Evaluation and utilization of CloudSat and CALIPSO data to analyze the impact of dust aerosol on the microphysical properties of cirrus over the Tibetan Plateau

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Abstract

The present study elucidates on the evaluation of two versions (V3 and V4.10) of vertical feature mask (VFM) and aerosol sub-types data derived from the Cloud-Aerosol LiDAR and Infrared Pathfinder Satellite Observations (CALIPSO), and its utilization to analyze the impact of dust aerosol on the microphysical properties of cirrus over the Tibetan Plateau (TP). In conjunction to the CALIPSO, we have also used the CloudSat data to study the same during the summer season for the years 2007–2010 over the study area 25–40°N and 75–100°E. Compared to V3 of CALIPSO, V4.10 was found to have undergone substantial changes in the code, algorithm, and data products. Intercomparison of both versions of data products in the selected grid between 30–31°N and 83–84°E within the study area during 2007–2017 revealed that the VFM and aerosol sub-types are in good agreement of 95.27% and 82.80%, respectively. Dusty cirrus is defined as the clouds mixed with dust aerosols or existing in dust aerosol conditions, while the pure cirrus is that in a dust-free environment. The obtained results illustrated that the various microphysical properties of cirrus, namely ice water content (IWC), ice water path (IWP), ice distribution width (IDW), ice effective radius (IER), and ice number concentration (INC) noticed a decrease of 17%, 18%, 4%, 19%, and 10%, respectively due to the existence of dust aerosol, consistent with the classical “Twomey effect” for liquid clouds. Moreover, the aerosol optical depth (AOD) showed moderate negative correlations between −0.4 and −0.6 with the microphysical characteristics of cirrus. As our future studies, in addition to the present work undertaken, we planned to gain knowledge and interested to explore the impact of a variety of aerosols apart from the dust aerosol on the microphysical properties of cirrus in different regions of China.

Keywords: CALIPSO; CloudSat; Dust aerosol; Cirrus properties; Tibetan Plateau

1. Introduction

Aerosols and clouds play a vital role in determining the climatic conditions of the Earth-atmosphere system...
(Mahowald and Kiehl, 2003; H.L. Pan et al., 2017; Z.X. Pan et al., 2018; Bu et al., 2016). The interactions of cloud-aerosol are a subject of scientific research and hypothesized to be critical in understanding climate change since clouds exert such a pivotal influence in controlling incoming and outgoing radiations (Kattsov et al., 2001). Aerosols are known to have an impact on the formation and modification of life cycle of clouds (Twomey, 1977; Albrecht, 1989).

The cirrus cloud (hereafter simply, cirrus) mainly composed of ice particles in the upper troposphere and formed with different aerosols serving as ice nucleation particles (INPs) (H.L. Pan et al., 2017; Murray et al., 2012). Unlike other cloud types, which have a smaller impact on the incident short-wave solar radiation, but can also absorb long-wave radiation reflected from the Earth’s surface. Consequently, the cirrus mainly has a warming effect on the radiation budget of the Earth-atmosphere system, and other types of cloud are quite opposite manner (Stephens, 2005). Moreover, the cirrus has a wide spatial distribution covering approximately 20–25% of the globe. However, aerosol’s effect on the cirrus can have a substantial impact on the variation of global radiative forcing with a change in the ice water path (IWP) (Lee et al., 2012).

The dust aerosol, one of the major aerosol species contributing more to global aerosol burden and optical depth, is a highly active component of the physical, chemical, and biogeochemical cycles of the earth system (Qian et al., 1999). It has a considerable impact on the regional climate, by altering the radiative balance between incoming solar and outgoing terrestrial radiations in the atmosphere (i.e., direct effect) (Huang et al., 2009; Han, 2010; Wang et al., 2018). Moreover, it can modify the microphysical properties of clouds and precipitation efficiency in the Earth-atmosphere system (i.e., indirect effect or semi-direct effect) (Chen et al., 2014; Guo and Yin, 2015).

The satellite observations, currently, become one of the most important ways in the cloud and aerosol studies because of its effective advantages containing wide coverage, high repetition rate, strong objective truth, and whole cloud and aerosol parameters, together with the reliable information sources (Dai et al., 2011; Wang et al., 2010; H.L. Pan et al., 2017; Lu et al., 2018). A large number of previous studies evidenced that there is a significant impact of dust aerosols on the cloud properties based on the satellite remote sensing data. Jin et al. (2015) utilized the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) data to analyze the impact of dust on the retrievals of cloud phase and found that the dust aerosols have a greater effect on the retrievals of cloud phase. They also reported and concluded that the CALIPSO has a better detection of ice phase clouds compared with the passive sensors. Wang et al. (2018) analyzed the effect of dust aerosol on the retrievals of cloud top height (CTH) over Northwest China using the cloud data detected by the CloudSat and CALIPSO satellites during the local spring season (March-April-May) of 2007–2011. Further, H.L. Pan et al. (2017) put forward a new retrieval method for the estimation of ice water content (IWC) of cirrus using the satellite data obtained from the CloudSat and CALIPSO.

In addition, Winker et al. (2006) argued that, unlike the previous generation of space-based remote sensing instruments, the CALIPSO can observe aerosols over bright surfaces and beneath thin clouds, as well as in clear sky conditions. Koren et al. (2005) also have analyzed the regional effect of aerosols on clouds over the Atlantic Ocean from June to August. They reported that dust, smoke, or pollution enhances the cloud formation and CTH. Added to the above, Kumar (2013) analyzed that the spatial correlation between aerosol optical depth (AOD) and cloud fraction (CF) which increases for those regions having more pollutant particles produced from the dust, biomass, industrial, and domestic activities. Huang et al. (2006) used the data observed by CERES, MODIS, and ISCCP to analyze the effect of dust aerosol on cloud water path (CWP) over East Asia. They found that the mean ice water path (IWP) and liquid water path (LWP) of dusty clouds are less than their dust-free counterparts by 23.7% and 49.8%, respectively. Further, Logan et al. (2014) investigated aerosol properties and their influences on cloud condensation nuclei (CCN) over the marine boundary layer (MBL) of Azores and analyzed how continental aerosols can influence the number concentration of CCN over the MBL. Followed this, Wang et al. (2015) analyzed the dust aerosol’s effect on cloud properties observed by the CALIPSO and CloudSat for the springtime in 2007 over Northwestern China. They illustrated that the values of cloud effective particle diameter, optical depth, IWP of cirrus under dust polluted condition are less.

However, the interaction between aerosols and cirrus is still uncertainty (IPCC, 2013), and few studies that consider dust aerosol impact on the microphysical properties of cirrus over the Tibetan Plateau from satellite retrievals. In this paper, we have used the CALIPSO and CloudSat data from 2007 to 2010 analyzing the dust aerosol impact on cirrus microphysical properties including ice water content (IWC), ice water path (IWP), and ice distribution width (IDW), ice effective radius (IER), and ice number concentration (INC). The study period is restricted due to the length of availability of CloudSat data products (2C-ICE and 2B-CWC-RVOD). Followed this, we have conducted the long-term (2007–2017) evaluation of vertical feature mask (VFM) to show consistency between two versions of CALIPSO over the defined grid between 30–31°N and 83–84°E within the study domain, Tibetan Plateau (TP). Also, we studied the relationship between above cirrus properties and dust aerosol optical depth (DAOD) for the same period over the study area. The structure of this paper is organized and grouped into several sections as follows: Firstly, the description of satellite data products and the classification of dusty clouds are demonstrated in Section 2. Later, the analysis conducted and results presented are given in Section 3. Finally, the discussions and main conclusions are illustrated in Section 4.
2. Data and methods

The CALIPSO and CloudSat are part of the A-Train satellite constellation with an equator crossing time at 1:30 PM (local time), and CALIPSO lags CloudSat by no more than 15 s. Therefore, two instruments achieve quasi-synchronous observation which can utilize their own advantages and make the acquired data more accurate to reflect the vertical and temporal profiles of aerosol and cloud properties (Winker et al., 2009; Sato and Okamoto, 2011; Bu et al., 2016).

2.1. Study area

Tibetan Plateau (TP), often called “roof of the world,” is located in the Southwest of China, with a mean elevation of above 4000 m. Therefore, the region plays a key role in Asian climatology and atmospheric circulation, especially given the elevated heat source in summer (He et al., 2013; Z.X. Pan et al., 2017). The study area TP covers in the grid-ded domain between 25°–40°N and 75°–100°E (Fig. 1). Dust aerosols originated from the Taklimakan Desert over the Tibetan Plateau in summer can reach a height of about 7–10 km, enabling the dust to mix with clouds (Huang et al., 2007). Accordingly, it is a basic and important aspect of global weather and climate research to realize deeply the effect of dust aerosol on cirrus over the TP.

2.2. The CloudSat instrument

The CloudSat launched on 28 April 2006 equipped with 94-GHz CPR (Cloud Profile Radar, W-band), is the first solar polar-orbiting satellite used for observing clouds (Stephens et al., 2008) with its horizontal resolution of 2.5 km, and 1.4 km in along-track and cross-track, respectively, and the vertical resolution of about 500 m (Yang et al., 2014; H.L. Pan et al., 2017). The most important microphysical quantities of cirrus are (besides crystal aspect ratios, single scattering properties, and surface roughness) the IWC, the ice particle size distributions (PSD), and their shapes (Heymsfield et al., 2016). Consequently, the ice number concentration (INC), and ice distribution width (IDW) were chosen from the 2B-CWC-RVOD version R04 product (IO_RVOD_AP_log_number_num; IO_RVOD_AP_dis_trib_width_param). Here, we consider that all particles in cirrus are ice crystals.

In addition, the cirrus properties like ice water content (IWC), ice water path (IWP), and ice effective radius (IER) were selected from the 2C-ICE version R04 product to investigate the effect of dust aerosol on microphysical properties. This 2C-ICE cloud product combined inputs of measured radar reflectivity factor obtained from the CloudSat (2B-GEOPROF product) with measured attenuated backscattering coefficients observed at 532 nm from the CALIPSO lidar to obtain more accurate results compared to the radar-only product (Deng et al., 2010). The 2B-GEOPROF version R04 product which defines a cloudy range bin with a confidence mask value (i.e., Cloud Mask) ranging from 0 to 40. The value between 20 and 40 proves that clouds are detected, and increasing value represents clouds with a lower chance of being false detection (Marchand et al., 2008).

2.3. The CALIPSO satellite

The CALIPSO launched on 28 April 2006 equipped with CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), is a dual wavelength (532 and 1064 nm) sensitive Lidar. The satellite with the vertical and horizontal resolutions for the CALIOP is 30 m and 333 m, respectively from...
the surface to top of 8.2 km; and above 8.2 km, the values are 60 m and 1 km, respectively (Deng et al., 2010; Winker et al., 2009; H.L. Pan et al., 2017; Z.X. Pan et al., 2017; Z.X. Pan et al., 2018; Bu et al., 2016).

At present, the researchers all over the world are utilizing the CALIPSO products to a large extent to understand the interactions between aerosol and cloud. The VFM product (version 3 and version 4.10) are used in this study which can derive a set of feature classification flags for each layer detected in the backscatter data like the feature type (e.g., cloud, aerosol, stratospheric layer, and surface/sub-surface), the cloud sub-type (e.g., Ci, Ac, As, Cu, etc.), and aerosol sub-type (e.g., dust, smoke, polluted dust, etc.), ice/water phase of cloud (Omar et al., 2009).

We also select the level 1B profile product (V4.10) and level 2 5 km APro product (V4.10) to obtain the information of attenuated depolarization ratio (ADR) and total attenuated backscatter (TAB), as well as AOD, respectively. The former can be used to further verify and validate the existence of dust aerosol and cirrus, and the latter can be regarded as a substitute of aerosol concentration to calculate the correlation coefficient between AOD and cirrus properties, and further, verify the effect of dust aerosol on cirrus microphysical properties.

2.4. Identification of dusty cirrus cloud

In this study, dusty cirrus clouds are referred to as cirrus polluted by dust (i.e., the cirrus in the dust environment). The detailed criterion is chosen based on the works of Wang et al. (2017) that if the height difference between the base height of cloud layer and a top height of dust layer is less than 50 m in the same region, then we define the cloud as the dusty cirrus cloud. At the same time, the cirrus in the dust-free environment is regarded as pure cirrus (cirrus without dust) in the same scenario to better compare the impact of dust aerosol on cirrus. Moreover, to obtain the accurate cirrus information we only selected the single-layered dusty cirrus clouds with cloud mask values ≥ 30 from the CloudSat 2B-GEOPROF product, and the ADR and TAB profile products from the CALIPSO level 1B and the same are considered in this study. Meanwhile, we also utilized the radar reflectivity data of 2B-GEOPROF version 04 product to further obtain the complete and accurate information of vertical profile combined with the CALIPSO data.

3. Results and discussion

3.1. Inter-comparison of VFM from both versions of CALIPSO

Version 4.10 (V4.10) is the first new release of the CALIPSO Lidar level 2 data products on 8 November 2016, since the initial release of the Version 3.0 (V3) series of products in May 2010. As expected, V4.10 provides a substantial advance over V3 and earlier releases. The known retrieval artifacts have been eliminated and numerous enhancements have been made to increase the accuracy of data, while simultaneously reducing the uncertainties (Vaughan et al., 2016). The most significant code, algorithm, and data product changes between V3 and V4.10 are conducted such as (i) using a major overhaul of the aerosol subtyping separate algorithms to classify tropospheric and stratospheric aerosols; (ii) the revised probability density functions (PDFs) for the cloud-aerosol discrimination (CAD) algorithm is performed; (iii) application of the CAD algorithm to layers detected at single shot resolution and in the stratosphere; (iv) improved cloud subtyping and ice-water phase determination; and (v) introduction of a new 5 km merged layer product that reports the spatial and optical properties of all cloud and aerosol layers detected in a single file.

Several improvements to VFM type have been implemented in V4.10 products of the CALIPSO data. The most fundamental change is that aerosol layers are now classified as either tropospheric or stratospheric aerosol feature types depending on the location of the attenuated backscatter centroid relative to the MERRA-2 reanalysis troposphere height. In previous versions, the aerosol is only identified

<table>
<thead>
<tr>
<th>Feature Type (ver.3)</th>
<th>Feature Type (ver.4.10)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invalid</td>
<td>Invalid</td>
<td>0</td>
</tr>
<tr>
<td>Clear air</td>
<td>NIIL 96.40% 0.52% 2.54% 0.01% 0.42% NIIL NIIL NIIL 22,453,539</td>
<td></td>
</tr>
<tr>
<td>Cloud</td>
<td>NIIL 3.68% 86.50% 4.56% 2.01% 1.25% 968,860</td>
<td></td>
</tr>
<tr>
<td>Aerosol</td>
<td>0.03% 6.20% 1.82% 89.52% Nil 2.31% Nil 0.12% 1,957,314</td>
<td></td>
</tr>
<tr>
<td>Strat- feature</td>
<td>Nil NIIL NIIL NIIL 0.20% 0.09% 98.01% 0.20% 0.09% 2,807,423</td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>NIIL 0.43% 0.48% 0.79% 4.40% 97.40% 1.20% 3,540,268</td>
<td></td>
</tr>
<tr>
<td>Sub- surface</td>
<td>NIIL NIIL NIIL NIIL 1.40% 1.55% 1.95% 1.05% 85.3% 2,075,142</td>
<td></td>
</tr>
<tr>
<td>No signal</td>
<td>NIIL 9.50% 0.65% 1.55% 1.95% 1.05% 3,000,577 3,475,625 1,854,264 33,802,546</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>587 22,011,430 1,017,409 2,440,408 2245 3,000,577 3,475,625 1,854,264 33,802,546</td>
<td></td>
</tr>
</tbody>
</table>

Overall agreement between V3 and V4.10 is 95.27%.
below the troposphere. Given that the CAD algorithm is applied at all altitudes in V4.10, aerosol layers detected above the troposphere are classified as stratospheric aerosols and are assigned subtypes commonly found in the stratosphere and the detailed content can be found at the following web link in the description of a summary of CALIPSO data quality (https://www-calipso.larc.nasa.gov/resources/calipso_users_guide/qs/cal_lid_l2_all_v4-10.php).

Fig. 2. CALIPSO (ver. 3 and 4.10) derived vertical feature mask types on (a) 26 June 2007, (b) 08 August 2008, (c) 28 July 2014, and (d) 02 August 2016 for the altitudes between −0.5 km to 8.2 km.
To investigate the differences in the feature of vertical profiles detected by the CALIPSO, an analysis was implemented by extracting the feature classification flag (FCF) of each detected layer from VFM files within the defined geographical region of 30°–31°N and 83°–84°E during June 2007 - September 2017. The vertical feature type is obtained by decoding the FCF bits of 1–3 in decimal form and with the confidence level of $50 < \text{CAD score} < 70$ for cloud and aerosol layers (using FCF bits of 4 and 5) (Vaughan et al., 2016). The changes in VFM noticed from the two versions were explained by constructing the confusion matrix as shown in Table 1. The overall agreement between V3 and V4.10, in this case, was computed by summing the samples which remained unchanged (e.g., aerosol - aerosol, cloud - cloud) divided by the total number of samples expressed in percentage; and was found to be 95.27%, when a total of 300 days were taken into account.

It was observed that 6.56% of the ‘cloud’ in V3 is converted to ‘tropospheric Aerosols’, and about 15% of the features that were ‘totally attenuated’ (‘no signal’) due to opaque clouds, aerosols, and/or stratospheric layers in V3 were classified as ‘clear air’, ‘aerosol’, ‘cloud’ or as ‘surface’ in V4.10. Furthermore, 8% of the ‘aerosol’ is identified as the ‘cloud’ and ‘clear air’ approximately. This may be due to the changes in the layer detection schemes between V3 and V4.10.

To illustrate some of the major changes in the vertical features between the CALIPSO versions, four typical cases were selected and transacted on 26 June 2007, 08 August 2008, 28 July 2014, and 02 August 2016, and the results are shown in Fig. 2a–d. It can be inferred that in V4.10 there is an enhancement in the feature detection compared to V3. Surface detection was typically higher in V4.10 in comparison to V3, and the same is clearly evident in Fig. 2. It is also visible that some of the ‘clouds’ and ‘clear air’ features in V3 were changed to ‘tropospheric aerosols’ in V4.10.

The CALIPSO VFM product also provides the sub-types of aerosols and clouds, except the information of feature types (Omar et al., 2009) for the same study period over the defined region in TP. The VFM product V4.10 identifies the seven major aerosol sub-types based on the geographical location, surface elevation, surface type, backscatter attenuation (no signal), color ratio, and the volume depolarization ratio (i.e., clean marine, dust, polluted continental/smoke, clean continental, polluted dust, elevated smoke, and dusty marine) (Vaughan et al., 2016). In comparison to the aerosol sub-type classifications defined in V3, it is found that two sub-types were re-defined; and one additional sub-type is included in the CALIPSO product of V4.10. Also, the ‘polluted continental’ and ‘smoke’ in V3 changed to ‘polluted continental/ smoke’ and ‘elevated smoke’, respectively in V4.10 which overcome the misclassification under certain circumstances as reported in the earlier studies (Powell et al., 2009; Adams et al., 2012). And the inclusion of ‘dusty marine’ in V4.10 is to distinguish it from the clean marine aerosol.

### Table 2

<table>
<thead>
<tr>
<th>Aerosol Sub-Type (ver.3)</th>
<th>Aerosol Sub-Type (ver.4.10)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not determined</td>
<td>Not determined</td>
<td>90.26%</td>
</tr>
<tr>
<td>Clean marine</td>
<td>Clean marine</td>
<td>2.28%</td>
</tr>
<tr>
<td>Dust</td>
<td>Dust</td>
<td>1.27%</td>
</tr>
<tr>
<td>Polluted continental</td>
<td>Polluted continental</td>
<td>68.20%</td>
</tr>
<tr>
<td>Clean continental</td>
<td>Clean continental</td>
<td>0.68%</td>
</tr>
<tr>
<td>Polluted dust</td>
<td>Polluted dust</td>
<td>40.21%</td>
</tr>
<tr>
<td>Elevated smoke</td>
<td>Elevated smoke</td>
<td>0.42%</td>
</tr>
<tr>
<td>Polluted smoke</td>
<td>Polluted smoke</td>
<td>16.46%</td>
</tr>
<tr>
<td>Dusty marine</td>
<td>Dusty marine</td>
<td>6.25%</td>
</tr>
<tr>
<td>Smoke</td>
<td>Smoke</td>
<td>16.23%</td>
</tr>
<tr>
<td>Other</td>
<td>Other</td>
<td>1.02%</td>
</tr>
<tr>
<td>Total</td>
<td>Total</td>
<td>5,563,526</td>
</tr>
</tbody>
</table>

Overall agreement between V3 and V4.10 is 82.80%.
and is applicable for the cases where the marine aerosols are contaminated with dust and anthropogenic pollution (Kaufman et al., 2005).

To understand the changes over the specified region, the FCF bits 10–12 that define the aerosol sub-types are decoded after confirming the feature type as ‘aerosol’ with the quality assurance level as “high” (FCF bit 13) in both the CALIPSO versions (V3 and V4.10). Later, the confusion matrix is formed illustrate in Table 2 to show the changes in aerosol sub-types retrieved using both the versions of CALIPSO data. In the case of aerosol sub-type, the overall agreement between the two versions is 82.80% when the CALIPSO VFM profiles were taken into account for a total of 300 days.

Fig. 3. CALIPSO (ver. 3 and 4.10) derived vertical aerosol sub-types on (a) 15 April 2017, (b) 04 May 2015, (c) 16 September 2014, and (d) 10 April 2017 for the altitudes between −0.5 km to 8.2 km.
From Table 2, it is depicted that in V3 the aerosol sub-types identified as ‘dust’ (approximately 17.46%), ‘smoke’ (about 17.61%) and ‘polluted continental’ (~22.54%) were changed to ‘polluted dust’ in V4.10. The major portion of ‘clean continental’ (~40.21%) in V3 were converted to ‘polluted continental/smoke’ in V4, and about 46.23% of ‘smoke’ and around 16.46% of ‘polluted dust’ in V3 were changed to ‘polluted continental/smoke’ and ‘dust’ in V4.10. All these changes in aerosol sub-types are attributed to the major revisions done in the aerosol retrieval and classification algorithms of V4.10 and the detailed content can be found at the link of CALIPSO Data Quality.
Summary. Fig. 3a–d illustrated some of the major changes in aerosol sub-types between V3 and V4.10 for the CALIPSO data transacted on 15 April 2017, 04 May 2015, 16 September 2014, and 10 April 2017. As seen in Fig. 3a and b, it is evident that the ‘smoke’ and ‘dust’ aerosol sub-types were changed to ‘polluted dust’ and ‘polluted smoke’ in V4.10, respectively. Further, it can be seen from Fig. 3c–d that some of the ‘smoke’ and ‘clean continental’ aerosol sub-types in V3 were classified as ‘polluted continental/smoke’ in V4.10.

3.2. Impact of dust aerosol on cirrus properties: a case study

A typical case study was conducted to examine the impact of dust aerosol on cirrus cloud (dusty cirrus) which was noticed on 2 June 2009 and is presented in Fig. 4. The CALIPSO Lidar level-2 VFM-Standard-V4-10 product which describes the vertical and horizontal types of cloud and the aerosol layer is used to distinguish dust and cirrus from other types of aerosols and clouds. From Fig. 4a, clouds (light blue) are seen to be surrounded by aerosols (green) between the northern latitudes of 36.0°N and 36.5°N. Fig. 4b presents the clouds type and found that the cloud type is cirrus (purple). Fig. 4c demonstrated the aerosols type and identified that the aerosol type is dust (orange). Fig. 4d showed the cloud phase and found that the phase is ice (white). In addition, to further identify and obtain the accurate information on dust aerosol and cirrus, we utilized the CloudSat 2B-GEOPROF version R04 product and CALIPSO level 1B profile product. As

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**Fig. 5.** CloudSat and CALIPSO observations for a typical dusty cirrus case on 2nd June 2009 over the Tibetan Plateau. (a) Ice water content (IWC) observed by the CPR. (b) Ice water path (IWP) observed by CloudSat CPR. (c) Ice distribution width (IDW) observed by CloudSat CPR. (d) Ice effective radius (IER) observed by CloudSat CPR. (e) Ice number concentration (INC) observed by CloudSat CPR. (f) Aerosol optical depth (AOD) from the CALIPSO lidar (CALIOP).
illustrated in Fig. 4c, the high values of radar reflectivity (yellow line) located at a height of 5 km were attributed to the ground surface (combined with Fig. 4a) and is consistent with the mean altitude/elevation of TP.

Fig. 4f demonstrated that the cloud mask ≥ 30 (yellow) confirms the existence of cirrus. Fig. 4g revealed that the total attenuated backscatter signal at 532 nm and aerosols were generally shown as yellow/red/orange, stronger cloud signal corresponds to grayscale confirmed the existence of aerosol and cloud. As shown in Fig. 4h, the image is used for classifying the difference between spherical and non-spherical particles (i.e. dust, ice crystals). The cirrus generally presents a depolarization ratio in the range 0.25–0.40; whereas, dust aerosols are usually in the range 0–0.15. The detailed content can be found at the link providing information on the CALIPSO Data User’s Guide (https://www-calipso.larc.nasa.gov/resources/calipso_users_guide/browse/index.php). Combined with the aforementioned analysis from Fig. 4, the cirrus surrounded by dust aerosols is defined as the dusty cirrus located in the northern latitudes of 36.0–36.5° following the criterion adopted from Wang et al. (2017).

The results of microphysical properties of this dusty cirrus and AOD are shown in Fig. 5. In Fig. 5a, we used the log value of IWC to replace it to simplify the figure and its description; and the mean value is −2.4 log (g/cm³). It can be seen from Fig. 5b-e, the respective mean values of cirrus microphysical properties (IWP, IDW, IER, INC) were 22.35 g/cm², 0.54, 42.36 μm, 1.79 log (L¹). As shown in Fig. 5f, the maximum value of AOD was 0.25. We also studied the relationship between the AOD and these microphysical properties of dusty cirrus in the following sections.

To better estimate dust aerosol effect on the microphysical properties of cirrus derived from the CALIPSO and CloudSat data, 23 cases representing dusty cirrus were chosen and analyzed in this study (Table 3). Moreover, we also selected dust-free cloud (cirrus without dust aerosols) cases to collocate with the cases of dusty cirrus and compared the results with the dusty clouds to discuss whether the differences are due to dust aerosols. The methods described in Section 2 are applied to select dusty cirrus cases observed in the summer season (June-July-August) during 2007–2010 over the Tibetan Plateau (25°N–40°N, 75°E–100°E). The study period is restricted to the fact due to the length of availability of CloudSat data (2C-ICE and 2B-CWC-RVOD).

### Table 3

<table>
<thead>
<tr>
<th>Case</th>
<th>Date</th>
<th>UTC (in hrs)</th>
<th>Latitude (°N)</th>
<th>Longitude (°E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2007-06-03</td>
<td>20</td>
<td>36.00–36.28</td>
<td>86.36–86.43</td>
</tr>
<tr>
<td>2</td>
<td>2007-06-24</td>
<td>20</td>
<td>32.15–32.55</td>
<td>80.66–80.70</td>
</tr>
<tr>
<td>3</td>
<td>2007-06-26</td>
<td>20</td>
<td>33.97–34.11</td>
<td>84.25–84.28</td>
</tr>
<tr>
<td>4</td>
<td>2007-06-28</td>
<td>20</td>
<td>36.41–36.52</td>
<td>88.05–88.06</td>
</tr>
<tr>
<td>5</td>
<td>2007-08-12</td>
<td>20</td>
<td>34.38–34.45</td>
<td>84.46–84.47</td>
</tr>
<tr>
<td>6</td>
<td>2008-06-14</td>
<td>20</td>
<td>33.78–33.88</td>
<td>87.37–87.40</td>
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<td>19</td>
<td>30.50–30.95</td>
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</tr>
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</table>

3.3. Comparison of dusty and dust-free cirrus

Cirrus plays an important role in the Earth-atmosphere system (Lee et al., 2012). It is composed of ice crystals formed on the aerosols particles and coarse dust particles floated in the atmosphere are regarded as the effective INPs in the troposphere (Huang et al., 2007; Murray et al., 2012). Two ways of ice formation (i.e., homogeneous and heterogeneous ice nucleation processes) can determine the microphysical properties of cirrus. Consequently, the cirrus is mainly influenced by the dust aerosols (Jin et al., 2015; Z. X. Pan et al., 2017; Z.X. Pan et al., 2018).

The frequency distribution of IWC of dusty cirrus cloud and dust-free cirrus cloud is shown in Fig. 6a. We used the log value of IWC to replace it to simplify the figure and its corresponding description. The mean value of IWC in the case of dusty cirrus cloud was −2.26 log (g/cm³); while for the dust-free cirrus, it was −2.18 log (g/cm³) with a decrease of 17% compared to dust-free cirrus cloud. As shown in Fig. 6b, the value of IWP of dusty cirrus was mostly found in the interval between 0 and 20 g/cm², but its value for the dust-free cirrus was mainly centered in the range from 20 to 60 g/cm². The mean value of IWP for dusty cirrus cloud was observed as 55.56 g/cm², while the mean value was 67.19 g/cm² for dust-free cirrus with a decline of 18% compared to dust-free cirrus cloud. The frequency distribution of IDW for the dusty cirrus and dust-free cirrus cloud is shown in Fig. 6c and the mean value of IDW for dusty cirrus was 0.57, with a reduction of 4% compared to the dust-free cirrus. Fig. 6d demonstrated the frequency of IER between dusty cirrus and dust-free cirrus. In both the cases, the mean values of IER were found to be 42.42 μm and 52.19 μm, respectively observed with a decrement of 19% for the dust-free cirrus cloud. In addition, Fig. 6e showed the frequency distribution of INC with the mean value of 1.8 log (L⁻¹) was found in the case of dusty cirrus cloud. In contrast, the mean value of INC in dust-free cirrus was 2.0 log (L⁻¹) revealed a reduction of 10% for dust-free cirrus cloud. These results are in agreement with those of Wang et al. (2015) which indicate that the dust aerosol is one of the absorbing-type aerosols that can absorb the solar radiation and evaporate...
the large ice crystals also possibly due to increased homo-
geneous nucleation process. A large number of aerosols
can give rise to more and smaller ice crystals is consistent
with the Twomey effect for liquid clouds (Twomey, 1977).

Followed this, we have conducted the statistical signifi-
cance $t$-test (Robert, 2017; Statistical Software, SPSS 20.0)
to verify the above differences observed in the microphysical
properties of cirrus during the dust and dust-free episodes.
Although there were 23 cases for dusty cirrus, the samples
chosen for the statistical test are based on individual pixels,
which are strikingly sufficient to conduct the significance
test. The results of significance test for the observed differ-
ences in the case of dusty and dust-free cirrus are given in
Table 4, and revealed that all cases passed the significance
test at the confidence interval of 95% ($p < 0.05$).

To further verify the effect of dust aerosol on cirrus
microphysical properties, we utilized the AOD as a substi-
tute for aerosol concentration and calculated the correla-
tion coefficient ($r$) between dusty cirrus microphysical
properties and AOD. Fig. 7a–e showed moderate negative
correlations between AOD and cirrus microphysical
properties (IWC, IWP, IDW, IER and INC) with the
respective correlation coefficients of $-0.48$, $-0.47$, $-0.38$,
$-0.43$, $-0.44$. Further, it is revealed that the dust

<table>
<thead>
<tr>
<th>Property</th>
<th>Mean (dust cirrus)</th>
<th>Mean (dust-free cirrus)</th>
<th>$t$-test</th>
<th>p-value</th>
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<tr>
<td>IWC</td>
<td>0.0055</td>
<td>0.0066</td>
<td>1.65</td>
<td>&lt;0.01</td>
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<td>IWP</td>
<td>55.555</td>
<td>67.189</td>
<td>1.66</td>
<td>&lt;0.01</td>
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<td>IDW</td>
<td>0.566</td>
<td>0.590</td>
<td>1.65</td>
<td>&lt;0.05</td>
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<td>IER</td>
<td>42.416</td>
<td>52.186</td>
<td>1.65</td>
<td>&lt;0.01</td>
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<tr>
<td>INC</td>
<td>1.814</td>
<td>2.004</td>
<td>1.65</td>
<td>&lt;0.01</td>
</tr>
</tbody>
</table>
aerosol-cirrus cloud interactions can be interpreted from the above relationships apart from the other factors such as key meteorological parameters (e.g., relative humidity and wind) may also have effects on cirrus microphysical properties and its formation (Kumar, 2013). Our results illustrate that the mean values of IWC, IWP, IDW, IER and INC for dusty cirrus are smaller than the dust-free cirrus indicate that dust aerosol can absorb the solar radiation and cause evaporation of ice crystals in the cirrus, and more aerosols (i.e., INPs) possibly contribute to more and smaller cloud droplets. Consequently, dust aerosols modify the microphysical properties of cirrus cloud to some extent. This is consistent and good agreement with the previous findings reported by Huang et al. (2006) and Wang et al. (2015).

4. Conclusions

The interactions between dust aerosols and cirrus clouds are a major subject of scientific research as both play an important role in the Earth-atmosphere system. In this paper, we investigated the impact of dust aerosol on microphysical properties of cirrus observed during the summer (June-July-August) over the Tibetan Plateau. The data presented in this work is derived from the CALIPSO and CloudSat instruments for the selected grid within the study domain for the period between 2007 and 2010. The degree of closeness between the two CALIPSO versions (V3 and V4.10) in terms of vertical feature mask (VFM) and aerosol sub-type detections were estimated and found as 95.27% and 82.80%, respectively over the selected grid area during June 2007–September 2017. In the case of dusty cirrus cloud, there was a 17% decrease in IWC, 18% decline in IWP, 4% decrease in IDW, a reduction of 19% in IER, as well as a 10% decrease in INC when compared for the dust-free cirrus cloud. Meanwhile, we also studied the relationship between AOD and cirrus microphysical properties (IWC, IWP, IDW, IER, and INC) which is found to be negative observed with the correlation coefficients of $-0.48$, $-0.47$, $-0.38$, $-0.43$, $-0.44$, respectively. These results

![Fig. 7. Scatterplots of correlation coefficient (r) between dust AOD and microphysical properties of dusty cirrus (a) AOD versus IWC, (b) AOD versus IWP, (c) AOD versus IDW, (d) AOD versus IER, and (e) AOD versus INC observed from the CALIPSO and CloudSat instruments.](image-url)
indicate that the dust aerosols can modify cirrus properties, which in turn absorb solar radiation and cause evaporation of cirrus cloud. This is also possible due to the enhanced homogeneous nucleation processes that can raise more aerosols to give abundant smaller ice crystals which are consistent with the Twomey effect for liquid clouds. Moreover, the statistical analysis revealed that the observed differences between dusty cirrus and dust-free cirrus are significant and in good agreement with the earlier reports.

It is important to note that the present work was limited to short-term statistical analysis based on the satellite remote sensing datasets to study the impact of dust aerosol on cirrus properties. Meteorological factors (such as relative humidity and wind) also have effects on cirrus cloud microphysical properties and its formation, apart from the dust and other aerosol types. Such effects require sophisticated model simulations and the analysis of which was beyond the scope of this paper. In the future, large-scale and long-term monitoring with thorough and detailed analyses is needed to study the impact of different aerosols on microphysical properties of cirrus cloud.

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Conflict of interest

Authors declare no conflict of interest in the present work.

Data availability

Data will be provided and available at the request of the readers.

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Wang, W.C. et al., 2010. Dusty cloud properties and radiative forcing over dust source and downwind regions derived from A-Train data during the pacific dust experiment. J. Geophys. Res. 115, D00H35.


