Research Article

Spatial and Temporal Features of the Frequency of Cloud Occurrence over China Based on CALIOP

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Spatial and temporal distribution of cloud vertical structure are key components of global climate change. The occurrence of clouds over China and its surrounding areas has been calculated based on cloud layer products from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) at 1 km resolution. Results show significant regional differences in the frequency of cloud occurrence. Fewer clouds are found over the Mongolian Plateau and northern Indian Peninsula, with more clouds apparent over tropical seas and southern China. Cloud cover at night is slightly higher than during the day. Single-layer clouds are more common than multilayer clouds in most areas. In most areas, high-level cloud accounts for the largest proportion of single-layer clouds. The occurrence of clouds in summer and autumn is generally greater than in spring and winter. Single-layer clouds over the Mongolian Plateau and northern Indian Peninsula occur less frequently than multilayer clouds, especially in winter. Furthermore, single-layer clouds are common over the eastern part of southwest China all year round. Over parts of the Tibetan Plateau in summer, high clouds account for the largest proportion (>35%) of annual single-layer clouds, as a result of topography and enhanced summer convection.

1. Introduction

Clouds can act as a radiation source, emitting thermal radiation, while also absorbing or scattering shortwave solar radiation and outgoing longwave radiation. Accordingly, they regulate and influence the energy distribution of the earth-atmosphere system, which has an important impact on global climate. For example, when covered by clouds, the earth's albedo is double that under clear-sky conditions [1–3]. An important prerequisite for studying the effects of clouds on the earth's radiation balance is accurate understanding of the cloud vertical structure (CVS) [4]. The CVS incorporates the height distribution of clouds (i.e., the difference in height between the cloud top and cloud bottom), the distance between adjacent layers, and the height difference between cloud layers. Different cloud heights have different radiative effects: the reflectivity of low-level clouds often causes a cooling effect, while high-level clouds heat the earth-atmosphere system via a greenhouse effect. The in-depth study of different cloud heights can therefore help to more fully understand the interactions between clouds and

radiation [5, 6]. To date, it has been difficult to obtain an accurate parameterization scheme for establishing a model of cloud impact on climate change, due to a lack of in-depth understanding of CVS and cloud characteristics in climate model simulations of large-scale weather. As a result, the ability to accurately simulate climate is greatly reduced [7–9]. Therefore, accurate and comprehensive studies of CVS parameters, as well as their spatial and temporal distributions, are important in analyzing the interactions between clouds and radiation and their relationship to global climate change.

Using data from the International Satellite Cloud Climatology Project (ISCCP) for July 1983 to September 2001, Ding demonstrated regional differences and a decreasing trend in global average cloud amount, closely related to the dynamic effects of thermodynamic and microphysical processes within clouds [10]. Wang and Rossow undertook a preliminary analysis of CVS effects on large-scale circulation, using 13 experiments from the Goddard Institute of Space Studies Global Climate Model (GISS GCM) [9]. The development of detection technology has allowed more in-depth

FIGURE 1: Spatial distribution of the numbers of (a) observation orbits and (b) observation profiles from 2006 to 2016 over China and surrounding areas.

studies of clouds and their vertical structure. The preliminary analysis shows that the temporal and spatial variation of single- and multilayer cloud are significant; the occurrence of single-layer cloud is higher than that of multilayer clouds [11, 12]. Due to the topography-induced compression effect, the variation characteristics of CVS in Tibetan Plateau (27°N – 40°N , 70°E – 103°E , TP) are obviously different from those of adjacent land area (20°N – 27°N , 70°E – 103°E) and tropical ocean regions in the south of the TP (20°S – 20°N , 60°E – 150°E) [13]. By using CALIOP data to study tropical areas, it is found that thin mid-level clouds (TMLCs) have larger occurrence frequency in this area [14]. These previous studies have focused on cloud height distribution; however, the relationship between the different number of cloud layers and cloud height has not been studied in detail. This paper analyzes the spatial and temporal distributions of single-layer clouds and their occurrence.

2. Information and Methods

2.1. Research Data. The CALIOP forms a part of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) platform: dual-band (532 and 1064 nm) linearly polarized lidar. A short-wavelength detector and a high sensitivity to thin clouds in the atmosphere result in good detection; for example, CALIPSO has a good detection capability in the cloud with an optical depth of 0.01 or less [15]. After extensive comparison and verification of different lidar systems [16–18], we found that detecting performance of CALIOP is better compared with ground-based lidar, specifically, in the detecting abilities of physics and optical properties of cirrus clouds [15, 19, 20]. Compared with ground observations and passive remote-sensing satellite

detectors, an obvious advantage of CALIOP is that active remote sensing can be used for the first time to collect global CVS data. Accordingly, a more comprehensive and detailed observational dataset is available for investigating the effects of cloud radiation on the earth-atmosphere system, thereby optimizing the representation of large-scale weather in climate models [7, 21]. However, it is difficult for CALIOP to penetrate thicker cloud cover, resulting in inaccurate or missing information about cloud base heights and the presence of clouds below the thicker cloud layer. Despite this disadvantage, the use of CALIOP data to analyze global cloud distribution and CALIPSO cloud-penetration statistics demonstrates its feasibility for studying cloud distribution [22, 23]. In order to ensure the quality of this study, high confidence data of cloud-aerosol discrimination (CAD) were selected between 70 and 100, which indicates a reliable range of the data source.

Based on CAL_LID_L2_01kmCLay-Standard-V4-10 cloud layer products from June 2006 to May 2016, this study statistically analyzed the horizontal distribution and seasonal variation of cloud occurrence and the single-layer cloud at different height over China and surrounding areas (0°N – 55°N , 70°E – 140°E).

2.2. Research Methods. Observational satellite data along orbits were calculated on a $1.2^{\circ} \times 1.2^{\circ}$ latitude-longitude grid. More than 95% of grids had >400 observation orbits and $>40,000$ observation profiles (Figure 1). Without specification in the paper, “cloudy sky” was defined as the area where a laser profile detected the cloud layer through a grid. Factors related to observing earth from polar-orbiting satellites result in a greater number of observations at high latitudes than at low latitudes (Figure 1(a)). This study also

FIGURE 2: Horizontal distribution of the occurrence of cloudy skies during (a) the whole day, (b) day-time, and (c) night-time over China and surrounding areas, %.

TABLE 1: Classification of cloud heights.

Cloud level	Layer top pressure
High	$P_{\text{Top}} < 440$ hpa
Mid	$440 \text{ hpa} < P_{\text{Top}} < 680$ hpa
Low	$P_{\text{Top}} > 680$ hpa

carried out a comparative analysis of day-time and night-time observational data, based on local-time satellite observations.

International Satellite Cloud Climatology Project (ISCCP) classifies clouds according to the cloud top pressure and cloud optical thickness [24], which is different from the cloud types determined from surface observations [25]. High clouds, including the cirrus, cirrostratus, and deep convective clouds, are in the ice phase. Middle clouds including the altocumulus, altostratus, and nimbostratus are considered as being the ice phase, and low clouds including the cumulus, stratocumulus, and stratus are in the liquid phase. According to the classification of ISCCP, this study used the layer top pressure (P_{Top}) provided by CALIOP, and the single-layer clouds were divided into high- ($440 \text{ hpa} \leq P_{\text{Top}} < 50$ hpa), mid- ($680 \text{ hpa} \leq P_{\text{Top}} < 440$ hpa), and low-level ($1000 \text{ hpa} \leq P_{\text{Top}} < 680$ hpa), in order to analyze the single-level clouds at different heights (Table 1).

3. Horizontal Distribution of Cloud Occurrence and Cloud Height

3.1. Occurrence of Cloudy Skies. The results show significant regional differences in the year-round occurrence of cloudy skies (Figure 2(a)). The occurrence of cloudy skies over southern China (south of 35°N) is greater than over northern China, with the cloudiest conditions found over the Sichuan Basin, the northeastern Yunnan–Kweichow Plateau, and tropical areas (0°N – 10°N , 90°E – 120°E). Over the Sichuan Basin, the local cloud can maintain a relative long life cycle mainly because the occlusive topographic landscape

has caused low wind speed and high humidity. This further hinders the atmospheric horizontal diffusion [26]. The occurrence of cloudy skies is lowest over the Mongolian Plateau and the northwestern Indian Peninsula. This theory is supported by Pan et al.'s findings [12]. A comparison of Figure 2(b) and 2(c) shows that the occurrence of cloudy skies over the western side of the Tibetan Plateau at night is 10%–20% lower than during the day. In most other areas, cloudy skies at night are slightly more frequent than during the day.

3.2. Diurnal and Altitudinal Differences in the Frequency of Single-Layer Clouds. The ratio of the sample number of single-layer clouds to total clouds indicates the frequency of single-layer clouds, which reflects the contribution of single-layer cloud to the total year-round occurrence of clouds. The occurrence of single-layer clouds during day-time (night-time) is expressed by the proportion of the sample number of single-layer clouds during day-time (night-time) to the total clouds during day-time (night-time). The occurrence of single-layer clouds over southern China (south of 35°N) is greater than in the north; single-layer clouds over the Mongolian Plateau are less frequent during the whole year. The occurrence of single-layer clouds over the Sichuan Basin, eastern parts of southwest China, and the eastern East China Sea is greater than 60%. The occurrence of single-layer clouds in South Asia is less than 40%, with the lowest values found over the northwest Indian Peninsula (Figure 3(a)). A comparison of Figure 3(b) and 3(c) shows that the occurrence of single-layer clouds over the Tibetan Plateau and Sichuan Basin is slightly higher during the day than at night; no differences between day-time and night-time are found in other areas [27, 28].

Figure 4 shows the occurrence of single-layer clouds in the case of high- (most frequent), mid- (second most frequent), and low-level (least frequent) clouds. Tibetan Plateau is dominated with single-layer high-level cloud, caused by high altitude and low air pressure with average altitude above 3.1 km and the air pressure less than 680 hpa. Making the

FIGURE 3: Horizontal distribution of the occurrence of single-layer clouds during (a) the whole day, (b) day-time, and (c) night-time over China and surrounding areas, %.

FIGURE 4: Horizontal distribution of the occurrence of single-layer (a) high, (b) middle, and (c) low cloud over China and surrounding areas (unit: %). The shaded part indicates that the surface elevation is above 3.1 km (680 hpa).

initial height of cloud in this area is higher than other regions in the same latitude and also brings lower cloud top pressure, which is usually below 440 hpa [12]. High-level cloud cover, exceeding 90%, dominates the Tibetan Plateau due to the influence of topography. Over continental areas away from the plateau, the occurrence of high-level cloud north of 30°N is higher than that south of 30°N (Figure 4(a)). The occurrence of high-level cloud in the northern part of India ocean and the Western Pacific is greater than that of eastern continent and coastal areas in China because deep convection in the tropics is more frequent than in the subtropics, and vapor is more adequate [28, 29]. The occurrence of mid-level cloud over southwest China is greater than 50%. High- and low-level cloud cover is greater over coastal areas than mid-level cloud cover, especially over the sea south of 20°N, including the Bay of Bengal and South China Sea, where the occurrence of mid-level cloud is less than 10% (Figure 4(b)). The occurrence of single-layer, low-level cloud

over the Western Pacific Ocean and Chinese coastal areas is higher than over the Chinese mainland. Over northeast and northern China, the middle and lower Yangtze, and southeast coastal areas, the occurrence of low-level cloud is 10%–30%; over the remaining inland areas, low-level cloud cover is less than 10%. Over oceanic regions south of 15°N, including the Bay of Bengal and South China Sea, the occurrence of low-level cloud is less than 20%, which is significantly lower than over the Western Pacific Ocean north of 15°N (Figure 4(c)). This theory is supported by Yu's findings in the research [30]. Results show no significant difference in the occurrence of different height clouds between day and night. The occurrence of mid-level cloud is slightly higher during the day than at night, whereas the occurrence of high- and low-level cloud is slightly higher at night than during the day.

The occurrence of single-layer clouds of different heights (Figure 4) has similar large value with its cloud top temperature (Figure 5(a)). The single-layer cloud in Tibetan Plateau

FIGURE 5: (a) Horizontal distribution of the cloud top temperature of single-layer cloud over China and surrounding areas; (b) PDF of the cloud top temperature of single-layer cloud over Tibetan Plateau (TP) and East China (EA). The shaded part indicates that the surface elevation is above 3.1 km (680 hpa).

(TP) (27.6°N~46.8°N, 70.8°E~106.8°E) is mainly formed by high cloud, and the average cloud top temperature is higher than -40°C . The cloud top's average temperature of single-layer cloud at the eastern China area (EA) at the same latitude (27.6°N~46.8°N, 106.8°E~120°E) is about -45°C . The average cloud top's temperature of single-layer cloud at TP and EA is shown in Figure 5(b). The proportion of warm clouds near -20°C is greater than EA; this may be because of the uplifting of the TP terrain and the thermal effect.

4. Seasonal Variations in the Occurrence of Clouds and Cloud Heights

Regional differences in the occurrence of clouds are apparent throughout the year. Seasonal variations in the horizontal distribution of clouds are due to different weather systems, atmospheric circulation structures, water vapor amount, and seasonal differences in the intensity of convection [31, 32]. In this study, seasonal differences in the occurrence of cloudy skies and single-layer clouds are analyzed in detail.

4.1. Seasonal Changes in Cloudy Skies. To describe the seasonal distribution and variation in cloud characteristics, the occurrence of cloudy and clear skies was calculated as the ratio of the sample number of cloudy skies or clear skies in each season to the total cloud cover over the whole year (Figure 6). Cloudy skies are more frequent over northern areas ($>35^{\circ}\text{N}$) of the Chinese mainland in each season than over southern areas ($<35^{\circ}\text{N}$). The Mongolian Plateau is typically a cloud-free area, in contrast to northern areas of the Chinese mainland. Over the northwest Indian Peninsula, cloudy skies are more frequent in summer, whereas clear skies are more frequent in autumn.

Significant seasonal differences are also apparent in the occurrence of cloudy skies. Summer and autumn contribute most to the annual occurrence of cloudy skies. In summer,

areas of maximum cloud cover are located over southwest China, the Indian Peninsula, the Indochina Peninsula, the Bay of Bengal, and the South China Sea, accounting for 20%–25% of the total annual cloud cover. In autumn, the Sichuan Basin, northeast parts of southwest China, and tropical areas south of 15°N exhibit maximum cloud cover. Winter cloud cover contributes little to the total annual cloud cover over northeast and northern China, the Mongolian Plateau, the Tibetan Plateau, the Indian Peninsula, the Indochina Peninsula, and the northern Bangladesh Gulf.

4.2. Seasonal Variations in the Occurrence of Single-Layer Clouds. Seasonal variations in the occurrence of single-layer clouds are shown in Figure 7. The occurrence of seasonal single-layer clouds was calculated as the ratio of single-layer cloud samples in each season to the total number of single-layer cloud samples throughout the year. The occurrence of single-layer clouds in the same season is demonstrated by the ratio of single-layer cloud samples in each season to the total sample number in the same period (Figure 8), reflecting the contribution of single-layer clouds to the occurrence of total clouds in that season.

Over northwest and southern China, seasonal variations in single-layer clouds are not significant. Over the Mongolian Plateau, the Indian Peninsula, and the Bay of Bengal, single-layer clouds are most frequent in summer, especially over northern parts of the Indian Peninsula, where the occurrence of single-layer clouds exceeds 40%. Single-layer clouds are less frequent over these areas in winter.

In spring and summer, mainland China south of 35°N is dominated by single-layer clouds. In autumn and winter, single-layer clouds are less frequent over the Yellow Sea than during the rest of the year. Over the Sichuan Basin and eastern parts of southwest China, single-layer clouds account for more than 70% of total cloud occurrence. Single-layer clouds over the Mongolian Plateau are less frequent than multilayer

FIGURE 6: Horizontal distribution of cloud-free and cloudy sky occurrence in different seasons (MAM, JJA, SON, and DJF), %.

clouds, especially in winter, when the contribution of single-layer clouds to total cloud cover is less than 30%. Over the Tibetan Plateau, single-layer clouds are most common in spring and summer, while multilayer clouds are more common in fall and winter. In summer, single-layer clouds are slightly more frequent than multilayer clouds over the Indian Peninsula, while multilayer clouds are more frequent during the rest of the year. In winter, for example, the contribution of single-layer clouds to total cloud cover is less than 20% over central areas of the Indian Peninsula. Single-layer clouds dominate oceanic areas for most of the year, accounting for more than 70% of the total cloud cover, especially in spring over the South China Sea and east of the Philippines and in winter over the East China Sea. In summer, single-layer clouds over the ocean east of the Ryukyu Islands are slightly less frequent than multilayer clouds.

The occurrence of single-layer clouds at different heights in each season is the ratio of high-, mid-, and low-level clouds to single-layer clouds throughout the year. The ratio shows the contribution of clouds at different heights to annual single-layer cloud cover (Figure 9). Most of the areas studied are dominated by single-layer high-level cloud cover all year round. However, high-level cloud is rare over the northeast Yunnan–Kweichow Plateau in autumn and over southern and northeast China and adjacent waters in winter. In spring and summer, high-level cloud accounts for a large proportion of total cloud cover over the Tibetan Plateau, exceeding 30% in some places. The factors that lead to high-level cloud occurrence over the Tibetan Plateau in summer include the effects

of topography, irradiation, and heat source. In summer, the air around the Tibetan Plateau is converged to the plateau as a heat source and makes convective activities at Tibetan Plateau violent. Meanwhile, affected by the Asian summer monsoon, the vapor of the Tibetan Plateau is relatively humid in summer. All of the factors above collectively enforce larger occurrence of the clouds over the Tibetan Plateau in summer [13]. High-level cloud in summer accounts for over 25% of cloud cover over eastern parts of the South China Sea, the Indian Peninsula, and the Bay of Bengal. The single-layer middle-level cloud appears in mainland China around whole year. Blocked by plateau, the water vapor in the Bay of Bengal meets the cold air over the southwest China and causes relative humidity in southwest China to be relatively higher in autumn and winter. Also, the occurrence of local stable single-layer middle-level cloud is larger. As a result of the topographic influence of the Tibetan Plateau, single-layer mid-level clouds appear during most of the year over mainland China. Over southwestern regions of China, there is high occurrence of mid-level clouds in autumn and winter. Over oceanic regions south of 20°N, the occurrence of single-layer mid-level clouds is less frequent than other single-layer clouds at different heights in each season. Single-layer low-level cloud occurs more frequently over the ocean than over land. This is particularly true in winter, when single-layer low-level cloud is more frequent over northern parts of the South China Sea, Yellow Sea, and Sea of Japan. This is closely related to the conditions for the upward transportation of

FIGURE 7: Seasonal variations in the distribution of single-layer cloud occurrence in different seasons (MAM, JJA, SON, and DJF), %.

water vapor provided by the sea surface in winter, especially low atmospheric unstable stratification of Japan Sea [29].

Single-layer high-level cloud is the most common cloud type in different regions and different seasons. Conversely, single-layer low-level cloud is rarely seen, especially in summer. This may be caused by the frequent convective activities of the Asian monsoon areas in summer mainly formed by multilayer cloud and high-level cloud [29]. Single-layer mid-level clouds occur more frequently over southwest China than high- and low-level clouds. However, low-level cloud is more common over northern parts of the South China Sea, Yellow Sea, and Sea of Japan, and the occurrence of clouds at night is similar to that during the day. Conversely, over northern parts of the Indian Peninsula, high-level cloud occurs more frequently at night than during the day.

5. Conclusion

In this study, the CALIOP 1km cloud layer data products from June 2006 to May 2016 were used to analyze the occurrence of clouds over China and surrounding areas. The occurrence of single-layer cloud at different heights in different regions and seasons was compared and analyzed, leading to the following conclusions.

(1) Taking 35°N as a boundary, the occurrence of cloud over southern China is greater than over the north. Clouds occur most frequently in the Sichuan Basin, north-east Yunnan-Kweichow Plateau, and tropical regions over 0°N–10°N, 90°E–120°E. Throughout the year, few clouds are found over the Mongolian Plateau. The occurrence of single-layer clouds is greater than 60% in the Sichuan Basin, eastern

FIGURE 8: Contribution of single-layer clouds to total cloud occurrence in different seasons (MAM, JJA, SON, and DJF), %.

regions of southwest China, and eastern regions of the East China Sea. In South Asia, single-layer clouds are less frequent than multilayer clouds, especially over the northwest Indian Peninsula, where single-layer clouds account for less than 30% of cloud cover. Total cloud amount and single-layer cloud over the Tibetan Plateau in the day are slightly higher than at night, whereas other regions exhibit little difference between day and night.

(2) Single-layer high-level clouds occur most frequently, followed by mid-level, with low-level clouds being the least frequent. Topographic effects influence the probability of high-level cloud cover over the majority of the Tibetan Plateau, where 90% of cloud base heights are greater than 6 km. Mid-level clouds are common over southern China, where the frequency in southwest regions is greater than

60%. While northern regions of the Western Pacific Ocean are often covered with low-level cloud, the occurrence of single-layer low-level cloud is only 40%–50%. In contrast to other regions, the occurrence of single-layer mid-level cloud is slightly higher during the day than at night.

(3) The occurrence of clear-sky conditions north of 35°N over China is greater than that south of 35°N. Cloud occurrence in summer and autumn is generally greater than in spring and winter. Single-layer clouds are less frequent than multilayer clouds over the Mongolian Plateau and the northern Indian Peninsula, especially in winter. Single-layer clouds are more frequent in eastern regions of southwest China all year round. The Tibetan Plateau has a greater frequency of single-layer clouds in spring and summer and more multilayer clouds in autumn and winter.

FIGURE 9: Distribution of single-layer cloud occurrence at different heights (high, middle, low) over China and surrounding areas in different seasons (MAM, JJA, SON, and DJF), %. The shaded part indicates that the surface elevation is above 3.1 km (680 hpa).

Single-layer clouds dominate oceanic areas all year round, especially over the South China Sea in spring, the eastern part of the Philippines, and the East China Sea in winter, where they account for more than 70% of the total cloud amount.

(4) Persistent single-layer high-level clouds are apparent within most study areas. The complex topography of the Tibetan Plateau, combined with strong convective activity in summer, means that high-level cloud occurs more frequently (>35% in some areas) in summer than in other seasons. In addition, persistent single-layer mid-level clouds are apparent over the Chinese mainland and Tibetan Plateau, with more frequent occurrence over southwest China in autumn and winter. Single-layer low-level clouds are more frequent over sea than over land, especially in northern parts of the

South China Sea, the Yellow Sea, and the Sea of Japan. The distribution of single-layer clouds at different heights at night is the same as that during the day. The occurrence of high-level clouds at night in northern parts of the Indian Peninsula is slightly higher than during the day.

Regional and seasonal differences in the occurrence of clouds at different heights are apparent. The radiative transfer model is useful for understanding the nature of their radiation. Future research will consist of in-depth analyses of the impact of CVS on the atmospheric radiation balance.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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