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Study on cloud types distribution over northern India using raDAR-liDAR (DARDAR)

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Abstract

A detailed study on the distribution of basic cloud types over the northern states of India (NSI) is performed using the decadal (2007-2016) DARDAR data, which facilitates merged raDAR and liDAR observations onto the high resolution matched geographical grid points. Study demonstrates the seasonal variations, with southwest monsoon (June-September) exhibiting the maximum (> 50%) cloud appearances while during the active period of western disturbances (December-March), ~25% of the total annual clouds, over the NSI region. Altostratus is found to be the most frequent cloud type (~ 20%) among others in the last decade over this region, while during southwest monsoon and western disturbances, the most dominant cloud types are deep convective (~25%) and nimbostratus (~33%), respectively.

1. Introduction

Clouds are critical and multi-scale atmospheric features least understood as they occurs over wide spatio-temporal scales, and play a crucial role in the Earth's radiation budget by modulating the flow of incoming solar and outgoing thermal radiation, climate, weather, hydrological cycle, circulations and chemical reaction processes occurring in the atmosphere [1-4]. The quantitative investigation on the vertical structures, spatial variability, distribution, and properties of clouds is a necessary step [5-6]. Their accurate representation, especially on regional scales, is needed to understand their association with underlying forcing and feedback mechanisms in which they are involved. The study on regional scale may help in unravelling the subtle influences e.g. due to orography. Additionally, the study may further be supportive in forming the base-lines for the development and validation of the regional climate models and simulations [7-9], for better predicting the weather and climate changes.

Observing clouds with in-situ [10], ground-based [11] sensors and the satellite systems [12], contribute in understanding the composition and distribution of clouds in the atmosphere. However, satellites are the only observing platform that offers the characterization of clouds over large areas with better spatio-temporal resolution and the proliferation of satellite platforms carrying modern and advanced sensors nurtured wealth of cloud related information with accuracy [12-14].

2. Study region

The NSI region considered for study is confined within 23° - 38°N and 72° - 85°E, which encompasses Jammu & Kashmir, Himachal Pradesh, Punjab, Haryana and Chandigarh, Uttarakhand, Delhi & non-capital region (NCR), and Uttar Pradesh states as shown in Figure 1.

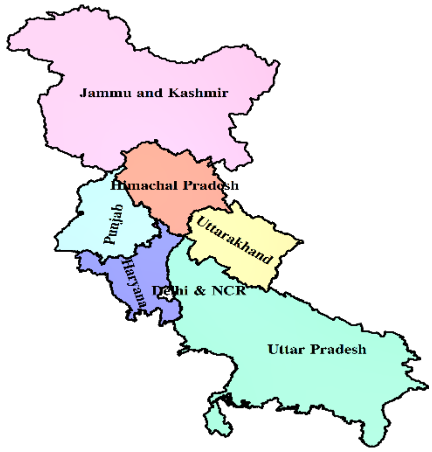

Figure 1. Study region i.e. Northern states of India

The understanding on cloud vertical structures, their spatio-temporal distributions, and the impact on changing climate is still poor. Therefore, the quantitative study focussed on the clouds over NSI region may be an important step in the direction of mitigating the natural catastrophes like -cloudbursts, flash floods, and landslides causing the loss of life and ecosystem. The analysis on cloud related parameters over this region will help reducing the uncertainties associated with regional climate models, and in quantifying the feedback by the clouds in radiation and latent heat calculations [4, 7].

The varied and complex topography of NSI region, covering the major part of Indo-Gangetic plains (IGP) as well as the Himalayas, possesses the large variability in meteorological parameters which are mainly controlled by two major atmospheric circulations– southwest monsoon and the western disturbances. These two contrasting periods: (i) June to September (JJAS), and (ii) December to March (DJFM), respectively, are hence taken up for the seasonal investigations over the region.

3. Data products

National Aeronautics and Space Administration (NASA) A-train satellite mission [15] provides a simultaneous multi-sensor view of clouds. Therefore, the present work is inclined towards the A-train satellite retrievals, and specifically, the potential of its two most popular and widely used satellites: Cloud aerosol liDAR infrared pathfinder satellite observations (CALIPSO) [16] and CloudSat [17], is explored. The 94 GHz (wavelength ~2 mm) nadir-looking CloudSat raDAR, is more sensitive to thick clouds, and in contrast, the CALIPSO liDAR (532 nm and 1024 nm) signals probes the thin clouds but gets attenuated by thick cloud layers [16, 17]. The combination of CloudSat raDAR and CALIPSO liDAR, so called DARDAR [18-20] is a state-of-the art multi-sensor extraction that not only provides vertical cloud information but also offers a view on both thick and thin clouds as well. The product is derived using variational method [19], applied on the combination of the CloudSat raDAR reflectivity (dBZ_e) and CALIPSO parallel and perpendicular attenuated backscatter (β) and retrieves the profiles of visible extinction (σ), ice-water content (*IWC*) and effective radius (r_e) [19, 20]. It was developed by Drs. Julien Delanoë and Robin Hogan at Department of Meteorology in the University of Reading [19, 20]. One of the most recent DARDAR version 2.0 product: CSTrack CLOUDSAT-2B-CLDCLASS that provides the cloud types information at CloudSat footprints with the resolution of ~1.1 km (horizontal) and 60 m vertical (over -1.92 to 40.02 km) is utilized for the period between January 2007 and December 2016 over the NSI regions (overpasses between 06:30 - 07:40 UTC). The required data is taken from Interactions Clouds Aerosols Radiations Etc (ICARE) Thematic Centre.

4. Clouds: classification and distribution

Clouds are not uniform across the globe, but shows regional patterns [21]. The DARDAR product provides the classification of clouds as eight different cloud types - cirrus (Ci), altostratus (As), altocumulus (Ac), stratus (St), stratocumulus (Sc), cumulus (Cu), nimbostratus (Ns), and deep convective (DC) (i.e., cumulonimbus) [6]. According to the world meteorological organization (WMO) 1956 [22], these clouds are further classified as low, middle or high levels on the basis of their altitude above the surface of earth and their appearances. Generally, the clouds lying within ~2 or 3 km vertical are classified as low level clouds (Sc, St and Cu), between 2-7 km as middle level (Ac, As, and Ns), and above 7 km as high level clouds (Ci that includes cirrocumulus, cirrostratus, and cirrus). Cumulonimbus clouds (DC) extends through all the range of altitudes.

The above classified cloud types do not have the same characteristics, and they do not form under the same conditions or in the same regions. Their impact on the hydrological cycle and weather are different, some of them produces precipitation on the ground and the others do not, and they also interact with the solar radiation differently. Therefore, it is important to understand their distribution patterns over the NSI region separately. In this context, the DARDAR data is analysed for studying the distribution of seven different cloud types (Sc, Cu, Ac, As, Ns, Ci, and DC) over the NSI (up to 18 km from the mean sea level) during the period 2007-2016. The St cloud type is not taken into account due to its negligible frequency of occurrence over this region. The analysis is subjected to the identified daytime (between 06:30 - 07:40 UTC) data records of 163 days (2007), 126 days (2008), 142 days (2009), 147 days (2010), 53 days (2012), 94 days (2013), 121 days (2014), 133 days (2015), and 89 days for the year 2016, amounting to be a total of 1,068 days. It is to be noted that the cloud type information for the year 2011 is not taken into account in the present and the henceforth investigations, due to very less data records (30 days). It is to mention that the studied years have different days of data records, hence to make a valid comparison of the cloud types on an annual scale, at first, the matrices are generated for an individual cloud types, say x_{ijk}, where, x represents the cloud type, i represents year numbers (2007-2016, excluding the year 2011), j = height bins (0 – 18 km, 60 m vertical resolution), and k is the accumulated counts of x in each height bins. The individual cloud type data, x_{ijk}, is then normalized throughout the height range with the maximum value of k obtained individually for the study period. The results obtained are shown in Figure 2 that portrays the normalized distribution of seven different cloud types.

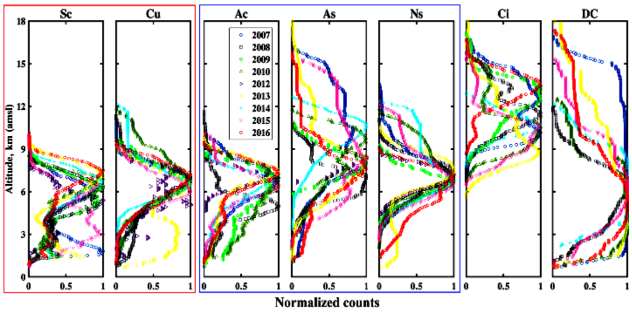

Figure 2. Normalized distribution of Sc, Cu, Ac, As, Ns, Ci, and DC cloud types over NSI region for period 2007-2016. Figs in the red box represents low level clouds, and those in the blue box are the middle level clouds.

Further, the statistics is computed, that revealed that the frequencies of DC clouds is high during 2007 (~22.2%) and 2013 (~14.7%), while the Ns clouds are on the higher side in 2014 (~15.2%) and 2015 (~13.1%). Both these cloud types have association with heavy precipitation, snow and severe weather events. The mean occurrences of low level clouds i.e. Sc and Cu are highest in 2015 (~14.1%) and 2013 (~16.4%), respectively, while the middle level clouds Ac and As have maximum mean occurrences in 2010 (~17.1%) and 2015 (~19.5%), respectively. The Ci appeared more in 2007 (~17.9%) and 2013 (~15.5%) in comparison to the remaining years.

Clouds occur frequently over NSI, and based on the investigation, its distribution (considering all the seven cloud types) over a decade (2007-2016) and during two seasons – JJAS and DJMF is deduced by accumulating the vertical granules representing any of the seven cloud scenes (Sc, Cu, Ac, As, Ns, Ci, or DC) between the surface to 18 km height over the grid box resolution of 1° X 1°, and the obtained result is shown in Figure 3. The multi-year (annual and seasonal) accumulation approach in this case is adopted to provide a better representation of cloud statistics.

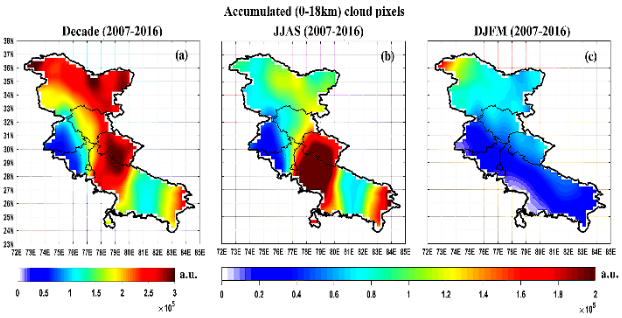

Figure 3. Cloud (Sc, Cu, Ac, As, Ns, Ci, and DC altogether) distribution over the northern states of India, accumulated over 0-18 km height for (a) decade period 2007-2016, (b) season JJAS, and (c) season DJFM.

The vertical profiles of the seven different cloud types shown in Figure 2 revealed their occurrences over NSI region, and so far it is also established that these clouds are distributed over the entire study zone (Figure 3), and are more dominant over Uttarakhand, Himachal Pradesh, Jammu & Kashmir, and major portions of western Uttar Pradesh during JJAS as compared to DJFM seasons. Further, to understand the contribution of individual cloud types, a detailed investigation is performed on their relative frequency distribution averaged on an annual and seasonal scales, and the following relevant statistics were deduced:

i. During JJAS more than 50% of the clouds/annum appears, and DJFM season accounts for ~25% of the annual cloud occurrences.
ii. On an annual scale, the 'As' cloud type showed maximum frequency of occurrence when compared with other cloud-types, and the order of occurrences over the last decade (2007-2016) followed: As (19.2%) > Ns (17.1%) >DC (15.8%) > Ci (14.9%) > Sc (13.8%) > Cu (11.2%) > Ac (8%).
iii. The most dominant cloud types over NSI region during JJAS and DJFM seasons are 'DC' and 'Ns', respectively.
iv. In JJAS season, the order of cloud occurrences followed: DC (24.6%) > As (20.5%) > Ci (13.6%) > Cu (12.2%) > Ac (11.5%) > Sc (10.8%) > Ns (6.8%).
v. During DJFM, the order is: Ns (32.8%) > Ci (21%) > Sc (16.3%) > As (16.1%) > Cu (7.5%) > Ac (4%) > DC (2.3%).

5. Concurrent occurrences of cloud types

There could be the possibility that at some instance more than one cloud type appears in a single vertical column. To quantify the same, the statistics on such concurrent occurrences over the NSI region is investigated for the seasons JJAS and DJFM (Table 1). From the table, it can be interpreted that during both the seasons, the mid level clouds (Ac and As) dominate the cloud regime, accompanying clouds at low level (Sc and Cu). The low and mid level (except Ns) clouds, together with the cirrus in isolation are very rare and on an average ~40 % of them are accompanied with the other cloud types. In JJAS, the Ci is found to appear maximum alongwith Ac (11.1 %) cloud type, while during DJFM, it appears most often alongwith Sc (23.4 %) cloud type. Ns and DC are found mostly isolated (more than 80 %), and their remaining volumes are mostly accompanied by As and Ci cloud types, respectively during both the seasons.

Table 1. Frequency of concurrent occurrences of different cloud types over NSI region during 2007-2016

	Simultaneous occurrence frequency for JJAS in % for DJFM in %						
cloud type	Sc	Cu	Ac	As	Ns	Ci	DC
Sc	--	3.9 1.3	10.5 3.9	6.6 10	0.4 1.7	4.7 13.2	0.4 0.03
Cu	9 6.9	--	5.9 2.9	7.5 15.1	0.5 0.5	2.8 5.1	0.1 0.2
Ac	21.2 24.8	5.2 3.5	--	11.2 10.3	1.1 nil	10.8 10.9	0.6 0.3
As	18.1 26.7	9 7.7	15.1 4.3	--	1.9 7.7	5.2 13.1	0.4 nil
Ns	1.9 3.4	1 0.2	2.8 nil	3.6 5.8	--	0.2 0.3	nil nil
Ci	9.7 23.4	2.6 1.7	11.1 3	4 8.7	0.1 0.3	--	6.3 0.2
DC	2 1.9	0.3 2.1	1.5 3.1	0.8 nil	nil nil	14.7 7.3	--

6. Conclusion

For the first time, the detailed study on the distribution of seven cloud types using synergic spaceborne raDAR and liDAR data is done over the NSI region. The frequency of occurrences of different cloud types and their characteristics over annual and seasonal scales is shown. The frequencies of DC is found high during JJAS, whereas a large fraction of Ns clouds appears in DJFM.

The concurrent occurrences of different cloud types were also noted and quantified.

7. Acknowledgements

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