First simultaneous observation of a glory and in-situ microphysical cloud properties

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Received 23 January 2017; revised 16 March 2017; accepted 20 March 2017; posted 22 March 2017 (Doc. ID 285524); published 12 April 2017

Whilst making airborne measurements of cloud particles, a bright glory was observed on a thin layer cloud. By deliberately flying through this glory-producing cloud on several occasions, cloud particle size distributions were obtained. We found that warm liquid clouds with narrow cloud droplet size distributions are responsible for producing the observed glory. This paper presents these results and compares the results of Mie theory simulations with an image of the glory. © 2017 Optical Society of America

OCIS codes: (010.1615) Clouds; (290.1090) Aerosol and cloud effects; (290.4020) Mie theory.

https://doi.org/10.1364/AO.56.0000G5

1. INTRODUCTION

The glory is one of the most beautiful natural meteorological phenomena. Appearing as colored concentric rings surrounding the shadow of the observer, it is caused by backscattering of sunlight from clouds. This phenomenon has been the subject of intense interest and study for several decades through laboratory experiments, field observations [1-3] and numerical simulations [4-8]. For theoretical considerations and various hypotheses about the formation of glories, readers are referred to [9-17].

Despite the above advancements in the understanding of glory phenomenon, in-situ observations of clouds capable of producing glories are rarely available. Recently, observations of glories have been reported from the space shuttle [18] and from a satellite [19]. Apart from the glory, the first quantitative remote sensing measurement of the cloudbow, another atmospheric phenomena, from space was provided by POLDER instruments, which suggested that clouds capable of producing cloudbows have narrow cloud droplet distributions [20]. To the best of our knowledge, in-situ measurement of clouds producing glories have not previously been reported. Here, we present properties of in-situ measurement of a thin layer cloud where glory was observed from the surface of the same cloud (from the instrumented aircraft). The observation was made in October 2014 over Mahabaleswar, India during the Cloud Aerosol Interaction and Precipitation Enhancement Experiment (CAIPEEX) [21]. We utilized measurements of the cloud droplet size distribution to understand the microphysical properties of these clouds. Using these measurements as an input to the Mie scattering theory, we simulated the glory and compared the simulation with the observed concentric rings.

This paper is arranged as follows: section 2 describes the data analysis and methodology which also includes description of the instruments. Section 3 presents our results. Finally, section 4 summarizes the major findings of this study.

2. DATA ANALYSIS AND METHODOLOGY

Aircraft observations of a thin layer cloud producing glory phenomenon were made on 28th October 2014 (73.66 °E, 18.08 °N). The cloud properties were measured by a Cloud Droplet Probe (CDP) at 2Hz resolutions (~45 m of spatial resolution at 90 ms⁻¹ of true air speed). The CDP, manufactured by Droplet Measurement Technologies, USA, is a spectrometer that works on the principle of forward scattering. The CDP uses a laser and the forward scattered light from the illuminated particle is used to size the droplet (http://www.dropletmeasurement.com/cloud-droplet-probe-cdp-2). It measures cloud droplet size distribution (DSD) in the diameter range from 2.5 to 50 µm in 30 unequal range bins. The total number concentration (Nc, cm⁻³), mean diameter (Dm, µm) liquid water content (LWC, g m⁻³) and spectral width (σ, µm) can be calculated from the DSDs [22]. The altitude of the cloud measurement and temperature are obtained from the Aircraft Integrated Meteorological Measurement System (AIMMS) probe and Rosemount Temperature probe respectively. We also used concentrations of supermicron aerosol (1<D<2.5 µm) to understand the haze particles present in the atmospheric boundary layer. Aerosol data is obtained from onboard Passive Cavity Aerosol Spectrometer Probe (PCASP) that provide aerosol concentrations in the diameter range of 0.1 to 2.5 µm.

The measured DSDs are utilized to simulate glory phenomenon by Mie scattering theory. We utilized the MiePlot computer...
program (available at [www.philiplaven.com/mieplot.htm](http://www.philiplaven.com/mieplot.htm)) to simulate the glory using the measured DSD and compared with the glory rings photographed.

3. RESULTS

During a research sortie on 28th October, 2014 near Mahabaleswar, India, we noticed a glory phenomenon from the surface of a thin layer cloud. The glory phenomenon was observed in the afternoon hours at around 11:00 UTC. The photograph of the layer cloud is shown in Fig. 1. The cloud layer was above several convective clouds, but it was detached from the cloud systems below (see Fig. 1A). From the figures Fig.1B, C & D it can be seen that the layer cloud was thin and transparent as the ground was visible. It may also be noted that a thick haze layer between 1.8 km and 2.5 km was observed. Mean concentration of supermicron size particles (1< D< 2.5 µm) between these two altitudes was found to be 1.20 cm^{-3}. In addition, the aircraft was flying over the dark green mountainous regions of the Western Ghats. The mountainous regions and the presence of boundary layer haze thus provided a dark background to observe the glory. The colored rings of the glory were formed in the transparent sections which were located at the edges of the layer cloud. Three horizontal cloud transects were made with the help of a CDP. From the vertical positions of the aircraft the geometrical thickness of the cloud was estimated to be of nearly 100m. Using the mean cloud droplet effective radius (r_e, µm) and LWC we calculated the cloud optical depth (COD) [23]. It is assumed that the average microphysical properties of the layer cloud is uniform vertically. Using mean r_e ≈ 5.74 µm and LWC≈ 0.03 g m^{-3} values obtained from three cloud transects, COD is found to be ≈0.78. This COD value suggests presence of a very thin layer cloud.

We consider one cloud pass to discuss microphysical properties of this glory-forming cloud.

Figure 2(a) shows the altitude and temperature of the cloud pass. The observations were made at an altitude of 4.8 km above mean sea level. The temperature range was from 2.33 °Cto 2.37 °C, indicating that the cloud droplets are in the liquid phase. Note that the glory was observed in the first few hundred of meters of the thin layer cloud.

![Glory producing Layer Cloud](image)

![Fig. 1 Photographs of the thin dark layer cloud where the glory phenomena was observed.](image)

![Fig. 2(Color online)(a) Altitude and Temperature of the aircraft observation of clouds on 28th October, 2014. Glory phenomenon was observed formed by these thin layer clouds. (b) Variations of total droplet concentrations (N_c, cm^{-3}), mean diameter (D_m, µm), liquid water content (LWC, g m^{-3}) and spectral width (σ) of the droplet spectra. DSDs used to simulate the glory phenomenon was of the first few seconds of cloud pass (shown by an ellipse).](image)
Fig. 2(b) shows the properties of cloud droplet spectra e.g. $N_c$, $D_{m}$, LWC and $\sigma$ in which the glory phenomenon was observed. Total droplet number concentrations ($N_c$, cm$^{-3}$) of the cloud transect are shown on Fig. 2(b). It suggests that low cloud droplet number concentrations ($<45$ cm$^{-3}$) are present in these clouds. The mean diameters ($D_{m}$, $\mu$m) of the cloud droplets are also shown in Fig. 2(b). At the edges of the cloud, $D_{m}$ values are close to 13 $\mu$m while in the later part of the cloud transect their values are decreased nearly to 11 $\mu$m and remained constant thereafter. Decreased $D_{m}$ values may indicate evaporation of cloud droplets. The spectral width ($\sigma$, $\mu$m) of the DSDs are more or less constant throughout the cloud transect with their values close to 1. Small values of $\sigma$ indicate that the DSDs are narrow, implying that the cloud droplets are tightly clustered around a droplet diameter, even though the sampling frequency is only 2Hz. As expected these clouds contain very small amounts of liquid water content i.e. LWC$<0.05$ g m$^{-3}$.

To understand the DSD properties capable of producing a glory, an instantaneous DSD measured at 2 Hz resolution is shown in Fig. 3. We selected this droplet spectrum from the first few hundred meters of cloud pass. In addition, in order to distinguish its properties from other types of clouds, we also plotted typical DSDs observed in convective and stratus clouds, also measured at 2Hz resolution. It clearly shows that the DSD which can produce glory phenomenon is narrower than the DSDs of convective or stratus clouds. Note that this distinction is true for data at 2Hz resolution in the present scenario. A peculiar distinction of the glory cloud from other DSDs is the well defined $N(D)$ peak at around 12-13 $\mu$m. The width of the DSD is also extremely narrow. This implies that the glory DSDs are well ordered at certain droplet diameter ranges e.g. here it is 12-13 $\mu$m.

We used the various DSDs shown in Fig. 3 as inputs to the MiePlot program to simulate the backscattering of sunlight as shown in Figs. 4(a-c). The inner red ring in Fig 4(a) has a radius of about 1.5°, which corresponds to scattering from a droplet of about 32 $\mu$m diameter. The rings of the glories in Figs. 4(b) and (c) are significantly larger, implying that they are caused by smaller droplets. All three simulations in Fig. 4 show glories, but it is important to recognize that glories were observed only on the cloud corresponding to the DSD used for Fig 4(c).

The reason for this discrepancy is that the simulations consider only single scattering. In practice, the colored rings of glories on clouds are generally seen against an almost white background which is due to multiple-scattering from the cloud droplets. Further work is necessary to model the effects of multiple scattering for the cloud parameters measured in this study.

![Fig. 3 Typical Cloud droplet size distribution of glory-producing cloud (shown as glory cloud), convective and stratus cloud as observed from aircraft observation at 2Hz resolution. DSD parameters e.g., $N_c$, $D_m$, $\sigma$ and LWC are provided for each distribution.](image)

![Fig. 4 Simulations of single-scattering of sunlight using the measured DSDs shown in Fig. 2 for (a) the convective cloud, (b) the stratus cloud and (c) the glory-producing cloud.](image)
producing clouds by an instrumented aircraft. Furthermore, this particular cloud is characterized by low small spectral width (≈1 µm). Narrow cloud droplet distributions (D < 20 µm) are also reported for clouds producing cloudbow from the space. Thirdly, the close match in Fig. 5 between the photograph and our simulations using Mie theory was obtained assuming that the refractive index of water is about 1.33, whereas Nevzorov postulated D ≈ 13 µm, whereas Nevzorov assumed droplets at sub-zero temperatures. The droplet size distribution is very narrow, characterized by low liquid water content (LWC < 0.05 g m⁻³). This confirms the validity of the Mie theory simulations.

Our results do not support Nevzorov’s hypothesis [15] that glories are caused by scattering by particles of amorphous water. Firstly, our temperature measurements indicate that the water droplets causing the glory were in the liquid phase at T=2.33-2.37 °C, whereas Nevzorov assumed droplets at sub-zero temperatures. Secondly, our measurements indicate mean droplet diameters Dₘ ≈ 13 µm, whereas Nevzorov postulated Dₘ > 20 µm or even larger. Thirdly, the close match in Fig. 5 between the photograph and our simulations using Mie theory was obtained assuming that the refractive index of water is about 1.33, whereas Nevzorov’s calculations assumed a refractive index of about 1.8.

4. CONCLUSIONS

Whilst flying in a research aircraft equipped to measure the properties of cloud particles, a visual observation of a glory allowed us to investigate the cloud microphysical properties that generate glories. Our principal findings are:

i. The glory phenomenon was observed on the surface of a warm thin cloud with temperatures of T = 2.33-2.37 °C. This means that liquid droplets in the cloud are capable of producing a glory by backscattering of sunlight.

ii. The droplet size distribution is very narrow, characterized by small spectral width (≈1 µm). Narrow cloud droplet distributions are also reported for clouds producing cloudbow from the space [19]. Furthermore, this particular cloud is characterized by low concentrations of droplets (Nc < 50 cm⁻³), small mean diameter (Dₘ ≈ 13 µm) and low liquid water content (LWC < 0.05 g m⁻³). Significantly, the cloud parcels consists of droplets clustered around a droplet diameter, even though the measurement is relatively coarse resolution i.e. 2Hz.

iii. Using the measured DSDs, Mie theory simulations closely resemble the observed colored rings.

This study provides the first direct measurement of glory-producing clouds by an instrumented aircraft.

Acknowledgement

ITM is funded by Ministry of Earth Science, Govt. of India. The authors sincerely acknowledge the effort of CAIPEEX team members for successfully conducting the aircraft observations. Information on CAIPEEX data can be obtained from http://www.tropmet.res.in/~caipeex/about-data.php. Authors thank the Editor and two reviewers for their helpful suggestions that improved quality of the manuscript.

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