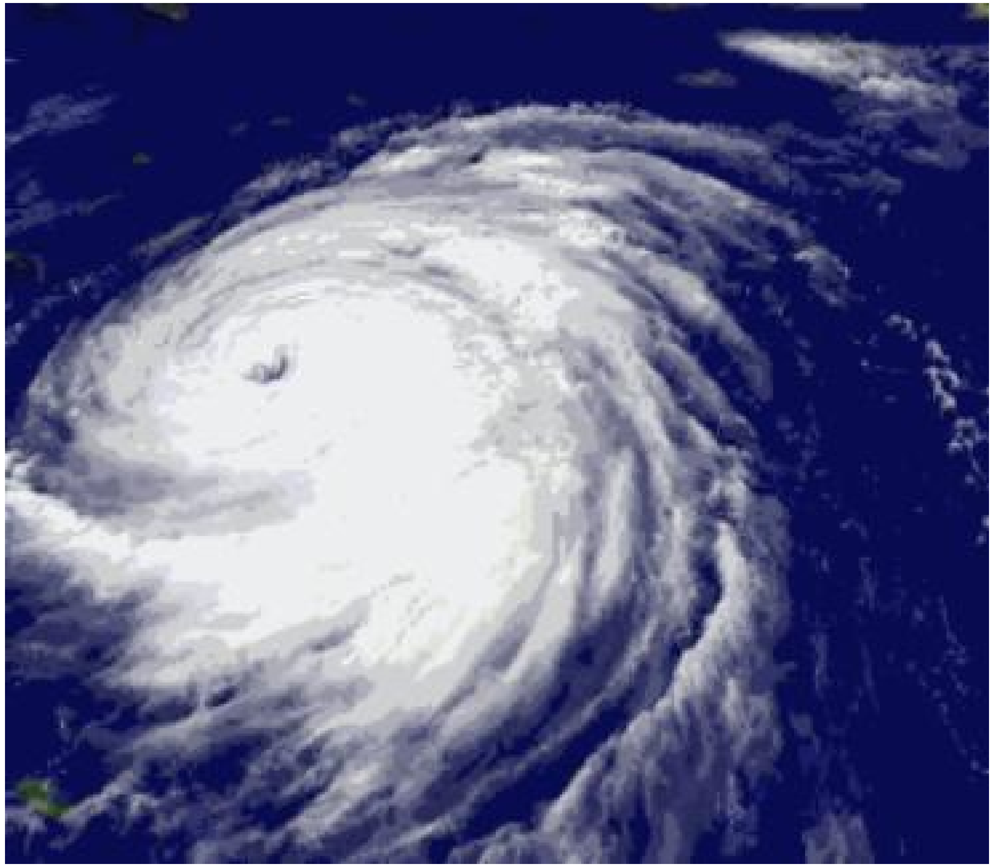
Tropical Sea Surface Temperature and Seasonal Tropical Cyclone Genesis Forecasts



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November 28, 2023

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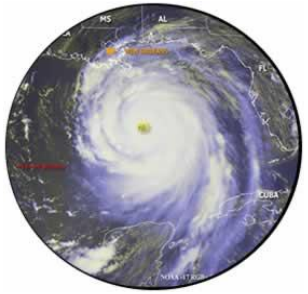
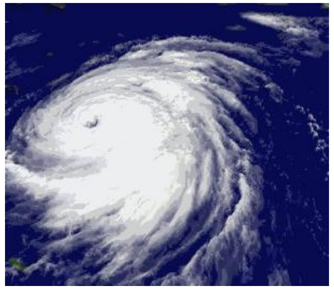
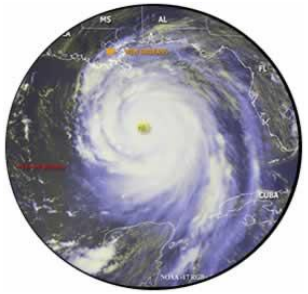
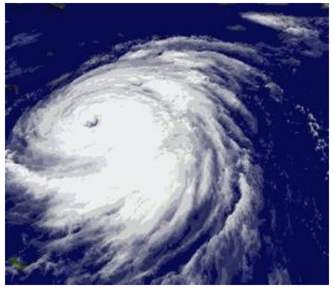
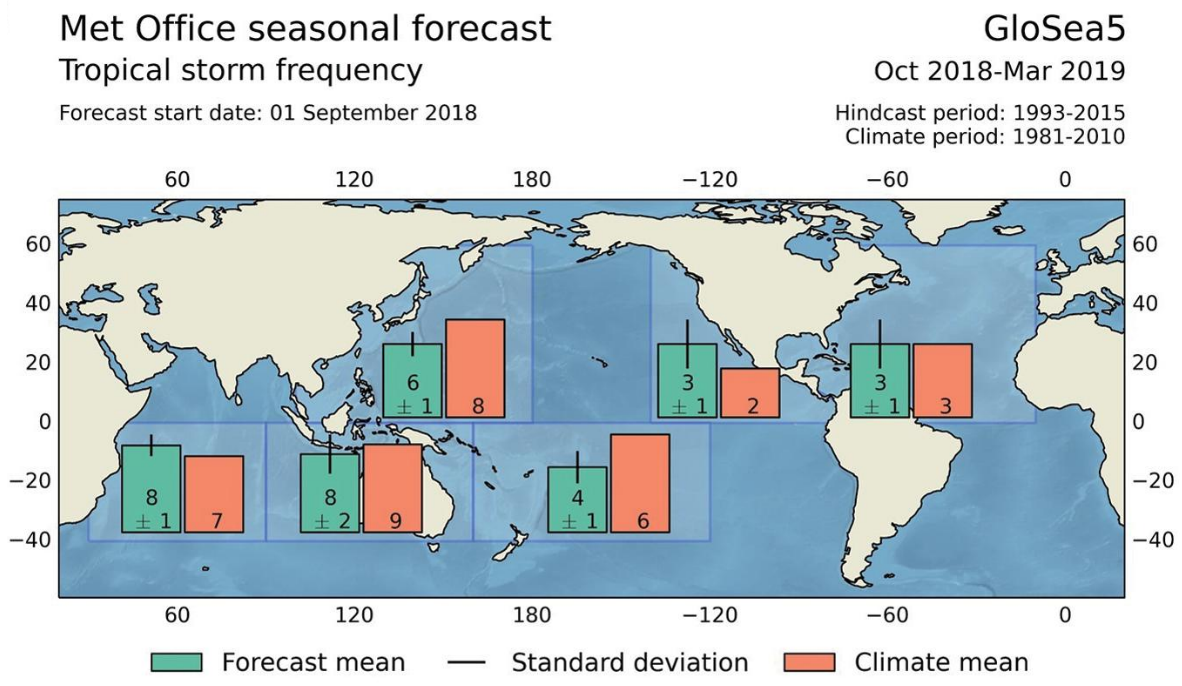


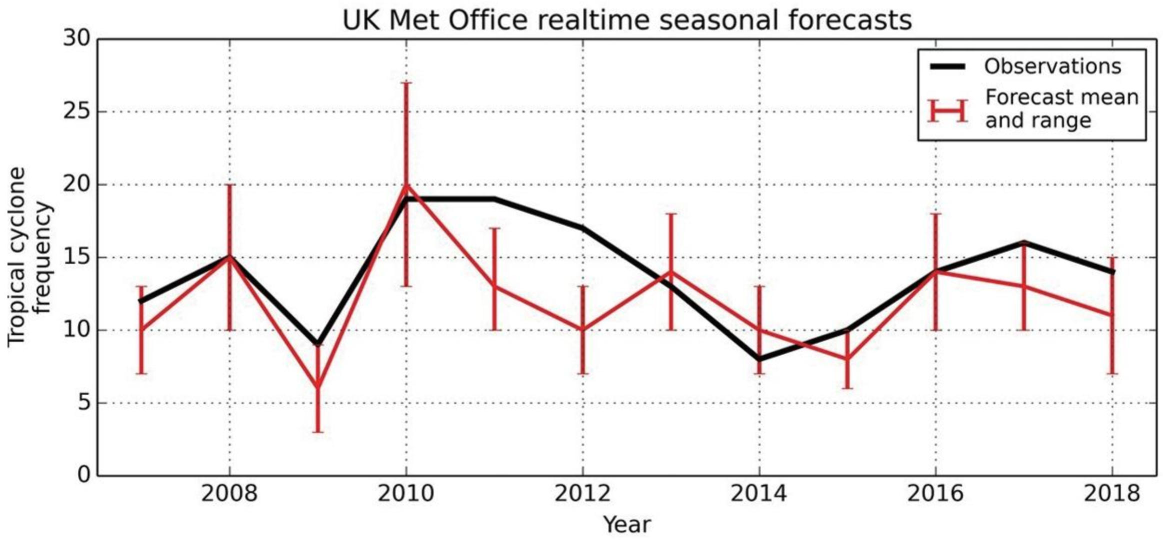


1. Fundamentals

Seasonal tropical cyclone forecasts





Seasonal tropical cyclone (TC) forecasts began with the pioneering work of Neville Nicholls at the Australian Bureau of Meteorology for the Australian region (Nicholls 1979, Nicholls 1984, Nicholls 1985) and William Gray at Colorado State University (CSU) for the Atlantic basin (Gray 1984a, b).

These original forecasts were based on statistical relationships between climate phenomena such as El Niño-Southern Oscillation (ENSO) and TCs.

The first hurricane outlook for the Atlantic basin relied on a statistical model based upon three predictors (ENSO, the phase of the Quasi-Biennial Oscillation, and sea-level pressure over the Caribbean Sea).

Tropical sea surface temperature (SST) anomalies are important predictors for seasonal TC forecasts in statistical models.

Seasonal tropical cyclone forecasts

Table 1. Forecast agencies, TC basins predicted, metrics forecast, techniques used, and websites where the forecasts are published.

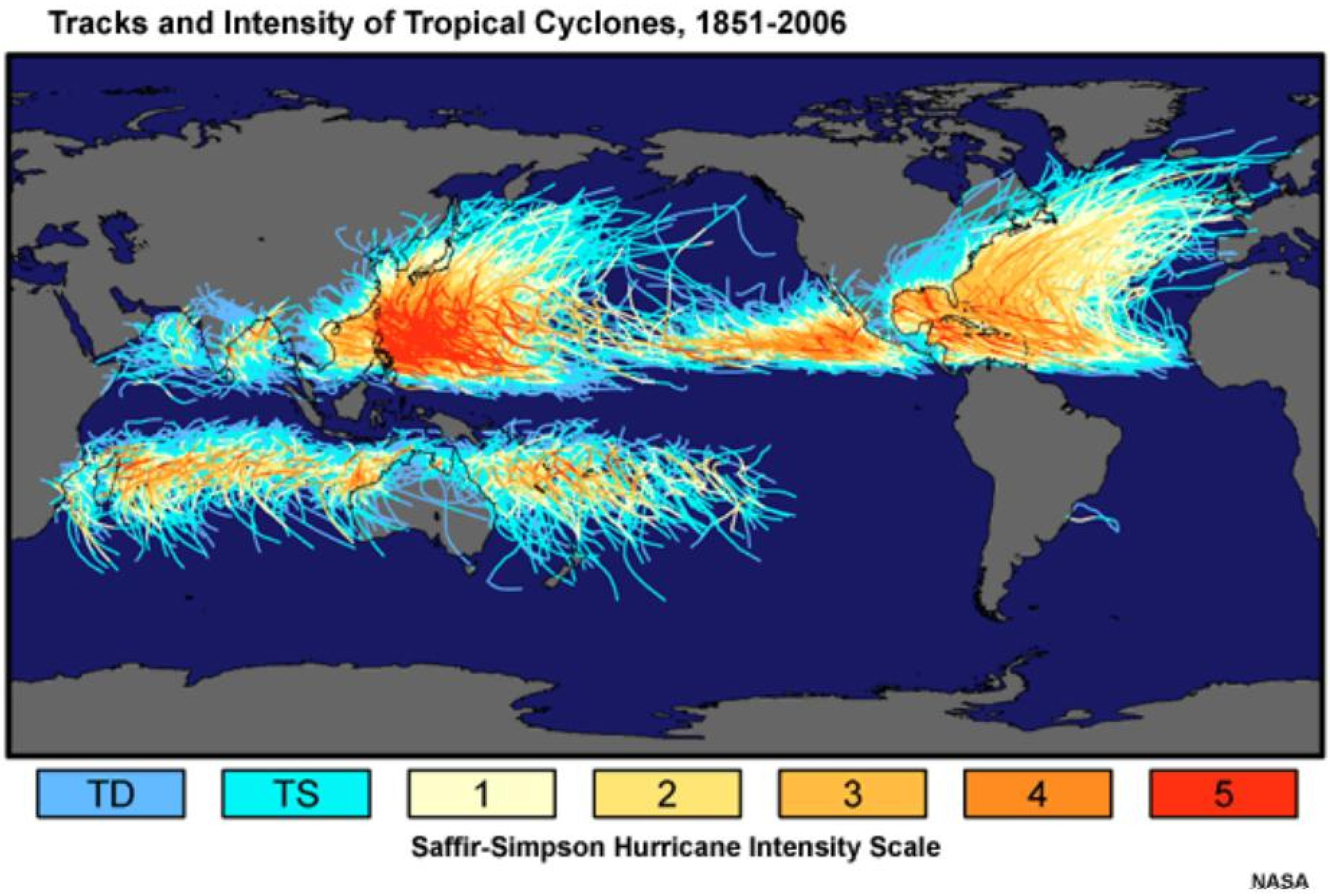
Forecast Agency	TC Basins Predicted	Metrics Forecast	Techniques Used	Forecast Website
Colorado State University	North Atlantic	Basinwide activity; Continental US and Caribbean landfall probability	Statistical, Statistical-Dynamical	http://tropical.colostate.edu
National Oceanic and Atmospheric Administration	North Atlantic, Eastern North Pacific	Basinwide activity	Statistical, Statistical-Dynamical, Dynamical	https://www.cpc.ncep.noaa.gov/products/outlooks/hurricane.shtml
Tropical Storm Risk	North Atlantic, Western North Pacific	Basinwide activity; Continental US landfalling activity; Caribbean Lesser Antilles landfalling activity	Statistical	https://tropicalstormrisk.com
UK Met Office	North Atlantic, Eastern North Pacific, Western North Pacific, South Indian, Australia, South Pacific	Basinwide activity	Dynamical	https://www.metoffice.gov.uk/weather/tropicalcyclone/
		Global map for increased/decreased risk of tropical cyclone tracks		
Australian Bureau of Meteorology/University of Melbourne	Australia, South Pacific	Australian region and sub-region activity; South Pacific Region and sub-region activity	Statistical	Australia: http://www.bom.gov.au/climate/cyclones/australia/archive.shtml South Pacific: http://www.bom.gov.au/climate/cyclones/south-pacific/archive.shtml
City University of Hong Kong	Western North Pacific	Basinwide activity; Landfall numbers for 3 sections of East Asian coast	Dynamical	http://weather.cityu.edu.hk/tc_forecast/forecast.htm
Hong Kong Observatory	Western North Pacific	Annual number of tropical cyclones within 500 km of Hong Kong	Statistical, Statistical-Dynamical, Dynamical	https://www.hko.gov.hk/wxinfo/season/anlf.htm
European Centre for Medium-Range Weather Forecasts	North Atlantic, Eastern North Pacific, Western North Pacific, South Indian, Australia, South Pacific	Basinwide activity	Dynamical	https://www.ecmwf.int/en/forecasts/charts
		Global map of increased/decreased risk of tropical storm strike probability		Only available to member countries and commercial users.
Geophysical Fluid Dynamics Laboratory	North Atlantic, Eastern North Pacific, Western North Pacific	Basinwide major hurricane activity; Continental US landfalling activity; East Asian landfalling activity	Statistical-Dynamical, Dynamical	Only available internally to forecasters at NOAA
Japan Meteorological Agency	Western North Pacific	Basinwide activity and sub-region activity	Dynamical	Only available internally to forecasters at the Japan Meteorological Agency
Shanghai Typhoon Institute of China Meteorological Administration	Western North Pacific	Basinwide activity; Number of TCs making landfall in China and affecting subregions	Statistical, Statistical-Dynamical, Dynamical	Only available internally to forecasters at the China Meteorological Administration
National Typhoon Center/Korea Meteorological Administration	Western North Pacific	Basinwide activity (number, intensity, track); Annual number of tropical cyclones affecting the Korean peninsula	Statistical, Statistical-Dynamical, Dynamical	Only available to the fourteen member countries under the ESCAP/WMO Typhoon Committee's perennial operating plan. Only available internally to the forecasters at the Korea Meteorological Administration

Statistical methods are used in many forecast agencies

The predictability of seasonal TC activity mainly comes from the slowly-evolving sea surface temperature (SST) conditions and the large-scale atmospheric circulation teleconnection patterns.

It is important to understand the relationships between the interannual TC variability and tropical SST forcing and variations of various climate modes.

Global distribution of observed tropical cyclone tracks

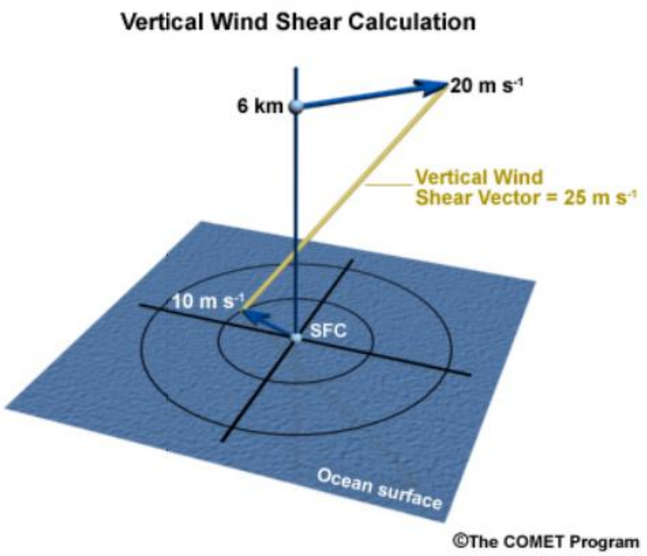


Necessary Conditions for Tropical Cyclone Formation

Six features of the large-scale tropics were identified by Gray (1968) as *necessary, but not sufficient* conditions for tropical cyclogenesis:

(i) sufficient ocean thermal energy [SST > 26°C to a depth of 60 m],
(ii) enhanced mid-troposphere (700 hPa) relative humidity,
(iii) conditional instability,
(iv) enhanced lower troposphere relative vorticity,
(v) weak vertical shear of the horizontal winds at the genesis site, and
(vi) displacement by at least 5° latitude away from the equator.

thermodynamic parameters: (i), (ii), (iii)
dynamical parameters: (iv), (v), (vi)

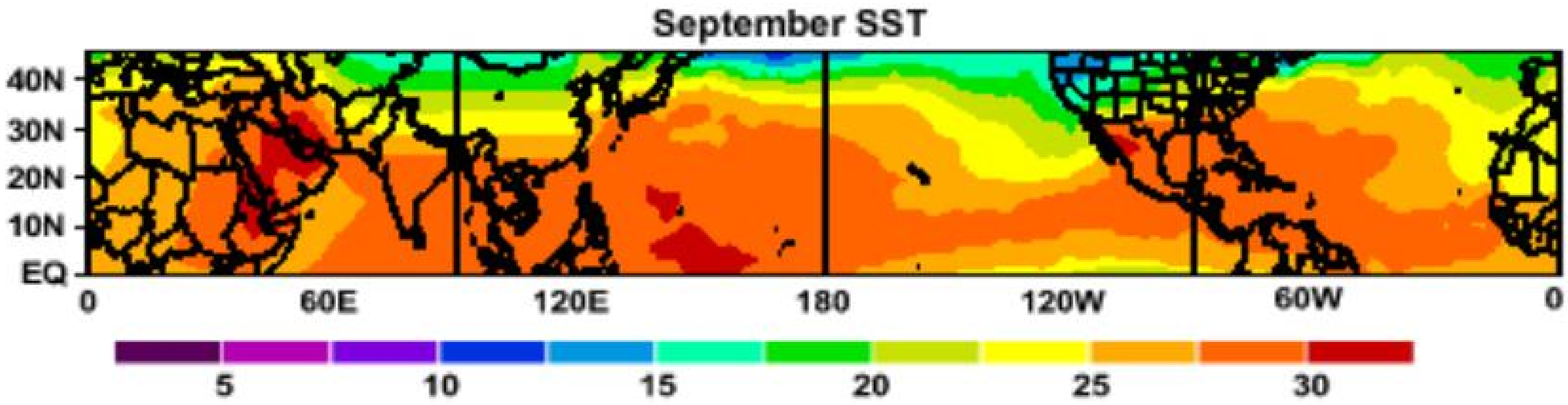


"Necessary but not sufficient" means that all of these conditions must be present simultaneously before tropical cyclogenesis can occur, but even if all of these conditions are met, tropical cyclogenesis may not occur. *Thus, the necessary, but not sufficient, criteria for tropical cyclogenesis may be summarized as the ability to support deep convection in the presence of a low-level absolute vorticity maximum.*

Local and remote SST effects on TC genesis

Local SST → Sufficient ocean thermal energy → Local TC genesis

Remote SST → Atmospheric teleconnection → Vertical wind shear, relative vorticity etc. → TC genesis



Genesis Potential Index (GPI)

$$GP = \left|10^{5}\eta\right|^{3/2}\left(\frac{f}{50}\right)^{3}\left(\frac{Vpot}{70}\right)^{3}\left(1+0.1V_{shear}\right)^{-2}$$

(Emanuel and Nolan, 2004)

η **: absolute vorticity at 850 hPa**

V_{shear} **: Vertical wind shear**

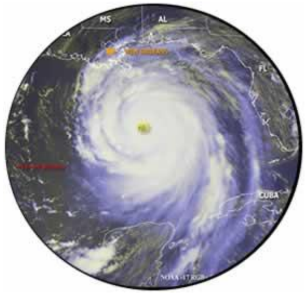
Dynamic components

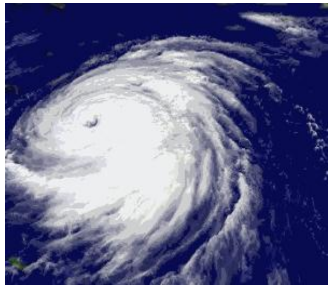
f **: relative humidity at 600 hPa**

V_{pot} **: Potential intensity**

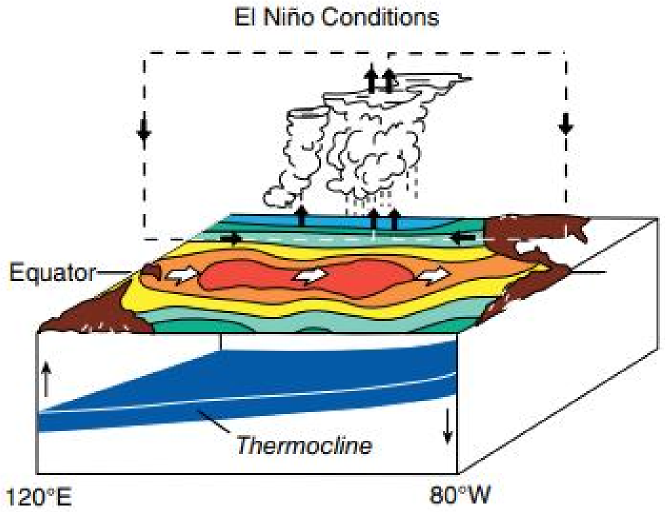
Thermodynamic components

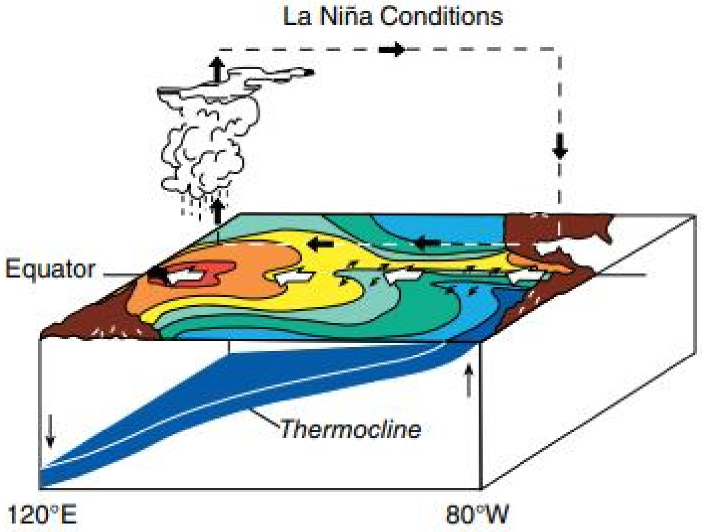
2. Tropical sea surface temperature and tropical cyclone genesis climatology





ENSO and tropical cyclone





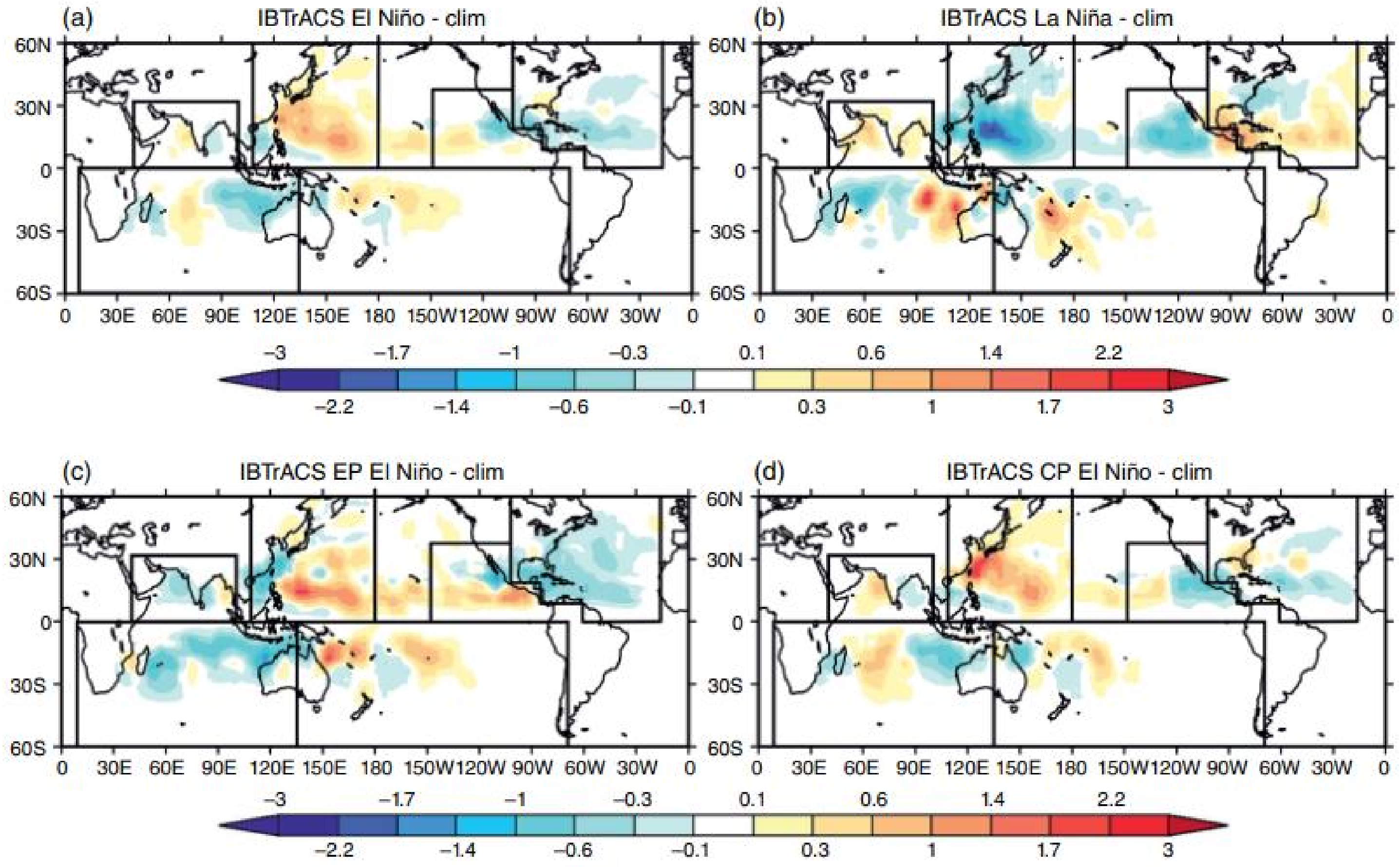


Figure 17.2 Tropical cyclone track density anomaly maps during May–November in the Northern Hemisphere and October–May in the Southern Hemisphere. Data source: IBTrACSv03r10. Track density is based on storm transits/month/10^6 km^2 or equivalent to a 5° radius). (a) El Niño years minus 1979–2010 climatology. (b) La Niña years minus 1979–2010 climatology. (c) EP El Niño years minus 1979–2010 climatology. (d) CP El Niño years minus 1979–2010 climatology.(a) and (b) are reproduced following the original figure and style of Bell et al. (2014) (© American Meteorological Society. Used with permission). (c) and (d) are added to illustrate the different impact from EP and CP El Niño events. The definition of different ENSO years is from Patricola et al. (2016). El Niño years are 1982, 1986, 1987, 1991, 1994, 1997, 2001, 2002, 2004. La Niña years are 1988, 1998, 2010. EP El Niño years are 1982, 1987, 1997. CP El Niño years are 1986, 1991, 1994, 2001, 2002, 2004. (Courtesy of Dan Fu)

ENSO and tropical cyclone

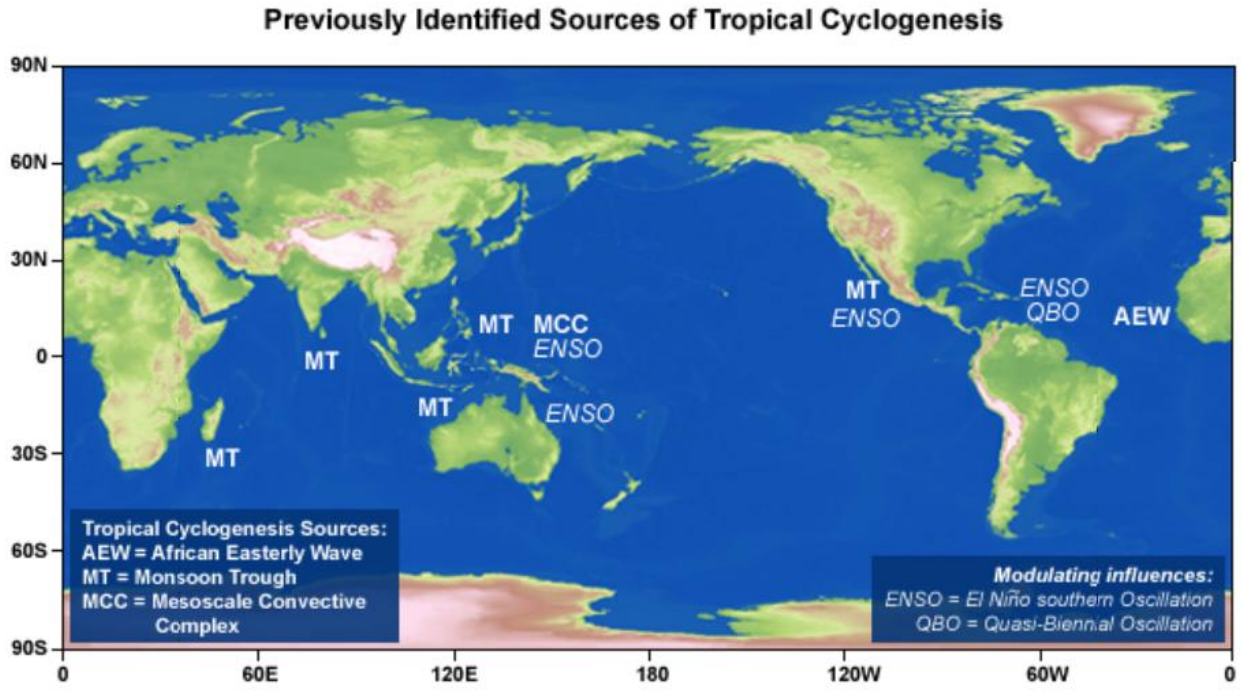
One of ENSO's most important influences is its worldwide modulation of tropical cyclone (TC) activity.

ENSO's influences on TC basins around the globe, including local effects and remote influences via teleconnections.

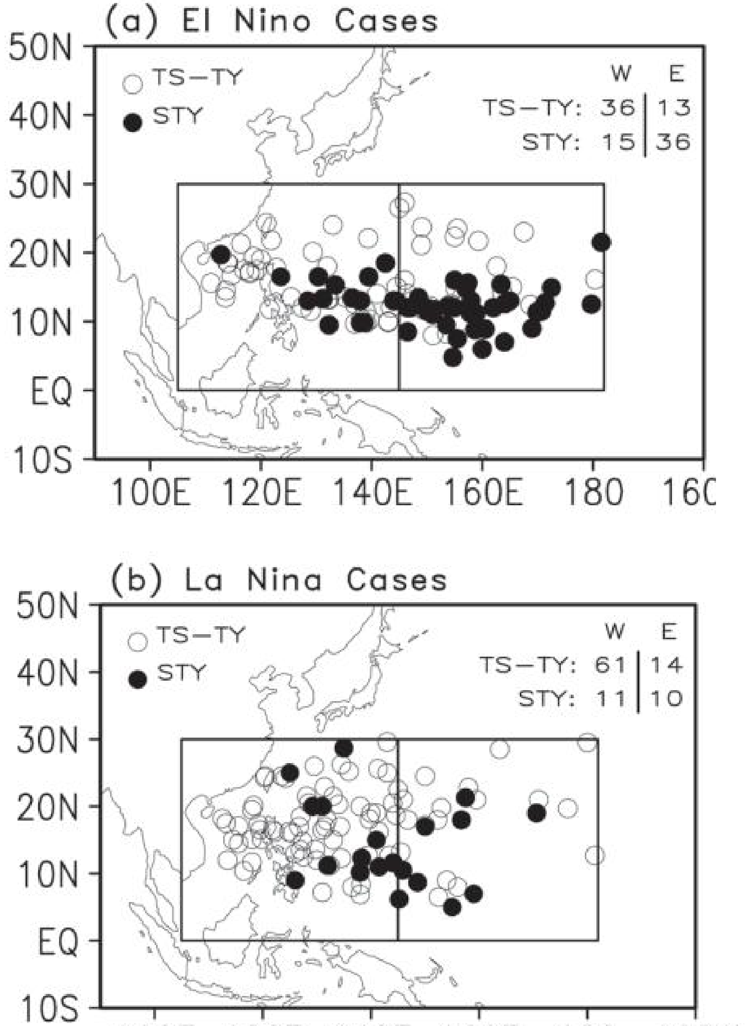
Because TC attributes (e.g. genesis, track and landfall locations, intensity) are largely controlled by large- scale environmental conditions, TC activity can be substantially altered by ENSO, via ENSO's strong modulation on both the atmosphere and ocean.

Atmospheric modulations include changes in vertical wind shear, humidity, low- level vorticity, and the strength and position of subtropical highs.

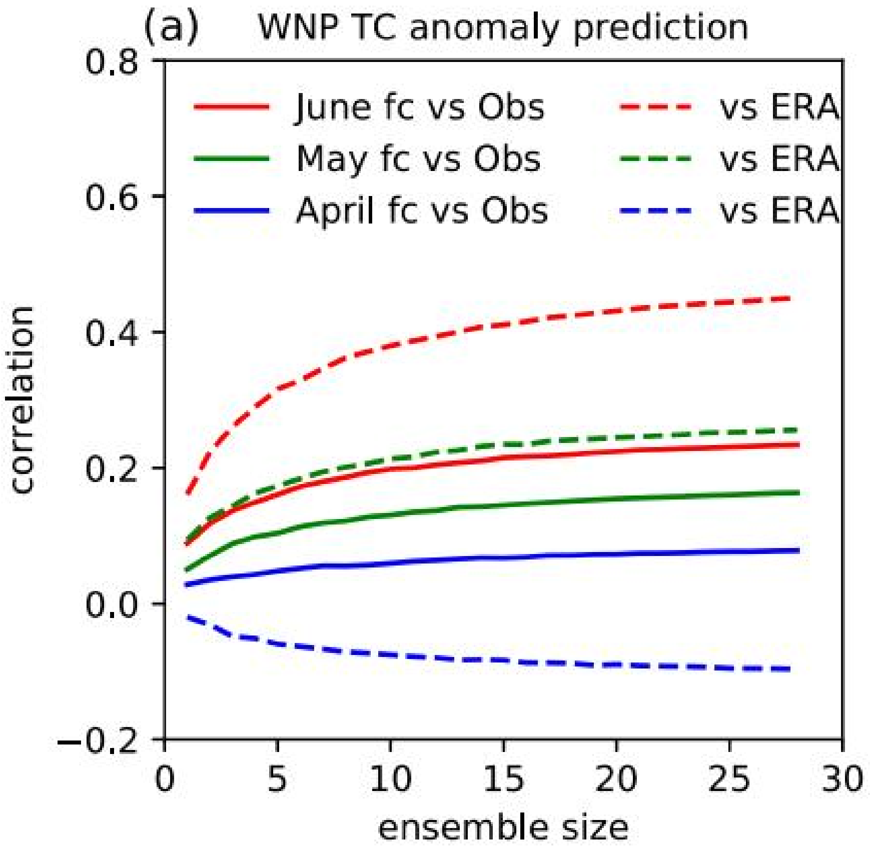
The ocean influences TCs via changes in sea- surface temperature and upper- ocean heat content and structure.



Traditionally, the prediction capability for seasonal TC activity has predominantly ***relied on ENSO*** (Feng et al. 2020, Gray 1984a, 1984b, Zhan et al. 2012 for review), which is ***the dominant mode of tropical variability with widespread global influences***.



(From Zhan et al., 2011)

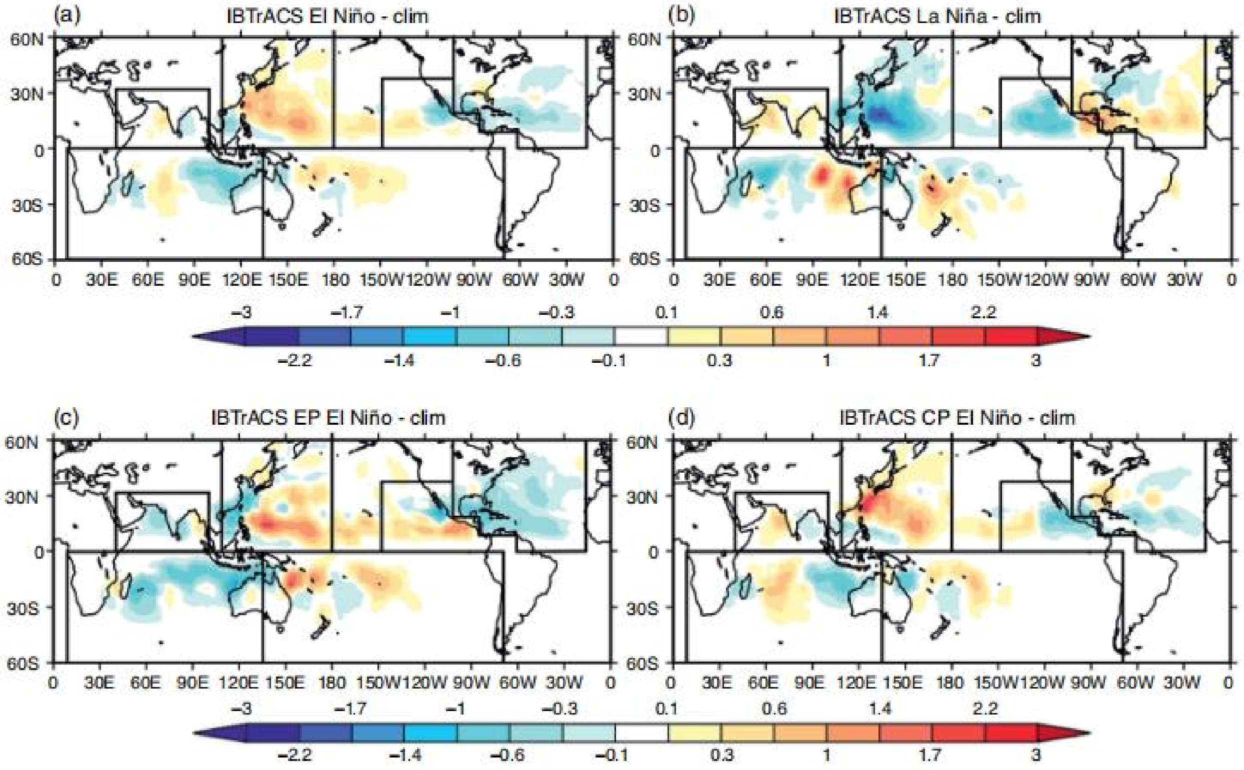


(From Feng et al. 2020)

The Met Office Global Seasonal Forecast System **(GloSea5-GC2)** for tropical cyclone (TC) frequency for the western North Pacific (WNP):

The need to reduce biases in environmental conditions and **associated ENSO teleconnections in GloSea5** to improve the TC prediction performance in the NWP.

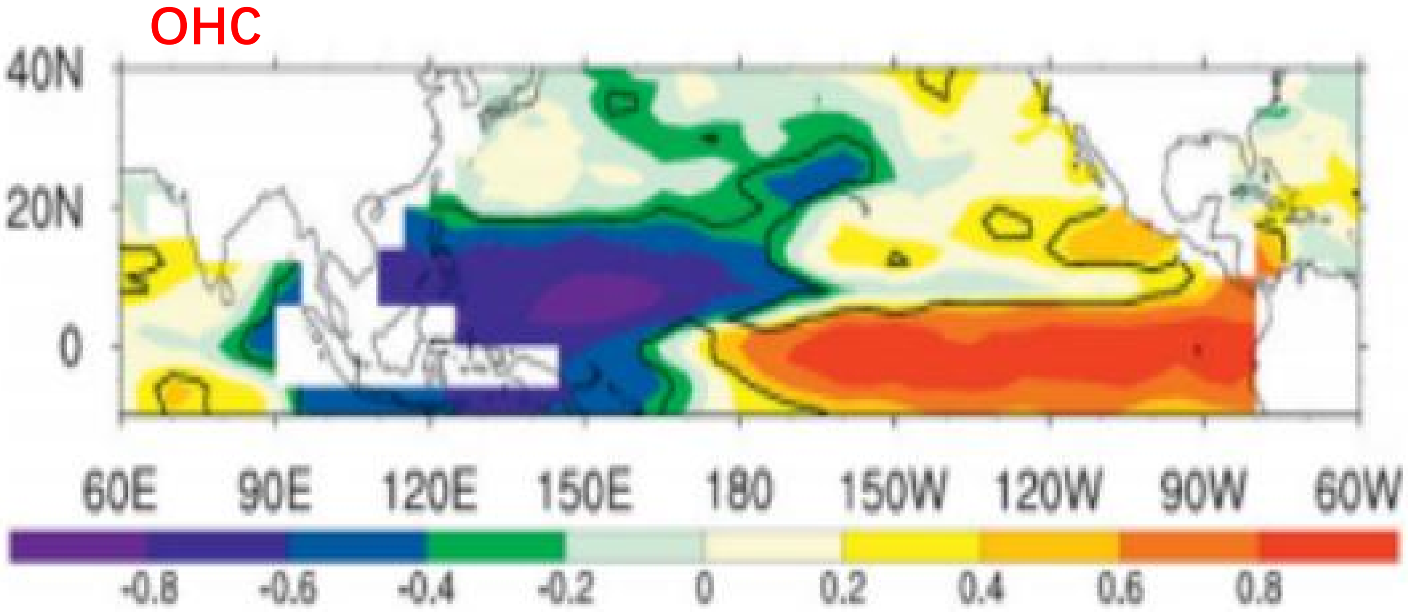
➢ The Influence of ENSO on Western North Pacific （WNP） TCs

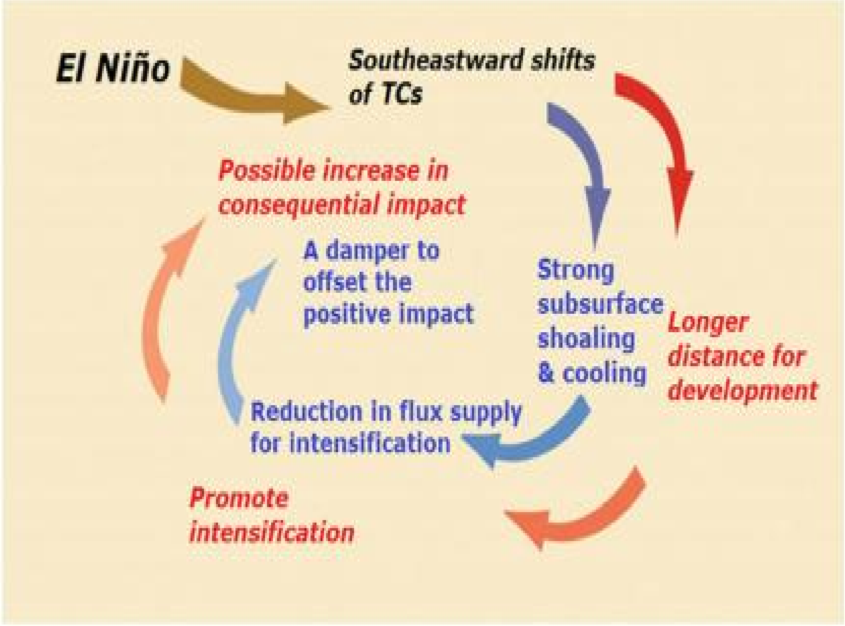


TC Track density
(From Lin et al., 2021)

During **El Niño developing years**, WNP TC seasons tend to be characterized by **longer-lived** TCs that are **larger in size** and **generate greater Accumulated Cyclone Energy(ACE)**. These TCs also tend to **track away from the Asian coast** and **form closer to the international date line**. During **El Niño decaying years**, WNP TC frequency **drops** considerably (Chan, 1985; Chan, 2000; Chia & Ropelewski, 2002; Wang & Chan, 2002; Wu et al., 2004; Yuan et al.,2007).

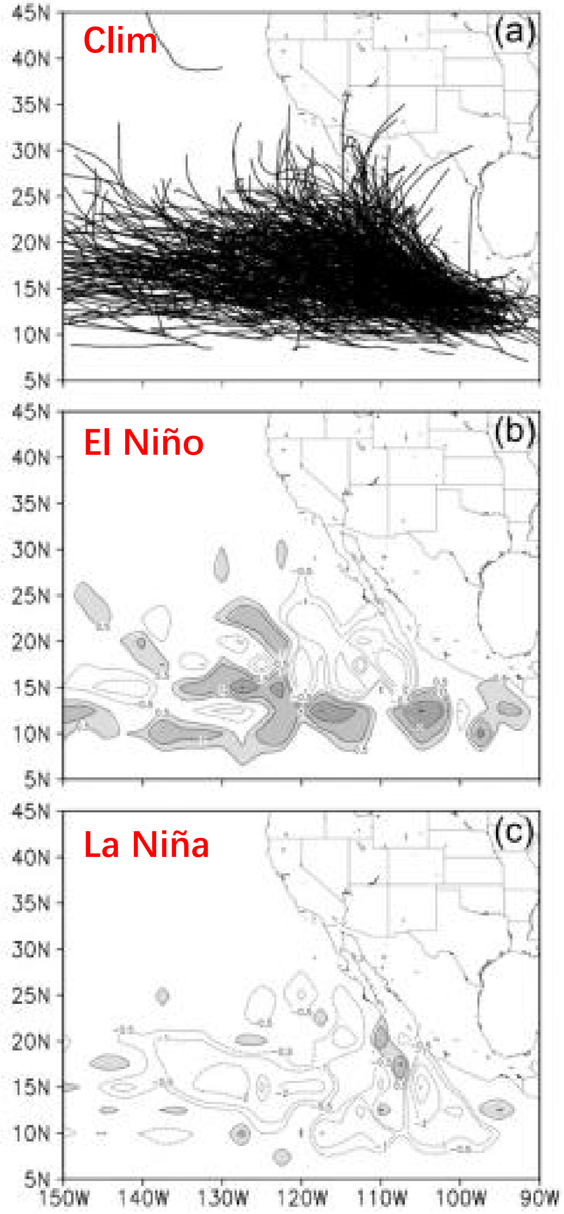
During **El Niño developing years**, **upper ocean heat content** (OHC) can **decrease** by as much as 30% and has a **negative impact** on TC intensification. This change in OHC can counteract with other positive factors (**longer track and increased low-level vorticity**) for TC intensification during El Niño, and the final sign after offset is moderately positive (Li and Zhou, 2012; Zheng et al., 2015, Lin et al.,2015).





(From Li and Zhou, 2012； Lin et al.,2015)

➢ The Influence of ENSO on Central and Eastern North Pacific (CEP) TCs



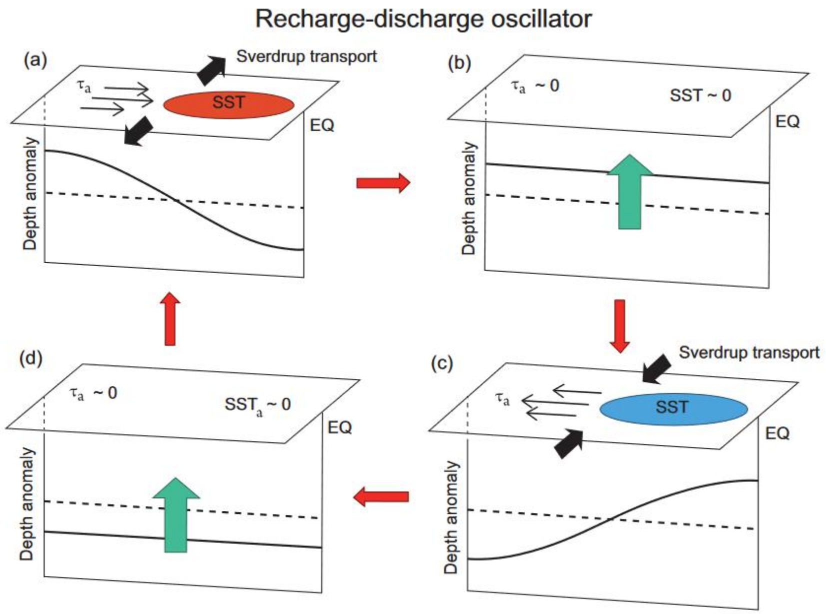
TC genesis location, and lifetime, genesis frequency: El Niño can strongly modulate CEP TC activity by shifting the **active regions toward the dateline** and promoting **enhanced seasonal TC activity** during **El Niño years**, as well as a **longer TC lifetime**. (Chu & Wang, 1997; Kimberlain 1999; Chu, 2004; Toma & Webster, 2010; Wood & Ritchie, 2013; Bell et al., 2014; Caron et al., 2015; Jien et al., 2015; Fu et al., 2017; Huang et al., 2017)

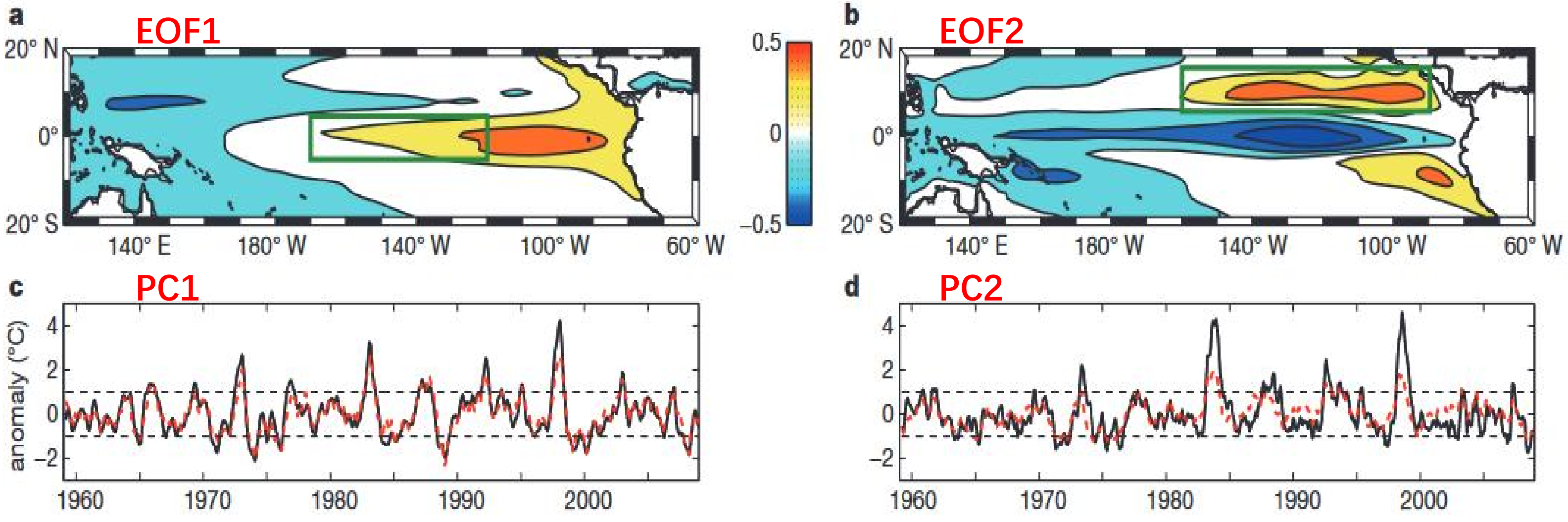
During El Niño developing years, the increase in TC activity is primarily due to changes in **atmospheric conditions** (reduction in vertical wind shear, Chu & Wang, 1997; Whitney & Hobgood, 1997; Chu, 2004; Collins, 2007)

(From Wood and Ritchie, 2013)

During **El Niño decaying years**, large-scale oceanic movement via the **subsurface recharge-discharge mechanism** brings additional heat to the CEP, causing an **increase** in numbers of major TCs (category ≥3, Jin et al., 1997; Jin et al., 2014).

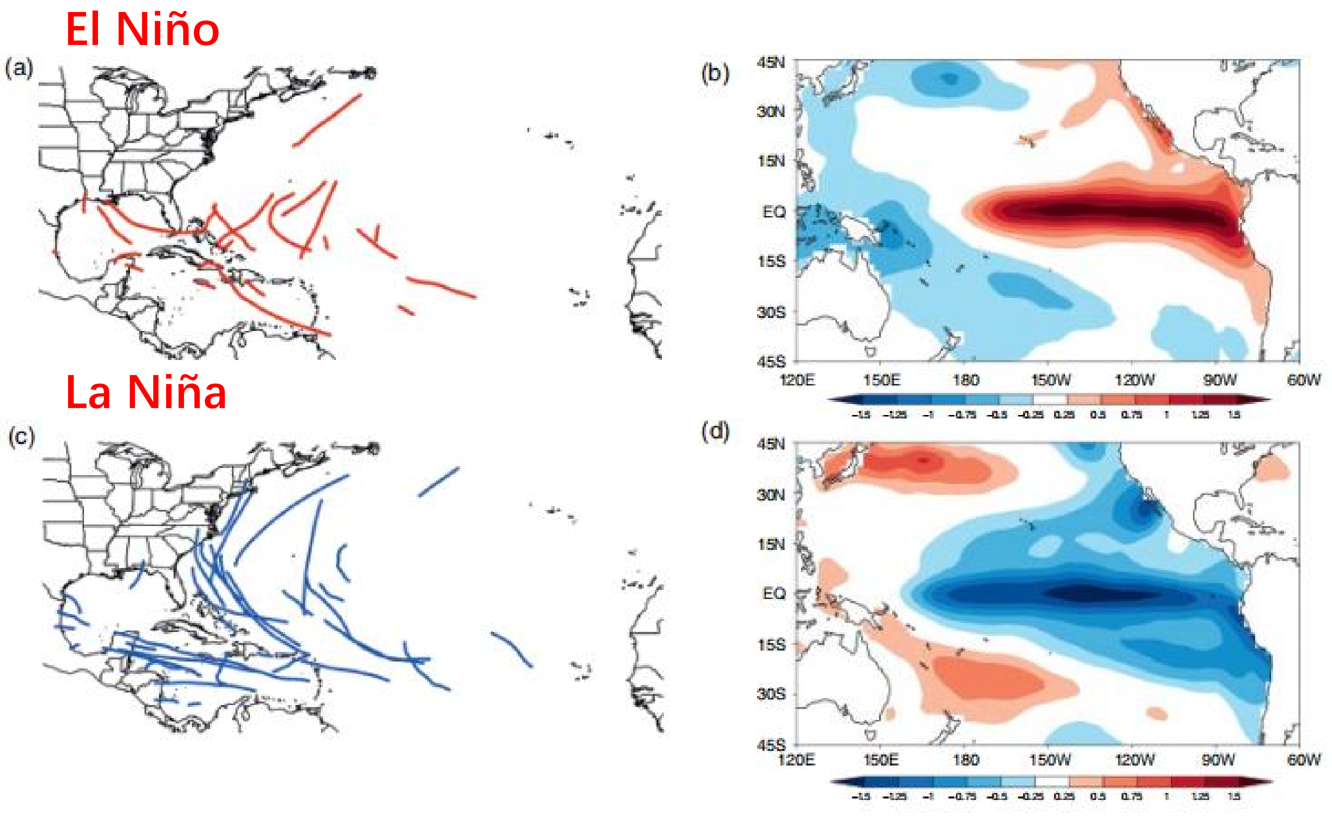
Due to the higher predictability of this mechanism as compared to other factors, it has potential to improve intense TC seasonal forecast by up to a **6-month lead time**.





(From Jin et al.,2014, Wang et al.,2018)

➤ The Influence of ENSO on North Atlantic (NA) TCs



(From Lin et al., 2021)

El Niño significantly **suppresses** NA TC activity, with a **reduction** of landfall along the U.S. coastline, while NA TC activity and U.S. landfall likelihood are **increased** during **La Niña** (Bove et al., 1998; Klotzbach, 2011; Klotzbach et al., 2018).

Track: El Niño tends to **weaken the NA subtropical high**, promoting recurvature of Atlantic TCs (Colbert and Soden, 2012).

TC genesis frequency: During **El Niño developing summer**, the NA had **fewer hurricanes**, which is attributed to **increased vertical wind shear** associated with anomalous upper-level westerly winds driven by an **eastward-shifted** and **weaker Walker Circulation** (Gray et al., 1994; Tartaglione et al., 2003; Camargo et al., 2007; Klotzbach et al., 2017).

➢ The Influence of ENSO on North Indian Ocean (NIO) TCs

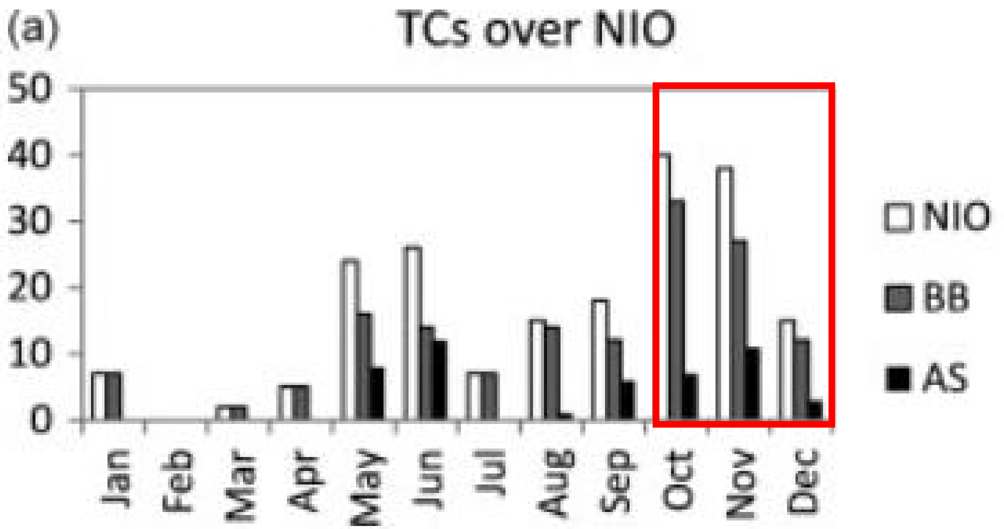
Table I. Correlation coefficients between climatic oscillation and TC parameters over the entire NIO basin (top), BB (middle), and AS (bottom) during the period of OND. Numbers in italic indicate correlations that are statistically significant at the 95% confidence level. Both Nino 3.4 index and DMI are averaged over the period of OND.

	NTC	ACE	NIC
NIO			
Nino 3.4	−0.14	*−0.68*	*−0.60*
DMI	*−0.47*	*−0.48*	*−0.48*
BB			
Nino 3.4	−0.23	*−0.66*	*−0.61*
DMI	*−0.41*	−0.36	*−0.48*
AS			
Nino 3.4	0.13	0.05	0.05
DMI	−0.05	−0.19	−0.03

Table II. Same as Table I, except for AMJ.

	NTC	ACE	NIC
NIO			
Nino 3.4	0.01	−0.04	0.01
DMI	−0.26	*0.41*	*0.42*
BB			
Nino 3.4	0.09	0.13	0.16
DMI	−0.09	0.34	0.34
AS			
Nino 3.4	−0.11	−0.17	−0.18
DMI	−0.37	0.16	0.16

(From Ng and Chan,2011)



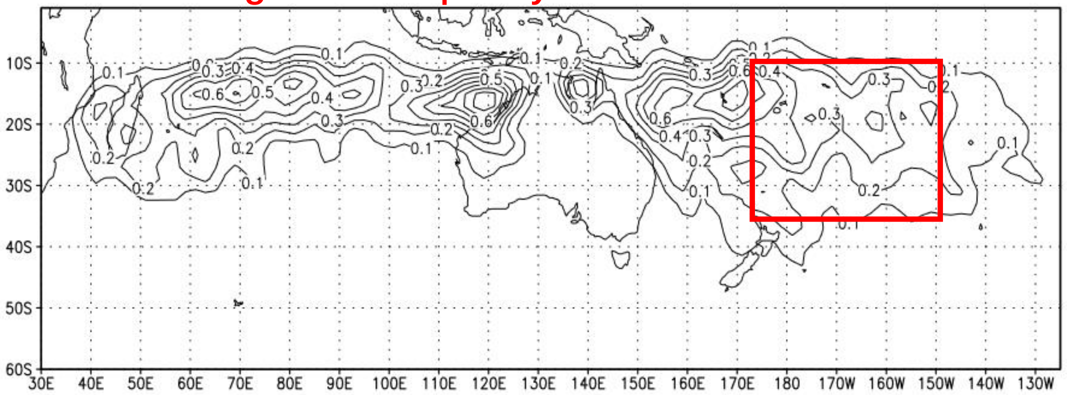
ENSO affects NIO TCs mainly during the **post-monsoon season** as ENSO events mature toward the end of the calendar year.

During an **El Niño developing year**, **fewer intense TCs** are observed in the **Bay of Bengal (BB)** (Singh et al., 2000; Ng & Chan, 2012).

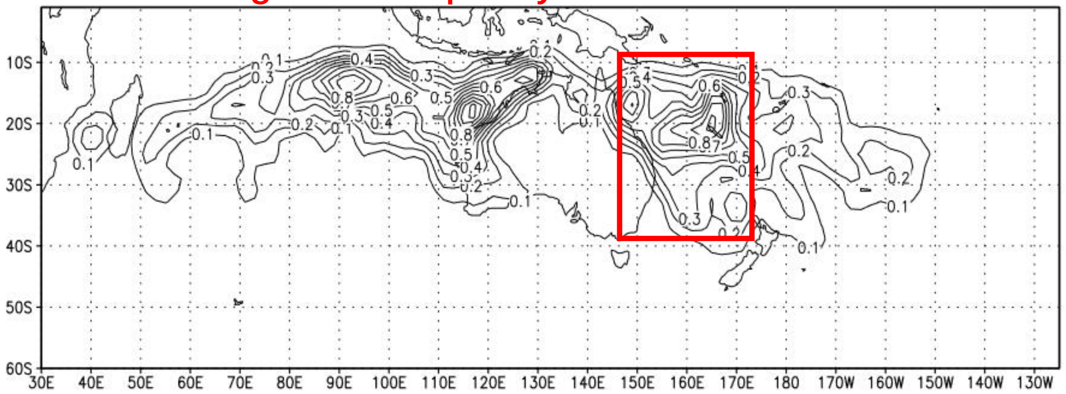
During **La Niña developing years**, weak vertical wind shear over the central and northern BB and increased relative humidity due to enhanced moisture transport favor TC development.

➢ The Influence of ENSO on South Pacific TCs

El Niño TC genesis frequency



La Niña TC genesis frequency



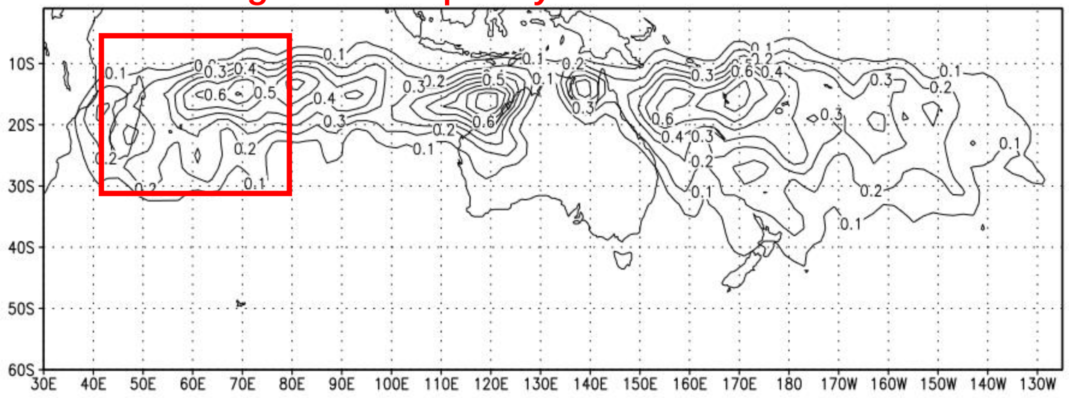
(From Y. Kuleshov et al.,2008)

The changes in **South Pacific TC genesis location** due to ENSO are controlled by the associated shifts in the **South Pacific Convergence Zone** (SPCZ).

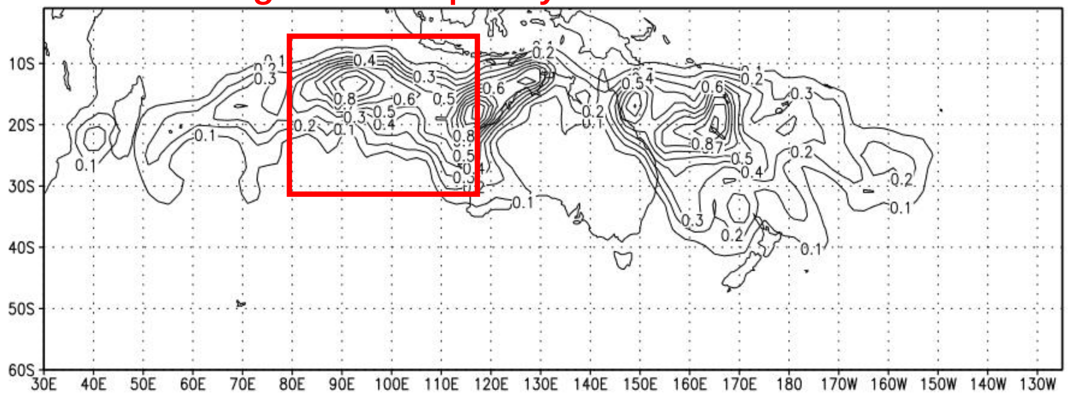
A **southwestward shift** in the SPCZ during **La Niña** corresponds to more TCs forming farther west in the South Pacific, and a **northeastward shift** in the SPCZ during **El Niño** corresponds to more TCs forming around the central and eastern South Pacific regions.

➢ The Influence of ENSO on South Indian TCs

El Niño TC genesis frequency



La Niña TC genesis frequency



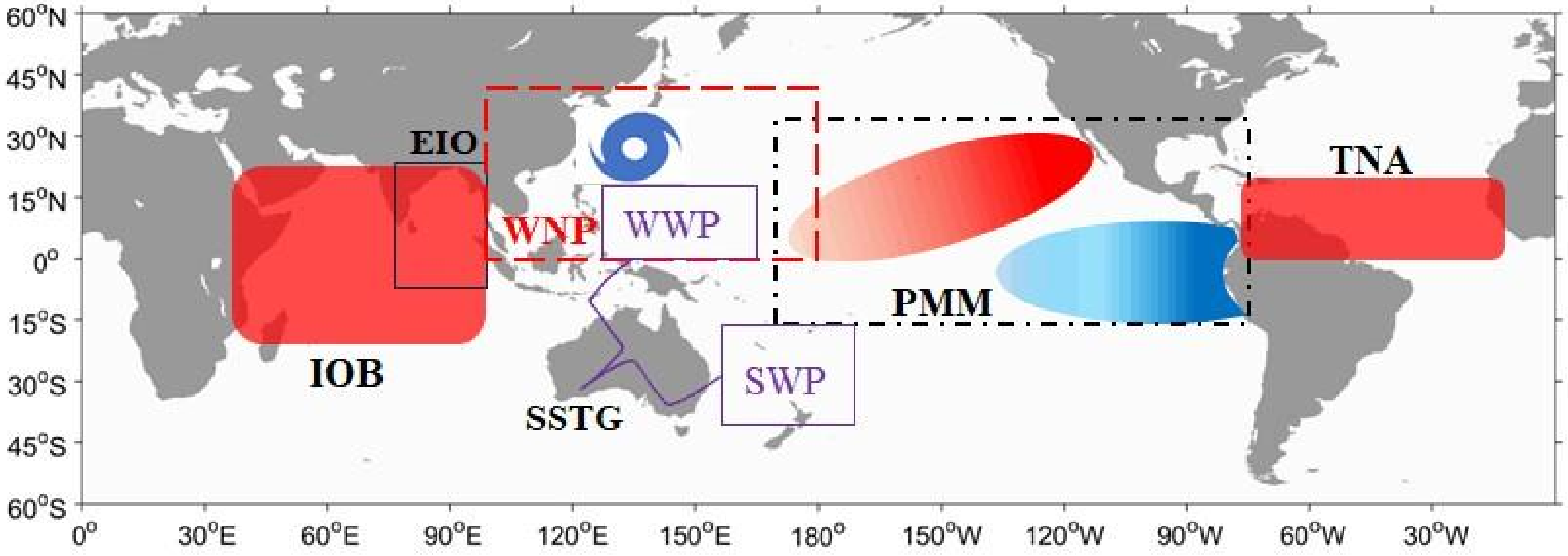
(From Y. Kuleshov et al.,2008)

During **El Niño** developing years, TC activity is **enhanced west of 75°E**, extending as far west as the East African coast, and **suppressed east of 75°E** in the South Indian Ocean basin. However, the opposite happens during **La Niña** developing years when TC activity is **suppressed west** of 75°E and **enhanced east** of 75°E (e.g. Ho et al., 2006; Camargo et al., 2007b; Kuleshov et al., 2008, 2009; Dowdy & Kuleshov, 2012).

Other tropical SST and tropical cyclone

Various sources of seasonal TC predictability other than ENSO that have been identified, thus providing predictability in ENSO-neutral conditions for some basins.

- **Pacific Meridional Mode (PMM)**
- **Tropical North Atlantic (TNA) SST**
- **Tropical Indian Ocean (TIO) SST**
- **Western Pacific SST**

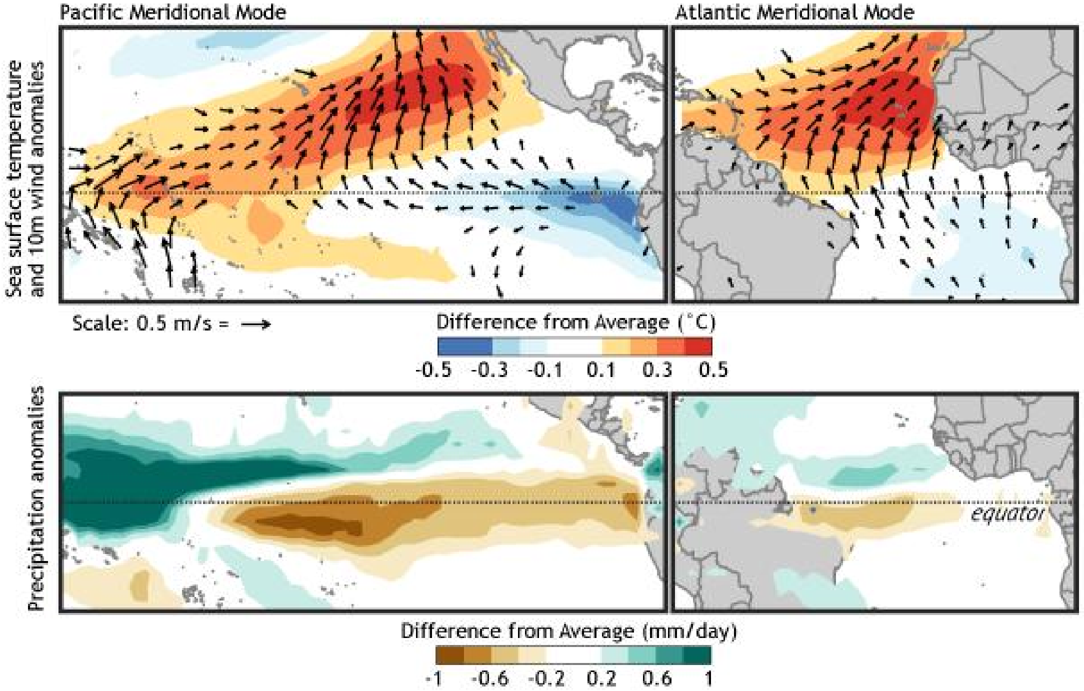


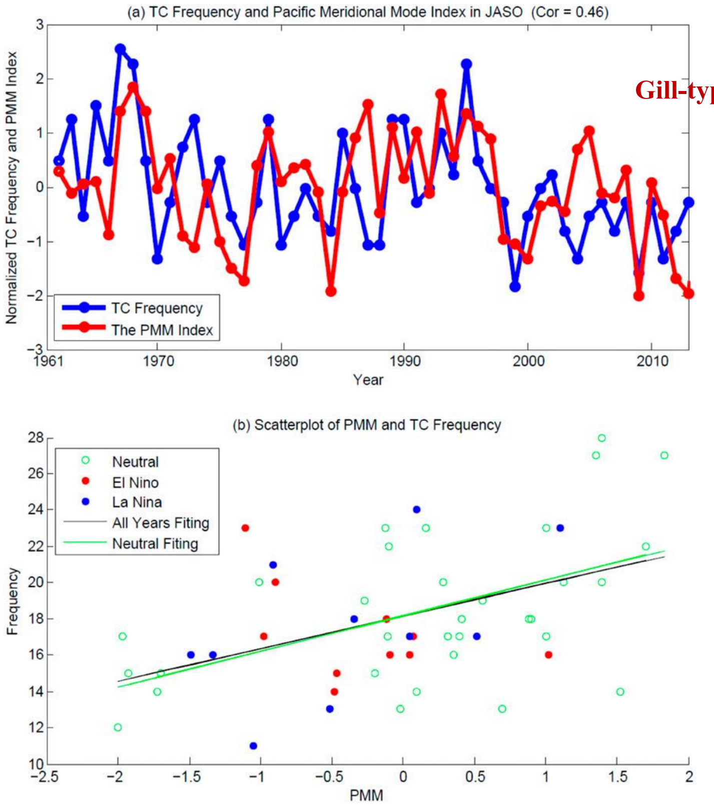
➢ Pacific Meridional Mode (PMM)

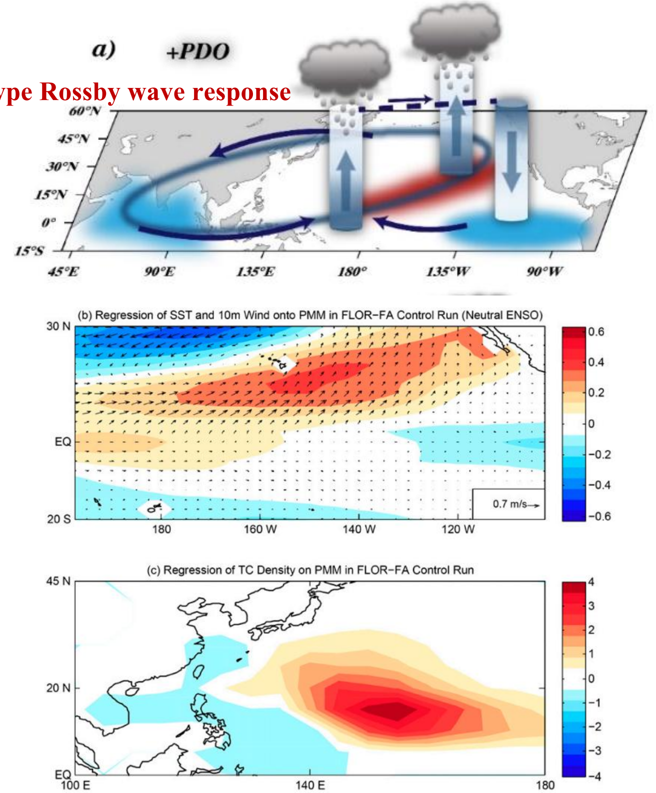
PMM is an *atmosphere–ocean coupled variability mode* in the subtropical North Pacific.

Several recent studies have shown a significant impact of the Pacific Meridional Mode (PMM; Chiang and Vimont 2004) on the interannual variability of WNP TC activity (Zhang et al. 2016; Gao et al. 2020a; Liu et al. 2019; Takaya 2019).

Positive phases of the PMM increase TC activity by inducing anomalous cyclonic winds and positive vorticity anomalies over the WNP.







(From Zhang et al., 2016; Wang et al., 2023)

➢ Tropical North Atlantic (TNA) SST

The tropical North Atlantic (TNA; 0°–20°N, 80°–10°W; Gao et al. 2020b) is another important driver of WNP TC activity.

Many studies have documented **significant correlations between TNA sea surface temperature (SST) anomalies and both WNP cyclogenesis and landfalling events** (Huo et al., 2015; Yu et al., 2016; Gao et al., 2018).

Gao et al. (2020b) also found **a significant positive correlation between spring TNA SST and the**
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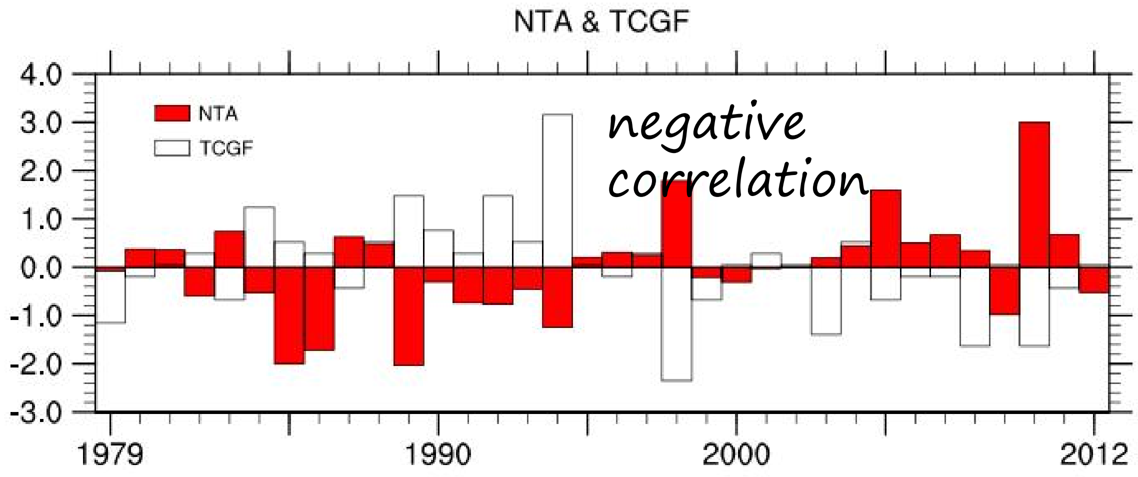
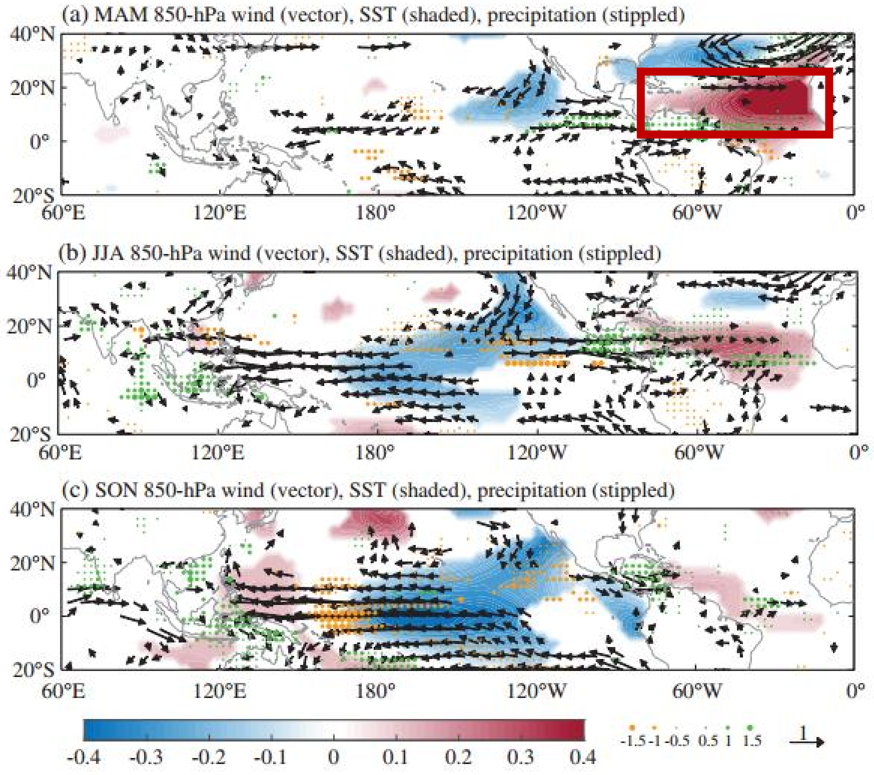




Key Points:

- Spring NTA SST anomaly significantly correlates with WNP TC genesis frequency
- The remote teleconnection initiated from the Atlantic affects WNP TC genesis
- Spring NTA SST anomaly could be a new predictor for seasonal WNP TC activity

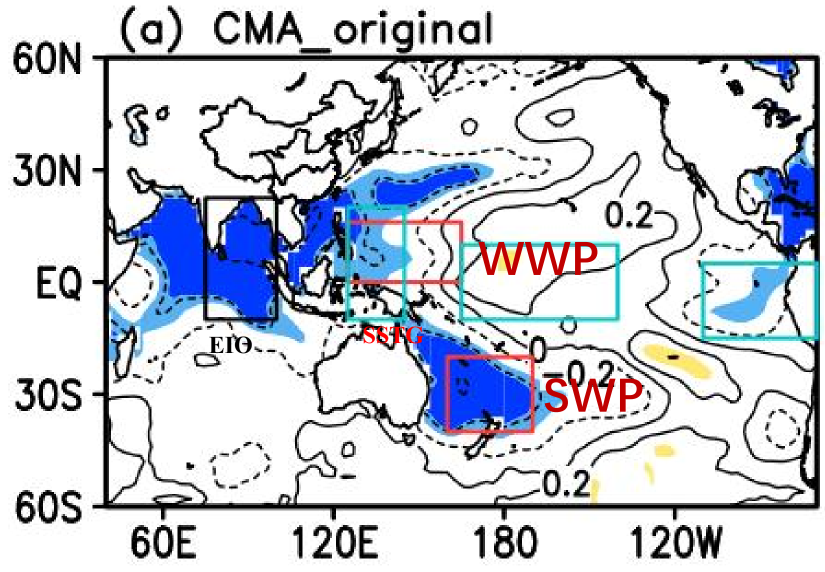
a chain of air-sea coupled processes such as Rossby-wave response, wind-evaporation-SST feedback.

(From Huo et al 2015; Gao et al., 2020b)

➢ Tropical Indian Ocean (TIO) and western Pacific SST

SSTs *in the Indian Ocean (IO) and the western Pacific* are other contributors to seasonal TC activity in the WNP.

Zhan et al. (2019) developed statistical seasonal prediction model to predict the WNP TCGF in the typhoon season by a combination of the May *east Indian Ocean* (EIO) and the spring SST gradient (SSTG). The new model can reproduces well the observed WNP TCGF and provide a good tool for seasonal prediction of WNP TCGF.



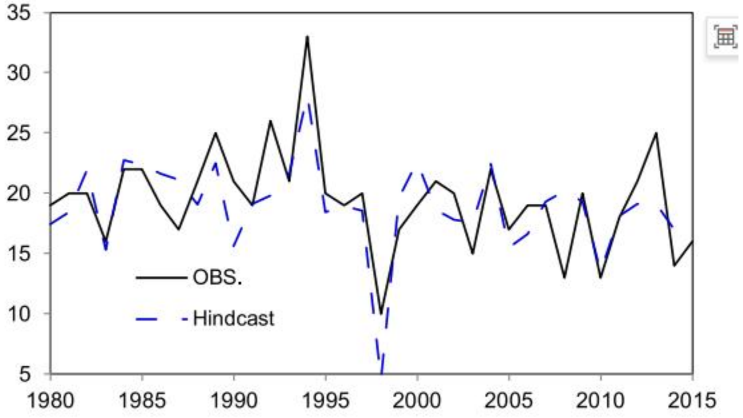
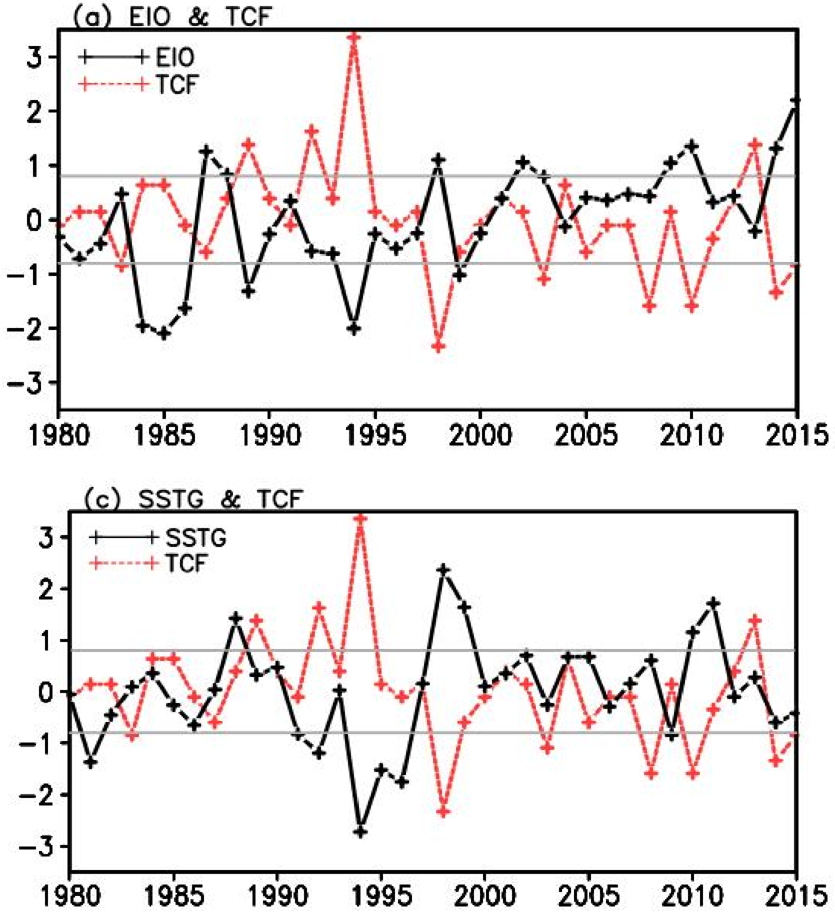


FIG. 11. Time series of the observed TCGF and the cross-validated estimates of the TCGF with the May EIO index and the spring SSTG index as predictors in the typhoon season for the period 1980–2015. The correlation between them is 0.72, which is significant at the 99% confidence level.



EIO SSTA index: 10S–22.5N, 75–100E.

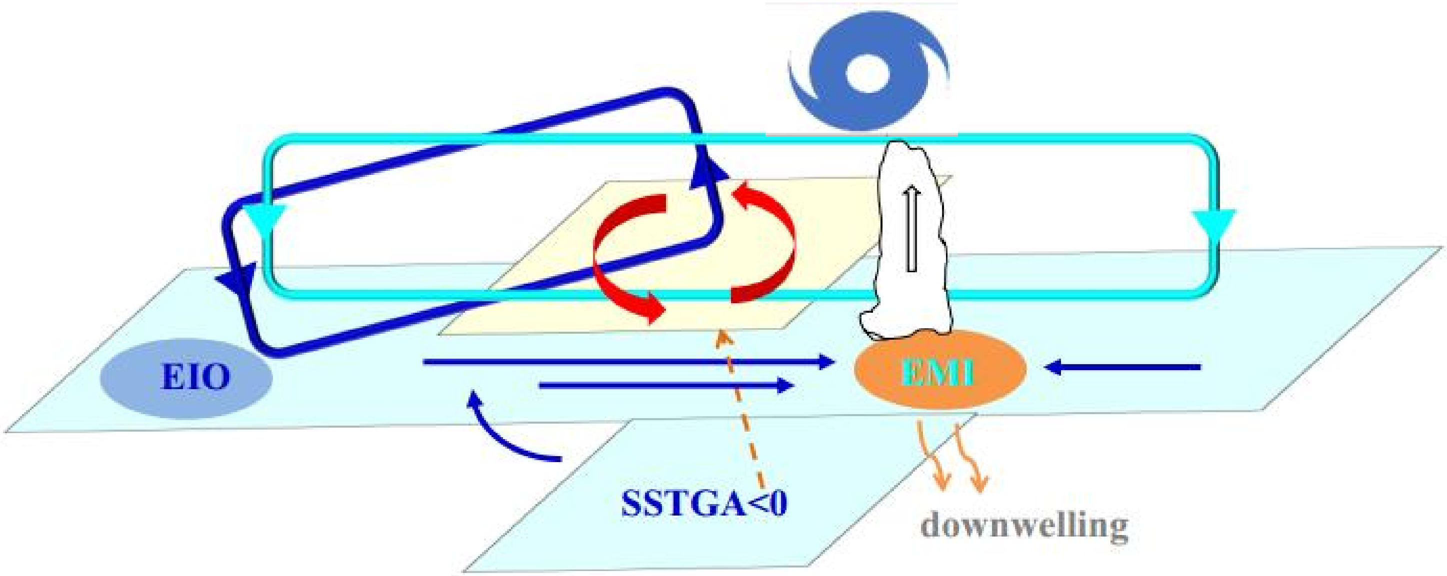
The SSTG index: the difference in SSTAs between the SWP (40–20S, 160E–170W) and the WWP (0–16N, 125–165E)

SWP: the southwest Pacific east of Australia

WWP: the western Pacific warm pool

(From Zhan et al., 2019)

➢ Tropical Indian Ocean (TIO) and western Pacific SST



(From Zhan et al., 2019)

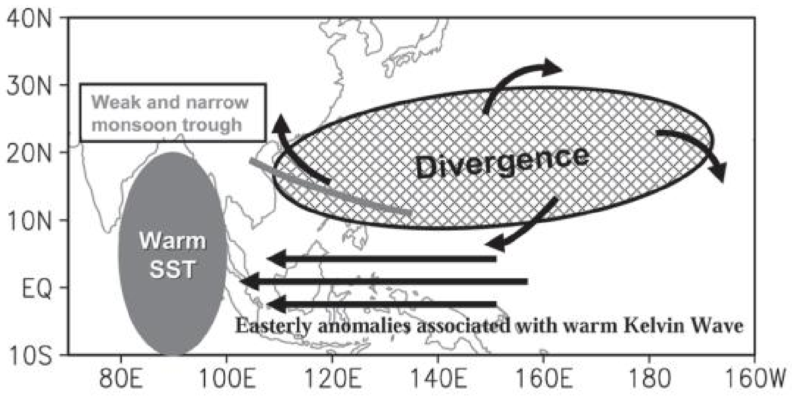


Fig. 3. Schematic diagram showing the response of the atmospheric fields over the WNP to the EIO warming. Warm SSTA in the EIO reduces the land-sea thermal contrast to the north and weakens the East-Asian and WNP summer monsoon. It also excites a warm equatorial Kelvin wave to the east with low-level easterly anomalies with negative surface pressure anomalies near the equator over the WNP. Consequently, positive surface pressure anomalies accompanied with anticyclonic divergent circulation occur in the tropics off the equator over the WNP TC genesis region, suppressing the TC formation over the WNP (Zhan et al. 2011b).

The EIO SSTA affects the WNP TCGF by modulating the WNP summer monsoon and the activity of the equatorial Kelvin waves.

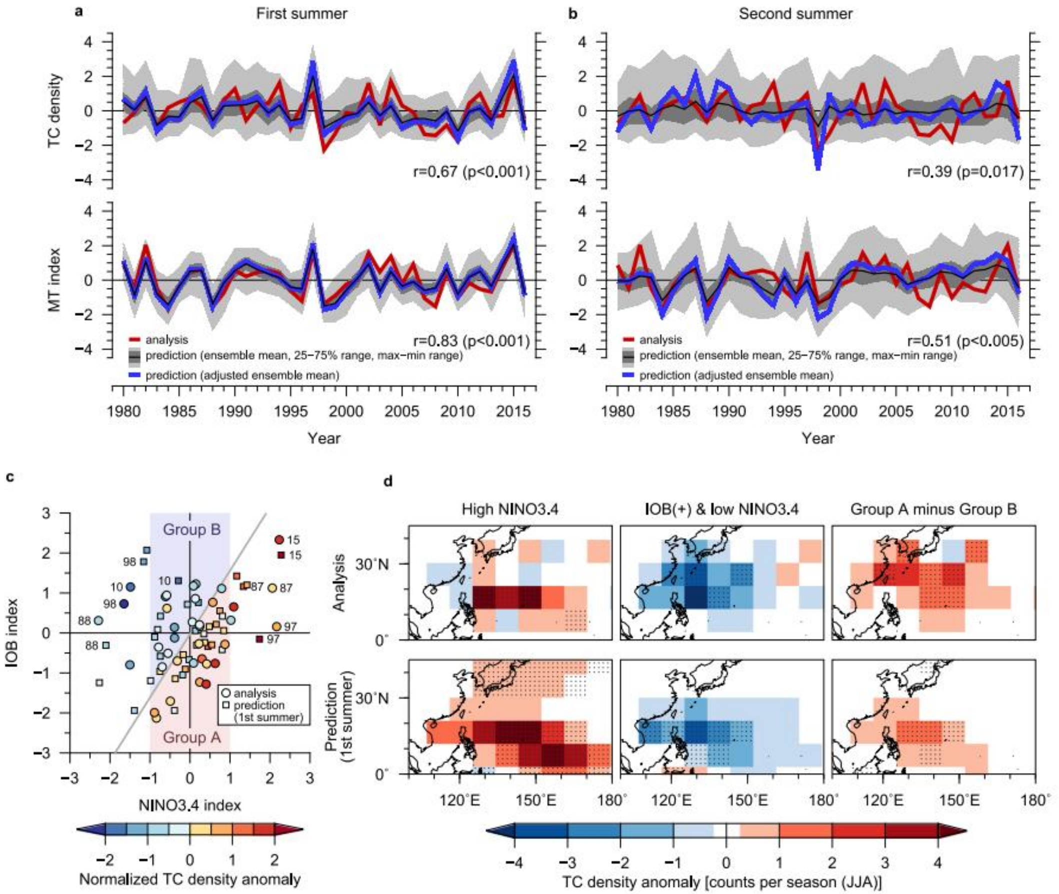
The spring SSTG anomaly affects the WNP TCGF by two mechanisms:

(1) The negative SSTG anomaly leads to a cross-equatorial pressure gradient, which forces anomalous northward cross-equatorial flow and tropical westerlies in the lower troposphere over the WNP.

(2) The equatorial westerlies in response to the negative SSTG anomaly act to warm the equatorial CP by inducing local downwelling and deepening the thermocline in the east. This warm SSTA further enhances the equatorial westerlies and thus TC genesis over the WNP.

➢ Tropical Indian Ocean (TIO) and western Pacific SST

Takaya et al. (2021) also investigated seasonal TC activity in the WNP in relation to IO basin (IOB; 20°N–20°S, 40°E–100°E) and Niño3.4 SSTs. They suggested that **the IO mediates the delayed influence of preceding El Niño due to IO warming following El Niño** (Indo-western Pacific Capacitor mode; Xie et al. 2016), and **also modulates WNP TC activity in summers that follow El Niño events.** In addition, they found that the combined effect of the IOB and Niño3.4 SSTs can explain WNP TC a… …ses.

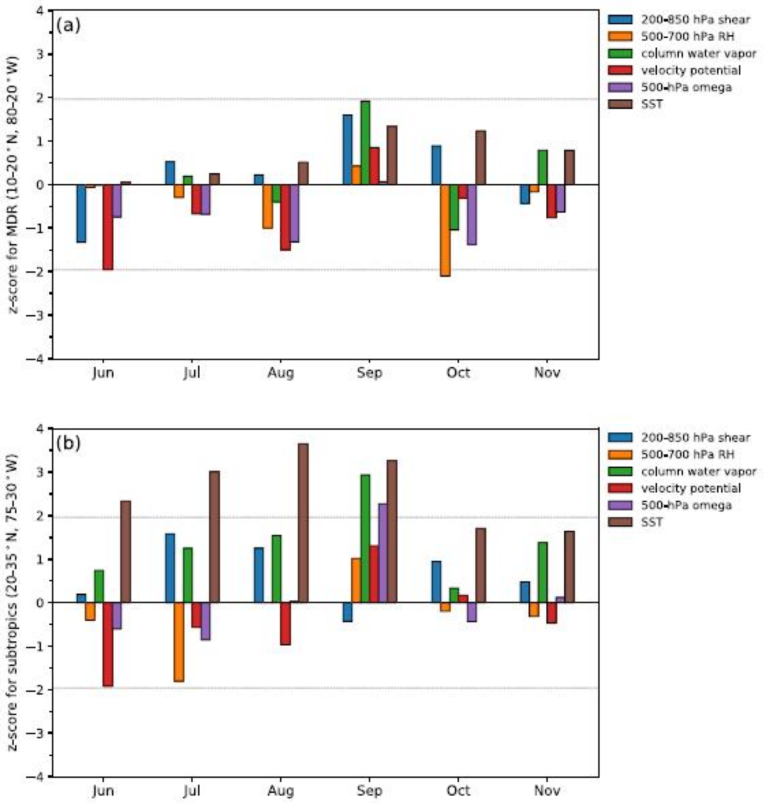


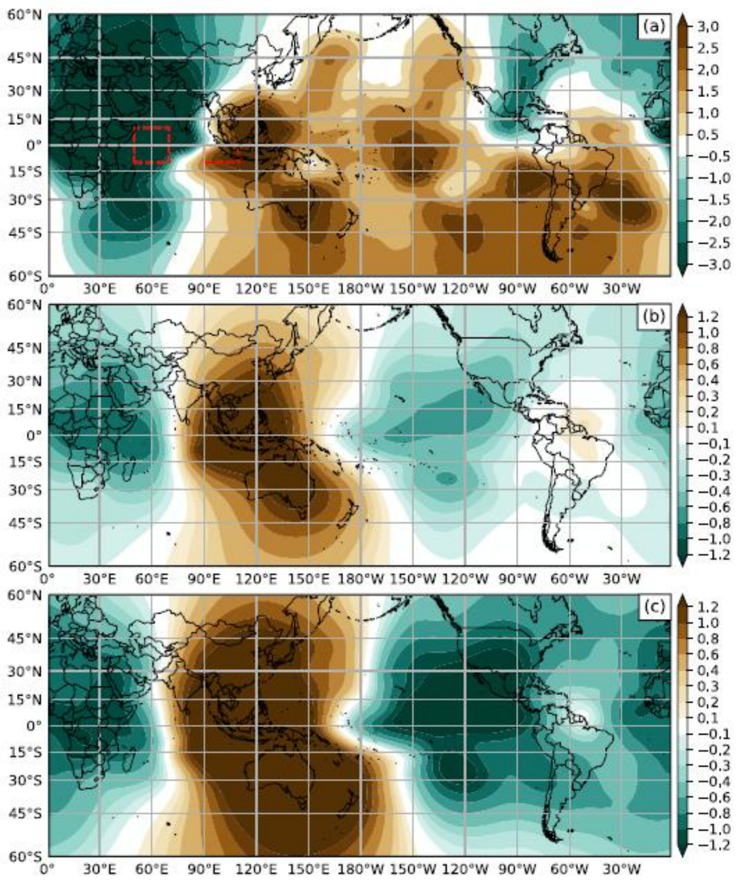
The key to this long-range prediction is successfully simulating El Niño–Southern Oscillation evolution and realistically representing the subsequent atmosphere–ocean response in the Indian Ocean–western North Pacific in the second boreal summer of the prediction.

TC prediction skill and influence from ENSO and IOB SST (From Takaya et al., 2021)

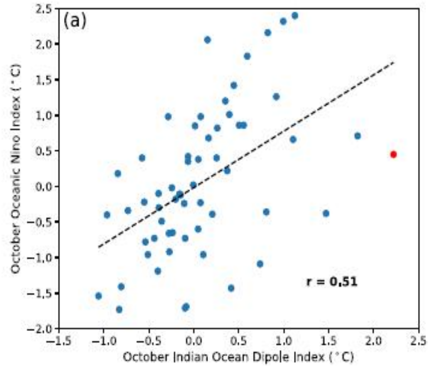
Predictability of TC activity over the North Atlantic in ENSO-neutral conditions

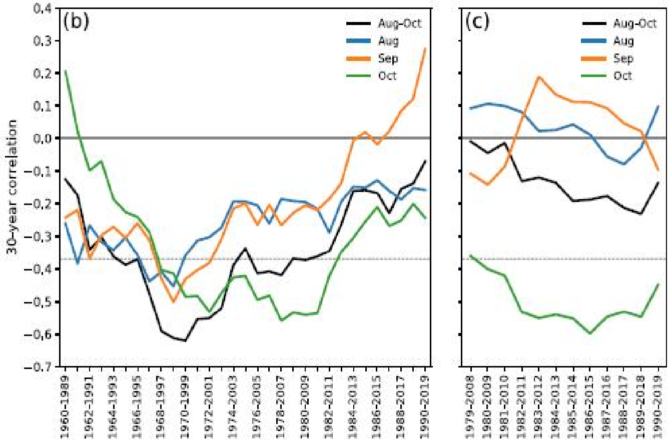
Wood et al. (2020) suggested that the **Indian Ocean Dipole (IOD)** may be another source of seasonal TC predictability over the NA during neutral ENSO phases. The IOD played a role in suppressing late-season TC activity during the 2019 NA hurricane season with ENSO-neutral conditions during August–October. By modulating the Walker circulation, **positive IOD phases (warm western IO and cool eastern IO) suppress NA TC activity** by increasing vertical wind shear (VWS) and reducing RH over the NA MDR, while negative IOD phases are associated with more favorable environmental conditions for NA TC





200- hPa velocity potential anomalies



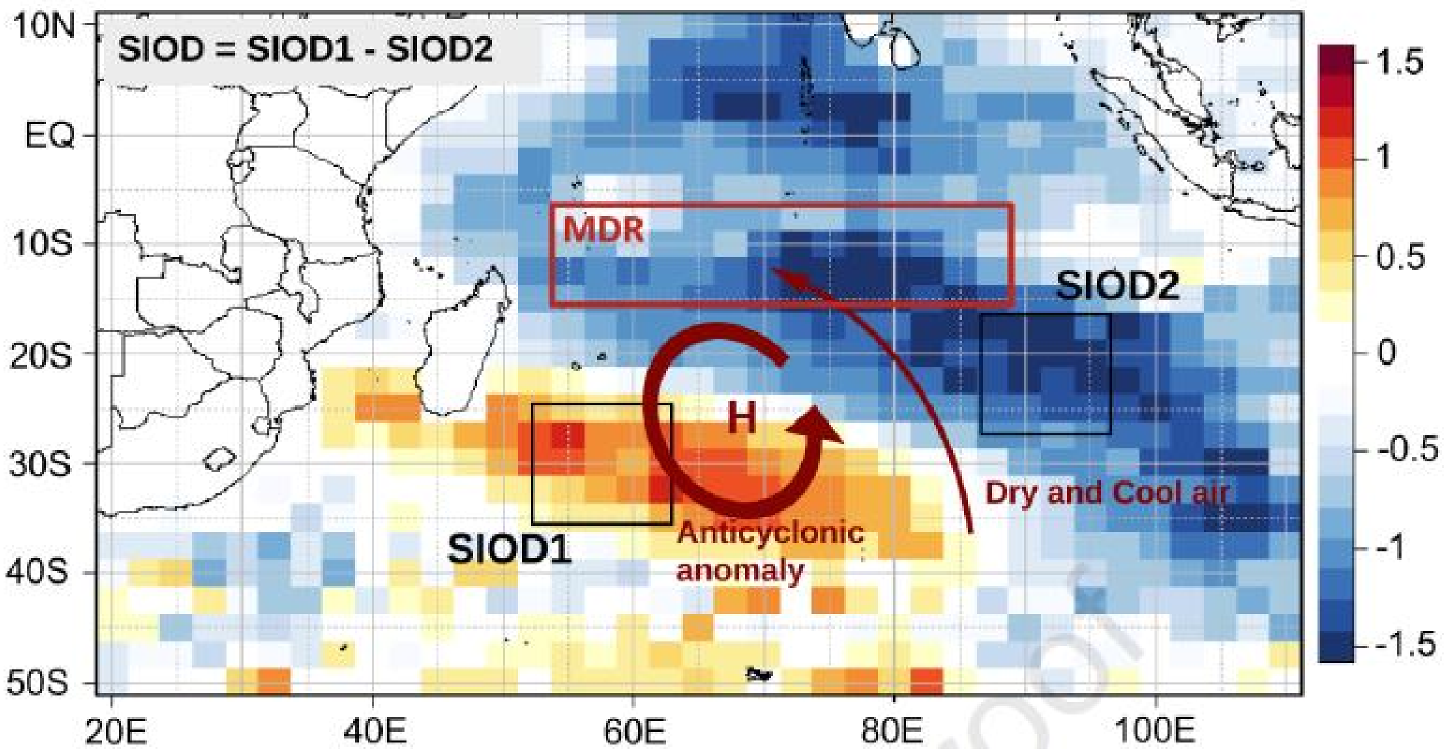


Correlations between Atlantic ACE and the IOD index

(From Wood et al., 2020)

Seasonal TC activity modulation over the South West Indian Ocean associated with Subtropical Indian Ocean Dipole events

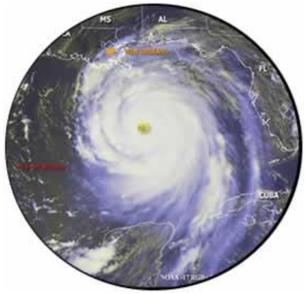
the **Subtropical Indian Ocean Dipole (SIOD)** is a promising source of predictability for South West Indian Ocean (SWIO)TC activity at seasonal time scales, bringing additional information for TC seasonal outlooks to that provided by ENSO.

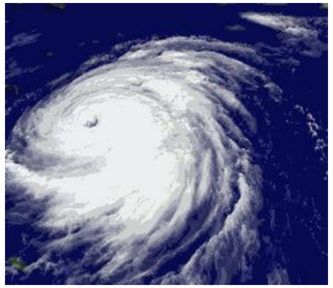


(From Takaya et al., 2023)

Positive SIOD events are associated with colder-than-normal SST off Australia and a positive SLP anomaly over the tropical and subtropical south central IO. This atmospheric anomaly drives cool and dry air from austral latitudes all the way to the MDR of the SWIO basin (5°S–15°S, 55°E–90°E), reducing basinwide TC activity by ~20%. Similarly, negative events result in a negative SLP anomaly pattern driving moisture and warm equatorial air over the MDR, Consequently, negative SIOD events tend to facilitate TC development within the MDR, enhancing overall TC activity by

3.Relationship between tropical cyclone, subtropical high and monsoon





Subtropical High predictability establishes a promising way for monsoon and tropical storm predictions

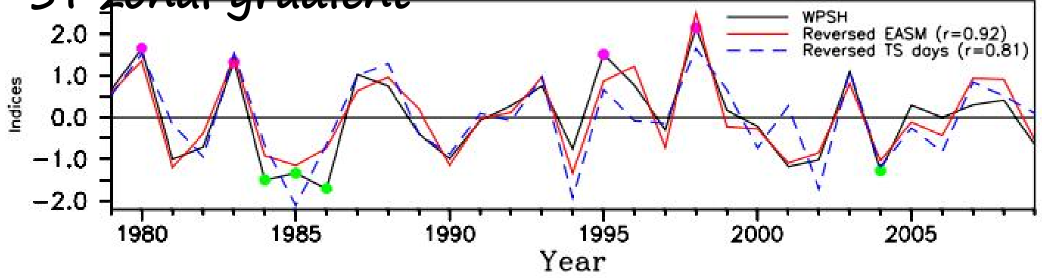
Bin Wang[a,b,1], Baoqiang Xiang[b], and June-Yi Lee[b]

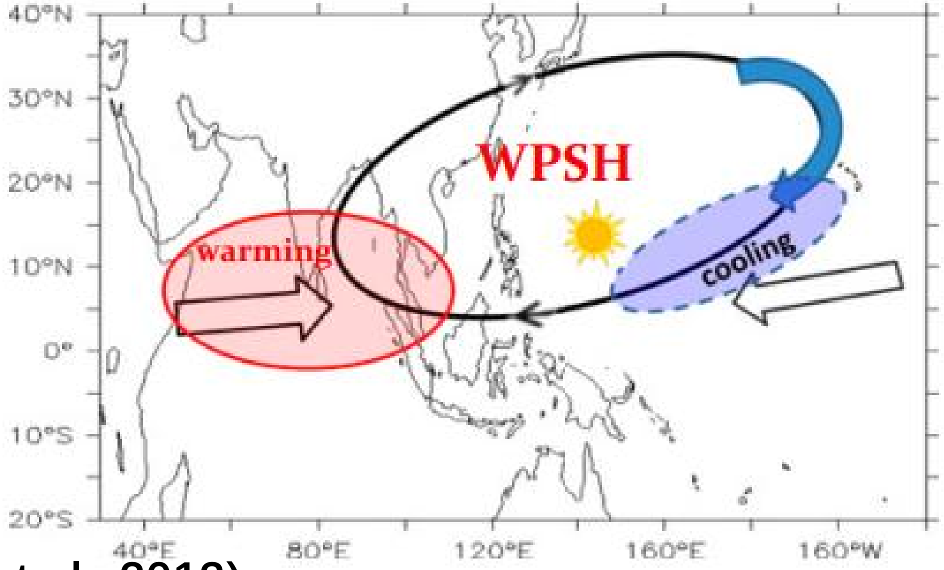
[a]Department of Meteorology, and [b]International Pacific Research Center, University of Hawaii at Manoa, Honolulu, HI 96822

The western Pacific Subtropical High (WPSH)–ocean interaction can provide a source of monsoon and TC climate.

$$\text{WPSH index} = 1.704 \times \text{SSTA(IO} - \text{WNP)} - 0.713 \times \text{ENSO}_{\text{develop}} - 0.283 \times \text{NAOI},$$

SSTA(IO-WNP): the springtime Indo-Pacific warm pool ST zonal gradient

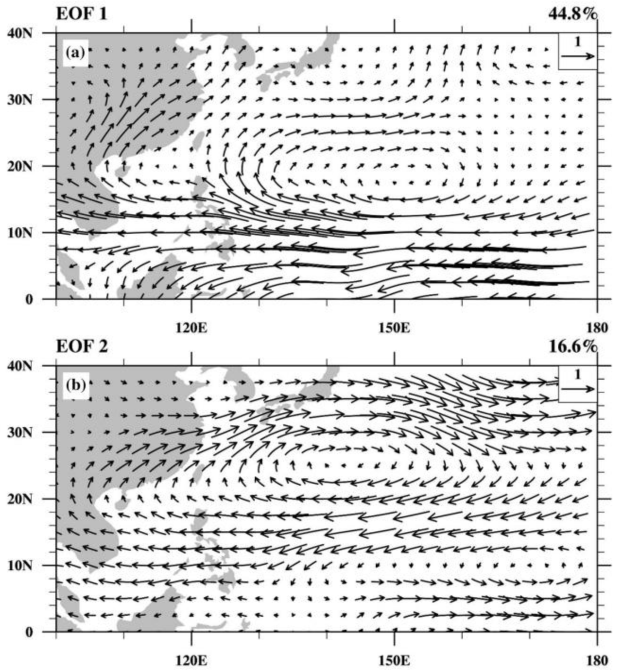




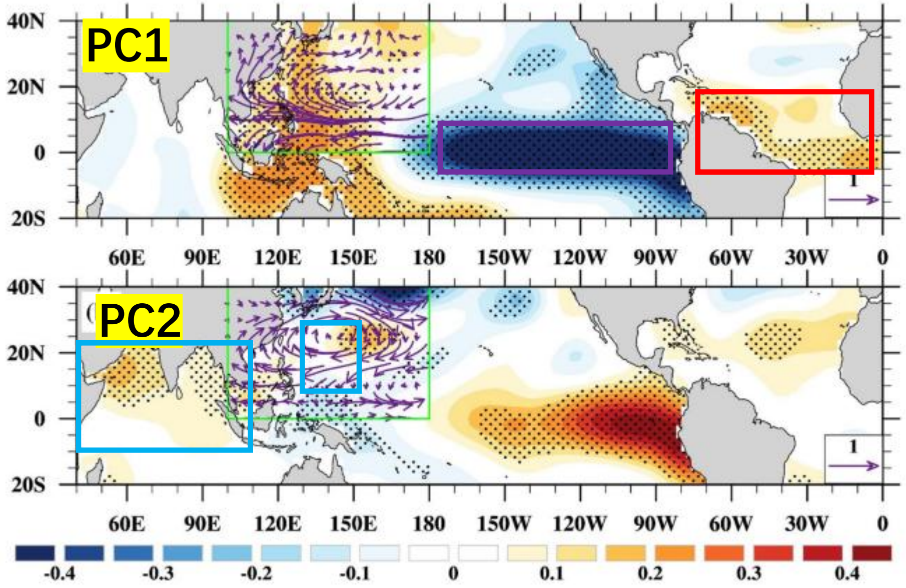
(From Wang et al., 2013)

TC, subtropical high and monsoon may be considered together in climate prediction

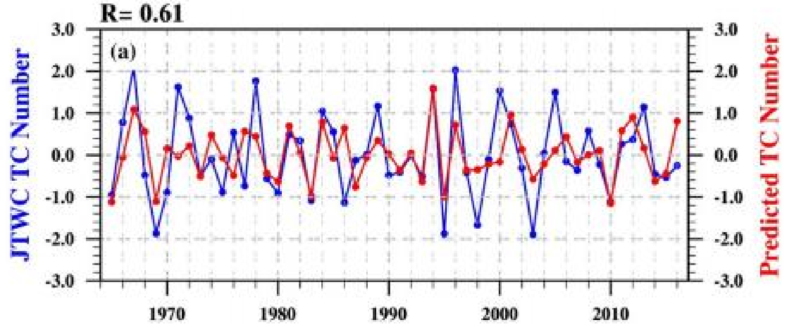
Relationship between tropical cyclone and subtropical high



Multivariate EOF for 850-hPa wind



Regressed SST and wind



Observed & Predicted

Name	Definition	Meaning
CEP	May–June SSTA over (10°S–10°N, 180°W–100°W)	Central-eastern Pacific SST predictor
TA	May–June SSTA over (10°S–20°N, 60°W–20°W)	Tropical Atlantic SST predictor
IOWP	May–June SSTA difference between (10°S–25°N, 50°E–110°E) and the (10°–30°N, 130°E–150°W)	Indo-Pacific dipole SST predictor
NPT	May–June minus December–January SST tendency over (45°N–55°N, 150°E–170°W)	North Pacific SST predictor

SSTA predictor

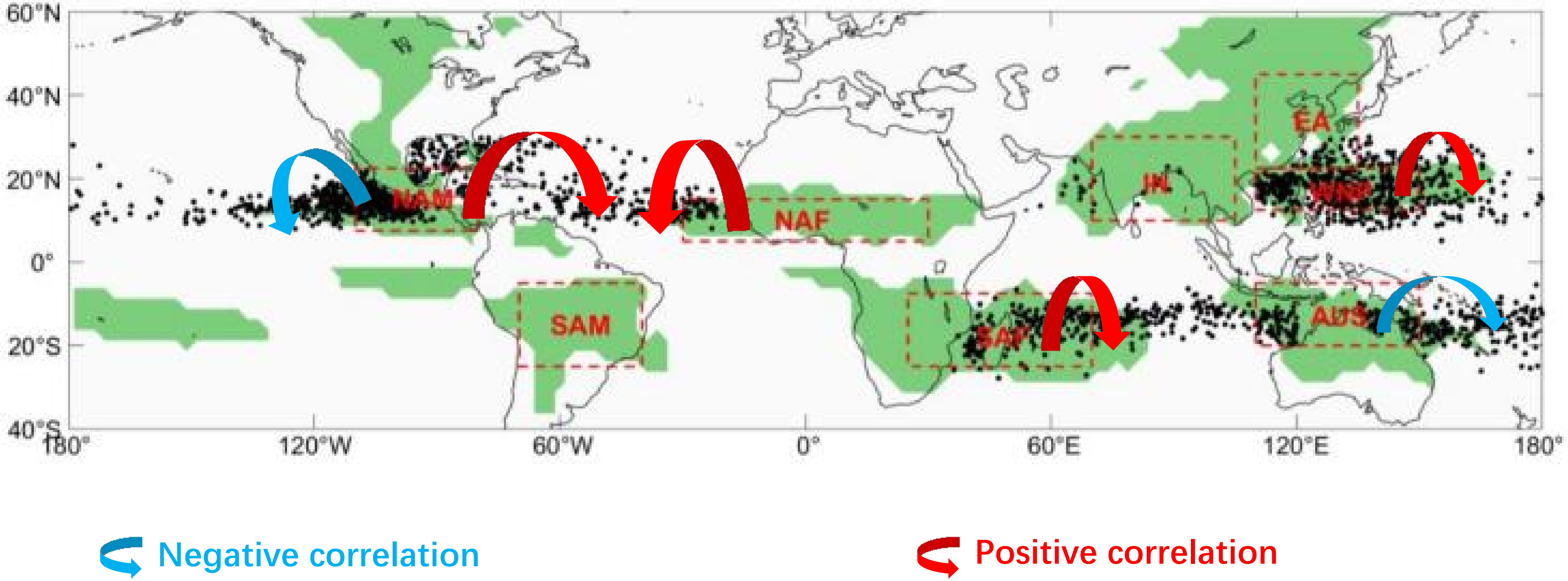
(From Wang and Wang, 2019)

The collectively influences of tropical SSTAs in the three oceans can be understood via two leading modes of variability of WNP subtropical high (WNPSH).

The first mode affects the TC tracks, total number of tropical storm days, and power dissipation index (PDI). The second mode, has a significant control on the total TC genesis number.

Physics-based empirical models is built to predict the two WNPSH modes and TC activity in the peak TC season with preceding season trans-basin SST predictors. (Wang and Wang, 2019)

Relationship between global monsoon and tropical cyclone



The global distribution of monsoon regions and TC genesis locations

NAF: North African monsoon
SAF: South African monsoon
IN: Indian monsoon
EA: East Asian monsoon
WNP: western North Pacific monsoon
AUS : Australian monsoon
NAM : North American monsoon
SAM : South American monsoon

Monsoons and TCs are both global phenomena, and their activities can be found in various regions across the world.

Global monsoon regions and the generation of tropical cyclones are overlapped or adjacent in space.

Western North Pacific summer monsoon & Western North Pacific TCs

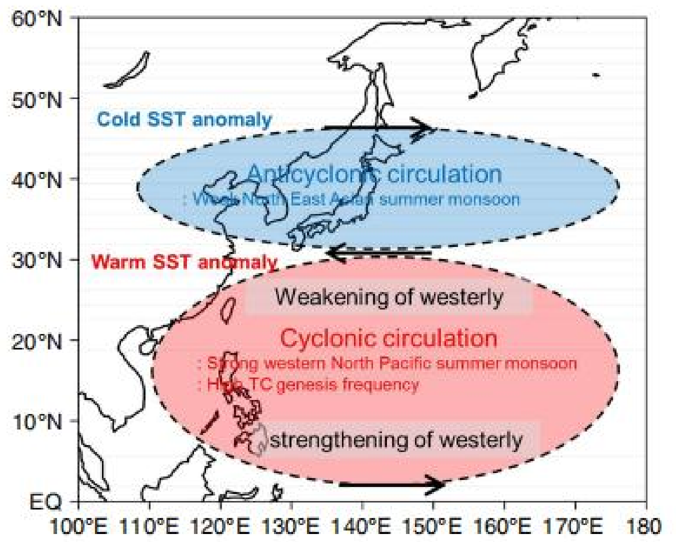
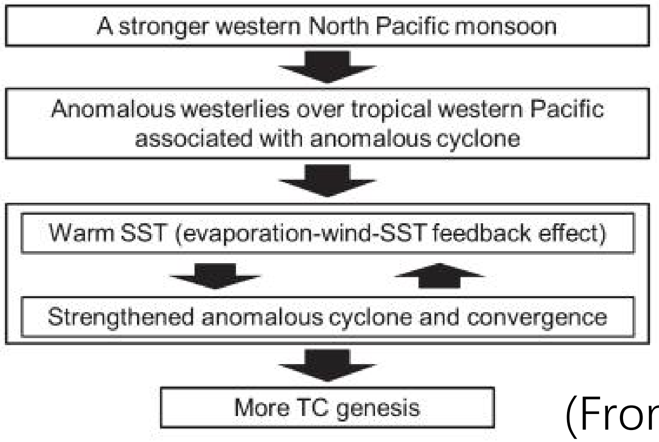


Figure 12. Schematic illustration of anomalous atmospheric changes occurring during the positive WNPMI phase.



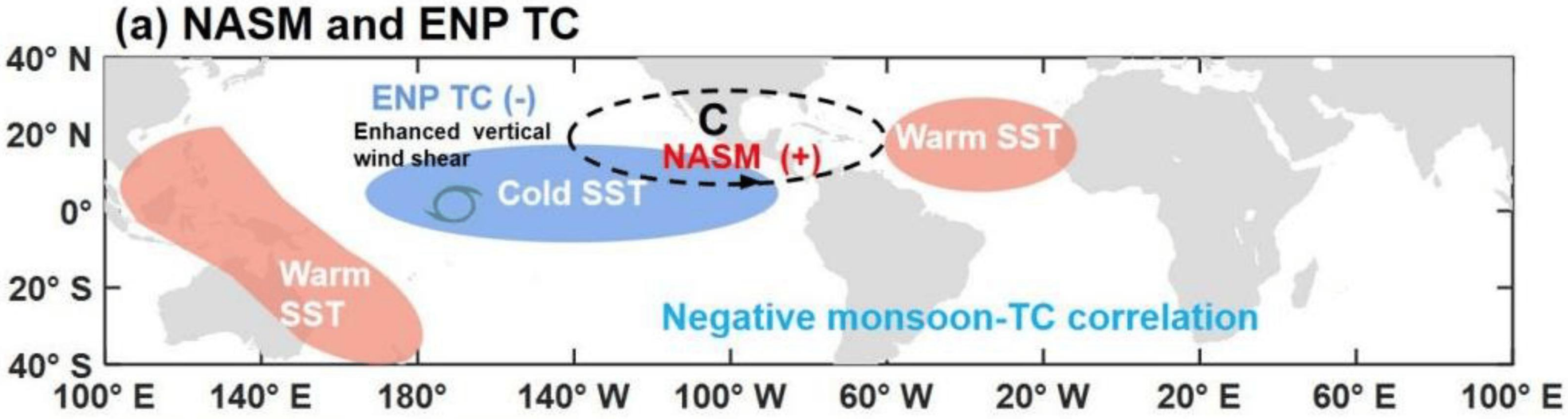
(From Choi et al., 2016)

A high **positive correlation** was found between the **intensity of Western North Pacific summer monsoon** and the **TC genesis frequency** in the **western North Pacific** in the summer season.

When the western North Pacific summer monsoon develops, an **anomalous cyclone** becomes intensified in the subtropical **western North Pacific** and the anomalous westerlies in the south flank of the **anomalous cyclone** in the tropics also intensify.

The anomalous westerlies is favourable for the increase of SST through the **wind-evaporation-SST feedback effect**. As a result, the **anomalous cyclone and anomalous convergence** become **stronger** in this region, thereby **increasing the TC genesis frequency**. (Choi et al., 2016)

North American summer monsoon (NASM) & Eastern North Pacific (ENP) TCs



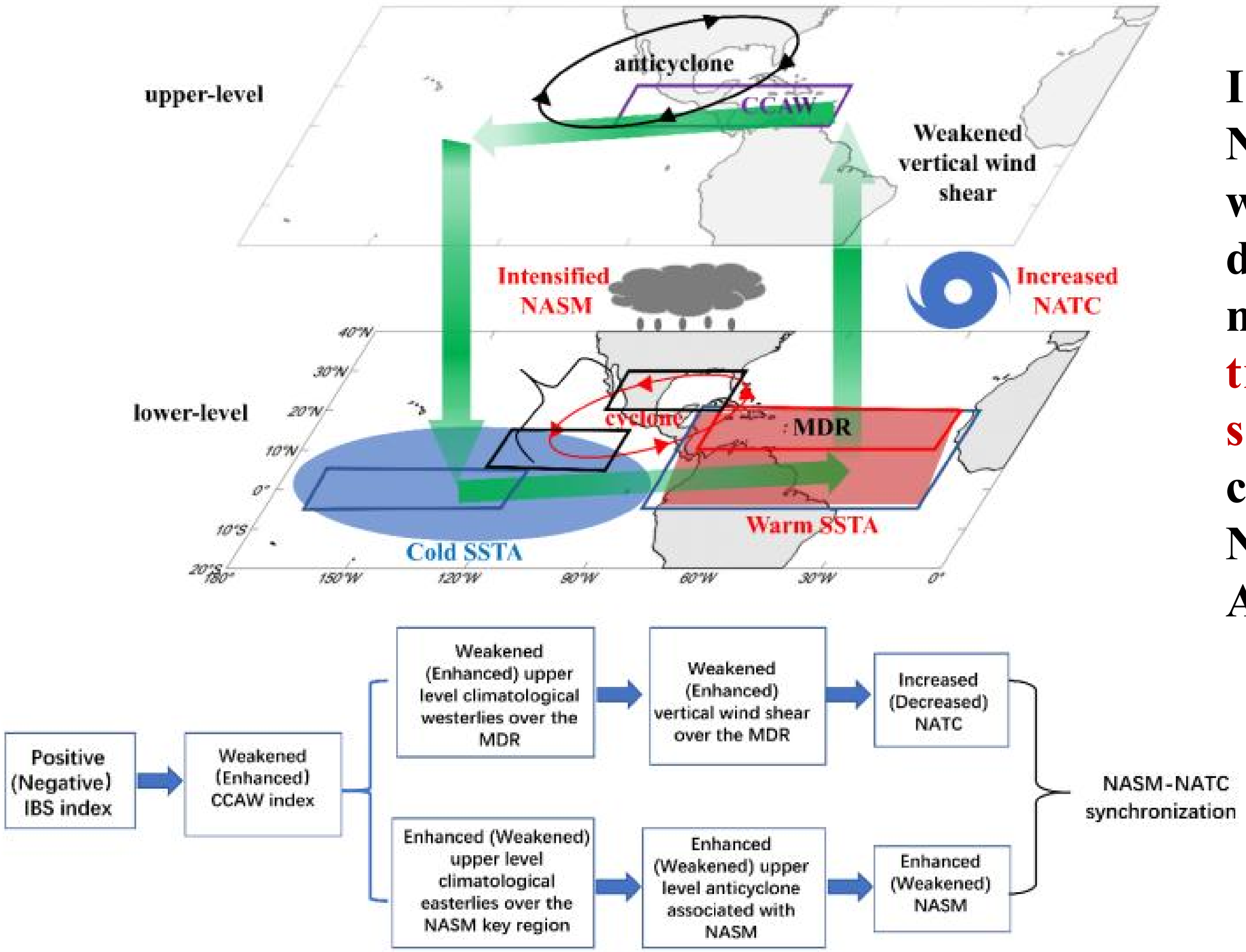
(From Weng et al.,2022)

A significant **negative correlation** was identified between the intensity of **North American summer monsoon** (**NASM**) and the **TC genesis frequency** (TCGF) over the **eastern North Pacific** (ENP).

In **strong NASM years**, the **strong vertical wind shear** could **inhibit the TCGF** over the ENP.

The **signs** of tropical Pacific–Atlantic SST anomalies influencing the NASM were almost **opposite** to those affecting the TCGF over the ENP.

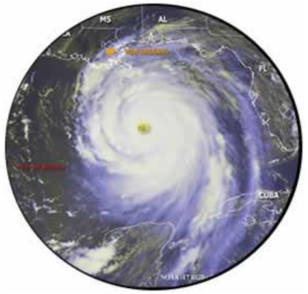
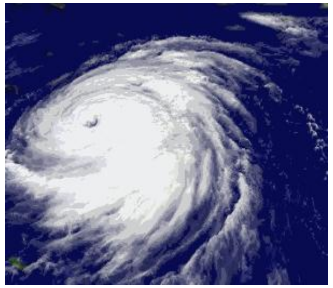
North American summer monsoon & North Atlantic TCs



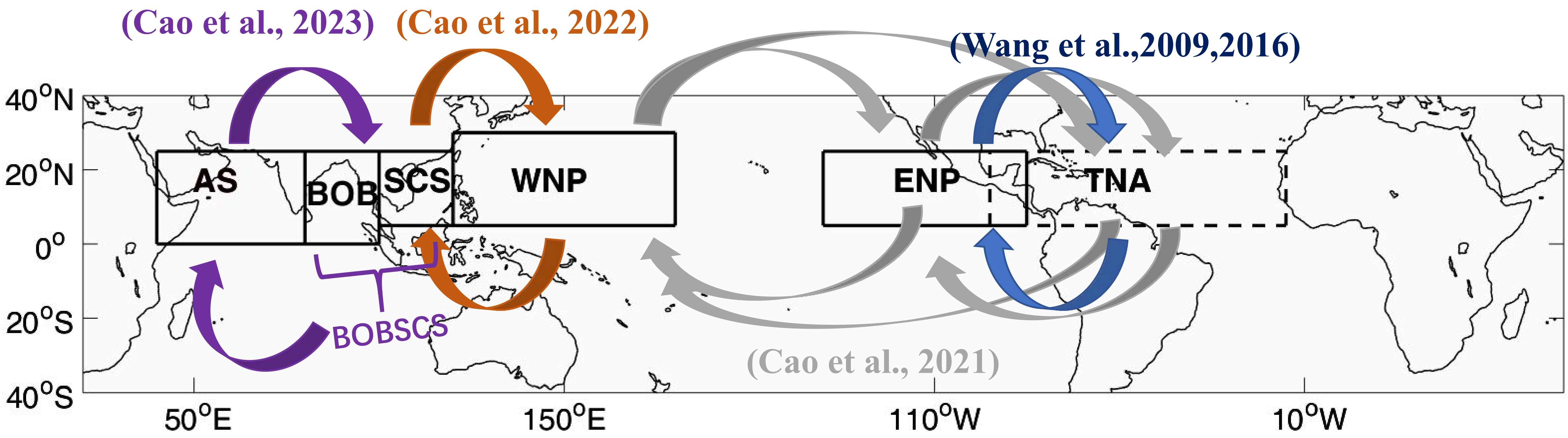
(From Luo et al.,2023)

In years with stronger NASM intensity, the NATC genesis frequency tends to be higher , which could be explained by simultaneous decreases of vertical wind shear in the NATC main development region (MDR). The tropical Pacific and Atlantic interbasin sea surface temperature (SST) anomalies play a critical role in bridging the NASM and NATC, by modulating the cross-Central American wind (CCAW).

4. Relationship between tropical cyclone genesis in different ocean basins

Relationship between tropical cyclone genesis in different ocean basins



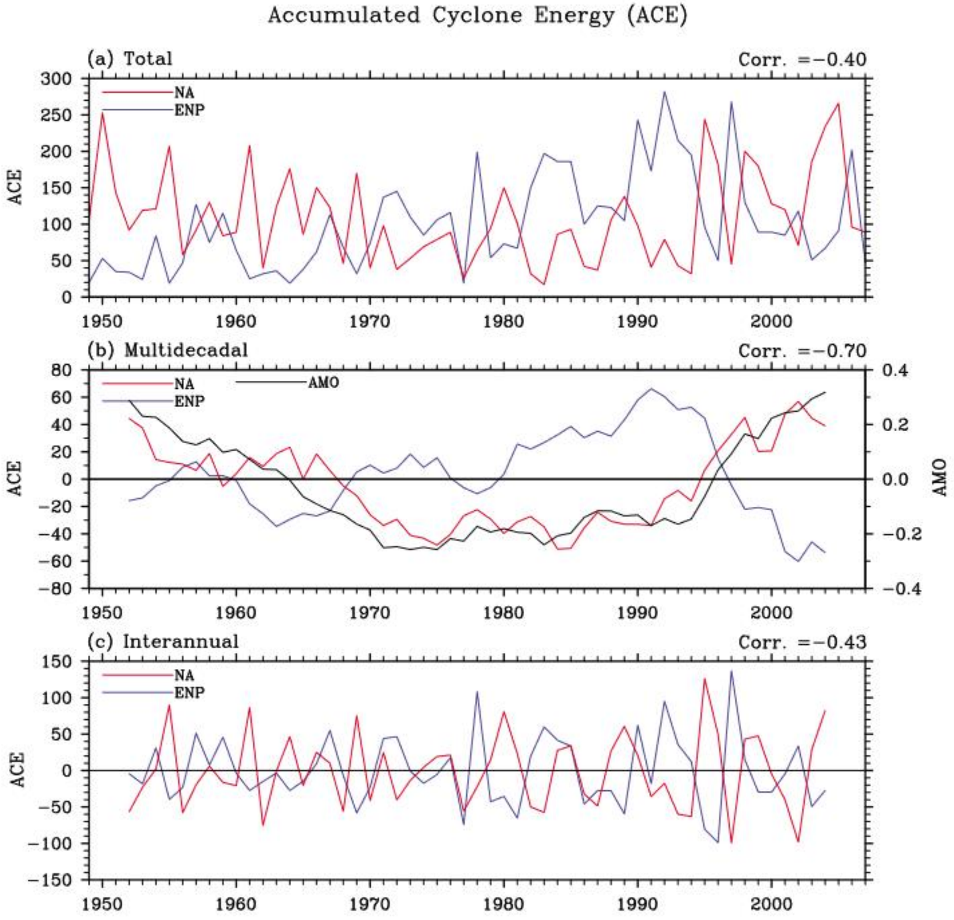
Eastern North Pacific : ENP
Tropical North Atlantic : TNA
Western North Pacific : WNP
South China Sea : SCS
Bay of Bengal : BOB:
Arabian Sea : AS

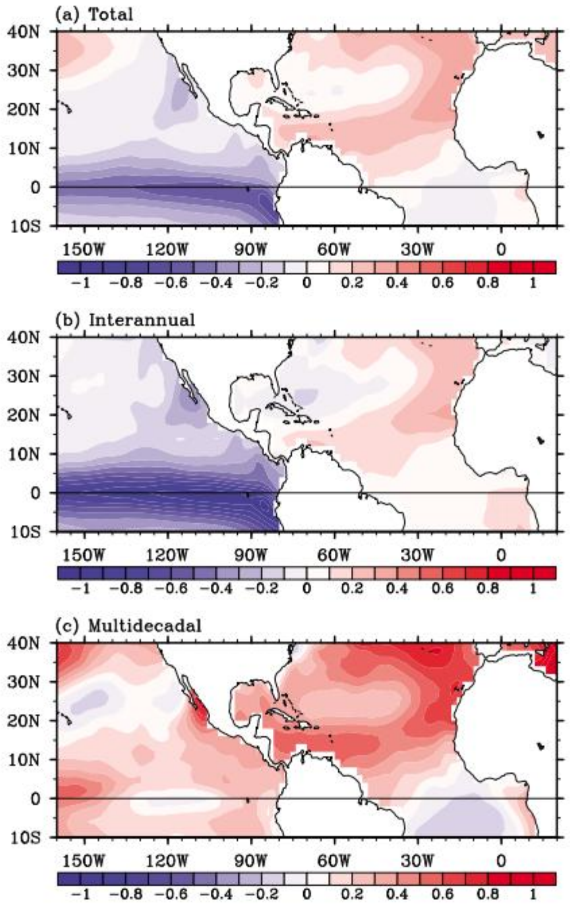
ENP &TNA : Wang et al., 2009,2016
WNP & ENP & TNA : Cao et al., 2021
SCS & ENP : Cao et al., 2022
AS & BOB-SCS : Cao et al., 2023

TC activities in some basins may be considered together in climate prediction

➢Eastern North Pacific (ENP) TCs and North Atlantic (NA) TCs

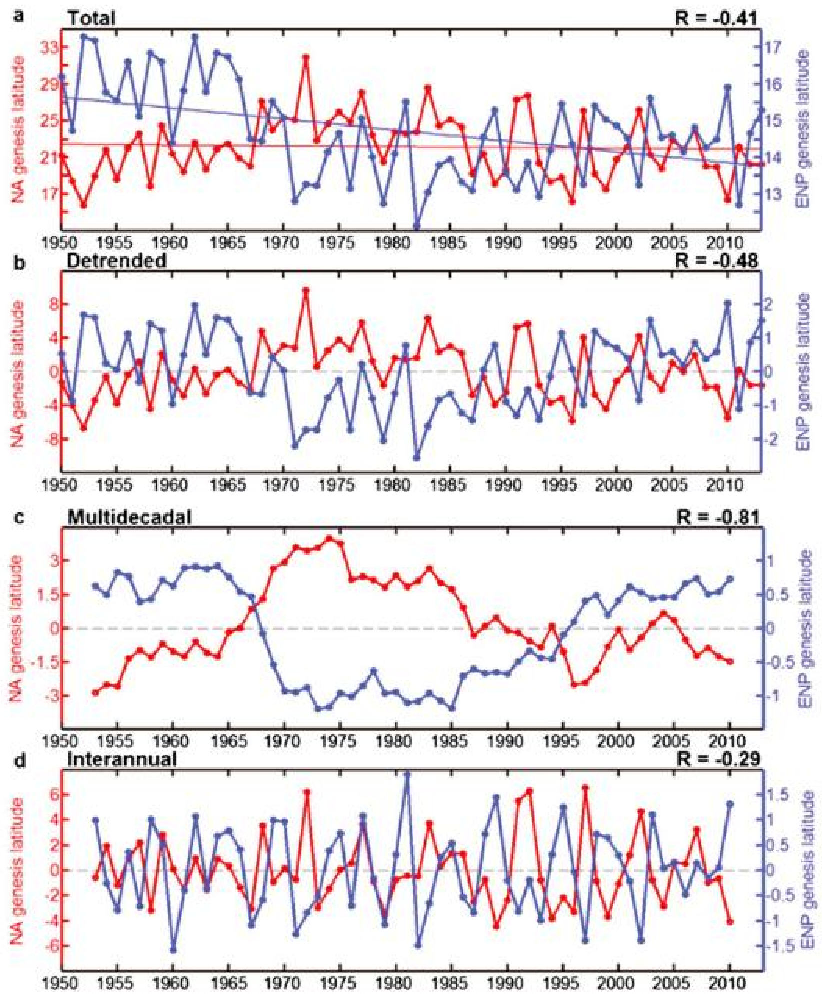
TC activity in the NA varies **out-of-phase** with that in the ENP on both **interannual and multidecadal** timescales. Both **vertical wind shear** and **convective instability** contribute to the out-of-phase relationship. A combination of a **La Niña** (El Niño) year, a **warm** (cold) year in the tropical NA, and a **warm** (cold) phase of the **AMO** will greatly increase the probability of an **active** (inactive) hurricane season in the **NA** and an **inactive** (active) season in the **ENP**. (Wang and Lee, 2009).

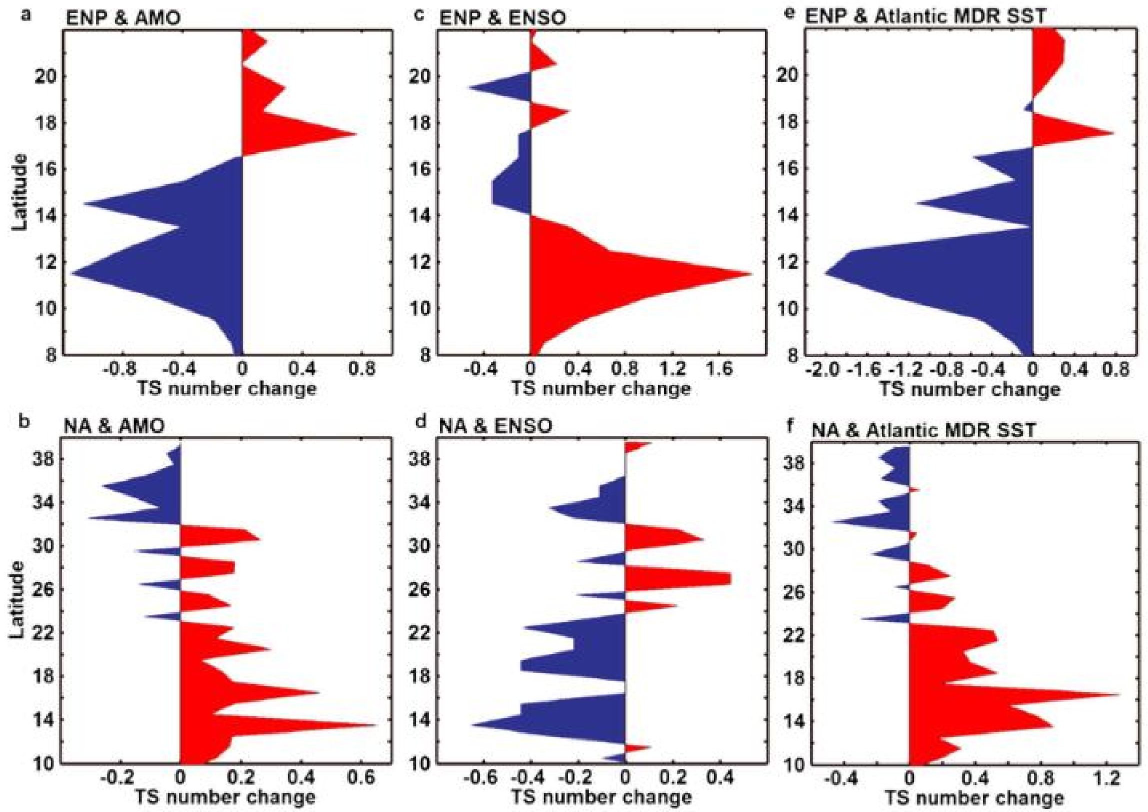




(From Wang and Lee, 2009)

On both interannual and multidecadal time scales, a **northward** (southward) shift of the **TS genesis location** in one ocean basin is associated with a **southward** (northward) variation in the other ocean basin. The change of **cross-Central America wind** in the upper troposphere, which induces an **out-of-phase** variation of vertical wind shear, bridges storm activity in the two ocean basins. **SSTs** in both the **tropical Pacific** and **North Atlantic** are responsible for the zonal wind change across Central American (Wang et al., 2016).





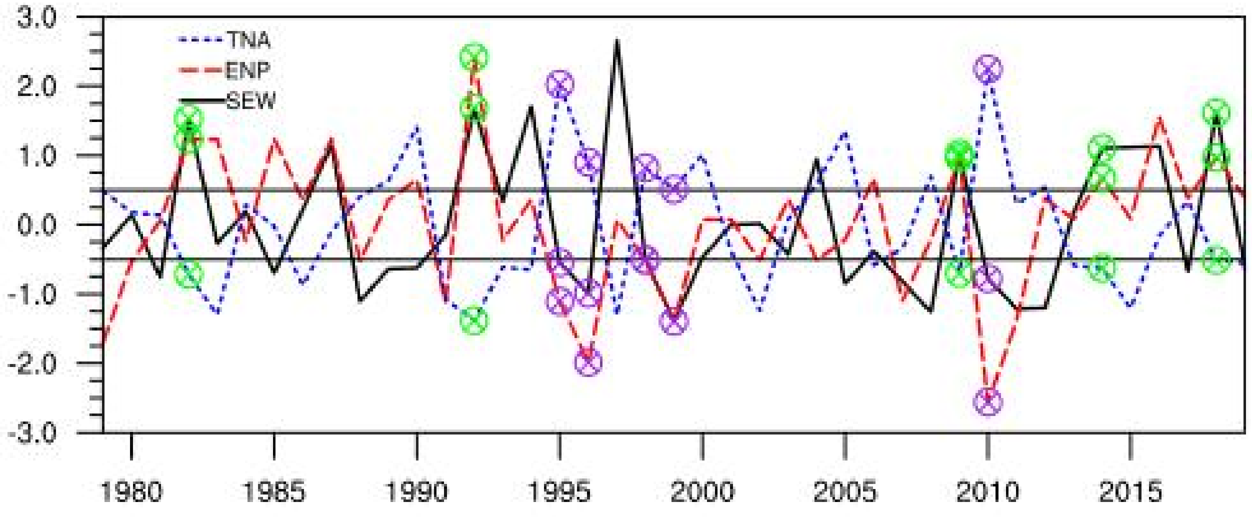
(From Wang et al., 2016)

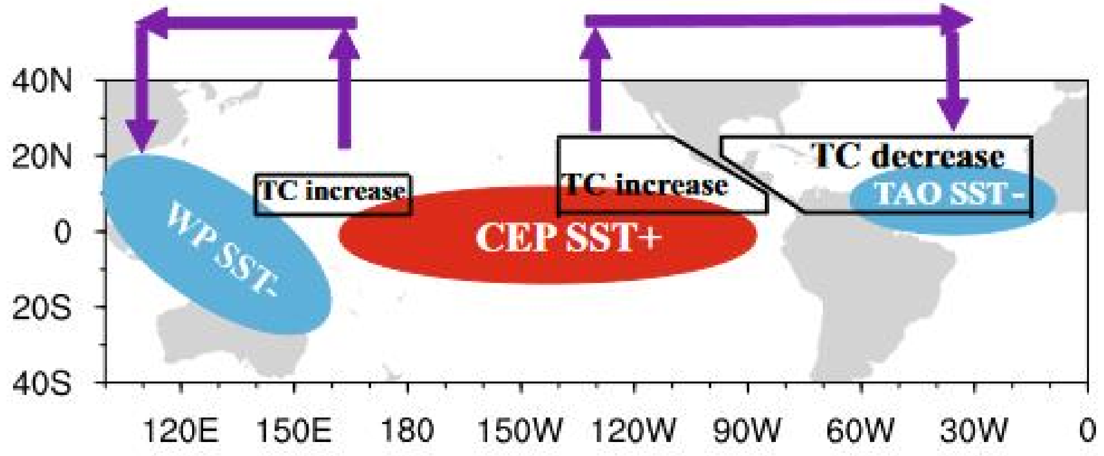
➢ East North Pacific (ENP), Western North Pacific (WNP) and tropical North Atlantic (TNA)

When there are **more** TCs generated over the **southeastern part of the WNP** (SEW), TC geneses are **more** than normal over the **ENP**, but **less** than normal over the **TNA**.

The zonal tripole SST anomalies provide favorable environmental field anomalies for TC genesis over the **SEW** (**positive absolute vorticity, relative humidity and weakened vertical wind shear**) and **ENP** (**weakened vertical wind shear**) , but unfavorable environmental field anomalies over the **TNA** (**enhanced vertical wind shear**).

JASO



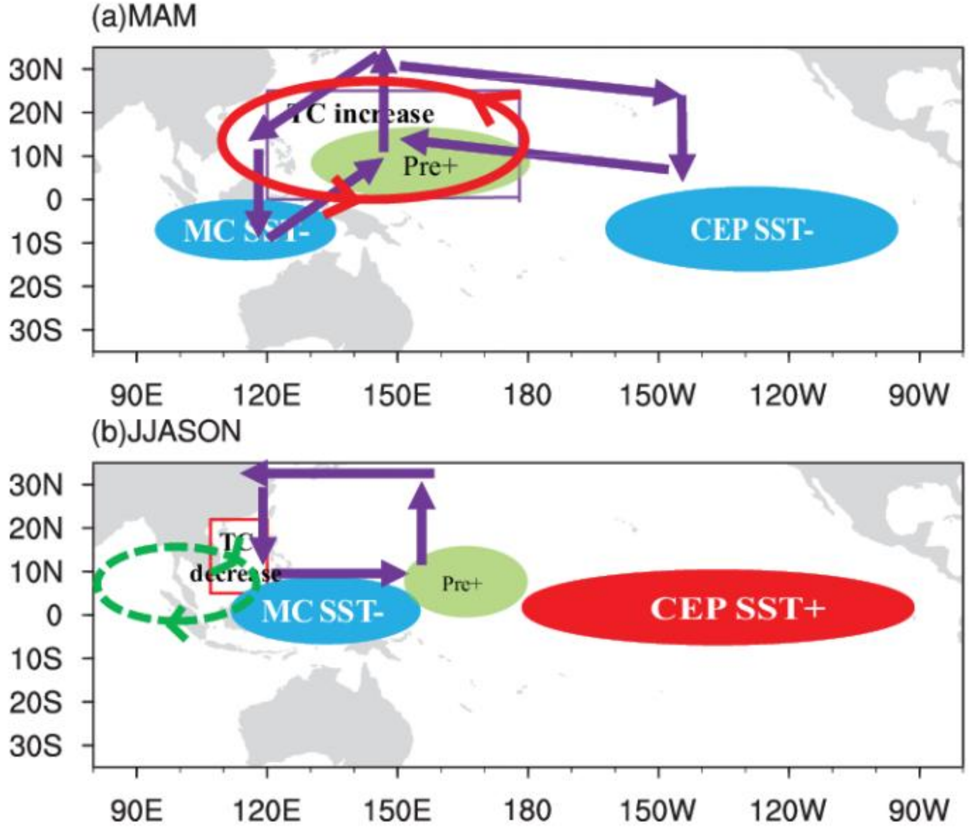


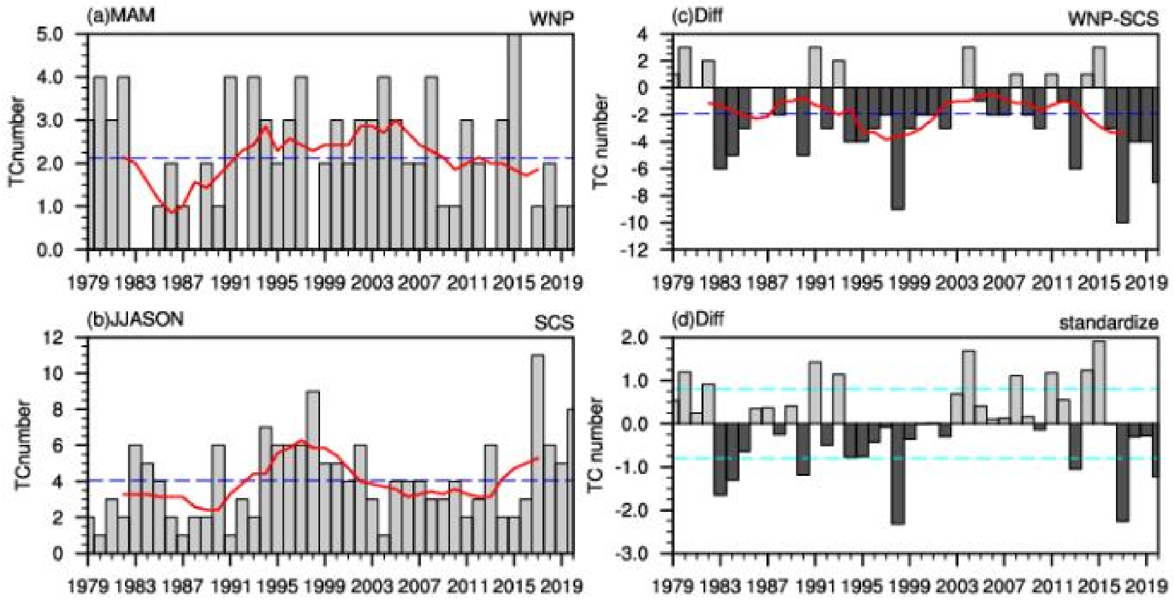
(From Cao et al., 2021)

➢ The Western North Pacifc (WNP) TCs and South China Sea (SCS) TCs

More Spring (MAM) TC genesis over the **WNP** are followed by **less** TC genesis over the **SCS** succeeding summer-autumn **(JJASON)**.

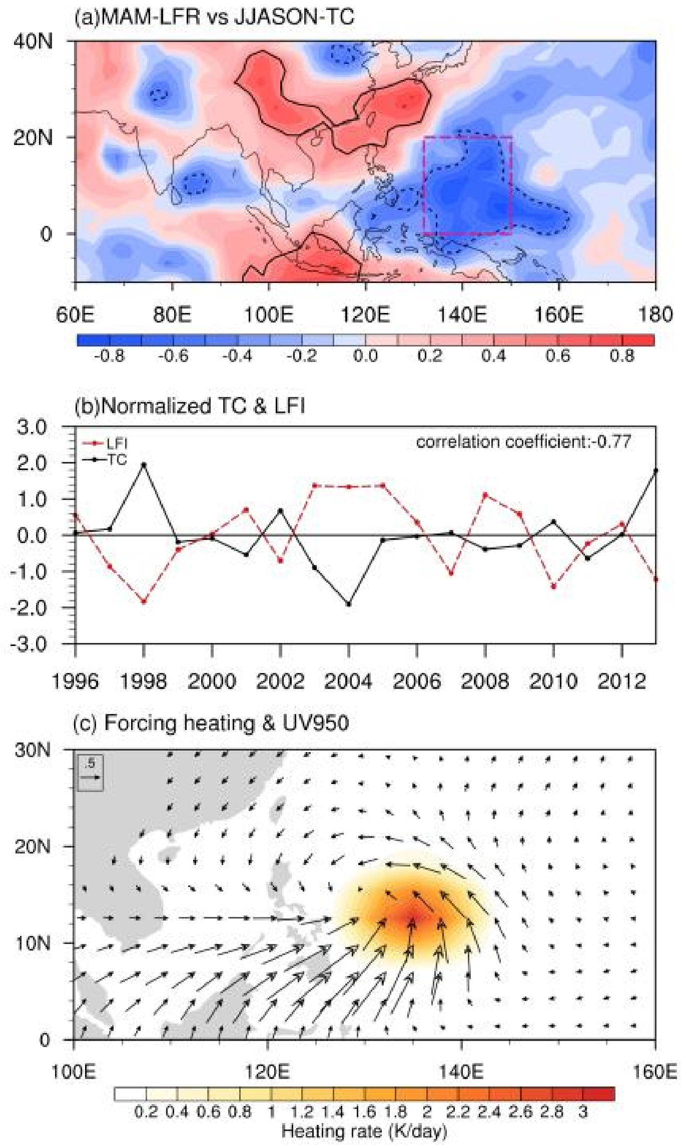
Negative sea surface temperature (SST) anomalies during MAM in the tropical central–eastern Pacific (CEP) and southeastern Indian Ocean (including Maritime Continent, MC) work together to produce this out-of-phase variation (Cao et al., 2022).





(From Cao et al., 2022)

the spring total lightning flash rate east of Philippines may serve as a precursor of the SCS TC genesis



an increase of lightning-represented convection east of the Philippines in MAM

↓

anomalous heating east of Philippines

↓

westerly and northerly anomalies over the SCS and east of China via a Gill-type response

↓

an increase of convection over the SCS

↓

negative SST anomalies persisting from MAM to JJASON in the SCS due to the decrease of shortwave radiation

↓

suppressed convection and reduced specific humidity over the SCS

↓

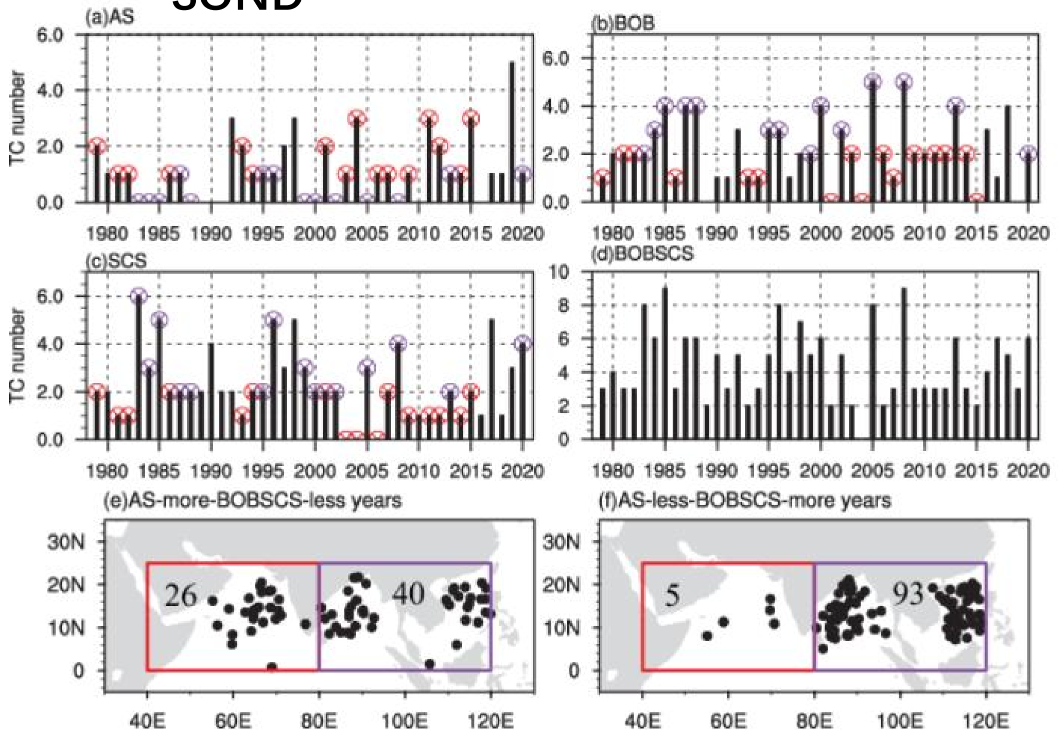
an decrease of TC genesis over the SCS in JJASON

(From Xu et al., 2022)

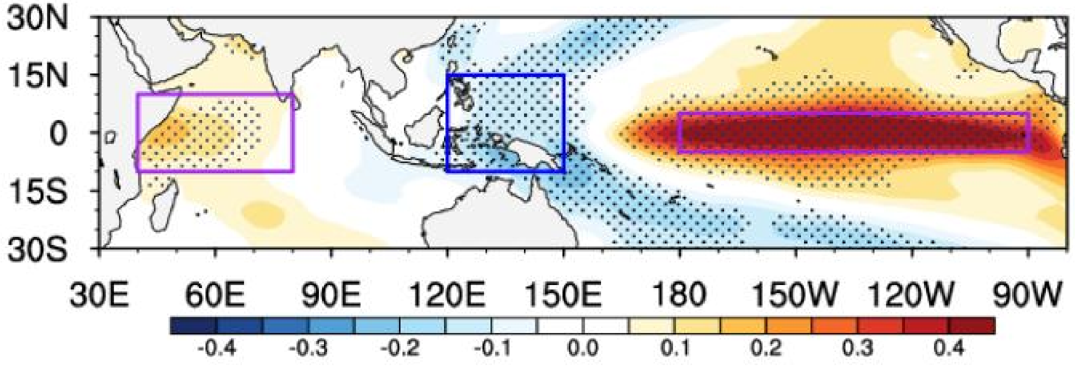
- **A significant correlation exists between the South China Sea TC genesis with total lightning flash rate east of Philippines.**
- **The connection is through a westward Rossby wave response and air-sea interaction.**
- **Lightning may serve as a predictor in the seasonal forecasts of TC genesis.**

➢ Arabian Sea (AS) TCs and Bay of Bengal-South China Sea (BOBSCS) TCs

SOND



SOND

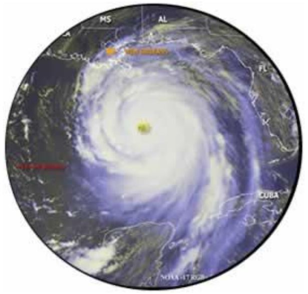


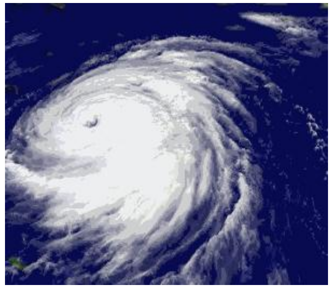
(From Cao et al., 2023)

More TCs over the AS tend to concur with **fewer** TCs over the BOBSCS.

The zonal tripole distribution of SST anomalies attribute to this zonal see-saw relation by influencing the **vertical-zonal overturning circulation and TC genesis-related background** conditions over the **AS (upward motion, mid-level humidity increase, and low vertical wind shear)** and **BOBSCS (downward motion, mid-level water vapor decrease and lower-level anticyclonic vorticity anomalies)** (Cao et al., 2023).

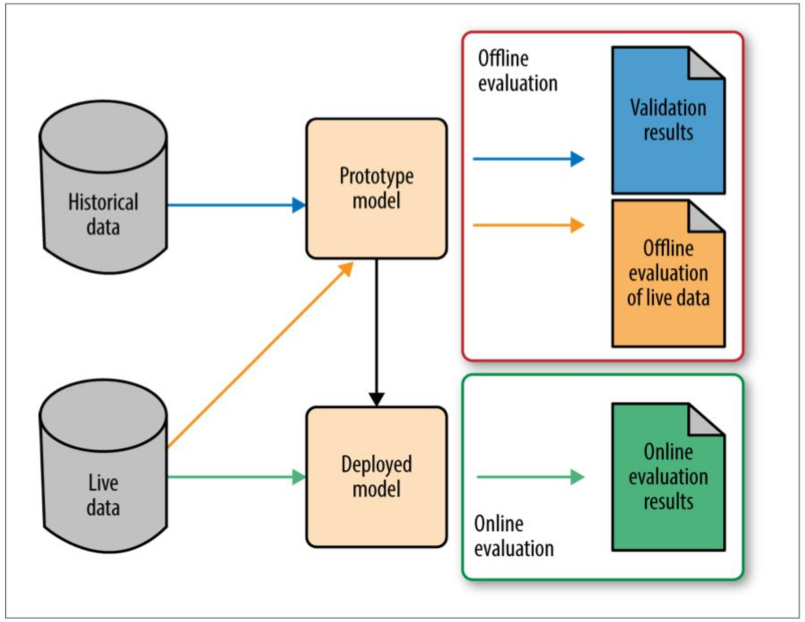
5. Recent development and application of Machine Learning to the seasonal tropical cyclone forecasts

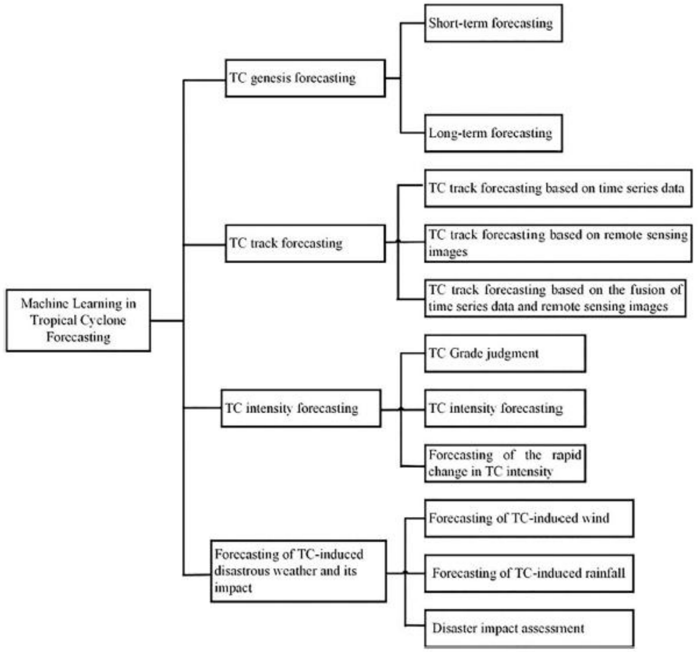




Application of Machine Learning to the seasonal tropical cyclone forecasting

- In the last decade, the use of Machine Learning (ML) and Artificial Intelligence (AI) algorithms has shown huge potential for a wide range of applications. These techniques have emerged also in climate, meteorological and oceanographic fields (among others) with convincing results.
- The **key concept behind ML is to provide data to machines and let them infer rules from it.**
- a user will define the algorithms, **a potential target (e.g., the number of TCs in a given basin),** and a scoring method (minimising a particular type of error). Then, during the training phase, the machine will automatically adjust the different degrees of freedom in the model and optimise the skill. Then the algorithm can





(From Wang et al., 2022)

Machine Learning (ML) can strongly benefit two key aspects of TC seasonal forecasting:

(1) constructing statistical models for useful parameters (number of TCs, major TCs (Category 3-4-5 on the Saffir-Simpson scale), ACE, etc.);

(2) mining databases to extract physical patterns that can be used in statistical models.

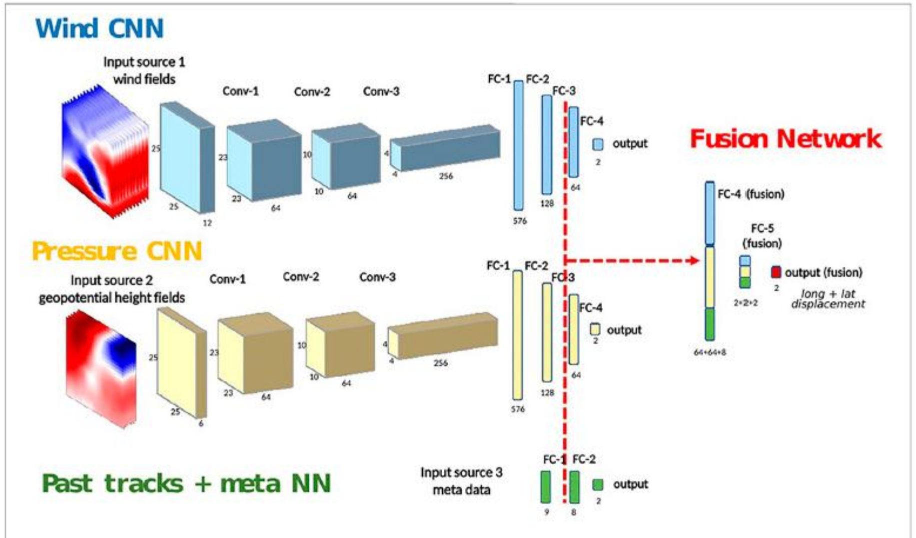


FIGURE 3 | General architecture: a neural network model fusing past trajectory data and reanalysis atmospheric images (Giffard-Roisin et al., 2020).

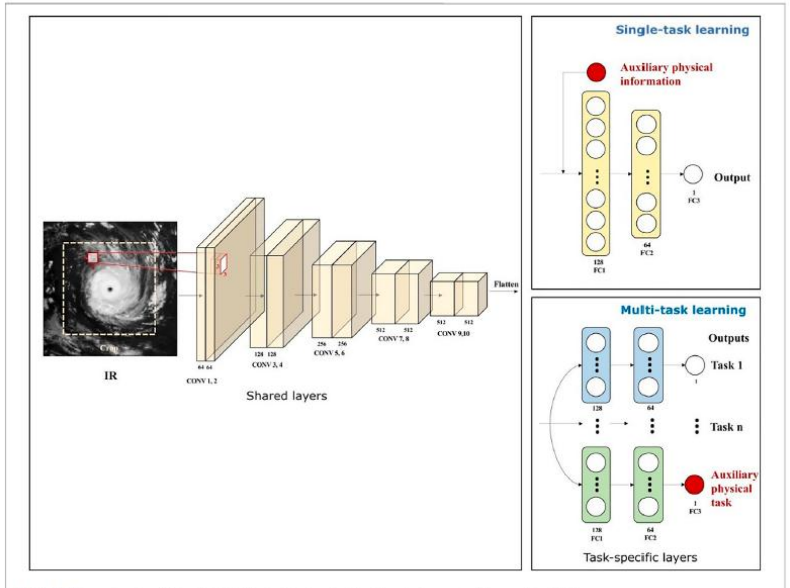


FIGURE 4 | The configuration of DeepTCNet in both single-task and multitask learning frameworks (Zhou and Tan, 2021).

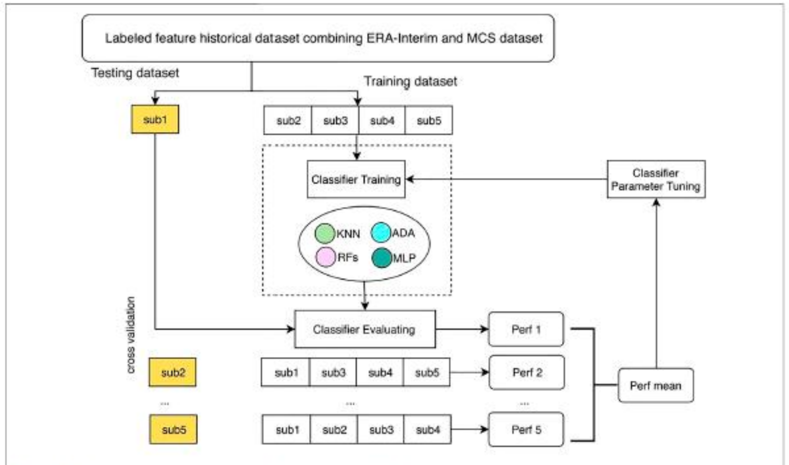
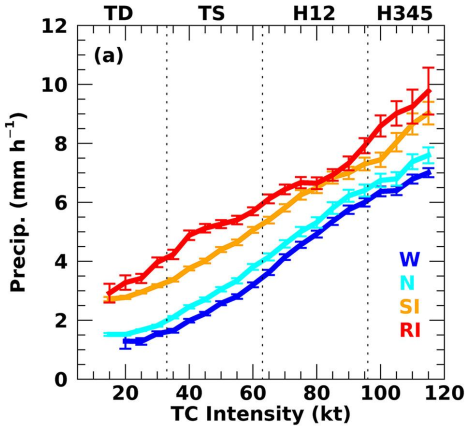
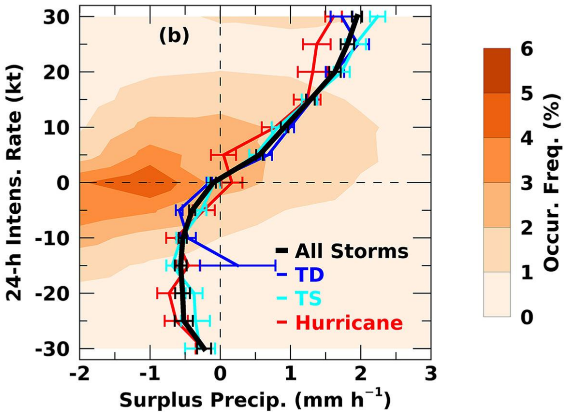


FIGURE 2 | Flow diagram of TC genesis prediction by using machine learning (Zhang et al., 2019).



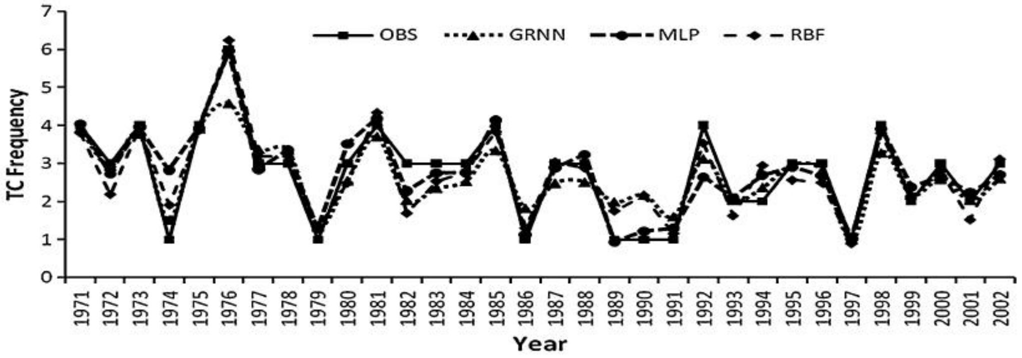


(From Wang et al., 2021;Su et al., 2020)

Predictive models of seasonal TC activity

ML can advance and improve statistical forecasting approaches

- Nath et al. (2016) used different types of neural networks combined with large-scale climate variables to predict seasonal TC activity over the North IO (NIO).
- Richman et al. (2017) used support vector regression (SVR) to predict the number of seasonal TCs in the NA, leading to 40% improvement compared to multiple linear regression.
- Sun et al. (2021) used ML to select and weight top performing ensemble members for basinwide NA activity prediction.



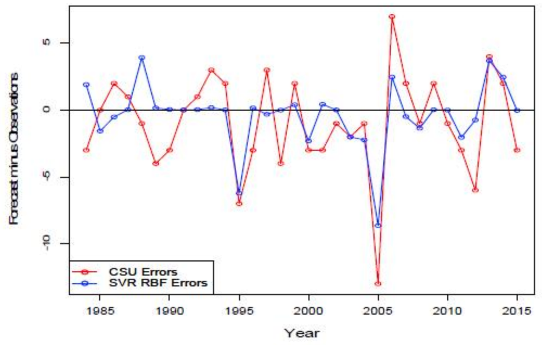
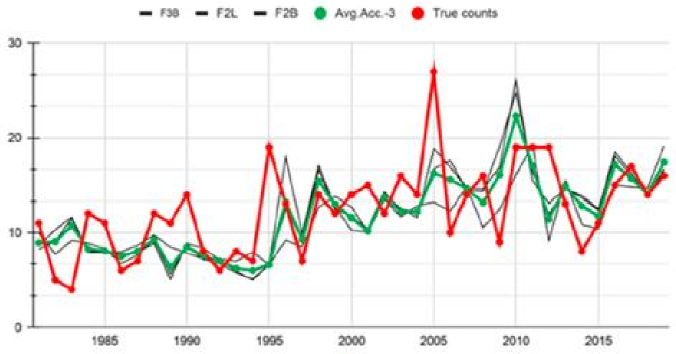
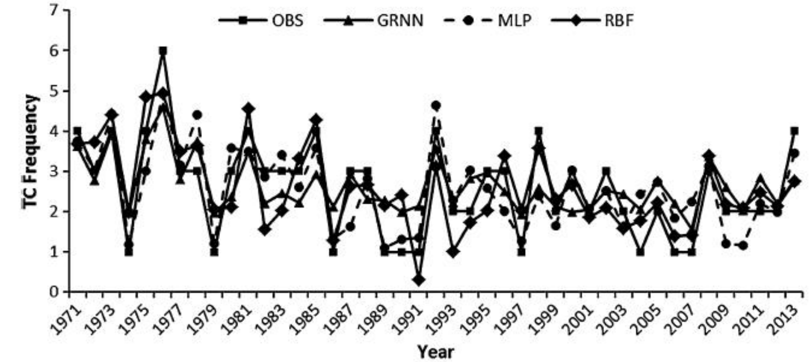
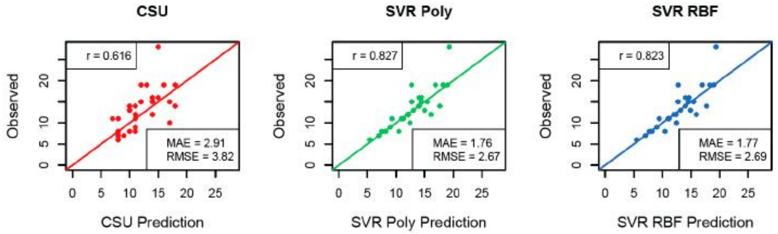


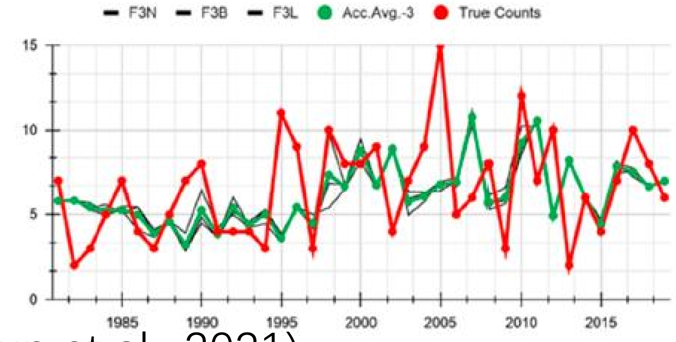
Fig. 6. Time series of CSU TC predictions versus SVR RBF predictions for the same years.



(a)







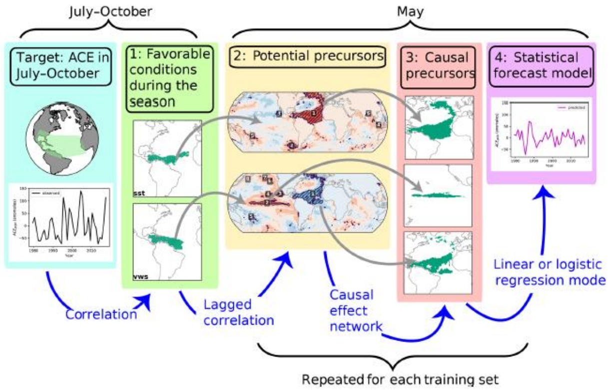
(b)

(From Nath et al., 2016; Richman et al., 2017; Sun et al., 2021)

Predictors mining and patterns extraction

For extracting key modes of variability driving TC activity, ML can play a key role in mining the large amount of observed data and modelled ensemble data collected and generated over the past decades. These physical climatic patterns can then be directly used in predictive models.

- **Pfleiderer et al. (2020) used a causal effect network approach to identify skillful spring predictors of seasonal Atlantic hurricane.**
- **Asthana et al. (2021) developed a Fused Convolutional Neural Network forced by climatic fields (SLP, SST, among others) that achieved a prediction skill similar to that of other statistical models for ACE in the NA, but at longer lead times.**
- **Machine learning offers a new way to extract potential climate patterns driving TC activity around the world and could be particularly useful for basins that have been previously less studied. ML could also help in predicting potential correlations between basins. Recent reviews by Chen et al. (2020) and Wang et al. (2022) further illustrate this growth in the use of ML for short- to long-term TC forecasting.**



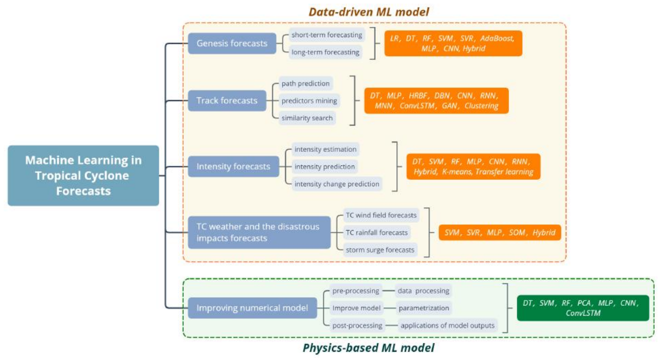


TABLE 3 | Machine learning in TC intensity forecasting.

Tasks	Algorithms	References
TC grade judgment	multiple logistic regression, support vector machine and back-propagation neural network	Chen et al. (2018)
	convolutional neural networks-DeepMicroNet	Wimmers et al. (2019)
	Two-dimensional and three-dimensional convolutional neural networks	Lee et al. (2019)
	multi-layer deep convolutional neural network	Pradhan et al. (2018); Cui et al. (2020)
TC intensity forecasting	back-propagation neural network	Baik and Paek (2000)
	partial least squares regression	Zhou (2014)
	support vector machine and genetic algorithm	Gu et al. (2011)
	decision tree	Gao et al. (2016)
	logistic regression and bayesian network	Rozoff and Kossin (2011)
	deep convolutional neural network	Pradhan et al. (2018)
	ResNet deep learning	Qian et al. (2021)
	convolutional neural network-long short-term memory network	Chen et al. (2019b)
	deep neural network-long short-term memory network	Zahera et al. (2019)
	shallow learning and DL algorithms	Jiang et al. (2018)
	DL convolutional neural network- DeepMicroNet	Wimmers et al. (2019)
	DL-based method augmented- DeepTCNet	Zhou and Tan (2021)
Forecasting of the rapid change in TC intensity	C4.5	Zhang et al. (2013)
	recurrent neural network	Chandra and Dayal (2015)
	support vector machine	Mercer and Grimes (2015)
	decision tree	Gao et al. (2016)

(From Pfleiderer et al., 2020; Chen et al., 2020; Wang et al., 2022)

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Thank you !