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Diurnal Variations of Different Cloud Types and the Relationship between the Diurnal Variations of Clouds and Precipitation in Central and East China

Cuicui Gao^{1,2}, Yunying Li^{1,*} and Haowei Chen²

- ¹ College of Meteorology and Oceanography, National University of Defense Technology, Nanjing 211101, China; gaocc2016@foxmail.com
- ² Shaoguan Meteorological Office, Shaoguan, Guangdong 512000, China; chen_haowei@foxmail.com
- * Correspondence: ghlyy@mail.iap.ac.cn

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Abstract: In this paper, the diurnal variations of various clouds are analyzed using hourly cloud observations at weather stations in China from 1985 to 2011. In combination with merged hourly precipitation data, the relationship between the diurnal variations of clouds and precipitation in the summers from 2008 to 2011 are studied. The results show that the occurrence frequencies of total cloud and various cloud types exhibit significant diurnal variations. The diurnal variations of the occurrence frequencies of altocumulus and stratocumulus show a bimodal pattern, with peaks appearing in the early morning and late afternoon. The early morning peaks of altocumulus and stratocumulus appear earlier in the summer than in the other seasons, while the late afternoon maxima show an opposite trend. The occurrence frequency of nimbostratus peaks in the morning between 07 and 12 LST (local solar time), and the peak value lags 2 to 3 h from west to east along the Yangtze River valley; meanwhile, the diurnal variation shows no clear differences caused by changes in the latitude or seasons. Cumulus shows an afternoon (14 LST) maximum, while cumulonimbus peaks in the late afternoon during 16–20 LST, and both of them present a great diurnal range. Cirrus usually reaches its peak at 17–18 LST, and it differs by 1 to 2 h with a change in the latitude. The results of the study first show that the diurnal variations of precipitation among different regions are dominated by different clouds. The upper reaches of the Yangtze River valley present a midnight precipitation maximum that is mainly dominated by cumulonimbus. For the middle reaches of the Yangtze River valley impacted by nimbostratus, the precipitation peaks in the early morning. In South and Northeast China, the precipitation peaks in the afternoon and is determined by the diurnal variations of convective clouds. In the region between the Yangtze River valley and Yellow River valley, the precipitation peaks in the early morning and afternoon; the early morning peak is mainly determined by stratiform clouds, while the afternoon peak is closely related to convective clouds.

Keywords: clouds; precipitation; diurnal variation

1. Introduction

Diurnal variations are the most basic period of change in the Earth's climate system, the most important driving force of which is solar radiation. Various meteorological parameters, such as the temperature, wind, pressure and precipitation, all show significant diurnal variations. Rutledge noted that stratiform and convective precipitation are produced by different cloud microphysical processes [1]. The formation mechanism of precipitation is complex, but it ultimately originates from clouds. Clouds are the external manifestation of dynamic and thermodynamic processes in the atmosphere, and there are many differences in the nature of precipitation sourced from different types of clouds. The



diurnal variation of clouds reflects the changes in the internal movements throughout the atmosphere. However, the diurnal cycle of clouds also plays a feedback role in the movements of the atmosphere in addition to the radiation process and the water cycle [2]. Furthermore, the diurnal variation of clouds also reflects the atmospheric stability and changes in the weather. Therefore, studying the diurnal variation of clouds is of significance for understanding the diurnal cycle of the internal movements throughout the atmosphere. In addition, understanding the relationship between the diurnal variations of clouds and precipitation is beneficial to provide a physical basis and observe relevant facts for cloud parameterization schemes in weather and climate models, which is helpful for improving the ability to simulate weather and climate models.

Precipitation exhibits significant diurnal variation characteristics. Consequently, many scholars have carried out a great deal of research [3–9]. Yu et al. noted that the summer precipitation over contiguous China has large diurnal variations with considerable regional features [10]. Over southern inland China and northeastern China, the summer precipitation peaks in the late afternoon, while the precipitation in some regions peaks between midnight and the early hours of the morning. Zhou et al. verified the above results by comparing satellite to rain gauge observations, showing that the diurnal phase of rainfall frequency and intensity were similar to those of the rainfall amount in southern China [11]. A study by Li et al. showed the clear differences in the diurnal cycle of precipitation between southwestern China and southeastern China [12]. The diurnal cycle of the annual mean precipitation in southwestern China tends to reach a maximum either at midnight or during the early morning, while the precipitation in eastern China peaks in the late afternoon. Yuan et al. analyzed the sub-seasonal characteristics of the diurnal variation of summer monsoon rainfall over eastern central China and found that the early-morning diurnal peaks experience sub-seasonal movements similar to those of the monsoon rain belt [13]. The aforementioned scholars have obtained many meaningful conclusions about the diurnal variation of precipitation. Moreover, since precipitation originates from clouds, the diurnal variation of precipitation is closely related to the diurnal variations of different types of clouds, and therefore, studying the relationships between the diurnal variations of clouds and precipitation could be helpful for further understanding the mechanism of precipitation.

William et al. presents observational evidence in support of the existence of a large diurnal cycle of oceanic, tropical, deep cumulus convections [14]. Zheng et al. used satellite infrared temperature of black body (TBB) data to explore the climatological characteristics of deep convection over southern China and the adjacent seas during the June-August periods of 1966–2007 [15]. They found that sea-land and mountain-valley breezes accounted for the propagation of deep convection from sea to land in the afternoon and from land to sea after midnight. Based on hourly infrared brightness temperature data acquired by the FY-2C satellite to classify clouds into cold clouds, middle clouds and warm clouds according to the cloud top temperature, Chen et al. analyzed the diurnal variations of three types of clouds in southern China during the summer periods from 2005 to 2008 and the seasonal changes in the diurnal variations of those clouds [16]. Fujinami et al. studied the diurnal variations of high clouds and precipitation over the Tibetan Plateau, where observation stations are sparse, using satellite observations. He noted that the cloud cover frequency for high clouds increased in the afternoon along the ridges and reached a maximum near 18 LST, after which high cloud cover frequencies moved over the valley and persisted until early morning [17]. In addition, a similar evolution occurred in the frequency of rainfall. Zhao et al. based on MODIS observations, showed the statistical characteristics of cloud properties, along with the difference between morning and afternoon [18]. These conclusions have promoted the understanding of the diurnal variations of clouds; however, the corresponding research is relatively fragmented, and the relationship between the diurnal variations of clouds and precipitation has not yet been established. Therefore, this paper aims to analyze the climatic characteristics of the diurnal changes of clouds over China in addition to the relationship between the diurnal variations of clouds and precipitation to deepen the existing understanding of the correlation between clouds and precipitation and to provide the basis for a simulation of the diurnal variations of clouds and precipitation in weather and climate models.

2. Data and Analysis Method

2.1. Data

In this study, hourly cloud data during 1985–2011 are acquired from 114 surface observation stations after a quality-control procedure is performed. Since the distribution of stations to the west of 105° E is sparse, this study mainly analyzes the diurnal variations of clouds over eastern and central China. The dataset includes the information of total cloud (TC), and 10 cloud genera (cirrus (Ci), cirrocumulus (Cc), cirrostratus (Cs), altocumulus (Ac), altostratus (As), nimbostratus (Ns), stratocumulus (Sc), stratus (St), cumulus (Cu), and cumulonimbus (Cb)). Due to the light intensity and visual reasons, artificial observations on the ground will produce some random observation errors, however, many years of climatological normal results can significantly reduce the instabilities of artificial observations. In addition, the reliability of the dataset has been tested and verified [19]. From the perspective of surface observations, the diurnal variation of low clouds is relatively accurate. High clouds and middle clouds are sometimes blocked by low clouds, and the article therefore analyzes the diurnal variation of a certain type of high (middle) cloud when it appears.

Hourly merged precipitation data during 2008–2011 were obtained from the National Meteorological Information Center of the China Meteorological Administration with a spatial resolution of $0.1^{\circ} \times 0.1^{\circ}$. These hourly precipitation data were merged with more than 30,000 automatic weather stations over China in addition to global Climate Prediction Center morphing technique (CMORPH) precipitation estimates with a temporal interval of 30 min and a resolution of 8 km provided by the American Climate Prediction Center. The merged precipitation product effectively combines the advantages of surface precipitation observations with satellite retrieved precipitation products. The overall error of the product is less than 10%, which is better than the same type of product worldwide [20]. The quality of the merged precipitation products in the sparse station areas still needs improvement. However, the stations in eastern and central China studied in this paper are densely and effectively distributed, and the precipitation values are accurate since station falls during the summertime throughout most of China [21], this paper mainly analyzes the relationship between the diurnal variations of clouds and precipitation during the summer.

The diurnal variation of clouds is the average of the data from the stations from 1985 to 2011. Since the precipitation data range from 2008 to 2011, to match the precipitation data, the cloud data are truncated from 2008 to 2011, when the relationship between the diurnal variations of clouds and precipitation is analyzed.

2.2. Analysis Method

The diurnal variations of the meteorological parameters are the changes in the meteorological parameters with the local solar time (LST) [5,22]. Therefore, statistical work on the diurnal variations of clouds and precipitation should be conducted according to the local solar time. The time system for the hourly cloud data used in this paper corresponds to China Standard Time (CST), and the method used to convert CST into LST is as follows:

$$T1 = \left[\frac{\ln + 7.5}{15}\right] - 8 + T \tag{1}$$

LST =
$$\begin{cases} T1 & 0 < T1 \le 24\\ 24 + T1 & T1 \le 0\\ T1 - 24 & T1 > 24 \end{cases}$$
(2)

where lon represents the longitude of the station, and the unit of lon is degree, T denotes CST, LST is the local solar time, and [] indicates an operation to change the number into an integer.

The time system for the precipitation data used in this paper corresponds to Greenwich Mean Time (GMT), and the method used to convert GMT into LST is similar to CST, and it just don't need to subtract the time zone in the first step. The time used hereafter in this study is LST.

The occurrence frequency of a cloud is defined as $F = (rec_{cld}/rec) \times 100\%$, where F represents the occurrence frequency of a cloud at a certain time, rec_{cld} represents the number of cloud occurrences at a certain time within the analysis period, rec is the number of observations at a certain time, and the definition of the occurrence frequency is suitable for all types of cloud, including TC. The maximum occurrence frequency of a cloud from 01 to 24 LST in a day is the daily peak. The amplitude of the diurnal variation of clouds reflects the magnitude of the maximum and minimum occurrence frequency of cloud in 24 h and is defined as $A = cld_{max}/cld_{avg}$, where A is the amplitude, cld_{max} is the daily peak of the cloud occurrence frequency, and cld_{avg} is the daily occurrence frequency of the cloud. When analyzing the diurnal variation of clouds in different seasons, to eliminate the differences in the occurrence frequencies of cloud among the different seasons, this paper calculates the anomalies in the occurrence frequencies of clouds in each month from 01 to 24 LST.

3. Climatic Characteristic of Diurnal Variation of Clouds

3.1. Diurnal Variation of Different Types of Clouds

To obtain an overall understanding of the diurnal variations of the total clouds (TC) and of the various types of clouds over central and eastern China, this paper first analyzes the diurnal variations of the average occurrence frequencies of the TC and various clouds at 114 stations over central and eastern China. The diurnal variation of the frequency of TC shows a bimodal pattern; the main peak appears in the late afternoon, and the second peak appears in the early morning (Figure 1a). During the day, the occurrence frequency of the TC is significantly greater than that of nocturnal clouds. After 04 LST, the occurrence frequency of the TC increases rapidly and reaches a peak at 07 LST. The frequency of the TC changes slightly during 07–09 LST, and it begins to increase again after 09 LST and reaches the main peak at 14–15 LST. Ac also shows a diurnal variation with a bimodal pattern with peaks at 07 LST and 18 LST, and the morning peak is larger. As occurs at a frequency of less than 3.5% but at a relatively high frequency in the afternoon.



Figure 1. The diurnal variation of the occurrence frequencies (%) of various cloud types in central and east China during 1981–2011: (a) TC, Ac, As, (b) Ns, Sc, St, (c) Cu, Cb, Ci(the horizontal axis represents the local solar time, and the vertical axis represents the occurrence frequency of clouds).

The diurnal cycle of the occurrence frequency of Ns is unimodal, and it occurs at approximately 08 LST. Ns is a component of frontal clouds, which are mainly formed as deep, moist air rises along the front surface; the relative humidity of the air is larger in the morning and is saturated more easily and condensed, and thus, Ns appears more frequently in the early morning. The diurnal variation of St is consistent with that of Ns, and its diurnal peak appears at 08 LST. St, whose formation mechanism is the same as that of fog, is generally formed by fog rising. Fog usually appears during the night until

08 LST, and it especially occurs throughout most of the morning; St also shows such a pattern in the morning. The diurnal variation of the occurrence frequency of Sc presents a bimodal pattern with a main diurnal peak at 06 LST and a second peak at 17 LST. As a typical boundary layer cloud, the diurnal variation of Sc reflects the diurnal variation of the boundary layer. The low temperature in the boundary layer and the stable atmospheric stratification in the morning are beneficial for water vapor below the top of the boundary layer to accumulate and form Sc. When the atmosphere stability deteriorates, the conditions are no longer favorable to the formation of stratiform clouds and the occurrence of Sc. As the solar radiation weakens in the evening and the atmosphere stratification tends to become stable, the frequency of Sc starts to increase again and reaches the second peak at approximately 19 LST.

The diurnal variation of Cu is also unimodal (Figure 1c). During the daytime, as the solar radiation gradually enhances, the atmosphere temperature around and above the ground surface gradually rises while the instability of the atmospheric stratification increases, and thus, the occurrence frequency of Cu begins to increase beginning in the early morning and reaches a peak at 14 LST, after which it decreases. The diurnal variation of the occurrence frequency of Cb shows a unimodal pattern as well. The occurrence frequency of Cb is high at 16–20 LST, and its main diurnal peak appears at 16–17 LST, which is 4–6 h behind the time when Cu reaches its diurnal peak, indicating that it takes some time for shallow convection clouds to develop into deep clouds. The frequency of Ci increases from 04 to 05 LST continuously, and it reaches a maximum at 17 LST, after which it rapidly decreases after 18 LST. Sometimes, Ci acts as an anvil to the development of Cb to a mature stage, and thus, there is a lag in the time required for Cu, Cb to Ci to reach their diurnal peaks.

Figure 2 shows the times of the diurnal peaks of different clouds and the spatial distribution of the amplitudes of their diurnal variations over central and eastern China. The figure shows the time when the occurrence frequency peaks at each station in the form of a clock, and the number indicates the amplitude of the diurnal variation of the cloud occurrence frequency. Figure 2a shows that the diurnal peak of the TC appears from the afternoon to the late afternoon, but it appears in the early morning at some stations. For example, at most of the stations to the north of 32° N in China, the diurnal peak appears at 15–18 LST; meanwhile, over the Liaodong Peninsula and Shandong Peninsula, the diurnal peak appears a little earlier at 13–14 LST. However, to the south of 32° N, the diurnal peak appears in two periods at 14–18 LST and 06–07 LST. For instance, the diurnal peak of the TC in the southeastern coastal areas of China mainly occurs in the early morning at 06–07 LST. The amplitude of the occurrence frequency of the TC is large in northern China (approximately 1.2–1.3), while that at most stations in southern China is approximately 1.1, indicating that the diurnal variations of the occurrence frequencies of clouds in northern China are greater than those in southern China.



Figure 2. Cont.



Figure 2. Spatial distributions of the phases and amplitudes of the diurnal cycles of various clouds: (a) TC, (b) Ci, (c) Ns, (d) Sc, (e) Cu, and (f) Cb. The directions of the vectors denote the local solar time (LST) of the maximum cloud occurrence frequency (phase clock in (b)), while the length of the vectors represent the amplitude of the diurnal cycle, the reference arrow represents the amplitude of diurnal cycle is 1.0.

According to this study, the diurnal peak of Ci appears at 17–18 LST consistently at each station (Figure 2b), and the diurnal variation amplitude is larger in South China and in the Sichuan Basin.

The diurnal peak of Ns occurs in the morning (08–09 LST) (Figure 2c), but those of some stations in Shanxi Province, western Henan Province, and Hubei Province and in the Sichuan basin occur around noon (11–14 LST). The Meiyu front near the Yangtze River valley is also a frequent area of Ns formation, yet the diurnal variation amplitude of Ns in this area is small. Sc is the cloud with the highest occurrence frequency over China. Its diurnal peak over most stations occurs at 06–07 LST (Figure 2d), but those in western Inner Mongolia and North China usually occur at 18–19 LST.

The diurnal peak of Cu over all stations appears in the afternoon (12–14 LST) (Figure 2e). The diurnal variation of Cu in most areas throughout China is large, and its amplitudes are basically above 2.9, while the diurnal variation of Cu in South China is relatively small with amplitudes between 1.9 and 3.1. The frequency of Cb usually reaches a peak value at 16–20 LST (Figure 2f); however, at very few stations, the peak occurs at 02–04 LST. In addition, the diurnal variation of Cb is large with the second-largest amplitude (approximately 1.5 to 2.7) following that of Cu.

The analysis above shows that there are regional differences among the diurnal peaks of Ac and Sc that are mainly due to the frequent occurrences of both cloud types in the early morning and evening with different peak times at different stations. As Ac and Sc occur more frequently, they have a great impact on the diurnal variation of the TC occurrence frequency, and thus, the TC shows a similar diurnal changing pattern with these two types of clouds. The diurnal peak of Ns mainly appears in the morning (07–12 LST), and the time difference in the diurnal peaks between different stations does not exceed 5 h. The diurnal peak of Ci usually appears in the evening (17–18 LST) while that of Cu appears in the afternoon but shows no clear regional difference. Finally, the diurnal peak of Cb mainly appears at 16–20 LST with slight differences among different regions. The diurnal variations of Cu and Cb are both relatively enormous.

3.2. Diurnal Variation Cycles of Clouds with the Latitude and Longitude

Figure 3 shows the diurnal variations of the TC and of various cloud types with the latitude; the zonal average of 110–120° E represents the occurrence frequency of cloud types at each latitude. Figure 3a illustrates that the diurnal peak of the TC to the south of 20° N appears in the afternoon (12–15 LST), which is closely related to the diurnal variation of convective clouds. Meanwhile, the diurnal peak of the TC at 20–26° N (i.e., southern China) appears in two periods during the early morning (06–08 LST) and afternoon (11–16 LST). This is probably due to the diurnal peaks of Ac and Sc in these areas that occur in the early morning and evening and have a great impact on the diurnal variation of the TC occurrence frequency. The diurnal peak of the TC at 26–36° N appears mainly in the afternoon. The occurrence frequency of the TC to the north of 36° N increases with the latitude with a maximum at 16 LST.



Figure 3. Diurnal variation cycles of occurrence frequency (%) of clouds with the latitude averaged over 110–120° E: (**a**) TC, (**b**) Ci, (**c**) Ac, (**d**) Ns, (**e**) Sc, and (**f**) Cb (the horizontal axis is the local solar time in hours, and the vertical axis represents the latitude).

The occurrence frequency of Ci at 20–32° N over China is small, but the occurrence frequencies over Hainan Province and to the north of 32° N are large, and the frequency of the latter area increases with the latitude (Figure 3b). Moreover, there is a slight difference in the diurnal peak of Ci between the two areas. The occurrence frequency of Ci over Hainan Province is large (approximately 35%), and the peak appears at 06 LST and 18 LST. The diurnal peak of Ci to the north of 32° N occurs at 16–17 LST, and the occurrence frequency of Ci near 45° N reaches 40% at 16 LST. The occurrence frequency of Ac increases with the latitude from south to north (Figure 3c); it reaches a maximum at 28–36° N and then decreases. At 28–36° N, the diurnal peak of Ac appears at 07 LST and 18 LST, while in other areas the diurnal peak of Ac appears at approximately 08 LST, indicating that its maximum daily peak appears at a difference of 1 to 2 h with a change in the latitude.

Figure 3d shows a high occurrence frequency of Ns within 26–29° N. After 04 LST, the high value of the frequency of Ns begins to expand to the south and to the north. In addition, a frequency of 10% expands to the south to 22° N at 08 LST and to the north to 32° N at 09 LST. After 09 LST, the frequency of Ns begins to shrink, as the maximum frequency of Ns occurs at 09 LST. The diurnal peak of Ns does not change significantly with the latitude. The diurnal peak of Sc occurs in two periods during the early morning (approximately 06 LST) and the late afternoon (18–19 LST) (Figure 3e). The diurnal peak of Sc over Hainan Province appears at 05 LST and 18 LST while that at 20–28° N over China occurs at 06 LST and 19 LST. Moreover, the diurnal peak of Sc at 18–25° N lags behind by approximately 1 h. The diurnal peak of Cb over Hainan Province is reached at 09 LST while that of Cb to the north of 20° N mainly occurs in the period of 16–20 LST, and its appearance time lags behind with the latitude (Figure 3f). There is no difference in the diurnal peak of Cu with the latitude, as it consistently occurs at 13–14 LST (figure omitted).

The diurnal variation cycles of clouds with the longitude are not as clear as that with the latitude. Ns shows clear zonal difference over the Yangtze River valley and its south side, where the occurrence frequency of Ns is the largest. In the upper reaches of the Yangtze River, the diurnal peak of Ns occurs at 06–09 LST, while the diurnal peaks over the middle and lower reaches of the Yangtze River appear at 07–13 LST (Figure 4a). The occurrence frequency of Cu is the largest in south China. And the diurnal variation of the occurrence frequency of Cu does not change with the longitude (Figure 4b) in south China. The peak occurrence frequency appears in the afternoon (13–14 LST); however, at 22–26° N, the frequency of Cu decreases clearly from west to east. The diurnal variations of the TC and the other types of clouds show no significant change with the longitude.



Figure 4. Diurnal variation cycles of clouds with the longitude: (**a**) Ns (averaged over 26–30° N) and (**b**) Cu (averaged over 22–26° N) (the horizontal axis represents the longitude, and the vertical axis is the local solar time in hours).

3.3. Diurnal Variation Cycles of Clouds with the Season

The diurnal peak of the TC over China during the spring occurs at approximately 16 LST (Figure 5a). In addition, there is a clear diurnal variation of the TC in the summer and autumn (i.e., from June to November). The maximum occurrence frequency occurs at 14 LST while the minimum occurs at 23 LST, and the difference between them reaches 28%. In addition, the amplitude of the diurnal

variation of the TC in the winter is small; at 13–15 LST, however, the occurrence frequency is relatively large. In contrast, the occurrence frequency of the TC during the summer reaches a peak time 1–2 h earlier than that during the spring, which may occur because the mean temperature increases more rapidly in the summer than in the spring, and thus, the conditions that are unstable for cloud formation are reached earlier.



Figure 5. Seasonal variations in the diurnal cycle of anomalous values of the occurrence frequencies of clouds: (a) TC, (b) Ci, (c) Ac, (d) Ns, (e) Sc, (f) Cu (the horizontal axis is the local solar time in hours, and the vertical axis represents the month).

The diurnal peak of Ci also changes with the season (Figure 5b). Ci reaches its maximum at 16–17 LST in December and at 18–19 LST in July, thereby lagging 1–2 h between the winter and summer. The changes in the peak times of Ac are the most clear from June to September (Figure 5c). The peak times of the two peaks appear from early winter to summer, while the early morning peak appears earlier and the evening peak appears later in the summertime. The diurnal peak times of Ns and Cu do not change with the seasons (Figure 5d,f), but both of the amplitudes of their diurnal variations are relatively large in the summer. The diurnal variation of Sc with the seasons is somewhat similar to that of Ac (Figure 5e), but the minimum occurrence frequency always appears at 14 LST and does not change with the seasons. The occurrence frequency of Cb in the winter is very small, and its seasonal variation is also not clear and therefore is not discussed here.

4. The Relationship between the Diurnal Variations of Clouds and Precipitation

4.1. Diurnal Variation of Precipitation

The study of Yu et al. showed that the regional differences in the diurnal variation of summer precipitation is significant across the Chinese mainland [10]. Therefore, in order to analyze the relationship between the diurnal variations of clouds and precipitation, the following analysis is based on the regional division of central and eastern China into five sub-regions (Table 1) by Yu et al. , who studied the diurnal variation of precipitation.

	Region 1	Region 2	Region 3	Region 4	Region 5
Latitude Range	27–32° N	27–30° N	23–26° N	40–50° N	30–40° N
Longitude Range	100–107° E	108–113° E	110–117° E	110–130° E	110–120° E
Region	The upper reaches of the Yangtze River (Sichuan Basin)	The middle reaches of the Yangtze River	South China	Northeast China	The area between the Yangtze River and the Yellow River

Table 1. The information of five regions in eastern China.

The reliability of the hourly merged precipitation data has been verified by Shen et al. [23]. To compare the error of the hourly merged precipitation data and rain-gauge data, we first analyzed the diurnal variation of the precipitation in each of the five regions by using the hourly merged precipitation data from 2008 to 2011 in summer (June-August). The diurnal variation of precipitation in each of the five regions is the average of grid data of each regions. Figure 6a shows that the maximum precipitation in the upper reaches of the Yangtze River occurs at midnight (24–02 LST), while the minimum precipitation falls at noon (12 LST). Meanwhile, the precipitation in the middle reaches of the Yangtze River reaches a diurnal peak in the early morning (06–07 LST) and a sub-peak in the afternoon (14–16 LST) (Figure 6b). The diurnal peaks of precipitation in South and Northeast China appear in the afternoon (16–17 LST) (Figure 6c,d). Although the peak precipitation between the Yangtze River valley and the Yellow River valley (region 5) differs among different stations (figure omitted), the diurnal variation of precipitation in this region is generally bimodal with peaks in the early morning (06–08 LST) and afternoon (16–18 LST). By comparing our results with the diurnal variation characteristics of the precipitation in the five regions from 1991 to 2004 reported by Yu et al. (Figure 2 in Yu's article), it is found that the hourly merged precipitation data can effectively reflect the diurnal variation of the precipitation in each region. However, the amounts of precipitation in these data are smaller than those observed by the stations. Therefore, in the following discussion, we mainly analyze the corresponding relationship between the diurnal cycles of clouds and precipitation regardless of the diurnal variation of the precipitation amount.



Figure 6. Diurnal variation of the 2008–2011 mean summer precipitation averaged over the five regions in Table 1 (the horizontal axis corresponds to the local solar time, units: mm/h).

4.2. The Relationship between the Diurnal Variations of Clouds and Precipitation

The probability occurrence of Ci and Ac with precipitation is relatively small, and thus, they are classified as non-precipitation clouds [19]. Therefore, this paper mainly discusses the correspondence between the diurnal variations of Ns, Sc, Cu and Cb and that of precipitation. Table 2 shows the correlation coefficients between the diurnal variations of various clouds and precipitation, where P_Ns represents the correlation coefficient between the diurnal variation of the occurrence frequency of Ns and that of precipitation, and it has a similar meaning for P_Sc, P_Cu and P_Cb, while the clouds are different.

Precipitation_Cloud	Region 1	Region 2	Region 3	Region 4	Region 5
P_Ns	-0.82	0.51	0.16	-0.13	0.17
P_Sc	0.82	0.42	-0.51	-0.27	0.13
P_Cu	-0.78	0.04	0.70	0.55	0.05
P_Cb	0.90	-0.57	0.68	0.88	0.09

Table 2. Correlation coefficient between the diurnal cycle of precipitation and the occurrence frequency of clouds in summer.

Note: Bold font indicates a 0.05 significance level.

Figure 7a1 shows that the diurnal variation of Cb is in good agreement with that of precipitation in the upper reaches of the Yangtze River; both reach a peak around midnight with a significant positive correlation coefficient of 0.90 (Table 2). While there is a clear negative correlation between the diurnal variations of Cu and precipitation, there is also a consistent correlation between the diurnal variations of Sc and precipitation (Figure 7a2), but the diurnal peak of Sc occurs slightly later than that of precipitation. This shows that the diurnal variation of precipitation in the upper reaches of the

Yangtze River relies upon the diurnal variations of Cb and Sc. Moreover, the correspondence between the diurnal variations of Cb and precipitation is better, and Cb may evolve into Sc after precipitation falls; thus, the diurnal peak of Sc lags behind that of precipitation by approximately 2 h.



Figure 7. Diurnal variations of the standardized occurrence frequencies of Cu, Cb and precipitation (in **a1–e1**) and of the standardized occurrence frequencies of Ns, Sc and precipitation (in **a2–e2**) (the black solid line corresponds to precipitation, while the blue dotted line and red dashed line represent the occurrence frequencies of Cu and Cb, respectively, in **a1–e1**; meanwhile, the blue dotted line and red dashed line represent the occurrence frequencies of Ns and Sc, respectively in **a2–e2**).

The precipitation in the middle reaches of the Yangtze River mainly occurs in the early morning (Figure 7b1). There is a sub-peak at approximately 15 LST, the occurrence of which corresponds to the sub-peaks of both Cu and Cb, indicating that the afternoon rainfall in the middle reaches of the

Yangtze River mainly originates from Cu and Cb. Figure 7b2 shows that the corresponding relationship between the diurnal variations of precipitation and stratiform clouds in the middle reaches of the Yangtze River is good, and there is a notable positive correlation between precipitation and Ns with a correlation coefficient of 0.51. These results show that the peak of early morning rainfall in the middle reaches of the Yangtze River is mainly caused by stratiform clouds, while the sub-peak of afternoon rainfall mainly depends upon Cu and Cb.

The diurnal peaks of Cu, precipitation and Cb appear sequentially over southern China (Figure 7c1). The peak frequency of Cu occurs at 12 LST, while those of precipitation and Cb occur at 16 LST and 20 LST, respectively. In addition, the occurrence frequency of Cu decreases during 12–16 LST, but those of precipitation and Cb rapidly increase during this period, implying that Cu begins to produce precipitation during this period and that a part of Cu develops vigorously into Cb under the favorable conditions. However, the corresponding relationship between the diurnal variations of stratiform clouds and precipitation is poor over South China (Figure 7c2). In conclusion, both Cu and Cb over southern China show a good correspondence with the diurnal variation of precipitation, indicating that the diurnal variation of precipitation in southern China is mainly attributed to the diurnal variations of convective clouds.

There is a significant positive correlation between the diurnal cycles of Cu and precipitation in Northeast China with a correlation coefficient of 0.55. Cb shows a better correspondence with the diurnal variation of precipitation (Figure 7d1), with a significant positive correlation of 0.88. For example, the diurnal peaks of Cb and precipitation are both almost synchronous at 09–16 LST, although the diurnal peak of Cb that occurs during 01–09 LST is a little earlier than that of precipitation, and the occurrence frequency of Cb peaks one hour later than that of precipitation. In addition, the correspondence between the diurnal variations of stratiform clouds and precipitation is also poor in these areas (Figure 7d2). This shows that the diurnal variation of precipitation in Northeast China is primarily dominated by convective clouds, especially Cb.

There are two peaks in the diurnal variation of precipitation in the region between the Yangtze River and the Yellow River (region 5). In the afternoon, Cu, precipitation and Cb reach their peaks sequentially (Figure 7e1). Cu peaks at 14 LST, while the occurrence frequencies of precipitation and Cb increase rapidly after 12 LST. Cb and precipitation both peak at 17 LST, indicating that the afternoon peak of precipitation is determined by convective clouds. Figure 7e2 shows that the diurnal peaks of Sc and Ns occur at 05 LST and 09 LST, respectively, while the precipitation peaks at 07 LST, meaning that the morning precipitation peak in the area is dominated by stratiform clouds. Therefore, the results show that the diurnal variation of precipitation in the area is comparatively complicated and is closely related to both convective and stratiform clouds. The morning precipitation is closely related to stratiform clouds, while the afternoon precipitation is dominated by convective clouds.

All of the above analysis shows that the precipitation peak in central and eastern China usually occurs in the early morning or afternoon. The precipitation peak in early morning is dominated by stratiform clouds, while the peak in the afternoon is dominated by convective clouds.

5. Discussions and Conclusions

Based on hourly cloud observations at weather stations in combination with merged hourly precipitation data, the diurnal climatic features of different types of clouds in central and eastern China are revealed and the relationship between the diurnal variations of clouds and precipitation are analyzed. The primary conclusions are as follows:

The TC and the occurrence frequencies of all types of clouds show significant diurnal variations. The diurnal variation of the TC shows a bimodal pattern with a main peak in the late afternoon. Ac, Sc and Ci contribute the most to the diurnal variation of the TC. The diurnal cycles of the occurrence frequencies of Ac and Sc also show a bimodal pattern with peaks appearing in the early morning and late afternoon. The occurrence frequency of nimbostratus peaks in the morning between 07 and 12 LST, and the daily difference is weaker. The diurnal peak of Ci usually appears at 17–18 LST in the late

afternoon, Cu peaks in the afternoon, and Cb peaks in the late afternoon during 16–20 LST, and there are slight differences among different regions. In addition, the diurnal variation amplitudes of Cu and Cb are larger, indicating that they both have significant diurnal variations.

The diurnal variations of clouds vary with both the latitude and the longitude. There is a slight difference in the time when the occurrence frequency of the TC reaches its peak value at different latitudes, while there is a difference of 1–2 h with a change in the latitude for both Ci and Ac. The peak times of Ns, Sc, Cu and Cb do not change with the latitude. In addition, the peak appearance time of the occurrence frequency of Ns in the Yangtze River valley lags by 1–2 h from west to east.

The diurnal features of clouds change with the seasons. All of the types of clouds show the largest diurnal amplitudes in the summer and autumn, and the time when the TC and Ci reach their maximum values tend to lag by 1–2 h from the spring to the summer. Ac and Sc present bimodal patterns with early morning peaks that appear earlier in the summer, while their late afternoon peaks appear later in the summer than in the other seasons. The maximum peak appearance times of Ns and Cu do not change with the seasons.

The diurnal variations of precipitation among the different regions are dominated by convective or stratiform clouds. The upper reaches of the Yangtze River valley present a midnight precipitation maximum that is mainly dominated by Cb. Both precipitation and Cb reach a peak around midnight with a significant positive correlation coefficient of 0.90. In other regions, the precipitation usually peaks in the early morning or in the afternoon, and there is a notable positive correlation between the early morning peak of precipitation and stratiform clouds, while the afternoon peak of precipitation shows positive relationship with convective clouds. The diurnal peak in the Yangtze River valley and the region between the Yangtze River valley and the Yellow River valley is mainly dominated by stratiform clouds, while it is mainly determined by convective clouds in South and Northeast China. The peak appearing in the afternoon over the Yangtze River valley is also dominated by convective clouds.

Nesbitt and Zipser suggested that the nocturnal rain is often caused by meso-scale convective systems (MCS) rather than isolated convection, and the MCSs are the strongest systems after midnight [24]. Lin et al. indicated that the nocturnal maximum rainfall is enhanced by instability due to nocturnal radiative cooling at cloud top [25]. This explains that the midnight precipitation maximum is mainly dominated by Cb in the upper reaches of the Yangtze River valley. The afternoon peaks of convective clouds and precipitation can be explained by the highest surface air temperature and the strongest instability in the lower troposphere occurring in the afternoon, which are beneficial to the trigger of the convection [22].

The study points out the relationship of diurnal variations of clouds and precipitation among different regions for the first time. However, the research on the physical mechanism of the diurnal variations of clouds and precipitation is not deep. We will study the diurnal variation of cloud microphysical characteristics, and analyze the influence of terrain, atmospheric stability and atmospheric circulation on the diurnal variation of clouds and precipitation in the next step. This is helpful for understanding the mechanism of clouds and precipitation, and for improving the ability to simulate weather and climate models.

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