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Cyclonic and anticyclonic circulations of 850 hPa over India and adjoining areas based on highly packed hand drawn streamline charts : part 1 - characteristics

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सार – चक्रवाती (‘सी’) और प्रतिचक्रवाती (‘ए’) परिसंचरण किसी क्षेत्र के मौसम को तय करने में निर्णायक भूमिका निभाते हैं। इसलिए, परिसंचरण की विशेषताओं और उनके स्थानिक-कालिक वितरण को समझना महत्वपूर्ण हो गया है। वर्तमान खोजपूर्ण अध्ययन भारत और आसपास के क्षेत्रों में 850 hPa दबाव स्तर के परिसंचरण की विशेषता बताता है। उपग्रहों, रेडियोसॉन्ड्स, पायलट गुब्बारों और डॉपलर मौसम रडार से पवन डेटा को एकीकृत करके 850 hPa के लिए अत्यधिक पैक्ड पवन स्ट्रीमलाइन तैयार की गई हैं। ‘सी’ और ‘ए’ परिसंचरण केंद्र बिंदुओं की पहचान की गई है और 2014 से 2020 के लिए भारतीय और आसपास के क्षेत्रों में मौसमी, दीर्घकालिक और मासिक समय के पैमाने पर उनके वितरण की विशेषताओं का स्थानिक रूप से पता लगाया गया है। ‘सी’ और (‘ए’) परिसंचरणों में कई मौसम संबंधी महत्वपूर्ण विशेषताएं स्पष्ट रूप से प्रकट होती हैं और गतिशीलता में उनकी भूमिका पर पांडुलिपि में चर्चा की गई है। आवृत्ति वितरण से पता चलता है कि उत्तर और उत्तर-पश्चिम भारत, सिंधु-गंगा के मैदान और पूर्वी भूमध्यरेखीय हिंद महासागर क्षेत्र में (‘सी’) परिसंचरण व्यापक और बड़ी संख्या में मौजूद हैं। मौसमी विश्लेषण से दक्षिण-पश्चिम मानसून गर्त, बंगाल की खाड़ी के मुख्य निम्न दबाव, भूमि पर और दक्षिणी प्रायद्वीप में गर्मी के निम्न दबाव के साथ संबंध का पता चलता है। (‘ए’) परिसंचरण केंद्र बिंदु वितरण गर्त क्षेत्र के दक्षिण में और मुख्य रूप से भूमि पर केंद्रित है। सर्दियों के मौसम में उल्लेखनीय रूप से अधिक (‘ए’) परिसंचरण होता है जिसे हैडली सेल के अवरोही अंग के लिए जिम्मेदार ठहराया जा सकता है। परिसंचरण का स्थानिक वितरण भूमि-समुद्र विपरीतता दर्शाता है। विश्लेषण में कई अनुप्रयोग हैं, जिनमें परिचालन मौसम पूर्वानुमान, विमानन और बैलिस्टिक मौसम विज्ञान और उन्नत अनुसंधान की गुंजाइश शामिल है।

ABSTRACT. Cyclonic (‘C’) and Anticyclonic (‘A’) circulations play a decisive role in deciding the weather of a region. Therefore, understanding the characteristics of circulation and their spatio-temporal distribution has become important. The present exploratory study characterizes circulations of 850 hPa pressure level over India and adjoining regions. Highly packed wind streamlines are drawn for 850 hPa integrating wind data from satellites, radiosondes, pilot balloons and Doppler Weather Radars. ‘C’ and ‘A’ circulations centre points are identified and the characteristics of their distribution are explored spatially on seasonal, long-term and monthly time scale over the Indian and surrounding regions for 2014 to 2020. Several meteorological significant features are visually manifested in ‘C’ and (‘A’) circulations and their role in dynamics is discussed in the manuscript. Frequency distribution shows wide-spread and large numbers of (‘C’) circulations are present over the north and northwest India, the Indo-Gangetic plain, and in the east equatorial Indian Ocean region. Seasonal analysis reveals an association with the southwest monsoon trough, the head Bay of Bengal lows, heat lows over land and in the southern peninsula. (‘A’) circulation centre point distribution is concentrated further south of the trough region and concentrated mainly on the land. The winter season has noticeably more (‘A’) circulation which could be attributed to the descending limb of the Hadley Cell. Spatial distribution of circulation shows land-sea contrast. The analysis has several applications, including operational weather forecasting, aviation and ballistic meteorology and scope for advanced research.

Key words – Cyclonic circulation, Anticyclonic circulation, Streamline analysis, Operational Meteorology, Monsoon.

1. Introduction

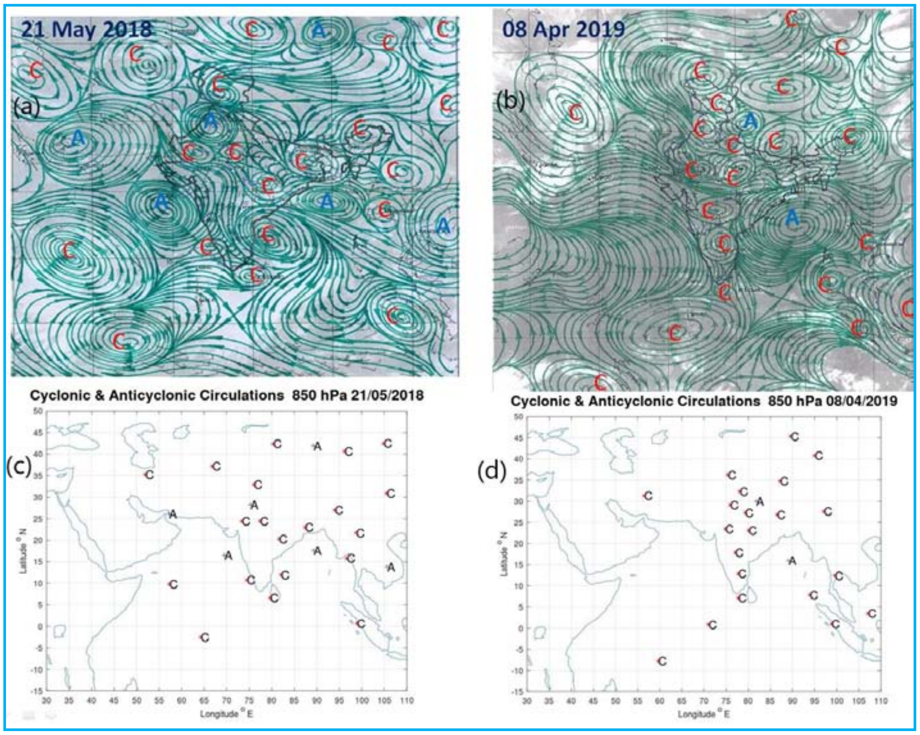
In tropical meteorology, 850 hPa (~1.5 km above sea level) is considered an important pressure level (standard pressure level) because of its pivotal role in the genesis of different weather systems. Winds at this level are also an important weather parameter in day to day weather forecasts. The horizontal winds (zonal component, u wind: east-west and meridional component, v wind: north-south) determine the horizontal convergence/ divergence and confluence / diffluence which greatly influences cyclonic/ anticyclonic vorticity. Horizontal convergence with moisture (water vapour) availability often leads to ascend of air parcel and vertical development of clouds. Horizontal divergence leads to dispersing of the air mass in the region, resulting in clearer skies. Both circulations could also trigger atmospheric turbulence in the region with varying intensity of serious concern in aviation and aerospace operations. In order to study these various dynamic variables, streamline analyses are most preferred by meteorologists worldwide [Ramage, 1995]. In wind streamline analysis, a continuous representation of wind fields from observations of horizontal vector wind is drawn for different standard pressure levels. The separation between streamlines is inversely proportional to the wind speed [Keshavamurthy, 1973, Byers, 1974]. Streamlines are set of lines drawn tangential to wind [Keshavamurthy, 1973]. Such analysis brings a wealth of information about the transport of different types of air mass, their interaction and becoming a front triggering a weather system [Riehl, 1948, Palmer, 1951]. Streamline analysis provides a pictorial/ visual representation of transport / advection of different airmasses, their confluence, divergence, curl, shear, stretch, etc. It helps in clearly interpreting the possible weather features, and often gives an indication of the frequency of impending weather. In tandem with the prevailing season, cyclonic/ anticyclonic circulations over a region can differ. The day-to-day weather, especially the temperature and pressure, strongly influence the circulation types over the region. In addition to this, the prevailing wind direction could veer or back with the influence of orography over a wide region. It is a well studied topic that the westerly low level jet stream during the monsoon season has a wind core at 850 hPa level [Joseph and Sijikumar, 2004]. Circulations could also alter spatially with the active/break/lull phases of the monsoon. The monsoon trough is a semi-permanent system which has a lot of internal dynamics. The large and small circulations in this trough region are not yet characterised; and not understood well by the scientific community.

Deep convective regions are often areas of cyclonic vorticity [Grossman and Garcia, 1990; Gambheer and Bhat, 2000; Zuidema, 2003; Meenu *et al*., 2010]. Similarly, Inter-Tropical Convergence Zone (ITCZ) are locations of low level convergence [Meenu *et al*., 2007,] and often have strong cyclonic circulations. On the other hand, descending zones of the Hadley cell are regions of subsidence and strong anticyclonic circulation which are prominent in the south Indian Ocean where stratocumulus clouds [Wood, 2012] are abundant (inhibited to develop vertically by strong downdraft.

'Pool of inhibited cloudiness' [Nair *et al*., 2011] - a region of strong subsidence and anticyclonic circulation exists in the southwest Bay of Bengal and Sri Lanka during the southwest monsoon. Deep convection far away from it has an important role in the dynamics and mini-circulation embedded in the large scale monsoon circulation [Nair *et al*., 2017]. Such small/large scale circulations have a large influence on the horizontal convergence/divergence of the region. Many such cloud-circulation feedbacks still remain unexplored by the scientific community or are not clearly represented in the models [Roy *et al*., 2019]. Deep convection in the equatorial trough, east equatorial Indian Ocean region etc. can be identified clearly from satellite images. Corresponding regional circulations were not explored well by the investigators. Streamline analysis provides insight into the horizontal wind field and its characteristics. Understanding the type of circulation and relating to the associated weather therefore, becomes important. Streamline analysis of wind is the best solution for the case. Such a detailed long-term analysis integrating actual observations (radiosonde, pilot balloon, radar, satellite derived) still remains a lacuna. Through the present study, we tap the potential of integrating a large number of such database in preparing streamline maps and then deriving out spatial distribution of cyclonic and anticyclonic circulation centres. In the following sections the methodology of identifying the centre points of circulations are briefed followed by the characteristics of long-term, seasonal and monthly distribution of circulations. The analysis has several operational and research applications. Several unexplored and un-noticed characteristics are expected to be revealed in the study.

2. Data

Meteorology Facility (METF) of Vikram Sarabhai Space Centre (VSSC), ISRO does an innovative task by preparing hand-drawn highly packed streamline charts on almost all working days for 00GMT. Wind data (850 hPa level) is integrated from DWR, radiosonde (India Meteorological Department), data from University of Wyoming (www.weather.uwyo.edu/upperair/sounding.html), satellite derived wind from Indian Space Research Organisation - Space Application Centre's Meteorology



Figs. 1(a-d). Typical examples of 850 hPa hand drawn streamline charts (a) 21 May, 2018 and (b) 08 Apr, 2019 depicting the wind streamlines as well as cyclonic 'C' and anticyclonic 'A' circulations. (c) and (d) depicts the derived centre point distribution of circulations for (a) and (b)

and Oeanographic Satellite Data Archival Centre (MOSDAC www.mosdac.gov.in)and from Meteorology Satellite (METEOSAT), These streamline charts form the primary data for the study. The study period spans six winter seasons (DJF), five pre-monsoon seasons, six southwest monsoon seasons (5 JJAS + 1 AS) and six post monsoon seasons (ON). Each center point (latitude, longitude) of circulation is identified from 1228 streamline analysis chart from August 2014 to February 2020. Streamline analysis is an operational activity carried out at METF since August 2014 regularly without any major break till Covid lockdown period of 2020 and continuing thereafter.

3. Methodology

On the Indian National Satellite - Infrared (INSAT-IR) imager's most recent image print out, wind barbs for 850 hPa are pen marked carefully from the following sources (*i*) satellite derived cloud motion vectors (INSAT and METEOSAT) over the region, (*ii*) wind vector at 850 hPa from available Doppler Weather Radars in India, (*iii*) wind data at 850 hPa from radiosonde and Pilot Balloon ascends at 0000 GMT selecting available locations from the entire region. Highly packed streamlines are carefully hand-drawn by considering the strength of isotachs, isogons, weather patterns, synoptic isobaric chart, prevailing season and daily meteorological features. This integrated approach for preparation of highly packed streamline charts analysis and methodology adopted thereof at METF, VSSC may be unique in character and the first time in the history of streamline analysis.

As the next step, centre coordinates (latitude-longitude) is picked out from the daily hand-drawn streamline analysis chart after digitising them individually. Graph data extractor software (g3data/Getd ata Graph) are used for the extraction. Figs. 1(a&b) shows two typical days of streamline chart (21 May, 2018 and 08 Apr, 2019). Firstly, the mean horizontal wind flow at 850 hPa can be visualised from the streamlines. In the northern hemisphere, there are regions where streamlines curl anticlockwise direction and finally converge to a centre. This circulation is called cyclonic circulation. On the other hand, when the streamlines curl clockwise (starting from a centre point) and diverge out, it is anticyclonic circulation. The case is just the opposite in the southern hemisphere. Fig. 1 represents a streamline analysis for two typical days. Cyclonic centre co-ordinates are represented as 'C' and anticyclonic circulation centres are represented as 'A'. The bottom panel figures depict

TABLE 1

No. of cyclonic circulations, anticyclonic circulations and No. of days observations tabulated season-wise from 2014 to 2019. 'C' and 'A' indicate No. of cyclonic and anticyclonic circulations respectively. 'D' indicates No. of days data is available

Year	Winter DJF			Pre-monsoon MAM			SW monsoon JJAS			Post monsoon ON			Annual Total		
	C	A	D	C	A	D	C	A	D	C	A	D	C	A	D
2014	182	130	53	-	-	-	29	7	8	177	95	38	388	232	99
2015	238	175	57	345	106	60	648	178	85	312	126	39	1543	585	241
2016	301	244	57	311	144	54	516	128	73	199	132	36	1327	648	220
2017	381	207	57	474	245	55	521	167	65	289	199	41	1665	818	218
2018	562	208	58	646	192	58	744	201	72	362	176	37	2314	777	225
2019	411	195	50	748	209	61	812	219	74	391	221	40	2362	844	225
All	2075	1159	332	2524	896	288	3270	900	377	1730	949	231	9599	3904	1228
%	64%	36%	-	74%	26%	-	78%	22%	-	65%	35%	-	71%	29%	-

the centre point distribution of circulations for the corresponding figures. All cases of 'C' and 'A' circulation centres are re-plotted and checked again for their correctness in location coordinates. An advantage of this type of analysis is that even the smaller sized circulations which often go unrepresented in global models get detected here. The study area is divided into 2.5° × 2.5°, 5° × 5° and 10° × 10° latitude longitude grids and the frequency distribution of 'C' and 'A' circulation centre in each grid point are computed. This process is followed to get monthly, seasonal, annual and long-term average of the frequency of occurrence of a 'C' / 'A' circulation in a grid box. This would provide a broader and clearer insight into the frequency of occurrence of circulation spatially. To delineate the continuity of circulation, streamlines are drawn through interpolation over the Tibetan Plateau and the Himalayas using available data from the adjoining areas.

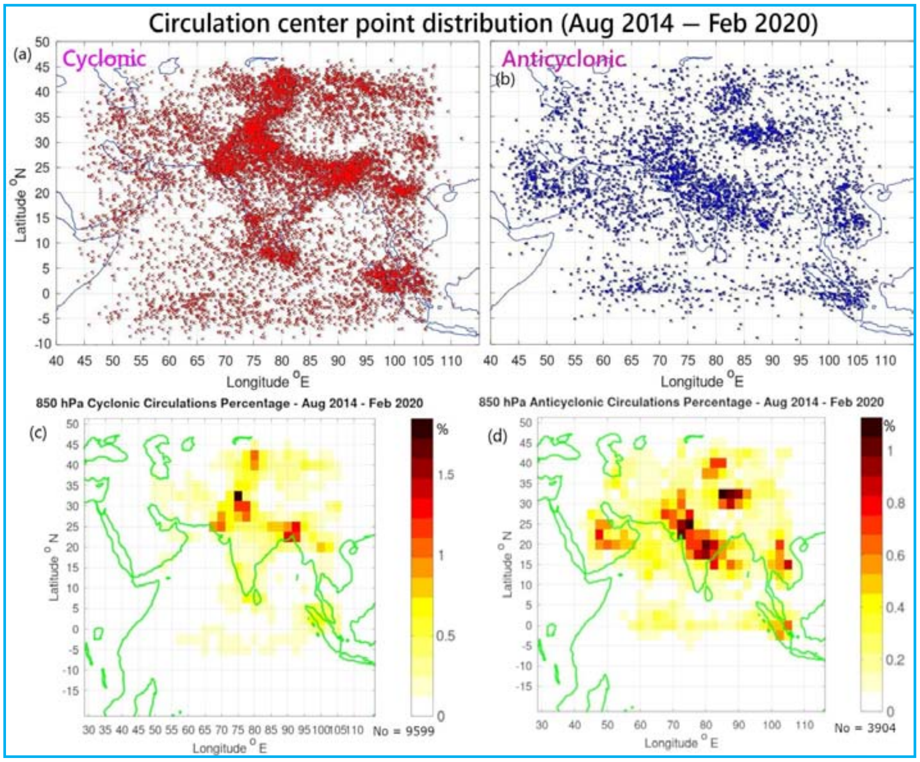
4. Results and discussion

'C' and 'A' circulation centres are regions of low pressure and high-pressure respectively. While 'C' circulation favors the development of weather phenomenon, 'A' circulation promotes clearer skies. Table 1 represents the number of 'C' and 'A' circulations detected for each season during the analysis period. 'D' indicates the corresponding number of days of observations. Seasonal, annual and inter-annual variations are also represented in the table. The last row shows the percentage of 'C' and 'A' circulation with respect to the total number of circulations. Out of 1228 days of analysed streamline charts at 850 hPa used in the present study, 9599 'C' circulation cases and 3904 'A' cases are identified over the study region. It is distinct that the frequency of occurrence of 'C' circulations is always larger than the frequency of occurrence of 'A' circulations. The difference between number of the C and A circulation is maximum during the southwest monsoon season. Conversely, 'A' circulation occurrence maximise during winter season. During the entire analysis period, 71% of circulation was 'C' and 29% 'A'.

4.1. *Annual characteristics*

The entire data points can be depicted as two figures. Figs. 2(a&b) represents the centre point distributions of all cyclonic and 'A' centre points during Aug 2014 to Feb 2020 (c) and (d) represents the frequency distribution of circulations (in percentage) for each pixel (2.5° × 2.5° grid) for 'C' and 'A' cases, respectively. It denotes with what frequency (in percentage) cyclonic or 'A' circulation centre point occurs in a 2.5° × 2.5° pixel/grid compared to the study domain. Analysis is also carried out for 5° × 5° and 10° × 10° (Figures not shown).

Cyclonic circulation distribution very clearly shows several associated meteorological s s features. Notable ones are the Indo-Gangetic plain monsoon rough (with several hotspots of 'C' circulation), the Baluchistan heat low, the Head Bay of Bengal monsoon depression/low associated deep convection, southwest peninsular off-shore trough related circulation and cyclonic vortices, the east equatorial Indian Ocean semi-permanent cyclonic circulation which regulates deep convection, etc. The Himalayan foothills boundary can be identified with the strong gradient in the number of cyclonic circulations near the region. A vast blankness over the Tibetan plateau



Figs. 2(a-d). Spatial distribution of centre point of circulations (a) cyclonic,(b) anticyclonic during Aug 2014 to Feb 2020. (c) and (d) represents the probability distribution (in percentage) of circulation for each 2.5° × 2.5° grid for cyclonic and anticyclonic cases, respectively

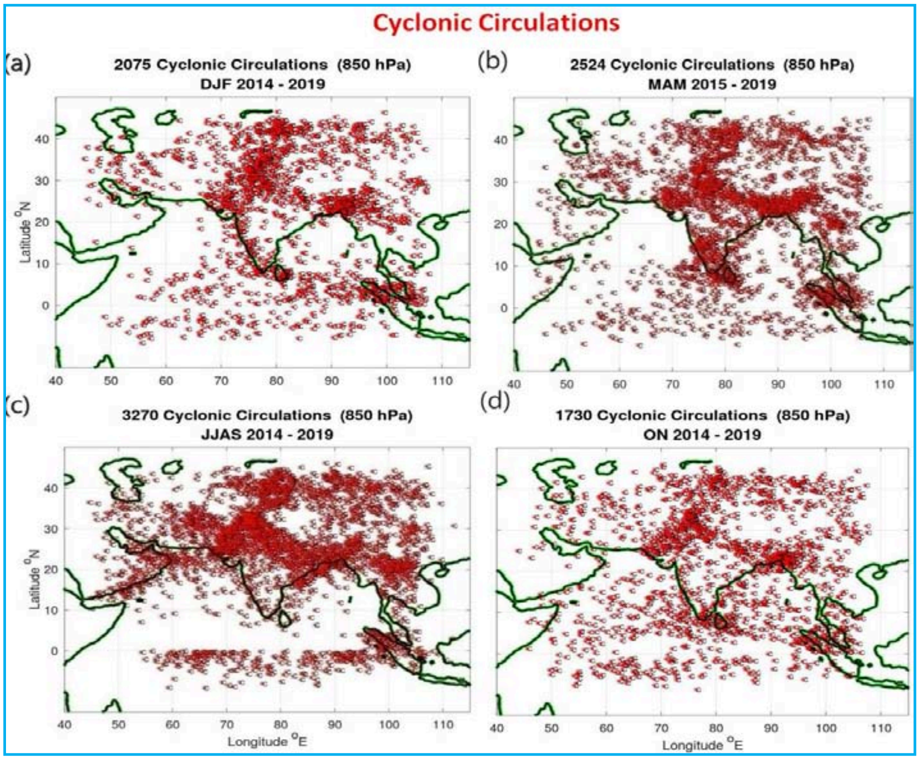
could also be distinguished. It is quite interesting to observe that the 'C' circulations are denser over the Indian landmass, revealing significant land-sea contrast in its spatial distribution.

The concentrations of 'C' circulations in the Pakistan and Afghanistan region are also a noticeable observation. Circulations are more prominent in number over the Bangladesh and northeastern states. Anticyclonic circulation pattern reveal the concentration of circulations in the south of the monsoon trough region stretching zonally. The Tibetan high (anticyclone) can be clearly made out in the figure with the concentration of 'A' circulations. High-pressure areas in the Arabian region, west equatorial trough etc can be identified as A circulations. The corresponding frequency distribution shows the concentration of 'A' centre points over the above mentioned regions. A broad ridge in central India can be visualized in Figs. 2(b&d) showing unorganized tilt in the 'A' distributions. It is to be noted that it has a high frequency distribution of A circulations as evidenced by (d). Widespread 'A' circulation points are noted in the Arabian region landmass (desert) pointing to the presence of high-pressure and large scale subsidence because of the strong descending air of Hadley circulation cell.

The frequency distribution of occurrence of circulation for the entire region (Fig. 2) shows the hotspots in the clusters. The monsoon heat-flow region stands out with a higher probability of occurrence of 'C' circulations (larger frequency of occurrence). This dry circulation is pronounced during the southwest monsoon season. On the other hand, hotspots in the West Bengal, Bangladesh regions correspond to weather activities like deep clouds and larger rainfall. It mainly impacts the landmass compared to the head Bay of Bengal. The western coast also shows considerably higher values, indicating more amount of circulation in the region. The equatorial trough (deep convection) is represented in the figure with higher values, in the East Equatorial Indian Ocean (EEIO) region which is the area of rising limb of zonal Walker circulation cell. In the case of 'A' circulations, hotspots get duly highlighted in south-central India, the Tibetan region, the Arabian region, including the northwest Arabian Sea, as well as north of the equatorial trough region.

4.2. *Seasonal characteristics*

To understand the seasonal characteristics of circulations, spatial distribution of centre points for both



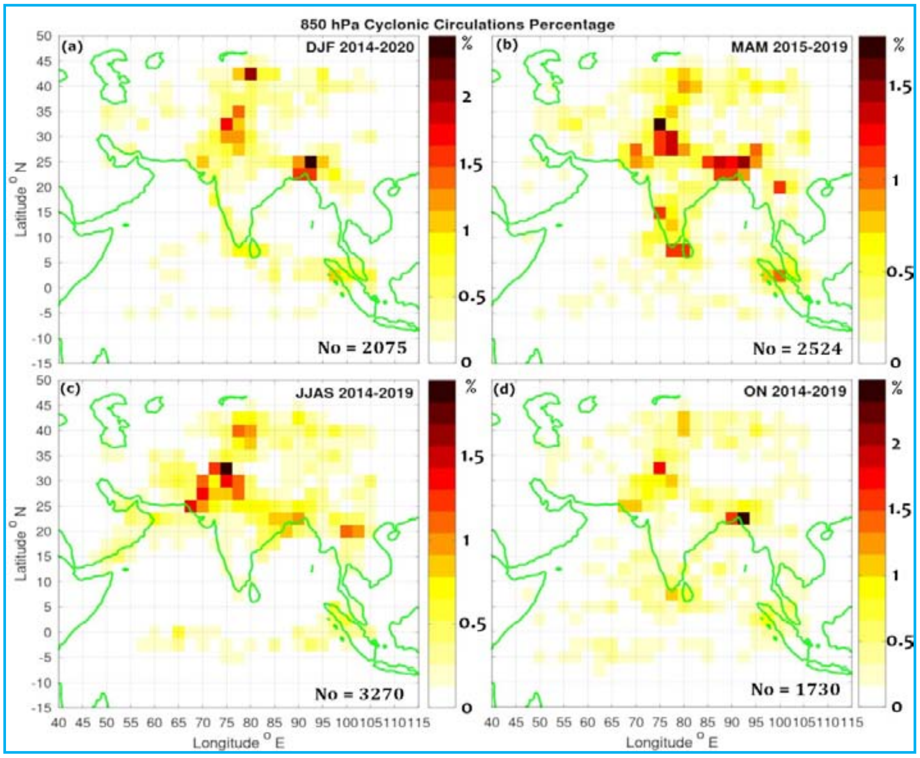
Figs. 3(a-d). Seasonal centre point distribution of cyclonic circulations during the study period. (a) Winter (Dec-Feb), (b) pre-monsoon (Mar-May), (c) southwest monsoon (Jun-Sep) and (d) post monsoon (Oct-Nov)

'C' and 'A' circulations are plotted for winter, pre-monsoon, southwest monsoon and post monsoon seasons.

4.2.1. *Cyclonic circulations*

Seasonal spatial distribution of 'C' circulation centre points can be visualized in Figs. 3(a-d) where, (a) represents winter (Dec-Feb 'DJF'), (b) pre-monsoon (Mar-May 'MAM'), (c) southwest monsoon (Jun-Sep 'JJAS') and (d) post monsoon (Oct-Nov 'ON'). From 332 days of streamline chart availability, 2075 'C' circulations are identified during DJF. Seasonal statistics of No. of 'C' circulations are given in Table 1. From Fig. 3(a), 'C' circulation is concentrated in north, northwest India, partly in northeast and Bangladesh. This can be directly attributed to the western disturbances which are frequent during the winter season. No. of 'C' circulation per day, are minimum during this season. During MAM, 2524 'C' circulations are identified from 288 days of streamline charts spread over the region with more frequency over landmass than the seas. A plausible reason could be - this season is characterised by high temperatures over the land resulting in thermally induced lows triggering cyclonic circulation aloft. No. of 'C' circulation per day is maximum during this premonsoon season. There were 3270 'C' circulations during JJAS spread over the landmass and ocean out of 377 days of streamline analysis. 'C' circulations are abundant over the monsoon trough, heat low region (Baluchistan, Rajasthan etc) and in the head Bay of Bengal. During ON, 'C' circulation are scattered and shows a sharp decrease in occurrence. In the present analysis, 1730 'C' circulations were counted in the region out of 231 days of streamline analysis.

Several interesting meteorological phenomena can be deciphered from the figures. For, *e.g*., comparing MAM and JJAS in the region near Somalia and south, suggests the disappearance of 'C' circulation in JJAS while, plenty of 'C' circulation are present during MAM. It explains the following phenomena - cyclonic circulations present in MAM is important in triggering the cross-equatorial flow of the Low Level Jet (LLJ) to strengthen, which prelude the conditions for the monsoon onset over Kerala. Also, locations of cyclonic vorticity during JJAS in the Arabian Sea influences moisture advection by directing LLJ through India or bypassing it creating active/break phases in the monsoon [Joseph and Sijikumar, 2004]. Another interesting feature is that 'C' circulations (from land lows and thermal lows/ heat lows) in peninsular India during MAM, are larger than in central India. The distinct and prominent scatter of 'C' circulations over the monsoon trough region during JJAS



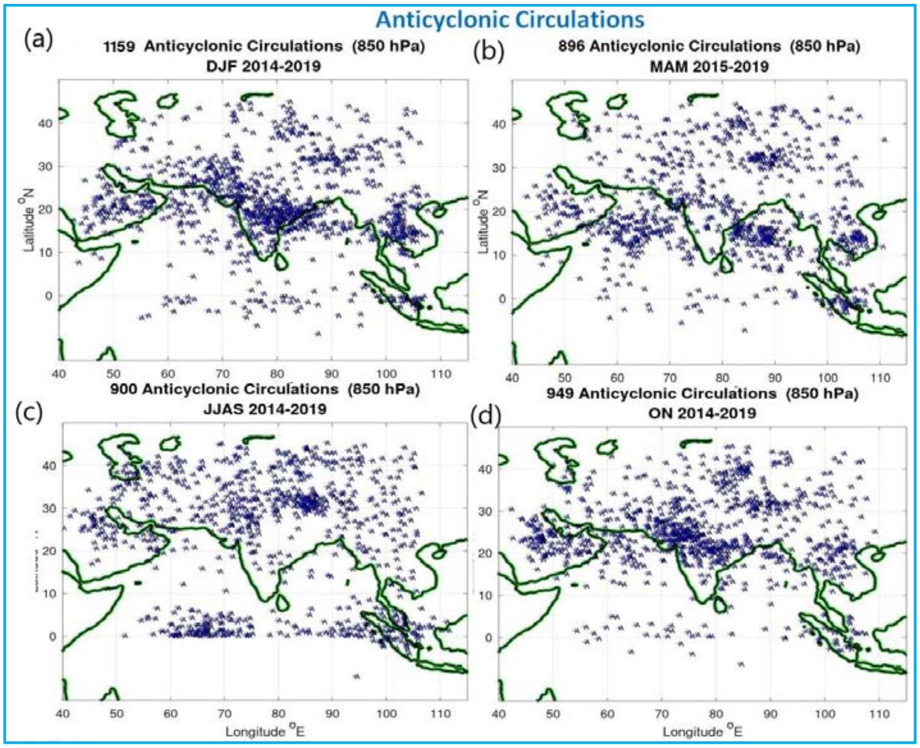
Figs. 4(a-d). Season wise frequency distribution of cyclonic circulations during the study period. (a) Winter (Dec-Feb), (b) pre-monsoon (Mar-May), (c) Southwest monsoon (Jun-Sep) and (d) post monsoon (Oct-Nov)

is clear evidence of circulation within the trough region. Perhaps this may be the striking feature of weather patterns with embedded circulations and well marked low pressure formations.

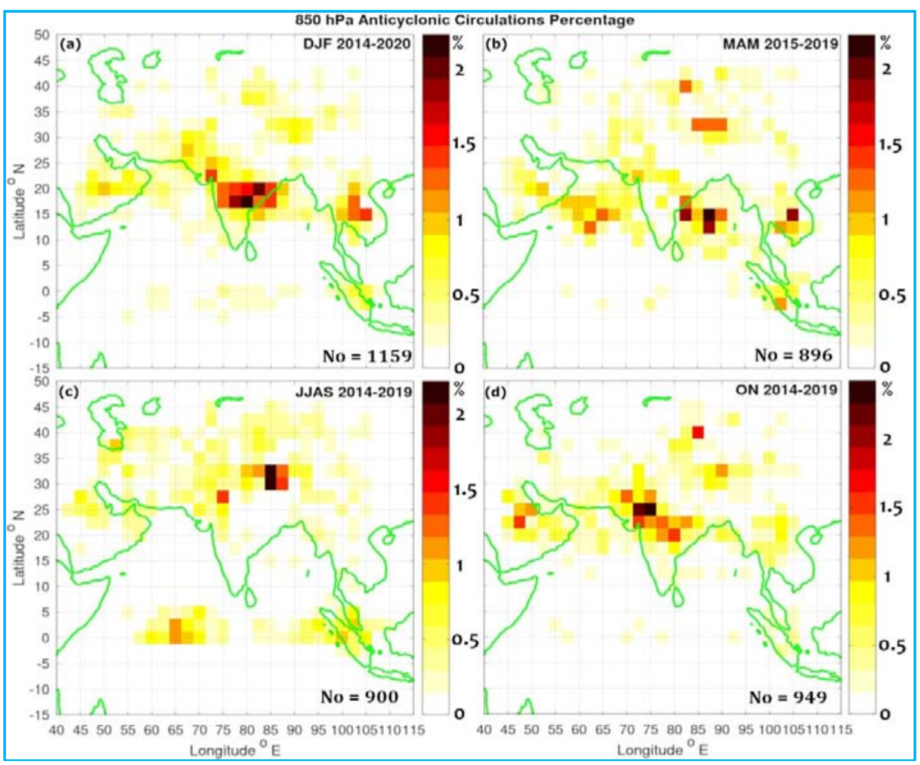
Cyclones develop in the Arabian Sea and the Bay of Bengal during MAM and ON. This can be deciphered from the present analysis. Daily tracks of cyclones that occurred during the data period [Liu *et al*., 2021] also happen to be embedded in Fig. 2 and Fig. 3. The cyclonic vorticity near the west coast of India over the Arabian Sea implies off-shore trough generation which promotes rainfall activity on the west coast. It is to be kept in mind that if the off-shore trough fails to develop into a 'C' circulation at 850 hPa, then it goes undetected in the present analysis. It is the reason why during the southwest monsoon season the number of 'C' circulation in the southeast Arabian Sea is relatively sparse. The scattered distribution of 'C' circulations centre points over the entire Bay of Bengal is observed during the post monsoon cyclone season, unlike those concentrated in the southwest and the southeast Bay of Bengal during MAM due to tracks of 'C' circulations and low pressure genesis in the respective regions. The deep convective zones over the East Equatorial Indian Ocean (EEIO) region are evident from Figs. 3(a-d) in almost all seasons, with more significant numbers during winter season. Clustering of 'C' circulations in the north-northwest during the pre-monsoon season is associated with Western Disturbances, those in the west peninsula due to thermal low in the Deccan Plateau and in the northeast to *'Kal Baisakhis'* activity. 'And his' occurring region can similarly be identified from 'C' circulation activities over the region.

4.2.2. *Anticyclonic circulations*

Seasonal statistics of the number of 'A' circulations are in Table 1. The corresponding spatial distribution of 'A' circulations can be visualised in Fig. 5. It provides an insight into the position and orientation of the lower tropospheric ridge-line. The frequency of occurrence of 'A' circulation per grid point is represented in Fig. 6. during the data period. Out of 332 days of streamline chart availability, 1159 'A' circulations were identified during DJF. During MAM, fewer number of 'A' circulations prevail in the region (896 circulations are identified from 288 days of the charts). Comparing with other seasons, there are 900 anticyclones identified from 377 days of observation during JJAS. It indicates that the monsoon season has a substantially lower frequency of occurrence of 'A' circulations in the region. ON had 949 'A' circulations during 231 days of observations. The



Figs. 5(a-d). Seasonal centre point distribution of anticyclonic circulations during the study period. (a) Winter (Dec-Feb), (b) pre-monsoon (Mar-May), (c) Southwest monsoon (Jun-Sep) and (d) post monsoon (Oct-Nov)



Figs. 6(a-d). Frequency distribution of 'A' circulations during the study period.(a) Winter (Dec-Feb), (b) Pre-monsoon (Mar-May), (c) Southwest Monsoon (Jun-Sep) and (d) post monsoon (Oct-Nov)

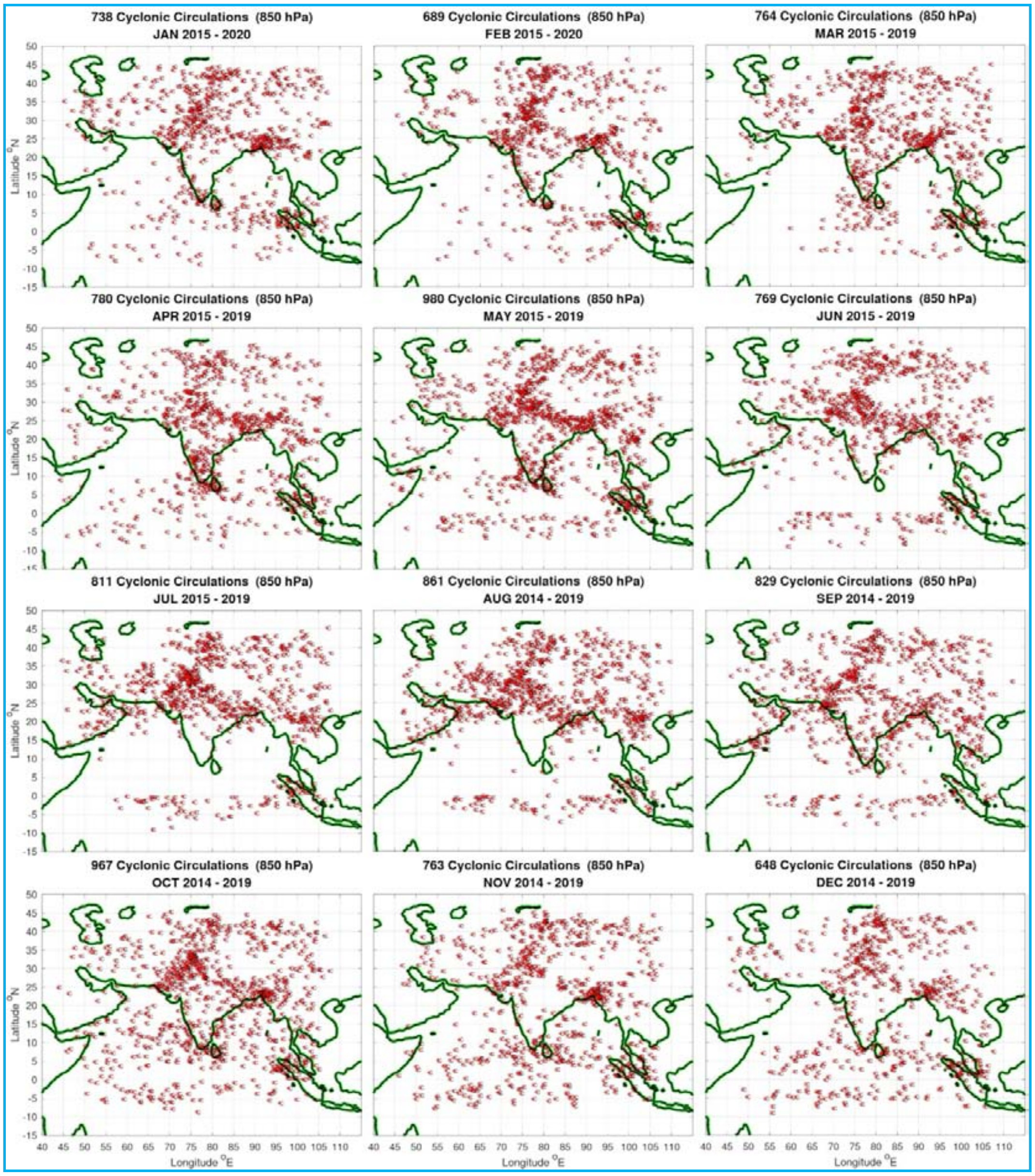


Fig. 7. Monthly centre point distribution of cyclonic circulations over the region

percentage of 'A' circulation increases to a maximum during ON there after decreasing in winter.

The frequency of occurrence of 'A' circulation is noticeably high during the winter season and is concentrated in clusters. Winter and post monsoon show its concentration in a northwest–southeast slanted axis over the south of the central Indian landmass. It shows a southward pattern parallel to the monsoon trough. This can be attributed to the subsidence of Hadley circulation cells during the post monsoon and winter season. 1 to >2 % of circulation occurring in the entire analysis region occurs in several of these grids. The largest frequency of occurrence is noted in regions surrounding Hyderabad area. Anticyclonic circulation clusters are observed throughout the year in the Arabian desert region, the Thar desert region (areas of strong subsidence). The pre-monsoon season shows significant number of 'A' circulations distributed in the seas and lesser numbers over the landmass. A noticeable feature is the cluster in the Tibet-Mongolia region present throughout the year with more concentration during the southwest monsoon season. No. of 'A' circulations over the Indian landmass and seas are least during this season. The west-central

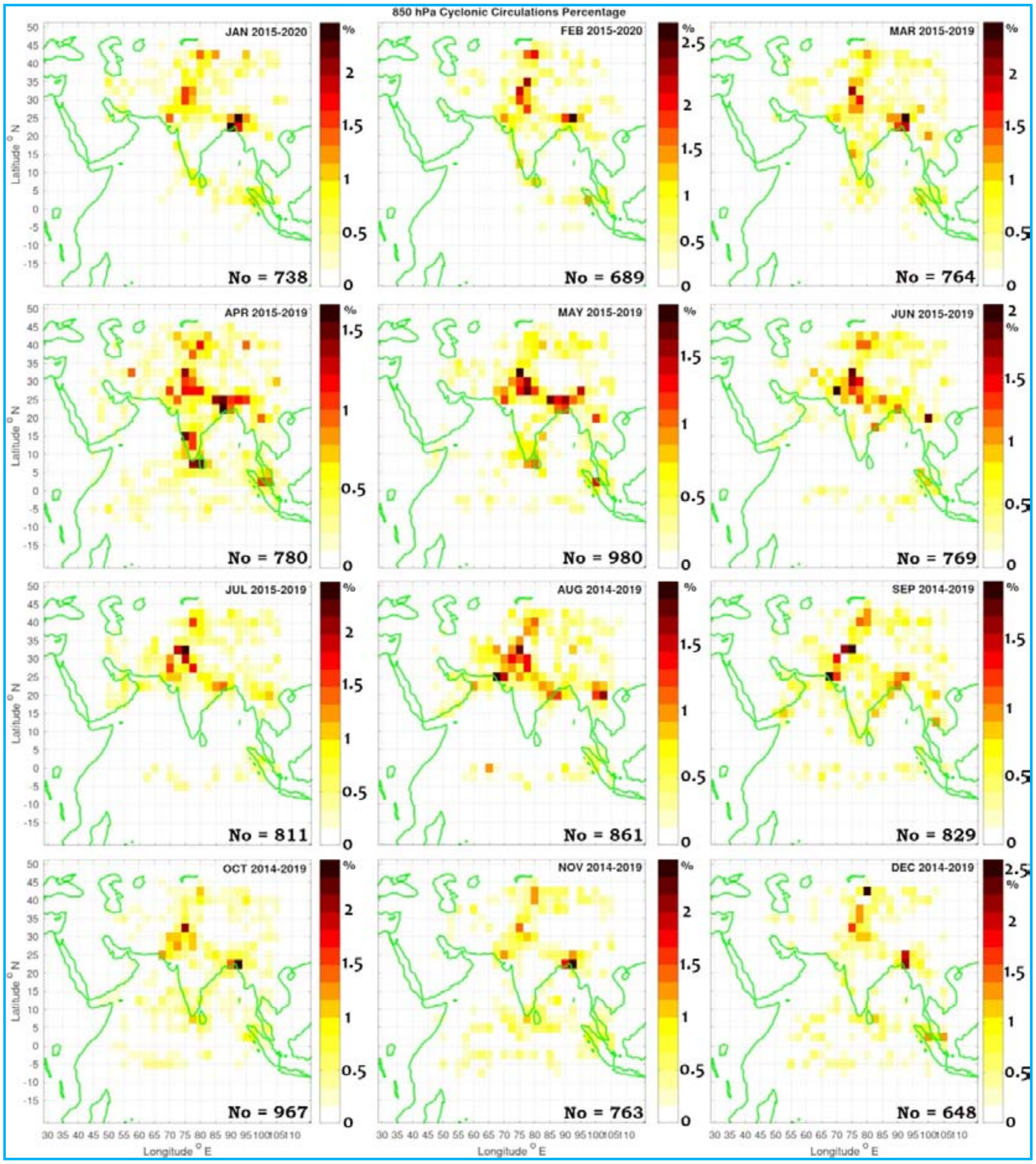


Fig. 8. Monthly frequency distribution of cyclonic circulations over the region

equatorial Indian Ocean is a region of 'A' circulation and plays an important role in the dynamics of the cross-equatorial flow. Post monsoon 'A' circulation is more concentrated on the landmass and develop like a prelude to the winter 'A' circulation distribution pattern.

4.3. *Monthly characteristics*

In order to understand the characteristics of both 'C' and 'A' circulations on a monthly scale, Figs. 7 and 9 are plotted for the analysis period. Corresponding latitude-longitude of centre points are identified. The spatial distribution frequency of occurrence is analysed. Corresponding monthly frequency distributions are presented in Fig. 8 and Fig. 10, respectively. Grossly, they represent the seasonal feature but careful observations reveal several interesting transition features (inter-seasonal and intra-seasonal changes) which are discussed below under two subsections 4.3.1 and 4.3.2.

4.3.1. *Cyclonic circulations*

Spatial distribution of centre points of 'C' circulations for Jan, Feb, ..., Dec are represented in Fig. 7.

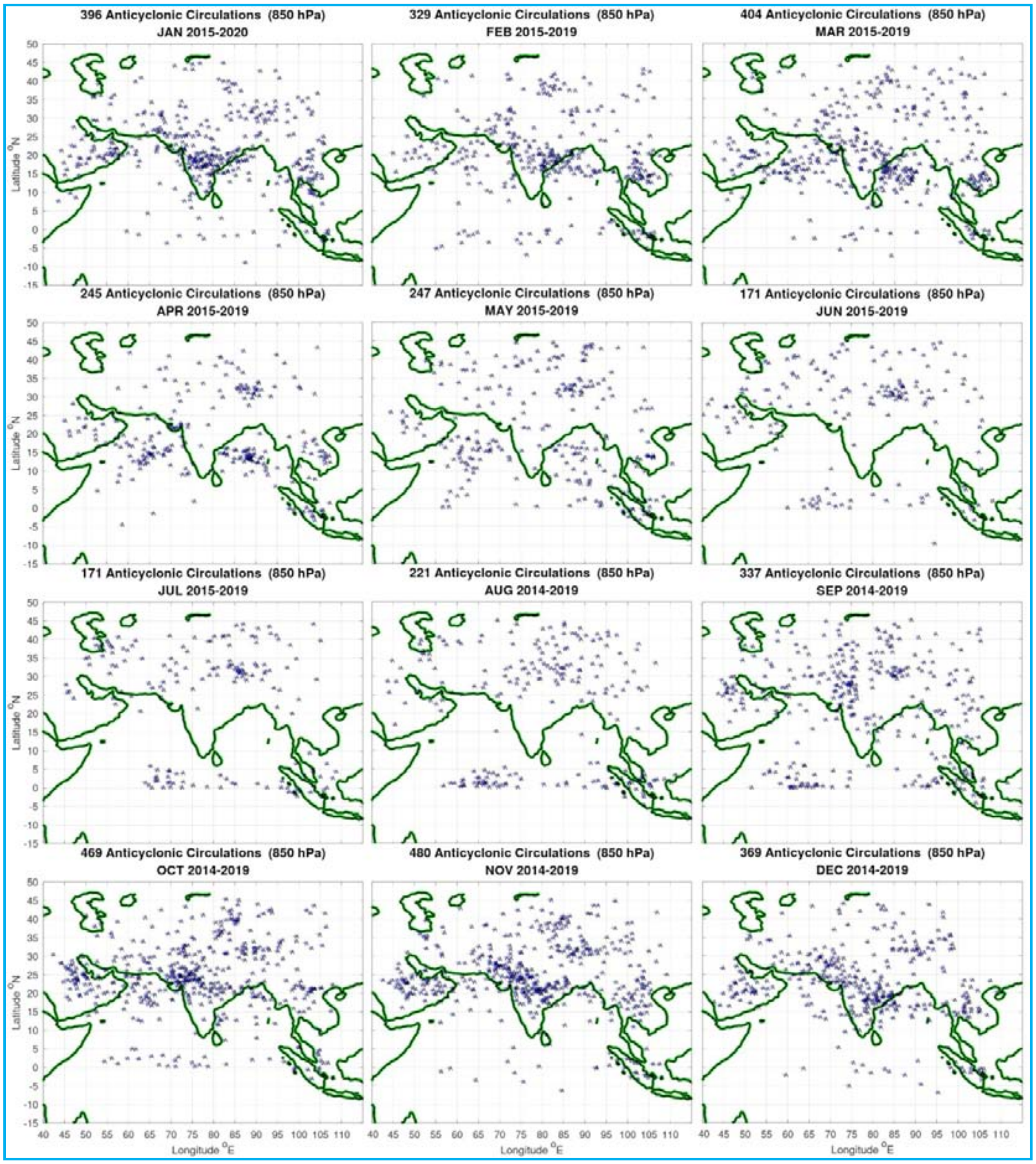


Fig. 9. Monthly centre point distribution of anticyclonic circulation

Corresponding grid-wise frequency distributions are represented in Fig. 8. Cyclonic circulations are present in certain regions throughout the year with varying intensity and with considerably less shift in centers. These 'C' circulation clusters are mainly in the Indo-Gangetic plain, the head Bay of Bengal, Jammu & Kashmir, Baluchistan region, equatorial trough region, etc. Dec, Jan and Feb, being winter months, are dominated by passing western disturbances in the north. This gets represented in Fig. 7 (north of 25° N) and Fig. 8. The large number of 'C' circulations is concentrated over this region (north and northwest India, Pakistan, Afghanistan, etc.).The passing low pressure systems in occluded form as western disturbance originating from the Mediterranean Sea shows its 'C' presence right from south Mediterranean, Iran towards India and southwest China without much effect over the Tibetan plateau. The eastward movement of trough and crest can be visualized in daily streamline charts (not shown). Compared with Fig. 8, hotspots for more probability of 'C' circulations (larger frequency of occurrence) match well in these regions.

The Indo-Gangetic belt and northeast India also come under the influence of these cyclonic circulations. It

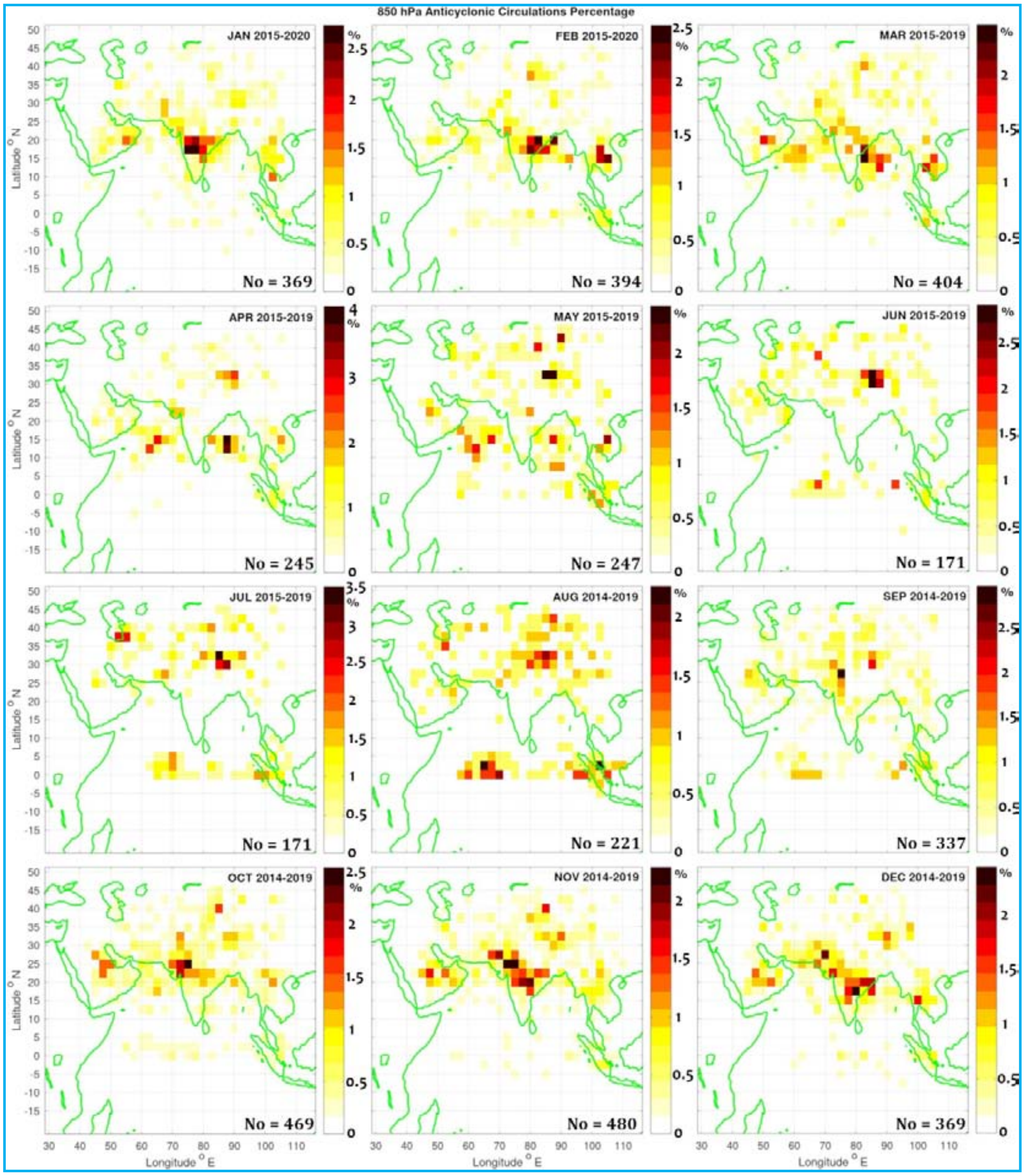


Fig. 10. Monthly frequency distribution of anticyclonic circulations

is a notable characteristic feature that only a small number of these 'C' circulations are observed over the Sea. During the winter season, central India is a region of subsidence (northward limb of the Hadley cell), 'C' circulations are absent. Meanwhile, the east equatorial Indian Ocean region is highly convective (rising limb of the Hadley cell), experiences a noticeably large number of 'C' circulations. The equatorial convergence zone can also be identified in 'C' circulations which extend from the east to the south of peninsular India. Fig. 8, shows larger 'C' probability density in the Kashmir, Baluchistan region, the Bangladesh and adjoining Indian states during these months. Indo-Gangetic belt 'C' circulations per grid are smaller than those in Bangladesh and Kashmir regions. During the pre-monsoon months of Mar-Apr-May, land area becomes warmer than the seas and starts building a large land-sea contrast in temperature.

Over the entire study region, Indian landmass shows an increasing number of cyclonic circulations over months, which is also evident in Fig. 8. These thermal low pressure systems support air convergence and drive cyclonic vorticity. 'C' circulation points are widespread over the north Indian and the Indo-Gangetic plain region. Compared to winter months, number of 'C' circulations over central and peninsular India is larger. Similarly, circulations over the coastal Arabian Sea and equatorial Indian increased overtime. The southwest monsoon months of Jun, Jul, Aug and Sep are characterized by low pressure in the north and high-pressure towards the south. Fig. 7 represents the dense distribution of 'C' circulations over monsoon low (heat low), monsoon trough, the head Bay of Bengal. Monsoon season - equatorial trough region is well demarcated in 'C' circulation. It is to be noted that 'C' circulation regions mostly correspond to low OLR regions. Where they have a good negative correlation, weather activities involving cloud development are present. For, *e.g*., deep convective clouds are present (low OLR) in the head Bay of Bengal, regions in the monsoon trough, northeast India, EEIO. On the other hand, spatial anti-correlation is noted in several region like the south peninsular India, southeast Arabian Sea, Baluchistan area, Iran, Arabian regions etc. Cyclonic circulations north of the Tibetan High during JJAS form an easterly wave pattern, but is a little explored from atmospheric kinematics viewpoint.

Two contrasting cases of cloud formation without 'C' circulation and cloud absence in the presence of 'C' circulation are, (*i*) in case of the south peninsular India and southeast Arabian Sea, LLJ advects large volumes of moisture, generating substantial cloudiness and rainfall. Interestingly, though a complete 'C' circulation is absent, occasionally off-shore troughs develop which leads to good rainfall in the west. (*ii*) In the case of Baluchistan, Iran and Arabian regions, thermally generated surface heat lows resulting in 'C' circulations are aloft but lack sufficient moisture, thereby inhibiting cloud development.

During post monsoon season, 'C' circulations are observed mainly in the southern peninsular and adjoining seas. During Oct, cyclonic vortices are plenty throughout the Bay of Bengal, especially near to the coast. During Nov,it is concentrated in the southern Bay of Bengal and the south Arabian sea. This is conducive for cyclogenesis. Those cyclones originating far north of equator, tend to recurve towards Bangladesh. Indo-Gangentic belt of 'C' circulation is nullified from Oct and Nov months. Cyclonic circulations cluster around the EEIO and south-equatorial Indian Ocean during the months. The 'C' circulation pattern suggests the possibility of the formation of a double ITCZ ([Saha, 1972; Meenu *et al*., 2007] in the west equatorial Indian Ocean region. From Fig. 7 and Fig. 8, it is evident that several changes occur within a season, but the general pattern remains the same. Cyclonic-Anticyclonic circulations are so dynamic that some months are more prone to 'C' circulations in a region while, it may reverse in the next month to 'A'.

4.3.2. *Anticyclonic circulations*

The monthly mean distribution of 'A' circulations is represented in Fig. 9. The corresponding spatial frequency of occurrence is shown in Fig. 10. From the Figures, monthly transition in the distribution of high-pressure centres can be easily identified. The number of 'A' circulation is tabulated in Table 1. A concentration/ clustering of 'A' circulations points are observed over central India in a zonal direction with a northwest to southeast tilt (prominent from Oct to Feb). Anticyclones are large in number from Oct to Feb and less during the southwest monsoon months. The concentration of 'A' circulation points to high-pressure over the region. These are mainly areas of subsidence of the Hadley cell in the northern hemisphere. No significant weather brews over the region, inhibiting vertical development of clouds and convection. The winter months of Dec, Jan and Feb are characterised by the concentration of 'A' points over central India and the Tibetan region. The near equatorial region has a band of anticyclones. A few 'A' points are formed over the Arabian Sea and the Bay of Bengal.

During the pre-monsoon months (Mar to May), anticyclonic circulations gets widely scattered spatially and become less pronounced over the land. Above the sea, it follows a disorganized pattern. An interesting feature during the southwest monsoon months of Jun, Jul and Aug is the near absence of 'A' circulations over the Indian landmass. During these months 'A' circulation exist in north of 30°N. While, Sep is a transition month, with 'A' circulation existing in north and west India. It moves is in tandem with monsoon rainfall withdrawal isochrones. Since the present study investigates changes in circulation on a monthly and seasonal scale, day to day and epoch changes in the circulation during active-break phases of the monsoon are not discussed. During the post monsoon season months of Oct and Nov, many anticyclones show their presence in north, west and central India. The western disturbance and near reversal of wind direction with the season are leading factors for this behavior. Genesis of clustering of 'A' circulations in the north Arabian Sea begins from Feb and becomes pronounced in Mar and Apr. It is also found in lesser concentration in May. This is evidenced by Fig. 10. Hot spots in the cluster indicate grids of a larger frequency of occurrence of 'A' circulation. It can be understood that once the LLJ starts setting in, the anticyclones drastically reduces and disappear. Therefore, anticyclones are absent during southwest monsoon months in the north Arabian Sea. With the weakening/withdrawal of LLJ as the season ends, circulation starts its presence in the above regions.

As an extension of the clustering of ‘A’ circulations in south central India, several anticyclones are present over the west Bay of Bengal during the winter months.

5. Conclusions

The present study is a first time analysis incorporating data from multiple sources (satellite, DWR, radiosonde, pilot balloons) in preparing hand drawn streamline charts for 850 hPa (1.5 km) aloft and extracting the centre coordinates of ‘C’ and ‘A’ circulations for detailed analysis. It brings out several interesting characteristics of circulation prevailing over the Indian and surrounding regions from Aug 2014 to Feb 2020. This paper discusses the characteristics of the spatial distribution of both ‘C’ and ‘A’ circulations in the long term, seasonal and monthly scale.

Irrespective of the season, frequency of occurrence of ‘C’ circulation is always larger than the frequency of occurrence of ‘A’ circulation. There are regions where ‘C’ circulation dominates and there are regions where ‘A’ circulation dominates. For, *e.g*., north India, Baluchistan and Kashmir, Indo-Gangetic plain, northeast India has ‘C’ while Gujarat, south-central India, central Arabian Desert experiences ‘A’ circulation at 850 hPa.

A few of the salient characteristics of circulation as deciphered from the present study are as follows.

(*i*) Several meteorological features are directly represented in ‘C/A’ circulations. For, *e.g*., the monsoon trough region has abundant ‘C’ circulation centre points, Hot spots of ‘C’ circulation present in Baluchistan heat low region and the head Bay of Bengal region; the Tibetan region and the Arabian region with clusters of ‘A’ activities etc.

(*ii*) ITCZ becomes visually manifested in ‘C’ circulations as a meridionally elongated distribution of ‘C’ circulations. Similarly, the case for deep convective regions of EEIO, head BoB, etc.

(*iii*) This analysis provides a new visual representation of ascending and descending regions of meridional (Hadley circulation) and zonal (Walker circulation) especially over regions where it is stronger.

(*iv*) Over the study region, The largest number of ‘C’ circulations are noted during the southwest monsoon season followed by the pre-monsoon season. They are comparatively lesser during winter and post monsoon season.

(*v*) Anticyclonic circulations are most prominent in number during winter followed by the post monsoon season. They are less and comparable in number during southwest monsoon and the pre-monsoon seasons.

(*vi*) The post monsoon and winter seasons are rich with ‘A’ circulations over the landmass while, it is concentrated more aloft the seas during the pre-monsoon season.

(*vii*) The generation mechanism of both types of circulation is dependent on seasonal wind fields and constrained by geographic location/orography. Traveling low/ high- pressure systems also trigger circulations.

(*viii*) Chain of several circulations and mini-circulations trapped between two nearby circulations were observed for several days where, they are indirectly controlled by them.

(*ix*) Cyclonic circulations over land are more in number than compared to those over the seas. Especially during the pre-monsoon season (thermal heat low - triggered ‘C’ circulations). Extremely sparse ‘C’ circulations are noted in the Arabian Sea during winter and the pre-monsoon seasons. Widely spatial distributed ‘C’ circulations in the Bay of Bengal during pre-monsoon and post monsoon season were observed.

(*x*) Cyclonic circulation hotspots are observed in southwest peninsular India, Sri Lanka and the adjoining southwest Bay of Bengal during pre-monsoon, post monsoon and winter season. While, they are sparse during the southwest monsoon season.

(*xi*) Almost ‘Nil’ ‘C’ and ‘A’ circulations over the “pool of inhibited cloudiness region” during Jun, Jul, Aug.

(*xii*) The anticyclonic circulation centre point distribution over India follows a parallel and southward pattern parallel to the monsoon spatial pattern (850 hPa ridge) compared to the tilt of the monsoon trough.

(*xiii*) Strong descending regions of the Hadley circulation cell could be visually manifested in the spatial distribution of anticyclonic circulation.

(*xiv*) The migration of circulation patterns on a monthly scale is in-line with the intra-seasonal changes. In various regions, clusters of circulations develops, spreads and dissipate, indicating month-to-month transitions. For, *e.g*., (*a*) Over the months, it can be noticed that the density of cyclonic circulations gradually undergoes transition from Pakistan-Afghanistan to the Indo-Gangetic plain upto north-west India. (*b*) Double ITCZ like pattern is observed in ‘C’ circulation centre points in the Arabian Sea. (*c*) Transitions of the equatorial trough over the months could be identified.

(*xv*) Clustering of 'A' circulations in the north Arabian Sea starts forming from Feb and becomes pronounced in Mar and Apr. It is also found in lesser concentration throughout May.

(*xvi*) Dec, Jan, Feb months show the northeast region with 'C' circulations but they are largely devoid of a substantial amount of rainfall.

(*xvii*) In the central Indian Ocean region adjacent to the Somalia coast, cyclonic circulations that often starts showing their presence during Mar-Apr, become sparse and disappear by May-June-July with the establishing of cross-equatorial wind flow (LLJ).

(*xviii*) Circulations generated due to frontal disturbances, western disturbances, 'Kalbaishaki' (Nor'westers), 'And his' also represented in the analysis for 'C' circulations.

(*xix*) Cyclone tracks in the seas over pre-monsoon and post monsoon seasons suggest different areas of genesis in the BoB.

(*xx*) The central Indian region experiences a strong subsidence contributing to the Hadley cell descending limbs during the winter season to a large number of anticyclonic circulations and a minimum of 'C' circulations. Low latitudes experience considerably lesser 'A' circulations aloft.

This detailed study began with application oriented daily tasks and later with an increase in databases, expanded into this present form with several applications including usefulness for air traffic planning. The study is expected to be useful for daily weather analysis and in operational weather forecasting. It could be a reference tool for pre-determining the frequency of cyclonic and anticyclonic circulations in a season. This is a major input towards planning for ISRO rocket launch activities (rocket meteorology sector) in a particular season/month from SHAR or TERLS or other range or from anywhere within the region of operation of interest. Also, analyses could be utilized as input and test beds for atmospheric modelers to assess their models under different scenario. This study is useful for region-wise or localised weather foresting purposes and is already been used in ISRO for providing "next 24 hr forecasts". Spatial-seasonal distribution of cyclonic and anticyclonic circulations is likely to be attractive for researchers, operational and commercial utilisation by meteorologists as well as students as it provides the visual manifestation of several weather phenomena. Inferences deduced from streamline analyses for different scenario could be utlised for short-time forecasting weather over a region. This study opens the door for newer dimensions of advanced research in meteorology. Voluminous database generated from several years of streamline analysis (as .jpg and data files) is potential to be used for machine learning tool for automating the process by machine learning and artificial intelligence application.

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