Atmospheric Research 183 (2017) 73–83

Contents lists available at ScienceDirect

Atmospheric Research

journal homepage: www.elsevier.com/locate/atmosres

Clouds vertical properties over the Northern Hemisphere monsoon regions from CloudSat-CALIPSO measurements

Subrata Kumar Das [a,*], R.B. Golhait [b], K.N. Uma [c]

[a] Indian Institute of Tropical Meteorology, Pune, India
[b] Savitribai Phule Pune University, Pune, India
[c] Space Physics Laboratory, Vikram Sarabhai Space Centre, Trivandrum, India

ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 7 July 2016
Accepted 11 August 2016
Available online 16 August 2016

Keywords:
Clouds
Monsoon
CloudSat-CALIPSO

ABSTRACT

The CloudSat spaceborne radar and Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) space-borne lidar measurements, provide opportunities to understand the intriguing behavior of the vertical structure of monsoon clouds. The combined CloudSat-CALIPSO data products have been used for the summer season (June–August) of 2006–2010 to present the statistics of cloud macrophysical (such as cloud occurrence frequency, distribution of cloud top and base heights, geometrical thickness and cloud types base on occurrence height), and microphysical (such as ice water content, ice water path, and ice effective radius) properties of the Northern Hemisphere (NH) monsoon region. The monsoon regions considered in this work are the North American (NAM), North African (NAF), Indian (IND), East Asian (EAS), and Western North Pacific (WNP). The total cloud fraction over the IND (mostly multiple-layered cloud) appeared to be more frequent as compared to the other monsoon regions. Three distinctive modes of cloud top height distribution are observed over all the monsoon regions. The high-level cloud fraction is comparatively high over the WNP and IND. The ice water content and ice water path over the IND are maximum compared to the other monsoon regions. We found that the ice water content has little variations over the NAM, NAF, IND, and WNP as compared to their macrophysical properties and thus give an impression that the regional differences in dynamics and thermodynamics properties primarily cause changes in the cloud frequency or coverage and only secondary in the cloud ice properties. The background atmospheric dynamics using wind and relative humidity from the ERA-Interim reanalysis data have also been investigated which helps in understanding the variability of the cloud properties over the different monsoon regions.

1. Introduction

The clouds and associated thermodynamic processes can modulate the Earth radiation budget, the hydrological cycle and the large-scale circulation of the Earth through the feedback mechanism (Hartmann et al., 1992; Liou, 1992). The presence of cloud induces the gradient (both in vertical and horizontal directions) in radiative and latent heat fluxes (Webster and Stephens, 1984). The net effect of clouds on the radiation budget strongly depends on various factors like cloud type, cloud amount, occurrence height, geometrical thickness and other cloud microphysical parameters (Waliser et al., 2009). These cloud properties are often poorly represented in parameterization schemes of the climate and weather forecasting models and therefore remain one of the largest sources of uncertainties in estimating the climate change assessment in the global climate models as reported in earlier literature (e.g., Randall et al., 2003; Waliser et al., 2009; Liu et al., 2013; Stevens and Bony, 2013; Li et al., 2016). Therefore, quantitative investigation of the cloud vertical structure, both spatially and temporally, can give an insight on the microphysical processes during different stages of the cloud lifecycle, which will improve our understanding of the cloud feedback mechanism in the climate system (Wang et al., 2000; Gao et al., 2014).

The monsoon region is distributed globally and synchronized with the solar cycle (Wang et al., 2011 and references therein). Wang et al. (2011) have defined the global monsoon domain as the areas in which the annual range rainfall (local summer-minus-winter rainfall) exceeds 2 mm day^{-1} and total precipitation during the local summer should be >70% of the total annual rainfall. These domains include the South and East Asia, Indonesia-Australia, Northern and Southern Africa, and North and South America. To understand the monsoon many attempts in the past have been made by investigating the rainfall, monsoon circulation pattern, intraseasonal variations, and mesoscale convection (for e.g., Webster et al., 1998; Lee et al., 2011; Goswami et al., 2011; Sikka, 2011). However, only limited studies have been

* Corresponding author at: Indian Institute of Tropical Meteorology, Pashan, Pune 411008, India.
E-mail address: skd_ncu@yahoo.com (S.K. Das).

http://dx.doi.org/10.1016/j.atmosres.2016.08.011
0169-8095/

carried till now to understand the vertical structure of clouds during the monsoon. This understanding of the vertical structure of clouds during the monsoon season is important as during monsoon various types of cloud form resulting in different radiative effects and precipitation formation (Li et al., 2016 and references therein). Also, the uncertainties resulting from constraints in examining the vertical distribution of the monsoon cloud systems result in an inaccurate representation of diabatic processes in the large-scale numerical simulation and prediction of the monsoon (Johnson and Houze, 1987).

With the above motivation, the present study investigates and intercompares the vertical distribution of the cloud macrophysical and microphysical properties over the NH monsoon regions. This became possible with the operation of active remote sensing sensors like radar and lidar in space. These observational tools have enhanced our understanding of the cloud vertical structure on a global scale. The Cloud Profiling Radar (CPR) onboard the CloudSat (Stephens et al., 2002) and Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO (Winker et al., 2007) satellite were launched in June 2006 and continuously provide the cloud profile data throughout the Earth's atmosphere. Once the quality control data were archived from those satellites, several studies (e.g., Luo et al., 2009; Stein et al., 2011; Rajeevan et al., 2013; Das et al., 2013; Zhang et al., 2015) had made use of the CloudSat radar and CALIPSO lidar data in combination with other measurements and reanalysis data to investigate the three-dimensional structure and distribution of clouds on a global scale. For example, Luo et al. (2009) compared the hydrometeor occurrence and their vertical structure between Eastern China and Indian summer monsoon (ISM) regions using one year of the CloudSat-CALIPSO data. They reported that the hydrometeor occurrence frequency averaged over the Eastern China is ~80% while over the Indian region is ~70%. However, the single hydrometer occurrence frequency over the Eastern China and India is about 63% and 53% respectively. Rajeevan et al. (2013) and Stein et al. (2011) summarized the cloud distribution over the ISM and West African monsoon areas respectively. Stein et al. (2011) from the CloudSat–CALIPSO data products investigated the cloud structure over the West African Monsoon region and found that the deep convection enhanced during night results in extensive anvil and cirrus formation while more shallow cloud and congestus clouds are observed during the daytime. During the ISM period, Rajeevan et al. (2013) from the CloudSat data showed that the deep convective clouds with the large vertical extent are more over the northern Bay of Bengal, north Arabian Sea, and south equatorial Indian Ocean and along the west coast of India. Das et al. (2013) characterized the vertical distribution of clouds macrophysical and microphysical properties during the active and the break spells of the ISM using the combined CloudSat-CALIPSO data products. They showed more high cloud during the break conditions compared to the active periods. Gao et al. (2014) investigated the warm cloud properties over the Northern Hemisphere and showed that the total hydrometeor occurrence frequency over land (ocean) is ~65.8% (77.5%), to which single layer warm clouds contributed about 9.5% (20.9%) to the total profiles. They have also discussed the cloud growth processes using the profiles of liquid-water content and radar reflectivity. Recently, Zhang et al. (2015) have examined the aerosols impact on subfreezing cloud thermodynamic phase change over the East Asia and found that the mean occurrence frequency of supercooled liquid, mixed-phase, and glaciated clouds over the East Asia is about 10.4%, 10.3%, and 16.9%, respectively. The glaciated (supercooled liquid) clouds (~60%) were dominant cloud types over the northwest (southeast) of East Asia.

The aim of this work is to examine the cloud vertical properties over the Northern Hemisphere monsoon regions. To accomplish the objective, the combined CloudSat-CALIPSO data products for the summer monsoon months (June–August) of 2006–2010 have been used. The paper is organized as: data and methodology are described in Section 2. Results and discussion are given in Section 3. Finally, the summary is presented in Section 4.

2. Data and methodology

The CloudSat and CALIPSO are nadir-viewing sun-synchronous satellites, orbiting the Earth's atmosphere at an altitude of ~705 km with an inclination angle of ~98°. Both the satellites are the part of A-Train constellation and take measurements at the same location approximately once in every 16 days. The CloudSat probes the atmosphere about 15 s ahead of the CALIPSO measurement.

The CloudSat CPR operating at 94-GHz (~3 mm) measures the backscattered power from the cloud- and precipitation-size particles. The CPR resolution is 1.5 km cross-track by 2.5 km along-track of radar footprint. The CPR pulse width is ~3.3 μs and thus has a vertical resolution of ~480 m. The CPR data oversamples at ~240 m. Details about the CloudSat measurements are given in http://cloudsat.atmos.colostate.edu. The CALIOP operating at dual wavelengths (532 nm 1064 nm) detect the backscattered power from the clouds and aerosols. The CALIOP horizontal resolution is ~333 m with a vertical resolution of ~30 m (below 8.2 km altitude) and ~60 m (between 8.2 and 20.2 km). Details about the CALIOP measurements can be found at http://eosweb.larc.nasa.gov/PRODOCS/calipso/table_calipso.html.

The CPR and CALIOP signals have different sensitivities to the cloud droplet size and concentration. Sassen et al. (2009) reported that the lidar signals usually get attenuated by the dense clouds and fail to detect multiple layers of cloud beyond the dense layer. On the other hand, there is a weak attenuation of the radar signal from the dense cloud and are less sensitive to the thin cloud. Thus, synergistic measurements of radar and lidar are required to characterize the cloud structure of the entire column of the atmosphere. Therefore, by combining the CloudSat and the CALIPSO data along with the data from the European Centre for Medium-Range Weather Forecasts (ECMWF), the CloudSat standard products have been used to investigate the cloud properties for each observed cloud pixel.

The present study uses the CloudSat Level 2 standard data products available in the website http://cloudsat.atmos.colostate.edu/dataHome.php. These products are 2B-GEOPROF (Mace et al., 2007), 2B-GEOPROF-LIDAR (Mace et al., 2009), and 2B-CWC-RVOD (Wood, 2008). The 2B-GEOPROF product contains the radar reflectivity factor and cloud mask information in the vertical column sampled by the CPR. The 2B-GEOPROF-LIDAR product provides information on the heights of the hydrometeor layer base and the layer top for different layers in each CPR vertical scan profile. This product combines the CALIPSO (lidar) and CPR (radar) data to estimate the cloud layer in each of the vertical radar bins. Non-valid hydrometeor layers are filled with the missing values. The CWC-RVOD is used to derive the cloud ice water contents, ice effective radii, and ice water paths. These RVOD products are derived using a combination of the measured radar reflectivity factor (uses 2B-GEOPROF product) along with the estimates of visible optical depth retrieved from the Moderate Resolution Imaging Spectroradiometer (MODIS) reflectance to constrain the cloud retrievals more tightly than in the radar-only product (2B-CWC-RO). Therefore, the RVOD product is a combination of RVOD and RO retrieval solutions yielding more accurate results by using the maximum information available through the CloudSat data system (Wood, 2008). The CloudSat cloud microphysical retrieval is based on the Forward Model algorithm and by assuming a log-normal size distribution (Wood, 2008; Austin et al., 2009). The uncertainties in the retrieval of ice cloud microphysical properties are <40% based on simulation test (Austin et al., 2009).

In addition, the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis data are used to derive the Outgoing Long wave Radiation (OLR) to quantify the convection. These data are available as the monthly means, at a grid resolution of 2.5° latitude × 2.5° longitude. Detail description of the NCEP/NCAR interpolated OLR data set is described in Liebmann and Smith (1996). Low values of OLR (<220 W m^{-2}) is used as a proxy to indicate the presence of deep convection (Das et al., 2011 and