

# Study of regional heterogeneity of cloud properties during different rainfall scenarios over monsoon-dominated region

Ruchita Shah, Rohit Srivastava and Jigisha Patel

## ABSTRACT

Variability in precipitation pattern is increasing even at regional scale due to advancement in global warming, which could be of higher importance in study for monsoon-dominated region such as India. Precipitation varies with region, thus the present study focuses on two types of heterogeneous regions: a region closer to the coast and an inland region. Long-term analysis over inland region shows that the high cloud fraction and low penetration of outgoing radiation at the top of the atmosphere may be due to the presence of thicker clouds during southwest monsoon. Further study of cloud parameters shows domination of stratiform clouds over nearby coastal region with high range specific humidity ( $6.67 \times 10^{-6}$ – $1.81 \times 10^{-2}$  kg/kg) and higher cloud effective radius (13.35–15.75  $\mu\text{m}$ ), probably due to fewer hygroscopic nuclei. Heterogeneity in rainfall may also depend on types of monsoon (viz., normal, excess and deficit) by altering cloud formation processes. During periods of low rainfall over the coast, clouds are observed at low altitude with high cloud top temperature ( $-0.52 \pm 3.08$  °C) but have low specific humidity and lower cloud effective radius, which depict mixed characteristics of stratiform and convective clouds. Thus, it has been observed that cloud characteristics depend largely on the region than on the rainfall scenario. Such studies can be useful to understand uneven rainfall patterns.

**Key words** | convective clouds, Indian subcontinent, rainfall scenarios, regional heterogeneity, stratiform clouds

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## HIGHLIGHTS

- It helped to quantify regional heterogeneity.
- It analyze formation of stratiform clouds as well as convective clouds.
- It also identified mixed characteristics of stratiform and convective nature of clouds.
- It clarified that the nature/type of cloud depends largely on the region as compared to rainfall scenario.
- A longer time period and more parameters would help strengthen the findings of this study.

## INTRODUCTION

Advancement in global warming has increased the frequency of extreme weather events such as floods,

droughts, heat waves, thunderstorms, extreme hot-cold temperatures and hurricanes (Seneviratne *et al.* 2012). Some of these events have not only increased in frequency of occurrence but also their magnitude and duration has been raised in recent decades, specially due to human activities (Pachauri *et al.* 2014); one such clear example being 2018 as the consistent fourth hottest year globally with a

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record of rise in average surface temperature by 0.9–1.1 °C (Steffen *et al.* 2019). Even though the mean precipitation over most of the subtropical and mid-latitude region has decreased, it is likely to increase the magnitude of precipitation events (Solomon *et al.* 2007). A greater number of intense extreme rainfall events could occur over the Asian monsoon region and tropical areas, which could cause a greater impact on weather as well as rainfall patterns (Solomon *et al.* 2007; Bhandari *et al.* 2016; Singh 2018). Not only on the land surface, but also rising ocean temperatures contribute to the change in magnitude of precipitation, floods and cyclones/hurricanes/typhoons (Trenberth *et al.* 2018). Both land and ocean are prominent factors to vary the rainfall pattern and this heterogeneity could affect atmospheric circulations and cloud formation processes. One such study of the northern hemisphere shows that land and ocean areas have significant differences in formation of warm clouds with the help of cloud microphysical as well as macrophysical properties (Gao *et al.* 2014). Along with land and ocean, coastal regions are also facing heterogeneity in rainfall patterns and this has been studied using cloud properties over southern West Africa (Maranan *et al.* 2018). Thus, it can be said that the magnitude of precipitation highly depends on the region (Sun *et al.* 2018). Along with regional, estimates of annual and seasonal rainfall also have large differences and are observed in tropical oceans and northern Africa. Sun *et al.* (2018) also added that variabilities in heavy precipitation were found to be slightly more at lower latitudes as compared to higher latitudes. Thus, climate-driven precipitation patterns have globally become a major concern as they vary highly with location, weather and surrounding environment (Walsh *et al.* 2014).

Climate-driven precipitation in the form of uneven rainfall pattern is of major concern for a monsoon-dominated country like India. The weather-beaten Indian subcontinent receives rainfall from the southwest monsoon (where winds blow from the Indian Ocean onto landmass), northeast monsoon (where winds reverse their direction from land to ocean) and western disturbances (which are non-monsoonal precipitation patterns driven by westerlies) (Gadgil 2003). Almost 70% of the annual mean rainfall is provided by the southwest monsoon (June–September) over most regions of India whereas the northeast monsoon brings rain to only limited parts such as Kerala, Andhra Pradesh and Tamil Nadu

(Kripalani *et al.* 2003; Menon *et al.* 2013). Western disturbances are extra-tropical storms and can bring sudden winter rain over northwestern parts of India. High dependency on rainfall also plays a significant role in agriculture, as it is the most prominent factor of the Indian economy (Solomon *et al.* 2007; Mukherjee *et al.* 2017). Due to the influence of many components on Indian rainfall, there is a need to understand spatial-temporal changes in rainfall using the latest datasets (Guhathakurta & Rajeevan 2008).

The impact of climate change in the form of uneven rainfall pattern has ravaged India with 20 excess and 27 deficit rainfall years during the long-term period of 1870–2016, and which are quite frequent after the 1960s (Kothawale & Rajeevan 2017). In a warming climate, the country is likely to notice a greater number of extreme weather events, especially high intensified extreme rainfall events (Guhathakurta *et al.* 2011). Various studies have shown that interaction of aerosol–cloud–precipitation plays a significant role in determining heavy rain (Sarangi *et al.* 2017; Varikoden & Revadekar 2019). Not only excess, but also deficit rains have become regular events in the country and have a larger effect than any other natural hazards (UN Children's Fund 2019). Most research studies have reported that Indian summer monsoons will intensify and may shift, causing dry, longer summers, which could have warmer weather, drier temperature, heat waves and droughts (Lal 2003; Seneviratne *et al.* 2012; Deng *et al.* 2018). During 1901–2004, droughts with severity and frequency have increased and further are expected to increase in 2050–2099 over west central, central northeast and peninsular regions of India (Solomon *et al.* 2007). Study of aerosol and cloud microphysics plays a significant role in determining drought events, and has also been studied for the Indian summer monsoon (Hazra *et al.* 2013). However, average monsoon rainfall has declined by ~10% over central India, but the country has faced a three-fold rise in frequency and magnitude of extreme rainfall events during 1950–2015 (Roxy *et al.* 2017). On the other hand, western India received the lowest rainfall in the southwest rainfall climatology (1951–2007). When compared to other regions of India, it could face large extreme variability in rainfall (Bhandari *et al.* 2016). Hence, extreme weather events are region-dependent phenomena that play a vital role in causing regional heterogeneity.

Occurrence of irregular rainfall pattern has been observed mostly due to variations in atmospheric

parameters as well as cloud formation processes (Willett *et al.* 2007). Water vapour acts as an effective atmospheric variable, that is almost controlled by the temperature (Myhre *et al.* 2013). Variation in temperature is very likely to perturb the evaporation process in the atmosphere, which may cause the vapour content in the atmosphere, radiative forcing, cloud formation processes and rainfall patterns to vary (Jones *et al.* 2016; Myhre *et al.* 2017; Bellouin *et al.* 2020). It has been reported that rising atmospheric water vapour in the lower troposphere induces precipitation by saturating the under-saturated cloud systems, particularly in convective zones (Srivastava *et al.* 2015; Zuidema *et al.* 2017). Variation in moisture content also affects instability of the atmosphere, which probably can form different types of cloud through variation in atmospheric circulation and complex cloud microphysical processes (NASA 1998; Collier 2003). One such long-term (2001–2016) study has shown an impact of rising temperature over cloud microphysical properties such as cloud effective radius (CER) and cloud liquid water content (LWC) over the Arabian Sea and central India (Shah & Srivastava 2019). This shows that study of cloud properties along with atmospheric parameters could play an important role in understanding cloud formation processes and irregular rainfall patterns, even at regional scale.

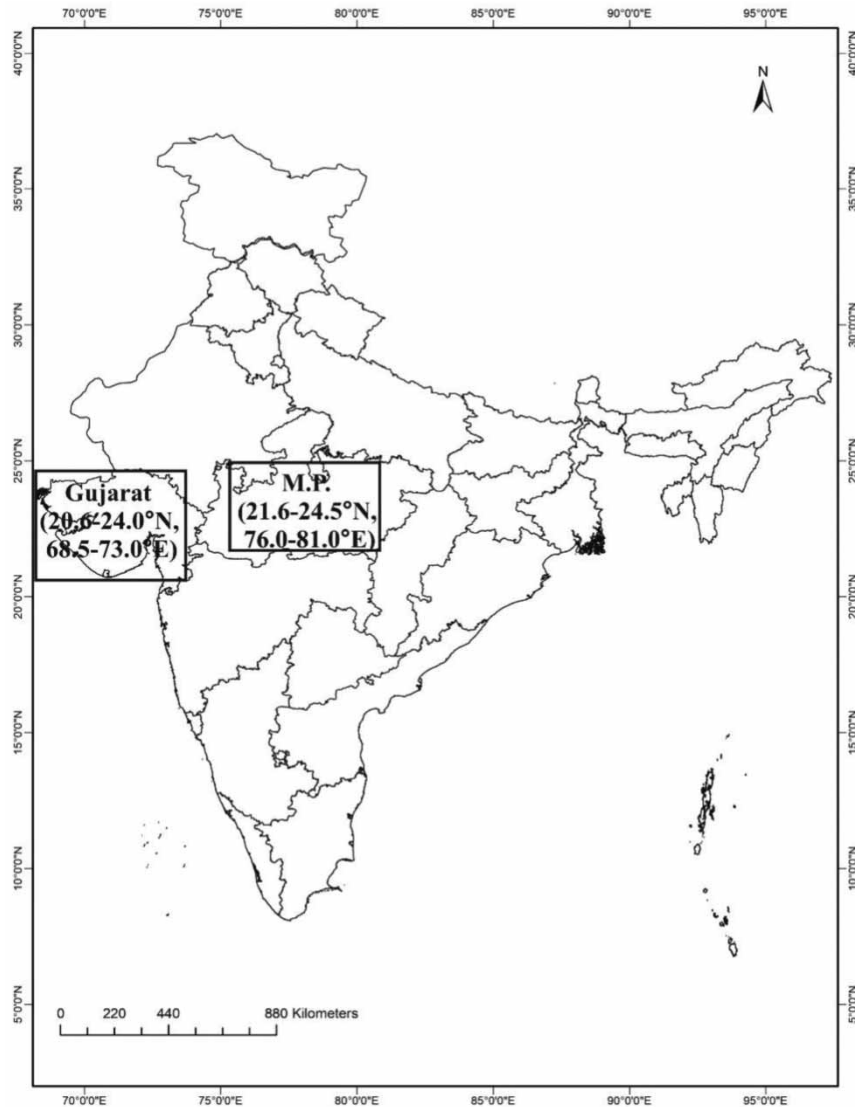
As per the geographical location, rainfall in India generally originates through maritime and continental clouds. Usually, maritime clouds are susceptible to a lower number of aerosol concentration (by a factor of 10–100 than over continents) and thus fewer cloud concentration nuclei (CCN) with large size of cloud droplets (30–50% than over continents) over the ocean (NASA 1998). Maritime clouds are spatially extensive, optically thin and frequently form in clean air masses with higher levels of humidity whereas continental clouds are comparatively thicker and consist of more smaller cloud droplets (NASA 1998; Turner *et al.* 2007; Leahy *et al.* 2012). Usually, such continental clouds are found at higher altitude as compared to maritime or oceanic clouds. *In-situ* measurements with aircraft show that although there are differences in concentration of aerosol and cloud droplets, the LWC remains almost constant in both types of clouds (NASA 1998). Along with this, it has been revealed that mostly stratiform and convective type of clouds are associated with

rainfall over India. They also have reported that less turbulent stratiform clouds are typically related to longer rain duration, while convective clouds disperse relatively soon for heavy rain by rising air thermals with strong updraft-downdraft movement of air masses (Liu 2003; Hu *et al.* 2011; Pokhrel & Sikka 2013; Saha *et al.* 2014; Sen Roy *et al.* 2015; Kumar 2017). Therefore, not only the region where cloud forms but also atmospheric conditions in which it evolves (i.e., different types of monsoon, namely normal, excess and deficit) also play an essential role in fluctuating cloud properties. Thus, not only over India but all around the globe, researchers need to investigate the causes of changing rainfall pattern as it has spatio-temporal dynamics (Campozano *et al.* 2016; Bushra *et al.* 2020).

To investigate uneven rainfall pattern or cloud type at regional scale, the present study focuses on understanding cloud properties over different regions as well as during different rainfall scenarios (namely normal, excess and deficit). Variability in rainfall patterns could be possible due to alteration in cloud properties and this may notably help to know about cloud type as well as cloud formation processes, which in turn may help to understand irregular rainfall pattern. Such regional analysis of cloud features could assist in better awareness of cloud dynamics, weather predictability, regional heterogeneity and climate change.

## MATERIALS AND METHODS

Most of the cloud originates from the ocean and moves towards land regions so, usually, cloud properties would vary over the ocean as well as over land. Along with this, regions nearer to the coast would also face heterogeneity. For the present monsoonal study, Gujarat (20.6–24.0°N to 68.5–73.0°E) as a region near to the coast is selected as it is very close to the Arabian Sea wherein the onset of the southwest monsoon is initiated. On the other hand, Madhya Pradesh (M.P.) (21.6–24.5°N to 76.0–81.0°E) is selected as an inland region as it is very close to Gujarat. The study needs to understand the level of regional heterogeneity over the regions, which are not far from each other. Also, the study focuses on finding changes in climatic conditions when cloud moves from the coast to inland (Figure 1).



**Figure 1** | Study regions marked with square boxes are named as Gujarat and Madhya Pradesh (M.P.).

As per data availability of the southwest monsoon (June–September) from the India Meteorological Department (IMD), Gujarat state has been sub-divided into two sub-regions (Gujarat and Saurashtra-Kutch), and M.P. state into east M.P. and west M.P. with different amounts of rainfall (IMD data). In addition to this, rainfall data over the four subdivisions helped to categorize the study period into normal, excess and deficit rainfall years, as per criteria given by IMD (IMD report). Thus, to know the amount of rainfall over selected regions, the area average of available actual rainfall data is computed. Along with this, normal rainfall data given by IMD helped to

calculate rainfall departure (IMD data, Kothawale & Rajeevan 2017). Long-term (2000–2017) datasets are usually preferred to understand regional heterogeneity with the help of atmospheric property (total column (995–25 hPa) specific humidity), cloud microphysical–macrophysical property (CER, LWC at higher pressure levels (995–850 hPa), cloud top temperature (CTT), cloud top pressure (CTP), cloud fraction (CF) and cloud optical thickness (COT) and radiance property (outgoing long-wave radiation at the top of atmosphere (OLR)). Details of these parameters are listed in Table 1 and a flowchart of different types of methodology and

**Table 1** | List of utilized parameters from *in-situ*, remote sensing and simulation model for Gujarat and M.P. states of India

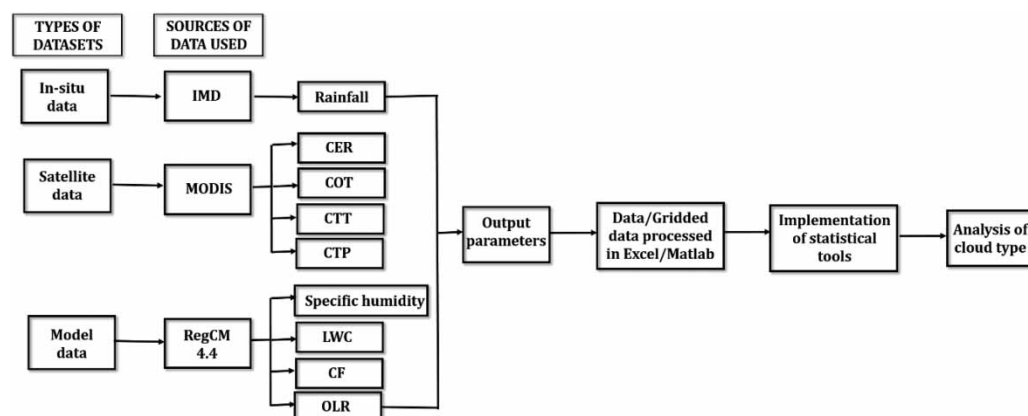
No.	Name of the parameter	Unit of the parameter	Type of data	Source of data	Resolution		Study period
					Spatial	Temporal	
1.	Rainfall	mm	<i>In-situ</i>	Rain-gauge	$0.25^{\circ} \times 0.25^{\circ}$		
2.	CER	$\mu\text{m}$	Remote sensing	MODIS	$1^{\circ} \times 1^{\circ}$		
3.	COT	–					
4.	CTT	$^{\circ}\text{C}$					
5.	CTP	hPa				Monthly	2000–2017
6.	Specific humidity	kg/kg	Model simulation	RegCM 4.4	$0.5^{\circ} \times 0.5^{\circ}$		
7.	Mass fraction of LWC	kg/kg					
8.	CF	%					
9.	OLR (TOA)	$\text{W/m}^2$					

proportion of data is presented in Figure 2. Types of datasets are as follows:

1. *In-situ* measurements: Monthly monsoon data of normal and actual rainfall (mm) are given for subdivisions of Gujarat and M.P. with a horizontal resolution of  $0.25^{\circ} \times 0.25^{\circ}$  (IMD data, Kothawale & Rajeevan 2017). This available dataset also helped to calculate rainfall departure and categorize the study period (2000–2017) into normal, excess and deficit rainfall years.
2. Satellite measurements: In this study, monthly data of CER ( $\mu\text{m}$ ), COT, CTT ( $^{\circ}\text{C}$ ) and CTP (hPa) are retrieved from the Moderate Resolution Imaging Spectro-radiometer (MODIS-Terra-EOS AM). It can capture the data in 36 spectral bands ranging from 0.4 to  $14.4 \mu\text{m}$  with a

spatial resolution of  $1^{\circ} \times 1^{\circ}$  from Giovanni – an online web portal of NASA, Earth Data (Acker & Leptoukh 2007, Giovanni data).

3. Model simulations: Regional scale heterogeneity can be understood better with the help of high resolution regional climate models such as regional climate model-RegCM 4.4. Earlier research studies have reported that RegCM 4.4, termed as the model hereafter, has the capability to capture monsoonal features well over heterogeneous regions (Yang et al. 2018; Giorgi et al. 2019). Parameters such as total column (995–25 hPa) specific humidity (kg/kg), mass fraction of LWC at higher-pressure levels (995–850 hPa) (kg/kg), total column CF (%) and OLR at top of the atmosphere ( $\text{W/m}^2$ ) are simulated with the help of the model. LWC

**Figure 2** | Flowchart of different methodologies chosen to analyse types of cloud at regional scale.



is studied at higher-pressure levels (995–850 hPa) to find the availability of liquid water during cloud formation processes. It configures with a single domain of horizontal resolution of 60 km ( $0.5^\circ \times 0.5^\circ$ ), 18 vertical levels (995–25 hPa) and model top at 50 hPa. Initial atmospheric fields and time-varying boundary conditions for simulation were taken from the National Centers for Environmental Prediction (NCEP) Reanalysis (NNRP1) and European Centre for Medium-Range Weather Forecast (ECMWF) ERA-Interim (EIN15) of  $2.5^\circ \times 2.5^\circ$  and  $1.5^\circ \times 1.5^\circ$  grid resolution, respectively (RegCM data). There are various convection schemes in the model, among which, Grell convective scheme is implemented, as it performs better than other alternative convective schemes, especially for southwest monsoon simulations (Grell 1993; Pattanayak *et al.* 2014; Shah & Srivastava 2018).

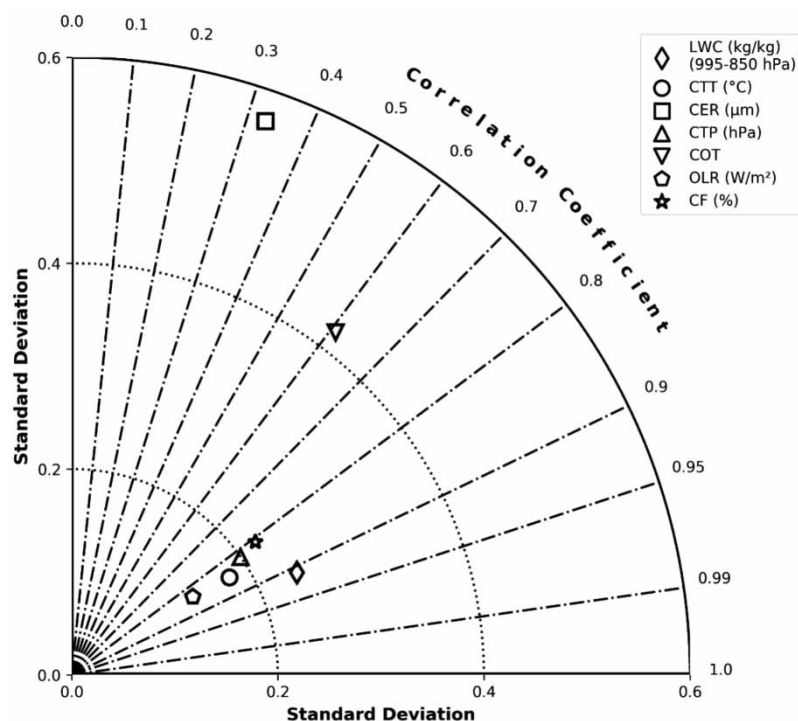
## RESULTS AND DISCUSSION

Mostly cloud evolves from the ocean and gets dispersed as it moves towards inland regions after losing energy. Various parameters such as temperature (of sea surface, surface and air), prevailing wind speed, concentration of CCN, surface–air interaction and cloud formation processes are important to determine precipitation from a cloud, which may vary a great deal from place to place and time to time. It shows that the precipitation pattern varies with season over ocean, over coast, as well as over inland region. The selected coast and inland regions are not far from each other but still they have received different amounts of rainfall, as mentioned earlier (IMD data, Kothawale & Rajeevan 2017). This indicates heterogeneity in rainfall pattern over nearby regions, which might have occurred due to variation in cloud properties. By looking at the rainfall amount differences, the present study investigates/compares changes in cloud properties with the help of linear correlation coefficient method over nearby heterogeneous regions, namely, M.P. and Gujarat. Long-term monthly averaged LWC shows highest correlation coefficient with low standard deviation ( $0.91 \pm 0.24$ ), which signifies characteristics of LWC are almost the same at higher-pressure levels (995–850 hPa) over M.P. and Gujarat (Figure 3).

On the other hand, their mutual dependency for CER shows low correlation value (0.33), which depicts difference in size distribution of cloud droplets but with high variance (0.57). Along with small-scale properties, the study continues to evaluate regional heterogeneity with large-scale properties also. CTT and CTP both captured good correlation of  $0.85 \pm 0.18$  and  $0.82 \pm 0.20$ , respectively. COT shows moderate dependency with  $0.61 \pm 0.42$ , whereas coordination for CF and OLR reproduces well with  $0.81 \pm 0.22$  and  $0.84 \pm 0.22$ , respectively (Figure 3). Thus, high correlation coefficient signifies less regional difference in calculated parameters, whereas low correlation values helped to indicate heterogeneity over the selected nearby regions. However, long-term correlation study is usually effective to understand diversified features of utilized parameters. Either the correlation coefficients are good or bad, but the difference in rainfall amount over nearby regions is also probably due to the presence of different types of cloud and different cloud formation processes in the study. Also due to increase in global warming, regional weather conditions vary faster over land than over the ocean due to less specific heat so also could be a significant contributor in varying regional heterogeneity (Bjurström & Polk 2011).

To know about cloud types and their formation processes, first there is a need to discover whether the region has a high or low fraction of cloud cover. Fraction of cloud plays a critical role in the atmosphere, as it is a source of precipitation, controller of energy budget and significant player in modulating cloud-rain formation processes. Various studies have reported that trap or penetration of OLR at the top of atmosphere depends majorly on presence or absence of cloud and thus they are linearly dependent on each other (Zhou *et al.* 2007; Cole *et al.* 2011). Therefore, the present study further continues to look how the proportion of cloud would vary OLR at regional scale. Thus, the study of long-term (2000–2017) monsoon climatology (June–September) is chosen here to visualize dependency of OLR on CF over a region closer to the coast (Gujarat) and an inland region (M.P.), as shown in Figure 4(a) and 4(b), respectively.

CF and OLR show negative correlation both over Gujarat ( $y = (-107.64 \pm 16.34)x + (298.62 \pm 8.27)$ ;  $r^2 = 0.73$ ;  $p < 0.05$ ) and M.P. ( $y = (-193.16 \pm 19.20)x + (327.24 \pm 10.64)$ ;  $r^2 = 0.86$ ;  $p < 0.05$ ) but with a significant



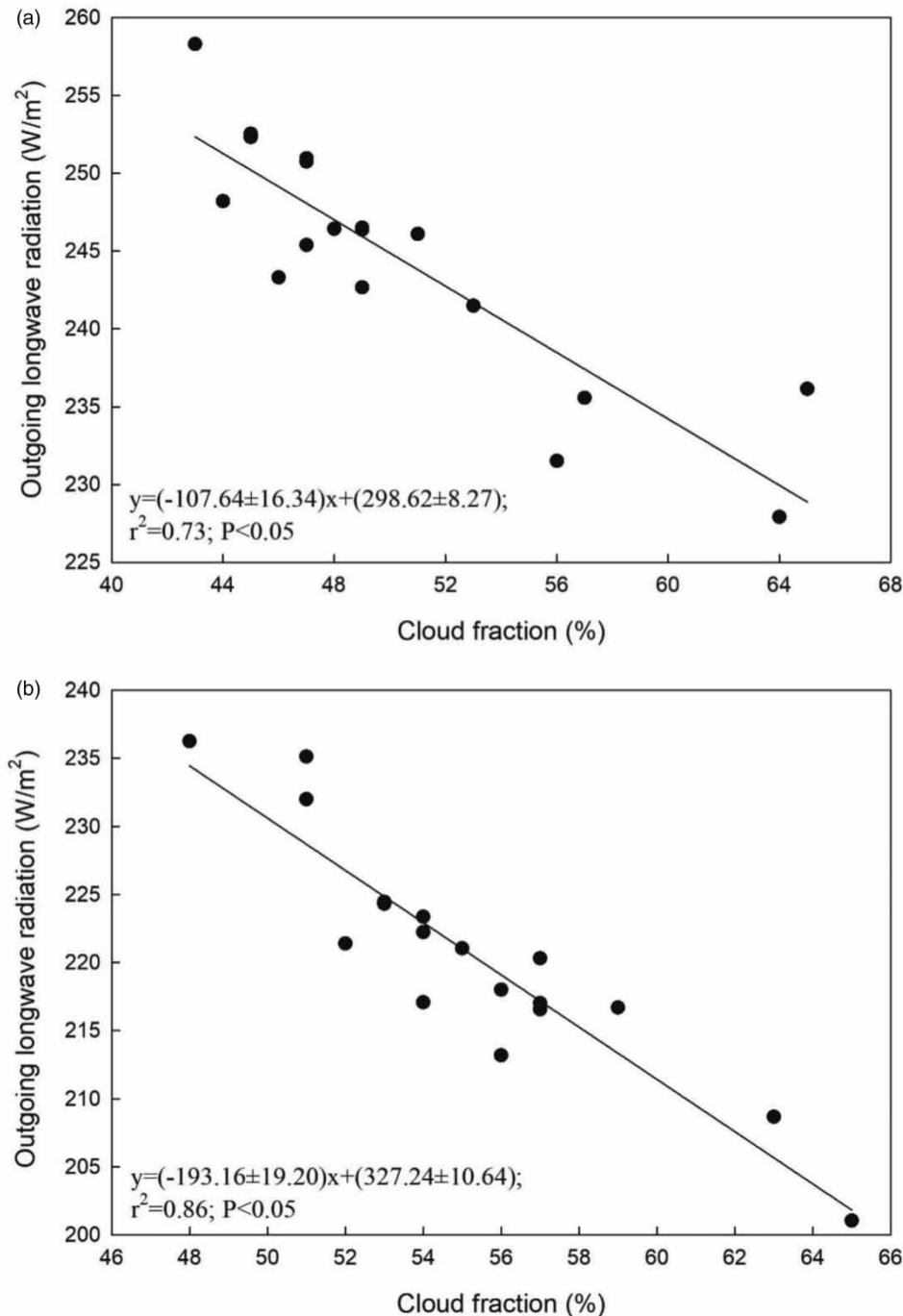
**Figure 3** | Taylor diagram showing spatial correlation coefficients and standard deviations between a region nearer to the coast (Gujarat) and an inland region (Madhya Pradesh) during the southwest monsoon (June–September) period of 2000–2017. All the correlation values are statistically significant at 95% confidence level.

difference in the slope (Figure 4(a) and 4(b)). With  $r^2$  values of 0.73 and 0.86, it could be interpreted that the interpolating values have justifications up to 73 and 86%, respectively, with the  $p$ -value being  $<0.05$ , which shows that these justifications are more than 95% true. Adequate values of  $r^2$  with significant slope difference are probably due to the formation of thicker clouds over M.P. as compared to Gujarat, that also links with regional heterogeneity. Further, to investigate cloud type over both the regions, study of cloud properties along with humidity is done to interpret characteristics of cloud and hence the rainfall pattern.

Long-term (2000–2017) mean values of utilized parameters along with their error bars are shown to see the regional differences between Gujarat and M.P. during the southwest monsoon (Figure 5). Calculated mean values of specific humidity along with their uncertainties are almost the same, which is not clearly depicting regional heterogeneity. High values of uncertainty are observed in specific humidity, as it is supposed to be a highly varying parameter (Figure 5(a)). However, the difference in the specific

humidity is less over both the regions but still it may perturb surface–atmosphere interaction, updraft–downdraft movement of air parcel, size distribution of water cloud droplets and LWC in the cloud, which in turn, may influence nucleation, condensation, collision and coalescence processes (Figure 5(a)). Along with these cloud formation processes, cloud radiative property such as COT also varies as it depends highly on moisture density as well as vertical depth of the cloud (Maizan *et al.* 2015).

Although the results obtained show higher specific humidity over Gujarat ( $7.21 \times 10^{-3} \pm 6.84 \times 10^{-3}$  kg/kg) than M.P. ( $7.01 \times 10^{-3} \pm 6.16 \times 10^{-3}$  kg/kg), within the calculated uncertainty both the values are almost the same (Figure 5(a)). Thus, it is difficult to distinguish the role of humidity over both these regions but it discontinued with the observations of CER. Distribution of CER shows a high range (13.35–15.75  $\mu\text{m}$ ) over Gujarat, whereas it declines over M.P. with low range CER (13.47–15.03  $\mu\text{m}$ ). The variation in size distribution of cloud droplets is differentiated with the range values of CER but is not clearly observed by the difference in mean values of CER, as the

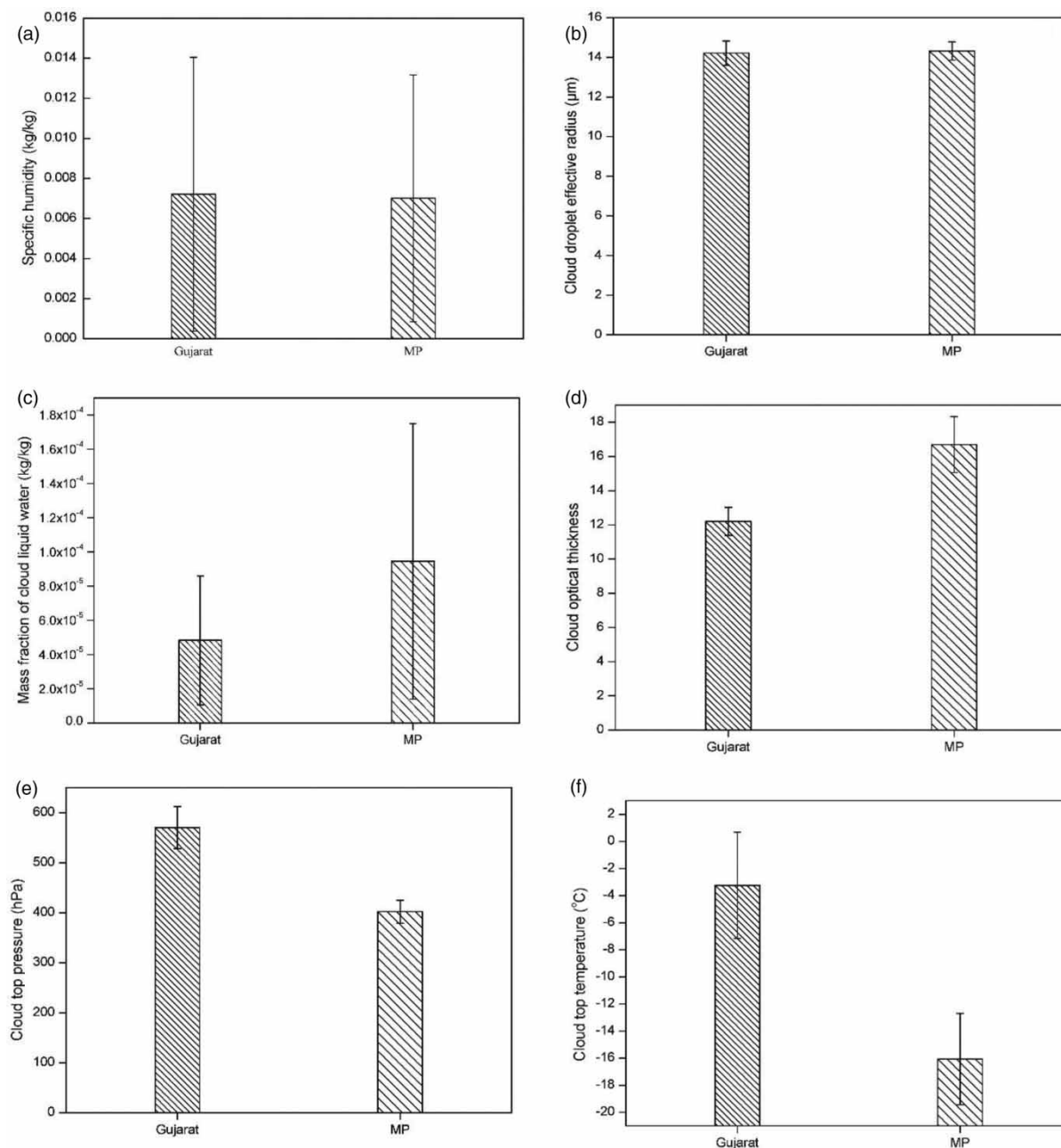


**Figure 4** | Monsoonal variation of cloud fraction with outgoing long wave radiation at the top of the atmosphere over (a) Gujarat and (b) Madhya Pradesh during 2000–2017.

difference is very small (Figure 5(b)). To gain confidence in the derived results, they are compared with an earlier study, which agreed with the reported range of CER as 14–20  $\mu\text{m}$  over Gujarat and M.P. during June–September

(Ramachandran & Kedia 2013). The presence of a bigger high range of cloud droplets is probably due to availability of less aerosol/CCN, whereas a smaller and low range of cloud droplets may have formed due to more aerosol/





**Figure 5** | Averaged variation of (a) total column (995–25 hPa) specific humidity, (b) CER, (c) mass fraction of LWC at 995–850 hPa, (d) COT, (e) CTP and (f) CTT over Gujarat and Madhya Pradesh during monsoons (June–September) of 2000–2017.

CCN. This interconnection has been reported using *in-situ* measurements with aircraft, which show that the concentration of aerosol is lower by a factor of 10–100 over oceans than over continents, and thus CCN would vary (NASA 1998). Hence, Gujarat – a region closer to the ocean may accommodate fewer CCN than the inland

region of M.P. Although the concentration of cloud droplets is less (by a factor of 5–10), the average radius of formed droplets is usually 30–50% larger as compared to continents (NASA 1998). Thus, formation of bigger droplets over Gujarat may be due to the presence of more moisture and less CCN, whereas less moisture may get distributed to

more CCN which form smaller droplets over M.P. Variation in LWC mostly depends on the strength of atmospheric motions during cloud formation processes (NASA 1998). Along with lower specific humidity and CER, high LWC ( $9.45 \times 10^{-5} \pm 8.05 \times 10^{-5}$  kg/kg) is observed at higher-pressure levels (995–850 hPa) over M.P., which may be due to the presence of a greater number of CCN with small curvature of cloud droplets that (Figure 5(c)). Conversely, more moisture and bigger cloud droplets that formed with less LWC ( $4.83 \times 10^{-5} \pm 3.77 \times 10^{-5}$  kg/kg) at 995–850 hPa over Gujarat may be due to fewer CCN of large curvature (Figure 5(c)). Thus, the formation of bigger droplets due to more moisture and less CCN over Gujarat are such characteristics of cloud, which matches well with maritime clouds (Lohmann & Lesins 2003). On the other hand, smaller droplets, less moisture and more CCN over M.P. indicate formation of continental clouds (Lohmann & Lesins 2003). In addition to this, it is also known that continental clouds generally form at higher altitude and thus are captured with lower CTP ( $402.20 \pm 23.00$  hPa) and CTT ( $-16.07 \pm 3.37$  °C) over M.P., whereas maritime cloud forms at lower altitude with higher CTP ( $570.23 \pm 42.28$  hPa) and CTT ( $-3.24 \pm 3.92$  °C) over Gujarat (Figure 5(e) and 5(f)). Study of the utilized parameters revealed that maritime and continental clouds might have formed over Gujarat and M.P., respectively, throughout the monsoons of 2000–2017.

According to the International Satellite Cloud Climatology Project, rainfall generally originates from two types of cloud, namely, convective and stratiform over the Indian subcontinent (Sen Roy *et al.* 2015). As the onset of the southwest monsoon is initiated, the western coast of India is fully in the grip of the monsoonal trough due to higher rate of convective cloud fraction and this continued throughout the monsoon seasons of 2002–2009 (Sen Roy *et al.* 2015). Along with convective, stratiform clouds are also found over the western coast of India due to formation of large cloud system outflows from the west coast of Myanmar. This stratiform cloud covers almost all the land regions except northwestern parts of India. In addition, research has also shown that it is difficult for convective clouds to build up much (~4 to 6%) over inland regions, whereas it is much easier (maximum ~8 to 14%) for large stratiform cloud systems to progress from the Bay of Bengal during

the southwest monsoon (Sen Roy *et al.* 2015). Thus, it is intimated that both types of cloud are responsible for rainfall over Gujarat and M.P., but the utilized properties signify difference in their measurements over both the regions which could be a sign of regional heterogeneity and thus needs to be studied further in detail.

As mentioned before, larger cloud droplets with lesser LWC are found over Gujarat. This may be due to high specific humidity and fewer CCN in the maritime troposphere, which are found to be of the same characteristics as stratiform clouds (Figure 5(a)–5(c)) (Radke *et al.* 1989). Also, these types of cloud are usually formed with lower cloud base under stable air masses and are relatively thin, which matches well with obtained results of low COT ( $12.20 \pm 0.82$ ), high CTP and CTT (Figure 5(d)–5(f)) (Turner *et al.* 2007; Leahy *et al.* 2012). In contrast, continental clouds have comparatively high concentration of CCN, which may trigger condensational droplet growth with less amount of moisture to form smaller cloud droplets and higher LWC (Figure 5(a)–5(c)). Such characteristics of continental cloud match well with the properties of convective clouds (Radke *et al.* 1989). These type of clouds are probably thicker and build up at higher altitude, mostly due to convectively unstable air masses, and hence have higher COT ( $16.69 \pm 1.64$ ), low CTP and CTT, which again, denotes formation of convective clouds (Figure 5(d)–5(f) (Radke *et al.* 1989). In addition, thin/thick clouds are found at low/high altitude with high/low CTT which also confirms formation of stratiform/convective type of clouds during the southwest monsoon, specially over selected regions. Also, thickness of cloud measured by COT is compared with an earlier study which reported its value lies between 14 and 22 over Gujarat and M.P. during June–September and thus agrees well with the obtained results (Ramachandran & Kedia 2013). Thus, by considering uncertainties in CER, it can be said that availability of bigger cloud droplets ( $13.35$ – $15.75$   $\mu\text{m}$ ) is greater over Gujarat as compared to M.P. ( $13.47$ – $15.03$   $\mu\text{m}$ ), which could play a significant part in understanding cloud formation processes and rainfall pattern at regional scale. Hence, study of specific humidity, cloud optical and microphysical properties may indicate a dominant role of the stratiform nature of clouds during the southwest monsoon over Gujarat. On the other hand, convection currents may have played a significant role comparatively more over the

inland region, thus all the utilized parameters signify a high fraction of the convective nature of clouds for rainfall over M.P. during 2000–2017. Even though it is difficult for convective clouds to form over an inland region, the obtained cloud properties over M.P. during monsoon climatology of 2000–2017 signify formation of convective clouds. This could be possible mostly when the rising thermals or convection currents might be consistently raised over the inland region which may be due to increase in surface temperature and hence depict the impact of warming climate at regional level.

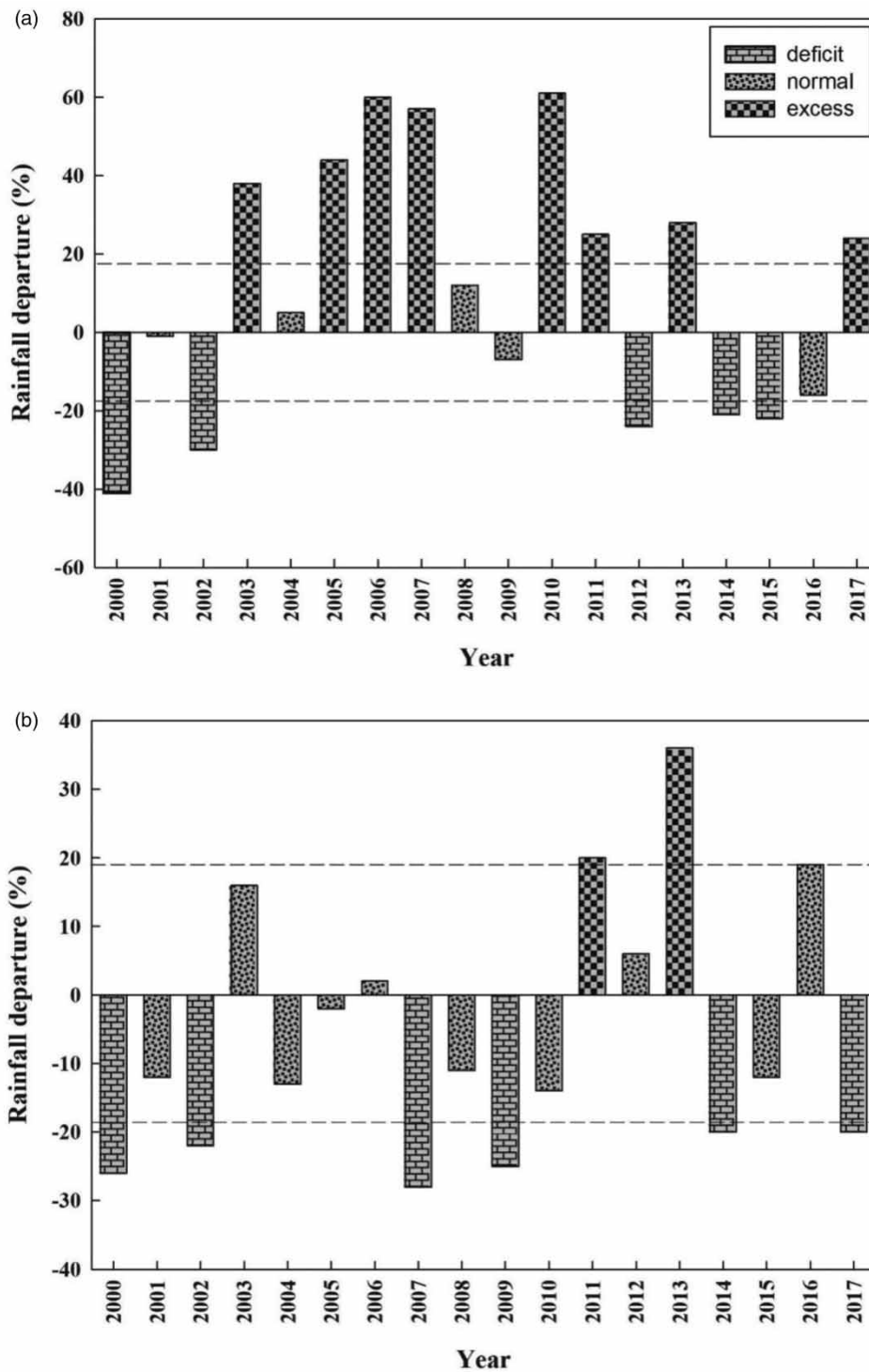
In continuation, cloud types and properties may also depend upon different monsoon scenarios such as normal, excess and deficit. Thus, to study cloud properties for different monsoon scenarios over chosen heterogeneous regions, selected years (2000–2017) are categorized under deficit (–20% to –59%), normal (–19% to +19%) and excess (20% or more) using rainfall amount (Figure 6(a) and 6(b)).

During 2000–2017, Gujarat faced more excess rain activity as compared to normal and deficit (Figure 6(a)). Excess rainfall years comprise bigger droplets ( $14.59 \pm 0.67 \mu\text{m}$ ) and less LWC ( $4.88 \times 10^{-5} \pm 4.44 \times 10^{-5} \text{ kg/kg}$ ) at 995–850 hPa, which may be due to higher specific humidity ( $7.35 \times 10^{-3} \pm 6.90 \times 10^{-3} \text{ kg/kg}$ ), and less CCN over Gujarat (Figure 7(a)–7(c)). As explained earlier, these properties indicate the stratiform nature of clouds over Gujarat. On the other hand, COT is high ( $12.84 \pm 0.60$ ) and this may be due to the high amount of moisture during extreme rain, as said moisture density depends upon COT (Figure 7(d)) (Maizan et al. 2015). It could possibly occur due to formation of thicker clouds over Gujarat and is also found with high cloud base of low CTP ( $539.88 \pm 32.47 \text{ hPa}$ ) and low CTT ( $-5.77 \pm 3.41 ^\circ\text{C}$ ) (Figure 7(e) and 7(f)). This in fact signifies the convective nature of clouds during excess rainfall scenario. Thus, observed cloud properties of excess rainfall years are of a mixed nature of stratiform as well as convective clouds. Formation of both types of clouds could be possible when the dynamics of stratiform clouds appear to assemble under unstable atmospheric processes, which in turn, may elevate cloud formation due to horizontal advection of moist air undergoing weak ascent.

On the other hand, deficit rainfall years are captured with smaller cloud droplets ( $13.71 \pm 0.30 \mu\text{m}$ ) and higher

LWC ( $4.97 \times 10^{-5} \pm 2.50 \times 10^{-5} \text{ kg/kg}$ ), and again may be due to less availability of moisture ( $7.09 \times 10^{-3} \pm 6.81 \times 10^{-3} \text{ kg/kg}$ ) and higher CCN over Gujarat (Figure 7(a)–7(c)). In addition, these clouds are comparatively thinner with low COT ( $11.56 \pm 0.40$ ), due possibly to low amount of moisture content, and are formed at lower pressure levels with high CTP ( $606.85 \pm 34.31 \text{ hPa}$ ) and high CTT ( $-0.52 \pm 3.08 ^\circ\text{C}$ ) (Figure 7(d)–7(f)). This may indicate mixed nature of clouds and could signify formation of low-level stratiform clouds embedded with convective bands, which in turn, might have triggered cloud formation under strong lower-tropospheric stability during the drought period of 2000–2017 over Gujarat. The same as excess and deficit, normal rainfall events also consist of mixed characteristics of stratiform as well as convective nature of clouds over Gujarat, except LWC (Figure 7). However, both convective and stratiform clouds might have formed but by considering uncertainties the present study confirms formation of bigger cloud droplets with a high range of CER ( $13.91\text{--}15.25 \mu\text{m}$ ) during excess rain as compared to normal ( $13.74\text{--}14.44 \mu\text{m}$ ) and deficit ( $13.41\text{--}14.01 \mu\text{m}$ ) rainfall scenarios over Gujarat. Further study needs to understand the nature of clouds while moving towards an inland region during different rainfall events.

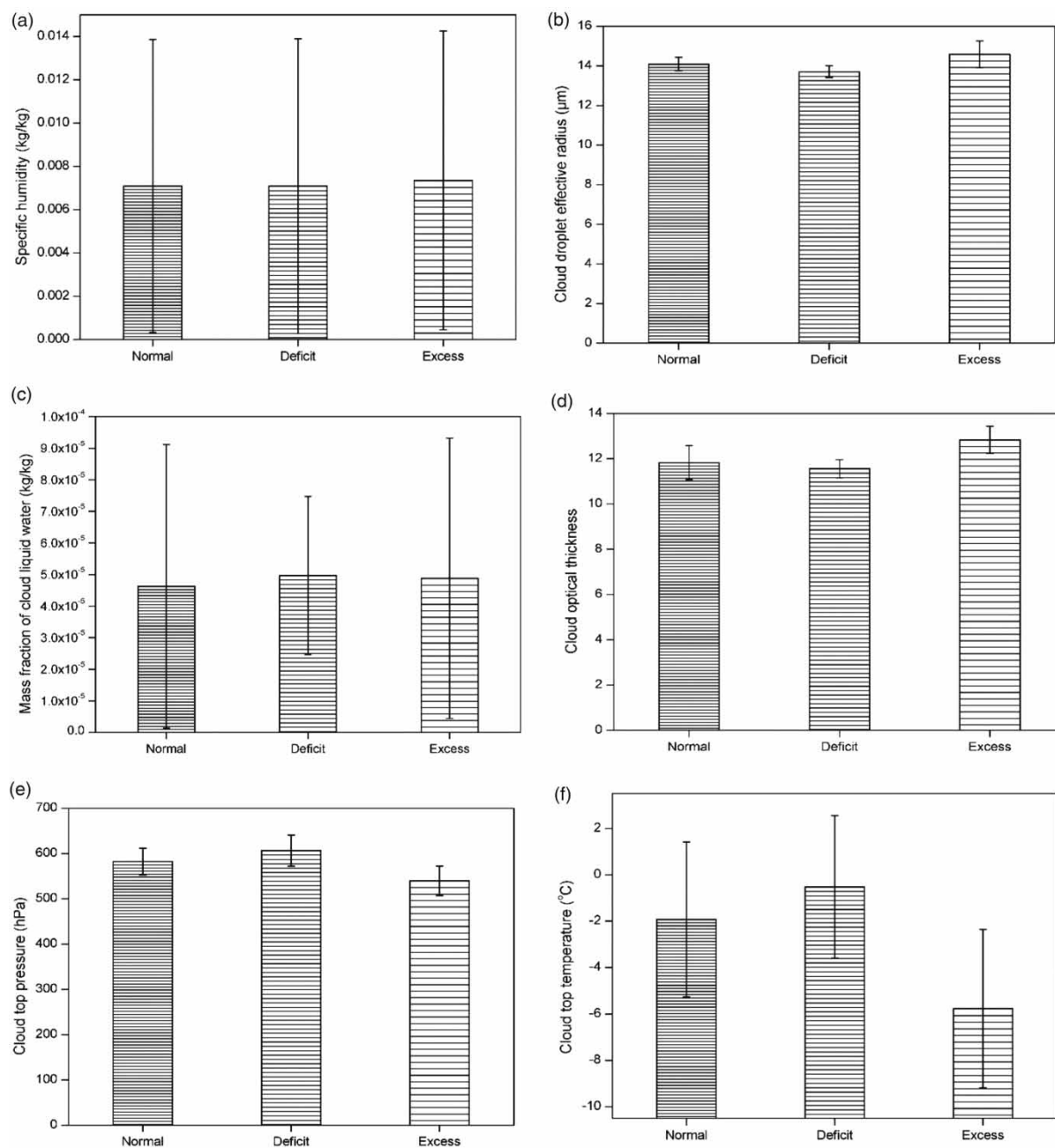
M.P., an inland region, was relatively less ravaged by catastrophic rain events than Gujarat as it has witnessed ten normal, only two excess and six deficit rainfall years during 2000–2017 (Figure 6(b)). The same as the excess scenario of Gujarat, M.P. also has larger droplets ( $14.56 \pm 0.18 \mu\text{m}$ ) with more LWC ( $1.09 \times 10^{-4} \pm 1.03 \times 10^{-4} \text{ kg/kg}$ ), possibly due to greater amount of moisture ( $7.22 \times 10^{-3} \pm 6.42 \times 10^{-3} \text{ kg/kg}$ ) in the total column (995–25 hPa) of the atmosphere (Figure 8(a)–8(c)). As explained, such characteristics match with the stratiform type of clouds. Along with this, high COT ( $18.43 \pm 0.14$ ), low CTP ( $394.04 \pm 22.05 \text{ hPa}$ ) and low CTT ( $-18.46 \pm 3.38 ^\circ\text{C}$ ) is obtained and represent formations of convective clouds too (Figure 8(d)–8(f)). Thus, shallow layers of stratiform clouds often might have driven strongly due to convective currents by destabilization of cloud layers, which in turn, could make clouds thicker. In contrast, small cloud droplets ( $14.05 \pm 0.63 \mu\text{m}$ ) have formed during deficit rainfall years possibly due to less availability of moisture ( $6.99 \times 10^{-3} \pm 6.17 \times 10^{-3} \text{ kg/kg}$ ) in the total atmospheric column



**Figure 6** | Rainfall departure (%) calculated using *in-situ* rainfall data during monsoon (June–September) from 2000 to 2017 over (a) Gujarat and (b) Madhya Pradesh.

(995–25 hPa) over M.P. (Figure 8(a) and 8(b)). These small droplets have a lesser amount of LWC ( $7.60 \times 10^{-5} \pm 4.53 \times 10^{-5}$  kg/kg) at higher-pressure levels (995–850 hPa),

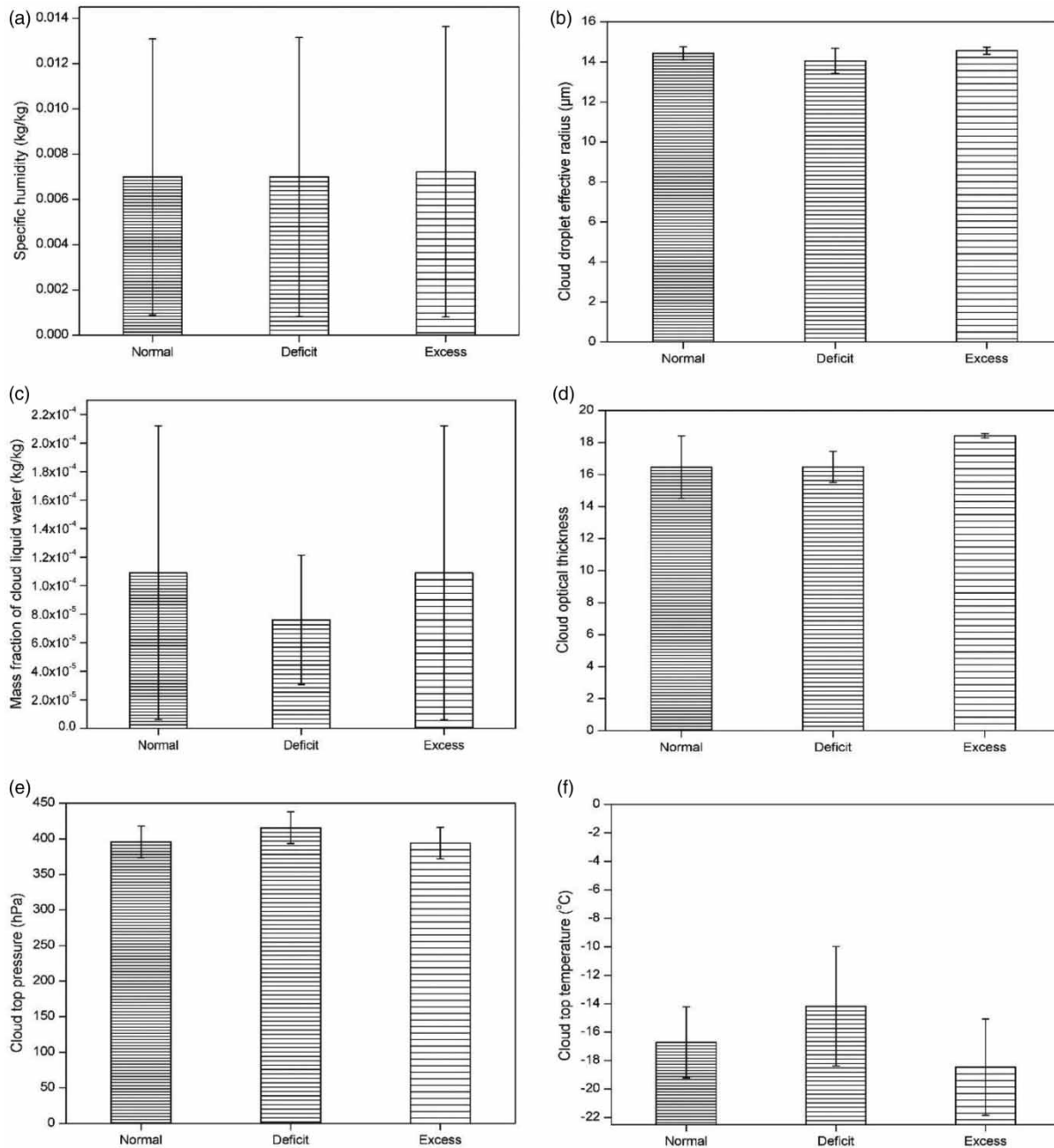
which may be due to dry conditions over inland region (Figure 8(c)). In the case of COT, it is low ( $16.48 \pm 0.97$ ), which depicts the formation of thinner clouds may be due



**Figure 7** | Averaged variation of (a) total column (995–25 hPa) specific humidity, (b) CER, (c) mass fraction of LWC at 995–850 hPa, (d) COT, (e) CTP and (f) CTT over Gujarat during normal, deficit and excess rainfall years of monsoon (June–September) throughout 2000–2017.

to low moisture content (Figures 8(a) and 8(d)). These transparent warm clouds are formed at higher altitude with high CTP ( $415.62 \pm 22.19$  hPa) and high CTT ( $-14.17 \pm 4.20$   $^{\circ}\text{C}$ ) (Figure 8(e) and 8(f)). Thus, the combined nature of stratiform and convective clouds may denote strong vertical mixing of rising thermals with upper level stratiform

clouds over M.P. during drought years throughout 2000–2017. The same as normal monsoon over Gujarat, M.P. comprises the combined nature of stratiform and convective clouds, except LWC (Figure 8). Like Gujarat, M.P. also has bigger cloud droplets ( $14.38$ – $14.74$   $\mu\text{m}$ ) during excess rain as compared to normal ( $14.10$ – $14.76$   $\mu\text{m}$ ) and deficit



**Figure 8** | Averaged variation of (a) total column (995–25 hPa) specific humidity, (b) CER, (c) mass fraction of LWC at 995–850 hPa, (d) COT, (e) CTP and (f) CTT over Madhya Pradesh during normal, deficit and excess rainfall years of monsoon (June–September) throughout 2000–2017.

(13.42–14.68  $\mu\text{m}$ ) rainfall events during 2000–2017. With the help of long-term study, a clear view of regional heterogeneity is visible which also helped to identify the nature of clouds at regional scale during different monsoon regimes. Usually excess and deficit rains are of interest to understand

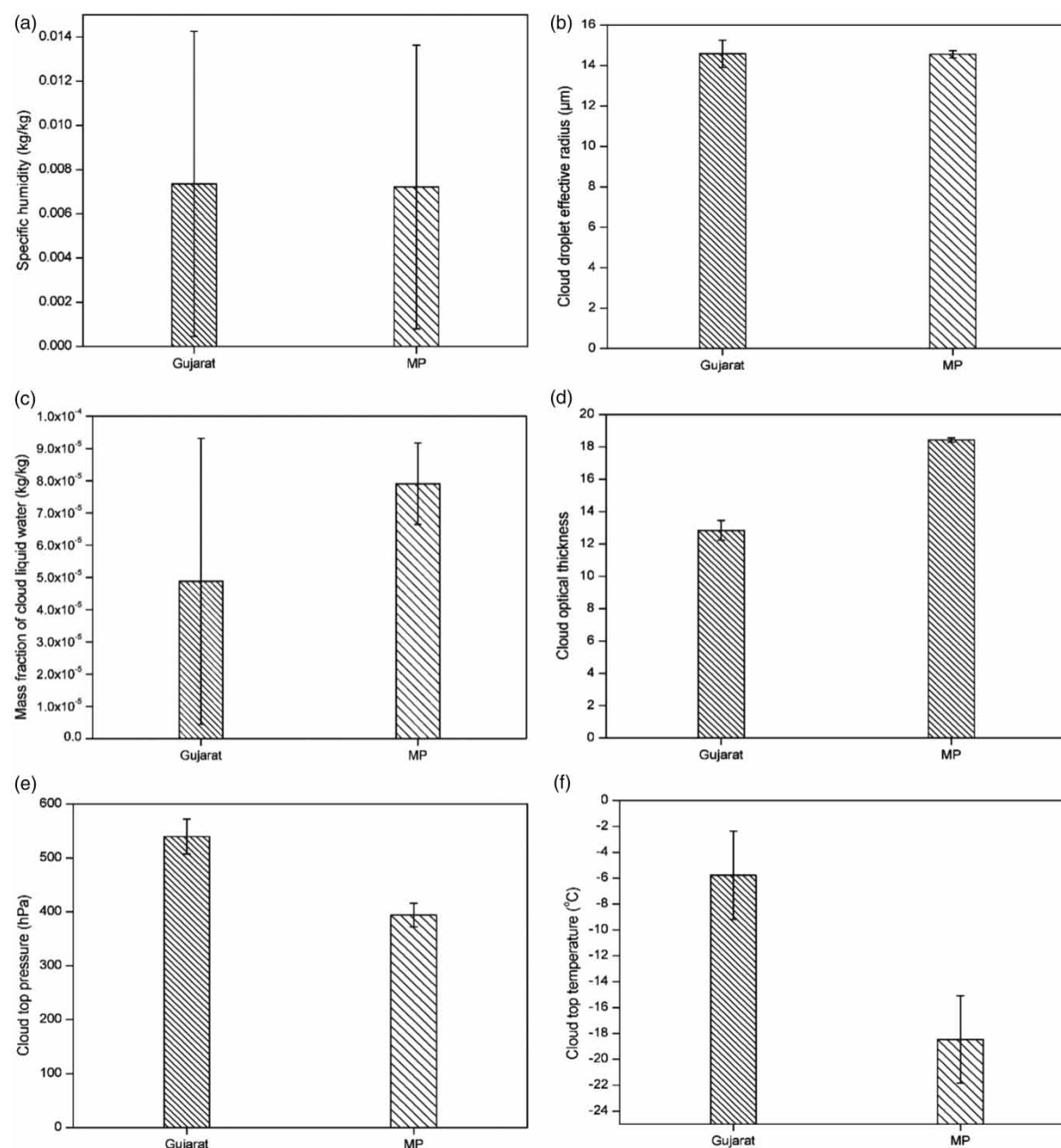
the behaviour of clouds over selected heterogeneous regions. Thus, further study should focus on the difference in the nature of clouds individually during excess as well as deficit rainfall years of 2000–2017 over M.P. and Gujarat. This regional rainfall scenario study may help to understand



whether the nature of cloud depends on the region, on the rainfall scenario, or on both. To identify this, a comparative study is needed between both the regions during excess and deficit rainfall throughout the years of 2000–2017.

Over a selected region nearer to the coast, the present study has observed formation of bigger cloud droplets with

high CER ( $14.58 \pm 0.67 \mu\text{m}$ ) which may be due to more moisture ( $7.35 \times 10^{-3} \pm 6.90 \times 10^{-3} \text{ kg/kg}$ ) distributed to fewer CCN throughout excess rainfall activities (Figure 9(a) and 9(b)). Also, excess amount of moisture during extreme rain may lead to formation of bigger droplets with lesser LWC ( $4.88 \times 10^{-5} \pm 4.44 \times 10^{-5} \text{ kg/kg}$ ) at 995–850 hPa,



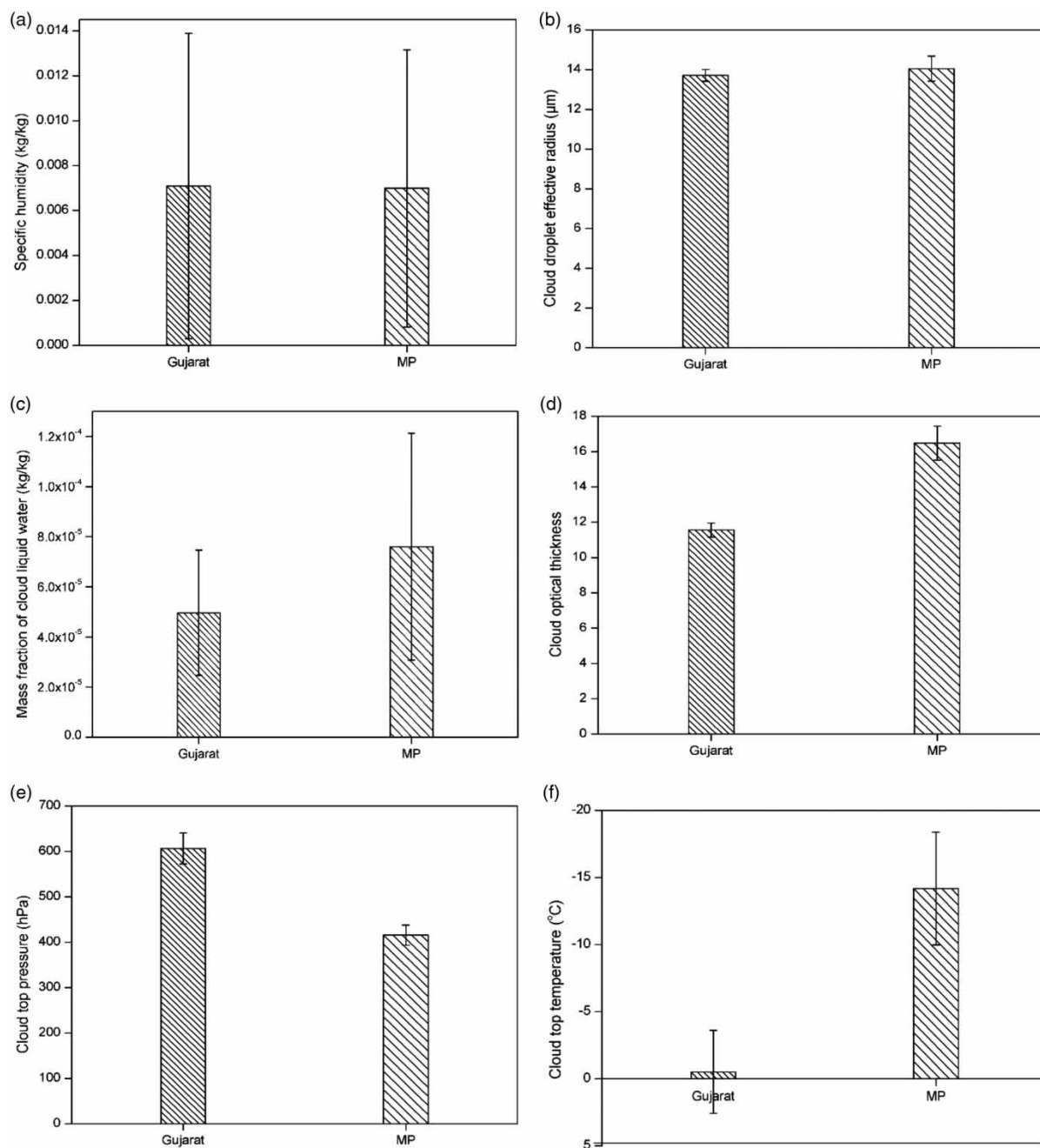
**Figure 9** | Averaged variation of (a) total column (995–25 hPa) specific humidity, (b) CER, (c) mass fraction of LWC at 995–850 hPa, (d) COT, (e) CTP and (f) CTT over Gujarat and Madhya Pradesh during excess rainfall years of monsoon (June–September) throughout 2000–2017.

which represents the stratiform nature of clouds (Figure 9(a)–9(c)). As known, such clouds are usually thinner with low cloud base and are captured well with low COT ( $12.84 \pm 0.61$ ), high CTP ( $539.88 \pm 32.47$  hPa) and CTT ( $-5.77 \pm 3.41$  °C) (Figure 9(d)–9(f)). Existence of these cloud properties may indicate the nature of stratiform clouds over Gujarat, which have caused extreme rains during the southwest monsoons of 2000–2017. Thus, a high fraction of stratiform type of clouds are available for excess rain over Gujarat possibly due to the role of various factors, such as availability of higher moisture content in the atmosphere, high rate of condensational growth, more turbulence entrained in the atmospheric circulation system and high rate of collision-coalescence.

Over an inland region, the present study shows lower specific humidity ( $7.22 \times 10^{-3} \pm 6.42 \times 10^{-3}$  kg/kg), low CER ( $14.56 \pm 0.18$  µm) and high LWC ( $7.91 \times 10^{-5} \pm 1.26 \times 10^{-5}$  kg/kg) at higher-pressure levels (995–850 hPa) during extreme rain periods (Figure 9(a)–9(c)). Formation of small droplets due to more CCN and low moisture represent characteristics of convective clouds. Also, the formed clouds are relatively denser with high COT ( $18.43 \pm 0.14$ ) and are found at high altitude with low CTP ( $394.04 \pm 22.05$  hPa) and low CTT ( $-18.46 \pm 3.38$  °C) (Figure 9(d)–9(f)). These cloud characteristics denote a high fraction of convective nature of clouds over M.P. for extreme rainfall activities. This could be possibly due to lifting of air masses with strong convection currents, more turbulence, high rate of condensation, collision as well as coalescence over inland region, which in turn, might have been responsible for extreme rains throughout the monsoon from 2000 to 2017. By considering standard deviations of CER, size of cloud droplets have a wide distribution (13.91–15.25 µm) for Gujarat whereas it was narrowed down with 14.38–14.74 µm for M.P. during excess rain activities. Thus, it is observed that probability of varying size of cloud droplets would be high over the coastal region as compared to inland region and that depicts a sign of regional heterogeneity during extreme rainfall.

The same as excess, drought years are also compared over both the regions to understand regional differences during 2000–2017. Although there is a lack of variation in moisture content is observed in the total column

(995–25 hPa), which might have changed the cloud properties over Gujarat and M.P. Results have shown high specific humidity ( $7.09 \times 10^{-3} \pm 6.80 \times 10^{-3}$  kg/kg) over the region closer to the coast and low ( $6.99 \times 10^{-3} \pm 6.17 \times 10^{-3}$  kg/kg) over the inland region under scanty rain conditions (Figure 10(a)). There is a dissimilarity found in CER over both the regions; instead of big cloud droplets over Gujarat, small cloud droplets ( $13.71 \pm 0.30$  µm) are found and instead of small, big cloud droplets ( $14.05 \pm 0.63$  µm) are found over M.P., which requires further analysis (Figure 10(b)). For LWC, it is found to be low ( $4.96 \times 10^{-5} \pm 2.50 \times 10^{-5}$  kg/kg) at 995–850 hPa over Gujarat, whereas it increases ( $7.60 \times 10^{-5} \pm 4.53 \times 10^{-5}$  kg/kg) over M.P. (Figure 10(c)). Less liquid water in cloud usually results in transparent clouds with low COT ( $11.56 \pm 0.40$ ) and more liquid water causes dense clouds with high COT ( $16.48 \pm 0.97$ ) (Figure 10(d)). Thin clouds appeared at low altitude with high CTP ( $606.85 \pm 34.31$  hPa) and high CTT ( $-0.52 \pm 3.08$  °C) over the region nearer to the coast (Figure 10(e) and 10(f)). Conversely, thick clouds are visible at high altitude with low CTP ( $415.62 \pm 22.19$  hPa) and low CTT ( $-14.17 \pm 4.20$  °C) (Figure 10(e) and 10(f)). Like excess cloud properties, all the utilized parameters, except CER, agree with the high fraction of stratiform and convective nature of clouds over Gujarat and M.P., respectively. Unlike excess rainfall scenario, deficit rain activities have a wide distribution of cloud droplets, i.e., 13.41–14.01 µm over Gujarat and 13.42–14.68 µm over M.P. This denotes uncertainties are high over both the regions, which may be due to unexpected observations of CER. Thus, the nature of clouds is largely dependent on region as compared to rainfall scenario. Study of cloud properties at high spatial resolution is quite significant to understand regional dynamics, which in turn, may help to improve prediction of uneven rainfall pattern. Such long-term studies are usually required to understand atmospheric processes, cloud formation processes and, hence, irregular rainfall pattern. The results obtained are significant and are able to indicate regional heterogeneity at fine scale, although more parameters as well as a greater number of rainfall years would strengthen these results. This study can also be useful for weather climate models to improve weather predictability and, hence, climate change.



**Figure 10** | Averaged variation of (a) total column (995–25 hPa) specific humidity, (b) CER, (c) mass fraction of LWC at 995–850 hPa, (d) COT, (e) CTP and (f) CTT over Gujarat and Madhya Pradesh during deficit rainfall years of monsoon (June–September) throughout 2000–2017.

## CONCLUSION

Due to advancement in global warming, direct or indirect impact on climatic variables has increased all around the globe. Uneven precipitation pattern may be caused specially

due to rise in surface temperature and high rate of evaporation/condensation, which has relatively larger impact on monsoon-dependent regions such as India. This may lead to a higher variation in atmospheric circulations, clouds as well as rain formation processes even at regional scale. To

find out about regional heterogeneity, the present study chose two types of heterogeneous region – a region closer to the coast (Gujarat) and an inland region (M.P.). Long-term (2000–2017) high resolution ( $0.5^\circ \times 0.5^\circ$ ) model simulations show comparatively low rate of change of CF and OLR at the top of atmosphere with  $y = (-107.64 \pm 16.34)x + (298.62 \pm 8.27)$ ;  $r^2 = 0.73$ ;  $p < 0.05$ , which might be due to the presence of thin clouds over Gujarat. Detailed study was conducted further with the help of an atmospheric parameter (specific humidity), cloud optical, macrophysical and microphysical properties (COT, CER, LWC at 995–850 hPa, CTP and CTT) to understand the nature of cloud. Study of these utilized parameters matches well with the characteristics of maritime clouds during the southwest monsoon over Gujarat. This study continued further with analysis of stratiform as well as convective nature of clouds over these selected regions. By considering uncertainty limits, it can be said that thin clouds (with COT ranges from 11.20 to 12.84) containing low amount of LWC ( $1.06 \times 10^{-5}$ – $8.60 \times 10^{-5}$  kg/kg) are stratiform clouds, whereas thick clouds (having COT 15.05–18.33) have more LWC ( $1.40 \times 10^{-5}$ – $17.50 \times 10^{-5}$  kg/kg) forming convective clouds. Along with different regions, different monsoon regimes (normal, excess and deficit) also could cause cloud properties to vary at regional scale. Under these climatic scenarios, high amount of mass fraction of total column specific humidity ( $7.35 \times 10^{-3} \pm 6.90 \times 10^{-3}$  kg/kg) was found during excess rain, whereas it decreases during scarce ( $7.09 \times 10^{-3} \pm 6.77 \times 10^{-3}$  kg/kg) and normal ( $7.09 \times 10^{-3} \pm 6.80 \times 10^{-3}$  kg/kg) rain throughout the monsoonal duration of 2000–2017 over the region closer to the coast. Similarly, availability of moisture triggered cloud formation processes with high CER ( $14.58 \pm 0.67 \mu\text{m}$ ), moderate CER ( $14.09 \pm 0.35 \mu\text{m}$ ) and low CER ( $13.71 \pm 0.30 \mu\text{m}$ ) during excess, normal and deficit rainfall years, respectively, by considering their uncertainties. Alternatively, excess rain clouds were relatively thicker, denser over Gujarat with high COT ( $12.84 \pm 0.61$ ) and were found at low altitude with low CTP ( $539.88 \pm 32.47$  hPa) and low CTT ( $-5.77 \pm 3.41^\circ\text{C}$ ) as compared to normal and deficit rainfall activities. These observations altogether show mixed characteristics of the stratiform and convective nature of clouds during excess, normal and deficit rainfall years over Gujarat. In addition to this, the results obtained depict that the nature of

clouds is largely dependent on the region rather than being dependent on monsoon scenarios during the southwest monsoon. These results are quite significant in identifying the nature of clouds over nearby regions of India, leading to in-depth knowledge of regional heterogeneity. These data also allow a comparison of cloud properties during different rainfall events over types of heterogeneous sites, which in turn, can enhance the understanding about regional cloud dynamics. Such cloud features can be included in climate models and thus could be utilized to improve weather predictability at high resolution and indirectly lead to the predictability of climate change. Data for more study regions as well as more years could be useful to improve these obtained results statistically.

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## DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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