A Global Survey of Middle Tropospheric Cyclones

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Abstract

Mid-Tropospheric Cyclones (MTCs) are moist synoptic systems with middle tropospheric vorticity maxima and little or no signature in the lower and upper troposphere. Apart from a few case studies over South Asia, the occurrence of MTCs in other parts of the tropics has not been explored. Here, we present MTC statistics over the globe (50 N - 50 S) using 20 years of MERRA-2 reanalysis data and compare them with monsoon lows, depressions, and tropical cyclones (together referred to as lower troposphere cyclones; LTCs). Automatic cyclone center detection on the 600 hPa geopotential height field is used to detect synoptic cyclone centers. Based on vertical profiles of vorticity, the detected systems are classified as MTCs or LTCs. We find that synoptic mid-level moist vorticity maxima are not limited to South Asia and are found over most of the globe's monsoonal regions. Apart from South Asia (Arabian sea, Bay of Bengal, and South China sea), MTCs are observed over the west and central Africa, eastern and western Pacific during the boreal summer. In the boreal winter, regions that support MTCs include northern Australia, the southern Indian Ocean, and South Africa. All these regions show monthly, as well as inter-annual variability in MTC and LTC activity. In particular, most regions show high MTC center density early in the monsoon and relatively high LTC activity during respective primary monsoon months. In both hemispheres, MTCs are more prevalent nearer to the equator and usually coincide with regions of cross-equatorial low-level monsoon flow. LTCs, on the other hand, are more common further polewards, usually within the monsoon trough itself. Finally, the global tropical probability distribution of the difference between middle and lower level vorticity versus the height of peak vorticity is bimodal; one peak corresponds to MTCs at about 600 hPa while the second 900 hPa corresponds to LTCs. Thus, tropical moist cyclonic systems naturally tend to reside in either the MTC or LTC category.

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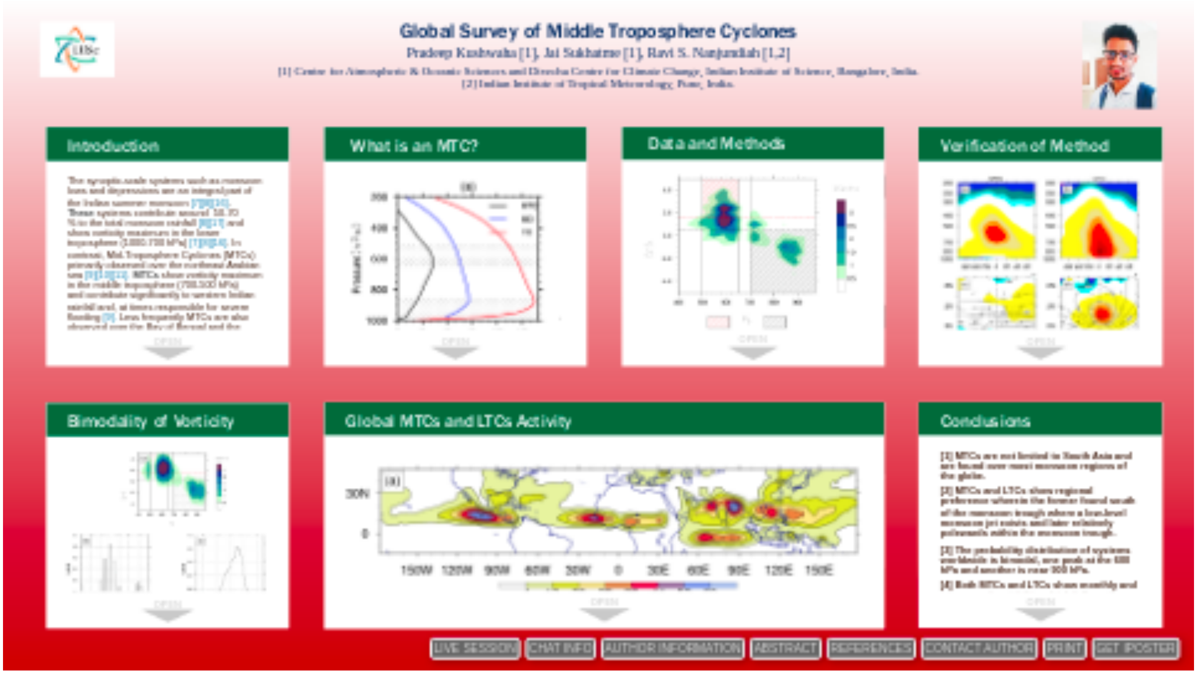

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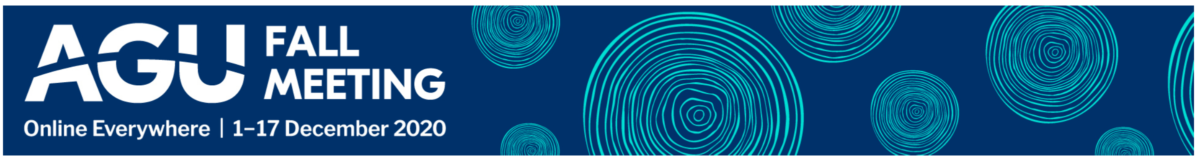

INTRODUCTION

The synoptic-scale systems such as monsoon lows and depressions are an integral part of the Indian summer monsoon [7][8][16]. These systems contribute around 50-70 % to the total monsoon rainfall [8][17] and show vorticity maximum in the lower troposphere (1000-700 hPa) [7][8][16]. In contrast, Mid-Troposphere Cyclones (MTCs) primarily observed over the northeast Arabian sea [9][10][11]. MTCs show vorticity maximum in the middle troposphere (700-500 hPa) and contribute significantly to western Indian rainfall and, at times responsible for severe flooding [9]. Less frequently MTCs are also observed over the Bay of Bengal and the South China sea [18].

Further, systems similar to MTCs, are Easterly Waves (EWs) [12][13][14]. EWs form over Africa [12][13] and East Pacific regions [14][15].These waves show vorticity maximum in the middle troposphere [13] and weak signature in the lower troposphere. Given limited work, regions of the global MTC occurrence is not available. Therefore here we explore the globe for MTCs occurrence. We also keep track of monsoon lows and depression that show vorticity maximum in the lower troposphere (Lower Troposphere Cyclones: LTCs). This allows the calculation of the fraction of these two types of systems. In particular, here, we attempt to answer the following questions:

(1) Which regions of the globe support MTCs and LTCs?

(2) Is there any regional preference for the occurrence of MTCs and LTCs?

(3) Are there any differences MTCs and LTCs monthly and interannual variability in different regions of the globe?

WHAT IS AN MTC?

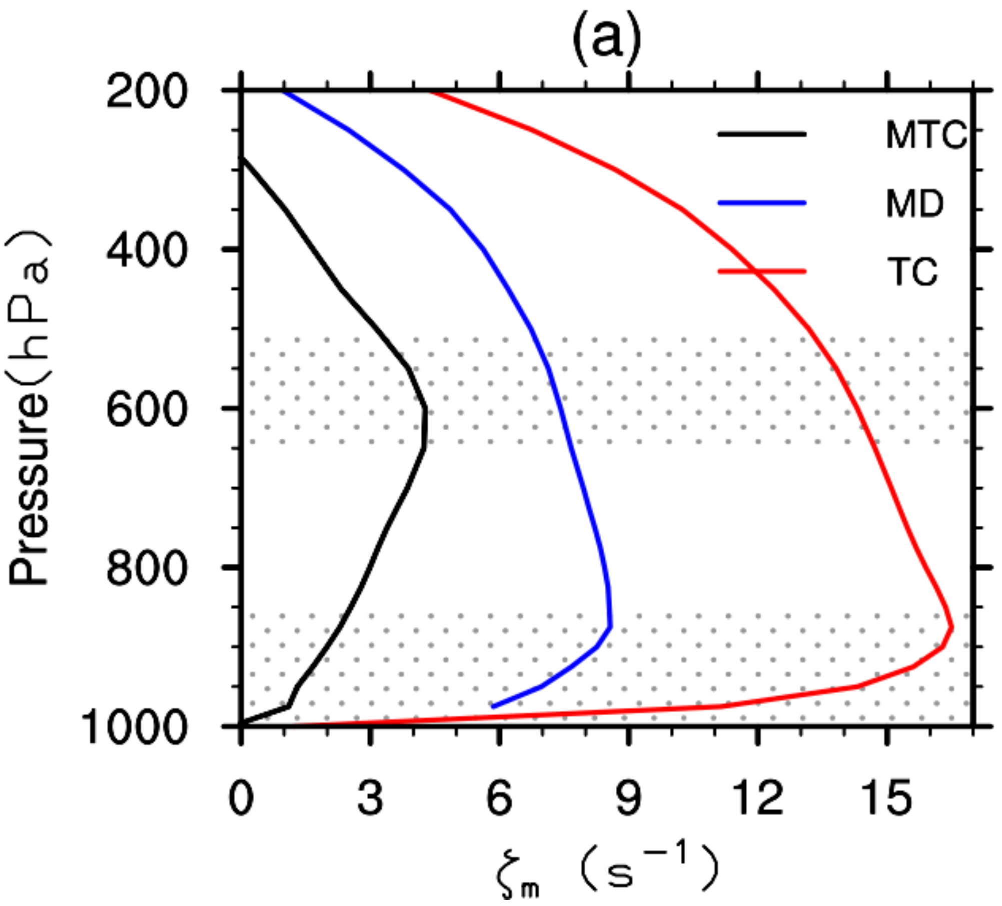

Figure-1 Black-observed vertical profile of relative vorticity of MTCs, blue is for MDs, red is for Tropical Cyclones (TCs);

Observed MTCs relative vorticity (Black), clearly shows vorticity maxima in the middle troposphere and very weak vorticity in the lower troposphere.
In contrast, the monsoon depression (blue) and tropical cyclone (red) show vorticity maximum in the lower troposphere.
This is the main difference between MTC and other tropical systems.

DATA AND METHODS

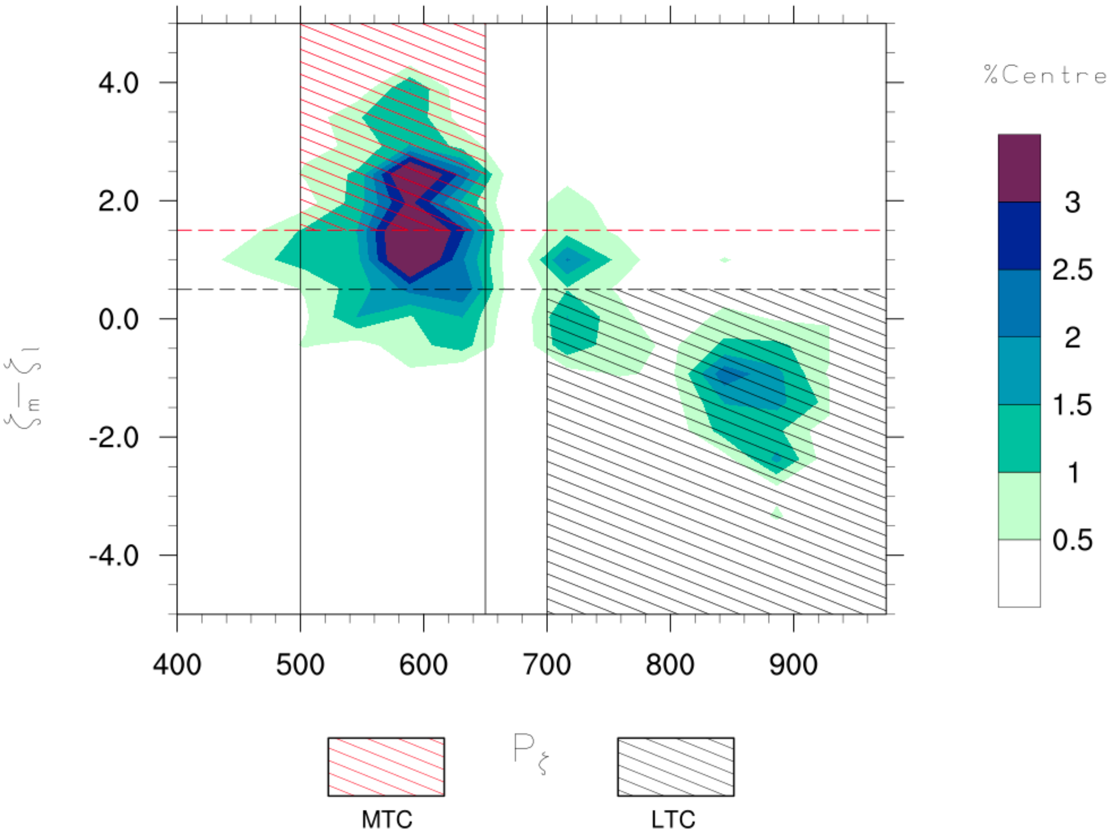

Figure-2: Joint probability distribution of $\delta\xi_p = \xi_m - \xi_l$ ($*10^{-5}$ s^{-1}) and the level of maximum relative vorticity (P_ξ) for 725 strong and moist cyclonic centers detected during the dates of 35 IMD MTC events over the region 5N-25N, 50E-95E. Red (black) hatching indicates the bounds of MTCs (LTCs).

Data:

In this study, we use once daily (12:00 UTC) Modern-Era Retrospective analysis for Research and Applications Version-2 (MERRA-2) reanalysis [19][21] spanning years 2000-2019. The data is available at a regular longitude-by-latitude grid with a resolution of 0.625 × 0.5 and 72 hybrid-eta levels from the surface to 0.01 hPa. We have selected the duration of 2000-2019 for our study. Data on 25 vertical levels between 1000 hPa and 100 hPa is used. As the systems, we are studying are greater than 150 km in scale, the data sets are interpolated to a 1.5 degree horizontal rectangular latitude-longitude grid from native resolution before application. Such reduced resolution usually helps filter out small-scale vorticity centers, whose inclusion introduces errors in tracking interest feature.

Identification of MTCs and LTCs:

Identification of cyclonic systems involves the following step:

1. In the first step, we detect geopotential minim at 600 hPa.
2. The second step involves the constrain to filter out system with vorticity maximum in the middle (MTCs) and lower troposphere (LTCs)
3. Further, the intense and moist stems are retained in the analysis.

Application of step-1 of the above method results in 725 strong and moist system during IMD dates of middle-level circulations during 1988-2008 (This data is used because it is the only known observational data available for MTCs). Figure-2 shows the joint PDFs of the level of maximum vorticity (P_{ξ}) of each detected system and the difference of middle (ξ_m) and lower level vorticity (ξ_l) of these 725 systems detected during IMD, MTCs dates. Invoking step 2-3 results in the bounds of MTCs (red) : ($\delta\xi_p > 1.5*10^{-5}$ s^{-1}, $650 > P_{\xi} > 500$ hPa, ξ_m >$1.5*10^{-5}$ s^{-1}, $\xi_l>0$, $Q_m>2$)**;** and LTCs (Black): ($\delta\xi_p < 0.5$, $1000 >P_{\xi} > 700$ hPa, ξ_m >$1.5*10^{-5}$ s^{-1},$\xi_l>0$, $Q_m>2$) in Figure-1, where $\delta\xi_p = (\xi_m- \xi_l)$ is the difference between middle (650-500 hPa) and lower layer (1000-700) mean relative vorticity, ξ_m and ξ_l respectively.

VERIFICATION OF METHOD

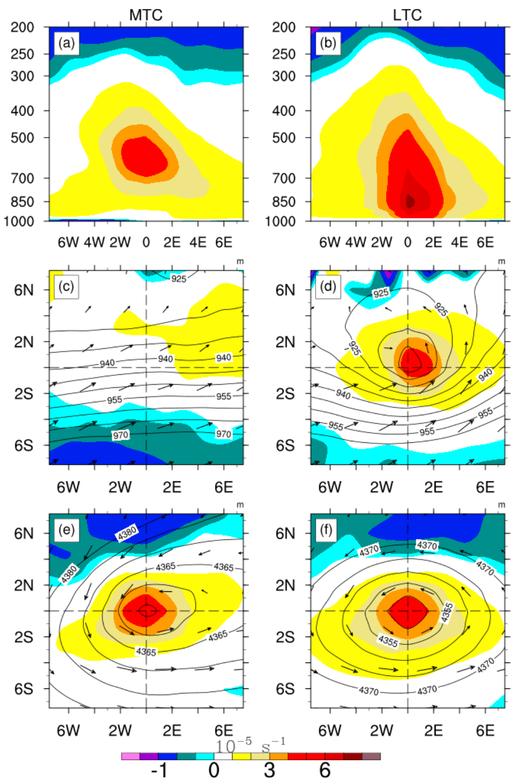

Figure-3: Relative vorticity composite from middle troposphere cyclonic centers, Left Panels:(a, c, e) and 246 lower tropospheric cyclone centers (Right Panels: b, d, f) from the Indian region. (a), (b) East-West-vertical cross-section through composite center y-axis is pressure in hPa. (c), (d) Horizontal cross-sections at 975 hPa and (e), (f) at 600 hPa. Dashed lines indicate axes through the composite center. Vectors indicate the composite wind of MTC and LTCs and contours represent the composite geopotential height at respective levels in m; Units of the x-y axes of sub-figures c-f are degrees east and degrees north with respect to composite cyclone center, respectively.

Figure-3 left panel shows the composite of MTCs and LTCs as defined by the parameter bound of Figure-2. The method employed faithfully able to differentiate the MTC and LTCs. Wherein MTCs show isolates vorticity maximum in the middle troposphere while LTCs show vorticity maximum in the lower troposphere. This is consistent with the observed structure of MTCs over the Arabian sea and LTCs over most of the monsoon regions.

BIMODALITY OF VORTICITY

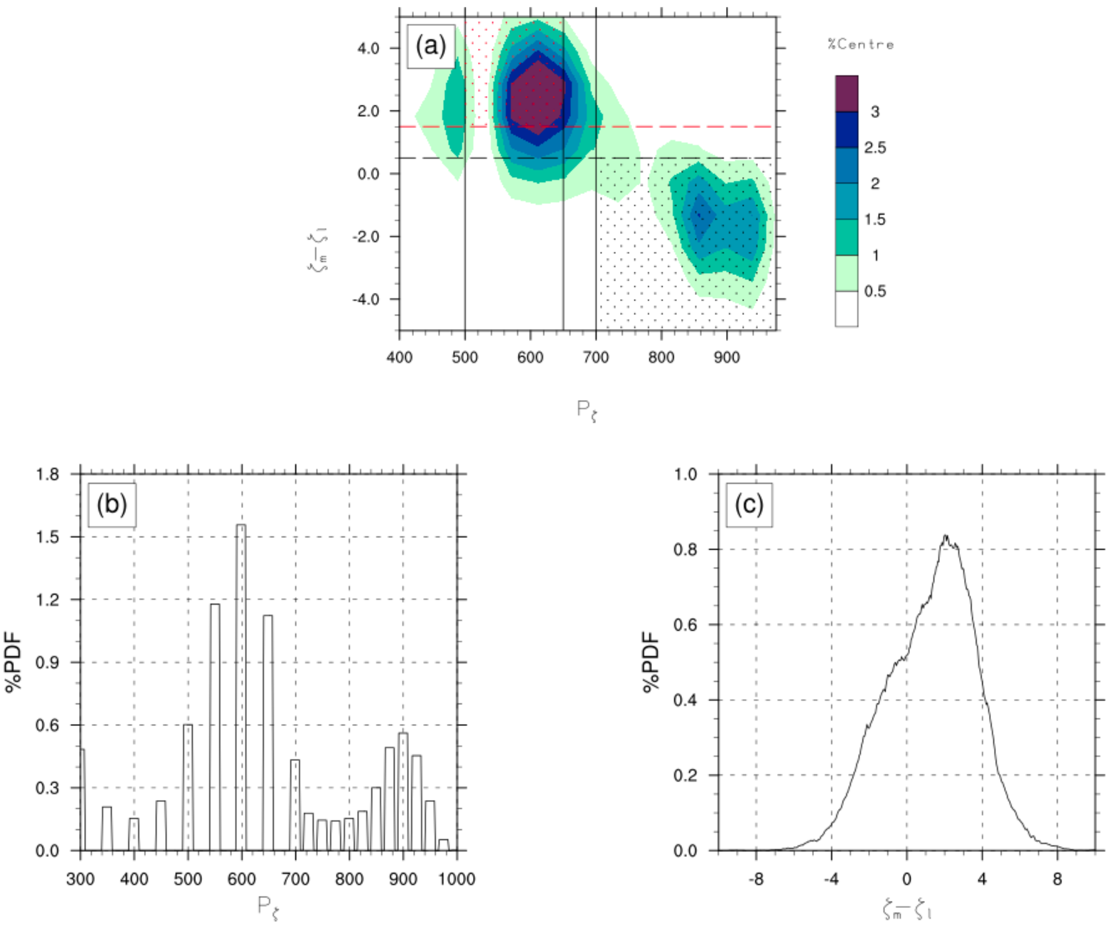

Figure-3: a) Joint PDF of P_ξ and ξ_m-ξ_l of all cyclonic centers from 50 N to 50S in 20 years of data. Notation follows Figure-2, (b) PDF of P_ξ; (c) PDF of ξ_m-ξ_l.

1. Naturally, two peaks emerge in the probability density of the vorticity maximum—one near 600 hPa and another near 900 hPa. Former is corresponds to MTCs and later with LTCs.
2. The joint PDF of the above figure clearly shows two peaks in density, which are exhibit clear separation among two different classes of system.

GLOBAL MTCS AND LTCS ACTIVITY

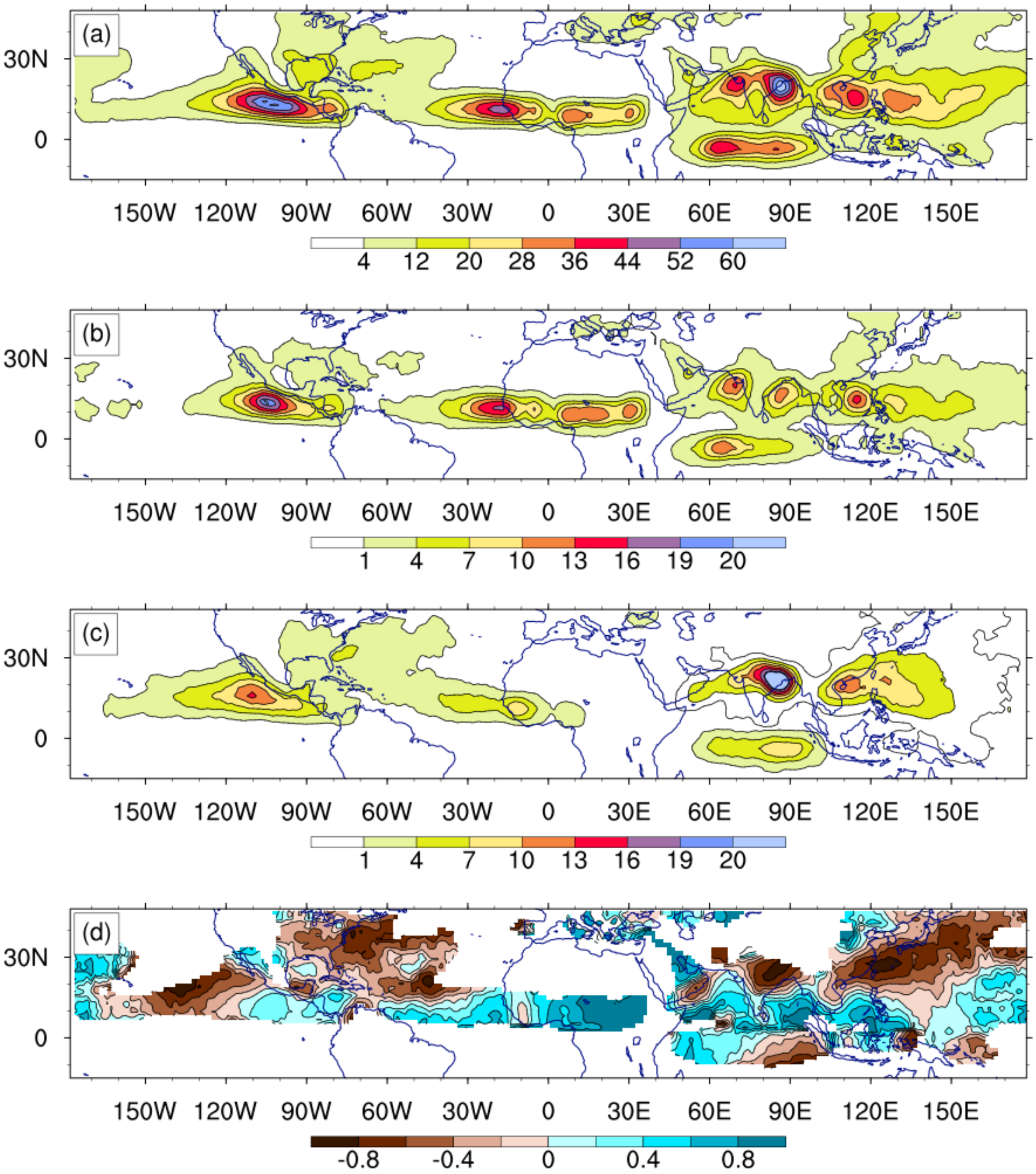

Figure-4 **(a) Overall cyclone center density collected over 8-degree square at 1.5 degree grid per for Northern5Hemisphere summer (i.e., June, July, August, September) for 20 years; (b) same as (a) except for MTC centers ($\delta\xi_p > 1.5$, $650 > P_\xi > 500$ hPa, $\xi\_m > 1.5$, $\xi_l > 0$, $Q_m > 2$); (c) same as (a) except for LTC centers ($\delta\xi_p < 0.5$, $1000 > P_\xi > 700$ hPa, $\xi\_m > 1.5$, $\xi_l > 0$, $Q_m > 2$), i.e., LTCs; (d) (b-c)/{b+c} only shown if total density exceeds 3; Unit of vorticity is $10^{-5}s^{-1}$ and specific humidity is in g/kg.**

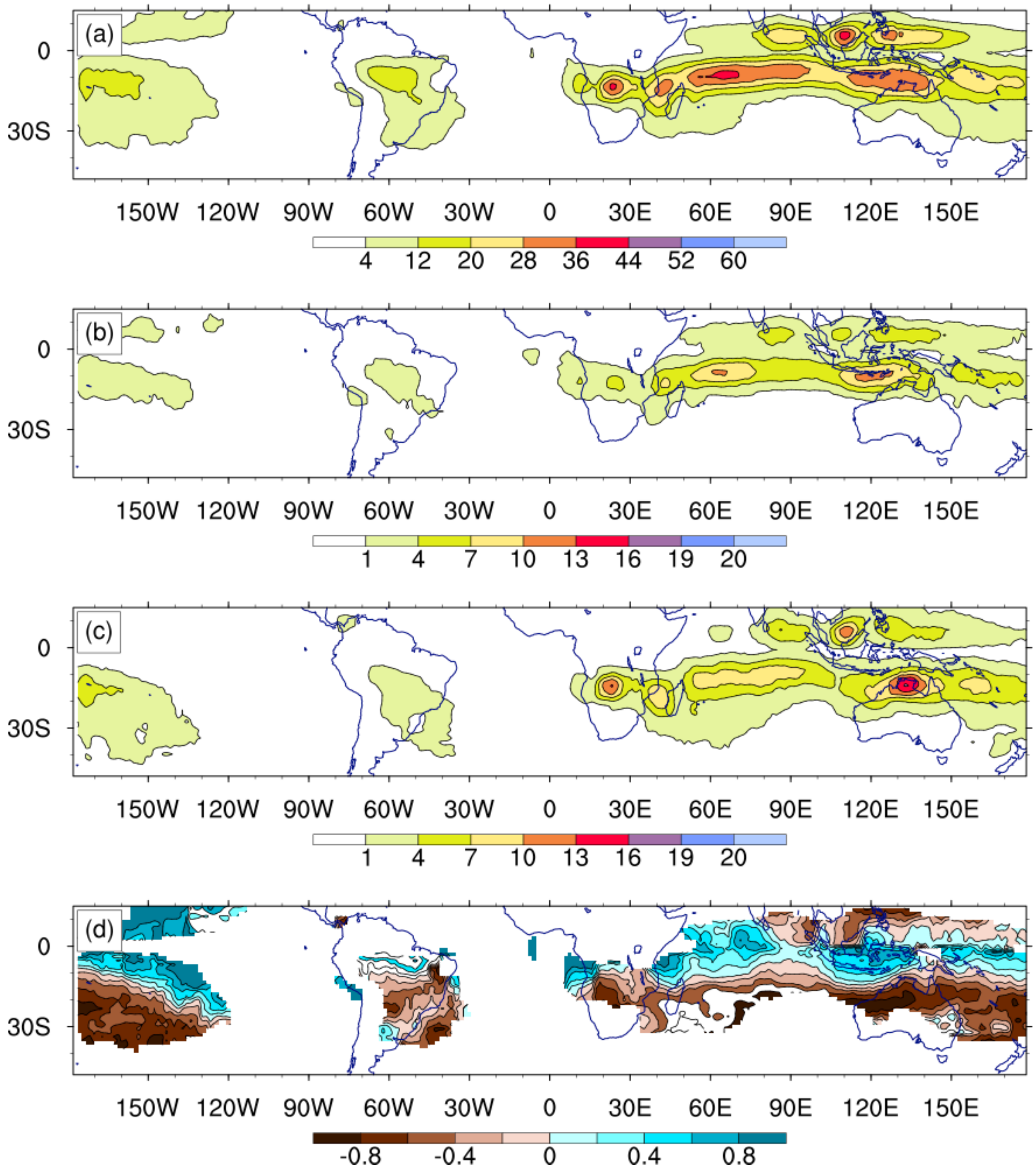

Figure-5 (a) Overall cyclone center density collected over 8-degree square at 1.5 degree grid per for NorthernHemisphere summer (i.e., Dec Jan, Feb, Mar) for 20 years; (b) same as (a) except for MTC centers ($\delta\xi_p > 1.5$, $650 > P_\xi > 500$ hPa, $\xi\_m > 1.5$, $\xi_l>0$, $Q_m>2$); (c) same as (a) except for LTC centers ($\delta\xi_p < 0.5$, $1000 > P_\xi > 700$ hPa, $\xi\_m > 1.5$, $\xi_l>0$, $Q_m>2$), i.e., LTCs; (d) (b-c)/{b+c} only shown if total density exceeds 3; Unit of vorticity is $10^{-5}s^{-1}$ and specific humidity is in g/kg.s

1) In boreal summer, MTCs are not only found in South Asia (Arabian sea, Bay of Bengal, South China sea), but they also occur over East and West Africa, East and West Pacific, and in the vicinity of the western equatorial Indian ocean.

2) In boreal winter, MTCs are found primarily over North Australia, the South Indian ocean, and a lesser extent over South America and Africa.

3) MTCs and LTCs fraction suggests that the MTCs primarily occurs south of the main monsoon troughs where low-level monsoon flow and upper level easterly exists. While LTCs occur in a large fraction further polewards in the vicinity of monsoon troughs.

Monthly Variability

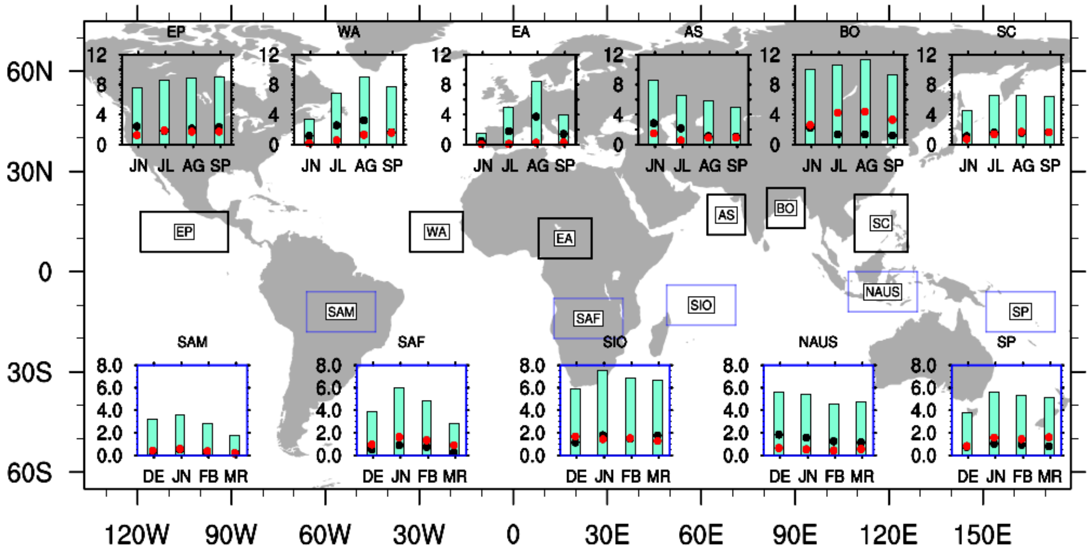

Figure-6 Monthly climatology of cyclone centers for total (Aquamarine Bars), MTC centers (black dots) and LTC centers (red dots) over East Pacific (EP), West Africa (WA), East Africa, (EA), Arabian Sea (AS), Bay of Bengal (BO) and South China Sea (SC) during June (JN), July (JL), August (AG) and September (SP); sub-panels south of the equator are for December (DE) January (JN) February (FB) and March (MR); for South America (SAM), South Africa (SAF), South Indian Ocean (SIO), North Australia (NAUS), South Pacific (SP) for total, MTC and LTC centers, respectively. The monthly climatologies are averaged over respected boxes to get a seasonal time series.

1) Over South Asia and Australia, LTCs are more frequent during the primary monsoon months and MTCs during early monsoon months

2) Over Africa, MTCs are prominent during the primary monsoon months.

Interannual Variability

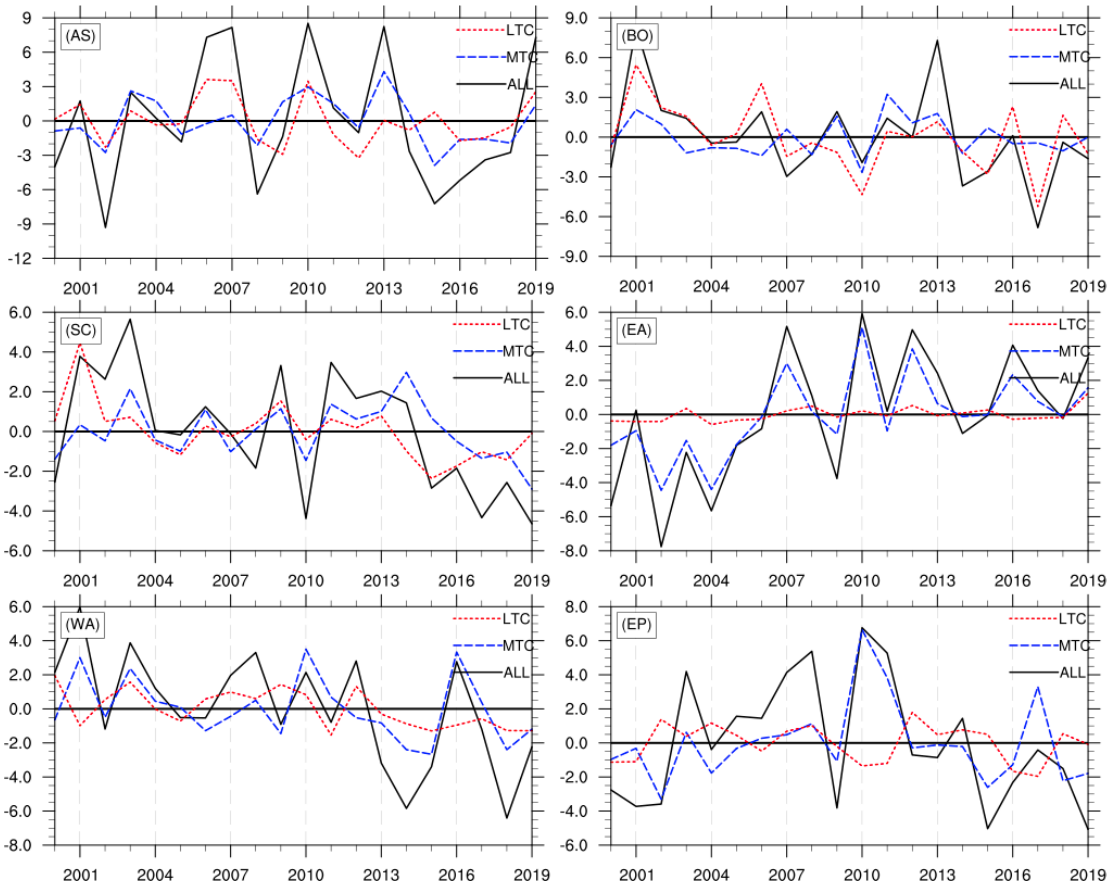

Figure-7 Seasonal (June-September) cyclone center density anomaly for all (bold back), MTCs (blue long doted) and LTCs (red dotted lines) over East Pacific (EP), West Africa (WA), East Africa, (EA), Arabian Sea (AS), Bay of Bengal (BO) and South China Sea (SC) averaged over respected boxes. The seasonal anomaly is based on a 20-year climatology averaged over respective boxes as shown in Figure-6

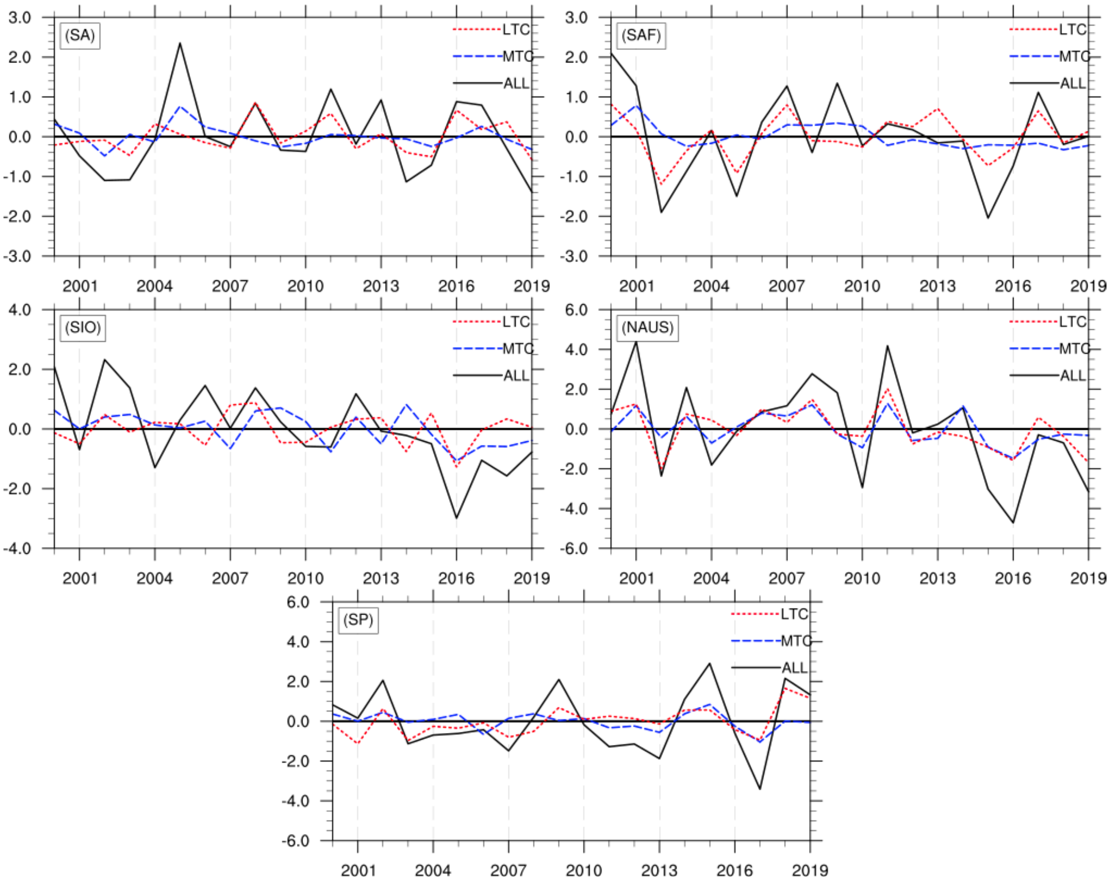

Figure-8 **Seasonal (December-March) cyclone center density anomaly for total (bold back), MTC centers (blue long doted) and LTC centers (red dotted lines) over for South America (SA), South Africa (SAF), South Indian Ocean (SIO), North Australia (NAUS), South Pacific (SP), averaged over respective boxes. The seasonal anomaly is based on a 20-year climatology averaged over respective boxes as shown in Figure-7**

1) Both MTCs and LTCs show interannual variability in boreal summer and winter and mostly follow the total cyclone activity.

2) Boreal summer LTCs and MTCs show massive year to year variability compare to boreal winter.

3) MTCs and LTCs activity follows the total cyclone activity indicates that these systems might be forced by the same large-scale field, which modulates the total cyclone activity.

CONCLUSIONS

[1] MTCs are not limited to South Asia and are found over most monsoon regions of the globe.

[2] MTCs and LTCs show regional preference wherein the former found south of the monsoon trough where a low-level monsoon jet exists and later relatively polewards within the monsoon trough.

[3] The probability distribution of systems worldwide is bimodal, one peak at the 600 hPa and another is near 900 hPa.

[4] Both MTCs and LTCs show monthly and interannual variability, which follows the cycle of total density.

[5] MTCs usually forms in the early monsoon months in Asia and Australia, while LTCs are found during the main monsoon months.

[6] Over Africa, MTCs are found in large numbers during the main monsoon months.

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ABSTRACT

Mid-Tropospheric Cyclones (MTCs) are moist synoptic systems with middle tropospheric vorticity maxima and little or no signature in the lower and upper troposphere. Apart from a few case studies over South Asia, the occurrence of MTCs in other parts of the tropics has not been explored. Here, we present MTC statistics over the globe (50 N - 50 S) using 20 years of MERRA-2 reanalysis data and compare them with monsoon lows, depressions, and tropical cyclones (together referred to as lower troposphere cyclones; LTCs). Automatic cyclone center detection on the 600 hPa geopotential height field is used to detect synoptic cyclone centers. Based on vertical profiles of vorticity, the detected systems are classified as MTCs or LTCs. We find that synoptic mid-level moist vorticity maxima are not limited to South Asia and are found over most of the globe's monsoonal regions. Apart from South Asia (Arabian sea, Bay of Bengal, and South China sea), MTCs are observed over the west and central Africa, eastern and western Pacific during the boreal summer. In the boreal winter, regions that support MTCs include northern Australia, the southern Indian Ocean, and South Africa. All these regions show monthly, as well as inter-annual variability in MTC and LTC activity. In particular, most regions show high MTC center density early in the monsoon and relatively high LTC activity during respective primary monsoon months. In both hemispheres, MTCs are more prevalent nearer to the equator and usually coincide with regions of cross-equatorial low-level monsoon flow. LTCs, on the other hand, are more common further polewards, usually within the monsoon trough itself. Finally, the global tropical probability distribution of the difference between middle and lower level vorticity versus the height of peak vorticity is bimodal; one peak corresponds to MTCs at about 600 hPa while the second 900 hPa corresponds to LTCs. Thus, tropical moist cyclonic systems naturally tend to reside in either the MTC or LTC category.

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