SPATIAL AND TEMPORAL DISTRIBUTION OF THE CLOUD HEIGHT AND CLOUD THICKNESS OVER CHINA AND THE ADJACENT AREAS BASED ON CALIOP

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Based on CALIOP data, spatial and temporal distribution of cloud height and thickness over China as well as the adjacent areas have been analysed in this paper. The results show significant regional differences. The heights of clouds that lie to the south of 27.6 °N are greater than those to the north of 27.6 °N. The highest and thickest clouds are located above the Bay of Bengal and the Western Pacific, while the lowest values distribute in the northwest of the Tibetan Plateau and Sichuan Basin. The clouds ranging from 0.3 km to 0.6 km thickness account for a large proportion of total clouds. And the probability of occurrence of clouds decreases as cloud thickness increases. Overall, within the area under study, the thick clouds are higher than the thin clouds. Besides, low and thin clouds occur more frequently than high and thick clouds. As for their seasonal variation, the height of clouds peaks in summer. In addition, the mean of cloud thickness to the south of 27.6 °N is 2.4 km thicker in summer than in any other season.

1. INTRODUCTION

The energy distribution of the earth-atmosphere system is regulated and influenced by cloud radiation. When covered by clouds, the earth's albedo is twice as high as that under clear-sky conditions (Ramanathan et al., 1989; Curry et al., 1996). This effect is closely related to the microphysical properties, macroscopic properties, and optical properties of the cloud (Charlson et al., 1987; Albrecht et al., 1988; Kiehl, 1994).In the analysis of cloud radiation characteristics, CVS (Cloud Vertical Structure) has been receiving much attention. Its essential components, namely, Cloud height (incl. Cloud Top Height, CTH, and Cloud Base Height, CBH) and thickness, are also significant for the study (Wang et al., 2000).

On the premise of considering the cloud as a uniform single layer, some studies have discussed the distribution characteristics of cloud amount and types, as well as their effects on the radiation balance of the earth-atmosphere system based on data detected via traditional methods. (Wang et al., 1998; Rossow et al., 1999; Chen et al., 2000; Warren et al., 2007).There are also preliminary studies that analyze the characteristics of the CVS distribution. (Wang et al., 2000; Mace et al., 2009; Bourgeois et al., 2016; Yan, 2016). However, studies have shown that multi-layer clouds (N>1) play a vital role in the radiation balance of the earth-atmosphere system when clouds overlap. (Stephens et al., 2004; Huang et al., 2006; Pan et al., 2015). Therefore, in order to obtain more accurate distribution characteristics of CVS, this paper analyses the distribution characteristics and variation laws of single-layer and multi-layer clouds at different heights in China and the adjacent areas during the past ten years by using satellite data, which may provide references for climate change research.

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2. DATA AND METHODS

This paper selects China and the adjacent areas (0°N~55°N, 70°E~140°E) as research subjects, and divides the areas into 1.2°×1.2° latitude and longitude grids according to the coverage of CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations) orbits (Figure 1). Using the 1km horizontal resolution cloud product of CALIPSO (CAL_LID_L2_01kmCLay-Standard-V4-10) from June 2006 to May 2016, the height and thickness distribution characteristics of different level in the areas under study were analysed.

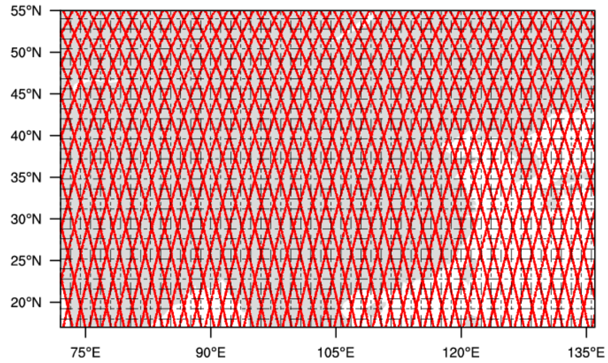

Figure 1. Track coverage of CLIPSO satellites over China and the adjacent areas within one year

In this study, the height of clouds is the relative height after subtracting the DEM_Surface_Elevation.

3. RESULTS

3.1 Horizontal Distribution of Cloud Height and Cloud Thickness

3.1.1 Horizontal Distribution of CTH and CBH: There is a significant regional difference between CTH and CBH in different level of clouds. Based on the detection method of CALIOP, the first layer contains the single layer clouds, the upper layer clouds of the double-layer clouds and the top layer clouds of the three-layer clouds.

With 27.6°N as the boundary, the CTH is over 9km to the south of 27.6°N. In the Bay of Bengal, the Indochina Peninsula and parts of the Malay Peninsula, the CTH of the first layer clouds can be as high as 14km. 27.6°N~36°N, in Tibetan Plateau with an altitude over 3.1km, the CTH in the western part of the plateau is 3~4km, which is 1~2km lower than the eastern part of the plateau.

At the same latitude, in the eastern part of China, in the eastern seas and in the Tarim Basin, the CTH of the first level clouds is 7~8 km. To the north of 46.8°N, the CTH of the Mongolian Plateau is about 6km (Figure 2).

As shown in Figure 2b, the CBH distribution characteristics of the first layer of clouds are consistent with CTH. In the low latitude tropics to the south of 27.6°N, CBH is more than 10km, except for the northern part of the Indian Ocean, and the Tibetan Plateau is less than 4km. The CBH in the Sichuan Basin and its surrounding areas are lower than that in the eastern part of China. The variation range of the Mongolian plateau CBH is 3~6km.

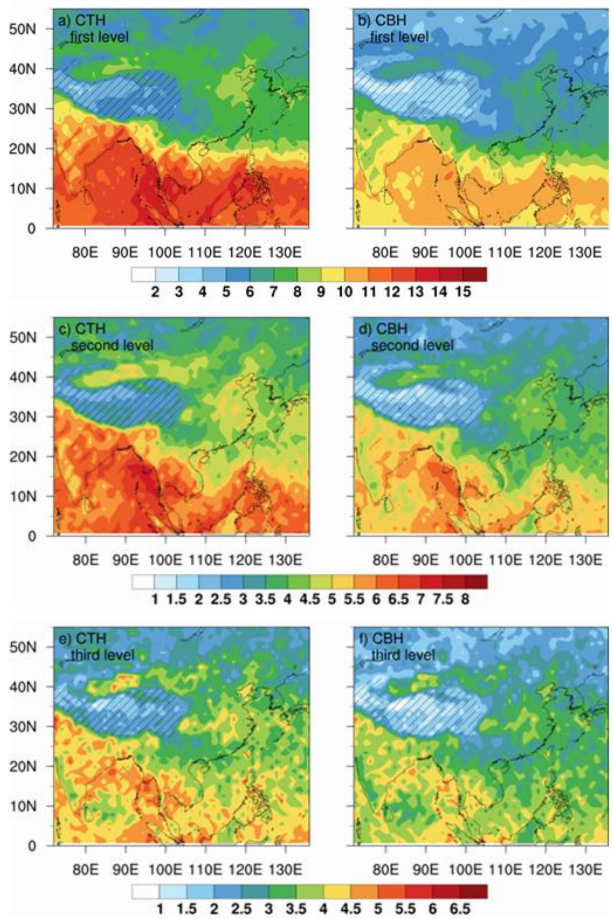

Figure 2. Horizontal distribution of CTH (a, c, e) and CBH(b, d, f) in different levels (first, second, third) of clouds. The shaded part indicates that the surface elevation is above 3.1km (680hPa)

The second layer of clouds consist of multi-layered clouds, including the upper layer cloud of the double-layered cloud and the middle layer cloud of the three-layered cloud. The horizontal distribution of the CTH and the CBH is similar to that of the first layer cloud (see Figures 2c and 2d).Values of cloud height are large in the area south of 27.6 °N. The CTH and CBH in the eastern region are lower than that in the west. The CTH and CBH are 6~7.5km and 5~6.5km in the Indian Peninsula and the Bay of Bengal, respectively. At the same latitude, CTH and CBH in the South China Sea and the western North Pacific are 4.5~6.5km and 4~6km, respectively. The Tibetan Plateau is still a low-value area of CTH and CBH. The CTH in the southern part of the Tibetan Plateau is no more than 3.5km, and CBH of the corresponding area is no more than 2.5km. The CTH in Southwest China is 4.5km and CBH is 3.5km. In other parts of central and eastern continents of China, CTH and CBH differ from the eastern sea by 0.5 to 1 km. The CTH and CBH of the Mongolian Plateau are about 1.5 km lower than the Tarim Basin and part of the region to the east of the Tarim Basin.

Since the probability of occurrence of clouds with four or more layers is less than 1%, the bottom layer of a three-layer cloud is the main component of the third layer of clouds. As shown in Fig. 2e, with a boundary of 106 °E, the CTH is above 4km in the low-latitude region to the west of 106 °E, and in a few areas it can reach 6km. 27.6 °N~36 °N, the CTH of the Tibetan Plateau is nearly 2km lower than the mainland China and the sea in the east. At the same time, there is a 1.5km difference between the Tarim Basin and the Mongolian Plateau. In the southeastern part of the Bay of Bengal and near the Malay Peninsula, the third layer of clouds has the largest CBH, and the Tibetan Plateau and the Mongolian Plateau have the smallest values. In the rest of the area under study, the CBH of the third layer of clouds varied from 2.5 to 4 km (Fig. 2f).

The cloud top pressure in the Tibetan Plateau and the Mongolian Plateau is less than 440hPa, and the altitude is above 7km, both of which are dominated by single-layer high clouds (Cai et al., 2017). Therefore, in this study, the characteristics of the relative heights of the clouds are smaller than those of other regions.

3.1.2 Horizontal Distribution of Cloud Thickness: Overall, the cloud thickness varies from 0.3km to 3.6km, with the range of 1.5~1.8km accounting for 37%, which concentrates in the area north of 27.6 °N, especially the main body of the Tibetan Plateau, the Tarim Basin and the Mongolian Plateau. The clouds thickness in the western part of the Tibet Plateau, the Sichuan Basin and the East China Sea is 1.2 to 1.5 km, and the PDF (Probability Density Function) is 21%. The thickness of the clouds between 2.1 and 2.4km accounts for 12%, mainly in the low-latitude region to the south of 27.6 °N.

In order to further analyse the regional characteristics of cloud height and thickness over China and the adjacent areas, this paper divides the research areas into six sub-regions according to the characteristics of CTH and CBH distribution in different regions. As shown in Figure 4, they areArea1(0 °N~27.6 °N, 70 °E~140 °E),Area2(27.6 °N~36 °N,70 °E~108 °E),Area3(36 °N~46.8 °N, 70 °E~140 °E), Area4(27.6 °N~46.8 °N,106.8 °E~122.4 °E), Area5(27.6 °N~46.8 °N, 122.4 °E~140 °E), Area6(46.8 °N~55 °N, 70 °E~140 °E).

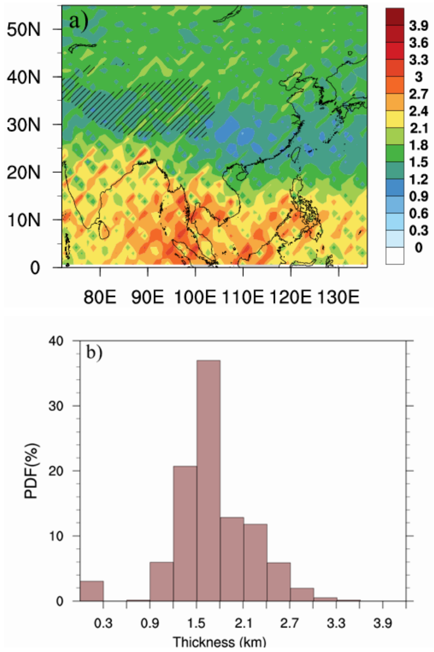

Figure 3. Horizontal distribution (a) and PDF (b) of the cloud thickness over China and the adjacent areas. The shaded part indicates that the surface elevation is above 3.1km (680hPa)

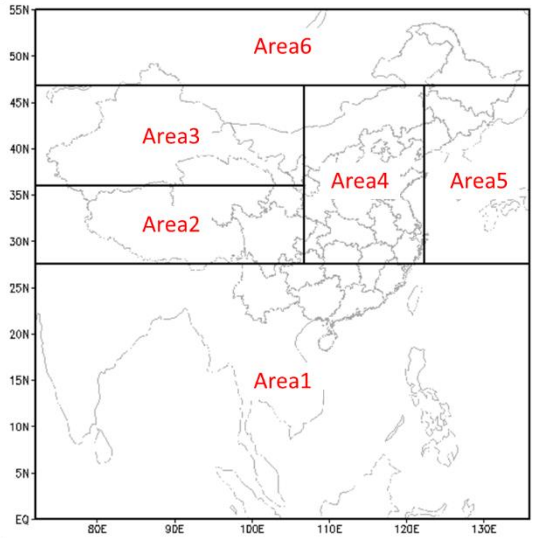

Figure 4. Six sub-areas of China and the adjacent areas.

According to the horizontal distribution of the cloud thickness in the area under study, the cloud thickness of 0.3~0.6km has the highest probability of occurrence in the six regions, with more than 25%, except for Area1 and Area6, and even more than 30% in Area2 and Area5. In Area1, Area5, and especially Area6, the cloud with a thickness below 0.3km is a little more than the cloud with a thickness of 0.6~0.9km. At the same time, the cloud with thickness of 0.6~0.9km in Area2 and Area3 contributes more to the total sample size of each region than cloud with thickness below 0.3km. As for the cloud with thickness above 0.6km, the probability of occurrence decreases as thickness increases. Except for Area1, the probability of cloud thickness of 3.3~3.6km is less than 1%in other areas (Figure 5).

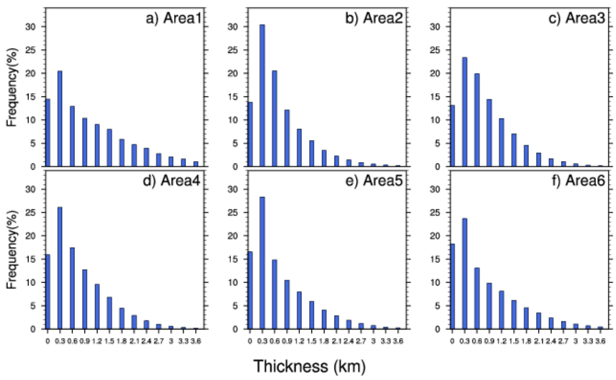

Figure 5. The probability of occurrence of clouds of different thicknesses in sub-regions (Area1, Area2, Area3, Area4, Area5, Area6) of China and the adjacent areas, %.

3.1.3 Relationship between Cloud Height and Cloud Thickness: By calculating the joint probability density of cloud height and thickness, their corresponding relationship in different regions is discussed (Fig. 6). Within the areas under study, the thick clouds are higher than the thin clouds, and low and thin clouds occur more frequently than high and thick clouds.

In Area1, the CTH with a high probability density is no more than 3km and the thickness is less than 1.5km. High and thick clouds have a maximum probability density of 5%. There are about 4% of the CTH in the 13~16km and the thickness is 4km. There are also some clouds in between, with a probability of around 5%. The clouds in Area2 are relatively higher and the thickness also increases, but the highest CTH does not exceed 12km. In Area 3, the CTH with a high probability density is 2 to 4 km, and the clouds are very thin. As for Area 4, the height and thickness of the clouds below 8 km vary uniformly. Compared with Area1，the clouds of Area5 are lower and thinner. The low and thin clouds in 1~3km have a higher probability of occurrence in Area5. This may be due to the stronger deep convection development in the Indian region than in eastern China.(Luo et al., 2009). For another, the clouds of Area6 are not much different from Area2. But, it is lower and thinner than the low clouds of Area1, and the high clouds are taller and thicker. This may be due to the relatively abundant water vapor and more convective activities in the Tibetan Plateau. Meanwhile, the troposphere of the Mongolian plateau has a high stability, which is not conducive to ascending motion and is prone to low clouds (Wang et al., 2011).

The distribution characteristics of CTH and CBH in each layer in China and the adjacent areas are as follows: the top layer of three-layer clouds is the highest; the top layer of double-layer clouds is the second; and the bottom layer of double-layer clouds and three-layer clouds is the lowest. At the same time, there are obvious regional differences in the height of single-layer clouds and three-layer clouds. In Area1 and Area3, the single-layer clouds are higher than the mid-layer of three-layer clouds, which are opposite to Area2, Area5, and Area6. In Area4, though the CTH of single-layer clouds is higher than the three-layer clouds, the CBH is similar. Meanwhile, the single-layer clouds are the thickest, and the bottom layer of three-layer clouds is the thinnest.

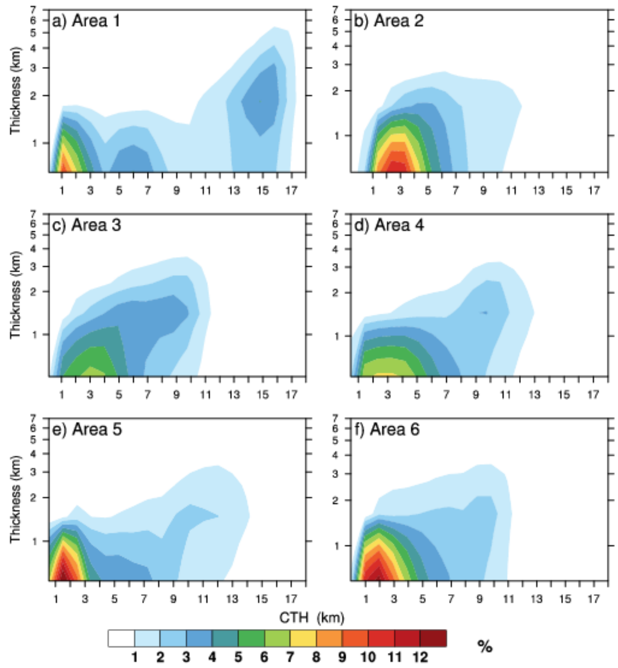

Figure 6. Joint probability density distribution of cloud thickness and CTH in sub-regions of China and the adjacent areas.

In summary, the cloud of Area1 is higher than other areas, and Area5 comes second, while Area6 is the lowest. The clouds develop higher in the low-latitude Area1 than mid-latitude Area5, and the clouds in the high-latitude plateau Area6 are lower than in the mid-latitude Area2. The single-layer clouds in each region are lower, but thicker, than the upper clouds of the three-layer and double-layer clouds.

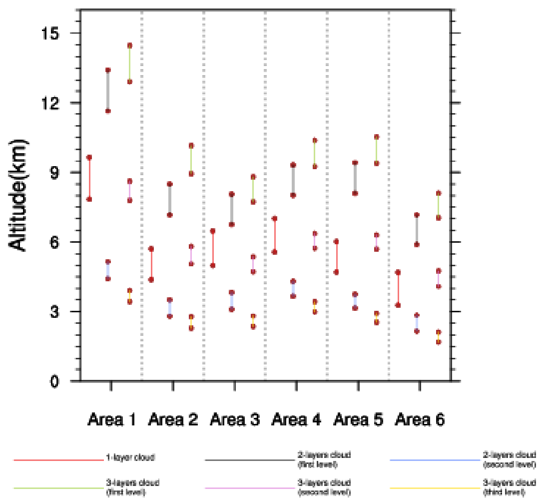

Figure 7. The height of different levels (first, second, third) clouds in sub-regions over China and the adjacent areas, km.

3.2 Seasonal Variations in Cloud Height and Cloud Thickness

3.2.1 Seasonal Variations in CTH and CBH: The distribution characteristics of CTH and CBH in different layers are basically the same as their horizontal distribution, but the seasonal variations are obvious (Figure 8 and Figure 9). Summer has the highest cloud height, followed by spring, autumn and winter. In summer, the CTH of the uppermost clouds in the area south of the Tibetan Plateau is above 11km, and the CBH is no less than 9km. The CTH and CBH in the eastern coastal areas of China are 8~10km and 6~9km, respectively. In the majority of other regions, CTH also exceeds 6km and CBH exceeds 5km. The CTH and CBH of the uppermost cloud of the Tibetan Plateau are 3~6km and 3~5km. In spring, the CTH of the first layer of clouds in the east of the Tarim Basin increases, while CTH of the remaining areas decreases by 1 to 2 km. The CBH changes are small. In autumn and winter, the CTH of the first layer of clouds does not change much in the Tibetan Plateau. In winter, the CBH of the Mongolian Plateau reduces by about 1km, and the CTH and CBH of the first level clouds in the eastern China decrease to 5km and 4km, respectively.

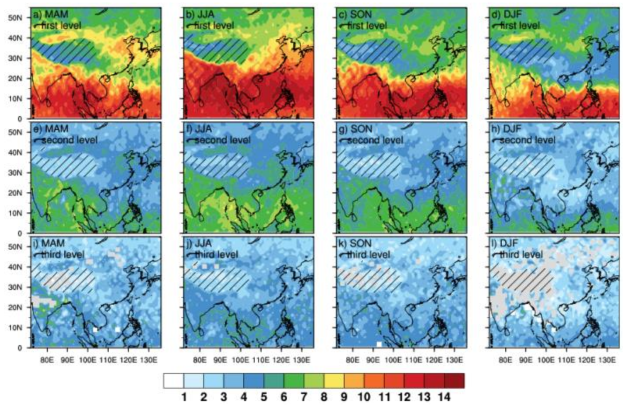

Figure 8. Distribution of CTH in different levels (first, second, third) over China and the adjacent areas in different seasons (MAM, JJA, SON, and DJF), km. The shaded part indicates that the surface elevation is above 3.1km (680hPa)

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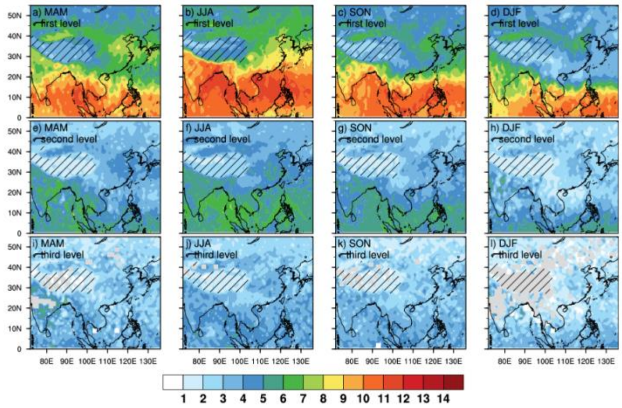

Figure 9. Seasonal Distribution of CBH in each level (first, second, third) over China and the adjacent areas in different seasons (MAM, JJA, SON, and DJF), km. The shaded part indicates that the surface elevation is above 3.1km (680hPa)

3.2.2 Seasonal Variation of Cloud Thickness: As shown in Fig. 10, the seasonal variation of cloud thickness is very prominent. In the low-latitude region to the south of 27.6°N, the clouds are the thickest in summer, exceeding 2.4km. In fall, the cloud thickness in the northern part of the Bay of Bengal and the Indian Peninsula decreases slightly. In winter, only in the tropics of 0°N~10°N, the cloud thickness is above 2.4km. The clouds in southern Tibetan Plateau during summer and those in northern Tibetan Plateau during spring are the thickest. The thinnest clouds can be found in the eastern and central parts of mainland China and the eastern sea. On the contrary, the cloud thickness in spring and winter in the east of Tarim Basin and Mongolian Plateau area exceeds 1.6km, and even 2.4km in some areas, and decreases in autumn. The thinnest cloud occurs in summer, mainly varying from 1.2km to 1.6km.

3.2.3 Seasonal Variation in the Relationship between Cloud Height and Cloud Thickness: In the area under study, the relationship between cloud height and thickness of single-layer clouds and multi-layer clouds in different regions and seasons is shown as follows (see Figure 11). In general, the seasonal variations of CTH and CBH in different levels in each region are basically the highest in summer and the lowest in winter. In winter, the cloud height of Area2 is significantly higher than that of the other three seasons. It is worth mentioning that, the CTH and CBH of single-layer clouds, and CTH of double-layer clouds, are higher in spring than in summer. In Area4, the CTH of the third layer of three-layer clouds is higher in winter than in summer.

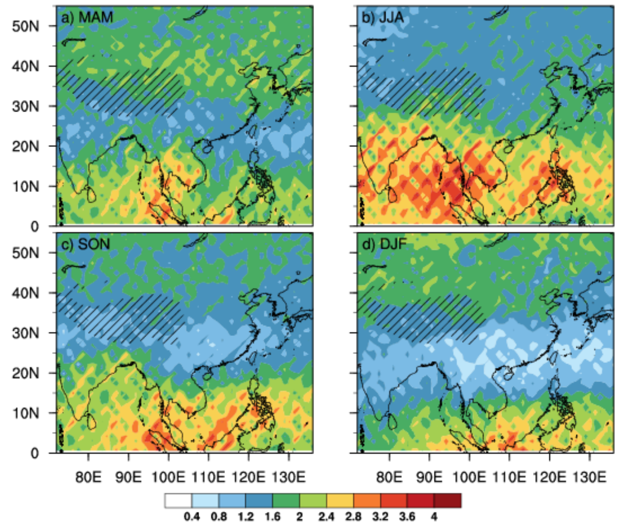

Figure 10. Distribution of cloud thickness in different seasons (MAM, JJA, SON, and DJF), km. The shaded part indicates that the surface elevation is above 3.1km (680hPa)

In summer, the single-layer cloud is the highest in Area1, with CTH and CBH of 11.5km and 9km, respectively, and the lowest in Area6. The heights of single-layer clouds in Area4, Area5, Area2, and Area3 sequentially reduce. In winter, Area5 is the lowest and Area1 is the highest, but Area6 has the thickest single-layer clouds.

For double-layer clouds, the first layer is still the highest in Area1 during summer, with CTH exceeding 14km and CBH of 12km. In Area3 and Area4, CTH is 8km and 7.7km, respectively. Cloud heights in other regions are within these values, and are the lowest in Area2 during winter, with CTH of 6.5km and CBH of 5.5km, respectively. For the first level of three-layer clouds, the cloud height in Area1 exceeds 12km in summer, and CTH is 12km and CBH is 11.5km in winter. In Area2, the cloud height is significantly lower in winter than in other seasons, as CTH is only 5km and CBH is 4.5km in winter. The mid-level of three-layer clouds, the second level of double-layer clouds, and the third level of three-layer clouds successively decrease in each season. In addition to single-layer clouds, cloud thickness of each region also decreases slightly as cloud height decreases in different seasons.

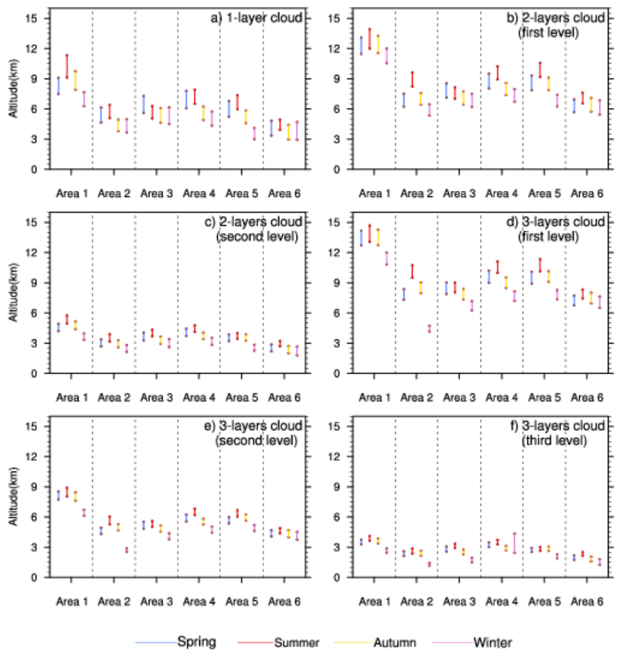

Figure 11. The height of different levels (the first, second and third) clouds in different seasons (MAM, JJA, SON, and DJF) in sub-regions over China and the adjacent areas, km.

4. CONCLUSIONS

Based on CALIOP data, spatial and temporal distribution of cloud height and thickness over China as well as the adjacent areas have been analysed in this paper. According to the characteristics of CTH and CBH distribution in different regions, the research scope has been divided into six sub-regions. By discussing the horizontal distribution and seasonal variations of cloud height and cloud thickness in different regions, we have a more detailed understanding of CSV in China and the adjacent areas. The analysis results are as follows:

(1) There is a clear regional difference between CTH and CBH in different levels of clouds.The heights of clouds that lie to the south of 27.6 °N are greater than those to the north of 27.6 °N. The highest and thickest clouds are located on the Bay of Bengal and the Western Pacific, as the CTH and CBH of the first layer clouds can be as high as 14km and 11km, respectively. The CTH in the western part of the Tibetan Plateau is 3~4km, while the CBH is less than 3km. Values of cloud heights in the southwest region, the southeast part of China's mainland, and over the eastern seas are similar to that in the Tarim Basin, but all in the middle of high and low limits. The cloud height in the Mongolian Plateau is lower than that in the Tarim Basin and its eastern regions. Compared with the first level clouds, the second level clouds and the third level clouds have the same distribution characteristics, but the height changes prominently.

(2) Overall, the cloud thickness varies from 0.3km to 3.6km. Among them, the range of 1.5~1.8km accounts for 37% of the total. The thickness of the clouds in the western part of the Tibet Plateau, the Sichuan Basin and the East China Sea is 1.2 to 1.5 km, and the PDF is 21%. The thickness of the clouds between 2.1 and 2.4km accounts for 12%, mainly in the low-latitude area to the south of 27.6 °N.

(3) The distribution characteristics of CTH and CBH in different layers are basically the same as their horizontal distribution, but the seasonal variations are obvious. Summer has the highest cloud height, followed by spring, autumn and winter. The seasonal variation of cloud thickness is very prominent. The clouds in the east of the Tarim Basin and the Mongolian Plateau are thicker in spring and winter, and the thinnest in summer.In addition, the cloud thickness in area to the south of 27.6 °N is more than 2.4 km in summer.

(4) The cloud in Area1 is highest overall, followed by Area5, and Area6 is the lowest. The clouds develop higher in the low-latitude Area1 than mid-latitude Area5, and the clouds in the high-latitude plateau Area6 are lower than in the mid-latitude Area2. Overall, the seasonal variations of CTH and CBH in different levels in each region are basically the highest in summer and the lowest in winter. Overall, within the area understudy, the thick clouds are higher than the thin clouds, and low and thin clouds occur more frequently than high and thick clouds. Nevertheless, single-layer clouds are both lower and thicker than the first layer of three-layer clouds and the upper layer of double-layer clouds.

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