Climatic characteristics and regionalization of fogs in China

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Abstract. Using trend coefficient method, vector analysis method, and monitored meteorological data across China, climatic characteristics and spatial pattern of fogs in China were investigated. The results show that most fogs occur in southeastern China. Thin fogs usually occur in fog-rare regions and dense fogs take place in fog-prone regions. The number of annual fog days in most regions of China exhibits a decreasing trend from 1980 to 2010. It also found that the regions with more fog days correspond to the lower concentration degree of fogs, and vice versa. In terms of the national scale, the concentration periods of fogs are mainly in November, December, and January in China. We further classified the occurrence frequencies of fogs into five spatial distribution patterns over a single year according to the spatial distribution characteristics of fogs occurrence frequencies of 36 dekads, namely, a whole year can be correspondingly divided into five phases. Based on this, multi-year average fog-prone regions in the five phases are obtained. Our results also identify the high incidence periods of fogs in different fog-prone regions.

1. Introduction

Fogs have strong influence on transportation, industrial and agricultural production, and human health. The understanding to the climate characteristics of fog could help greatly to reduce and avoid the disasters caused by fogs. A fog is defined as a collection of suspended water droplets or ice crystals near the Earth's surface that lead to a reduction of horizontal visibility below 1 km [1]. It has been reported that more fogs occurred in Southeast China and less in Northeast China based on statistics of fogs from 1971 to 2000 [2]. The number of heavy fog days in winter half year (October to March) was greater considerably than that in the summer half year (April to September) [3]. The fogs usually begin at 20 pm (Beijing time) to 8 am in the next day with highest rate of occurrence at 6 am ~7 am, ceasing at 8~12 am. The life time of fogs extended usually from 1 to 10h, and mostly about 3h[4,5]. Lin et al. [4] also characterized fog patterns based on low level atmospheric circulation patterns and revealed that uniform pressure and fore-front pattern were most popular fog patterns in China. Wang et al. [6] identified six major fog regions across China based on the analysis of average annual fog days. Niu et al.[7] revealed that the frequencies of fog events during the wintertime over Eastern-central China doubled over the past three decades (1976-2007), confirming with the results from Chen et al. [5]. They linked this considerable increase of fog events with the weakening of the Eastern Asian monsoon circulation and the increasing aerosol loadings.

This study aims at better understanding the climatic characteristics of fogs and helping the prediction to fogs occurrence in China. The objectives are (1) to elucidate the spatial and temporal

distribution characteristics and trends of fog days for different fog grades, (2) to investigate the concentration degree of fogs occurrence and major concentration periods of fogs occurrence, (3) to distinguish the fog-prone areas and its high-incidence periods.

2. Material and methods

2.1. Data sources and processing

Data at 581 observation stations across China were collected. They include atmospheric horizontal visibility (4 times per day), daily precipitation, and daily average relative humidity from January 1980 to December 2010. A fog day is defined if the atmospheric horizontal visibility is less than 1km and daily average relative humidity is greater than 90%, except for rainy days and dusty days.

2.2. Methods

The fog concentration degree (FCD) and the fog concentration period (FCP) are defined based on vector analysis [8]. The amount of fog days in each dekad can be regarded as the length of a vector whereas the corresponding dekad is viewed as the direction of the vector.

Using this approach, 36 vectors representing each dekad's fog days are synthesized as a new vector. The FCD can then be defined as the ratio of the modulus of the new synthetic vector to the total number of the annual fog days.

$$FCD = \frac{\sqrt{R_x^2 + R_y^2}}{R} \tag{1}$$

Where $R_x = \sum_{i=1}^{36} r_i \sin\theta_i$ and $R_y = \sum_{i=1}^{36} r_i \cos\theta_i$. R is the amount of annual fog days. The r_i is the amount of fog days in each dekad. Hence the FCD reflects whether the fogs occurrences are concentrate within a year.

The FCP measures the direction angle of the new synthetic vector.

$$FCP = \arctan(\frac{R_x}{R_y}) \tag{2}$$

The FCP is used to find the dekad of a year during which the maximal numbers of fog days are accounted for.

3. Results and discussion

3.1. Spatial distribution of average annual fog days

The spatial distribution of average annual fog days in China averaged over 1980 through 2010 is shown in Figure 1. The highest fog days can be observed in the east of Sichuan, Chongqing, the north of Hunan, the east of Guizhou, most areas of Fujian, and part of Yunnan where there were at least 30 fog days on an annual basis. Those areas filled by green color in Figure 1 also observed relatively high fog days with annual fog days greater than 10 days. The average annual fog days in the rest of China were less than 10 days.

To facilitate analysis, the fogs are divided into three classes according to the atmospheric horizontal visibility. The first class is termed dense fog when atmospheric horizontal visibility is less than 0.2km. The second class is termed thick fog when atmospheric horizontal visibility is less than 0.5km and greater than 0.2km, and the third is termed thin fog when atmospheric horizontal visibility is less than 1km and greater than 0.5km. Figure 2 marks fogs in different classes at 581 stations across China. The results suggest that thin fogs occur in those regions where fogs seldom occur whereas dense fogs usually take place in those regions with high occurrence frequency of fogs.

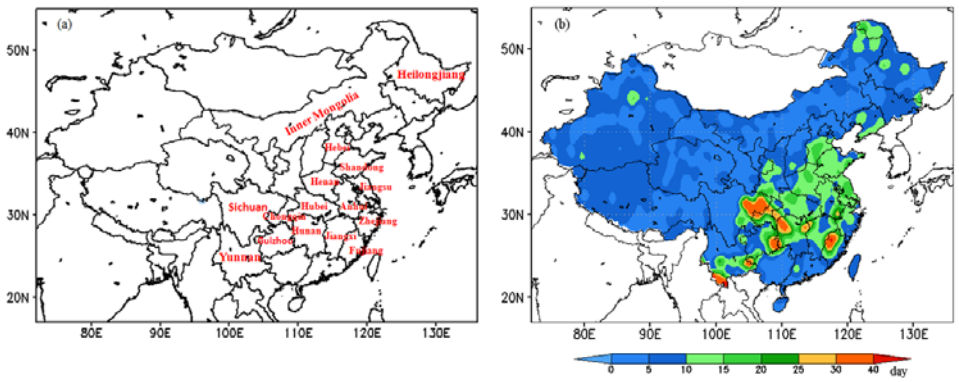

Figure 1. (a) Distribution of provinces and cities of China (b) The spatial distribution of average annual fog days in China from 1980 to 2010.

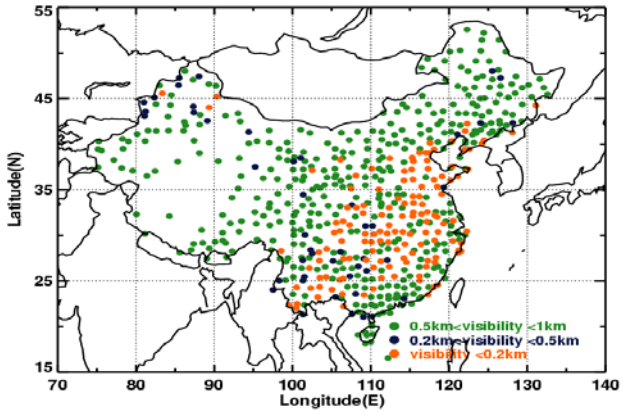

Figure 2. Atmospheric horizontal visibility at all 581 stations under condition of fog occurrence.

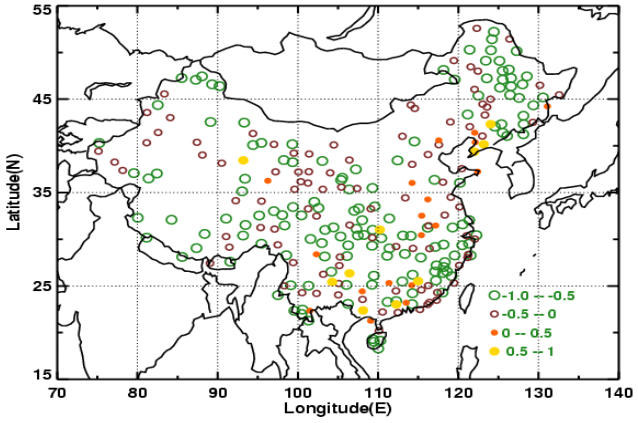

Figure 3. Spatial distribution of trend coefficients from 1980 to 2010. Hollow points represent negative trend and solid points represent positive trend, respectively.

3.2. Trend of fog days

The trend of annual fog days of 1980 through 2010 is presented in Figure 3. As shown, the fog days exhibit a negative trend in most areas of China. In particular, a strong decreasing trend can be observed in most places in Northeast China, Sichuan Basin, and the southeast Wuyi Mountain. On the other hand, there was an increasing trend of fog days at a certain number of stations in southern and

Eastern China, as well as in Bohai Rim region. Our results agree with previous works from Liu et al. [2], Lin et al.[4], and Liu et al. [9]. While the spatial distribution of the long-term trend of fog days was not fully understood, aerosols activity [7, 10, 11] may play a very important role in the long-term trend of fog days.

3.3. Concentration degree and concentration period of fog days

The spatial distribution of FCD in China from 1980 to 2010 is illustrated in Figure 4. It can be seen from the figure 4 that FCD in most areas of China is greater than 0.5, suggesting that the occurrence of fogs is relatively concentrated. The highest value of the FCD exceeding 0.8 can be found in Inner Mongolia, Gansu, eastern Qinghai, Xizang, western Sichuan, Yunnan, and southwest Guangxi. There are two regions with lowest FCD, one in east Yunnan-Guizhou Plateau and the north of Hunan province, the other in Jiangsu province and a small part of Shandong province. In contrast, the FCD values in North China Plain, the middle and lower reaches of the Yangtze River Plain, Loess Plateau, the east of Yunnan-Guizhou Plateau, and Wuyi Mountains are lower than that in the rest of China. This suggests that fogs occurring in the 36 dekads of a year decentralized in these regions.

Combined with the spatial distribution of the average annual fog days and the spatial distribution of FCD, we can found that the regions with more fog days corresponded to the lower concentration degree of fogs, and vice versa. This suggests that fogs occurred dispersedly in fog-prone regions within a year. Exception can be seen in the Sichuan basin where there exhibited the most annual fog days, while its FCD is not the lowest. But its FCD is still lower than that in those regions with less fog.

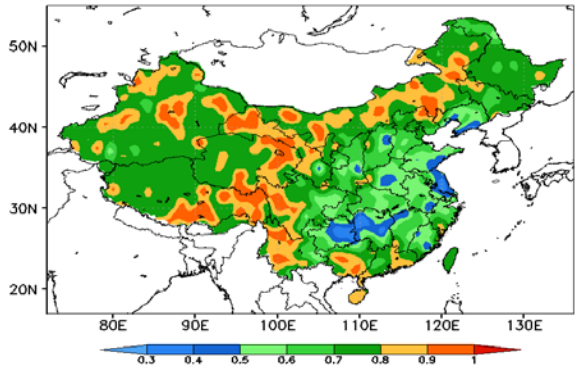

Figure 4. The spatial distribution of FCD in China from 1980 to 2010.

It can be seen from Figure 5 that the values of FCP have an obvious regional pattern. On the country scale, the FCP mainly occurred in January, November, and December. The regions with FCP values in January were mainly located in Inner Mongolia and Western China, where fogs seldom took place and the FCD was also higher than that of other regions. The area where FCP occurred in November was primarily the northern part of North China Plain. In Sichuan Basin and the middle and lower reaches of the Yangtze River Plain, the FCP was in December. Besides, in the southern China, the FCP mainly started from early October to the end of next March, mostly in January. In Northern and Northeastern China, the FCP included July and August. In the coastal area of Bohai Rim, closing to Yellow Sea, the FCP included June, July, and August.

3.4. Fog-prone regions and periods

We have analyzed the spatial distributions of fogs occurrence frequencies in 36 dekads from 1980 to 2010, respectively, in order to identify the high fog incidence areas for each dekad, and to reveal the high fog incidence periods for fog-prone regions in China. To do so, the spatial distributions of fogs occurrence frequencies for 36 dekads have been classified into 5 patterns. This is equivalent to separate 36 dekads into 5 phases, as shown in Figure 6. The duration of the each pattern is shown in Table 1.

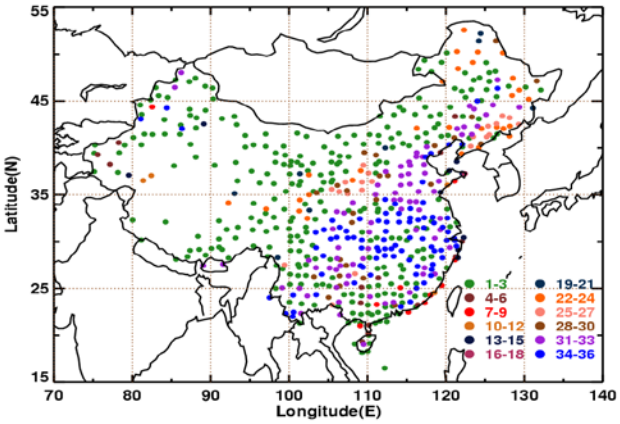

Figure 5. The spatial distribution of FCP in China from 1980 to 2010. (1-3 represents dekad1-dekad3, and so on)

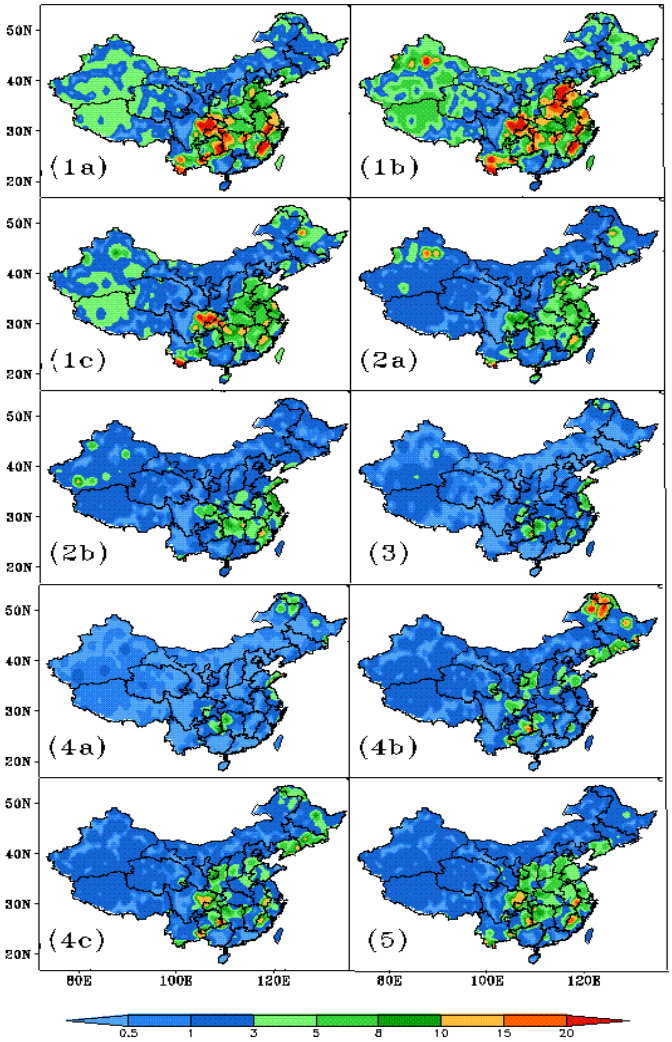

Figure 6. Spatial distribution of fogs occurrence frequency (%) in dekad 31 (1a), dekad 33 (1b), dekad 3 (1c), dekad 5 (2a), dekad 10 (2b), dekad 15 (3), dekad 17 (4a), dekad 24 (4b), dekad 24 (4c), dekad 29 (5), respectively.

Table 1. The duration of the spatial distribution for 5 types of fogs occurrence frequencies.

Phase1(Pattern1)	Phase2(Pattern2)	Phase3(Pattern3)	Phase4(Pattern4)	Phase5(Pattern5)
Dekad31-Dekad3	Dekad4-Dekad12	Dekad13-Dekad16	Dekad17-Dekad27	Dekad28-Dekad30

In the first phase, spanning dekad 31 to dekad 3 (1a, 1b, 1c in Figure 6), the highest fog incidence was found in Sichuan Basin and southwest corner of Yunnan-Guizhou Plateau, followed by western North China Plain, the west part of the middle and lower reaches of the Yangtze River Plain, and the east of Wuyi Mountains. The fogs occurrence frequencies in these regions were greater than 10%. This phase is the main period that fogs occurred most extensively and frequently.

The fogs occurrence frequencies reduced gradually till the 5th dekad over these areas with the high fogs incidence. The frequency was less than 10%. In this case, the fogs occurrence frequencies in Sichuan Basin, North China Plain and the middle and lower reaches of the Yangtze River Plain were greater than other parts of China at the values between 3% and 10%. This can be regarded as the second spatial distribution pattern of fogs occurrence frequencies, spanning dekad 4 to dekad 12 (2a, 2b in Figure 6).

From dekad 13 to dekad 16, the spatial distribution patterns of fogs occurrence frequencies were analogous (As is shown in Figure 6 (3)). From Figure 6 (3) we can also see that the fogs occurrence frequencies in the 15th dekad were low across China, except for small areas. From the beginning the 13th dekad, fogs seldom occurred throughout China.

In the fourth phase, the fogs in China still did not occur frequently (see Figure 6 (4a)). In this phase the fog-prone areas mainly include Chengshantou and its vicinity as well as the northernmost border between Inner Mongolia and Heilongjiang province. The fogs in Chengshantou vanished in dekad 24 whereas in the northernmost border area between Inner Mongolia and Heilongjiang province fogs were featured by an occurrence-dissipation process from dekad 17 to dekad 27. From the beginning of dekad 24, the fogs started to increase in southeastern Jilin province, Liaoning province, eastern Loess Plateau, Sichuan Basin, and southeastern Yunnan-Guizhou Plateau. (see Figure 6 (4b) (4c)).

The fifth phase, including dekad 28, dekad 29, dekad 30 (see Figure 6 (5)), can be regarded as the prophase of the first phase. At this phase, the fogs occurrence frequencies in Sichuan Basin, North China Plain, the middle and lower reaches of the Yangtze River Plain, the east of Wuyi Mountains, and part of Liaoning province was more than 3%. However, the occurrence frequency of fogs in above mentioned regions was lower than that in fog-prone regions in the first phase. And the occurrence range of fogs during this phase was also less than that in the first phase.

In summary, a wide range fogs occurred mainly in November, December, and January (dekad31-dekad3) in China. The high fogs incidence areas are mainly Sichuan Basin, northern part of the North China Plain, the southeast of Wuyi Mountains, the east of the middle and lower reaches of the Yangtze River Plain, and the westeast of Yunnan-Guizhou Plateau. Between April and July (dekad10-dekad22), the high fogs incidence areas shifted to Chengshantou and its surrounding regions. The fogs in the northernmost border between Inner Mongolia and Heilongjiang province occurred between July and September.

4. Conclusions

In this study extensive analyses were conducted to identify spatial and temporal characteristics of fogs using the meteorological data. The primary results are summarized below.

(1) The regions where fogs occur most frequently in China were Sichuan Basin, the Yunnan-Guizhou Plateau, and the southeast of Wuyi Mountains. Thin fogs usually took place in the regions where fogs seldom occurred whereas dense fogs usually occurred in the fog-prone regions.

(2) The number of fog days in most regions of China has been decreasing in the past 31 years.

(3) Given that the fogs concentration degree (FCD) was associated inversely with fog days. the FCD in fog-prone regions is relatively low. This suggests that fogs in fog-prone regions occurred

dispersedly. On a national scale, the fogs concentration periods (FCP) mainly were January, November, December, namely the wintertime.

(4) Seven major fog-prone regions were identified, and its high incidence periods were also clear. This maybe help to fog prediction and regional research.

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References

[1] National Oceanic and Atmospheric Administration 1995 Surface weather observations and reports *Federal Meteorological Handbook* **1** 94
[2] Liu X, Zhang H Z, Li Q X, Zhu Y J 2005 Preliminary research on the climatic characteristics and change of fog in China *Journal of Applied Meteorological Science* **16(2)** 220-229
[3] Cao Z Q, Wu D, Wu X J 2008 Climatic Characteristics of Heavy Fog Weather in China from 1961 to 2005 *Meteorological Science and Technology* **36(5)** 556-560
[4] Lin J, Yang G M, Mao D Y 2008 Spatial and Temporal Characteristics of Fog in China and Associated Circulation Patterns *Climatic and Environmental Research* **13(2)** 171-181
[5] Chen X X, Guo P W, Luo Y 2008 Climate Characteristics of Fog Days of Various Categories in China *Advances in Climate Change Research* **4(2)** 106-110
[6] Wang L, Chen S, Dong A 2005 The distribution and seasonal variations of fog in China *Acta Geographica Sinica-Chineses Edition* **60(4)** 689
[7] Niu F, Li Z, Li C, Lee K H, Wang M 2010 Increase of wintertime fog in China Potential impacts of weakening of the Eastern Asian monsoon circulation and increasing aerosol loading. *Journal of Geophysical Research Atmospheres* (1984–2012) 115(D7)
[8] Zhang L, Qian Y 2003 Annual distribution features of precipitation in China and their interannual variations *Acta Meteorologica Sinica-English Edition* **17(2)** 146-163
[9] Liu H N, Luo Y 2009 Projection of future fog in China for 2001-2050 *Advances in Climate Change Research* **5(5)** 266-270
[10] Fu C B, Wu J 2011 The different characteristics of sunny visibility over southwest china in recent 50 years. *Procedia Environmental Sciendes* 10 247-254
Deng X, Tie X, Wu D, Zhou X, Bi X, Tan H, Jiang C 2008 Long-term trend of visibility and its characterizations in the Pearl River Delta (PRD) region, China *Atmospheric Environment* **42(7)** 1424-35