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SATELLITE LIDAR OBSERVATIONS OF CIRRUS CLOUD PROPERTIES: DIFFERENCES IN THE HIGH- AND MIDLATITUDE REGIONS

Qiang Li, Silke Groß

Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre,
82234 Oberpfaffenhofen, Germany
Contact: qiang.li@dlr.de

ABSTRACT

Aerosols, e.g. from air traffic emissions can increase the global cloudiness and exert impact on the properties of naturally-formed cirrus clouds. The densities of civil air traffic show a large difference in the high- and midlatitude regions, which may modify the properties of cirrus clouds at different latitudes differently. In this study, we analyze one-year lidar observations in 2014 with CALIPSO to determine the occurrence rates (ORs) and particle linear polarization ratios (PLDR) of cirrus clouds and further compare them with the ice particle sizes at midlatitudes (ML: 35–60° N; 30° W–30° E) and high latitudes (HL: 60–80° N; 30° W–30° E). The resulting ORs show a distinct seasonal variation with the largest values in winter and the smallest in summer, especially for the results at HL. The occurrence heights of cirrus clouds at HL are nearly 2 km lower than at ML. The derived histograms of cirrus PLDR follow a right-skewed distribution in all seasons. In different seasons, the latitudinal differences in PLDR are slightly different. To study the potential causes of the latitudinal difference in the PLDR values, the altitude profiles of the effective radii of ice crystals (Reff) within cirrus clouds are determined from the DARDAR CLOUD products. The results show larger values of Reff at ML than HL, except for summer. The larger ice crystals related with the specific aerosols acting as INPs at ML are presumed to contribute to the enhanced PLDR values of cirrus clouds.

Index Terms — CALIPSO, lidar, PLDR, aviation impact, contrail, cirrus cloud, ice crystal

1. INTRODUCTION

Cirrus clouds are ubiquitous high-level clouds made of pure ice crystals in the cold upper troposphere. They play a crucial role in modifying the global radiation budget and hydrological cycle by increasing the reflection of solar radiation back to space (cooling effect) and by absorbing the outgoing infrared radiation from the Earth and underlying atmosphere (warming effect). The radiative effects of cirrus clouds strongly depend on their microphysical properties including particle number concentration, size, and habit (Haag and Kärcher, 2004). In general, high-level cirrus clouds are assumed to have a net warming effect other than the liquid-phase and low-level clouds (Chen et al., 2000). Cirrus clouds are globally distributed and their occurrence features a strong latitude dependence with a maximum of up to 70% over the tropics and a decrease towards the poles (Dessler and Yang, 2003; Sassen et al., 2008; Nazaryan et al., 2008). For the last decades, studies of midlatitude cirrus clouds have been intensively conducted because they are highly coupling with various weather patterns and atmospheric dynamics which are still challenging the science community to represent their effects in global and regional climate models (Boucher et al., 2013). Furthermore, air traffics mostly taking place in the northern midlatitudes significantly are suspected to affect the cirrus cloud by increasing the global cirrus cloudiness (e.g. formation of contrails) and modifying the properties of naturally-formed cirrus clouds (e.g. Tesche et al., 2016; Urbanek et al., 2018; Li and Groß, 2021, 2022). Compared to the midlatitudes where multiple measurements are carried out, cirrus clouds in the Arctic and high-latitude regions are rarely studied due to the sparse observations and general neglect in the model simulations. However, cirrus clouds in the high-latitude regions are presumed to provide a considerable coverage and tend to predominantly warm the planet due to the low elevation of the sun. In addition, observations show that the Arctic has been experiencing more rapid warming compared to the rest of the world nearly by a factor of four, which is known as Arctic amplification (AA) (Rantanen et al., 2022). This phenomenon is a consequence of climate change and is believed, on the other hand, to speed it up. Satellite lidar and radar observations can be used to drive cloud optical and microphysical properties of cirrus clouds in the high and midlatitudes. Those measurements have been provided by CALIPSO and CloudSat and will be provided with the improved sensitivity and resolution by the future EarthCARE mission (Wehr et al., 2023). In this study, we will present how those measurements can be used to compare cirrus cloud properties, e.g. occurrence rates (ORs) and particle linear depolarization ratios (PLDR) at midlatitudes and high latitudes based on the analysis of lidar measurements of CALIPSO in 2014.

2. OBERVATIONS AND METHODS

The CALIPSO mission has been providing a unique dataset of the atmospheric profiling since its launch in 2016, which enhances our understanding of the atmospheric aerosols and clouds and their climate impact on our planet (Winker et al., 2010; Stephens et al., 2018). The CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization) instrument onboard CALIPSO is a dual-wavelength lidar operating at 532 and 1064 nm and being capable of polarization at 532 nm (Hunt et al., 2009). By measuring backscattered light, CALIOP provides valuable profiles of the distributions and properties of particles within aerosols and clouds with a high vertical resolution including the particle linear depolarization ratio (PLDR). PLDR is the widely-used parameter in the lidar community to evaluate the changes in polarization states and to retrieve information on ice particle habits that depends on the formation processes of cirrus clouds involving INPs, supersaturation and temperatures. In this study, the Level 2 5-km cloud profile products have been used. With the help of the vertical feature mask (VFM) products, cirrus clouds, that we are interested in, can be distinguished from other features including aerosols and non-cirrus clouds (e.g. Liu et al., 2004, 2009).

3. RESULTS AND DISCUSSIONS

Cirrus ice crystals generally form either via heterogeneous ice nucleation in the presence of suitable ice nuclei or in regions with necessary supersaturation over ice created by ascending motions. Different formation mechanisms lead to different morphologies and properties of cirrus clouds (Krämer et al., 2016; Luebke et al., 2016). High degree variability in the microphysical properties of cirrus clouds strongly depend on the substantial variabilities in meteorological conditions. Therefore, the general meteorological conditions including temperatures and relative humidity with respect to ice (RHi) are directly derived from global ERA5 reanalysis data (Hersbach et al., 2020) (see Figure 1). First, there are seasonal variations in both parameters, precisely, with higher temperatures and lower humidities in summer than in winter in both latitudes. The comparisons between the high- and midlatitudes (HL and ML for short) show that a higher degree of variability in temperatures is seen at HL than ML, whereas a much higher degree of variability in RHi at ML than HL. The medians (means) of temperatures show a consistent result with higher values at ML than HL but the differences between HL and ML are larger in winter than in summer. For the case of RHi on the other hand, the values in the winter months (also including March and November) are much larger at HL than ML, whereas the values in the other months are very close at different latitudes. In addition, we note that the altitude profiles of RHi show in general larger values in the winter months at HL than ML along the whole altitude range, but in other months larger values at HL than ML in the troposphere and the other way around in the stratosphere. Nevertheless, the above comparisons show that it seems general meteorological conditions at HL are favorable for the formation of cirrus clouds. However, the formation of cirrus clouds also depends on the presence of available INPs and the updraft motions etc.

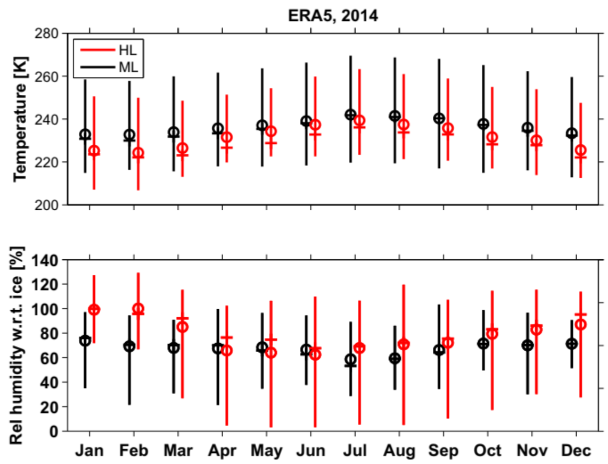

Figure 1. Variations in air temperatures and RHi at altitudes from 4 to 13 km, derived from the ERA5 reanalysis data in different months in 2014 at high- and midlatitudes. The vertical lines indicate the value ranges for both parameters. The circles stand for the mean values and crosses for medians. (DOI: 10.24381/cds.f17050d7)

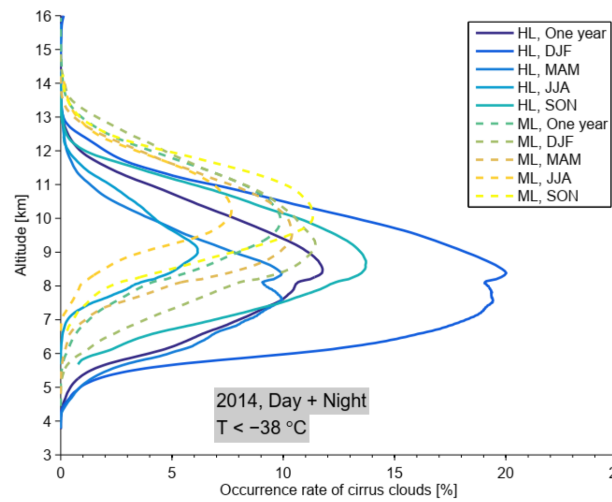

Figure 2. Cirrus occurrence rates derived from both day and night-time observations of CALIPSO in different seasons and the whole year of 2014 at HL (solid lines) and ML (dashed lines), respectively.

In addition to applying the VFM products to retrieve the information of cirrus clouds, we also filter out the data at temperatures above -38 ºC and cut off the data with PLDR values below 0.10 and above 0.80 to exclude the data which are correlated with large uncertainties and thus unphysical. In this study, both day and night-time observations are analyzed.

We first show the ORs of cirrus clouds in different seasons of 2014 as well as the composite mean values for the whole year in Figure 2. The large differences of the OR profiles are clearly noticed at HL and ML. For example, the OR profiles show the maximum values at the altitudes from ~7 to 9 km at HL while from ~9 to 11 km at ML. I.e., the occurrence heights of cirrus clouds at HL are on average ~2 km lower than those at ML. The OR profiles at HL show a much larger variability of values with maxima from 6% in summer to 20% in winter compared to the ML (only from 7.5% in summer to 11.5% in winter). We note here that the occurrence of cirrus clouds strongly depends on the general meteorological conditions shown in Figure 1, although the necessary condition for the formation of ice crystals also include other parameters.

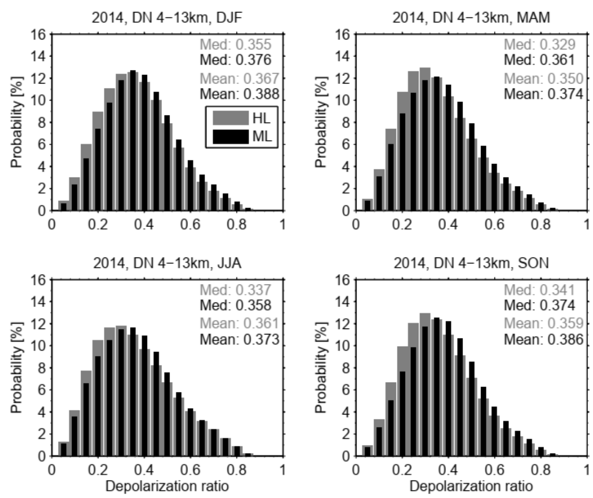

Figure 3. Distributions of the PLDR of cirrus clouds detected at temperatures below -38 ºC in different seasons at HL (gray) and ML (black). The corresponding medians and means of PLDR for each case are indicated in the plot.

According to the typical altitudes in which cirrus clouds form shown in Figure 2, we only consider the observations within the altitude range between 4 and 13 km and the resulting histograms of PLDR values of cirrus clouds in different seasons in 2014 at HL and ML, respectively, are shown in Figure 3. The corresponding PLDR medians and means are also indicated on the plot. The distributions of PLDR are right skewed with a long tail extending to larger values other than a Gaussian distribution for all the cases, I.e., their medians are smaller than their mean values. The distributions of PLDR show consistently larger values at ML than HL. In addition, the differences in medians at ML and HL are 0.021, 0.032, 0.021, and 0.033 of PLDR in different seasons, respectively. Furthermore, the PLDR values for all cases show a seasonal variation with larger values in winter and then autumn than in summer and spring by a difference of ~0.025 in medians.

Previous studies show that the PLDR values of cirrus clouds are closely correlated with the ambient temperatures and the microphysical properties of ice crystals including the ice particle size and number concentrations (e.g. Urbanek et al., 2018; Li and Groß, 2021; Groß et al., 2023). Since the temperatures in clouds are generally lower at HL than ML (see Figure 1), the cirrus clouds at HL are prone to have larger PLDR, which, however, is not the case. It is well known that aerosols acting as INPs have a large impact on ice crystal formation and properties, e.g. black carbon and mineral dust dominating at ML and sea salt at HL. The different types of aerosols can induce changes in the microphysical properties of ice crystals and then in the optical properties. The midlatitude regions focused on in this study cover a large part of the Northern Atlantic flight corridor and have much larger densities of air traffic than at HL. To identify the potential causes to the characterization of latitude dependence of cirrus PLDR values, we determine the distributions of the effective radii of ice crystals (Reff) within cirrus clouds from the DARDAR CLOUD products (Delanoë and Hogan, 2010) and show the results in different seasonal months in 2014 in Figure 4. In general, the values of Reff show a decrease along the altitudes. Reff are slightly larger in January and October than in April and July at ML, whereas Reff are much lower in January and October than in April and July at HL. Importantly, the comparisons of Reff between different latitudes show reduced values at HL than ML, except for July. The statistical results of Reff in July show slightly larger values at HL than ML, which is consistent with the recent study with in-situ observations during the Cirrus-HL campaign (De La Torre Castro et al., 2023), although the area coverages of both datasets are different. It is presumed that the formation ice crystals with larger Reff are closely correlated with the enhanced heterogeneous freezing induced by the aviation emissions at ML (Urbanek et al., 2018; Groß et al., 2023). The large ice crystals further contribute to the increased PLDR values of cirrus clouds. Cirrus clouds in summer characterized by low PLDR at both ML and HL are less influenced by aviation emissions (Li and Groß, 2022) since the occurrences of contrails and cirrus clouds are very low due to the warm and dry airmasses.

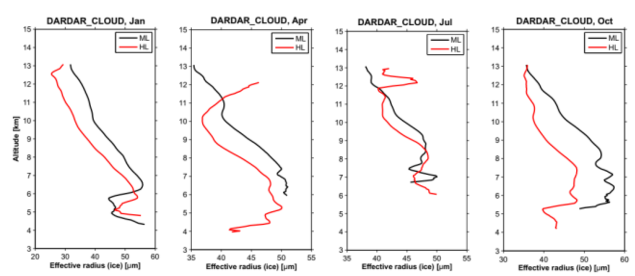

Figure 4. Altitude profiles of the medians of the effective radii of ice crystals (Reff) within cirrus clouds in different seasonal months in 2014 at HL and ML, respectively.

4. CONCLUSIONS AND OUTLOOK

In the current study, we have presented the altitude profiles of ORs and the distributions of PLDR values of cirrus clouds in 2014 based on the analysis of lidar observations with CALIPSO. The parameters of cirrus clouds have been retrieved by applying the VFM products along with additional filters at temperatures below -38 ºC and within altitude ranges between 4 and 13 km. The results derived from the observations in the high- and midlatitude regions have been compared for different seasons. The ORs show a distinct seasonal variation with the largest values in winter and the smallest in summer, especially for the results at HL. The ORs at HL can be as large as 20% in winter seen at ~8.5 km but only 6% in summer at ~9 km. At ML, however, the ORs are in general very stable with an exception of 7.5% in summer. The occurrence heights of cirrus clouds at HL are nearly 2 km lower than at ML. The maximum ORs are detected at the altitudes of 7-9 km at HL and of 9-11 km at ML. The derived histograms of cirrus PLDR follow a right-skewed distribution for all the cases. The PLDR values are consistently larger at ML than HL. In different seasons, the latitudinal differences in PLDR are slightly different, precisely, with larger differences in spring and autumn and smaller ones in winter and summer. To study the potential causes of the latitudinal difference in PLDR, we have presented the altitude profiles of the effective radii of ice crystals (Reff) within cirrus clouds from the DARDAR CLOUD products. The results show larger Reff at ML than HL, except for summer. The large ice crystals presumed to be related with the enhanced heterogenous freezing induced by aviation emissions are supposed to contribute to the enhanced PLDR values of cirrus clouds. The smaller impact of aviation emissions on cirrus clouds in summer has been presented by Li and Groß (2022).

Other reasons for the latitudinal difference in the cirrus cloud properties other than aviation emissions, however, should not be ruled out. Only one-year satellite observations have been analyzed in this study. Larger dataset will of course provide better statistics. Airborne observations through specific areas and different clouds during the Cirrus-HL campaign will give us a better insight into the cirrus cloud properties. Especially, the simultaneous observations of cirrus clouds and ice crystal properties can help us unravel some of mysteries in the formation and evolution of cirrus clouds. The corresponding studies will be carried out in the near future.

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