Unraveling of cloud types during phases of monsoon intraseasonal oscillations by a Ka-band Doppler weather radar

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Ground-based cloud radar has been used for the first time in the Indian subcontinent to explore the cloud population during the break, transition and active phases of monsoon intra-seasonal oscillation over a region in the Western Ghats mountain. The synergetic use of in situ measurements along with the supporting large-scale microphysical features from the reanalysis data has been utilized in order to have a closer look of the morphology of clouds along with its transition during the intra-seasonal phases. It has been observed that the active phase is dominated by deep clouds (~41%) along with some shallow (~28%) and congestus clouds (~29%) while the break phases are dominated by the shallow clouds (~72%) during precipitating and high-level cirrus clouds (~65.22%) during the non-precipitating times. The role of middle level moisture for modulating the nature of the clouds along with its role in determining the latent heating profile over the same region has also been presented.

KEYWORDS
Ka-band radar, intraseasonal phases, orographic precipitation

1 | INTRODUCTION

The rainfall during the South Asian monsoon season over the region comes in spells with “active” spells interspersed with “break” spells. The “active” and “break” spells are manifestations of the monsoon intra-seasonal oscillations (MISOs) propagating repeatedly from the southern preferred location of the oceanic Intertropical Convergence Zone (ITCZ) to the northern continental location of the ITCZ. The vigorous MISOs represent a building block for the South Asian monsoon contributing to the seasonal mean rainfall and its inter-annual variability on one hand while modulating the frequency of occurrence of the synoptic disturbances (lows and depressions) on the other hand (Goswami et al., 2006). The proper knowledge of the exact time and duration of both the active and break spell is very much useful for the farmers and the water managers to plan accordingly. Thus, its skillful prediction of 25–30 days in advance is of great importance for them. Although most climate models have difficulty in simulating the large spatial scale and northwards propagation of about 1°lat/day (Sabeerali et al., 2013), some models are beginning to simulate the space–time characteristics of MISO with some fidelity (Sharmila et al., 2015). However, skill of current generation of coupled models remains significantly below the potential limit on predictability of the MISOs (Goswami and Xavier, 2003).

The limited skill of predicting the MISO by models stems from their inadequacy in simulating the large spatial scale of the dominant MISO and its northwards propagation. Models have difficulty in simulating the organization of the clouds and precipitation in the MISO scale. The organization of clouds and precipitation and its northwards propagation in...
turn depend on the mean vertical structure of the non-adiabatic heating (Chattopadhyay et al., 2009). The vertical structure of the latent heating is largely determined by frequency of occurrence and the proportion of different types of clouds contributing to the total precipitation (Pokhrel and Sikka, 2013). It has also been shown recently that the evolution of the vertical structure of heating during a MISO cycle contributed by the stratiform clouds plays a crucial role in the large-scale aggregation of precipitation associated with the MISO (Kumar et al., 2017). The proportion of convective and stratiform clouds, therefore, varies over a cycle of a MISO. In the context of simulation of the MISO by the models, the inability to simulate the organization of precipitation with fidelity, therefore, is likely to be related to inappropriate frequency of occurrence of different types of clouds during a cycle of a MISO. Unfortunately, the vertical structures of the heating and how it is contributed by different types of clouds during the intra-seasonal phases of MISO have not been well documented from observations. Such documentation can play the role of a test bed for developing improved parameterization of convection and clouds for better simulation and prediction of MISO by models.

With the aforesaid background, the present paper tries to document the characteristics of cloud population during the different phases of monsoon intra-seasonal oscillation by using a Ka-band Doppler weather radar (Ka-DWR) over a high-altitude region of Western Ghats mountain (WG). The characteristic feature around this region of WG is that the rainfall from the southwest monsoon gradually increases along slope of western part of the mountain but finally decreases when coming down to eastern part. Recent studies by Utsav et al. (2017) by using the X-band Doppler weather radar showed an increased frequency of storm location and initiation along the windward side of the mountain compared to leewards side which highlights the orographic response to southwesterly flow with superimposed diurnal cycle. They pointed out that the propagation of the convective cells, which align in the east–west direction of the mountain, are steered by the large-scale winds in the lower level. By using the satellite and reanalysis data, Kumar et al. (2014) found that the region gets the convective rainfall basically from the shallow clouds. Although some other documentation could be found related to the precipitation characteristics over this region (Konwar et al., 2014; Deshpande et al., 2015; Das et al., 2017) but the role of clouds and its relation with the large-scale phenomena during the intra-seasonal phases has not been documented till now. Thus, the study presented here tries to bridge the gap and links the microscale features of clouds with the varied types of cloud population as obtained from ground-based radar data to the large-scale features over the region under consideration. Furthermore, it also tries to find out the probable microphysical and thermodynamical processes responsible for the typical distribution of cloud types during different phases of MISO. This study will serve as a case study for the detail distribution of clouds types over the shallow topographical region of western India and will help for verifying both the regional and global model simulations for clouds.

2 | DATA

In the present study, the active, break and transition spells of the Indian summer monsoon for the year 2014 have been identified by using the criteria proposed by Rajeevan et al. (2010). The updated version of gridded rainfall data developed by Rajeevan et al. (2006) has been used in this analysis. For identifying the intra-seasonal spells, the daily rainfall over the 1 × 1° grid (73.5°–74.5°E, 17.5°–18.5°N) centering the Mandhardev radar site has been averaged. The daily rainfall time series are further standardized by subtracting the long time normal (1901–2014) from it and by dividing with its daily SD. The active (break) spells have been identified as the period during which the rainfall anomaly is more (less) than +/(−) 0.8 SD, consecutively for 3 days or more. The phase between the break to active has been coined as the transition phase. The topographic map of the region under consideration along with the daily rainfall anomaly during the monsoon season has been depicted in Figure 1a,b, respectively. The vertical profile of radar reflectivity used in this study had been obtained from the Ka-DWR of Indian Institute of Tropical Meteorology (IITM), Pune, India. This Ka-band radar which had been mounted on a trailer truck has the capability of rotating full 360° motion in azimuth, 0–180° coverage in elevation angle and in vertical pointing mode. It operates at a frequency of 35.29 GHz (8.5 mm wavelength) and is installed at Mandhardev (18.02°N, 73.85°E) atop Western Ghats mountain about 1.3 km amsl (above mean sea level). The antenna diameter of Ka-DWR is 1.2 m and it emits a peak power of 2.2 kW and has a beam width of 0.5°. The sensitivity of the radar is −45 dBZ at 5 km. The receiver and transmitter units are mounted just below the antenna which helps to minimize the path attenuation loss in radar front end. The radar has been calibrated by using the corner reflector target located on a tower at a range of ~605 m. Nearly 80–85 vertical profiles are observed over a single day with a time interval of 13 min. Thus, all the daily profile are averaged to obtain a total composite profile of reflectivity for the 18 active days, 16 break days and 10 transition days separately for the year 2014. Data from the optical rain gauge (ORG) collocated with the Ka-DWR have also been used to identify the precipitating and non-precipitating clouds.

For the latent heat, the third levels pass wise daily gridded product of TRMM (Tropical Rainfall Measurement Mission) 3G31 data has been used. These data are basically the gridded product of the orbital convective–stratiform heating (CSH) from the combined orbital heating profile at 19 levels from the surface convective and
stratiform rainfall rate at 0.5 × 0.5° resolutions. The latent heat is estimated using the combination of both observed TRMM precipitation radar (PR) gridded data and cloud resolving model (CRM) simulated synthetic cloud process data. PR data of conditional rain intensity and stratiform fraction are used and in case of CRM simulation, latent heating, eddy heat flux convergence and radiative heating/cooling is used for the calculation of 3G31 heating profile. 3G31 data are more reliable than the previous CSH algorithm (Tao et al., 2010). Satellite passes co-locating or very close to the radar site was selected for understanding the latent heat profile during the active, break as well as transition days.

The vertical profile of cloud liquid water content and cloud ice water content has been used from the European Centre for Medium-Range Weather Forecasting (ECMRWF) interim re-analysis (ERA-Interim; Dee et al., 2011) data averaged over the same grid box as described above.

3 | RESULTS AND DISCUSSION

The year 2014 is considered to be a deficit year with the total seasonal (June–September) monsoon rainfall for the country as a whole being 88% of long period average (as per Annual climate summary, 2014 published by IMD, Pune). However, the study region that is the grid box of 1 × 1° centering the radar site, the annual rainfall during 2014 was 5,876 mm, close to its long-term climatology (5,868 mm). Correspondingly, it has also been found that almost all the active events over the region of study either coincides or occurs exactly before/after the low pressure systems (~10 in number), which were formed either over Bay of Bengal or Arabian Sea or land region and subsequently moves towards the radar location. This also corroborates the previous study of LPS contribution towards the active and break period of Indian summer monsoon (Goswami et al., 2003; Krishna-murthy and Ajayamohan, 2010). Hence, it became quite essential to study the characteristics of clouds prevailing in the radar region.
over the study region. As the radar reflectivity is indicative of cloud types (Feng et al., 2014), the composite vertical profile of radar reflectivity during break, transition and active phases of the MISO over the study box around the radar site for the year 2014 has been examined (Figure 2). The attenuation factor and saturation for the Ka-band radar has been taken care of in the analysis (Matrosov, 2005). The distinct identity of the three intra-seasonal phases are confined within an altitude of 3 km whereas the cirrus clouds in the reflectivity range of $-15$ to $-5$ dBz shows their domination in the break days from ~ 9 km. It is quite clear from the figure that the augmentation of the clouds up to an altitude of 3 km gives rise to the transformation from break phase to transition and finally to active phase. The negligible amount of clouds from the surface to 9 km during the break phase restricts from getting the error bar in that region. It is also to be mentioned that although a signature of the melting layer is visible in the transition phase from break to active phase at an altitude of around 3 km, but such features are not visible for the active phase. This is basically due to the factor that as the active phase is the combination of the composite profiles of both the stratiform and convective rain, hence the impact of the later part has eroded the bright band aspects in Figure 2c.

The present paper also portrays a detailed inter-cloud budget during the intra-seasonal phases of 2014 which was obtained by analyzing the cloud base and cloud top height from the profiles of Ka-DWR. The technique has been adopted as per the methodology of Feng et al. (2014) and Shupe (2007), wherein the parameters for tropical clouds have been tuned as per Comstock et al., 2013. The clouds are segregated as precipitating and non-precipitating types on the basis of the surface rainfall measurement. Figure 3 gives a pictorial view of the percentage of cloud systems that occur during the active, break and the transition phase of monsoon over the mentioned grid box with the above method. It is quite obvious that the precipitating clouds dominate the non-precipitating ones during the active phase with the frequency of occurrence of 61% and 39%, respectively, while during the break phase the situation reverses completely when the domination of non-precipitating clouds is visible with 68%. Both the cloud types are further subdivided into three categories each, that is, shallow, congestus and deep clouds in case of precipitating clouds and midlevel, cirrus and anvil clouds in case of non-precipitating ones. It is seen from the figure that all the three categories of clouds contribute to the formation of precipitating clouds in case of the active days while the domination of midlevel clouds are more for the non-precipitating clouds. Correspondingly during the break phase, the non-precipitating cirrus clouds dominate more than the other cloud systems. It is to be noted from Figure 3 that although the contribution of the deep clouds is more in case of precipitating ones of active days,
but the congestus clouds and shallow clouds are also present in considerable amount. This is due to the factor that the moisture supply in all the level of clouds are quite sufficient enough to nourish the transformation of shallow and the congestus clouds into the deep convective clouds. Correspondingly, during the break phase of the monsoon, the region gets the precipitation mostly from shallow clouds due to the large moisture availability only in the lower level. With increase in height, the moisture level decreases which hinder the shallow or congestus clouds to develop into deep clouds. It is interesting to note that during the transition from break phase to the active one, the occurrence of congestus cloud is around 70%, that is, much more in comparison to other cloud structures. Simultaneously, the percentage occurrence of non-precipitating cirrus clouds also decreased from 65% in the break phase to 16% in the transition phase. Thus, it can be presumed that the mid-level moisture present in the atmosphere plays a crucial role for all these evolution and decay of cloud structure at various levels.

Thus in order to understand the large-scale features of the inter-cloud transition during these intra-seasonal phases, it is essential to get the microphysical properties of the cloud which has been depicted in Figure 4 where the profiles of specific humidity, liquid and ice water content over the same region as obtained from the gridded ERA data have been plotted. Figure 4a clearly shows the abundance of moisture availability in the lower level up to 900 hPa during the break days which triggers the development of more low-level clouds. With the increase in altitude, the moisture content decreases rapidly as a result of which these shallow clouds could not transform into deep or congestus clouds. While in the active days, although the moisture level decreases with altitude, it is sufficient to provide nourishment for feeding the shallow clouds to transform into deep convective clouds. As such, all types of clouds contribute to the total cloud structure in the active phase as depicted in Figure 3. While during the transition phase, increase in moisture content in the mid level due to the entrainment of ascending moist convective clouds triggers the development of deep clouds from congestus (Johnson et al., 1999). This process leads to 42% occurrence of deep convective clouds during the active phase as compared to 22% during the transition phase. Thus, the mid-level moisture (893–400 hPa) availability plays a crucial role for the different phases of monsoon intra-seasonal oscillation. Correspondingly, from Figure 4b, which gives the vertical profile of cloud liquid water (CLW) content during the intra-seasonal phases, it is also evident that during the active phase, CLW has the highest peak of 0.14 g/kg at around 850 hPa pressure level and decreases thereafter with two minor peaks observed at an altitude of 3 km (~700 hPa) and 5 km (~540 hPa), respectively. While looking into the break phase, it has been observed that all the cloud liquid water content with the highest of 0.04 g/kg are confined to the low levels around the altitude of 1.5–3.0 km (~850–700 hPa). This is consistent with the presence of few low clouds and absence of precipitation from deep clouds during the break phase. Enhancement of cloud liquid water during transition from 800 to 400 hPa seems to prepare the environment for deep clouds to form during the active phase. The cloud ice mass (from Figure 4c)
is largest during the active phase with a maximum at 300 hPa—most likely coming from the larger propensity of deep clouds and their anvils during this phase. With very little deep convection during the break phases, the cloud ice mass is almost non-existent during such times.

The distribution of cloud types (Figure 3) and the vertical profiles of cloud liquid water and cloud ice mass (Figure 4) during different phases of MISO indicates that the total rain during active phase is likely to be contributed significantly by shallow convection (~58%) together with deep clouds contributing to ~42%. The stratiform precipitation arising from the decaying deep convection may explain the lower-level cooling of the vertical profile of latent heat (Figure 5) constructed from TRMM 3G31 data set. Correspondingly, during the break phase, the vertical profile of latent heat is consistent with the observation of some low-level clouds as well as upper-level cirrus clouds.

4 | CONCLUSION

The uniqueness of the present paper lies in the fact that it portrays for the first time the quantitative nature of both precipitating and non-precipitating clouds as obtained from the state-of-the-art Ka-band cloud radar, during the break, transition and active spells of Indian summer monsoon over a region of 1° x 1° grid box in the heavy precipitation belt of WG. The study reveals that clouds in all the atmospheric levels contribute for the development and sustenance of active phase in the atmosphere. Correspondingly, it has also been observed that during the break phase, the precipitating clouds are basically the shallow clouds while the high-level cirrus clouds show their pre-dominance during the non-precipitating periods. At the same time, the transition phase from break spell to active one during the wet period is characterized by the increase of the congestus clouds, leading to the entrainment of ascending moist-convective clouds in the mid-level that triggers the development of deep clouds and facilitates the transition from break to the active phase. The role of moisture in organizing the nature of clouds had also been highlighted [here].

The paper also brings to light the role of the vertical profile of cloud liquid water content and cloud ice water content over the study region which supports the findings as obtained from the Ka-DWR in respect to the microphysical point of view. The consistency of the latent heat profile during different phases of MISO had also been highlighted in the above analysis. This study will thus point up the significant role of weather radar for investigating the structure of cloud morphology during the monsoon processes at different timescales.

ACKNOWLEDGEMENTS

Indian Institute of Tropical Meteorology (IITM, Pune) is fully supported by the Ministry of Earth Sciences (MoES), Government of India, New Delhi. The authors like to thank the radar engineers at the site for maintaining the radar and managing the radar data. Sincere thanks to the reviewers, the Editor and the Associate Editor for their comments and suggestions, which greatly improved the manuscript. The authors also like to thank the IMD (India Meteorological Department), Pune, ERA, TRMM and Cloudsat Team Members for the data.

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How to cite this article: Chakravarty K, Pokhrel S, Kalshetti M, et al. Unraveling of cloud types during phases of monsoon intra-seasonal oscillations by a Ka-band Doppler weather radar. Atmos Sci Lett. 2018; 19:e847. https://doi.org/10.1002/asl.847