Determination of Cirrus Occurrence and Distribution Characteristics Over the Tibetan Plateau Based on the SWOP Campaign

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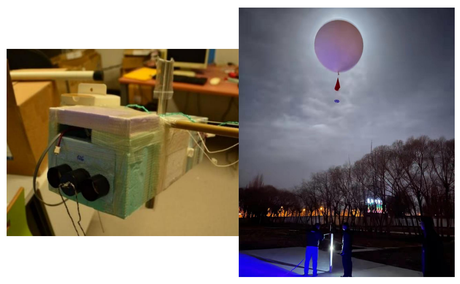
Introduction

1. Cirrus play a crucial role in the Earth's climate system.
2. The main datasets for studying cirrus clouds are based on satellite observations or in situ remote sensing instruments.
3. The sounding water vapor, ozone, and particles (SWOP) campaign has collected Compact Optical Backscatter Aerosol Detector (COBALD) and Frost Point Hygrometers (FPs) data.
4. In this study, eight summer balloon-borne measurements in Kunming and Lhasa over the Tibetan Plateau were used to show the distribution characteristics of cirrus clouds.

Data and Methods



$$BSR = \frac{\beta_m + \beta_p}{\beta_m} \quad (1)$$

$$CI = \frac{BSR_{940} - 1}{BSR_{455} - 1} \quad (2)$$

$$\mathrm{RH_{ice}} = \frac{e_{ice}(T_{mirror})}{e_{ice}(T_{ambient})} \quad (3)$$

Figure 1. shows the two sounding instruments, COBALD and FHs, and the process of releasing the sounding balloon.

- Based on the COBALD at wavelengths of 455 nm (blue) and 940 nm (infrared), the original COBALD signal is converted into the BSR, defined as Equation 1. The color index (CI) is defined by Equation 2. Equation 3 was used to calculate RH_{ice}.
- All three indicators are able to depict the occurrence of cirrus clouds.

Criteria Selection

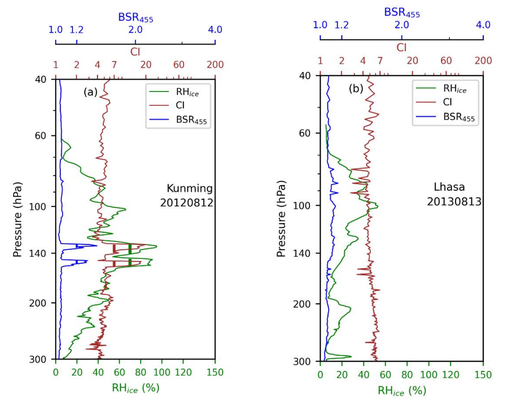


Figure 2. Profiles of the BSR_{455} (blue), RH_{ice} (green), and CI (brown) in Kunming on August 12, 2012 (left) and in Lhasa on August 13, 2013 (right). The thick solid blue, brown, and green lines indicate a $BSR_{455} > 1.2$, a $CI > 7$, and an $RH_{ice} > 70\%$, respectively.

- Figs. 2a and 2b illustrate the occurrence or nonoccurrence of cirrus clouds, respectively.
- There were differences in the thicknesses and locations of cirrus clouds, as indicated by the different indicators.

Figure 3. (a) The frequency of $CI > 7$ and $RH_{ice} > 70\%$ when BSR_{455} values are greater than different thresholds. Brown markers indicate $CI > 7$, and green markers indicate $RH_{ice} > 70\%$. Relative humidity measurements for (b) Kunming and (c) Lhasa are plotted against the CI. The points are colored according to the BSR_{455} measurements. The horizontal and vertical black dashed lines indicate $CI = 7$ and $RH_{ice} = 70\%$, respectively.

- The frequency of $CI > 7$ and $RH_{ice} > 70\%$ exhibited obvious changes when $BSR_{455} > 1.2$.。
- The CI and RH_{ice} can be affected under cloud-free conditions (not shown). a $BSR_{455} > 1.2$ was used as the criterion to obtain the distribution characteristics of cirrus clouds

Distribution Characteristics of Cirrus Clouds

■ Vertical Distributions of the CI and RH_{ice} Within Cirrus

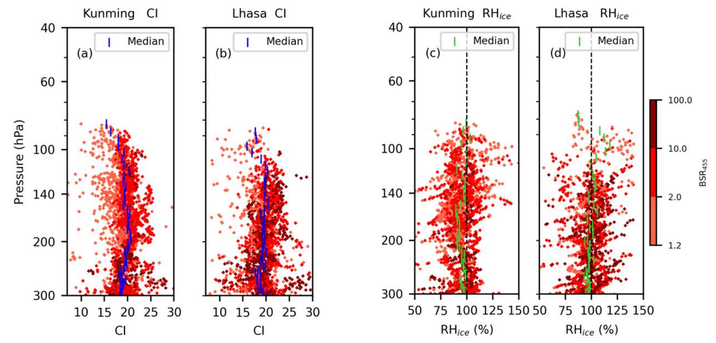


Figure 4. Distribution of CI (a, b) and RH_{ice}(c, d) values with height within cirrus clouds, colored according to BSR_{455} values. The blue and green vertical lines are the median CI and RH_{ice} values, respectively, at an interval of 5 hPa.

- Below 120 hPa, the median CI values at both sites were mostly in the 18–20 range. Above 120 hPa, the decrease in the median CI with height was likely due to the smaller diameter of the ice particles near the tropopause.
- the median RH_{ice} at 5 hPa height intervals, which basically fell within the 90%-110% range and did not change much as the height increased.

■ Distribution of Cirrus Occurrence With Height

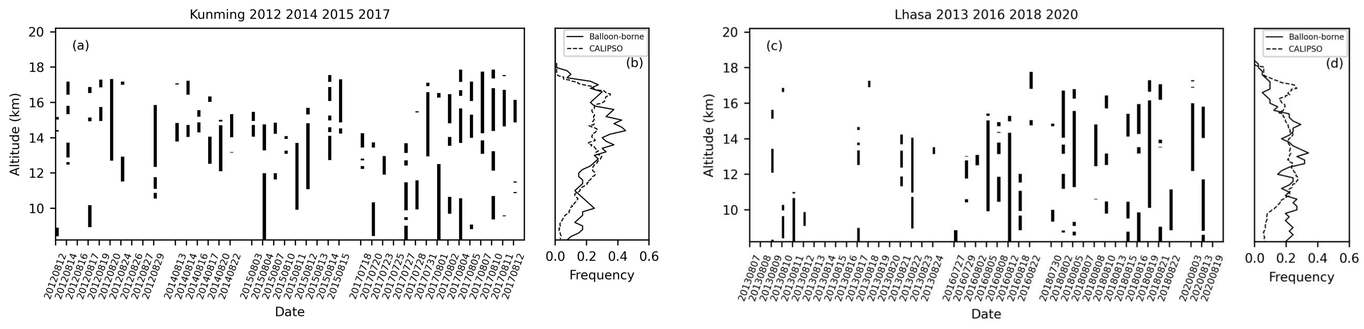


Figure 5. Vertical distribution of cirrus occurrence in (a) Kunming and (c) Lhasa from balloon-borne measurements. The date (yyyymmdd) is on the x-axis, and the black bars mark the cirrus layer. Depiction of the frequency of cirrus occurrence within 8–20 km at 0.2 km intervals from both the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (dashed black line) and the balloon-borne (solid black line) measurements is shown in (b) Kunming and (d) Lhasa.

- There is a high frequency of cirrus occurrence near the tropospause.
- The greatest height of cirrus occurrence observed by the balloon-borne and CALIPSO measurements in Kunming and Lhasa was near 18 km.

■ Distribution of Cirrus Occurrence With Tropopause

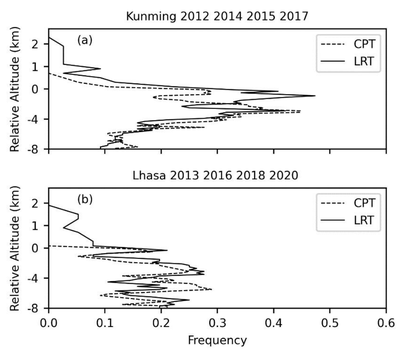


Figure 7. Frequency of cirrus occurrence relative to the tropopause in (a) Kunming and (b) Lhasa. The solid black line (dashed black line) refers to the tropopause defined by the lapse rate tropopause (cold point tropopause). The data are selected at intervals of 0.2 km for both sites.

- The COBALD could detect cirrus clouds above the tropopause.
- The frequency of cirrus cloud occurrence in both Kunming and Lhasa had a strong gradient at the CPT. The average frequency of cirrus clouds above the LRT was ~6% (~5%) in Kunming (Lhasa).

■ Distribution of Cirrus Thickness

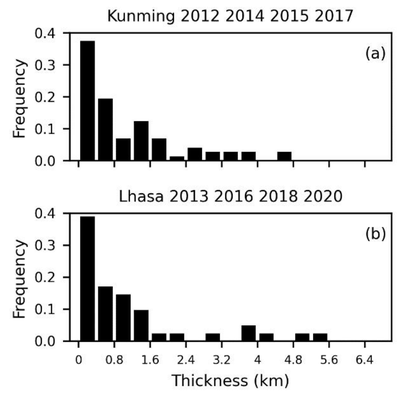


Figure 8. Cirrus thickness distribution in (a) Kunming and (b) Lhasa. The x-axis is the cirrus thickness at 0.4 m intervals, and the y-axis is the frequency of cirrus thickness in each interval.

- Both Kunming and Lhasa had the highest frequency of thin cirrus clouds in the 0–0.4 km range, with 38% in Kunming and 39% in Lhasa.

Criteria Selection

1. A backscatter ratio over 1.2/2 at a 455 nm/940 nm wavelength can effectively identify cirrus clouds over the Tibetan Plateau.
2. Cirrus clouds were observed above the cold point tropopause (CPT) in both Kunming and Lhasa.
3. About 38% (39%) of the cirrus clouds are thinner than 400 m in Kunming (Lhasa).

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