Abstract

Very small fractional area (0.1%) occupied by the cumulonimbus (Cb) clouds belies their importance in Earths hydrological cycle and climate. For example, Riehl and Malkus (1958) estimated that the vertical transport of energy needed for the global energy balance can be accomplished by 1500 to 5000 active, undiluted Cb clouds (i.e., hot towers). Cb clouds feed hydrometeors to the anvil cloud region in mesoscale convective system (MCS). Applications such as the estimation of the vertical profile of latent heating, cumulus parameterizations, satellite rainfall retrievals, inferring the probability of lightening, etc., require information on the vertical distribution of hydrometeors in convective clouds (e.g., Xu and Zipser, 2012). Knowledge of the vertical structure of Cb clouds near individual cloud scale becomes necessary for validating cloud resolving model results. However, information on the vertical structure of convective clouds at horizontal scales comparable to that of a deep convective cloud is not available over most regions in the tropics. The PR provides an unprecedented long time series of data on the 3D structure of precipitating clouds in the tropics. The TRMM PR equivalent radar reflectivity factor (Z_e) data product 2A25 version 6 is the main data used in the study. The present thesis work primarily focuses on the properties of convective clouds at the PR pixel scale. TRMM, operational since December 1997, is a non-sunsynchronous satellite with 35^0 inclination and samples the tropics several times a day (e.g., Kummerow et al., 1998, 2000). The PR works in K_u band (13.8 GHz or 2.2 cm wavelength), and its scan, consisting of 49 beams, had a width of 215 km when launched and ~250 km after August 2001. The beam width is 0.71^0; nearby beams are separated by 0.71^0, giving a maximum scan angle of 17^0 (Kummerow et al., 1998). There are 80 levels in the vertical,

each having 250 m resolution with the lowest level being the Earths ellipsoid. The height corresponding to different vertical levels in the 2A25 data set is the distance measured along the PR beam. Hence, corrections to pixel heights along different beams have been applied.

Present thesis presents the vertical structure of radar reflectivity factor in tall cumulonimbus towers (CbTs) and intense convective clouds (ICCs) embedded in the South Asian monsoon systems and other tropical deep cloud systems. CbT is defined referring to a reflectivity threshold of 20 dBZ at 12 km altitude and is at least 9 km thick. ICCs are constructed referring to reflectivity thresholds at 8 km and 3 km altitudes. Cloud properties reported here are based on 10 year climatology. It is observed that the frequency of occurrence of CbTs is highest over the foothills of Himalayas, plains of northern India and Bangladesh, and minimum over the Arabian Sea and equatorial Indian Ocean west of 90^0E. The regional differences depend on the reference height selected, namely, small in the case of CbTs and prominent in $6-13$ km height range for ICCs. Land cells are more intense than the oceanic ones for convective cells defined using the reflectivity threshold at 3 km, whereas land versus ocean contrasts are not observed in the case of CbTs. Compared to cumulonimbus clouds elsewhere in the tropics, the South Asian counterparts have higher reflectivity values above 11 km altitude. One of the main findings of the present thesis is the close similarity in the average vertical profiles of CbTs and ICCs in the mid and lower troposphere across the ocean basins, while differences over land areas are larger and depend on the reference height selected. Foothills of the Western Himalayas, southeast South America and Indo-Gangetic Plain contain the most intense CbTs, while equatorial Africa, foothills of the Western Himalayas and equatorial South America contain the most intense ICCs. Close similarity among the oceanic cells suggests that the development of vigorous convective cells over warm oceans is similar and understanding gained in one region is extendable to other areas.

South Asia contains several areas where the seasonal summer monsoon rainfall is influenced by the orography. One of the fundamental questions concerning the orographic rainfall is the nature of the associated precipitating clouds in the absence of synoptic forcing. It is believed that these are shallow and mid-level clouds, however, there is not much information in the literature on their vertical structure. Chapter 4 explores the vertical structure of active shallow (SC) and mid-level clouds (MLC) in Southeast Asia which are associated with the orographic features. Shallow and mid-level clouds have been defined such that their tops lie below 4.5 km and between 4.5 and 8 km, respectively. Only those TRMM PR passes are considered for active shallow and mid level cloud, which consists less than 5% deep cloud ($\geq$ 8 Km), compared to shallow cloud ($\leq$ 4.5 km) and mid level cloud (4.5 and $\leq$ 8 km). The reflectivity and height thresholds with constraint on percentage of deep clouds, ensure that we only captures the intense and isolated shallow and mid level clouds, away from deep cloud. The Western Ghats contains the highest fraction of the shallow clouds followed by the adjacent eastern Arabian Sea, while the Khasi hills in Meghalaya and Cardamom Mountains in Cambodia contain the least fraction of them. Average vertical profiles of shallow clouds are similar in different mountainous areas while that of mid-level clouds show some differences. Below 3 km, cloud liquid water content of the mid-level clouds is the highest over the Western Ghats and the eastern Arabian Sea. The average cloud liquid water content increases by 0.19 gm m^{-3} for SCs between 3 km and 1.5 km, while the corresponding increase for MLCs is around 0.08 gm m^{-3}.

MCS has a life cycle consisting of formative, intensifying, mature and dissipating stages. From the maximum projection of reflectivity on longitude and latitude plane from the 3D reflectivity fields, CS is defined as the common area of connected pixels with $Z_e \geq 17$ dBZ and polarized corrected temperature (PCT) ≤ 250 K, with atleast 500 km^2. A CS is considered in subsequent analysis if its area detected in the Z_e projection is at least 50% of its area seen in the PCT imagery. An algorithm is applied to obtain the phase of evolution. The algorithm is based on the average vertical profile of CSs and the reflectivity peak altitude (H_{max}). An index namely reflectivity difference (RD) and H_{max} is used to identify the phases of evolution. A close similarity has been observed during different phases in average vertical profiles as well as in CFAD. Growing or intensifying stage consists the highest reflectivity below the 2 km altitude. Mature phase does not show the much variation in Z_e below the freezing level, whereas in the decaying stage, shows the largest regional differences in this layer of the atmosphere. Melting band signature is most pronounced in the decaying stage. Fraction of convective area decreases as CSs go through its life cycle, except over Atlantic Ocean during winter.