A Dynamical Framework to Understand and Predict the Indian Summer Monsoon Low Pressure Systems

EGU 2023 General Assembly

AS1.13 — EGU23-4126

Supplementary Material

K. S. S. Sai Srujan[1], Sandeep Sukumaran[1,2], and Hariprasad Kodamana[2,3]

[1]Centre for Atmospheric Sciences, Indian Institute of Technology Delhi, New Delhi, 110016
[2]Yardi School of Artificial Engineering, Indian Institute of Technology Delhi, New Delhi, 110016
[3]Department of Chemical Engineering, Indian Institute of Technology Delhi, New Delhi, 110016

This presentation participates in OSPP

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April 26, 2023

Monsoon Low-Pressure Systems?

- Monsoon Low Pressure Systems (LPS) are synoptic-scale (~1000kms in diameter and lifespan of 3-7days) cyclonic vortices which are embedded in the large scale Indian summer monsoon (ISM) circulation which produces ~60% of the ISM rainfall (between June-Sept.) (Krishnamurthy and Ajayamohan, 2010; Praveen et al., 2015; Hunt et al., 2016). The genesis mechanisms of monsoon LPS are not fully understood, despite being an important component of the hydrological cycle over India.

- Although synoptic-scale vortices form over all monsoonal regions, these are more prominent over Indian region with an average of (12±2) systems per season (Hurley and Boos, 2015).

- LPS propagate North-Northwestward across the continental India. LPS can originate over Northern Indian Ocean (NIO), but more than 90% of the systems genesis over the Northern Bay of Bengal (BoB) making as a core region of LPS.

- LPS brings copious amount of rain and also distributes ISM rainfall into the interior parts of India.

Low pressure area --> depression --> deep depression --> cyclonic storms(>=34 knots) --> severe cyclonic storms --> very severe cyclonic storms --> Extremely severe cyclonic storms --> super cyclonic storms

Downstream amplification?

The formation mechanisms of LPS are categorised into two types

- **In situ** - Due to the local conditions or mechanisms over BoB.
- **Downstream Amplification** - Due to some westward propagating disturbance from Pacific ocean. It's downstream because mean tropospheric wind direction is East to West.

- Earlier studies believed that LPS would form only due to the local processes and also, the satellite images did not show any westward propagating cloud bands from the west confirms this notion of in situ.
- But in 1970's, Krishnamurthi et al. (1977) observed the downstream amplification from the hovmöller diagram of winds and observed a low-high-low surface pressure pattern from West Pacific (WP) to BoB in a 21-day window centered on a date when high pressure forms over Indochina.

Clustering of WNP TCs:

- A clustering analysis of the WNP TCs is being carried out as suggested by Camargo et al. (2007), using the a mixture regression model that fits the geographical trajectories tracks. Expectation-Maximization algorithm is used for optimisation.

- As our focus is on monsoon LPS, we consider the summer monsoon season (June – September) for the TC clustering analysis. TCs only above the intensity of cyclonic storms considered from 1979-2017 from JTWC.

- Mixture model is a soft clustering technique which assigns the probabilities to each data point rather than the hard clustering (which assigns into a specific cluster like K-means)

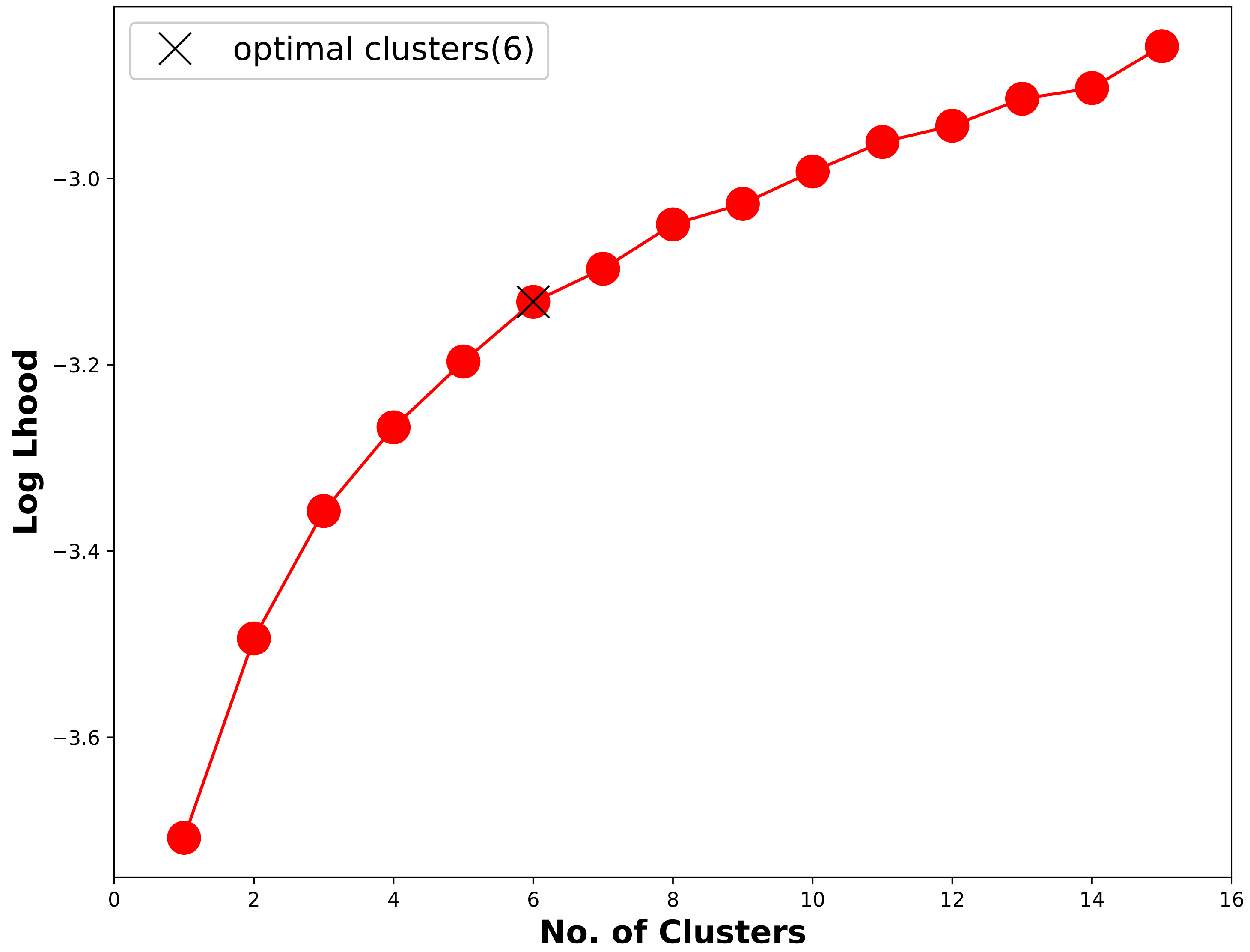
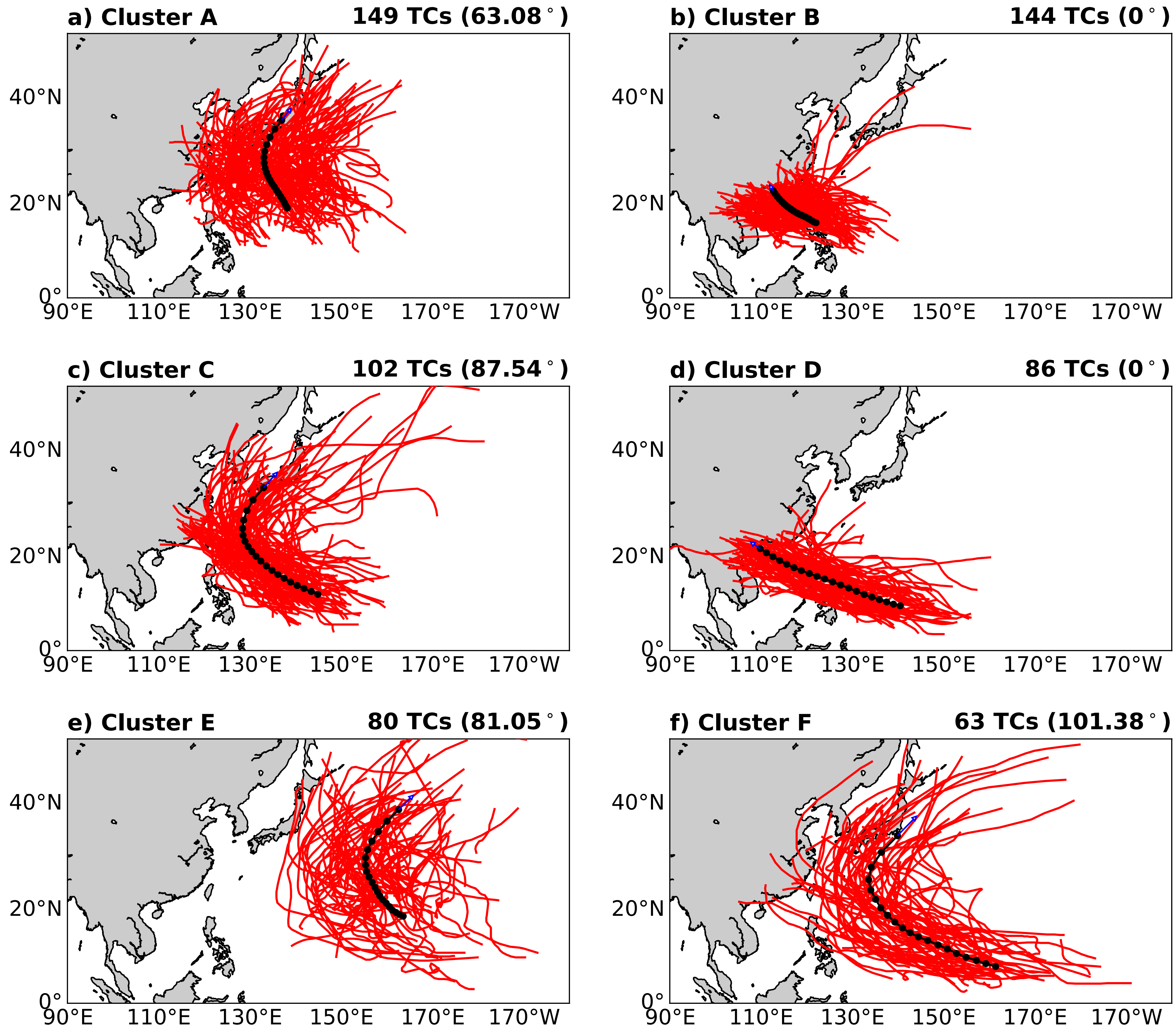


Fig. 1 The log-likelihood values for the different number of clusters (1-15 clusters). The log-likelihood values shown are the maximum of 20 runs, obtained by a random permutation of the 70% tropical cyclones given to the cluster model.

If the difference between the log- likelihood of 2 subsequent clusters is less than 0.05 then that is considered as termination.

Clustering of WNP TCs:

Fig. 2 The tracks of TCs over WNP from 1979-2017 during JJAS divided into six clusters from A-F with the mean track(Black line) of TCs interpolated to a length of 5 days in each cluster. The number of TCs in each cluster is indicated on top right side of the panels. The blue arrows in the mean track indicates the direction of the track. The values in brackets in each subplot title represents the angle of recurvature (in degrees) of mean TC track of each cluster.



Transfer Entropy:

- Transfer Entropy (TE), which is a measure to quantify the information transferred from the one variable to the another variable (Schreiber, 2000; Kaiser and Schreiber, 2002; Lizier et al., 2008).
- The TE is very useful tool in establishing the causality between the non-linear systems (Hlava ´˘ckov´a-Schindler et al., 2007).
- The TE is calculated from the PC1 of Rossby-filtered OLR anomaly over 100°E-180°E, EQ-20°N (box2) and the SLP over 90°E - 120°E, 15°N-25°N (box1).

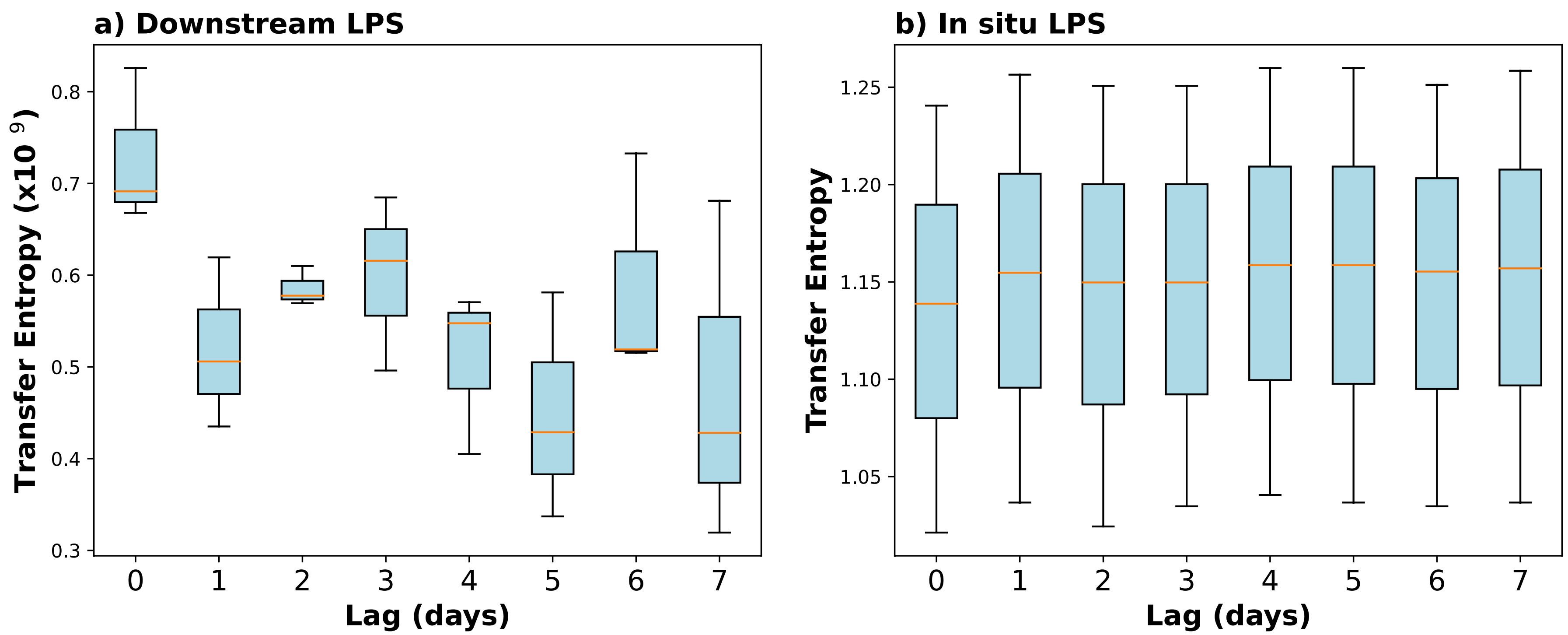


Fig. 3 TE between PC1 of Rossby filtered OLR anomaly and MSLP over BoB computed for a) downstream and b) in situ. Lag-0 indicates that both the time series have the same start and end dates and with increasing lags, the PC1 time series is shifted ahead of a fixed MSLP time series. At each lag, the TE is computed three times by varying the length of the time series

- To examine the existence of any predictive relationship between PC1 and MSLP, the TE is calculated for time lags ranging from zero to seven days by sliding the PC1 time series. The TE computations are repeated three times for each lag by increasing the length of the time series by one day for each calculation. For instance, at lag-0, the TE is computed initially by taking PC1 and MSLP time series from t-3 to t+2 days, where t-0 is the date of initiation of a downstream LPS. This calculation is then repeated two more time by changing the start date to t-4 and t-5, respectively.

Mean Rossby variance of OLR:

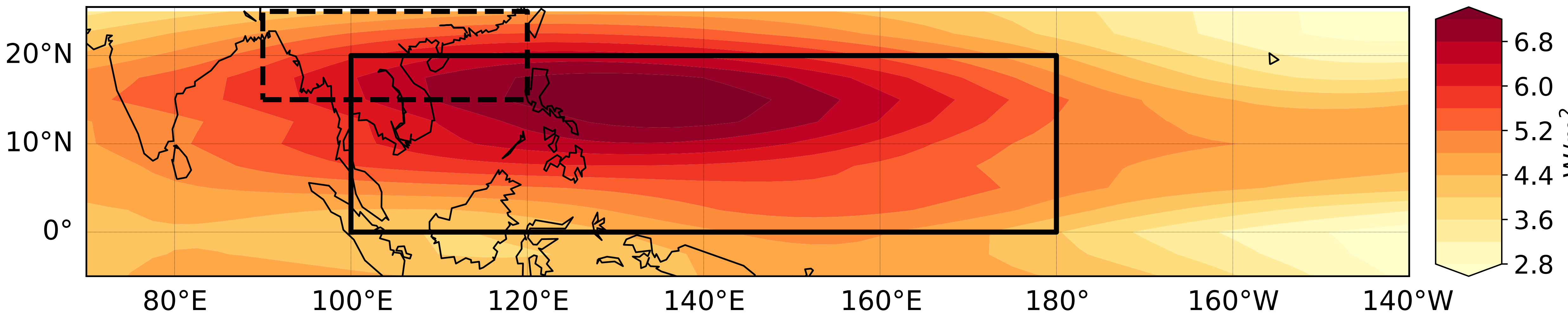


Fig 4 Mean Rossby variance of outgoing longwave radiation for JJAS during 1979 - 2017. The solid (dashed) box is the box2 (box1) respectively for which TE is computed.

For more information of the work, please checkout

Srujan, K. S. S. S., Sandeep, S., Suhas, E., & Kodamana, H. (2022). A dynamical linkage between Western North Pacific tropical cyclones and Indian monsoon low-pressure systems. *Geophysical Research Letters*, 49, e2022GL098597. https://doi.org/10.1029/2022GL098597

WK diagram for OLR:

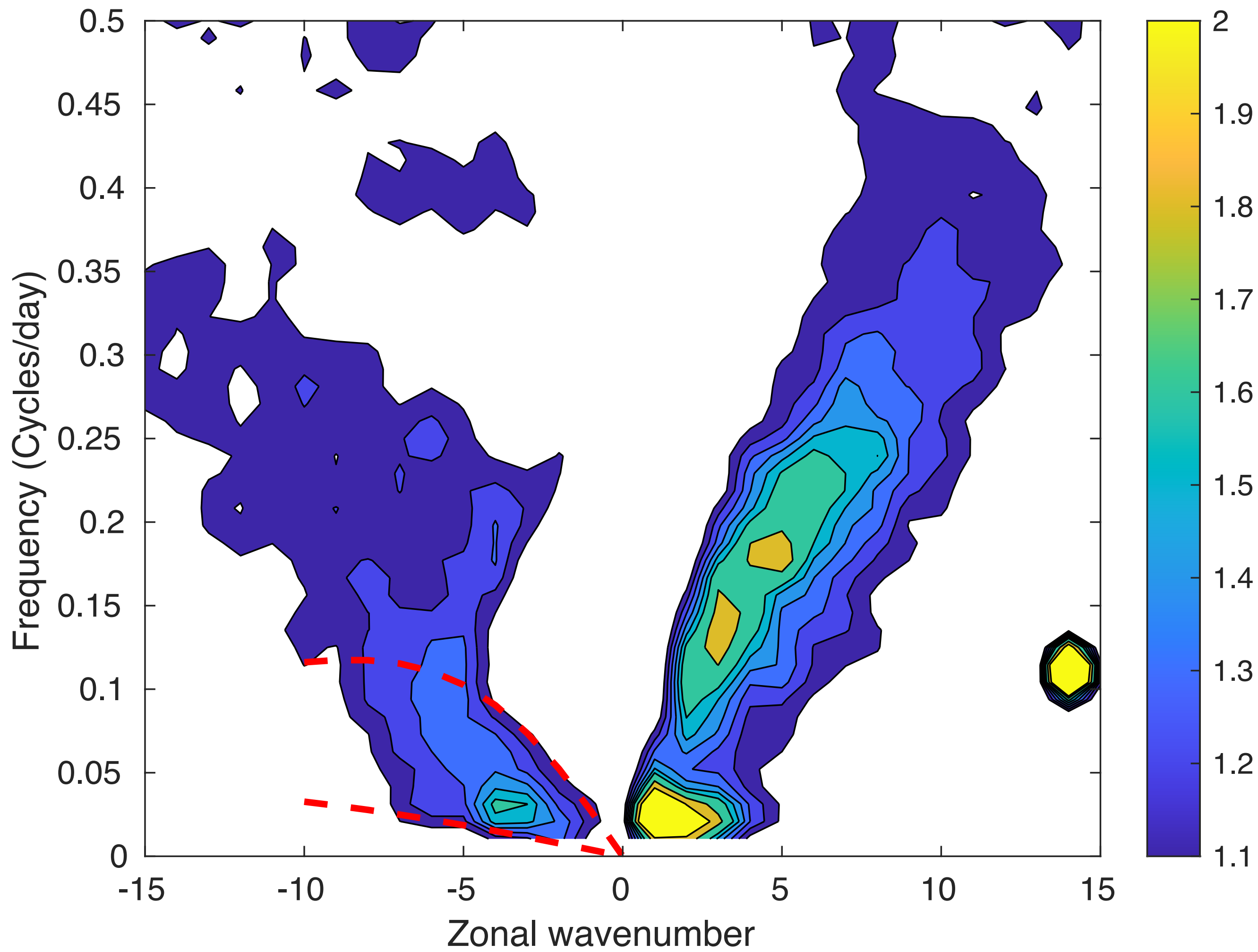


Fig. 5 The Wheeler Kiladis symmetric/background wavenumber-frequency spectra of daily outgoing longwave radiation anomaly from 1979 to 2017 (June-September). Red lines represent theoretical dispersion for n=1 Rossby waves for an equivalent depth equal to 10 m and 100 m, respectively.

Cluster wise distribution:

In order to understand the association between the downstream LPS genesis and the TCs in each cluster, we estimate the monthly number of LPS genesis within one to ten days of a TC genesis in each cluster (Fig. 5). The reason for choosing a 10-day window is because earlier studies suggested an average of 12 systems forming per June - September season, which translates into one storm genesis in 10 days (Hurley & Boos, 2015)

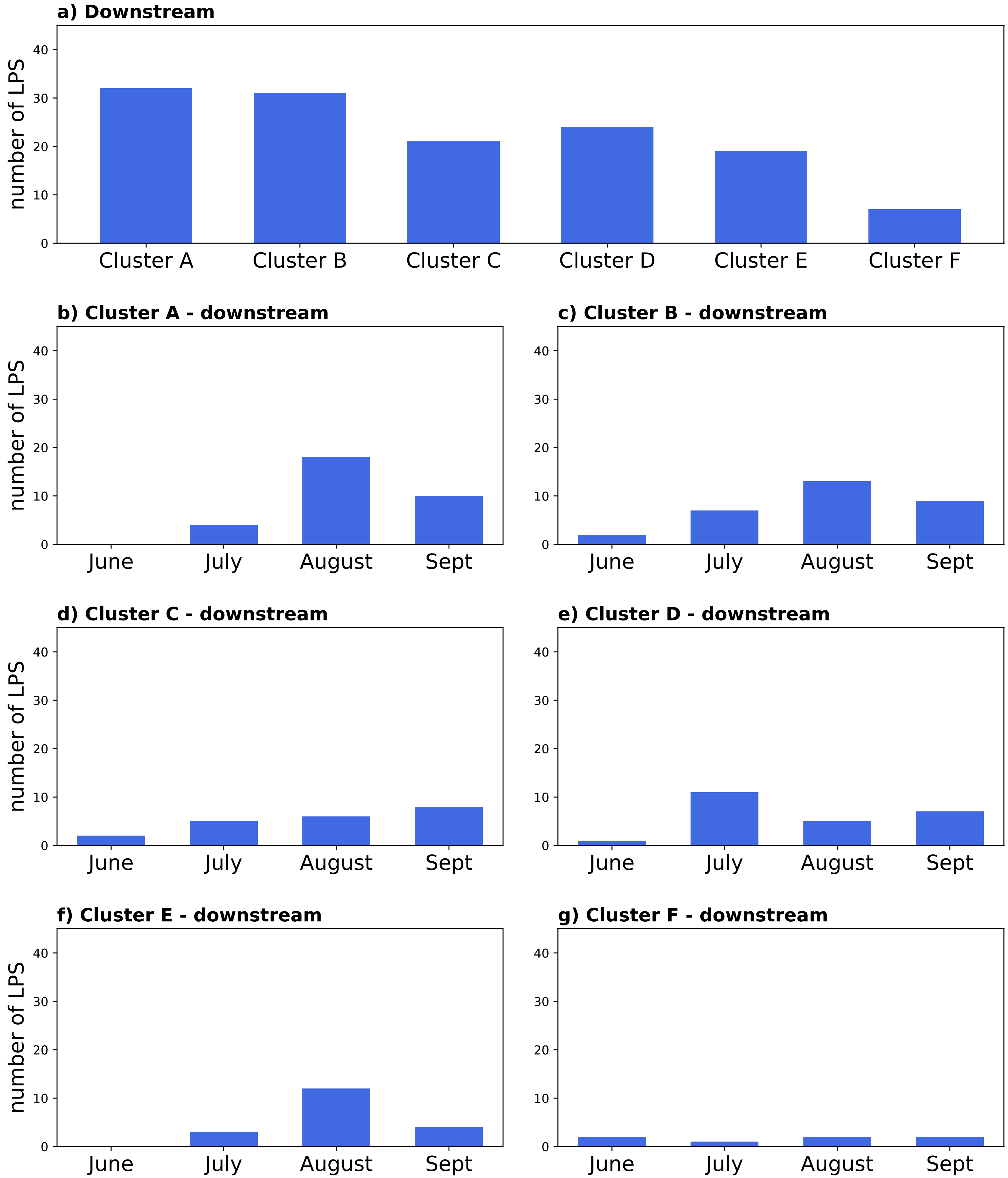


Fig. 6 a) The number of downstream LPSs associated with each TC cluster in the 10-day window prior to the initiation of the LPS. (b-g) monthly distribution of LPSs for each TC cluster

Monthly distribution of LPS:

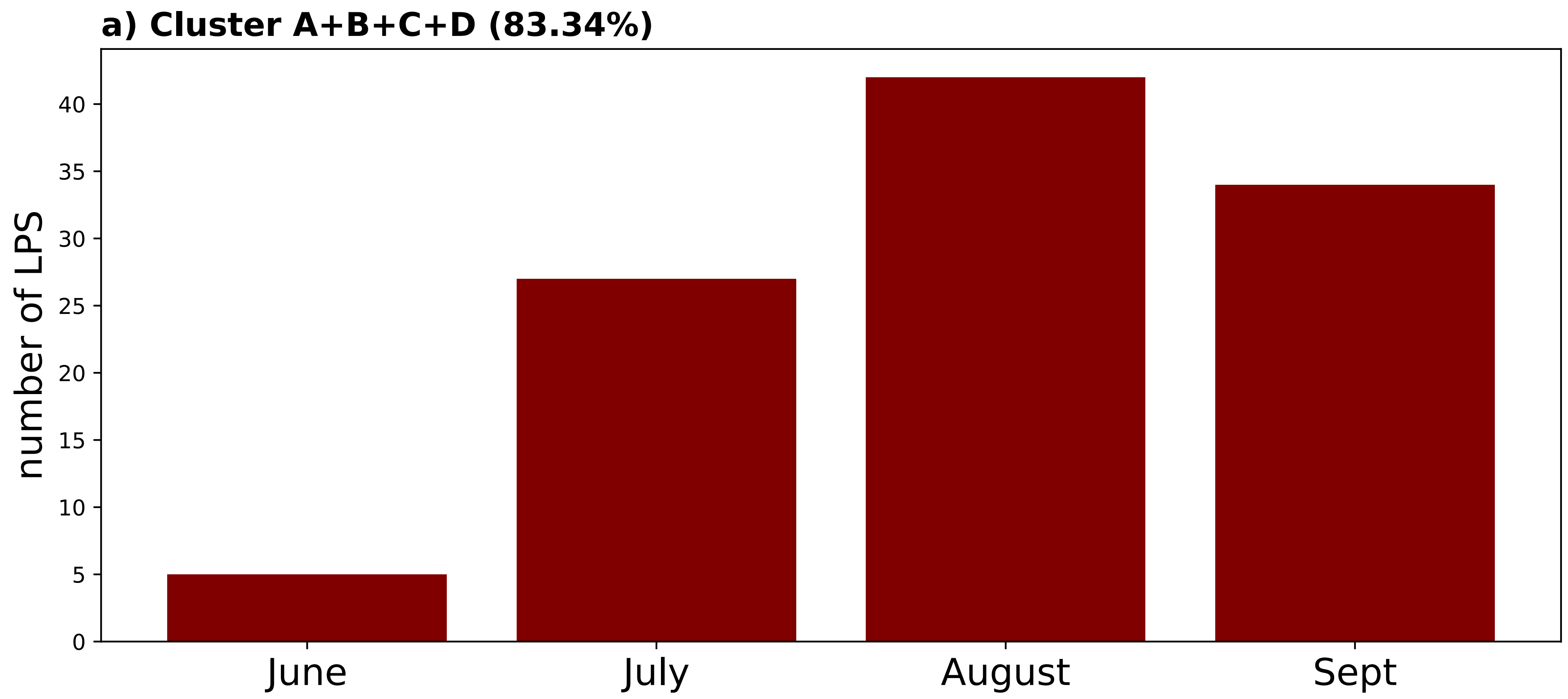


Fig. 7 Sum of monthly distribution of LPSs in clusters A,B,C, and D. The number of unique LPS in these four clusters are account to 83.34%. This analysis is done for June – September period during 1979 – 2017.

We aim to test this observed hypothesis of the remote influence of WNP on genesis of LPS over BoB

Clustering of LPS and TCs:

- **Three experiments have been conducted including a control run in Community Atmospheric Model (CAM5) by modifying SST over the Pacific.**
- **In the experiment 2, the SST over the region of TC genesis density over the West to central Pacific (From clusters A to D) has been raised; designated as Expt. CAD.**
- **In the experiment 3, the SST over the region of TC genesis density over the West Pacific (West of 120E, cluster B alone) has been raised; designated as Expt. CB.**
- **CAM5 is simulated for 5 years and three ensembles in each experiment are considered, therefore commutative of 15 annual cycles.**

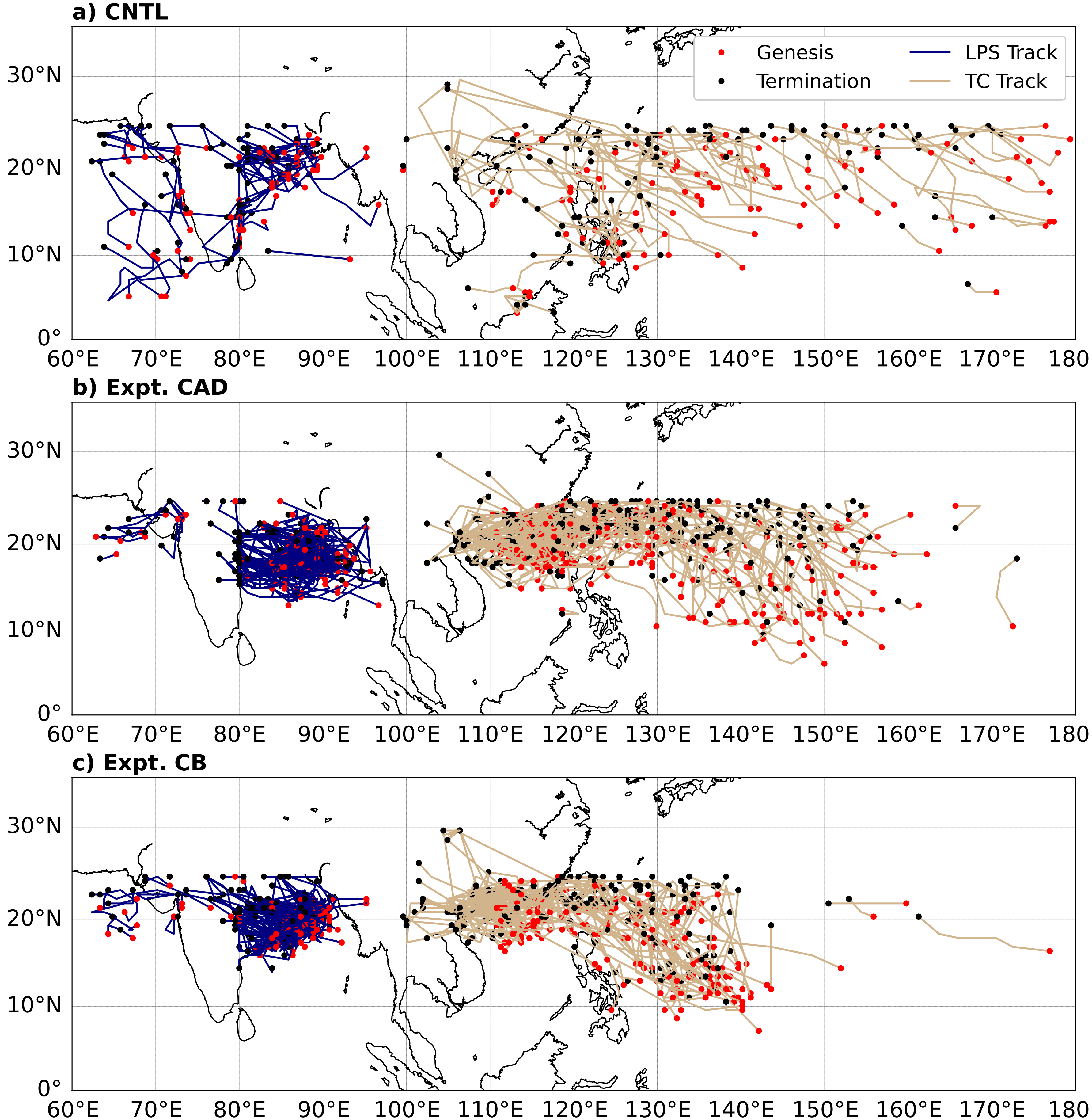


Fig. 8 The tracks of low-pressure systems (LPS) and tropical cyclones (TC) simulated in a) Control run (CNTL), b) Experiment CAD (Expt. CAD), and c) Experiment CB (Expt. CB). The blue and orange lines are the tracks of LPS and TC, respectively. The red and black points indicate the genesis and lysis of the storm, respectively.

Sea level pressure anomaly composite:

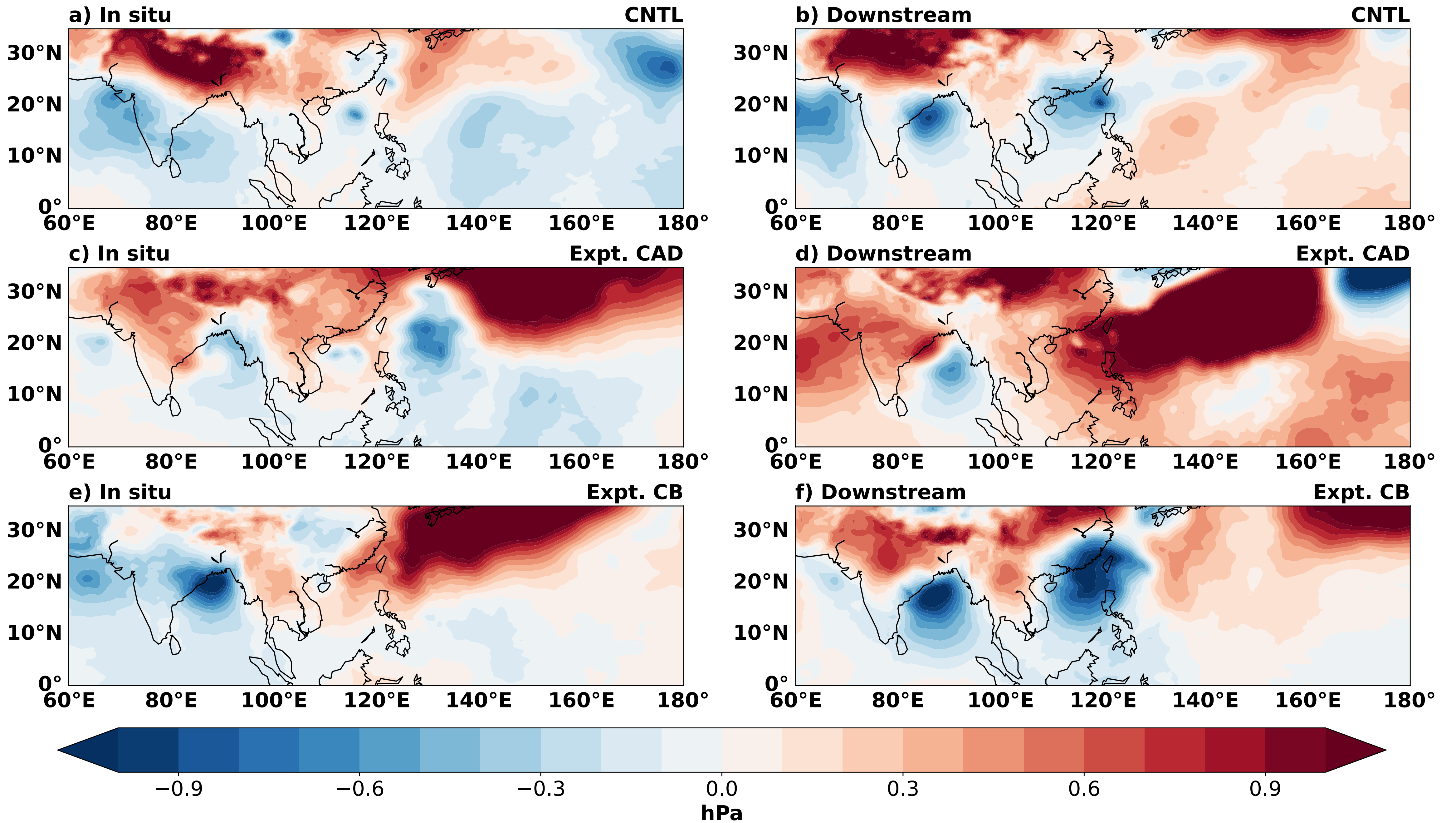


Fig. 9 The composite of mean sea level pressure anomaly (units: hPa) during the **1 lead day of genesis (t+1 day, where t is the date of genesis)** of downstream (right panels) and in situ (left panels) low-pressure systems (LPSs) simulated in (a,b) Control run (CNTL), (c,d) Experiment CAD (Expt. CAD), and (e,f) Experiment CB (Expt. CB) for the 15 simulated years.

Statistics of LPS simulated in sensitivity experiments:

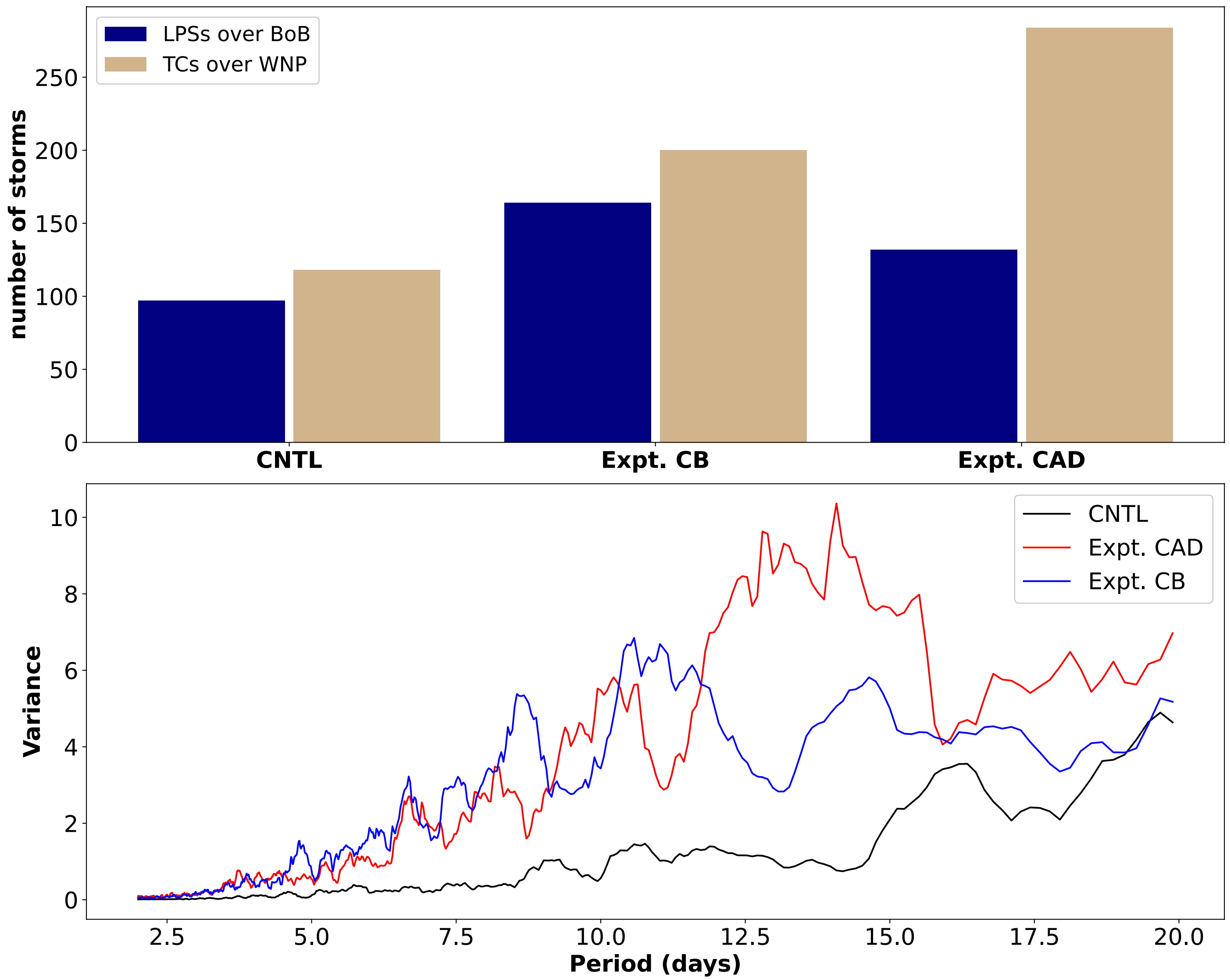


Fig. 10 The statistics of the Low-pressure systems (LPSs) and the tropical cyclones (TCs) as simulated in the control run, experiment CAD, and the experiment CB for 15 years of model-run are shown in the top panel. The power spectra corresponding with the period for the relative vorticity anomaly at 850 hPa (ζ_{850}) for the control run (black solid line), experiment CAD (red solid line, and experiment CB (blue solid line) are shown in the bottom panel. The time series of the ζ_{850} to compute the power spectra is computed by area-average between 15˚N — 25˚N and 110˚E — 130˚E for the 15 simulated years

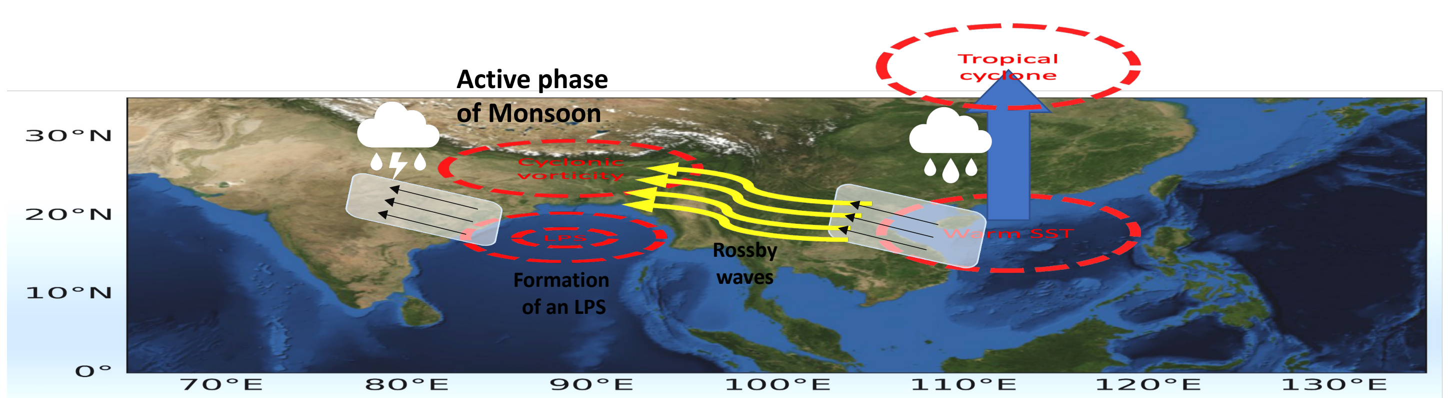


Fig. 11 The schematic of the likelihood of genesis of LPSs triggered by the Tropical cyclones in Western North Pacific. The black arrows indicate the propagation of the storm, and the yellow curved arrows indicate the Rossby waves.

Conclusions:

- The linkage between WNP tropical cyclones TCs and downstream LPS is well known from a long time (Krishnamurthi et al., 1977) but a strong causal relationship is not established.
- We established a causal relation between Rossby waves triggered from WNP TCs and fluctuations in SLP over BoB through a Transfer Entropy.
- WNP TCs are divided into 6 clusters based the genesis locations, trajectories and recurvature using the mixture polynomial regression model.
- 83% of the downstream LPS over BoB are linked to the four clusters of WNP TCs.
- Landfalling TCs over South china sea and adjoining region are associated with the downstream amplification LPS over BoB.
- Our results suggest a potential for the prediction of the downstream synoptic activity over the BoB at least seven days ahead.
- We observed that the rise in SST over the Pacific induces additional TCs and also altered the genesis of LPS over the BoB.
- It was also observed that the LPS are clustered over the head BoB with an increase in SST over WNP, whereas in the control run LPSs are scattered and with no particular preference for the genesis (like core zone).
- The experiment also agrees with the observed hypothesis of TCs landfall over the vicinity of the South China Sea triggers more downstream LPS. The Expt. CB simulates more downstream LPS over the BoB with no change in the in situ in both experiments.
- Further with the help of the above understood parameters, we are developing an ML algorithm to predict the LPS.

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Thank you

Extra SLIDE

EOF of relative vorticity anomaly at 850 hPa:

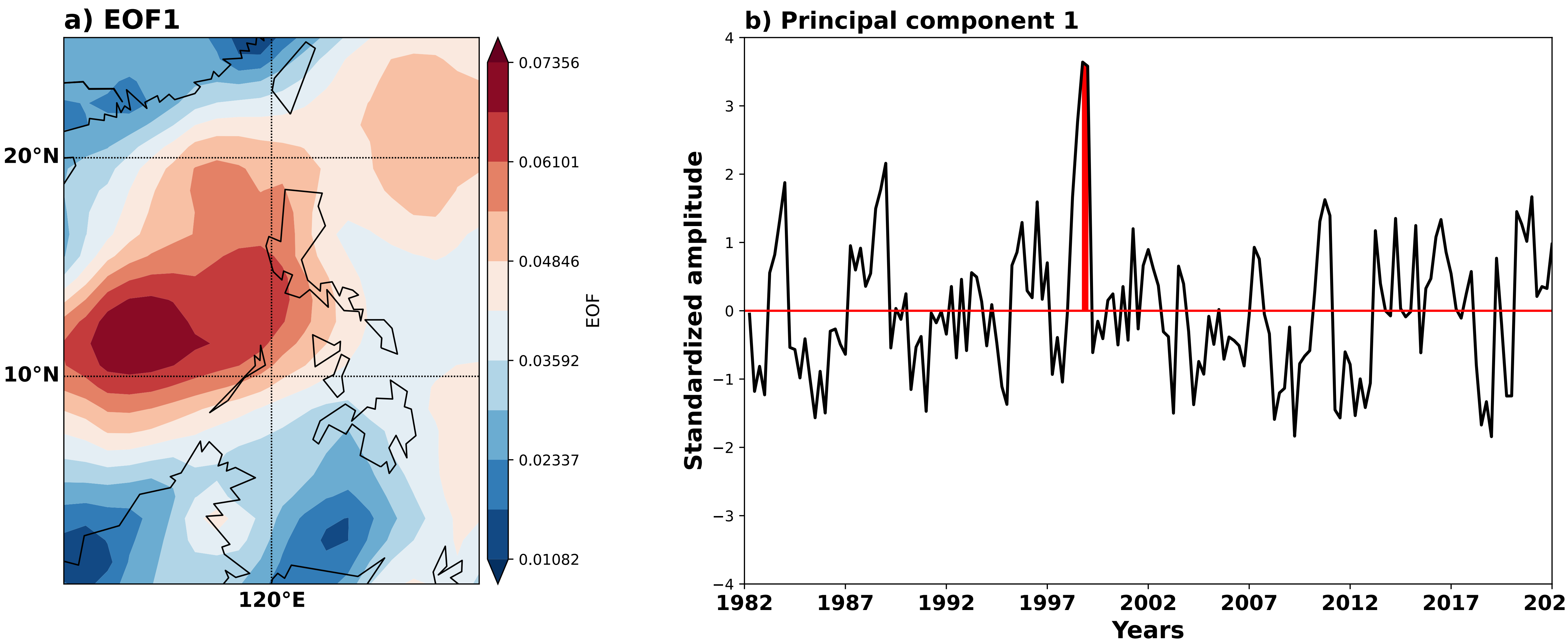

Figure (a) The first leading mode of Empirical Orthogonal Function (EOF) analysis performed on NOAA's sea surface temperature (SST) anomaly from 1982 — 2021 during the June -- September over 0 — 25˚N and 110˚E — 130˚E. The associated standardized principal component (PC1) is shown in (b). The red filled in (b) indicates the months that has values greater than 3 (extreme)

Based on the WNP index we defined (PC1 of the RV anomaly at 850 hPa), the SST in the above mentioned experiments has been raised by 3deg as the extreme deviation observed is about 3deg.