966)
- First instance of 3 simultaneous Category 4 hurricanes
- Hurricane Patricia, the second-most intense on record (872 hPa, 215 mph, $460 million USD damage)



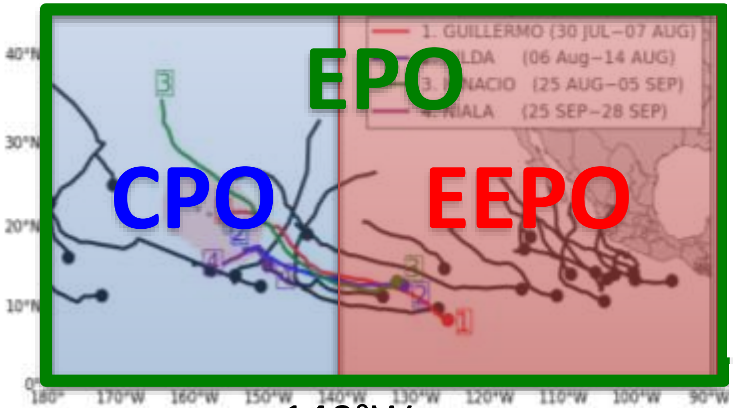
27 Tropical Cyclones in 2015



Hurricanes Kilo (left), Ignacio (center), and Jimena (right) on August 30

Hurricane Patricia

TC Frequency in Observations (1966–2015, May–November)

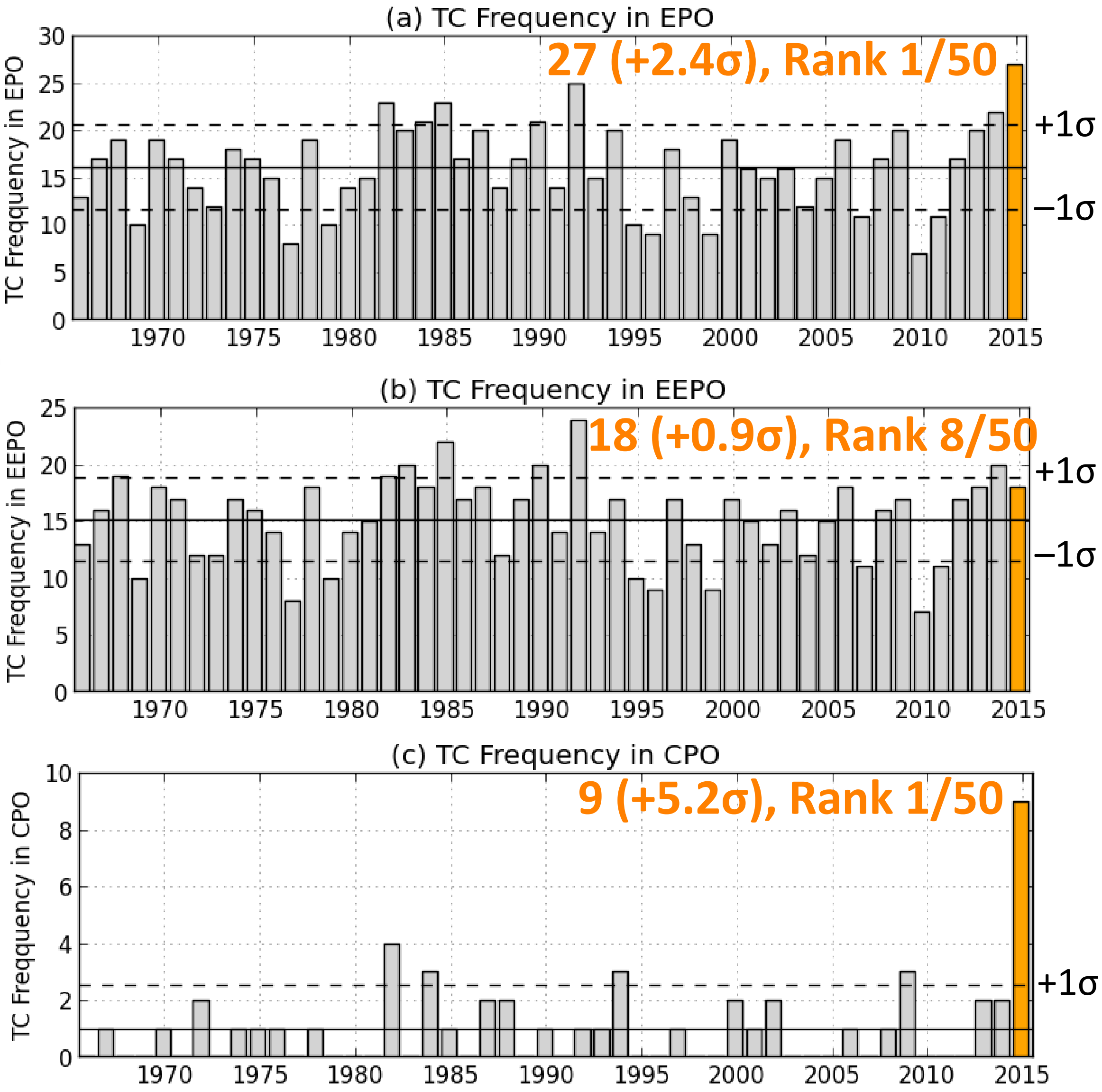


EPO is divided into two subdomains.

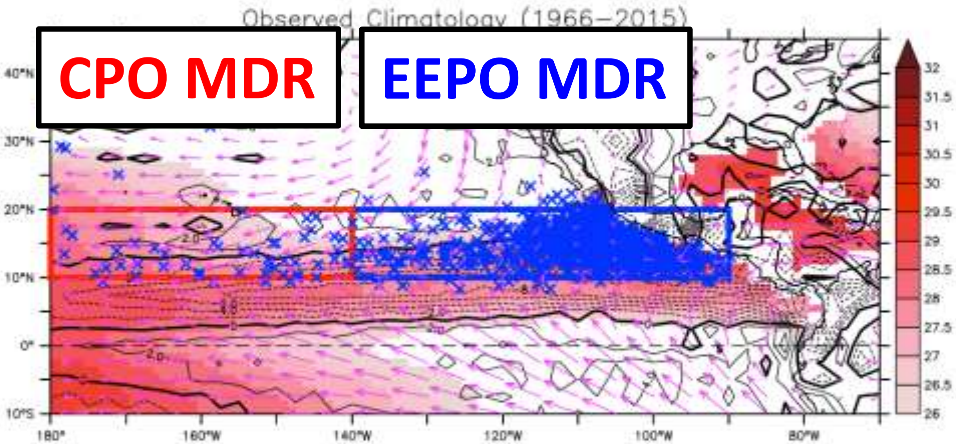
EEPO: Eastern quadrant of EPO

CPO: Central Pacific Ocean

TC (≥34kt) frequencies in EPO and CPO were extremely above normal in 2015.



Large-Scale Conditions in Observations (1966–2015, May–November, HadISST and JRA-55)



Anomaly for 2016 (May–Nov)

	CPO MDR	EEPO MDR
SST [K]	+0.9 (+2.5σ)	+1.0 (+3.0σ)
VWS [m/s]	−4.1 (−2.2σ)	−0.7 (−0.8σ)
RH600 [%]	+3.6 (+1.2σ)	+5.9 (+2.3σ)

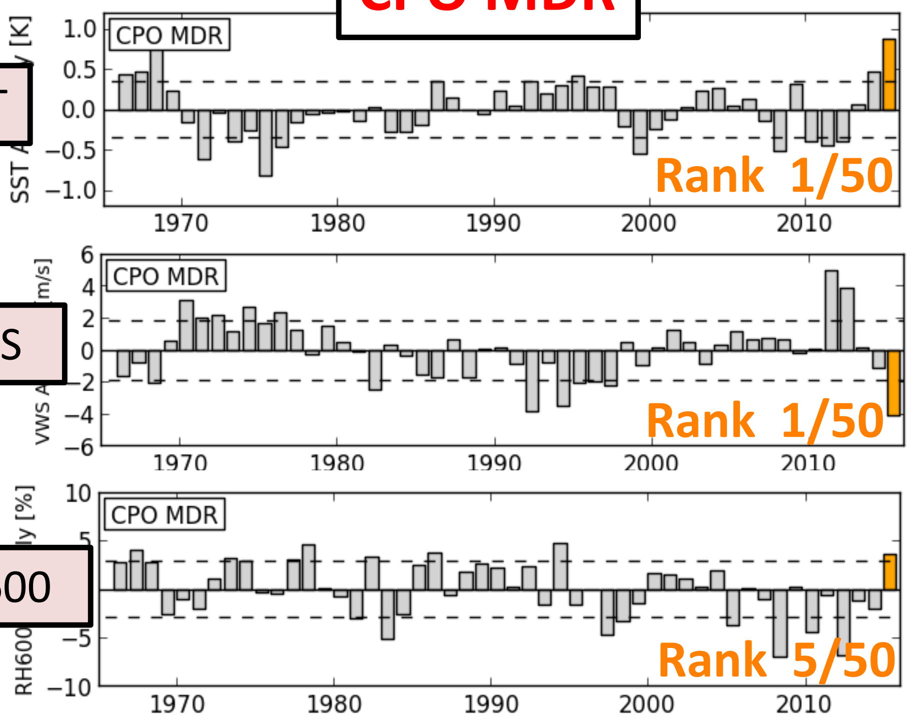
CPO MDR

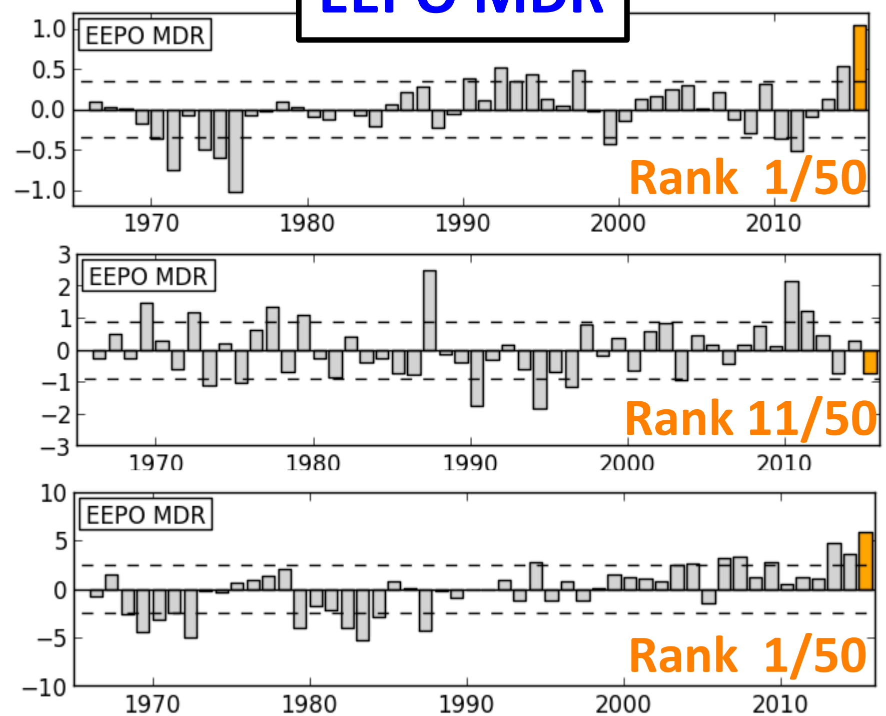
EEPO MDR

SST

VWS

RH600

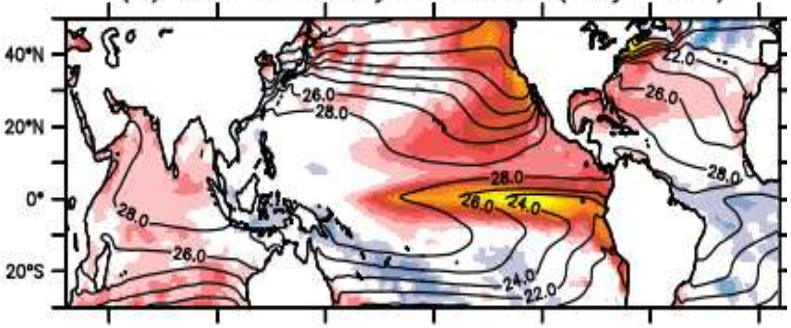




Why were TCs so active in 2015? Big El Niño?

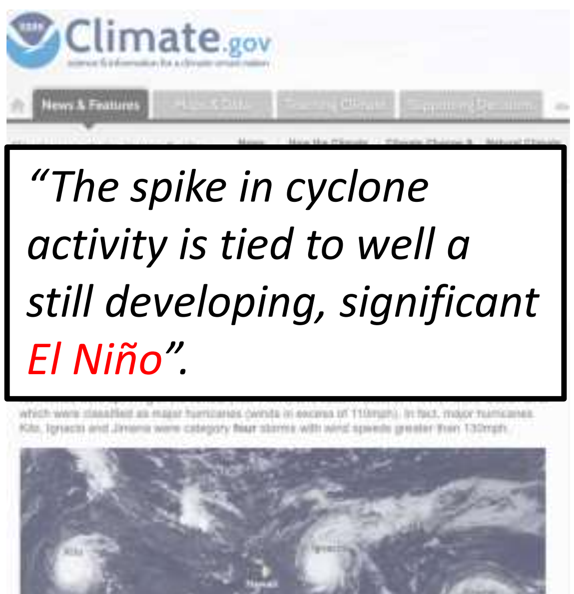
- A strong El Niño developed in 2015.

(a) SST anomaly in 2015 (May–Nov)

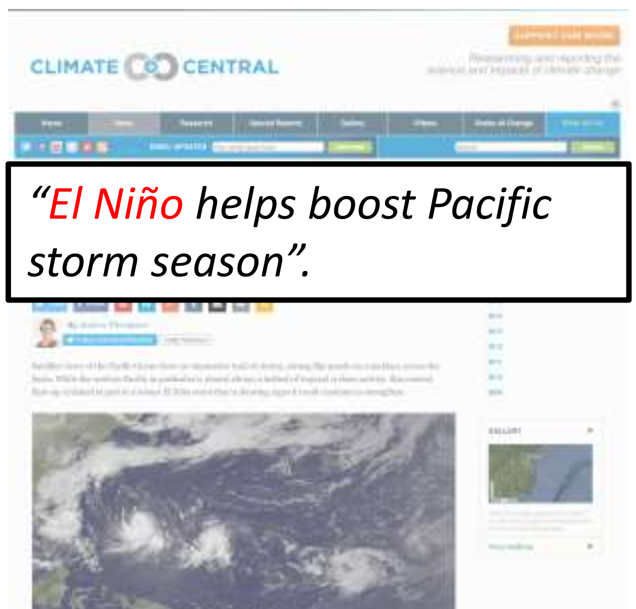


Nino-3.4 Index was **+2.4σ** during the 2015 summer season

- Media commonly reported that the extreme frequency of TCs in 2015 was due to the strong El Niño development.



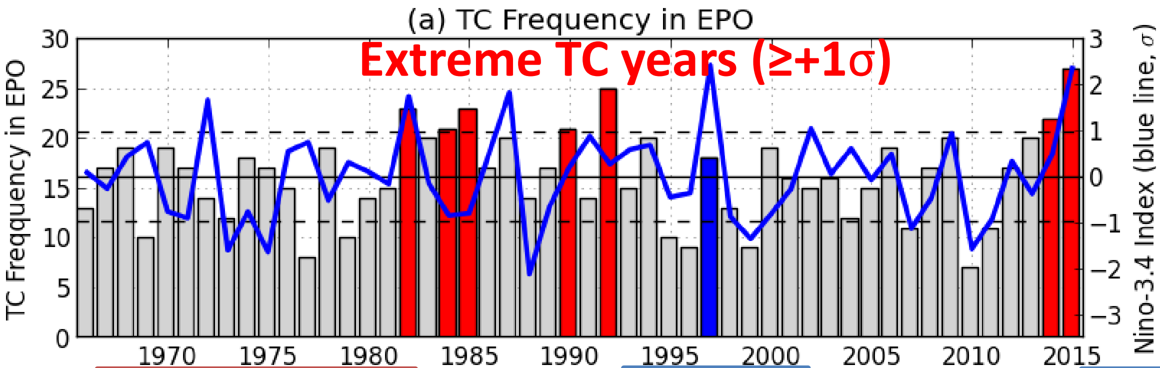
"The spike in cyclone activity is tied to well a still developing, significant El Niño".



"El Niño helps boost Pacific storm season".

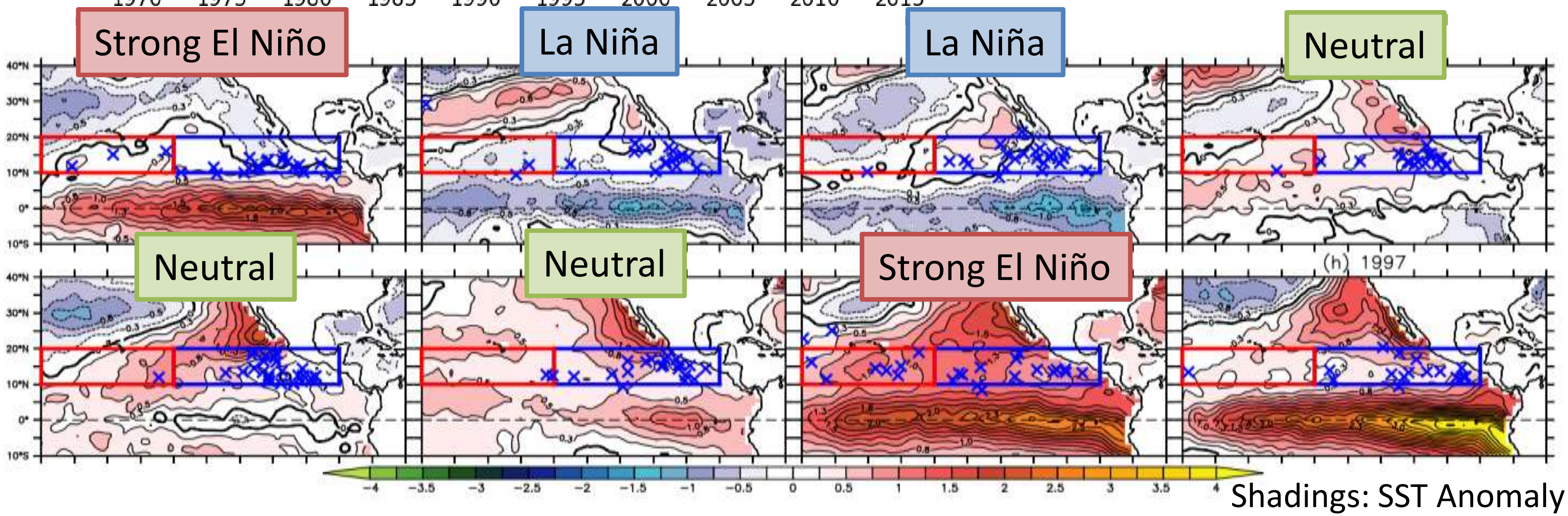
"The eastern Pacific basin sees an increase in named storms during strong El Niño…".

Is it true? Maybe NO!



The 7 extreme TC years during 1966–2015.

Correlation (Niño-3.4 vs TC freq.) = +0.33

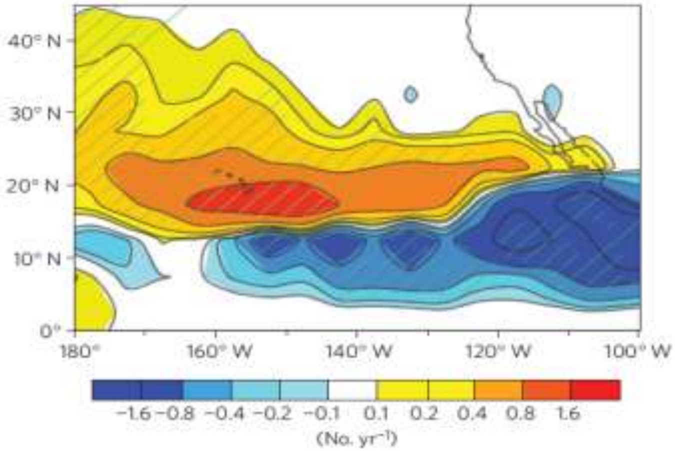


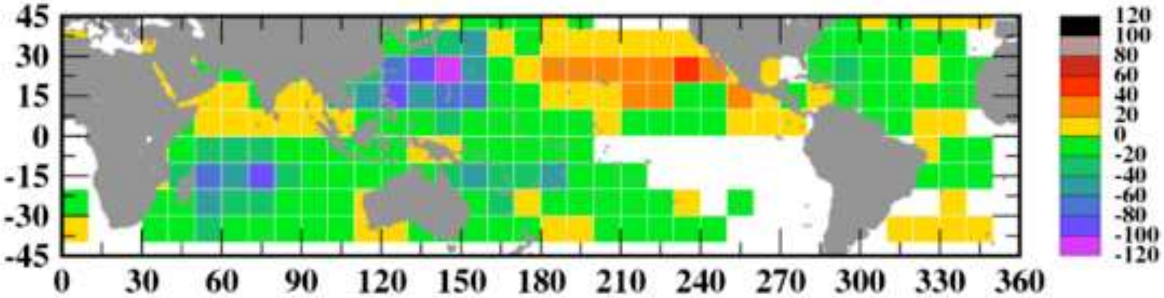
The extreme TC years were not always during El Niño.

The 1997 SST anomaly is similar to that in 2015, but 1997 wasn't an extreme TC year.

Effect of Anthropogenic Forcing?

Projected Changes in TC Density (Late 21st century minus present-day)





Knutson et al. (2015, *J. Climate*)

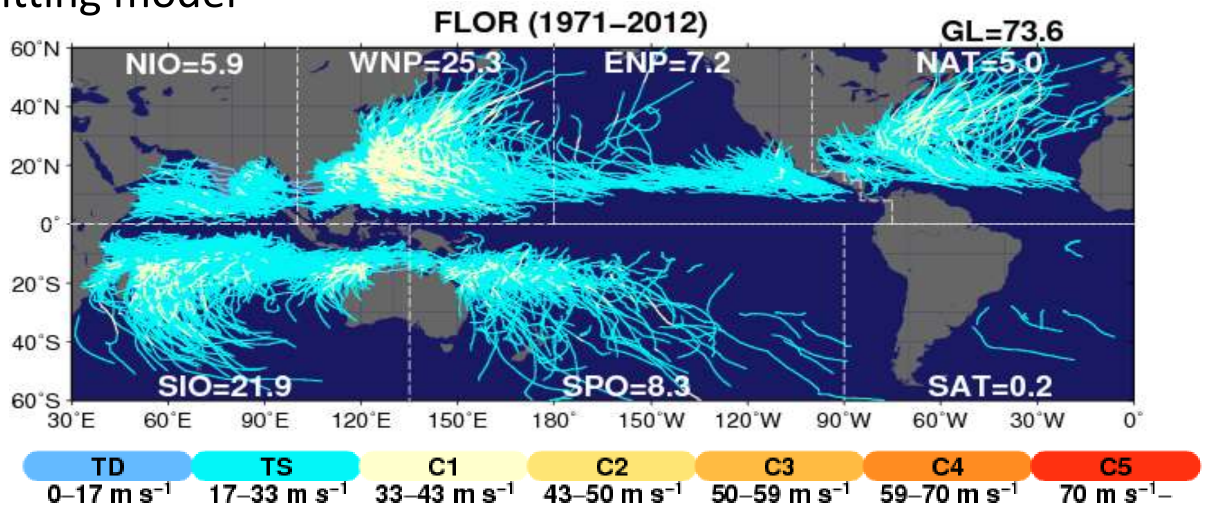
Murakami et al.
(2013, *Nature Climate Change*)

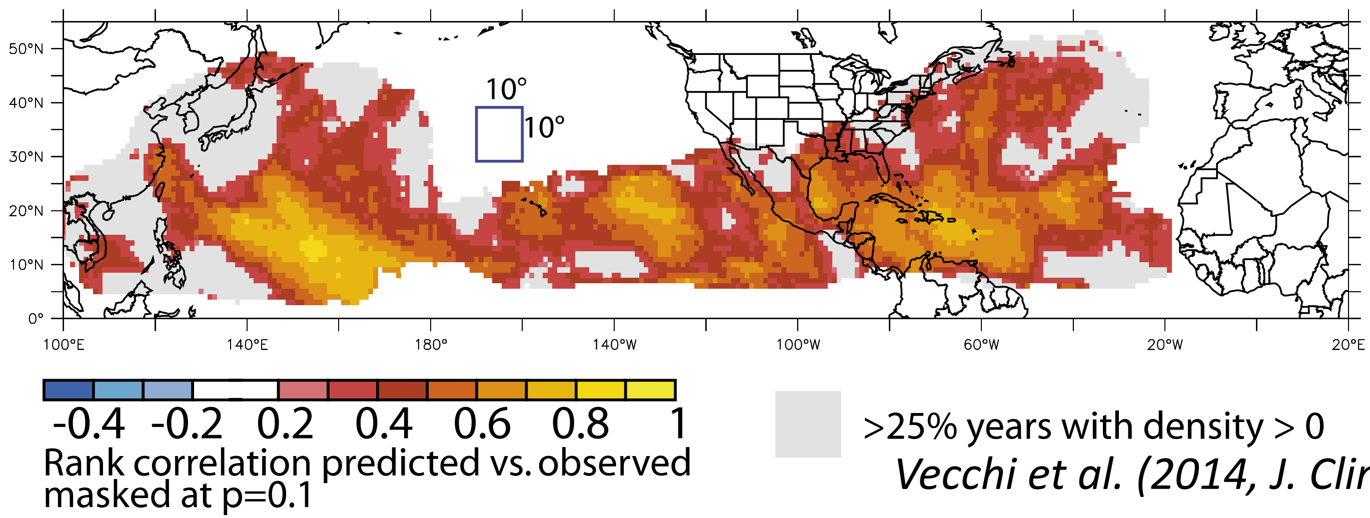
Models consistently project an increase in TC frequency of occurrence in the CPO in the future.

It is possible that the extreme 2015 event had happened influenced by anthropogenic forcing.

GFDL FLOR: Forecast-oriented Low Ocean Resolution version of CM2.5

- CM2.5: Fully coupled model with 50km-mesh atmosphere and 0.25° ocean/sea ice
  FLOR : Fully coupled model with **50km**-mesh atmosphere and **1°** ocean/sea ice
- FLOR is a TC-permitting model



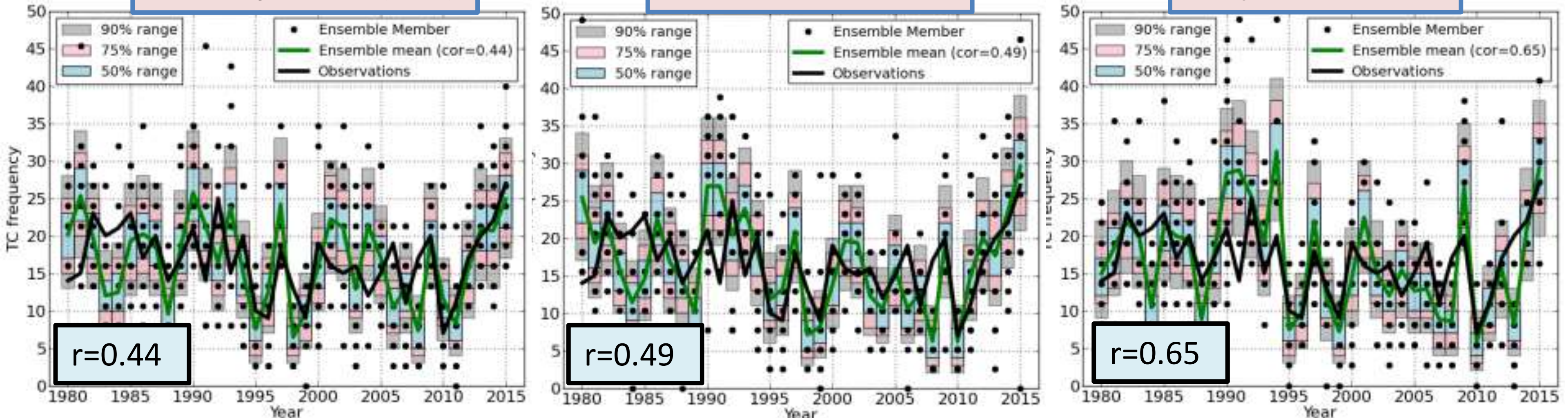


Vecchi et al. (2014, J. Climate)

GFDL FLOR Prediction/Simulation

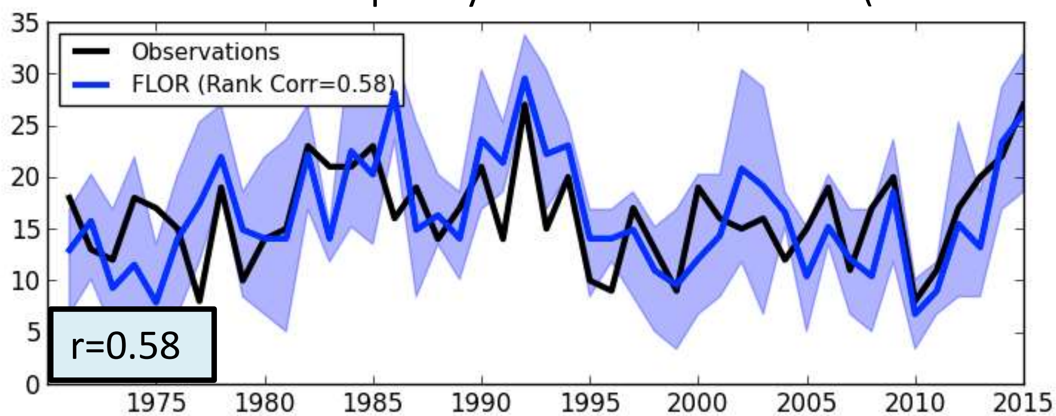
GFDL FLOR could predict the extreme active TC year even from 2015 January.

January Initial (L=6) March Initial (L=3) May Initial (L=0)



Given the observed SST, FLOR can reproduce the observed interannual variation of TC frequency in the EPO.

Simulated TC Frequency in the Eastern Pacific (1971–2012)



It instills greater confidence for the use of FLOR to clarify the possible reason for the 2015 extreme TC year.

Motivation

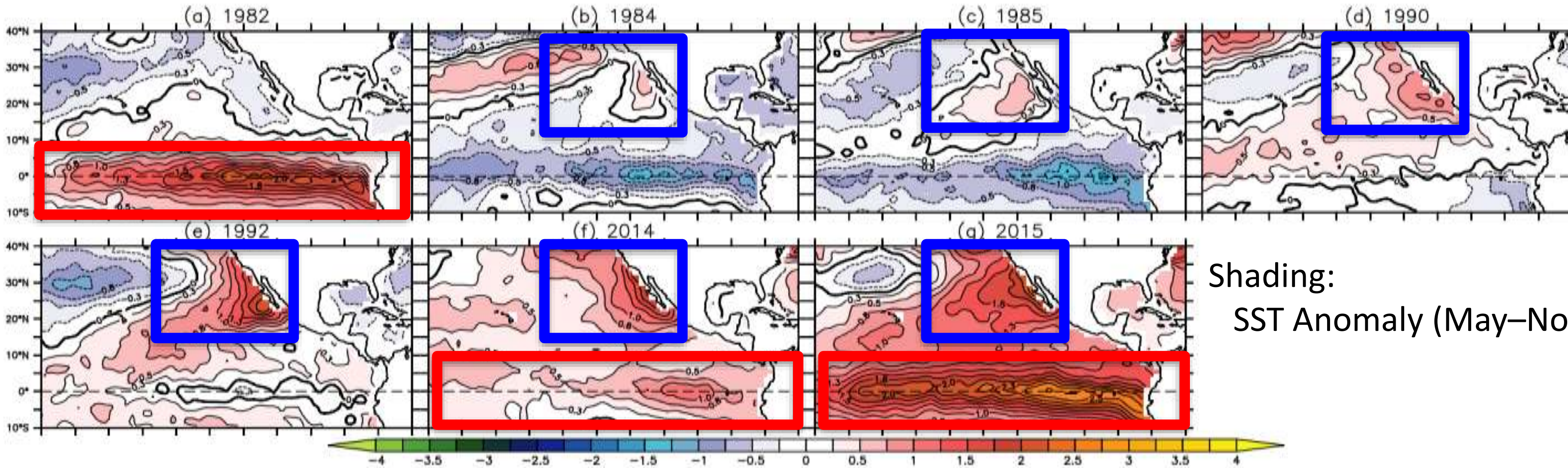
- To clarify the cause of the extreme 2015 TC year
  - Using observations and idealized retrospective seasonal forecast

- To investigate effect of anthropogenic forcing (and natural variability) on the probability of occurrence of extreme TC year
  - Using control and large-ensemble simulations by FLOR
  - Will we see extreme TC year like 2015 more frequent (or less) in the future?

Observed SST Anomaly in the Extreme TC Years

Observed 7 extreme TC years during 1966–2015

Subtropical warming



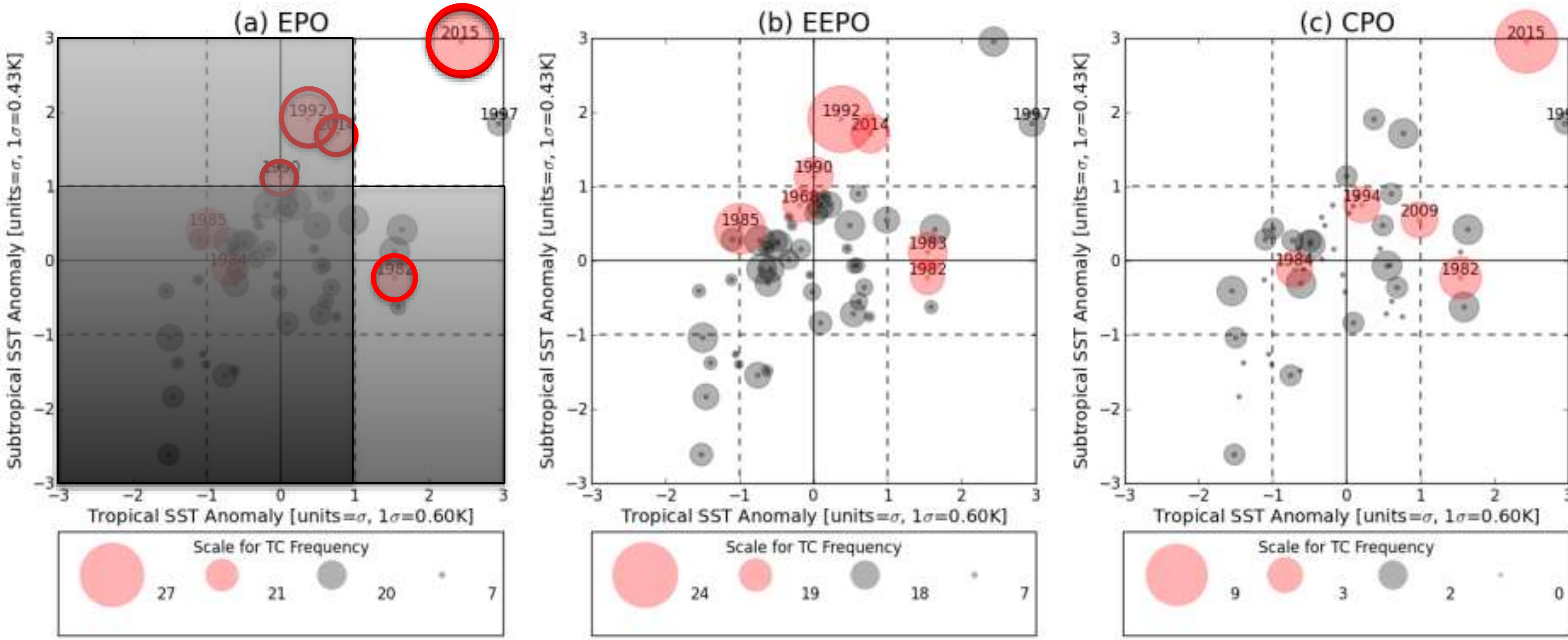
Shading:
SST Anomaly (May–Nov)

Tropical warming related to El Niño

Importance of the Subtropical SST Anomaly for the Extreme TC Years

The 7 extreme TC years during 1966–2015.

Red circle: Extreme TC year



Among the 5 subtropical warming years, 4 are extreme TC years in EPO (80%).

Among the 7 tropical warming years, 2 are extreme TC years in EPO (29%).

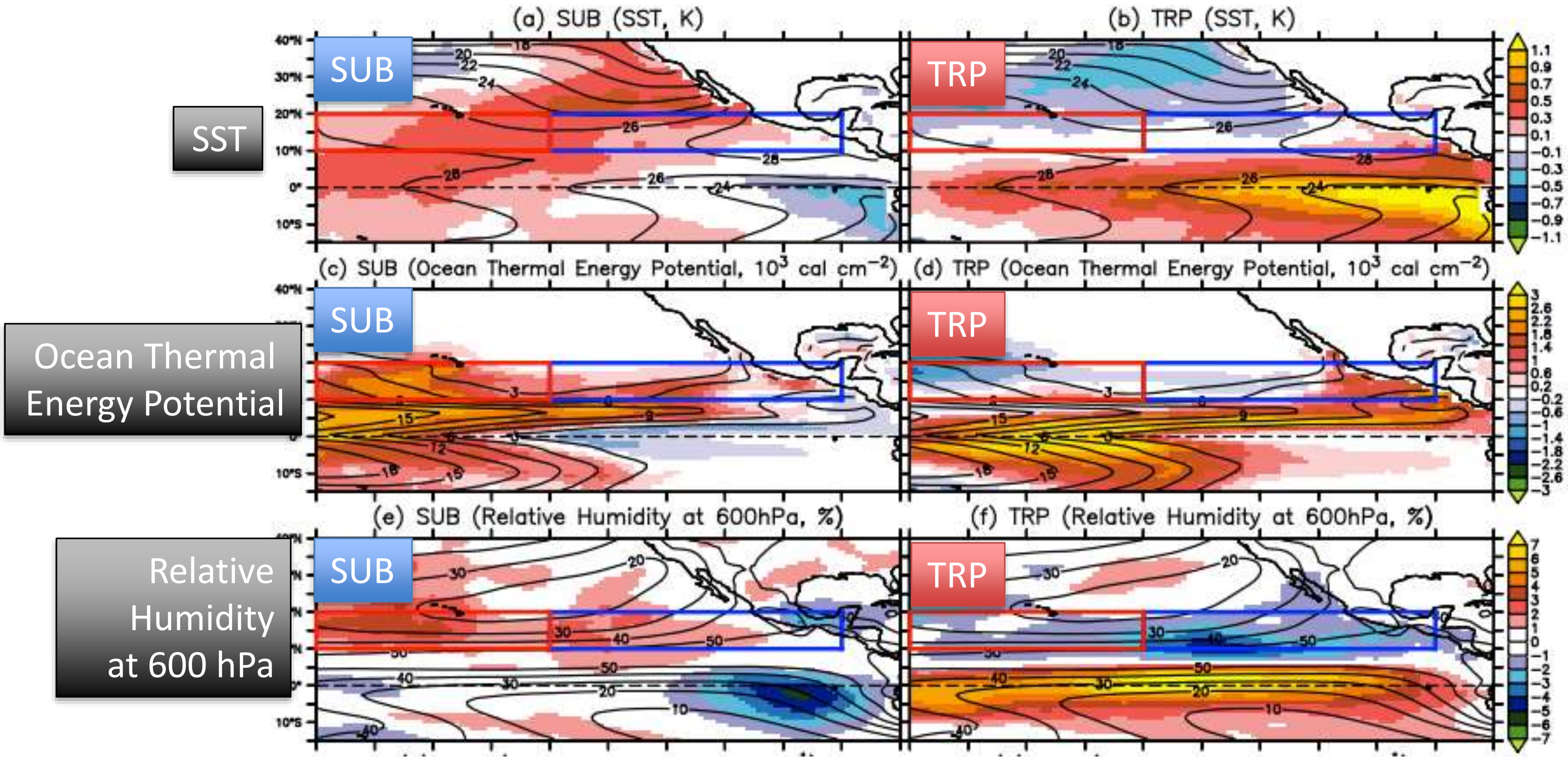
Composite Analysis (1/2)

SUB: The subtropical SST anomaly exceeds +1σ, but the tropical anomaly does not.

(10 years: 1969, 1972, 1976, 1982, 1983, 1987, 1991, 1998, 2002, and 2012)

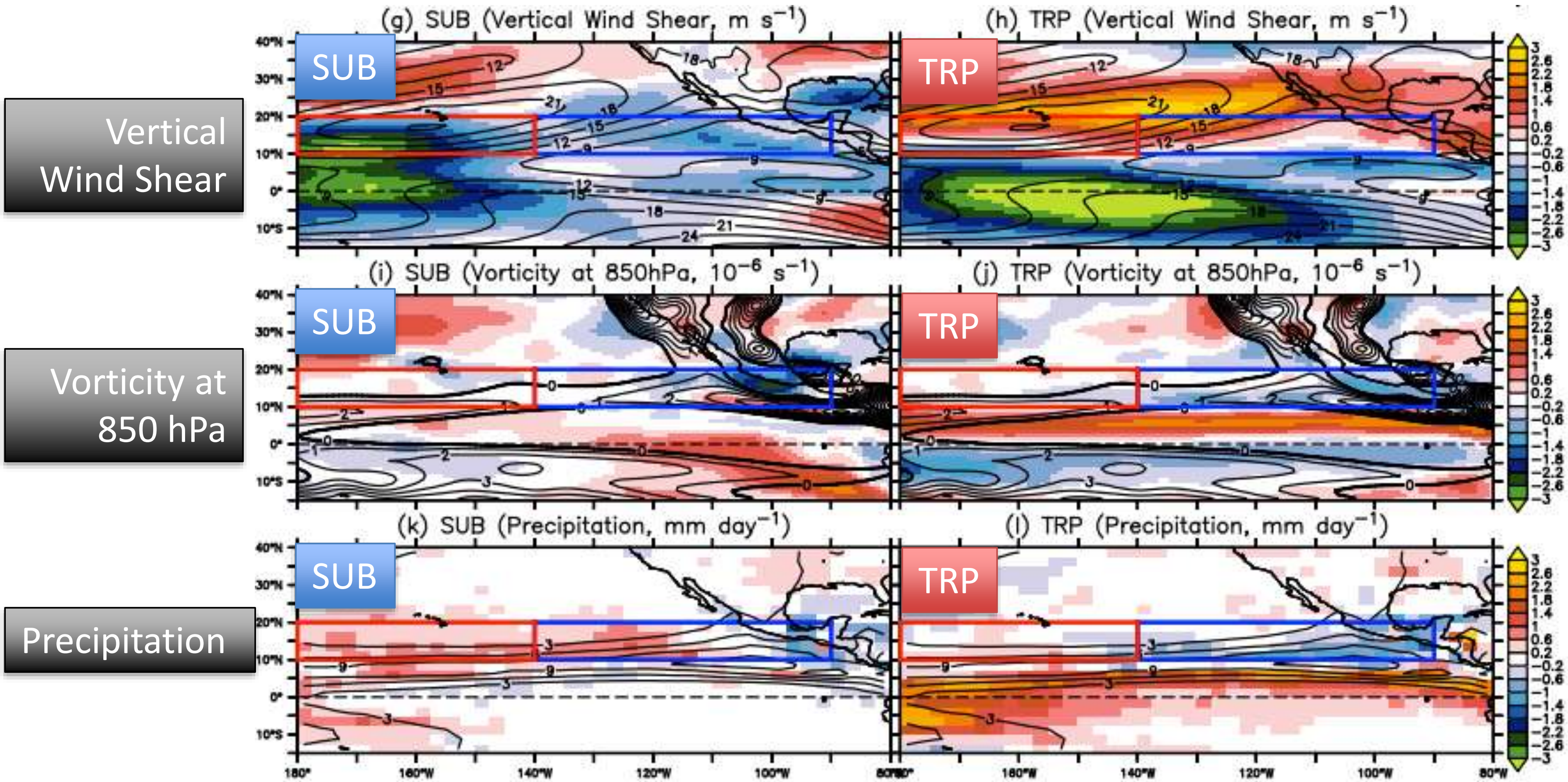
TRP: The tropical SST anomaly exceeds +1σ, but the subtropical anomaly does not.

(8 years: 1968, 1986, 1990, 1992, 1994, 1996, 2003, and 2004)



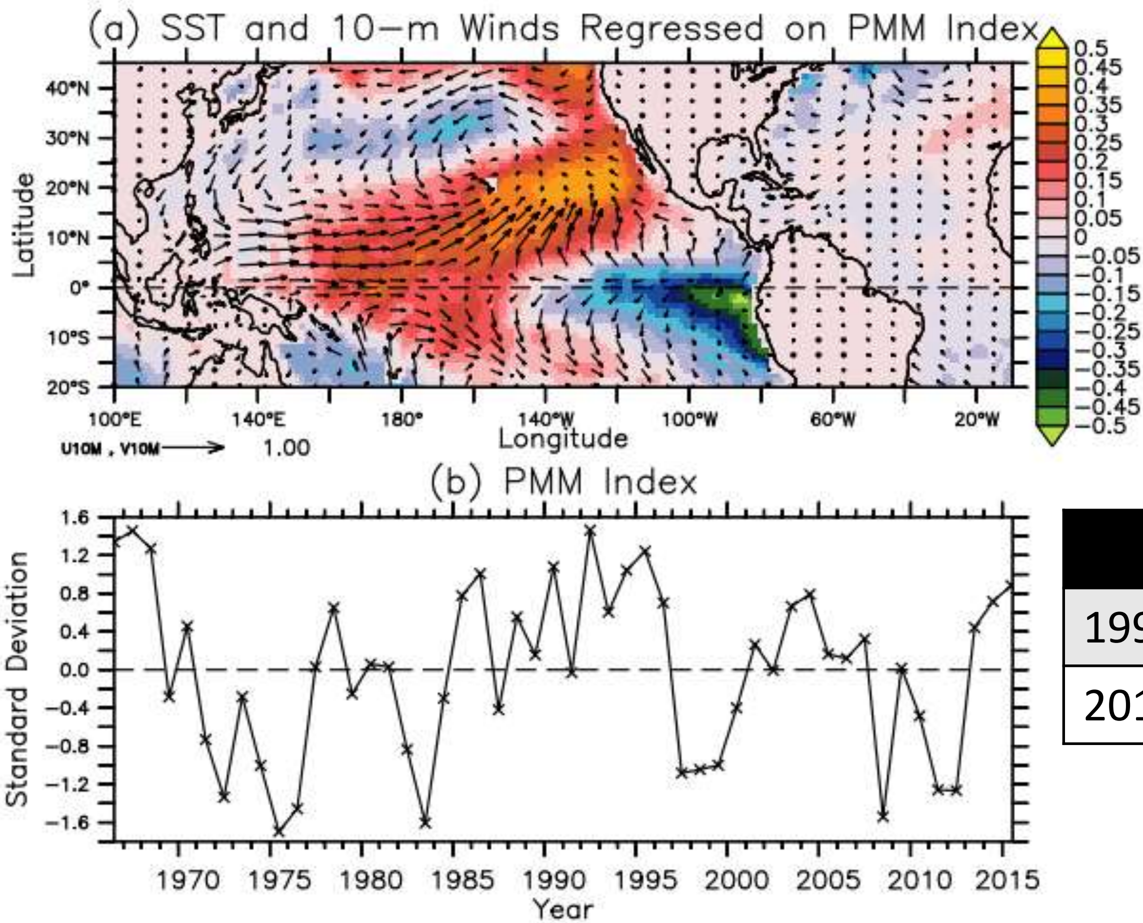
Contour: Climatology, Shading: Composite of Anomaly

Composite Analysis (2/2)



Subtropical warming provides more favorable large-scale conditions for TC activity than tropical warming does.

Pacific Meridional Mode (PMM)

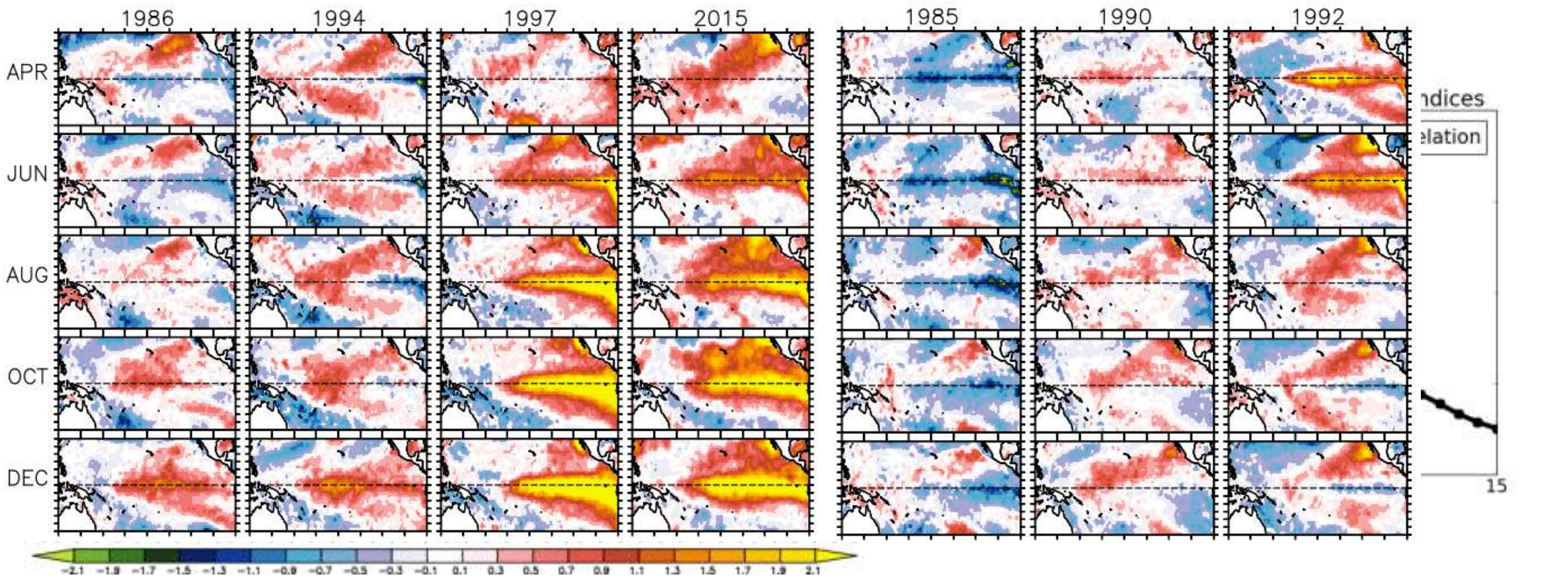


The PMM is the 1st singular decomposition (SVD) mode for the SST and zonal and meridional components of the 10-m wind field (*Chiang and Vimont* 2004).

	Niño-3.4	PMM
1997 (May–Nov)	+2.4σ	–1.0σ
2015 (May–Nov)	+2.4σ	+0.9σ

The difference in PMM between 1997 and 2015 may be important for the difference in TC frequency between the two years.

The PMM as a Trigger for El Niño



The positive PMM during spring time sometimes triggers El Niño development (*Chang et al.* 2007).

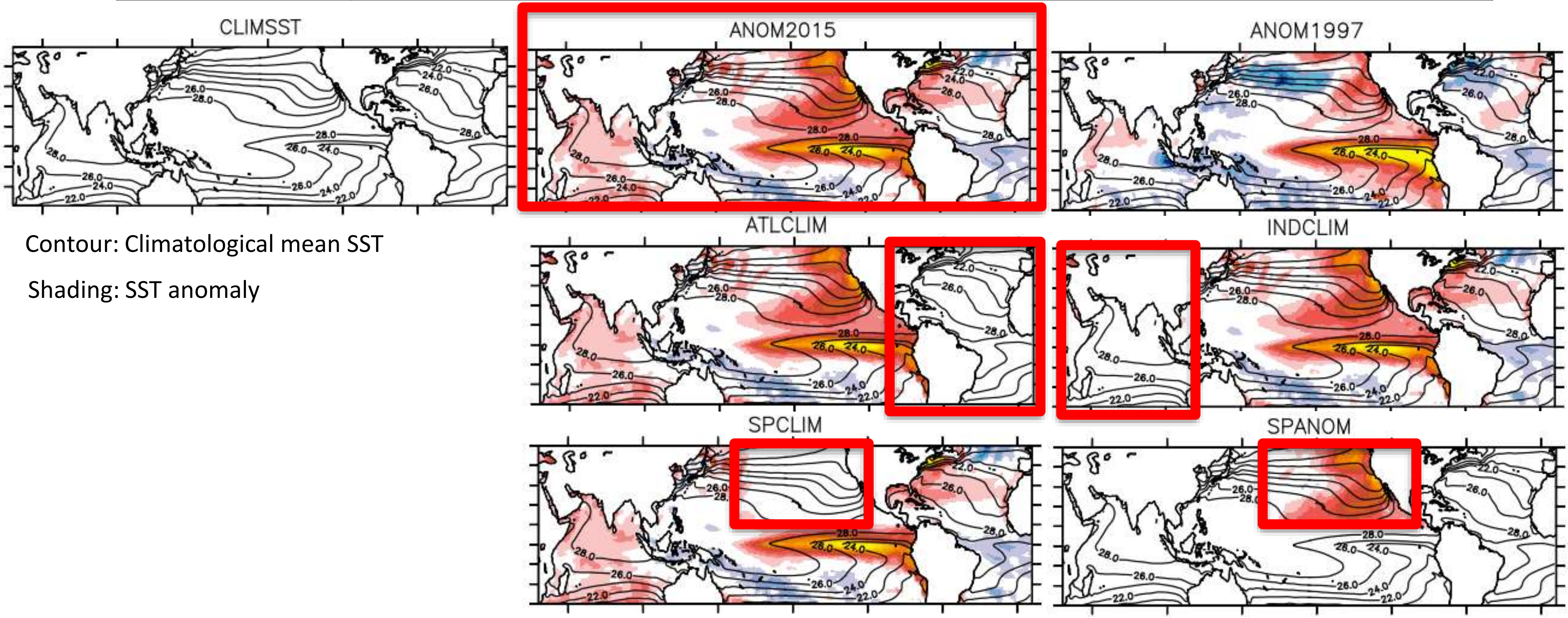
But not always…

In 2015, the high subtropical SST remained during the summer–autumn seasons along with the strong El Niño development.

Idealized Retrospective Seasonal Forecast (1/2)

- To reveal which of the subtropical or tropical SST anomaly is important for the extreme TC frequency in 2015 in the EPO, we conducted idealized retrospective seasonal forecasts.

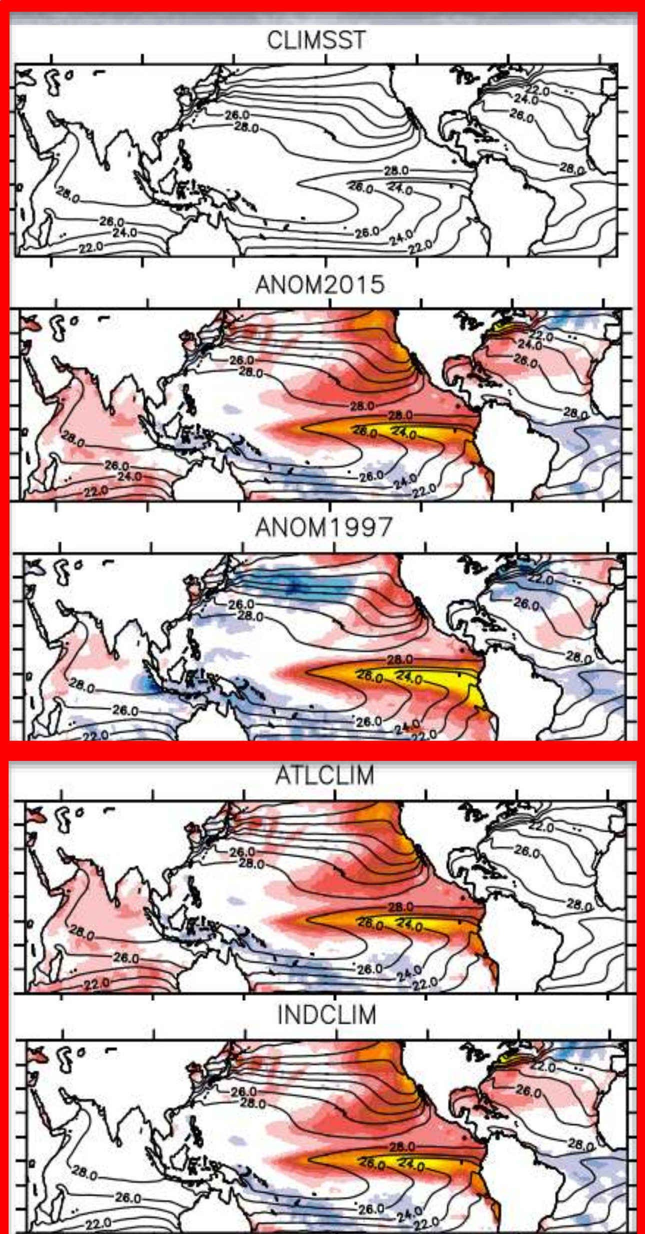
Model	Atmosphere component of FLOR (AM2.5, 50-km mesh)
Prediction	Initialized from 2015 May to predict May–November with 12 ensemble members
SST	Observed or idealized SST is prescribed (7 types)

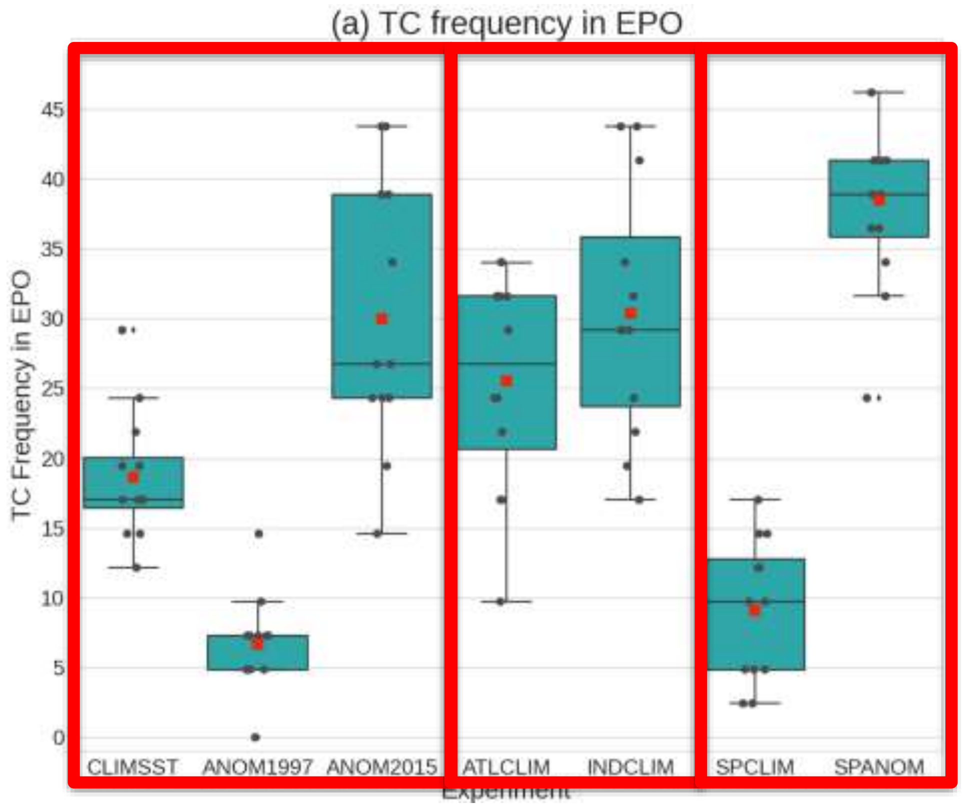


Contour: Climatological mean SST

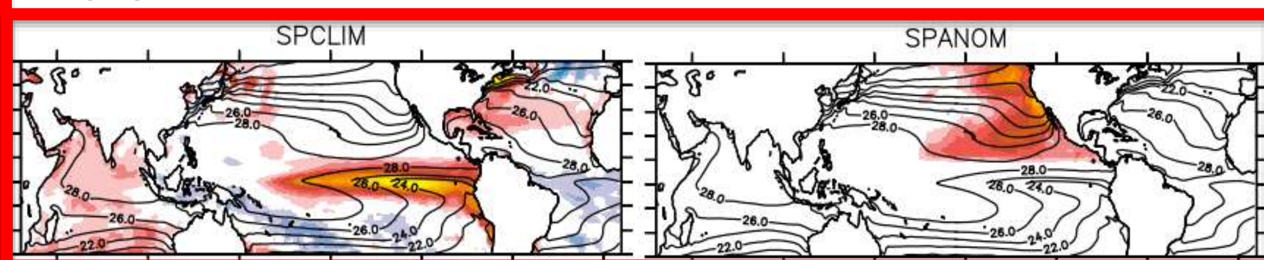
Shading: SST anomaly

Idealized Retrospective Seasonal Forecast (2/2)





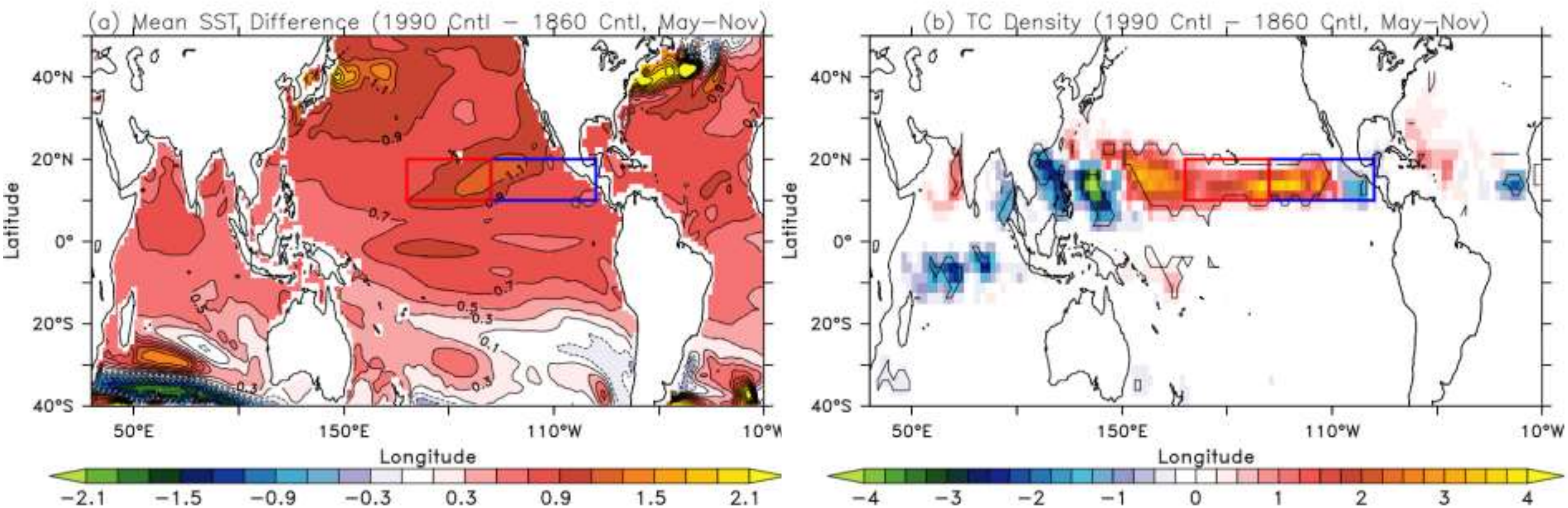
Subtropical SST anomaly is critical for the extreme TC year of 2015.



Effect of Anthropogenic Forcing to Frequency of Extreme TC Year (Control Simulations)

	Radiative Forcing	Simulation Years	Seasonal Mean TC Frequency		
			EPO	EEPO	CPO
1860 Control	1860 Level	3500	12.0	13.3	0.2
1990 Control	1990 Level	500	15.7	15.4	0.7
Diff (1990–1860)			+3.7*	+2.0*	+0.5*

* Statistical Significant at 99% by a bootstrap test

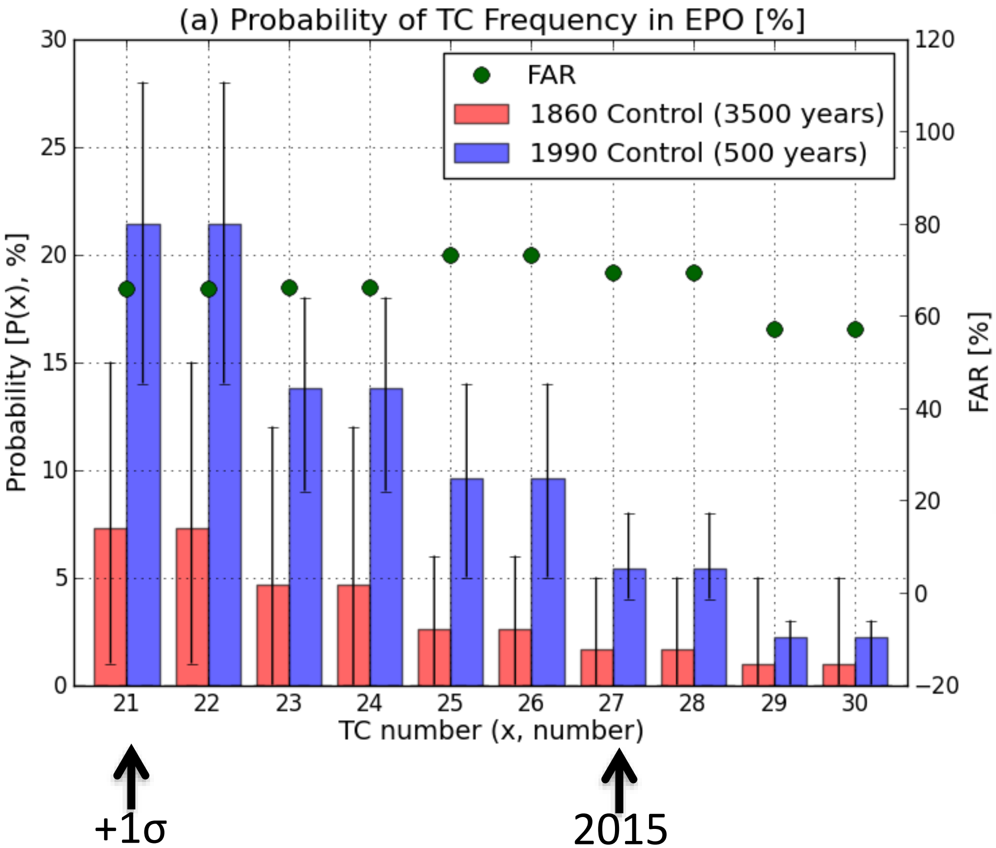


Effect of Anthropogenic Forcing to Frequency of Extreme TC Year (Control Simulations)

Probability of Exceedance

$$P(x) \equiv \frac{\text{Number of years with TC number } \geq x}{\text{Total number of years}}$$

x : TC frequency in a year



Fraction of Attributable Risk (FAR)

$$FAR(x) \equiv \frac{P(x|E_1) - P(x|E_0)}{P(x|E_1)}$$

E_1: Anthropogenic Forcing (1990 Contl)

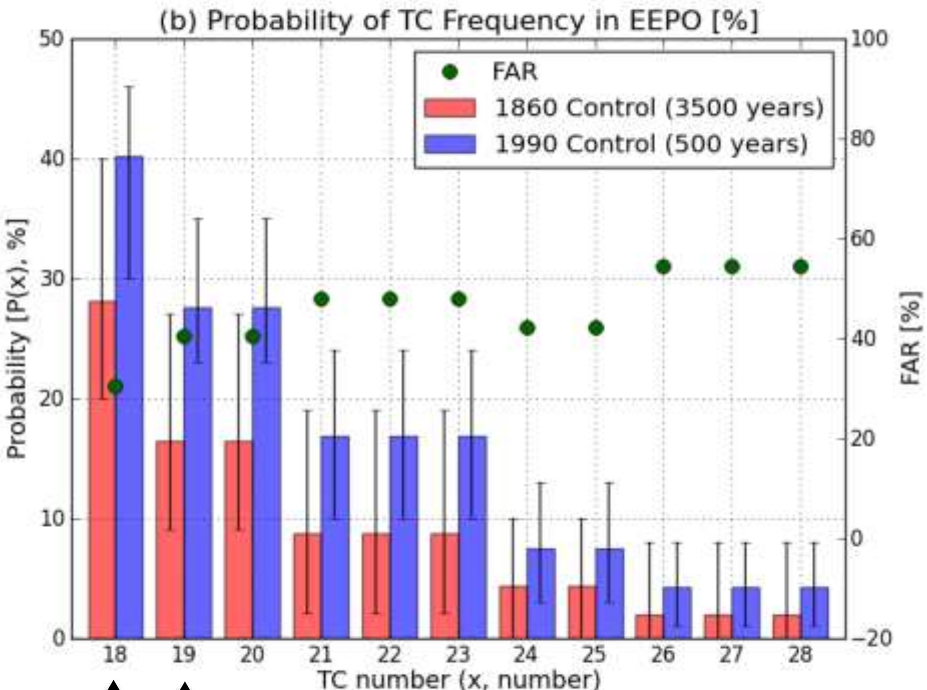
E_0: Non-anthropogenic Forcing (1860 Contl)

−∞ (not attributable) < FAR ≤ +1.0 (attributable)

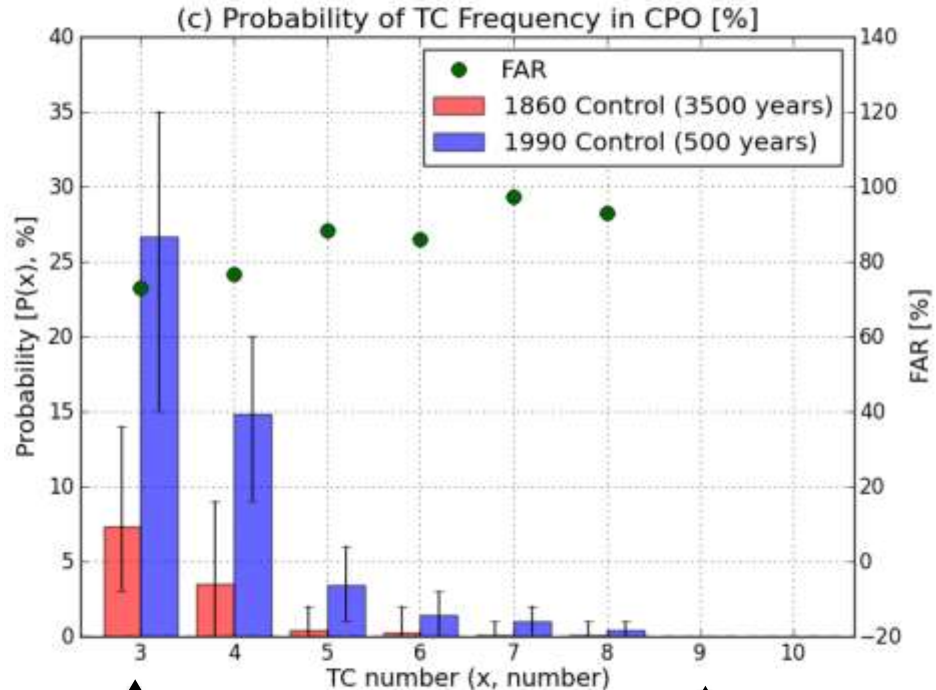
FAR(21) = 0.66

FAR(27) = 0.57

Effect of Anthropogenic Forcing to Frequency of Extreme TC Year (Control Simulations)



2015 +1σ



+1σ 2015

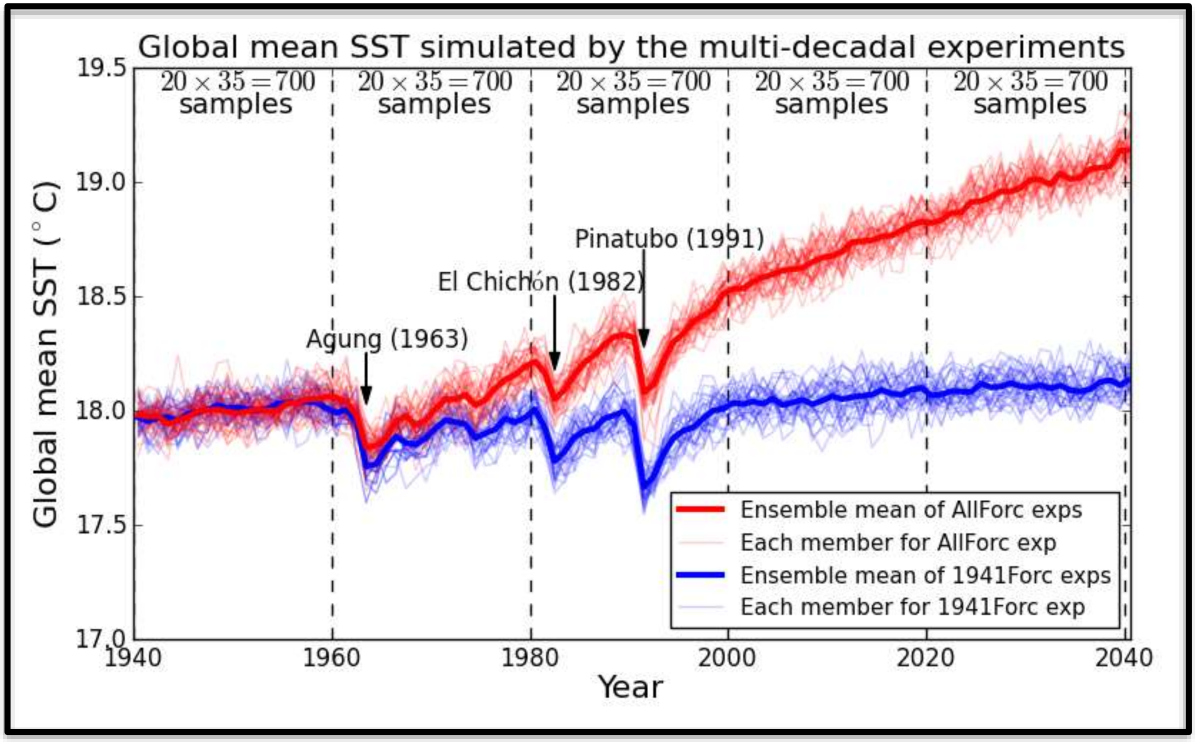
FAR(18) = 0.30
FAR(20) = 0.40

FAR(3) = 0.83
FAR(8) = 0.92

Anthropogenic forcing substantially changes the odds of extreme TC seasons like 2015 relative to natural variability alone.

Effect of Natural Variability and Anthropogenic Forcing to Frequency of Extreme TC Year (Large-Ensemble Simulation)

- Large-ensemble Experiments
  - 35-member uninitialized simulations starting from 1940 using FLOR
  - All Forcing (**AllForc**) Experiment
    - Prescribing historical anthropogenic forcing (e.g., CO_2, aerosols) and volcanic eruptions
  - 1941 Forcing (**1941Forc**) Experiment
    - Prescribing fixed anthropogenic forcing at the 1941 level and volcanic eruptions

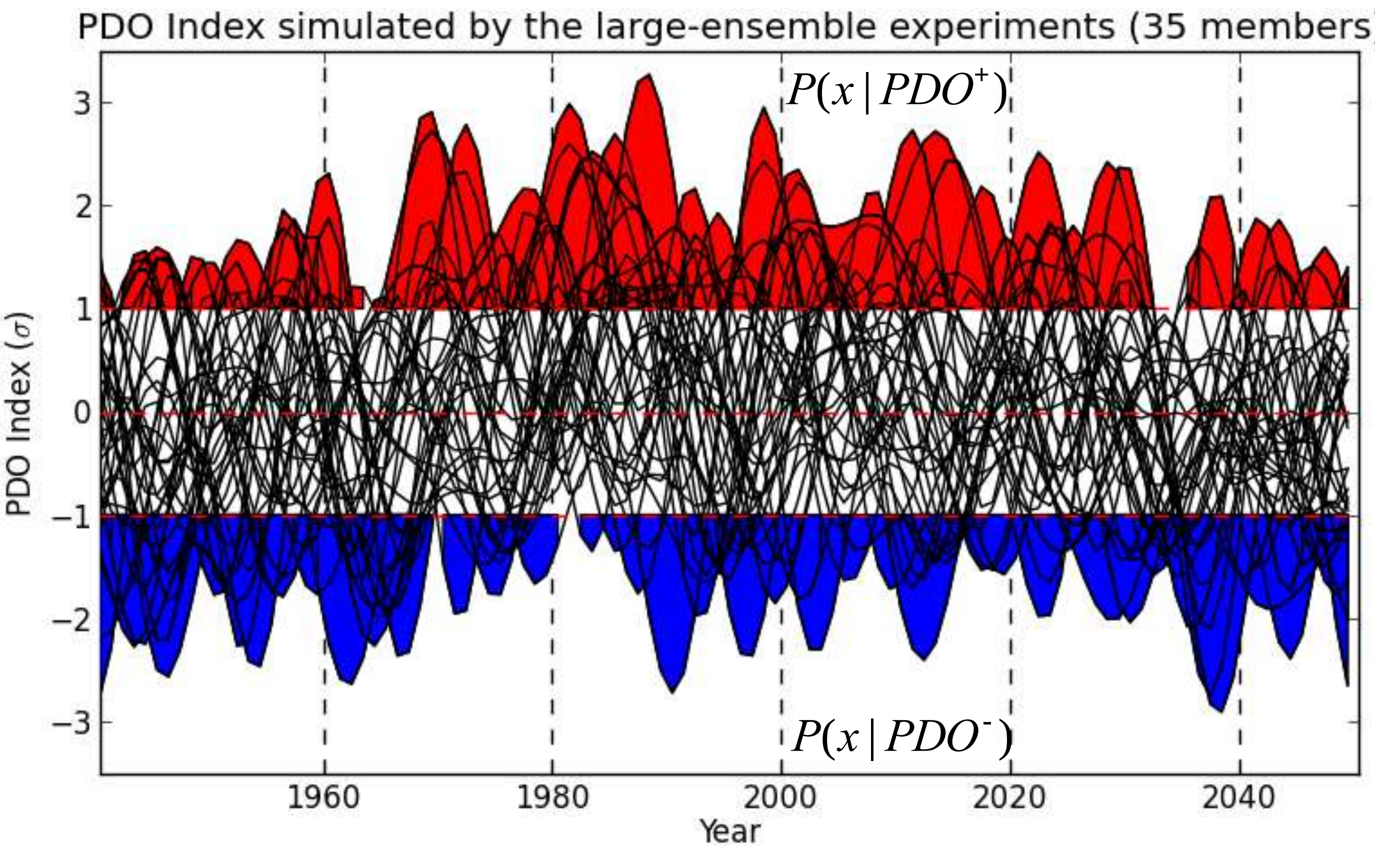


The mean difference between AllForc and 1941Forc is due to anthropogenic forcing.

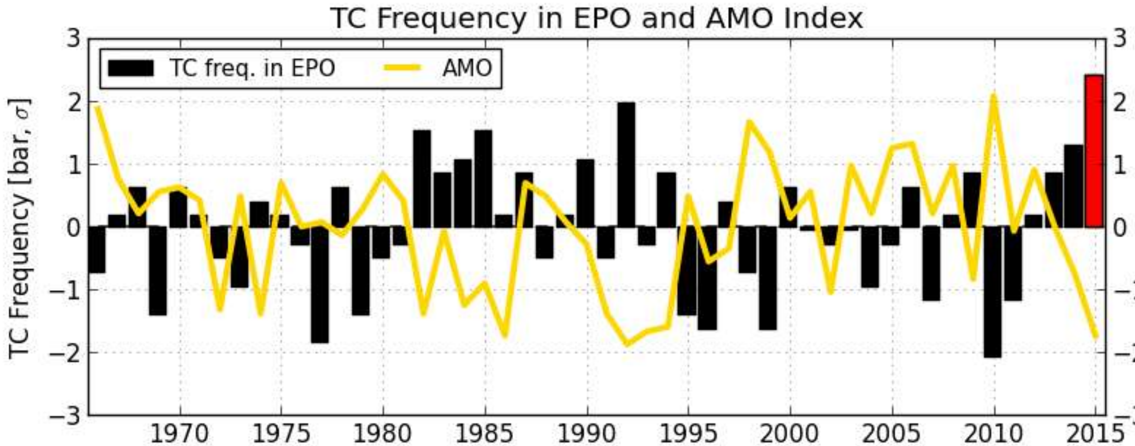
For each 20-year period, P(x) can be computed using 700 samples (=20 years × 35 members).

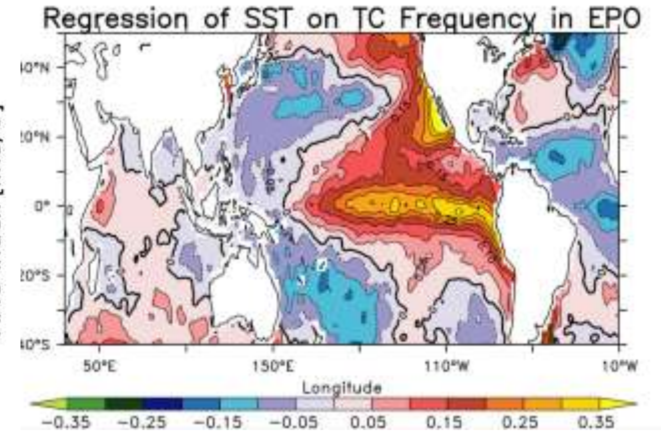
Effect of Natural Variability and Anthropogenic Forcing to Frequency of Extreme TC Year (Large-Ensemble Simulation)

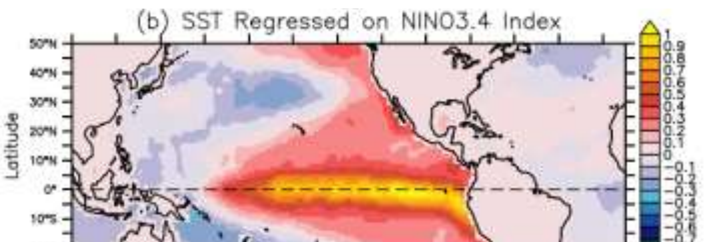
- Large-ensemble Experiments
  - Internal variability is independent among the ensembles.
  - We can compute conditional probability under any phases of natural variability in order to estimate impact of natural variability on P(x).

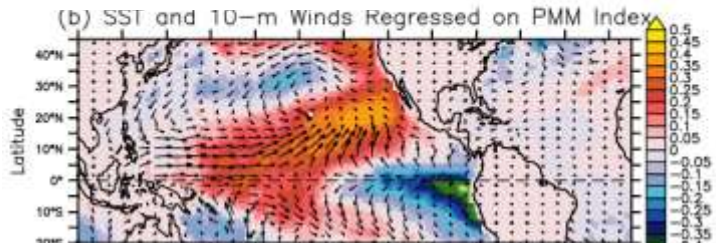


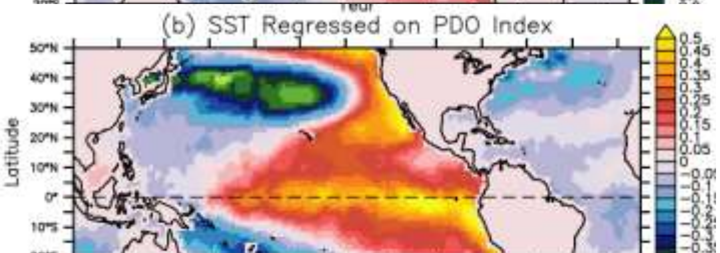
The Five Internal Variability (Nino-3.4, PMM, PDO, IPO, and AMO)

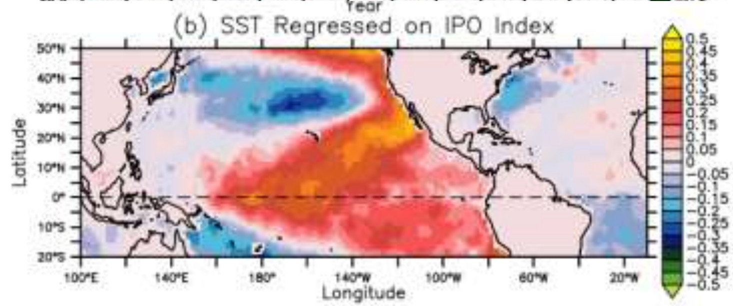


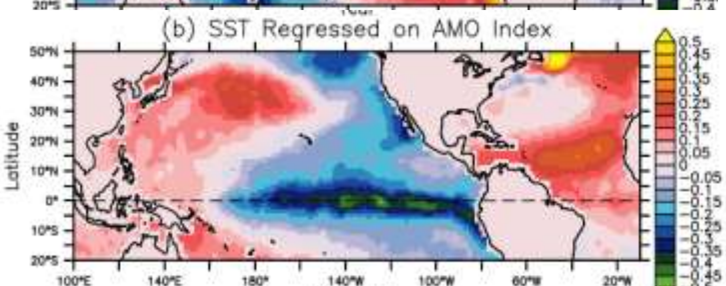




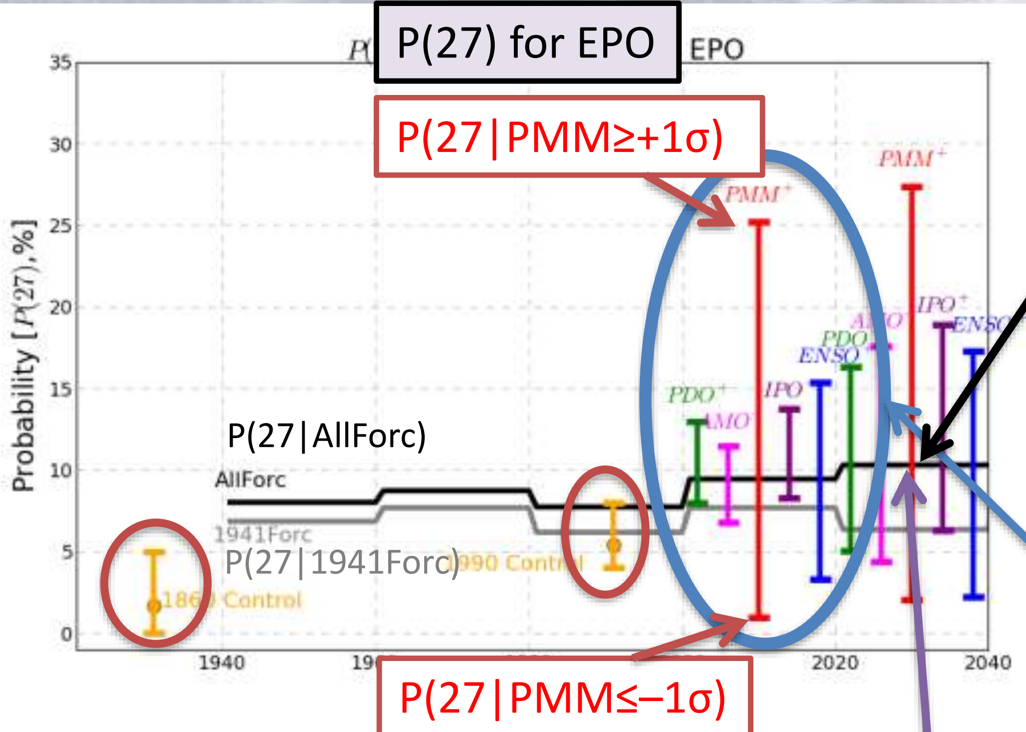








Effect of Anthropogenic Forcing and Natural Variability to Frequency of Extreme TC Year (Large-Ensemble Simulation)



Black line reveals a gradual increase from 1940 to 2040, indicating global warming generates more TCs in EPO.

The increase is consistent with the control experiments.

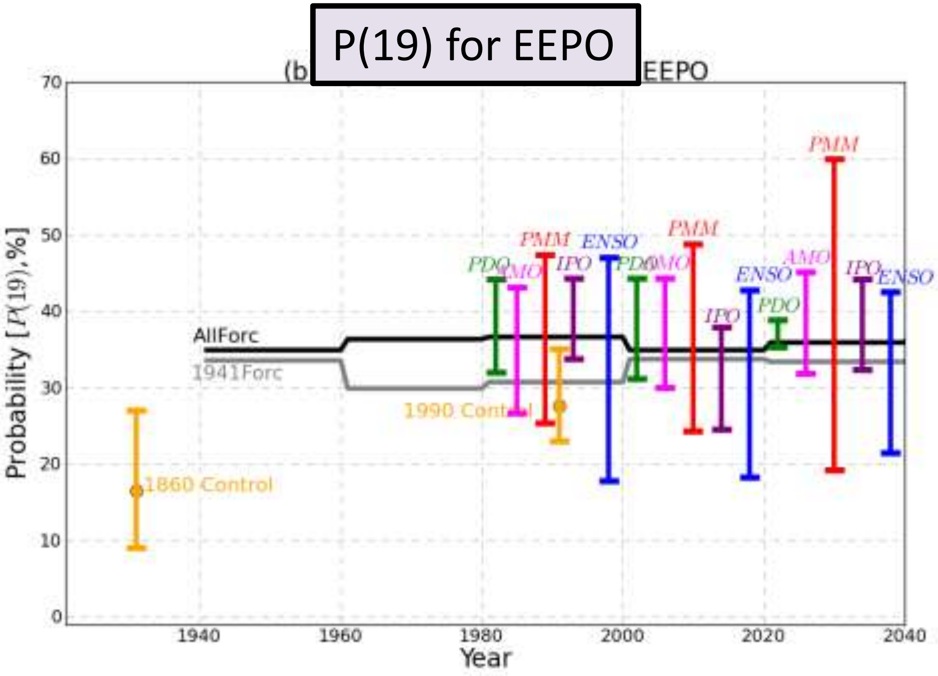
Colors bars indicate that natural variability has marked potential to influence the probability.

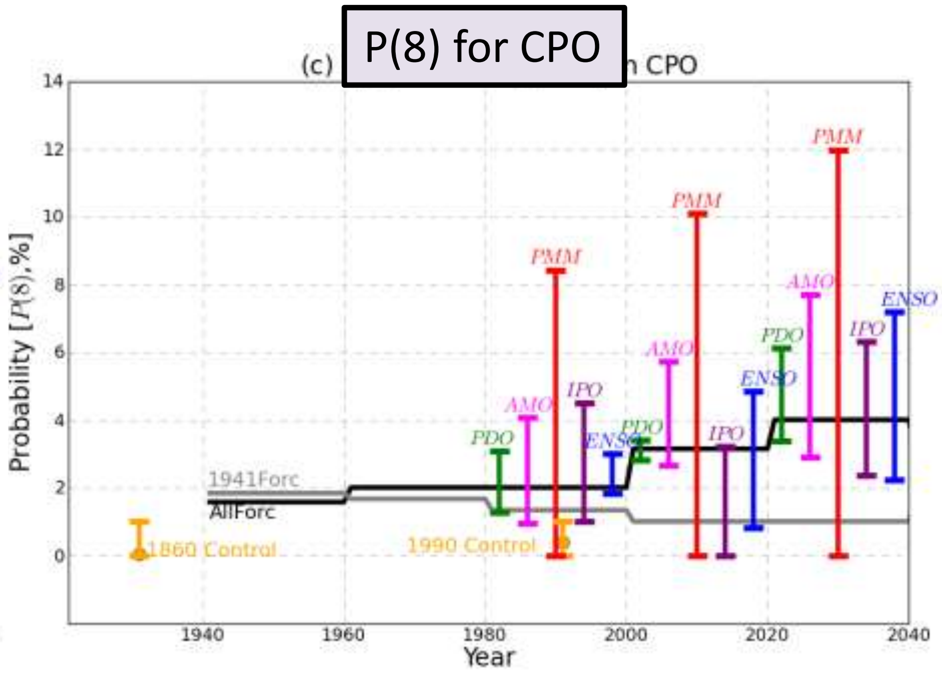
Among the indices, PMM has the largest influence on the variability of probability, followed by ENSO.

Continued increase of probability is expected in the following decades.

The projected increase in the probability depends on the phase of natural variability.

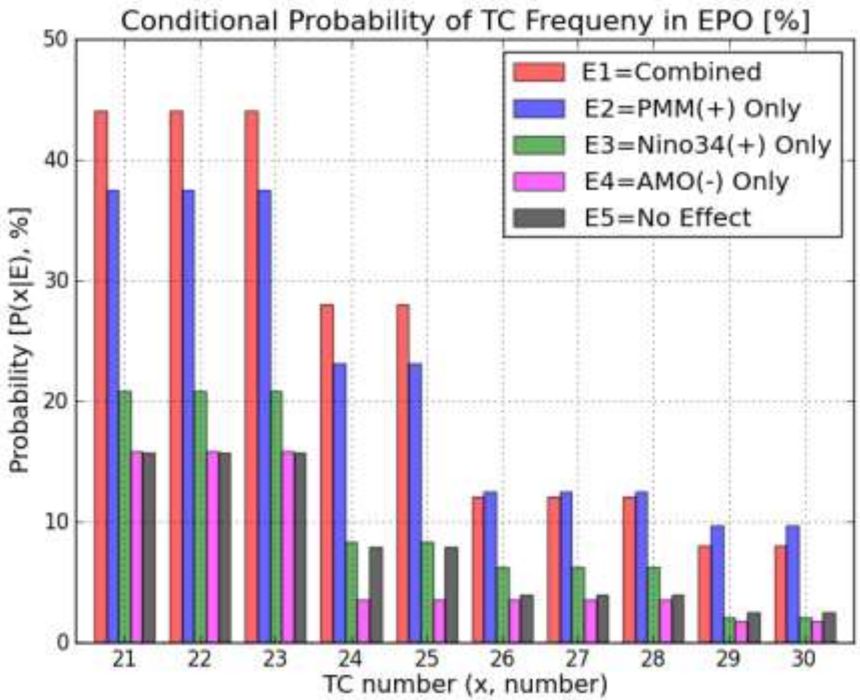
Effect of Anthropogenic Forcing and Natural Variability to Frequency of Extreme TC Year (Large-Ensemble Simulation)





Similar results are obtained for the EEPO and CPO.

Which of PMM, El Niño, and AMO was more important for the extreme TC year of 2015?



Using the 700 samples during 2001–2020 period in the AllForc, additional five conditional provability $P(x|E_n)$ are computed.

PMM(+) >> Nino-3.4 (+) > AMO (–)

E_n	PMM ≥ +1σ	Niño-3.4 ≥ +1σ	AMO ≤ −1σ	Sample size	Effect
E1	✓	✓	✓	44/700	Combined Effect
E2	✓			94/700	Positive PMM only
E3		✓		83/700	Positive Niño-3.4 only
E4			✓	55/700	Negative AMO only
E5				282/700	No Effect

Summary (1/2)

- The 2015 summer was an extreme year in terms of TC frequency in the Eastern Pacific Ocean (EPO), especially over the Central Pacific Ocean (CPO).

- Observations show the favorable large-scale conditions for TC genesis (the largest SST anomaly, highest mid-level relative humidity, and weakest vertical wind shear).

- It is likely that the tropical SST anomaly induced by an El Niño development is not a key factor for the extreme TC event, but the **subtropical SST anomaly related to positive PMM** is a key.

Summary (2/2)

- It is likely that **global warming has increased the odds** of the extremely large number of TCs in EPO, Central Pacific Ocean.

- The ensemble future experiments indicate **a continued increasing probability** of active seasons over the next few decades – though there will be substantial modulation on interannual and decadal timescales from internal variability.

Thank You!

The most destructive force brought by Hurricane Patricia (NASA)