Tendencies of Tropical Cloud Clusters Transformation Into Tropical Cyclones

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Research Article

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Abstract

Tropical cloud clusters (TCC) play a vital role in earth's climate by not only releasing a large amount of latent heat into the atmosphere but also by forming the basis for development of tropical cyclones (TC). However, not all the TCCs can be developed into cyclones and only a few of them develop into TC, selectively. There are large uncertainties in present understanding on why only certain TCC develops into a TC and others don't? The present study employs the global TCC observations generated by GridSat and IBTrACS datasets from 1980 to 2009 to investigate the TCC distributions over the various Oceanic basins such as North Atlantic (NA), South Atlantic (SA), East-West and South Pacific (EP, WP and SP) and North Indian (NI) and South Indian (SI) basins. The central objective of the present study is to characterize the size spectrum of TCCs and to investigate their potential transformation into TC. The TCCs are identified based on the different IR temperature thresholds in each basin. The present results suggest that overall ~ 5.5% of TCCs were developed into TCs per year across the globe and there is an increasing trend in number of TCCs that were grown into TCs during the study period. The size spectrum of TCCs showed a dominant peak at 100-200 km^2. About 48% of TCCs transform into TCs within 24 hr of being identified. Furthermore, 85% of TCCs develop in to TCs within 84 hr of the first identification and only 5% of TCCs develop into TCs after 84 hr. Further, we have also analysed the background environmental conditions such as low-level wind speed, vorticity, divergence, vertical shear, upper level relative humidly and latent heating (LH) for developing and non-developing TCCs over NI basin. It is noted that the relative humidity in the developing composite is around 10-20% higher than that in non-developing TCCs and LH in developing TCCs is 0.15 K/hr larger than that in non-developing TCCs. The significance of the present study lies in investigating the developing TCCs as function of their size and lifetime including their long-term trends and bringing out the favourable environmental conditions for developing TCCs in the NI Ocean.

1. Introduction

A group of deep convective systems, which are considerably larger than the individual cumulonimbus clouds and produce a contiguous precipitation over an area about 100 km or more in horizontal dimension, is called as 'mesoscale convective systems' (Orlanski, 1975). These mesoscale convective systems over the Tropics, which are organized called as 'Tropical Cloud Clusters' - TCC (e.g., Houze and Bett, 1981; Huang et al. 2018). These systems play a key role in driving the large-scale circulations through latent heating, modifying earth's radiation budget by interacting with both solar and terrestrial radiations and in precipitation processes. Further, clumping of these tropical clouds form genesis for tropical cyclones and influence their lifetime also. Qualitatively, TCC can be defined as a large and encircled group of thunderstorms over a tropical oceanic basin and should satisfy the basic condition of pre-existing disturbance, which provides the necessary fuel in terms of latent heat to drive the basis for tropical cyclogenesis (Houze, 1982). A typical TCC has diameter ranging from 250-2500 km and lifetime of about 6-24 hrs (Maddox, 1981). Houze (1982) introduced four stages of TCC such as early stage where isolated deep convection prevails, mature stage dominated by widespread cirrus shield interconnected by deep convective towers, weakening stage dominated by startiform precipitation and the dissipating stage where precipitation ceases. As the TCC progresses from early to mature stage, the mesoscale updrafts strengthen by deep convective towers at mid to upper troposphere and associated downdrafts at lower levels dominated by evaporation and melting. Therefore, as the TCCs develop there is a net heating in the upper region of troposphere and a net cooling in the lower region of troposphere (Leary and Houze, 1979). The TCCs are important elements of tropical convective systems and engender vertical distribution of diabatic heating with a peak around 400 hPa and minimum value at ~ 600 hPa (Hartmann et al., 1984). Moreover, they strongly interact with the large-scale circulations (Chen et al. 1996; Laing and Fritsch 2000; Moncrieff, 2010). Owing to their importance in cyclogenesis, there have been many field campaigns/experiments in the past to understand the characteristics of TCCs, such as GARP (Global Atmospheric Research Programme) Atlantic Tropical Experiment - GATE (Leary and Houze, 1979; Houze and Betts, 1981; Johnson and Houze, 1987), Cooperative Convection Precipitation Experiment - CCOPE (Hobbs, 1978), Taiwan Area Mesoscale Experiment - TAMEX (Akaeda et al, 1995), Winter Monsoon Experiment – W-MONEX (Webster and Stephens, 1980; Churchil and Houze, 1984), Australian Monsoon Experiment - AMEX (Holland et al., 1986), Equatorial Mesoscale Experiment - EMEX (Webster and Houze, 1991) and Tropical Ocean Global Atmosphere-The Coupled Ocean Atmosphere Response Experiment - TOGA-COARE. Among all these field campaigns, GATE provided a wealth of information on the TCCs and contributed to the present understanding. Around 500 cloud clusters were examined by Martin and Shrener (1981), which were observed during GATE campaign over the West Africa and Eastern Atlantic Ocean and they found that the average life time of the observed cloud clusters is ~ 28 hours. Further, the authors estimated the area of the observed cloud clusters, which is on average found to be ~$2x10^5$ km^2. It is reported that the life time varied as a function of the area of the cloud cluster. Machado and Rossow (1993) studied the structural characteristics and cloud proprieties of TCCs using International Satellite Cloud Climatology Project (ISCCP) data and found that the convective (stratiform) portion on an average ocuupies20% (80%) of the TCC. They suggested that observed TCC can be classified into two categories, first (second) with lower (larger) cloud top pressure and higher (lower) optical depth associated with deep convection (mesoscale startiform anvil clouds). Most of earlier studies have shown that the life time of TCC is important as the longer duration of TCCs can modulate the atmospheric environment through moistening and heating and can facilitate interaction between the TCCs and their environment (Houze, 1982; Schumacher et al. 2009). These interactions form the basis for transformation of TCCs into TC (e.g., Gray, 1968; DeMaria et al. 2001; Schumacher et al. 2009; Kern and Chen, 2013).

There have been studies focusing on the atmospheric conditions that are required for TCCs to develop into TCs (e.g., Chen and Frank, 1993; Kern and Chen, 2013; Hennon et al. 2013; Teng et al. 2014; Teng et al. 2019). It is observed that only a very few percentage of observed TCCs develop into TCs (Hartmann et al. 1984). It becomes important to investigate the differences in environmental conditions for developing and non-developing TCCs. In this regard, there have been many studies focusing on theses aspects in the past with emphasis on characterizing the large-scale environmental conditions for developing and non-developing TCCs (e.g., Hennon and Hobgood, 2003; Kerns and Zipser, 2009; Kerns and Chen, 2013; Teng et al. 2014 & 2019). In general, it is known that the warm tropical oceanic region away from the equator with low-level relative vorticity and weak vertical wind shear are required for the formation of TCs (Gray, 1968). These large-scale environmental conditions are the main factors determining the likelihood of cyclogenesis, among the other factors (DeMaria et al. 2001; Schumacher et al. 2009; Kern and Chen, 2013). It is also reported that the favourable conditions for cyclogenesis have dependency on the size spectrum of TCCs including their life time and their interaction with the large-scale environment (Houze, 2010; Hennon et al. 2013). Tory and Frank (2010) reviewed the processes responsible for genesis of TC and focused on large-scale environmental conditions. These authors reinforced the pre-conditioning of the large-scale environment for the cyclogenesis in terms of sea surface temperature in the 26-27^0 C range, deep oceanic mixed layer of ~50 m, a deep layer of conditional instability, enhanced low-level cyclonic absolute vorticity, organized deep convection with relatively high humidity in the mid-troposphere and weak vertical shear of horizontal winds. This study also emphasized the importance of equatorial waves in initiating the cyclogenesis processes.

Fu et al. (2012) studied the developing and non-developing TCCs in the western North Pacific region using global daily analysis from Navy Operational Global Atmospheric Predication systems from 2003 to 2008. These authors reported that the observed cyclogenesis over the western North Pacific region are sensitive to dynamical variables as compared to that over North Atlantic region, where thermodynamic variables play an important role. Hennon et al (2013) and Kern and Chen (2013) documented the distribution of TCCs over the tropical oceanic basins and the differences in environmental conditions for the developing and non-developing TCCs. Teng et al. (2014) investigated the influence of large-scale phenomenon such as El Niño–Southern Oscillation on the formation of TCCs and their development into TCs in western North Pacific region. Zhao et al., (2018) using thirty years of TCC observations over the Western North Pacific, reported the changes in the efficiency of TCCs in developing into TCs. These authors have shown a decrease in developing TCs, which they attributed to weakening of circulation patterns and westward shift in the tropical upper-tropospheric trough. Very recently, Teng et al. (2019) examined the TCCs during July to October from 1981-2009 over the Western North Pacific region in terms of environmental circulation patterns to investigate the factors influencing their transformation into the TCs. Despite continuous efforts by many researchers across the globe, there is no general concise on what factors influence the transformation of TCCs into the TCs. The complete knowledge on the physical processes responsible for the transformation of TCC into TC is still an active area of research.

It is evident from the above discussion as well as earlier studies that there are relatively more studies over the Western North Pacific region as compared other tropical ocean basins especially over North and South Indian basins using long-term datasets on the development of TCCs into TCs. Moreover, there are limited number of studies focusing on the size and lifetime of the TCCs with respect to the cyclogenesis. Whether there is any preferential size of developing TCCs? The central objective of the present study is to investigate the roles of the size and life time of TCCs in the formation of TCs over the various tropical ocean basins using global TCCs datasets during 1981-2009. The observed trends in number of TCCs and their transformation into the TCs as a function of their size are also investigated. An attempt is also made to discuss the favourable environmental conditions for developing TCCs over North Indian Ocean, which is relatively less explored as compared other oceanic basins. Section 2 provides the details on datasets employed in the study, results are discussed in section 3 and section 4 provides the summary.

2. Data And Methodology

The present study employs 28 years of global TCC data (version v01r01) during 1982-2009 generated by Hennon et al. (2011). GridSat IR brightness temperature data were used to identify the TCC based on the presence of convective system and its size, shape and duration (Knapp et al. 2011). GridSat dataset provides homogeneous measurements of IR from 32 geostationary satellite platforms, which includes GOES, Metsat, GMS and others (Hennon et al., 2011; Knapp et al. 2011). The threshold for brightness temperature data for identifying the TCC were given in Table 1 for different oceanic basins. In brief, the main criteria for identifying the TCC as reported by Hennon et al. (2011) are: the first criteria is size and intensity- GridSat IR pixels should satisfy the brightness temperature thresholds for each basins and its radius should be around 1 degree in order to be considered as a TCC group. Second criteria is that they should form only over the oceanic regions and those formed over the land were eliminated, since cyclogenesis cannot proceed over the land regions. Third criteria is to separate TCCs with close proximity to others. They should be separated by more than 1200km away from each other. The fourth criterion is about the life span. Once TCC identified, it must persist at least for 24 hours, a search radius algorithm is used to determine whether the TCC is newly or previously formed (Hennon et al. 2011). Further, global best cyclone track dataset (IBTrACS) (Knapp et al., 2010) is employed to identify the transformation of TCCs into TCs. Details on technical algorithms can be found in Hennon et al. (2011). However, this global TCC dataset does not detect all the developing cloud clusters and around 25% of TCs listed in IBTrACS are not tracked prior to genies (Hennon et al. 2011). In addition, a gap in geostationary coverage of the Indian Ocean produces artificially low global counts of TCCs prior to 1998 (which is not resolvable) (Hennon et al. 2011). Therefore, the above caveats are to be kept in mind while analysing and interpreting the global TCC dataset. For the present study the analysis is carried out separately for each tropical oceanic basin during the observational period. The number of TCCs that are developed into TCs are identified based on flag values given in global TCC dataset. The size spectrum of TCCs in terms of their average radius including their lifetime in each basin is analysed. Hennon et al. (2011) dataset provides information on the size of the identified TCCs in terms of maximum radius (largest distance from the geometric canter to the edge of the TCC around azimuth), minimum radius (smallest distance from the geometric canter to the edge of the TCC around azimuth) and average radius (average distance from the geometric canter to the edge of the TCC around azimuth). The average radius is regard as a good indicator of the TCC. In the present study, the efficiency of TCCs to transform in to TCs is investigated in terms of their size and life time. Time series of TCCs during 1982-2009 are employed to estimate their trends in each oceanic basin as well as trends in the efficiency of their transformation into TCs are estimated.

Table 1
Thresholds for identifying TCC based on brightness temperature information and dates of season for which they sampled for the present dataset (Hennon et al., 2011).

Basin	Threshold (K)	TC season
North Atlantic (NA)	224	1 June–30 November
South Atlantic (SA)	227	1 November–30 April
East Pacific (EP)	228	15 May–30 November
South Pacific (SP)	221	15 October–15 May
West Pacific (WP)	219	15 October–15 May
North Indian (NI)	218	1 April–15 December
South Indian (SI)	221	1 April–15 December

ERA-5 reanalysis data during the TCC events are employed to investigate the background environmental conditions. An attempt is made to distinguish favourable conditions for developing TCC in terms of background wind at 850 hPa, divergence, relative vorticity, wind shear and humidity. The analysis was limited to North Indian Ocean as the investigations over this oceanic basin are limited.

3. Results And Discussion

Figure 1 shows the global map of geographical locations of TCCs from 1982-2009. Blue colour dots indicate the positions of TCCs and red colour dots indicate the locations of TCCs that are grown into cyclogenesis. Though the TCCs are more or less uniformly distributed across all the oceanic basins, there are preferential locations for the TCCs that are developing into TCs. To demonstrate this aspect quantitatively, Figure 2(a&b) shows the spatial distribution of TCCs and distribution of TCCs that are developed into TCs, respectively. From figure 2(a), it can be noted that on average maximum number of TCCs is found over the regions of East Pacific (EP), North Atlantic (NA), North Indian (NI) and South Pacific (SP). But the maximum numbers of TCCs transformed into cyclonic storms are more over West Pacific (WP) and EP region, as shown in Figure 2(b). The genesis productivity (GP), which is the percentage of TCCs that develops into a TC, is estimated (Hennon et al., 2013) and shown in Figure 2(c). A higher (lower) GP indicates a more (less) favourable conditions for TCCs that develops into TCs. The high GP values are found over WP, EP, NA and South Indian Ocean (SIO) basins as seen in Figure 2(c). However, their efficiency of transformation of TCCs into TCs is high only over EP and WP regions. Though, the higher GP values are found over NA and SIO basins, the number of TCCs are less as compared to EP and WP regions. Overall, around 5.5% of TCCs are converted into TCs per year over the globe.

Figure 3 (a) shows the number of TCCs developed into TCs from 1980 to 2009 over all the oceanic basins. From this figure, it is evident that TCCs that are developed into TCs are increasing with time with a few large peaks. In order examine whether there is any preferential size of TCCs that are more efficiently developing into TCs, the size spectrum of TCCs are analysed. The size distribution of TCCs is shown in figure 3(b). The maximum number of TCCs are found to be having 100-200 km^2 size. It is also noted from this figure that the number of TCCs decrease with the size. This figure thus provides the mean size distribution of TCCs observed in all the oceanic basins. Figure 4(a-d) shows the spatial distribution of TCCs of size 0-100 km^2, 100-200 km^2, 200-300 km^2 and greater than or equal to 300 km^2, respectively that are developed into TCs. From figures 3 and 4, it is clear that the dominant size of TCC is 100-200 km^2 and at the same time it is the most favourable cloud cluster size to develop into a TC. The tendency of TCCs developing into TCs is significant for the sizes up to 300 km^2 in EP, NA, WP, SI and SP basins. There are relatively less number of TCCs with sizes greater than 300km^2 that are developing into TCs as shown in figure 4(d). Thus figures 3 and 4 provide information on TCCs size distribution and the preferential sizes that are favourable for developing into TCs, which is relatively a new aspect of the present study. Recently, Wang (2018) emphasized the importance of spatial structure of cloud cluster for the formation of tropical cyclogensis and noted that the organized cloud clusters is one of the key features for TCC to become TC. It is also to be remembered that the development of TCCs into TCs is more sensitive to environmental conditions apart from their size distribution as discussed in the section 1.

To examine whether the duration of a give TCC play a role in triggering cyclogenesis, the life time of these cloud clusters are investigated. Earlier works demonstrated that the life time of TCC plays significant role in formation of cyclogenesis. The knowledge of how long TCCs stay in the atmosphere is important information as they release a large amount of latent heat into the atmosphere. This further alters the vertical structure of atmosphere (e.g., Houze, 1982). Figure 5 shows the percentage of TCCs developed into TCs as a function of their lifetime. Around 48% of TCCs transforms into TCs within 24hrs of being identified. Furthermore, 85% of TCCs develop into TCs within 84hrs of the first identification and only 5% of TCCs develop into TCs after 84hrs. Interestingly, the occurrences of TCCs turned into TCs are increased very steep within 24hrs of first identification as seen in figure 5. It was found that the short lived TCCs develop rapidly into a TC and dissipate very quickly. In contrast, the long lived TCCs develop gradually to become a TC and decay slowly. Recently, Kern and Chen (2013) studied the differences between the developing and non-developing TCCs based on large-scale environments. They identified that the minimum life time of 8hrs is required for TCC to transform into a TC. Hennon et al. (2013) studied the lifespan of TCC and they observed that the most of the TCCs developed into TCs within 24hrs of their identification. Figure 6 shows the life time of TCCs with respect to their size for those developed into TCs. From this figure, it is clear that the cloud clusters having the size in the range of 100-200km^2 with 18-42hrs life time are most probable candidate to become cyclogenesis. The number of TCCs is relatively large in the size range of 100-200km^2 as compared to others. As the lifetime increases, the efficiency of transforming into TCs are declining at all the size ranges as shown in this figure. The life time of large TCC with size of the order of 600km^2 is found to be 18hrs. From this figure, it is evident that for a TCC to develop into a TC, its size as well as its life time are equally important.

To bring out the long-term changes in the TCCs with size ranging from 100-200 km^2 that are transforming into TCs, the time series is constructed over various oceanic basins as depicted in Figure 7. Overall increasing trends in developing TCCs are observed in NA, NI, SI and WP basins from 1980 to 2009 in this size ranges whereas decreasing trends are observed in SP and EP basins. Interestingly, the rate of increase is large from the year 2000 in all basins except SP and EP, wherein sharp decrease is observed. Initially, developing TCCs shows decreasing trends in the NA basin up to 1993 and then exhibit increasing trends as shown in figure 7 (a). It is interesting to note a plateau region in number of TCCs during 1992 to 1998 in the WP basin. A decreasing trend in developing TCCs is observed in the SP and EP basins. To quantify the observed long-term changes, the trend analysis is carried out and figure 8 shows the trends along with 95% confidence intervals in number of developing TCCs in various oceanic basins. From this figure it is clearly evident that number of developing TCCs are increasing in NA, WP, NI and SI basins. Though an increasing trend found in these oceanic basins, only NA and NI basins show the significant trends. If 95% confidence intervals contains zero, then the estimated trends are not significant as one cannot rule out the null hypothesis. The observed decreasing trends over EP and SP are also not significant as the confidence intervals contain zero. However, from the time series shown in figure 7(f) and (g), one can infer the decreasing trends. Further, one should have long-term measurements to arrive at any general conclusions. The present time series is limited to 1981-2009 and efforts have to be taken to extend this dataset on TCCs to arrive at any general conclusion.

As discussed in section 1, the background environmental conditions play a key role in deciding whether or not a TCC develop into a TC (Lee, 1989; McBride and Zehr, 1981; Zehr, 1992; Chan and Kwok, 1999; Fu et al., 2007 & 2012; Peng et al., 2012). There were many studies on this topic focusing on western North Pacific and North Atlantic basins. For example, Fu et al. (2012) reported that the western North Pacific region showed distinct large-scale synoptic conditions for developing TCCs as compared to the North Atlantic basin. However, large-scale synoptic conditions favourable for developing TCCs are relatively less explored in the NI basin. In this regard, in the present study, the differences in the background environmental conditions for developing and non-developing TCCs in the NI basin are analysed. The TCCs that are formed during 2005 to 2009 period are considered. Earlier, Pattanaik (2005) studied the environmental differences between the high frequency and low frequency storm activity periods in the NI ocean basin. The author found that low frequency storms are associated with relatively large vertical shear in horizontal winds and decrease in mid-level humidity compared to that of high frequency storm period. As of now, six geophysical parameters such as sea-surface temperature (SST), Coriolis parameter, low level vorticity, low level vertical shear, instability and tropospheric moistening in mid-level are identified as key parameters associated with the genesis of TCs (e.g., Teng et al., 2020). In order to understand the general background environmental conditions in NI basin, a composite of background environmental parameters are constructed. Table 2 provides the list of the cases considered for developed and non-developed TCCs in NI basin during 2005-2009. Strong low-level convergence, weaker vertical shear of horizontal winds, sufficient low-level vorticity and upper tropospheric humidity characterize the tropical cyclogenesis. Therefore, to identify the differences in background environment conditions for developing and non-developing cases, wind speed at 850hPa, divergence and vorticity at

850hPa, shear between 200 and 800hPa and relative humidity at 500hPa are considered. Further, we constructed the composite of all these parameters with respect to each storm center for all the cases listed in Table 2. The storm center location and date is taken from India Meteorological Department (IMD) as provided in Table 2. To investigate the background conditions for developing and non-developing cases, all cloud clusters are considered for the same year and season. These composite results indicate mean state of the atmosphere during the occurrence of TCCs in the NI basin.

Table 2
List of cases considered for developing and non-developing TCCs over NI basin during 2005-2009 period.

Developing				**Non-developing**		
S.No.	**Date**	**Longitude (ºE)**	**Latitude (ºN)**	**Date**	**Longitude (ºE)**	**Latitude (ºN)**
1	13-Dec-2005	90.75	4.75	9-Dec-2005	99	0
2	26-Jun-2005	89.5	22.25	20-Jun-2005	85	14
3	26-Nov-2005	93.25	9.25	15-Nov-2005	89	3
4	25-Oct-2005	84.75	11.75	29-Oct-2005	96	1
5	11-Sep-2005	86.25	19.5	18-Sep-2005	96	9
6	26-Oct-2006	78.75	7.5	7-Oct-2006	81	14
7	9-Nov-2007	94	10	3-Nov-2007	99	5
8	15-Jun-2008	89.5	21.5	21-Jun-2008	96	10
9	16-Oct-2008	64.75	8.25	22-Oct-2008	70	11
10	14-Sep-2008	89.5	19.25	22-Sep-2008	84	17
11	18-Jul-2009	89.25	20.5	28-Jul-2009	86	19
12	20-Jun-2009	70.25	16	25-Jun-2009	88	13
13	7-Nov-2009	76	9	10-Nov-2009	75	5

Figure 9(a and b) shows the composite of wind speed at 850 hPa for developing and non-developing TCCs. It can be noted that there is a pre-existence of low-level vortex for cyclogenesis cases as shown in figure 9(a), while it was not observed during non-developing cases as shown in figure 9(b). These figures are composite of 13 cases and thus assume their importance as only coherent structures will be retained while averaging. This figure thus emphatically shows that all the developing cases have strong low level vortex. Figures 9(c, e & g) depict the magnitude of the environmental divergence, vorticity and vertical shear of horizontal winds for developing cases. Strong low-level convergence, high vorticity and weak vertical shear are prevailed for developing cases around 500km from the disturbance center. From figures

9(g) and (h), it can be noted that the low-level vertical shear is weak in developing cases compared to non-developing cases, which is one of the necessary conditions for a TCC to sustain and develop into a TC at later stages. TCCs having the strong low-level vertical shear are less effective in cyclonic angular momentum (Holland, 1983). In non-developing cases, there is no low-level convergence and strong vorticity as shown in figures 9(d) and (f). Significant differences are noted in the vorticity between the developing and non-developing cases both in the pattern and magnitude. Gray (1968) discussed the importance of strong low-level vorticity and weak vertical shear of horizontal wind in determining the regions of high probability of tropical cyclogenesis. Earlier studies (e.g., Lee and Gray, 1984; Lee, 1986) reported that there are low-level large-scale wind surges which cause the vorticity build-up around the vicinity of the pre-cyclogenesis. Figures 9(i and j) shows the relative humidity composites at 500hPa for developing and non-developing cases. The maximum mid-level relative humidity is found to be closer to the center of the disturbance and the distribution is more symmetric with respect to the center, which is not seen in non-developing cases. The upper level moistening is one of the key components for a developing TCC (Sadler, 1976; Emanuel, 1994; DeMaria et al., 2001). Overall, the relative humidity in the developing composite is around 10-20% higher than that in the non-developing TCCs. Fu et al. (2012) also reported similar results in western North Pacific basin.

The latent heating (LH) in the TCCs also plays a pivotal role in the developing TCCs. The LH profiles obtained from TRMM measurements are analysed to investigate the differences between developing and non-developing TCCs. Figure 10 shows the composite distribution of LH in developing cases and non-developing cases in the NI basin. From this figure, it is evident that the larger LH values are found in developing cases within 500km radius form the disturbance center compared to non-developing cases. The net warming is due to the resultant of condensation, freezing and deposition of water molecules. Though there is relatively large LH at some pockets in non-developing cases, these regions are away from the center of disturbance as shown in figure 10 (b). Further, to investigate the vertical structure of LH inside the cloud clusters for developing and non-developing cases, the mean vertical profile of LH within a radius of 500km from disturbance center is estimated as shown in Figure 11. The mean latent heating is 1.12 K/hr for developing (red color line) and 0.97 K/hr for non-developing (blue color line) TCCs. Thus on average, LH in developing TCCs is 0.15 K/hr larger than that in non-developing TCCs. It is known that the larger LH release aids in stronger updrafts which leads more intense convection for developing TCCs. Collimore (2018) reported the difference in thermal structure for developing and non-developing cases. The author observed warmer temperature in the troposphere for the developing cases indicating the larger LH release. Thus from figure 9 and 10, it can be inferred that strong low-level vorticity, weak wind shear, mid-troposphere moistening and large LH are the key factors for TCCs to develop into a TC in the NI. These results are drawn from composite of thirteen developing and non-developing cases.

4. Summary And Concluding Remarks

In the present study, we analyzed the global TCC observations from GridSat and IBTrACS measurements during 1980 to 2009 to study their distribution and potential to develop into cyclogenesis over the various oceanic basins such as NA, SA, SP, WP, EP, NI and SI basins. It is noted that on an average ~5.5% TCs develop into TCs across all the oceanic basins. The size spectrum of TCCs including their life time is investigated to know whether there exits any preferential size of TCC that efficiently develop into TC. The results revealed that TCCs having sizes in the range of 100-200km^2 are preferentially developing into TC. Further it is noted that around 48% of TCCs developed into TCs within 24hr of being identified. By combining the size and lifetime of TCCs, it is found that TCCs having sizes in the range of 100-200km^2 with 18-42hrs lifetime are most probable candidates to develop into cyclogenesis. The time series of number of developing TCCs in the size range of 100-200 km^2 over the various oceanic basin showed an increasing trend in the NA, WP, NI and SI basins whereas it showed decreasing trends in the SP and EP basins. However, the estimated trends are significant at 95% level only in the NA and NI basins, which show an increasing trend in the developing TCs.

An attempt is also made to investigate the synoptic conditions conducive for developing TCCs in the NI oceanic basin, which relatively less explored, using reanalysis datasets. A composite of background synoptic conditions for developing and non-developing TCCs is constructed using thirteen case studies. The parameters such as low-level wind speed, vorticity, divergence, vertical shear of horizontal wind and mid-tropospheric relative humidity are chosen for the investigation. It is noted that a strong low-level vorticity, weak vertical shear of horizontal wind and mid-tropospheric moistening are the most favourable conditions for developing TCC. It was also found that the relative humidity at 500 hPa in developing TCCs is ~10-20% higher than those in non-developing TCCs. Further, the analysis showed that relatively larger LH released in developing cases within 500 km radius of the centre of the disturbance compared to non-developing cases. The present study thus brought out the distribution of TCCs including their size spectrum, life time and long-term trends. The background synoptic conditions favourable for developing TCCs in the NI oceanic basin are also discussed.

Declarations

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References

1. Akaeda K, Reisner J, Parsons D (1995) The role of mesoscale and topographically induced circulations initiating a flash flood observed during the TAMEX project. Mon Wea Rev 123:1720–1739
2. Bergman JW, Salby ML (1997) The role of cloud diurnal variations in the time-mean energy budget.J Clim101114–101124
3. Chen SS, Frank WM (1993) A numerical study of the genesis of extratropical convective mesovortices. Part I: Evolution and dynamics. J Atmos Sci 50:2401–2426
4. Chen SS, Houze RA, Mapes BE (1996) Multiscale variability of deep convection in relation to large-scale circulation in TOGA,COARE. J Atmos Sci 53:1380–1409
5. Churchill DD, Houze RA (1984) Development and structure of winter monsoon cloud clusters on 10 December 1978. J Atmos Sci 41:933–960
6. Collimore CC, Thesis (2018) https://escholarship.org/uc/item/5c9767b8
7. Copernicus Climate Change Service (C3S) (2017) ERA5: Fifth generation of ECMWF atmospheric reanalyses of the global climate. Copernicus Climate Change Service Climate Data Store (CDS), date of access. https://cds.climate.copernicus.eu/cdsapp#!/home
8. Demaria M, Knaff JA, Connel BH (2001) A tropical cyclone genesis parameter for the tropical Atlantic. Wea Forecasting 16:219–233
9. Emanuel KA (1994) Atmospheric Convection. Oxford University Press, Oxford, UK
10. Frank WM, Roundy PE (2006) The role of tropical waves in tropical cyclogensis. Mon Wea Rev 134:2397–2417
11. Fu B, Peng MS, Li T, Stevens DE (2012) Developing versus Non developing Disturbances for Tropical Cyclone Formation. Part II: Western North Pacific. Mon Wea Rev 140:1067–1080
12. Gray WM (1968) Global view of the origin of tropical disturbances and storms. Mon Wea Rev 96:669–698
13. Hartmann DL, Hendon HH, Houze RA (1984) Some implications of the mesoscale circulations in tropical cloud clusters for large-scale dynamics and climate. J Atmos Sci 41:113–121

14. Hennon CC et al (2013) Tropical Cloud Cluster Climatology, Variability, and Genesis Productivity. J Climate 26:3046–3066
15. Hennon CC, Hobgood JS (2003) Forecasting tropical cyclone cyclogenesis over the Atlantic basin using large-scale data. Mon Wea Rev 131:2927–2940
16. Hennon CC, Helms CN, Knapp KR, Bowen AR (2011) An objective algorithm for detecting and tracking tropical cloud clusters: Implications for tropical cyclogenesis prediction. J Atmos Oceanic Technol 28:1007–1018
17. Holland GJ, McBride JL, Smith RK, Jasper D, Keenam TD (1986) The BMRC Australian Monsoon Experiment: AMEX. Bull Amer Meteorol Society 67:1466–1472
18. Holland JG (1983) Angular momentum transports in tropical cyclones. Quart J Roy Meteor Soc 109:187–209
19. Houze RA, Churchill DD (2010) Mesoscale organization and cloud microphysics in a Bay of Bengal depression. J Atmos Sci 44:1845–1868
20. Houze RA (1982) Cloud clusters and large-scale vertical motions in the tropics. J Meteor Soc Japan 60:396–410
21. Houze RA (2010) Clouds in tropical cyclones. Mon Wea Rev 138:293–344
22. Houze RA, Bette AK (1981) Convection in GATE. Rev Geophysic 19:541–576
23. Hsieh YH, Lee CS, Sui CH (2017) A Study on the Influences of Low-Frequency Vorticity on Tropical Cyclone Formation in the Western North Pacific. Mon Wea Rev 145(10):4151–4169
24. Huang X, Hu C, Huang X et al (2018) A long-term tropical mesoscale convective systems dataset based on a novel objective automatic tracking algorithm. Clim Dyn 51:3145–3159
25. Johnson RH, Houze RA (1987) Precipitating cloud systems of the Asian monsoon. In Monsoon Meteorology (C.-P. Chang and T. N. Krishnamurti, Eds.), 298-353
26. Kerns BW, Zipser EJ (2009) Four years of tropical ERA-40 vorticity maxima tracks. Part II: Differences between developing and nondeveloping disturbances. Mon Wea Rev 137:2576–2591
27. Kerns BW, Chen SS (2013) Cloud clusters and tropical cyclogenesis: Developing and nondeveloping systems and their large-scale environment. Mon Wea Rev 141:192–210
28. Knapp KR et al (2011) Globally gridded satellite observations for climate studies. Bull Amer Meteor Soc 92:893–907
29. Knapp KR, Kruk MC, Levinson, Diamond HJ, Neumann CJ (2010) The International Best Track Archive for Climate Stewardship (IBTrACS). Bull Amer Meteor Soc 91:363–376
30. Laing AG, Fritsch JM (2000) The large-scale environments of the global populations of mesoscale convective complexes. Mon Weather Rev 128:2756–2776
31. Leary CA, Houze RA (1979) Structure and Evolution of Convection in a Tropical Cloud Cluster. J Atmos Sci 36::437–457
32. Lee CS (1989) Observational analysis of tropical cyclogenesis in the western North Pacific. Part I: Structural evolution of cloud clusters. J Atmos Sci 46:2580–2598

33. Lee CS (1986) An observational study of Tropical cloud cluster evolution and cyclogenesis in the Western North pacific, Thesis, Colorado state University
34. Lee CS, Gray WM (1984) Characteristics of north Indian Ocean tropical cyclone activity. Fort Collins Department of Atmospheric Science. https://doi.org/10.21236/ADA153085. Colorado State University
35. Lin YL, Lee CS (2011) An Analysis of Tropical Cyclone Formations in the South China Sea during the Late Season. Mon Wea Rev 139:2748–2760
36. Machado LAT, Rossow WB (1993) Structural characteristics and radiative properties of tropical cloud clusters. Mon Wea Rev 121:3234–3260
37. Maddox RA (1981) Satellite depiction of the life cycle of a mesoscale convective complex. Mon Wea Rev 109:1583–1586
38. Martin DW, Schreiner AJ (1981) Characteristics of West Africa and East Atlantic cloud clusters: A survey from GATE. Mon Wea Rev 109:1671–1688
39. Moncrieff MW (2010) The multiscale organization of moist convection and the intersection of weather and climate. Why Does Climate Vary? American Geophysical Union, Clim Dyn. https://doi.org/10.1029/2008GM000838. Washington, DC
40. Ooyama KV (1982) Conceptual Evolution of the Theory and Modeling of the Tropical Cyclone. J Meteorol Soci Jap 60:369–380
41. Orlanski I (1975) A rational subdivision of scales for atmospheric processes. Bull Amer Meteor Soc 56:527–530
42. Pacific PhD thesis, National Taiwan University, 178 pp
43. Pattanaik DR (2005) Variability of Ocenaic and Atmospheric conditions during active and inactive period of storms over the Indian region. Int J Climatol 25:1523–1530
44. Sadler JC (1976) A role of the tropical upper tropospheric trough in early season typhoon development. Mon Wea Rev 104:1266–1278
45. Schumacher AB, DeMaria M, Knaff JA (2009) Objective estimation of the 24-h probability of tropical cyclone formation. Wea Forecasting 24:456–471
46. Shige S, Takayabu YN, Tao WK, Johnson DE (2004) Spectral retrieval of latent heating profiles from TRMM PR data. Part I: Development of a model-based algorithm. J Appl Meteor 43:1095–1113
47. Simpson J, Garstang M, Zipser EJ, Dean GA (1967) A study of a non-deepening tropical disturbance. J Appl Meteor 6:237–254
48. Subrahmanyam KV, Kumar KK, Tourville ND (2018) Cloud type distribution in Tropical Cyclones formed in the North Indian Ocean using CloudSat observations. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing 11:339–344. doi: 10.1109/JSTARS.2017.2786666
49. Subrahmanyam KV (2019) **() Three Dimensional Distribution of Cloud Types over the India region and associated Dynamics**, **Thesis**, **Cochin University of Science and Technology** (**CUSAT**), **Kochi**, **India 33 pp**

50. Teng HF (2016) Formation and development of tropical cloud cluster in the western North Pacific. Ph.D. thesis, National Taiwan University, 178 pp
51. Teng HF, Lee CS, Hsu HH (2014) Influence of ENSO on formation of tropical cloud clusters and their development into tropical cyclones in the western North Pacific. Geophys Res Lett 41. doi:10.1002/2014GL061823
52. Teng HF, Lee CS, Hsu HH, Done JM, Holland GJ (2019) Tropical Cloud Cluster Environments and Their 1 Importance for Tropical Cyclone Formation. J Clim 32:4069–4088
53. Teng HF, Lee CS, Hsu HH, Kuo YH (2020) Large-Scale Environmental Influences on Tropical Cyclone Formation Processes and Development Time. J Clim 33:9763–9782. DOI: 10.1175/JCLI-D-19-0709.1
54. Tory K, Frank WM (2010) In: Chan JCL, Kepert JD (eds) Tropical cyclone formation. Global Perspectives on Tropical Cyclones: From Science to Mitigation. World Scientific Series on Asia-Pacific Weather and Climate, vol 4. World Scientific, pp 55–90
55. Wang Z (2018) What is the Key Feature of Convection Leading Up to Tropical Cyclone Formation? J Atmos Sci 75:1609–1629
56. Webster PJ, Stephens GL (1980) Tropical upper-tropospheric extended clouds: Inferences from winter MONEX. J Atmos Sci 37:1521–1541
57. Webster PJ, Houze RA (1991) The Equatorial Mesoscale Experiment (EMEX): An overview. Bull Amer Meteorol Society 72:1481–1505
58. Zhao HK, Chen SH, Klotzbach PJ, Raga GB (2018) Impact of the extended boreal summer intraseasonal oscillation on western North Pacific tropical cloud cluster genesis productivity. J Climate 31:9175–9191. https://doi.org/10.1175/JCLI-D-18-0113.1

Figures

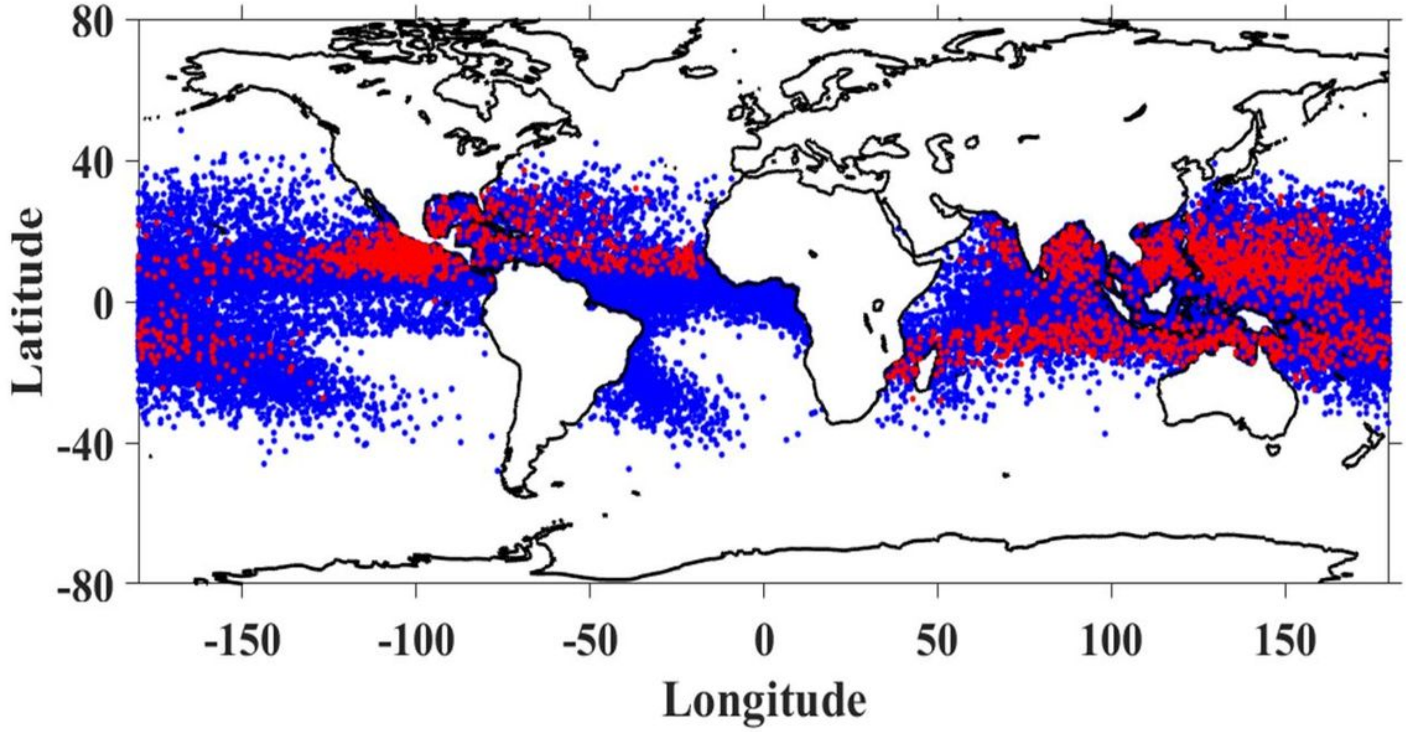

Figure 1

Global locations of TCCs during 1982-2009. Blue colour dots indicate the positions of TCCs and red colour indicates the locations of TCCs that are developed into cyclogenesis

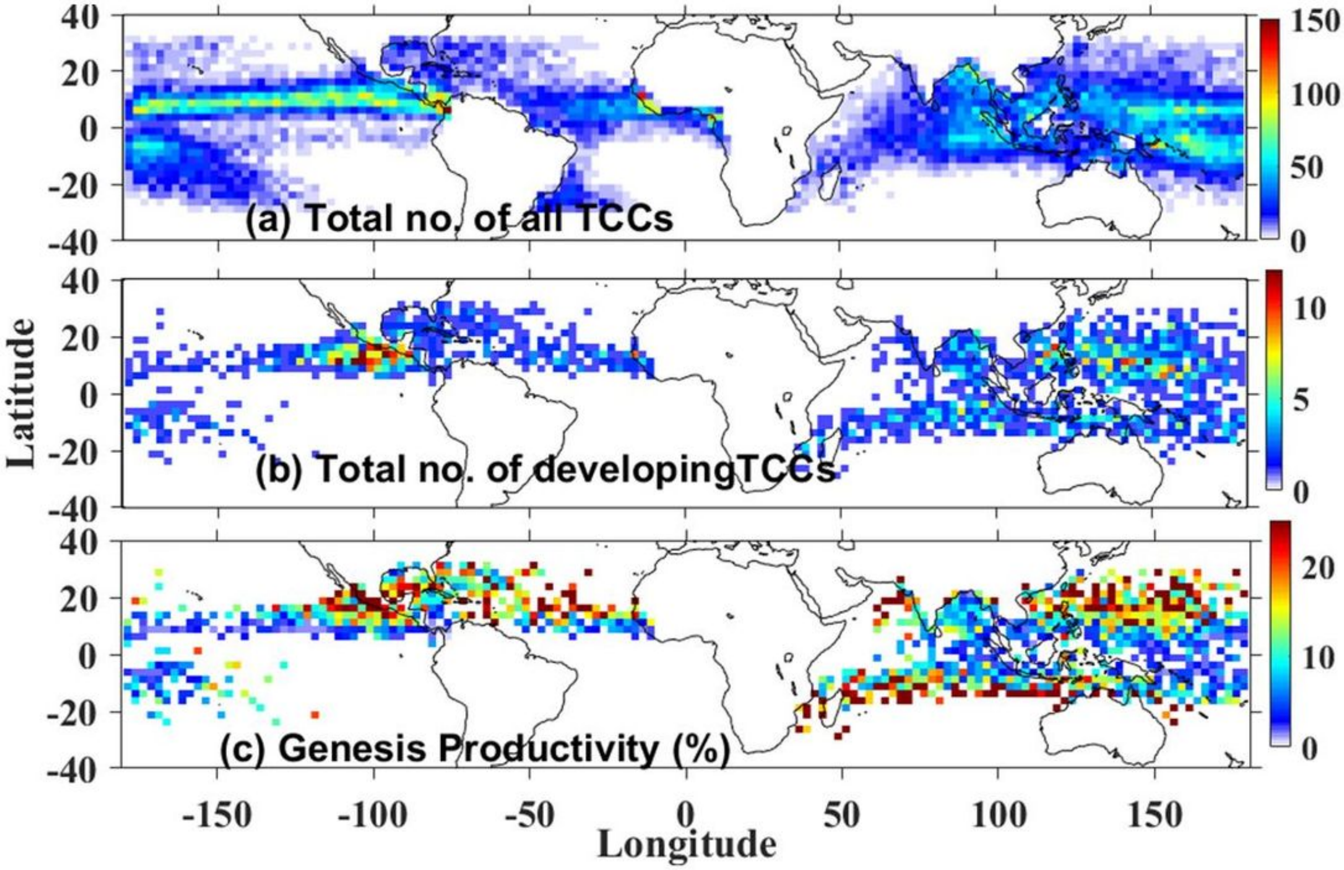

Figure 2

(a) Spatial distribution of number of TCCs, (b) number of TCCs, which are developed into TCs and (c) genesis productivity

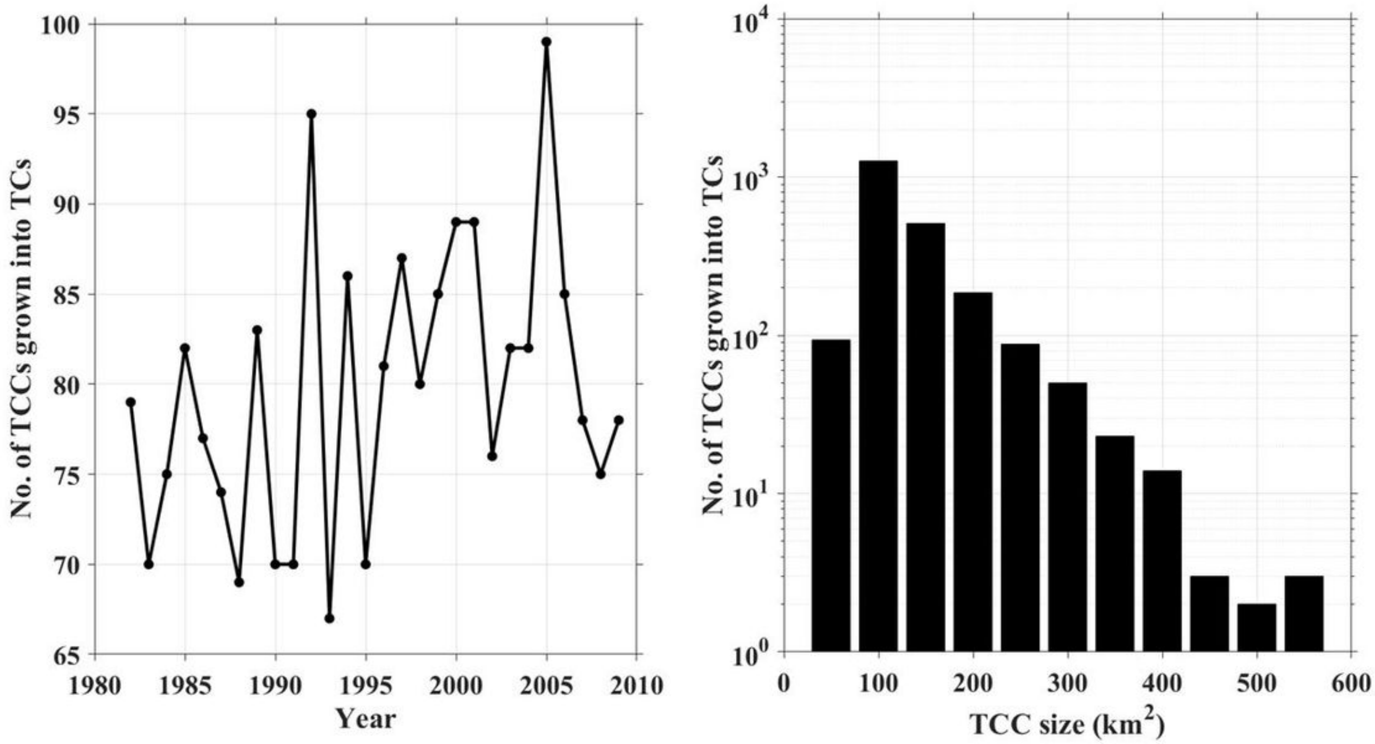

Figure 3

(a) The number of developing TCCs during observational period (b) size spectrum of TCCs with an interval of 100 km^2

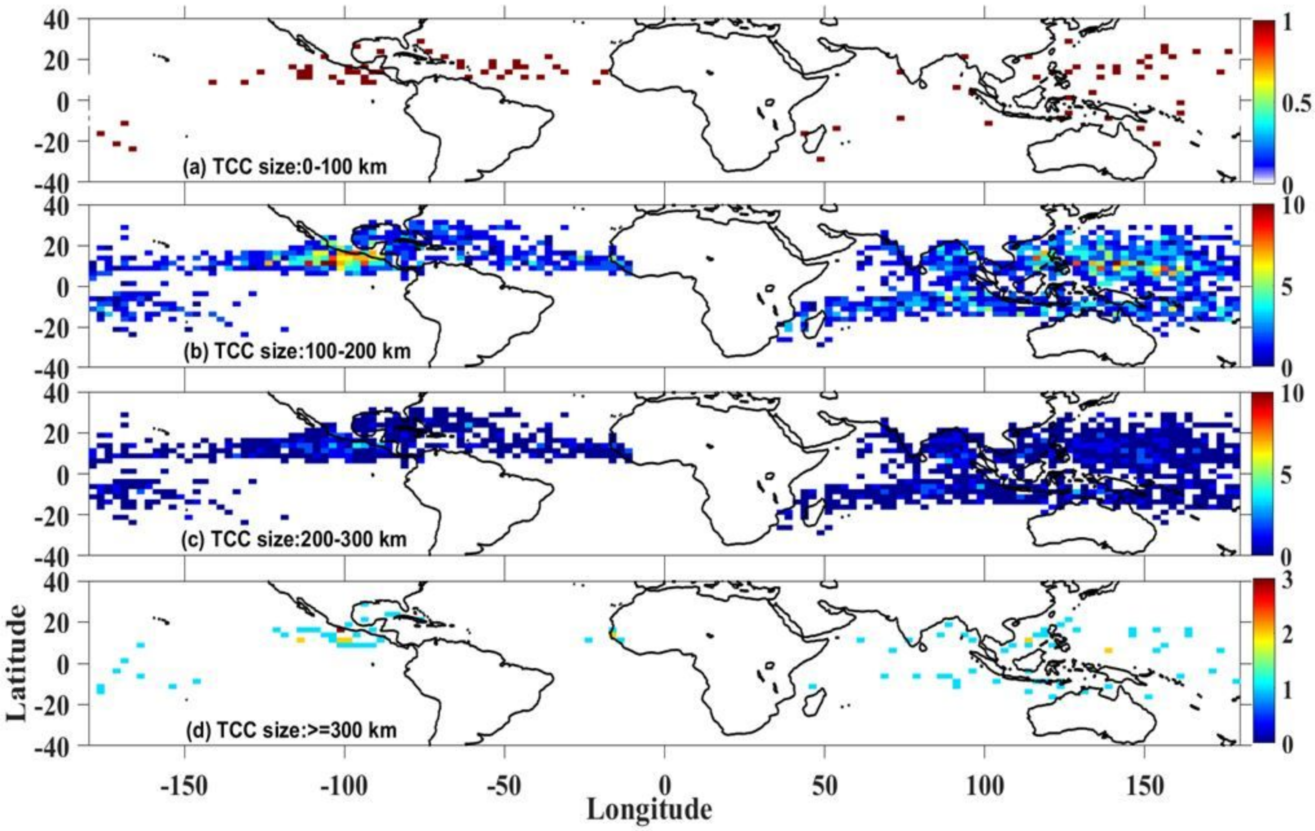

Figure 4

Spatial distribution of developing TCC of size (a) 0-100 km^2, (b) 100-200 km^2 (c) 200 300km^2 and (d) greater than or equal to 300 km^2.

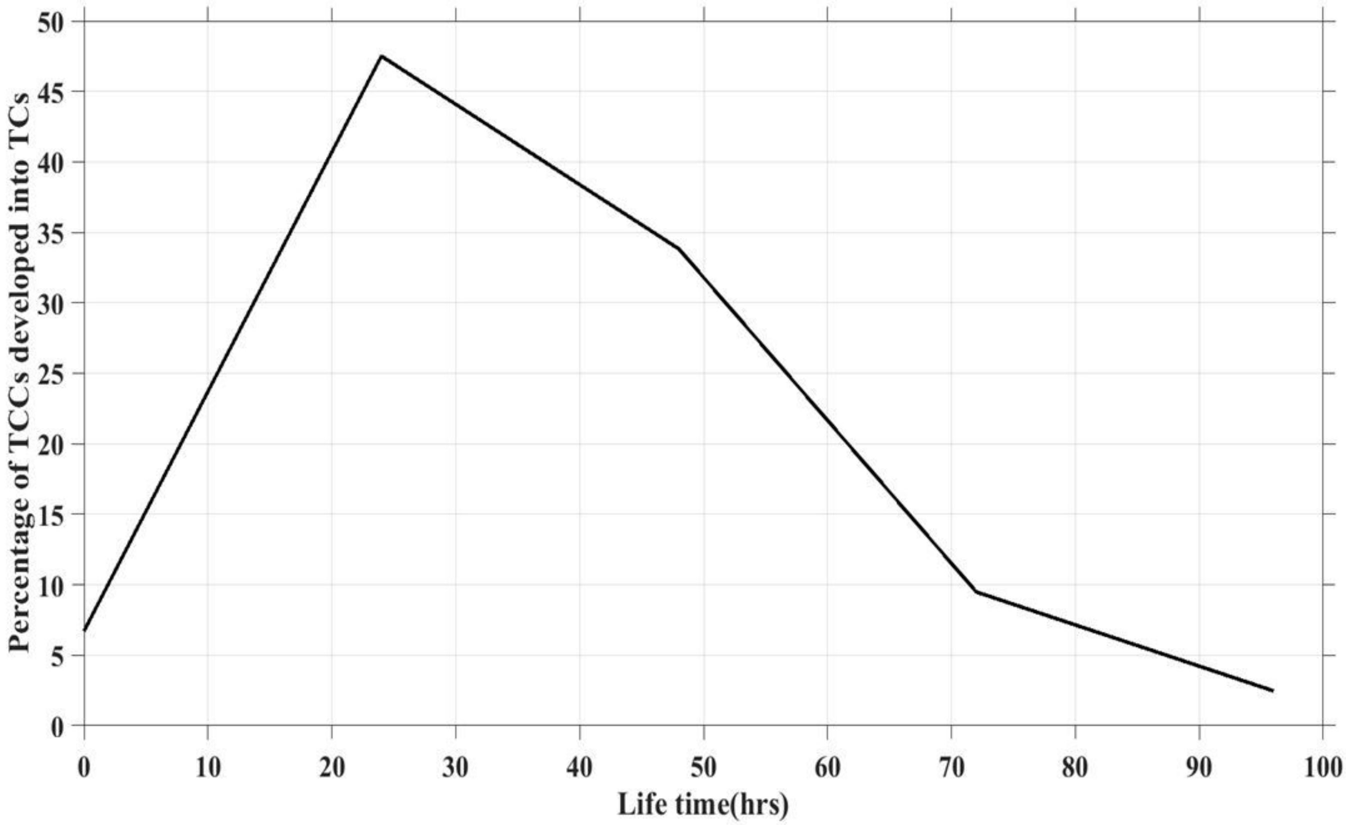

Figure 5

The percentage of TCCs developed into TCs as a function of their lifetime

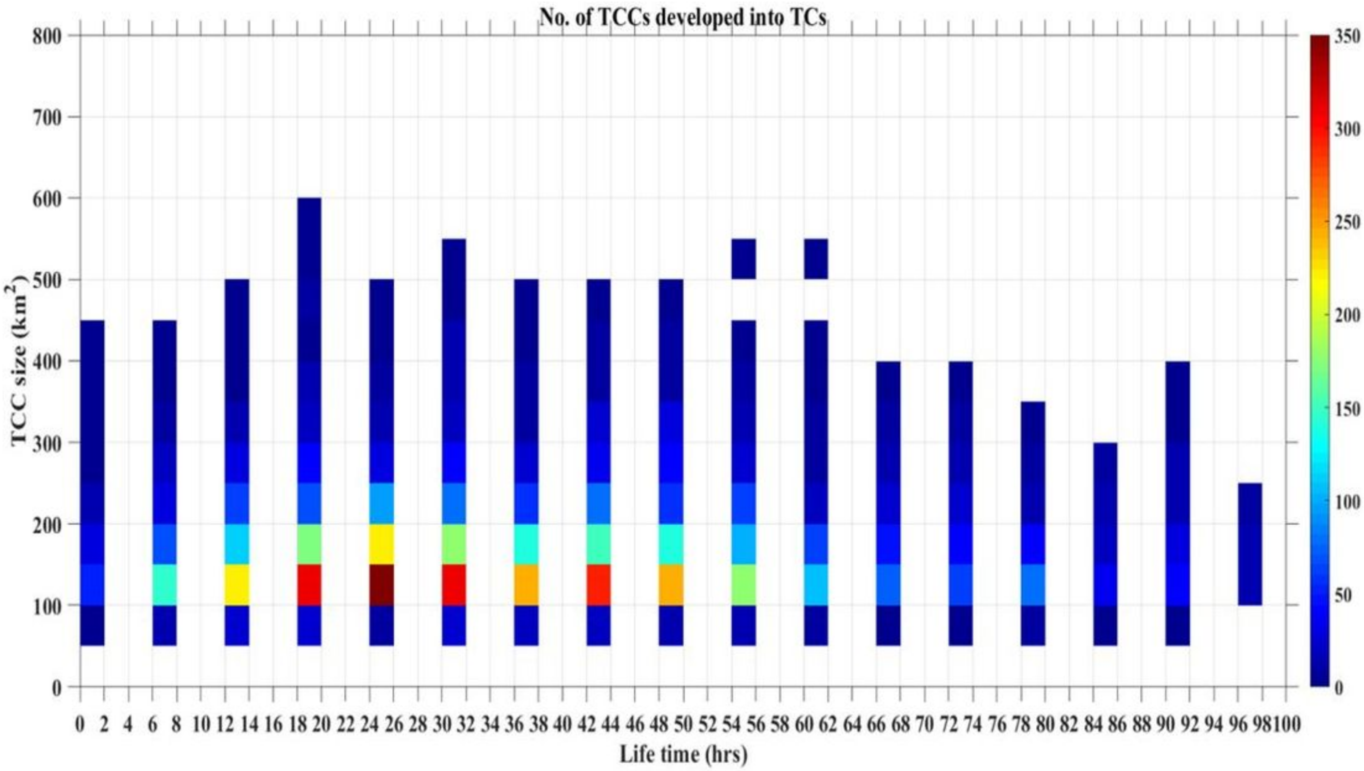

Figure 6

The life time of developing TCCs as function of their size

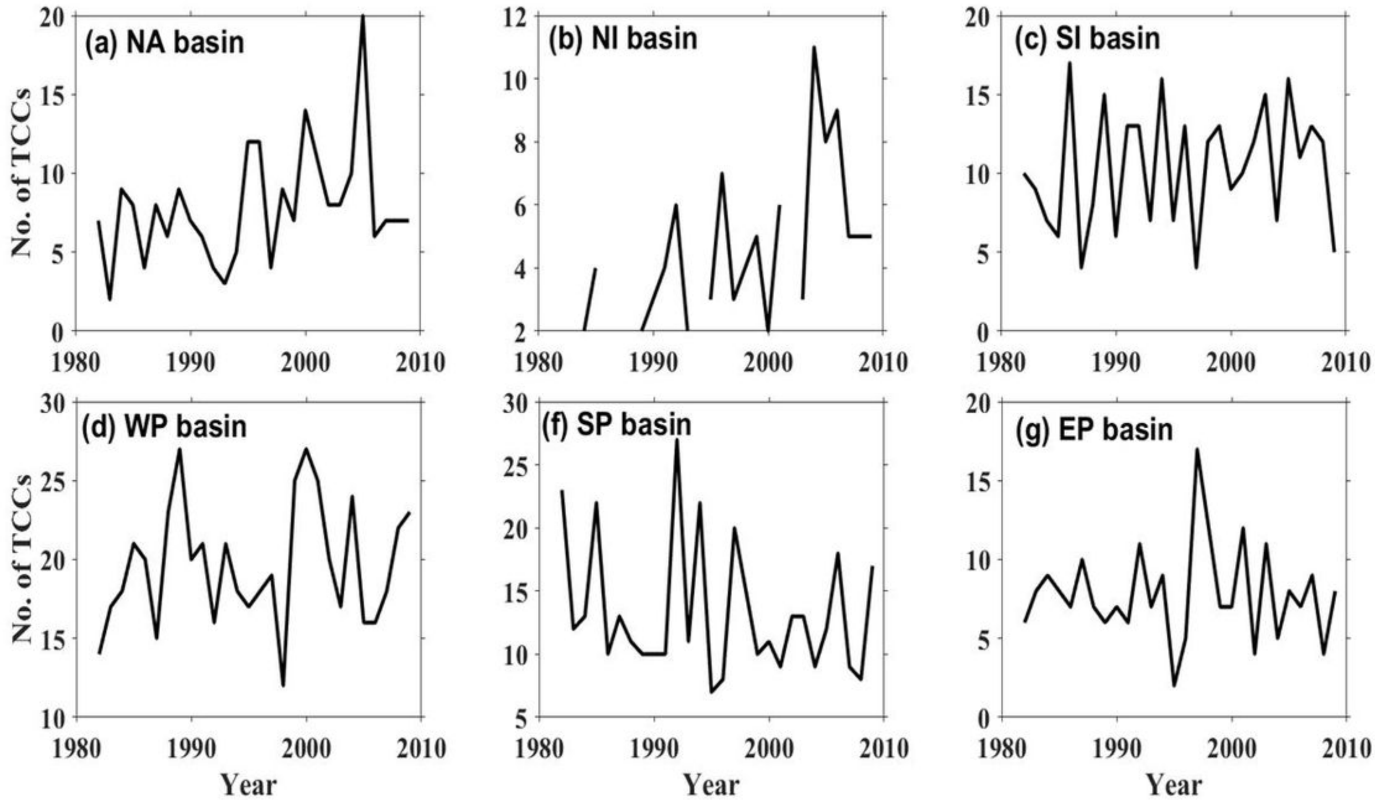

Figure 7

The time series of number of TCCs of size 100-200 km^2 over various oceanic basins (a) NA, (b) NI (c) SI (d) WP, (e) SP and (f) EP basins

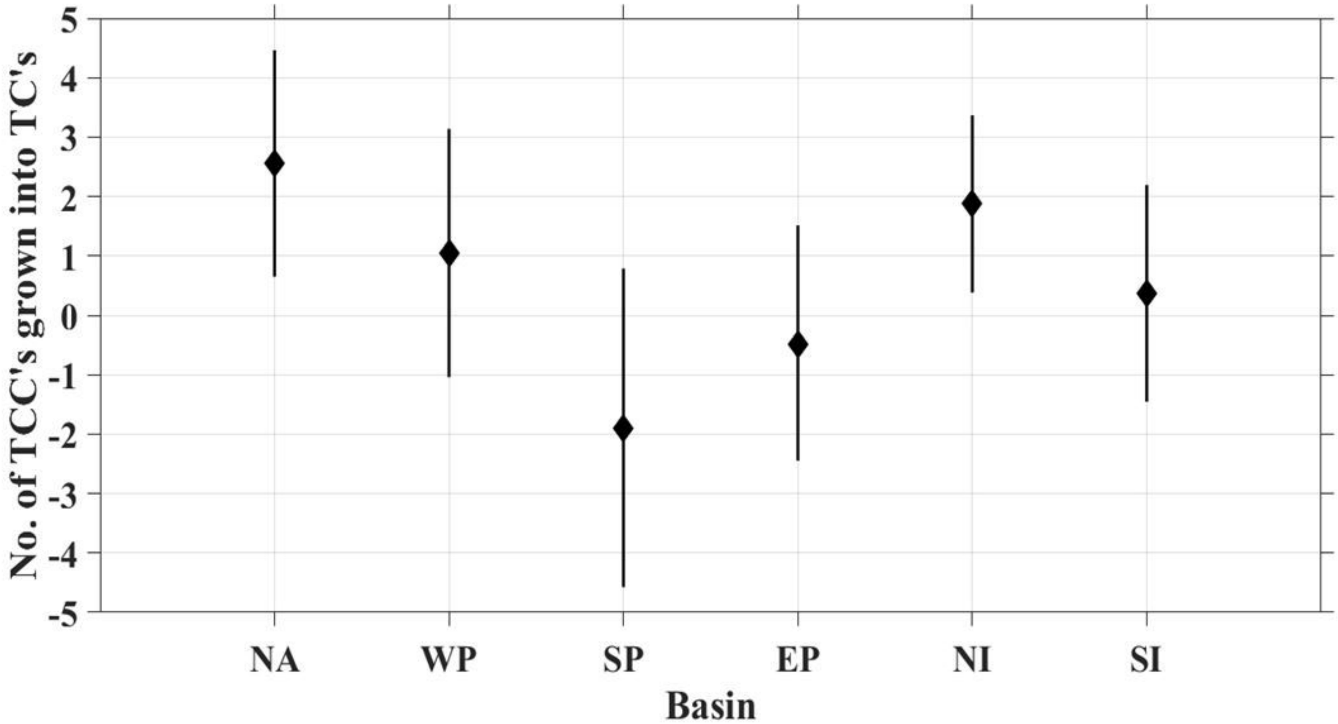

Figure 8

Trends of number of TCCs developed into TCs along with 955 confidence intervals.

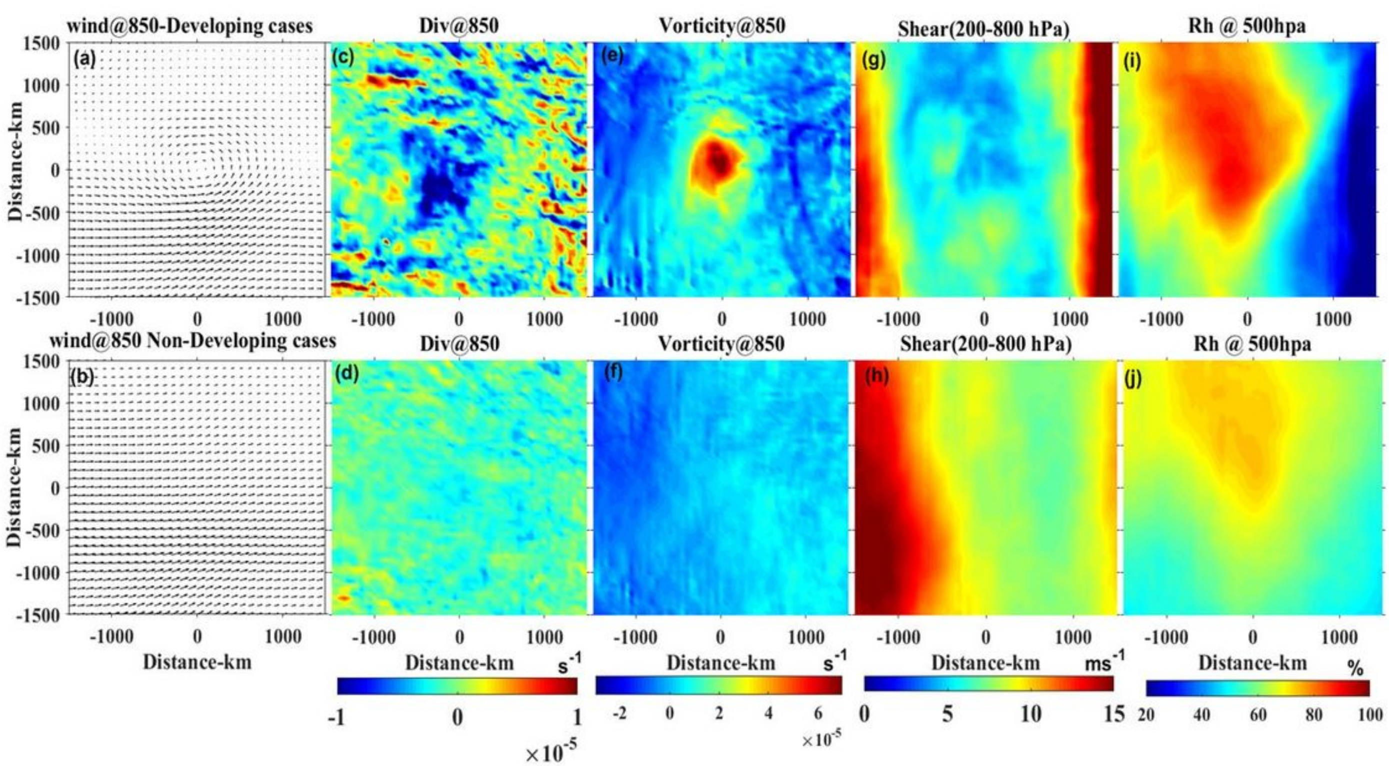

Figure 9

The composite of spatial distribution of wind speed, low-level divergence, low-level vorticity at 850 hPa, vertical shear of horizontal wind and relative humidity at 500 hPa for developing (a, c, e, g and i) and non-developing (b, d, i, h and j) TCCs.

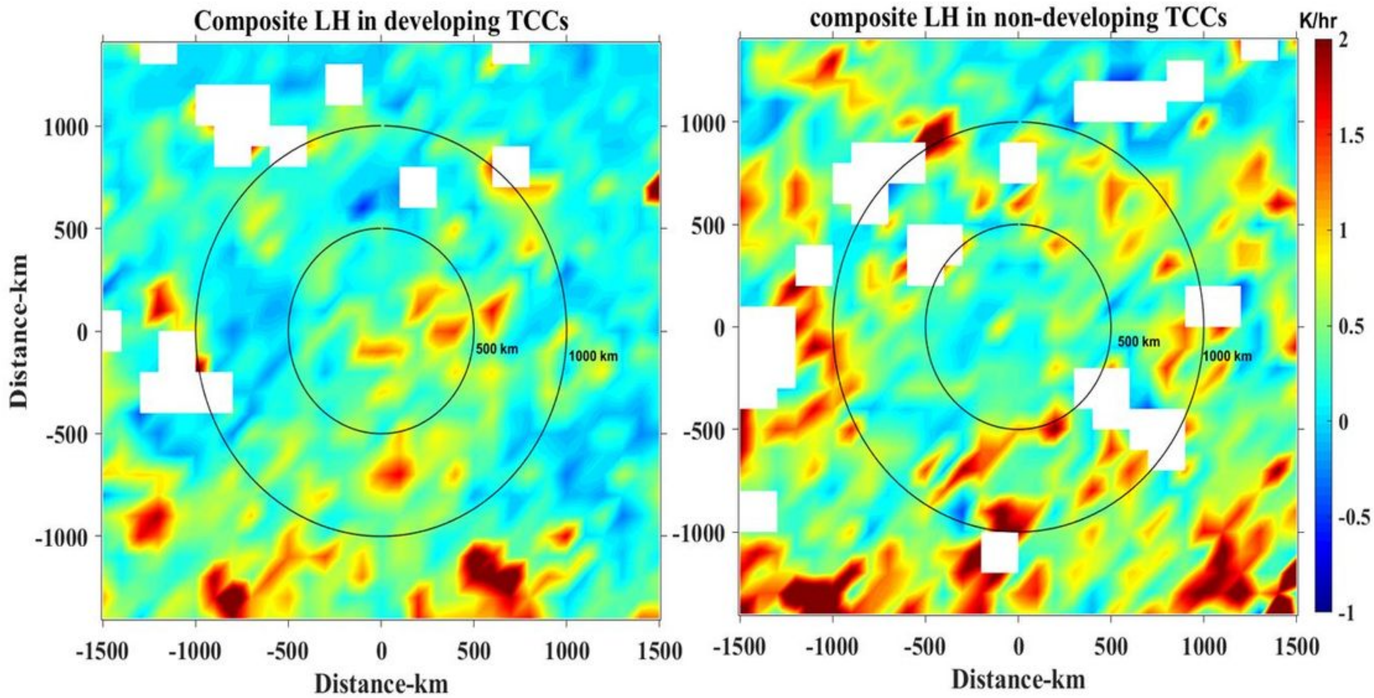

Figure 10

Same as figure 9, but for LH distribution.

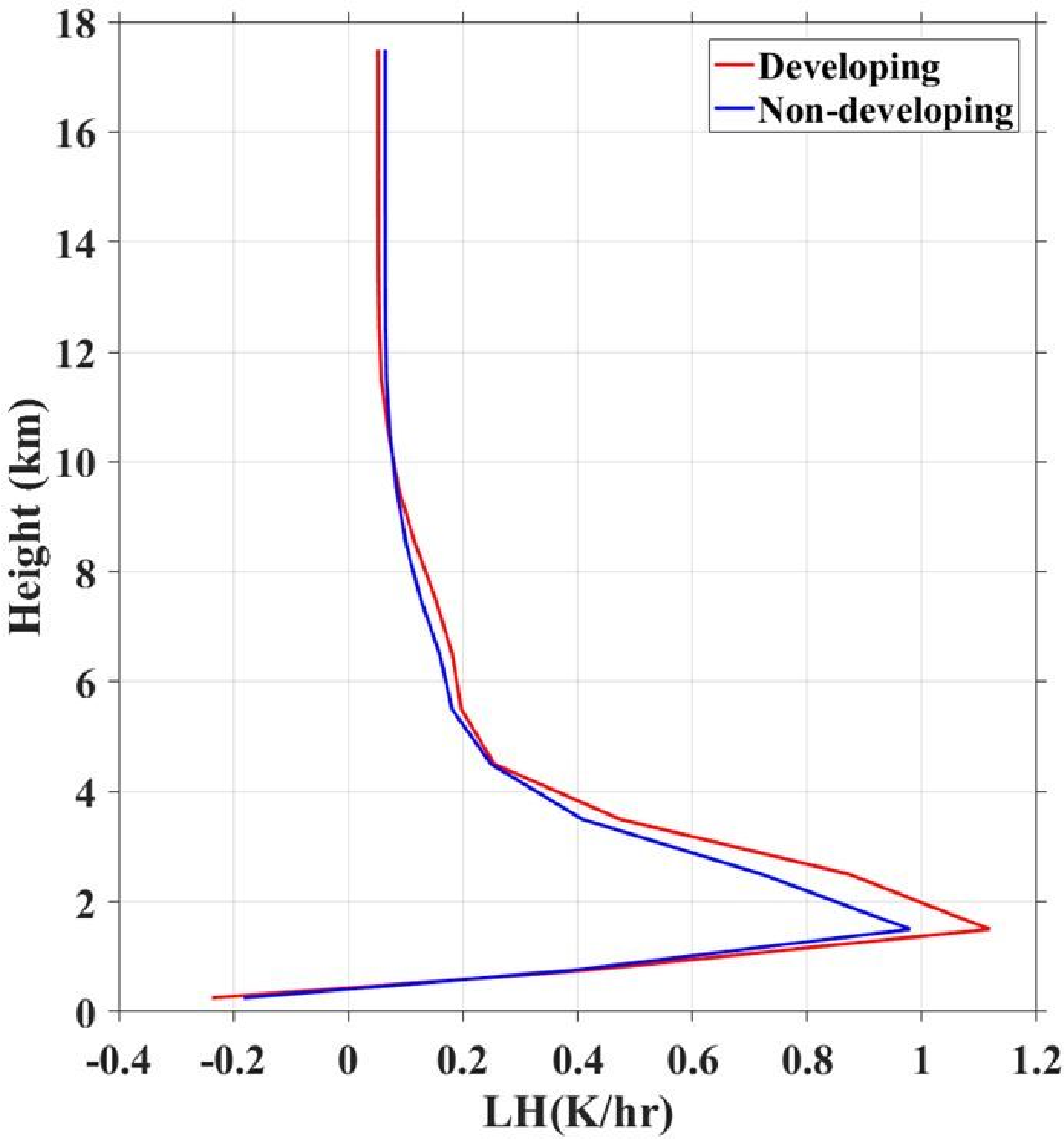

Figure 11

Vertical profile of mean LH (within a radius of 500km from the centre of disturbance) for developing and non-developing TCCs.