Atmos. Chem. Phys. Discuss., 10, 6199–6218, 2010
www.atmos-chem-phys-discuss.net/10/6199/2010/

Atmospheric Chemistry and Physics Discussions

This discussion paper is/has been under review for the journal Atmospheric Chemistry and Physics (ACP). Please refer to the corresponding final paper in ACP if available.

The challenge of improving visibility in Beijing

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Received: 18 December 2009 – Accepted: 18 February 2010 – Published: 5 March 2010

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

The "Blue Sky Project" was proposed in 1998 to investigate by how much emissions should be reduced to increase blue sky frequency in Beijing, which hosted the Summer Olympics in 2008. This paper focuses on the temporal variation of visibility and its dependence on meteorological conditions and suspended particles at Beijing using the hourly observed visibility data in Beijing Capital International Airport (BCIA) from 1999 to 2007. It has been found that about 47.8% (24.2%) of the hours in Beijing are "bad" ("good") hours with visibility below 10 km (equal or higher than 20 km) between 1999 and 2007. Due to the high Relative Humidity (RH), summer is the season with the lowest mean visibility in a year. Although PM_{10} index was reported in a decreasing trend, the increase of RH has resulted in a decreasing trend of visibility over BCIA in the summer from 1999 to 2007. To ensure blue sky ("good" visibility) for Olympics 2008, daily mean PM_{10} index should be reduced to 44 from 86.5. This requires that not only vehicle emissions, but also other emissions should be limited. Observations during Olympics 2008 verify that blue-sky-hour rate has been increased significantly after mean PM_{10} index was reduced to 56, however, the visibility during the same period of 2009 has returned to the mean standard before 2008.

1 Introduction

Since the end of last century, there has been a growing interest in the connection between air quality and human health effects, such as chronic respiration illness, cancer, and cardiovascular morbidity (Samet et al., 2000; Pope et al., 2002; Hauck et al., 2004). Visibility may act as an indicator for air quality (Bäumer et al., 2008). Recently, clear sky visibility has been found to decrease over land globally from 1973 to 2007 (Wang et al., 2009). Understanding the temporal variation of the atmospheric visibility and the factors affecting it is important in a mega-city because poor visibility has significance for not only human health but also air and ground transportation.

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Beijing hosted 2008 summer Olympics. Atmospheric visibility, as well as air quality, were important factors determining the success of the 2008 Beijing Olympic Games. Measures have been taken to improve the air quality of Beijing, including moving high-polluting industries out of Beijing, replacing coal fuel with natural gas, and phasing out leaded gasoline in recent years. Pollutants such as sulfates and nitrates have been reduced significantly since 1998 (Chan and Yao, 2008), and the PM_{10} (Aerosol particulate matters having diameter <10 µm) concentration has also been reduced after 2003 (Chan and Yao, 2008). The Chinese government has planned to increase Blue Sky frequency by limiting vehicle emission during Beijing 2008 Olympics. In this regard, understanding the relationship between visibility and meteorological conditions and aerosols is essential as a first step toward the development of a program to improve visibility in Beijing.

Visibility at a given location is controlled by the physical and chemical properties of the particulate matter and the ambient relative humidity (RH). Numerous studies carried out all over the world indicate that visibility impairment is largely due to the light scattering of ambient aerosols. Concentrations of these aerosols are governed by meteorological conditions and the emission source strength (Sequeira and Lai, 1998; Sloane, 1983, 1984; Lee, 1983; Dayan and Levy, 2005; Tsai, 2005; Vautard, 2009). Qin and Yang (2000) illustrate a clear trend of decreased visibility in Beijing during 1980-1994, using the visibility data at Beijing Local Time (LT) 14:00 in clear days. Decreased trend of visibility during 1973–2007 are also detected on the basis of the daily visibility, which was defined by a minimum of four synoptic observations per day from National Climate Data Center (Chang et. al., 2009). There is, however, no comprehensive visibility study based on hourly data for recent years in general. In this paper, the hourly operational meteorological data, including atmospheric visibility, RH, wind direction and speed, are used to investigate the temporal variation of visibility and its relationship with the meteorological conditions in Beijing Capital International Airport (BCIA) from 1999 to 2007. Considering that particles in the respirable (<2.5 µm) fraction account for 99% of the total particles in airborne PM samples in Beijing (Shi et al., 2003), daily mean

PM_{10} index data from 2005 to 2007 is used to analyze the correlation between visibility and suspended particles. Data are described in Sect. 2, which followed by result and discussion in Sect. 3, finally conclusions are given in Sect. 4.

2 Data descriptions

The data used in this study include all available hourly observational data (temperature, pressure, dew point temperature, RH, wind speed and direction) for the years of 1999–2007 from Automated Surface Observing System (ASOS) in BCIA provided by the information center of BCIA after quality control. The visibility observation is obtained manually. Data of visibility are on an hourly basis for the years of 1999–2007. In addition, we also have daily mean data of RH, visibility, and PM10 index for August from 2000 to 2009. The archived weather observations record on an hourly basis is used in the present study.

The daily mean concentrations of PM_{10}, a leading pollutant, in the Beijing city have been measured in the form of the ambient air pollution index (API). The relationships between API index of PM_{10} and PM_{10} concentration is given in Table 1. The daily PM_{10} data is spacially averaged from all monitoring stations in the whole city and have been obtained from Beijing Environmental Protection Bureau (BJEPB: http://www.bjee.org.cn/api/index.php).

A “good” hour, is defined as the hour with a visibility equal or higher than 20 km in this study. A “bad” hour is defined as the hour with a visibility lower than 10 km. A “very bad” hour is defined as the hour with a visibility lower than 2 km. In this paper, “blue sky rate” is defined as the occurrence frequency of the “good” hour.

3 Results and discussions

3.1 Temporal variations of visibility and RH

Hourly visibility data from 1999 to 2007 are summarized in Fig. 1 according to visual ranges. It is seen that only 24.2% of the hours in Beijing are "good" hours (blue bars and blue dashed line) and about 47.8% are "bad" hours (including yellow and brown bars and lines) from 1999 to 2007. The frequency of visibility between 2 km and 10 km, shown by yellow bars, has increased from 37% in 1999 to 43% in 2007. The frequency of "very bad" hours does not have much fluctuation from 1999 to 2007. This leads to an increase of the frequency of "bad" hours during the years. It should be noted that "very bad" hour in BICA is often influenced by several weather phenomena, such as fog, haze, dust and precipitation. From 1999 to 2007, about 68.7% of the "very bad" hours are caused by fog. About 27.7%, 3.0% and 0.6% of them are associated with haze, dust and precipitation, respectively.

Seasonal and diurnal variations of visibility (RH) and their trends from 1999 to 2007 are illustrated in Fig. 2 (Fig. 3). The data of precipitation and fog hours are excluded from analysis. Summer is the season with the lowest visibility. Mean visibility in summer is generally below 10 km during the night and morning, and exceeds 10 km only in the afternoon. Note that July is the "worst" month with a mean visibility of 9.4 km. The mean visibility in August, the month summer Olympics 2008 was held, is 9.8 km from 1999 to 2007. For the other seasons, mean visibility generally exceeds 10 km during the day time, and is lower than 10 km during the night time. October is the "best" month with a mean visibility of 12.8 km. The moisture abundance in the summer is responsible for the relatively low visibility (Fig. 3).

The lowest visibility of 9.7 km occurs at 01:00 LT, and the highest visibility, which is 13.7 km, appears at 15:00 LT. The relatively good visibility in the afternoon is mainly because of the high temperature (not shown) from solar heating that reduces the RH (Fig. 3), and on the other hand, the higher PBL (Planetary Boundary Layer) in the afternoon may provide suitable conditions for vertical mixing of pollutants, leading to

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better visibility.

In general, the annual mean visibility is decreasing at −0.13 km per year from 1999 to 2007, however the decreasing trend is not significant at the 95% confidence level. While there is an obvious decreasing trend of visibility in most months, summer is the main season that contributes to the decrease of annual mean visibility (Fig. 2). The decreasing trend in July is significant at the 95% confidence level. The decreasing rate peak is about −0.5 km per year in July, and it could be explained by the obvious increase trend of RH in summer (Fig. 3). The mean visibility trends are negative for every hour and reaches the minimum value of −0.17 km per year in the late afternoon (17:00 LT), when a slight increase of RH was found in Fig. 3, although none of them are significant.

3.2 Dependence of visibility on PM_{10} and meteorological conditions

Several former studies indicated that the decrease of visibility was related to the increase of PM_{10} in urban city Xian and Taiwan (Che et al., 2006; Tsai, 2005). The daily mean visibility of BCIA in relation to daily mean PM_{10} index of Beijing from 2005 to 2007 is shown in Fig. 4. The day with daily mean RH greater than 90% are excluded from analysis (Chang et al., 2009). Daily average PM_{10} index in spring is higher than those in other seasons. The correlation index between visibility and ln(PM_{10} index) for four seasons are statistically significant at the 99% confidence level. "Good day" hardly occur when PM_{10} index is greater than 150. The visibility may vary from 2 km to 45 km when PM_{10} index is below 100, and from which, most days with visibility below 10 km occur in the summer due to the high RH (Fig. 3).

Figure 5 demonstrates the occurrence frequency at different visibility and RH at BCIA from 1999 to 2007. Results show that low visibility is highly associated with high RH. Most "very bad" hours occur when the RH is 90∼100%. There are a few cases of "very bad" hours caused by sand storm when RH is about 20∼40%. For most hours with visibility higher than 2 km and lower than 10 km, the RH is around 60∼100%. The RH has a broad range of 10∼100% for visibility from 10 km to 15 km, but with a high

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frequency around 30~40%. Results also show that good visibility is highly related to low RH. For "good" hours with visibility equal or higher than 20 km, the RH is mostly around 20~40%. Results in this study are consistent with previous work that showed reduction in visibility under high RH (Malm and Day, 2001; Sequeira and Lai, 1998).

Although the annual PM_{10} concentration has been reported to decrease from 1999 to 2005 in Beijing (Chan and Yao, 2008), the increase of moisture over the years in the summer may intensify the hygroscopic growth of the aerosol particles, and therefore strengthen light extinction and reduce visibility. Specific humidity reveals an increasing rate of 0.16 $g\,kg^{-1}$ per year in the summer from 1999 to 2007 (not shown). This explains the trend of decreasing visibility from 1999 to 2007. Surface moisture increase is also reported by Dai (2006) in a global range and is found to be associated with global warming.

To understand visibility variation at a location, it is important to examine the relationship between visibility and the wind that can represent the transport of the pollutants. Figure 6 presents the visibility distribution in relation to wind direction and wind speed. It is obvious that the visibility over BCIA is low under the prevailing southerly, southeasterly and easterly wind conditions when industrial aerosols are carried over to Beijing (Song et al., 2006; Chan et al., 2005). Mountains around the north and west of Beijing also play a significant role in blocking these urban aerosols from being advected out of Beijing. Moreover, "bad" hours occur under weak variable wind conditions; this may be related to the dominance of local urban emissions. There are some cases of lower visibility under strong southerly or southeasterly wind (greater than 12 $m\,s^{-1}$) condition, which correspond to the low level jet under severe convective system in the summer. "Good" visibility are associated with northerly, northwesterly and westerly wind greater than 3 $m\,s^{-1}$, suggesting that regional transportation from the sparsely-populated northwestern China may have contributed less moisture and aerosols.

3.3 Visibility in August

Figure 7 summarizes the relationship of daily mean visibility with daily mean RH and PM_{10} index in August from 2000 to 2007. Also observations in 2008, represented by the symbols with "+" observation are shown in Fig. 7 as a verification. Precipitation and fog days are excluded. It is seen that low visibility is generally associated with high RH and high PM_{10} index, while high visibility occurs when RH and PM_{10} index are low. The daily mean RH in August varies from 42% to 98%, with an average of 79% during the years from 2000 to 2007. Its PM_{10} index varies from 10 to 160, with an average of 86.5. The averaged visibility in August from 2000 to 2007 is 9.8 km. The increasing moisture or RH brings more challenge to improve visibility during Olympics 2008. Since the RH modification is impossible, a possible way to increase visibility is to reduce PM_{10} index. Assuming a RH of 79%, Fig. 7 shows that PM_{10} index needs to be 72 (44) in order to get a visibility of 10 (20) km during August. Improvements in visibility have been experienced at UK after the reduction of pollution (Doyle and Dorling, 2002). A recent study shows that 24% of PM_{10} in Beijing is contributed by vehicle emission in a wet season (Zhang et al., 2007). Other emissions, such as soil dust, coal combustion, secondary biomass burning, and industrial emission also make 30%, 19%, 18%, and 9% contributions to PM_{10}, respectively (Zhang et al., 2007). If the visibility would be 10 km under a RH of 79%, 70% of vehicle emissions should be limited for the Olympics 2008. For RH higher than 64% in August, the visibility would not reach the standard of a "good" day even if all vehicles be limited. In addition to vehicle emission limitation, soil dust emission, coal combustion and secondary emission should also be limited during the Olympics 2008 if the visibility is to be improved to 20 km in Beijing. In fact, Chinese government has reduced soil dust by planting vegetation and limited coal combustion and industrial emission during Olympics 2008 (Zhang et al., 2009). The symbols with "+" which represent observation in 2008 show obvious decrease of daily PM10 index and increase of daily mean visibility compared with other symbols that represent observation from 2000 to 2007. The mean PM_{10} index in August 2008 has been reduced to 56 (Fig. 7). The mean visibility has been improved to 12.6 km in August of 2008 (Fig. 7). From the hour frequency in different visibility range in figure 8, blue sky hour rate has been increased 50.2% from 8th to 24th of August in 2008, when Olympic game was held. Unfortunately, in the same time period in 2009, the blue sky rate has been recovered to the average level before 2008. Although about 15% vehicle was limited for working day after Olympic Game in Beijing, it is not enough to improve blue sky rate obviously in August. The observed mean PM_{10} index is 74.5 and hourly mean visibility is 9.5 km in August of 2009 (not shown).

4 Conclusions

The hourly observation data of visibility, RH and wind field have been examined for the temporal variation of visibility and its relay on meterological condition over BCIA from 1999 to 2007. The daily mean PM_{10} index from 2005 to 2007 are also used to investigate the relationship between visibility and suspended particals in the air in Beijing city. About 47.8% (24.2%) of the hours in Beijing are "bad" ("good") hours between 1999 and 2007. Summer is the season with the lowest visibility in a year, and 01:00 LT is the hour with lowest visibility in a day. Analysis of the meteorological conditions reveals that high (low) RH is in high accordance with low (high) visibility. Topography plays an important role in blocking pollutant dispersion. A "good" hour in Beijing is associated with northerly, northwesterly, and westerly wind greater than $3\,m\,s^{-1}$; a "bad" hour is associated with weak variable wind and wind from the south, the southeast, and the east.

The data presented in this paper indicate that there is a significant decreasing trend of visibility over BCIA in the summer from 1999 to 2007. The decreasing trend is mostly contributed by the increase of RH. If the mean RH 79% is considered, a "good" day would occur if PM_{10} index were reduced to 44. Assuming 24% of PM_{10} in Beijing is contributed by vehicles, a "good" day will not happen during Olympics 2008 even if all vehicle emission is limited. Apart from vehicle emission limitation, soil dust, coal combustion and secondary emission limitation should also be considered to improve visibility for Bejing Olympics 2008. The result was verified in the August of 2008 during Beijing Olympics and in the August of 2009 later. Due to high RH in summer, the challenge of imporving visibility of Beijing in summer remains.

Acknowledgements. This study is supported by Chinese Ministry of Science and Technology Project (Grant No. 2009CB421500), Chinese National Science Foundation under Grant 40975059 and 40921160380. We thank BCIA to allow us to access their data.

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Table 1. The relationships between API index of PM_{10} and PM_{10} concentration.

PM_{10} index	PM_{10} Con. ($\mu g\,m^{-3}$)	Level of air quality
0–50	0–50	Excellent
50–100	50–150	Good
100–200	150–350	Slight pollution
200–300	350–420	Moderate pollution
300–400	420–500	Heavy pollution
400–500	500–600	Heavy pollution

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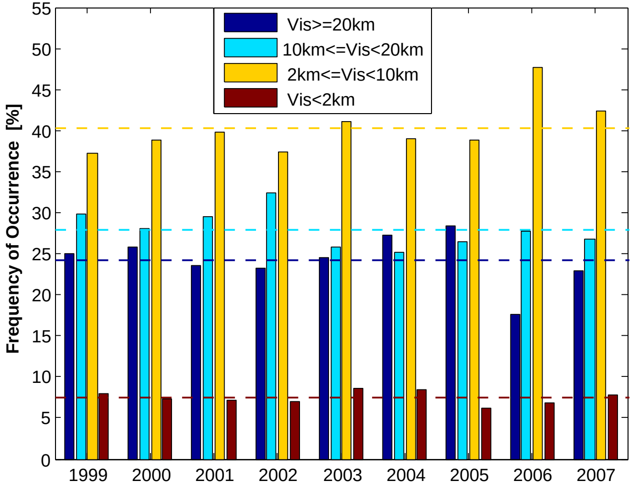

Fig. 1. Occurrence frequency of hourly visibility in different visual ranges from 1999 to 2007. Dashed lines show the 1999–2007 average frequency of visibility in different visual ranges.

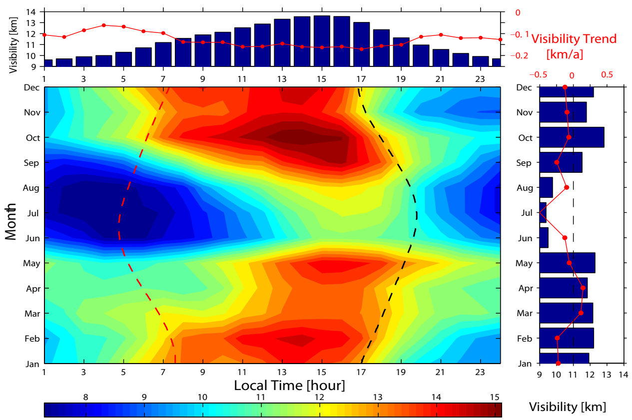

Fig. 2. Visibility distribution in relation to Month and Local Time (filled color). The blue bars at the top (on the right) denote mean visibility over the entire period 1999 to 2007 for each hour (month). The red curves denote visibility trend in BCIA from 1999 to 2007. Red dash line represents sunrise time and black dash line represents sunset time.

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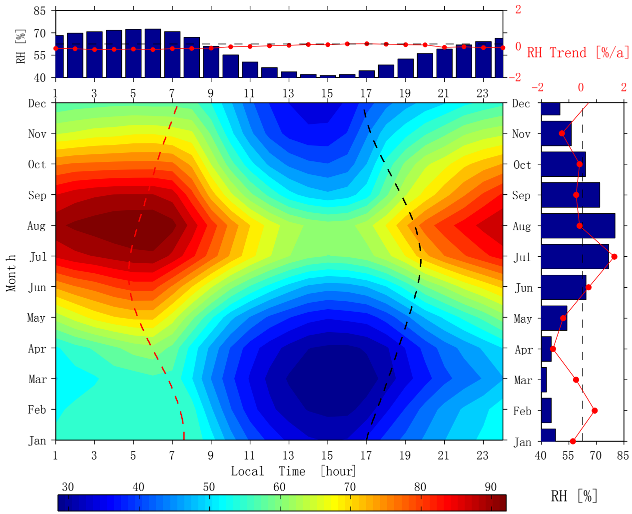

Fig. 3. RH distribution in relation to Month and Local Time (filled color). The blue bars at the top (on the right) denote mean visibility over the entire period 1999 to 2007 for each hour (month). The red curves denote visibility trend in BCIA from 1999 to 2007. Red dash line represents sunrise time and black dash line represents sunset time.

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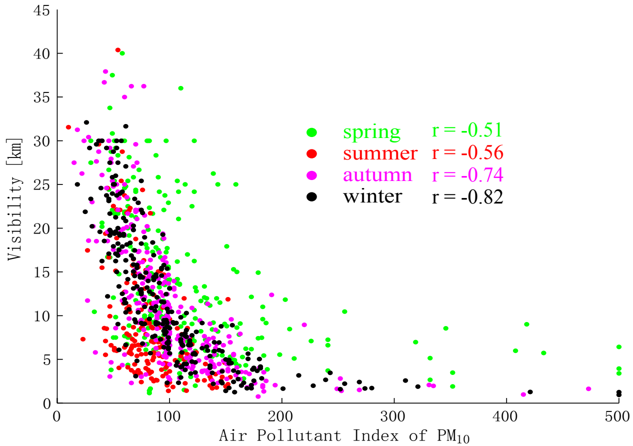

Fig. 4. Daily mean visibility of BCIA vs. daily mean PM_{10} index in Beijing from 2005 to 2007. The correlation index between visibility and ln(PM_{10} index) for four seasons is shown as the variable "*r*".

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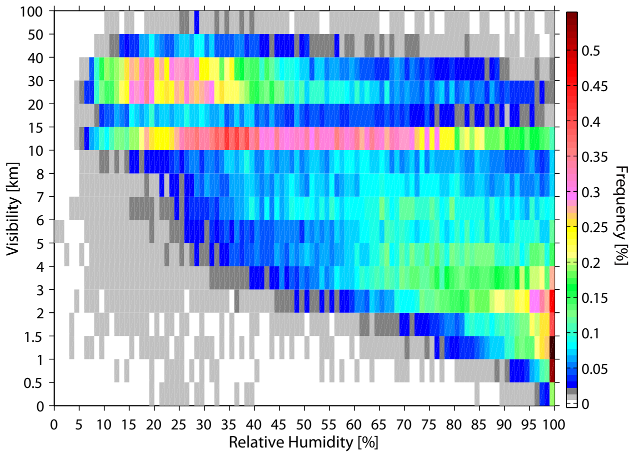

Fig. 5. Hourly occurrence frequency of visibility in relation to visibility and RH in BCIA from 1999 to 2007.

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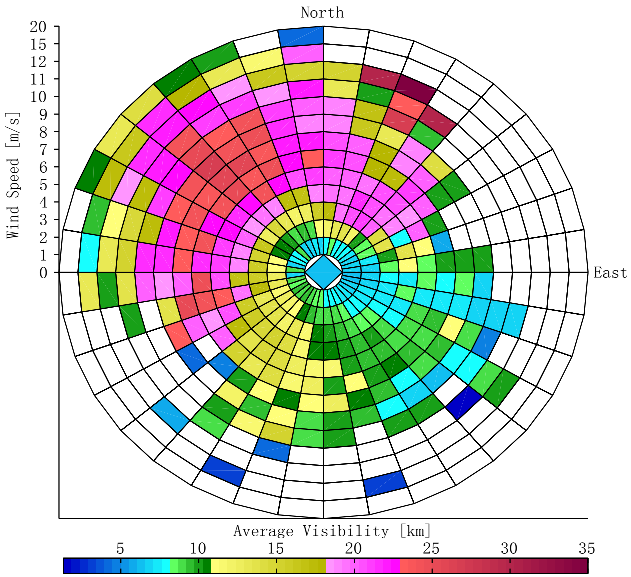

Fig. 6. Visibility distribution in relation to wind direction and wind speed in BCIA from 1999 to 2007.

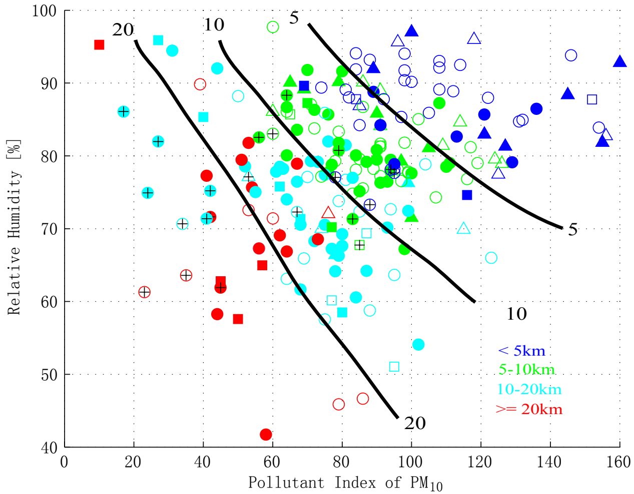

Fig. 7. Daily mean visibility distribution in relation to RH, PM_{10} index, wind speed, and wind direction for August from 2000 and 2008 in Beijing. Blue symbol represents visibility lower than 5 km, green symbol represents visibility lower than 10 km and no less than 5 km, cyan symbol represents visibility lower than 20 km and no less than 10 km, and red symbol represents visibility no less than 20 km. The symbols with "+" represent observation in 2008. Triangle represents wind speed lower than $1.5\,m\,s^{-1}$, circle represents wind speed greater than $1.5\,m\,s^{-1}$ and lower than $3\,m\,s^{-1}$, and square represents wind speed greater than $3\,m\,s^{-1}$. Hollow symbols represent wind directions of south, southeast, east, and southwest. Solid symbols represent wind directions of northeast, north, northwest and west. The black solid lines denote the visibility contour of 5 km, 10 km and 20 km.

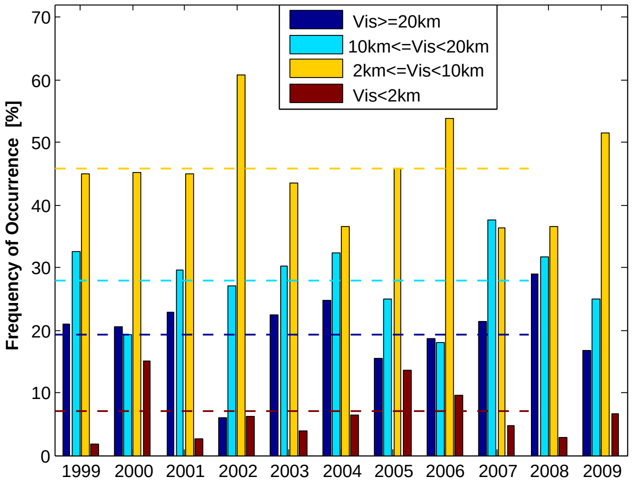

Fig. 8. Occurrence frequency of hourly visibility in different visual ranges from 8th to 24th August of 1999 to 2009. Dashed lines show the average frequency of visibility from 8th to 24th August in different visual ranges from 1999 to 2007.

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