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1. Introduction

With the rapid economic development in the Pearl River Delta, the deteriorating trend in visibility of Hong Kong (Chang and Koo, 1986; Cheng *et al.*, 1997; Leung *et al.*, 2004a and 2004b; Lam, 2006) has aroused much public concern.

Visibility is defined as the greatest distance at which a black object of suitable dimensions can be seen and recognized when observed against the horizon sky during daylight or could be seen and recognized during the night if the general illumination were raised to the normal daylight level (WMO, 1992). Apart from fog, mist, rain and other meteorological phenomena involving water droplets, reduced visibility occurs mainly as a result of the absorption and scattering of light by particulates suspended in the atmosphere. Past studies for cities such as Beijing of China (Wang and Liu, 2006), Los Angeles (Adam *et al.*, 1990) and Denver (Groblicki *et al.*, 1981) of the United States show that there is a close relationship between visibility and the concentration of suspended particulate. Visibility is therefore a good visual indicator of air quality. In Hong Kong, Leung *et al.* (2008) show that visibility and suspended particulate with diameter $\leqq$ 2.5 μm (PM2.5) have a strong reciprocal relationship with a correlation coefficient of 0.78, statistically significant at 5% level.

Suspended particulates may be dust of purely natural origin (e.g. loess from northern China). It could also be formed as a result of human activities such as construction, vehicular traffic, fossil-fuel power generation, cooking and burning of vegetation coupled with photochemical processes (Zhou and Shu, 1994; Wang and Xu, 2001; Lam, 2006). For Hong Kong, there has been an on-going debate on the relative significance of local and regional sources of suspended particulates in visibility impairment. But the answer is complex, being quite different depending on how one approaches the subject (Lau *et al.*, 2007). It could be argued that some of the increased turbidity of the atmosphere in Hong Kong is transported to Hong Kong from outside. But, considering the large consumption of energy within Hong Kong itself, which invariably involves combustion of one form or another with its attendant emissions, there is little question that some of this turbidity is locally generated by the urban form of living practised here (Lam, 2006).

As suspended particulates are carried and dispersed by wind, visibility impairment is significantly influenced by this meteorological element. Several past studies (e.g. Cheng *et al.*, 1997; Leung *et al.*, 2004b and 2008) have pointed out qualitatively or demonstrated by case studies the importance of wind, but there has been little systematic quantitative analysis. This paper quantitatively analyses for the first time visibility impairment attributable to wind direction in Hong Kong.

2. Data and Methodology

2.1 Visibility and wind data

This study is based on visibility and wind data in the Hong Kong Observatory archive. Currently, manned visibility observation stations are made at two locations in Hong Kong, one at the Hong Kong Observatory Headquarters (HKO) and the other at the Hong Kong International Airport (HKIA) at Chek Lap Kok. HKO is located at Tsim Sha Tsui, an urban area location and HKIA, near Lantau Island on the eastern side of the Pearl River estuary. At HKO, visibility observations are made hourly by trained observers since 1968. At HKIA, manual observations started in 1997 and automatic instrument readings were made available to observers for reference in making visibility reports in

November 2004. Visibility observations at Chek Lap Kok Island were also conducted in 1980-1982 during which the meteorological conditions of the airport site were investigated.

In line with the global trend towards automated observations including visibility, it has been decided that instrumental visibility readings at HKIA would be archived for climatological purpose from 2005 onwards. Careful comparisons were conducted to ensure that the continuity of visibility climatology at HKIA is preserved in the transition from human observations to instrumental readings (Chan and Shun, 2008).

Following Chang and Koo (1986), reduced visibility in this paper refers to visibility below 8 km, excluding cases of rain, mist, fog and high relative humidity (≧95%).

For the wind attribution analysis, wind data at HKO were not used because the anemometer exposure was handicapped by the many high-rise buildings nearby. Instead, wind data at King's Park (elevation of 65 m) located at a relative open location just 2 km to the north were employed.

2.2 Trend analysis

Long-term trend analysis was carried out for the occurrence frequency of reduced visibility. There are many statistical methods for calculating trends and testing their significance, including parametric methods such as regression and t-test (e.g. Easterling *et al.*, 1997; Karl *et al.*, 1993) and non-parametric methods such as Mann-Kendall test (e.g. Qian and Giorgi, 2000; Quereda Sala *et al.*, 2000). This study adopted the most commonly employed regression method and t-test. Linear regression lines were fitted to the parameters by least squares. The long-term trend could then be inferred from the slopes of these straight lines. Two tailed t-test was applied to test the statistical significance of the trends at 5% significance level.

The test statistics t for testing the null hypothesis H_0: *trend = 0* against the alternative hypothesis H_1: *trend ≠ 0*, is given by:

$$t = r\sqrt{\frac{n-2}{1-r^2}}$$

where r is the correlation coefficient and follows a t distribution with n-2 degrees of freedom.

2.3 Wind attribution analysis

A methodology has been developed to compare the occurrence frequency of reduced visibility in a specific year with that in a reference period, with a view to finding out the relative contributions of the changes in (a) the wind regime and (b) the source of suspended particulate. This is referred to as a "wind attribution analysis". The methodology examines changes in the 12 wind sectors centred at 0°, 30°, 60°, …, 300°, 330°.

Let f_i be the number of hours of wind in sector i, and P_i be the probability of occurrence of reduced visibility when wind is in sector i. Then the total number of hours of reduced visibility N can be expressed as

$$N = \sum_{i=1}^{12} f_i P_i$$

Using the subscript a to denote the average for a certain reference period of several years, j to denote a certain year, we have

$$N_j - N_a = \sum_{i=1}^{12} f_{ij} P_{ij} - \sum_{i=1}^{12} f_{ia} P_{ia}$$

Expressing f_{ij} and P_{ij} as $f_{ij} = f_{ia} + \Delta f_i$, $P_{ij} = P_{ia} + \Delta P_i$ where Δ denotes the change with respect to the reference period. Then

$$N_j - N_a = \sum_{i=1}^{12} (f_{ia} + \Delta f_i)(P_{ia} + \Delta P_i) - \sum_{i=1}^{12} f_{ia} P_{ia} = \sum_{i=1}^{12} \Delta f_i P_{ia} + \sum_{i=1}^{12} f_{ia} \Delta P_i + \sum_{i=1}^{12} \Delta f_i \Delta P_i$$

The first and second terms in the above equation represent the change in number of hours with reduced visibility as attributed by (a) the change in wind frequency and (b) the change in probability of reduced visibility respectively. The second term may also be interpreted, in layman term, as the change in reduced visibility arising from a change in the turbidity of the air such as that due to a high concentration of suspended particulate. The last term is a second-order term in Δf_i and ΔP_i, usually small in magnitude and representing the interaction of the two above factors.

2.4 Trajectory analysis

Backward trajectory analysis is useful in tracing the source of air parcels reaching Hong Kong. This study made use of the Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model from the US National Oceanic and Atmospheric Administration (NOAA), and also the Global Data Assimilation System (GDAS) data from the US National Centre for Environmental Prediction (NCEP) for the computation of backward trajectories. The temporal and spatial resolution of the GDAS data are 6 hours and 1° x 1° respectively.

HYSPIT model was adopted by many researchers (e.g. Chan *et al.*, 2007; Leung *et al.*, 2008) to understand the location of sources of air mass. Theoretical descriptions of how backward trajectories are derived and the operational details of the model are given in Draxier and Rolph

(2003).

3. Results

3.1 Visibility trend

The visibility observed at HKO from 1968 to 2007 has a deteriorating trend (Figure 1). In the first half (1968-1987) of the 40-year period, the rising trend was small (about 53 hours of reduced visibility per decade) though statistically significant at 5% level. However, for the latter half (1988-2007), there has been a dramatic rise in reduced visibility with a statistically significant trend of 580 hours per decade, some eleven times that in the first half. The deteriorating rate accelerated further after 2002. By 2007, the frequency of reduced visibility was about four times that in the seventies and eighties.

Figure 1 also showed that, at Chek Lap Kok where HKIA is now located, the occurrence frequency of reduced visibility has increased substantially in the last decade, compared with the early eighties. The construction and operation of airport, the new town development at Tung Chung nearby as well as the proximity of HKIA to the rapidly developing area of Pearl River Delta are potential factors contributing to this change. The frequency of reduced visibility observed at HKIA was generally higher than that at HKO. The more frequent occurrence of haze at HKIA in comparison to the urban areas is consistent with the findings by Lam (1981a and 1981b) in the early 1980s. This regional difference could be due to wind convergence in the vicinity of HKIA as a result of the local sea breeze circulation pattern (Leung *et al.*, 2004b; Chan and Shun, 2008).

3.2 Wind attribution analysis

The frequency of reduced visibility observed at both HKO and

HKIA fluctuated within a relatively narrow range in the period 1997-2002 but then rose noticeably thereafter (Figure 1). For this reason, a wind attribution analysis for the last five years viz. 2003, 2004, 2005, 2006 and 2007 was conducted using 1997-2002 as the reference period. The results of the wind attribution analysis at HKO and HKIA are summarized in Table 1 and 2 respectively. In the tables, the 12 wind sectors mentioned in Section 2.3 are grouped broadly into three regions (Figure 2a and 2b):

(a) “West to North” region – air generally from areas such as the Pearl River Delta to the west and north of Hong Kong;

(b) “Northeast to Southeast” region – coastal air mass generally from southeastern coastal areas of China to the east of Hong Kong; and

(c) “South” region – maritime air mass generally from the South China Sea.

Table 1 and 2 show that at both HKO and HKIA, the increase in the annual number of hours of reduced visibility as compared to the average that in 1997-2002 was mainly due to the increase in probability of reduced visibility for the various specified wind sectors, in other words, turbidity of the air. In the most recent period 2005-2007, its contribution exceeded 90%. The contribution from change in the wind frequency regime was much smaller (of the order of 10% or less). The residual contribution arising from the interaction of changes in wind frequency and probability (that is, second-order term mentioned in Section 2.3) was also small.

At HKO, the change in the wind frequency regime accounted for only 6% or less for the change in the annual number of hours with reduced probability observed. In contrast, the change in the probability of reduced visibility in specified wind sectors (that is, the “turbidity” factor) accounted for at least 88% in the individual years. Figure 3 showed that the increases in this "turbidity" factor in recent years as compared with the 1997-2002 average was large, especially in the "West to North" and "Northeast to Southeast" sectors. Because climatologically, winds at King's Park were more frequent in the "Northeast to Southeast" sector than the "West to North" sector, the contribution of the "Northeast to Southeast" sector to the increase in the annual number of hours of reduced visibility amounted to 59-80%, which was higher than that of the "West to North" sector (14-34%). The "South" sector only accounted for 2-12% (see item 2 in Table 1).

At HKIA, the change in the wind frequency regime and the change in the "turbidity" factor accounted for 4-16% and 81-91% respectively of the change in the annual number of hours with reduced visibility (Table 2). Similar to the situation at HKO, the increase in the "turbidity" factor in recent years when compared with the 1997-2002 average (Figure 4) was also large and occurred in nearly all directions. In contrast to HKO, Figure 4 also showed that the "turbidity" factor was much higher for the "West to North" sector than the "Northeast to Southeast" sector in 1997-2002. As in the previous study results on haze in 1979-1982 (Lam, 1981a and 1981b), this could be related to the geographical location of HKIA on the Pearl River estuary, with the Pearl River delta region located in the "West to North" sector. In recent years, the increase in "turbidity" factor in the "Northeast to Southeast" region was prominent when compared with that of the 1997-2002 average. For example, as Figure 4 shows, the value of probability in the sector centred at 90° increased from 0.09 (1997-2002 average) to 0.28 and 0.24 in 2006 and 2007 respectively. It hints that the loading of suspended particulates in air from places to the east including the southeastern coastal areas of China as well as Hong Kong itself has increased. Coupled with the fact that winds from the "Northeast to Southeast" sector is climatologically dominant, the contribution of the "Northeast to Southeast" sector is slightly higher than that of the "West to North" sector (see item 2 in Table 2).

3.3 Backward trajectories

By using the HYSPLIT model, daily backward trajectories were computed. In Hong Kong, backward trajectories can be generally classified into three categories: continental, coastal and maritime (Leung *et al.*, 2008). Hong Kong is situated in the East Asian monsoon region. In winter, under the dominance of northeast monsoon, the majority of the trajectories is continental. However, under the southwest monsoon in summer, the trajectories are mainly maritime in nature.

The daily positions of the air mass 24 hours before reaching HKO and HKIA at 100 m aloft at 8 a.m. of the individual days in 2007 were plotted in Figure 5 and 6 respectively. For the cases with 12 hours or more of reduced visibility observed at HKO on the day of arrival, almost all the 24-hour positions were in continental or southeastern coastal areas of China (Figure 5). Similar finding is also noted for the reduced visibility observed at HKIA (Figure 6).

Similar analyses were conducted but for a height of 500 m (Figure 7 and 8) above Hong Kong. The results also showed that most of the 24-hour positions were in continental or southeastern coastal areas of China.

4. Conclusion and Discussion

The visibility in Hong Kong has a significant deteriorating trend in the past 20 years. By 2007, the frequency of reduced visibility (< 8 km excluding cases with fog, mist, rain or relative humidity $\geqq$ 95%) was about four times that in the seventies and the eighties. The rising rate increased significantly after 2002.

The wind attribution analysis results showed that in the most recent years (2003 – 2007), the increase in the number of hours with reduced visibility is mostly attributable to the “turbidity” factor in certain wind sectors. The effect of inter-annual variations in the frequency of wind from different directions was rather small.

According to the observations at the Hong Kong Observatory Headquarters in recent years, the probability of reduced visibility in the "West to North" and "Northeast to Southeast" sectors was much higher than that of the 1997-2002 average. The contribution of the changed "turbidity" factor in the "Northeast to Southeast" sector accounted for most of the significant increase in the number of hours with reduced visibility after 2002, at least 59% (2004).

Similar analysis results were obtained for the Hong Kong International Airport. However, the contribution to the increase in reduced visibility after 2002 of the "West to North" sector was comparable to that in the "Northeast to Southeast" sector. This regional difference between the Hong Kong International Airport and the Hong Kong Observatory Headquarters could be related to their geographical locations.

Computations of daily backward trajectories in 2007 were carried out and the positions of the air mass 24 hours before arriving at Hong Kong were plotted. The results showed that the air mass for days with high number of hours of reduced visibility mainly originated from continental and southeastern coastal areas of China.

Apart from wind direction at the observation site, meteorological factors such as wind speed and atmospheric stability as well as mesoscale circulation patterns such as land/sea breezes also play an important role in the transportation and dispersion (or accumulation) of suspended particulates, with a bearing on visibility. Further attribution studies to take into account these factors would help to elucidate the problem further.

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Table 1. Attribution analysis for the increase in the number of hours with reduced visibility observed at the Hong Kong Observatory Headquarters with respect to 1997-2002. Reduced visibility refers to visibility below 8 km excluding cases of rain, mist, fog and high relative humidity (≧95%).

Attribution	Percentage contribution to the increase in number of hours with reduced visibility				
	2003	2004	2005	2006	2007
(1) Due to change in wind frequency	-6%	1%	-2%	5%	6%
(2) Due to increase in probability of reduced visibility for specified sector	91%	88%	97%	96%	97%
(a) Wind sector: "West to North"	28%	17%	23%	14%	34%
(b) Wind sector: "Northeast to Southeast"	60%	59%	66%	80%	59%
(c) Wind sector: "South"	3%	12%	8%	2%	4%
(3) Arising from interaction of (1) & (2)	15%	11%	5%	-1%	-3%

* Owing to the very low wind frequency in the sector centred at 300˚, the probability in this sector is computed as the average of that in the two neighbouring sectors centred at 270°and 330°.

Table 2. Attribution analysis for the increase in the number of hours with reduced visibility observed at the Hong Kong International Airport with respect to 1997-2002. Reduced visibility refers to visibility below 8 km excluding cases of rain, mist, fog and high relative humidity (≧95%).

Attribution	Percentage contribution to the increase in number of hours with reduced visibility				
	2003	2004	2005	2006	2007
(1) Due to change in wind frequency	16%	11%	5%	6%	4%
(2) Due to increase in probability of reduced visibility for specified sector	81%	81%	91%	91%	91%
(a) Wind sector: "West to North"	38%	30%	33%	25%	35%
(b) Wind sector: "Northeast to Southeast"	32%	43%	49%	50%	40%
(c) Wind sector: "South"	11%	8%	9%	16%	16%
(3) Arising from interaction of (1) & (2)	3%	8%	4%	3%	8%

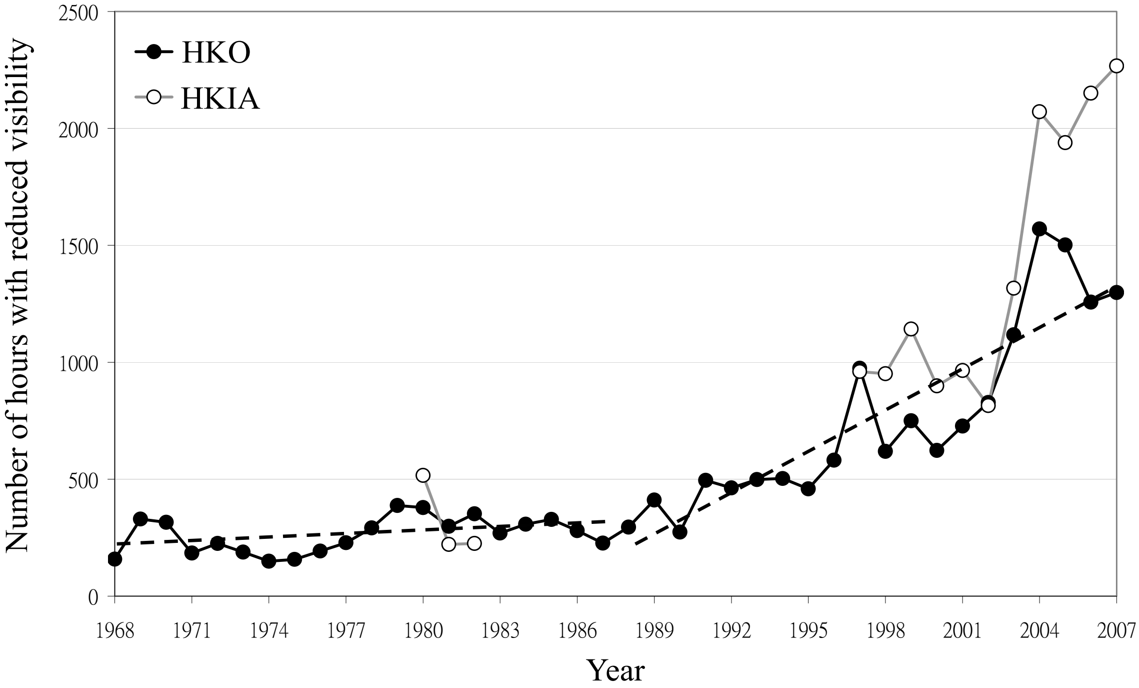
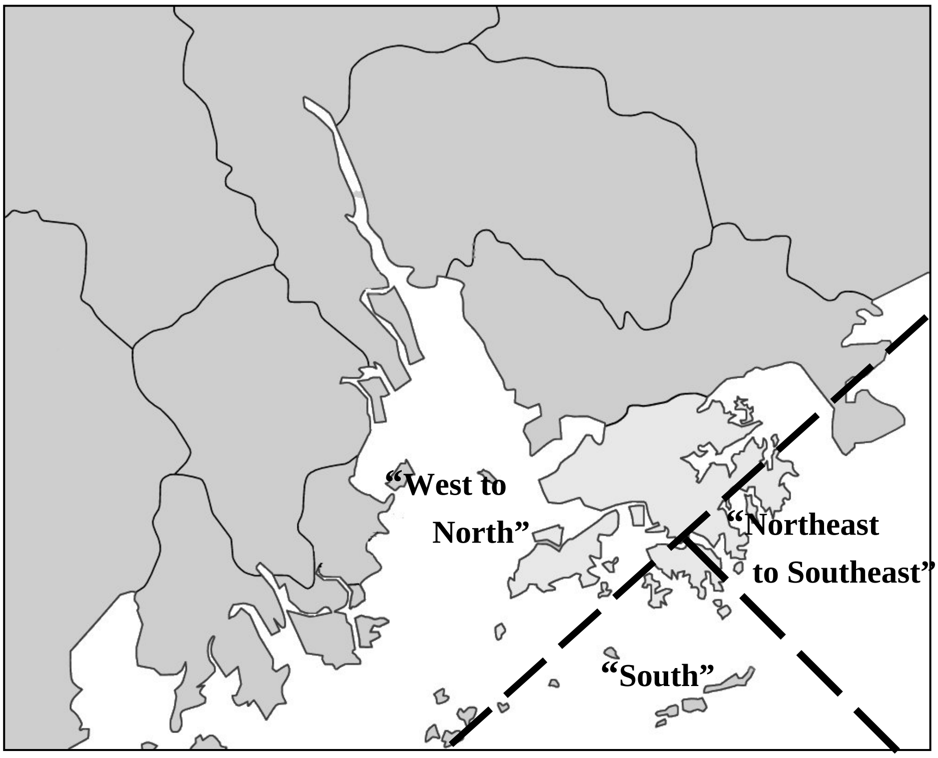
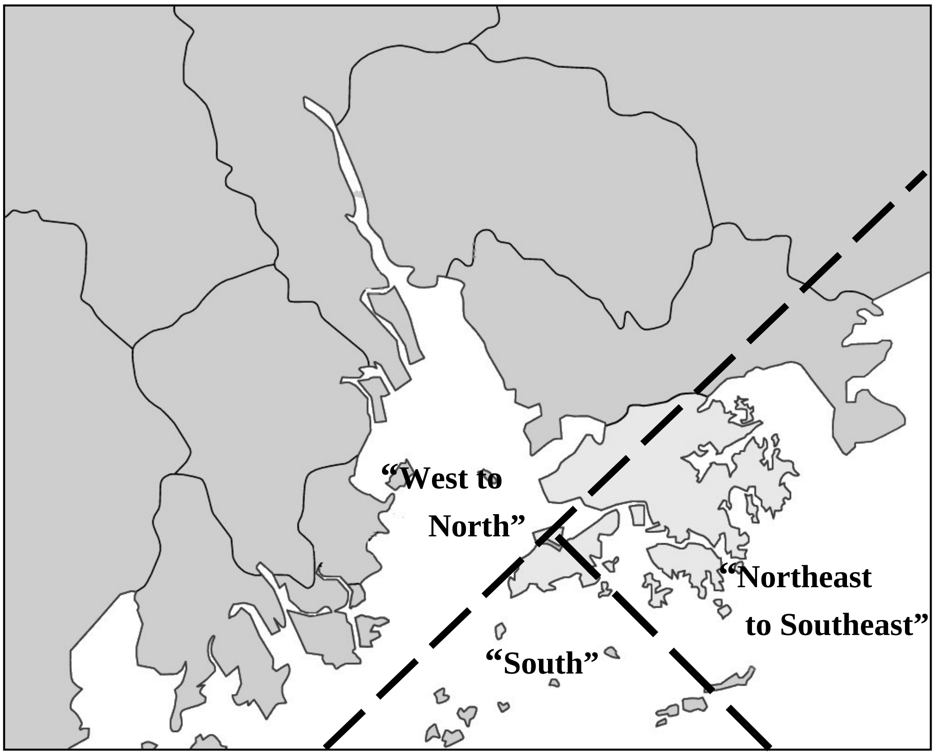


Figure 1. Time series of annual number of hours with reduced visibility observed at the Hong Kong Observatory Headquarters (HKO) and at Chek Lap Kok (now the Hong Kong International Airport (HKIA)) respectively. Reduced visibility refers to visibility below 8 km excluding cases of rain, mist, fog and high relative humidity (≧95%).



(a) Hong Kong Observatory Headquarters



(b) Hong Kong International Airport

Figure 2. Division boundaries of the three regions: "West to North", "Northeast to Southeast" and "South" for observations at the (a) Hong Kong Observatory Headquarters and (b) Hong Kong International Airport.

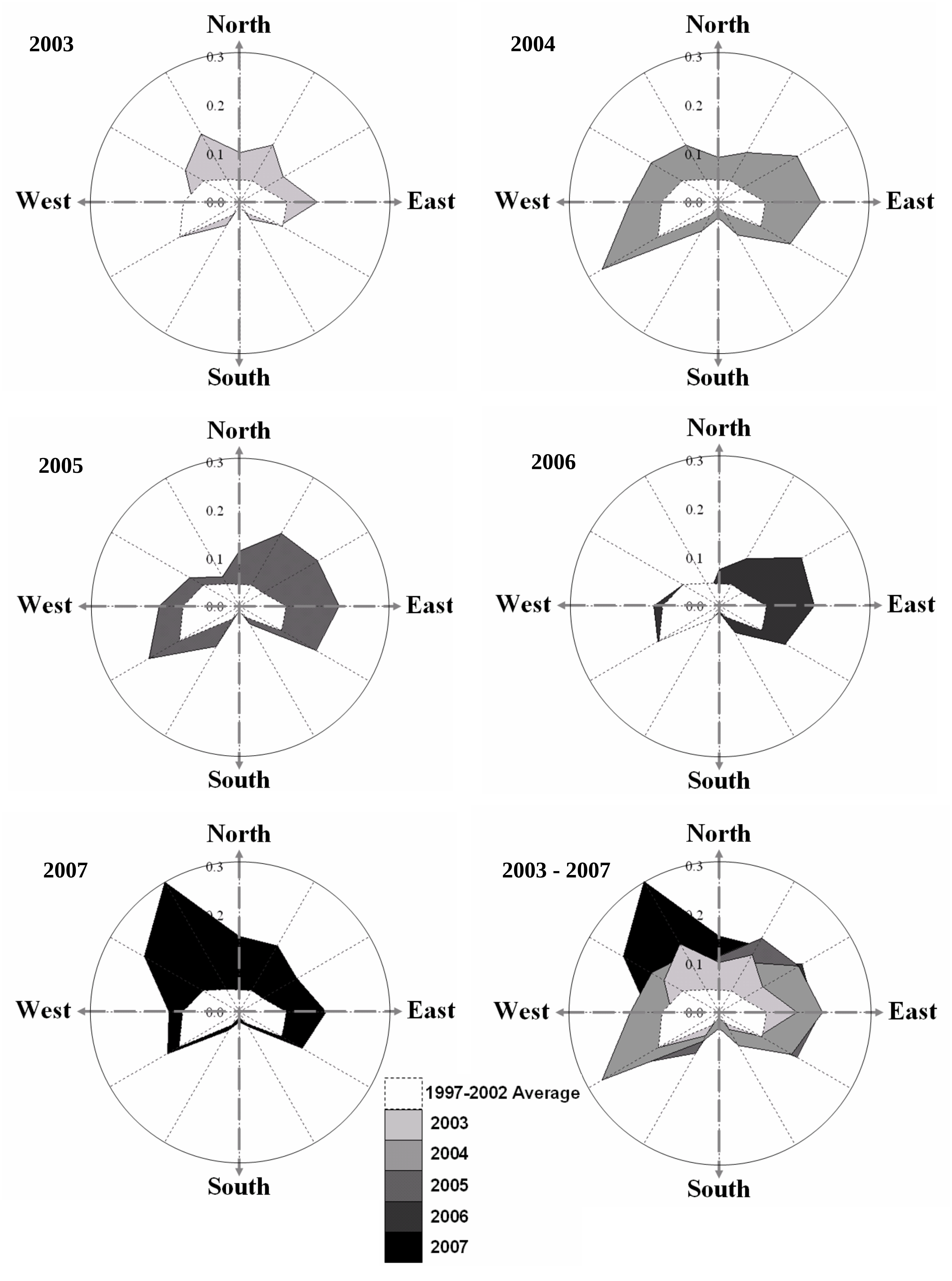


Figure 3. Relationship between probability of reduced visibility observed at the Hong Kong Observatory Headquarters and wind direction at King's Park (Owing to the very low wind frequency in the sector centred at 300˚, the probability in this sector is computed as the average of that in the two neighbouring sectors centred at 270° and 330°).

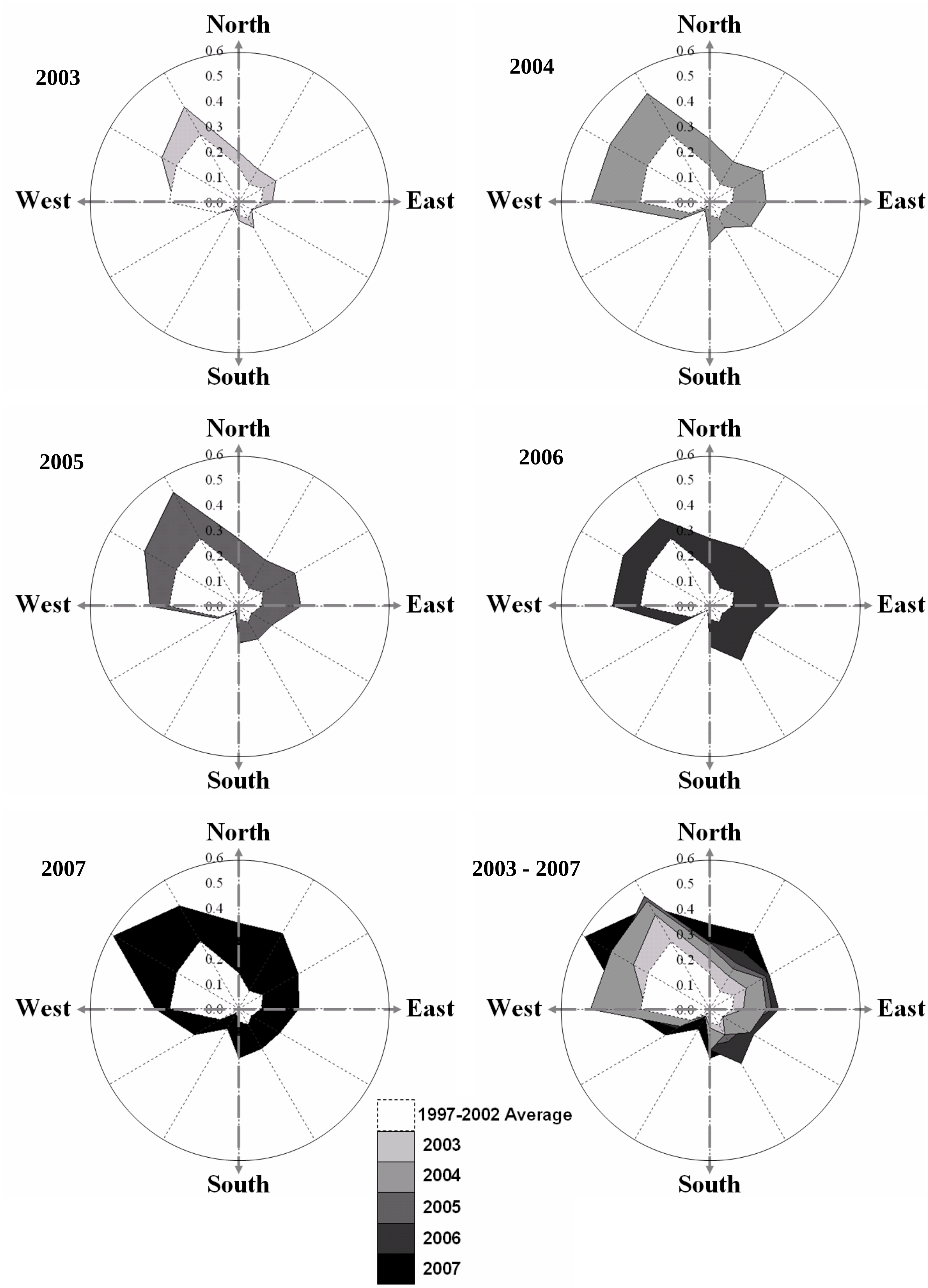


Figure 4. Relationship between probability of reduced visibility and wind direction observed at the Hong Kong International Airport.

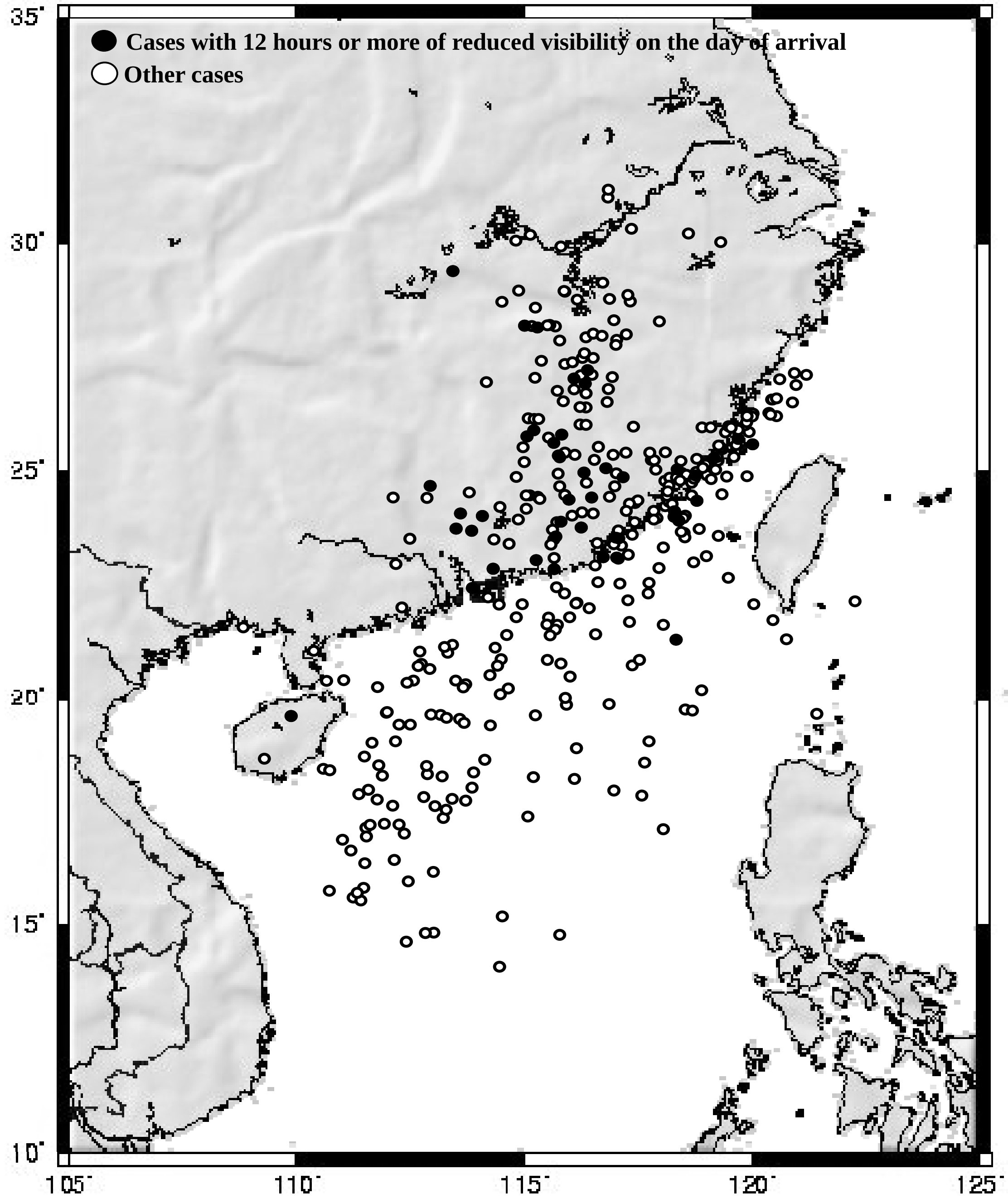


Figure 5. Positions of air mass 24 hours before arriving at the Hong Kong Observatory Headquarters (HKO) at a height of 100 m aloft at 8 a.m. For cases with daily number of hours of reduced visibility observed at HKO equal to 12 or above on the day of arrival, the positions are marked in black dots.

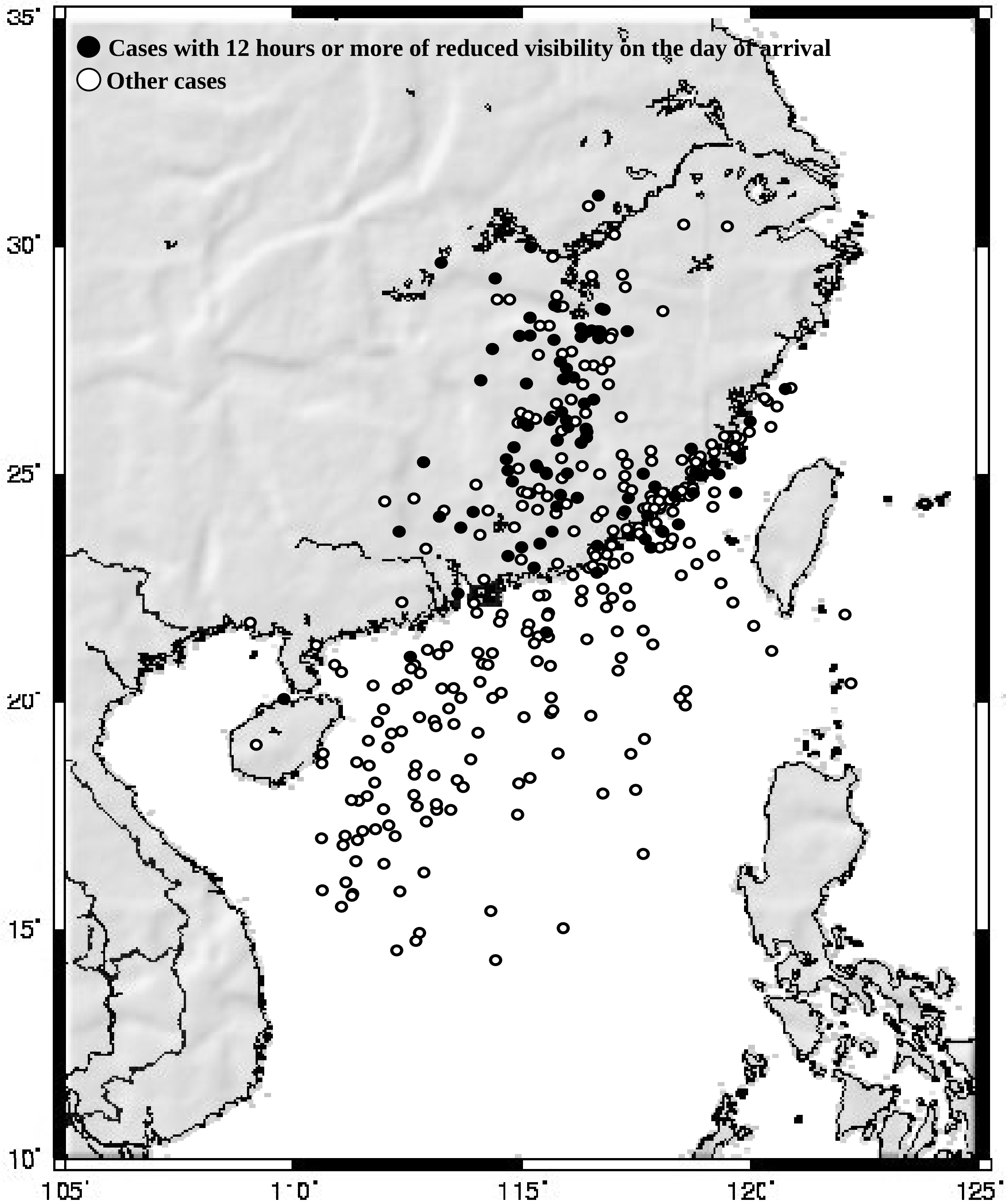


Figure 6. Positions of air mass 24 hours before arriving at the Hong Kong International Airport (HKIA) at a height of 100 m aloft at 8 a.m. For cases with daily number of hours of reduced visibility observed at HKIA equal to 12 or above on the day of arrival, the positions are marked in black dots.

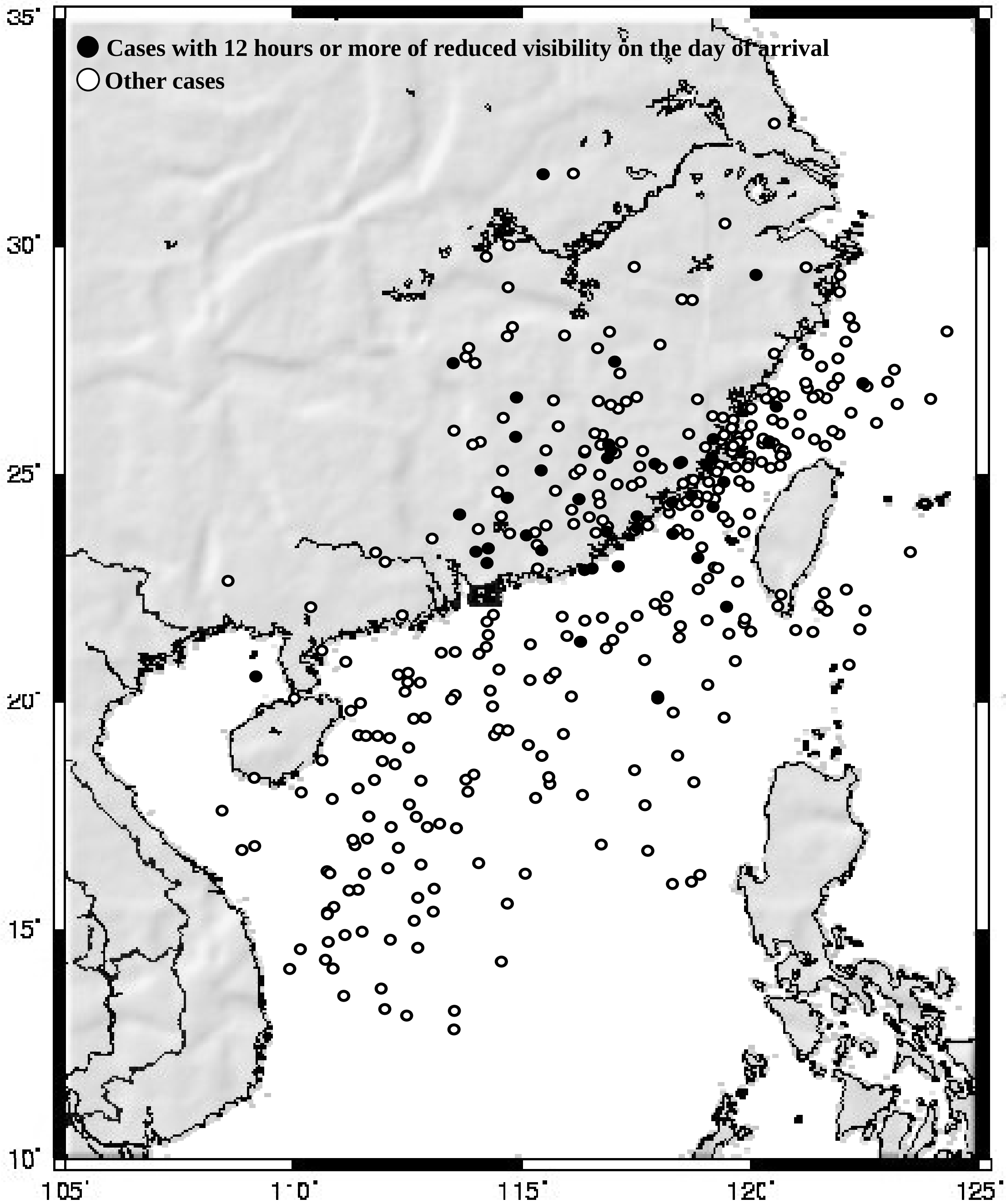


Figure 7. Positions of air mass 24 hours before arriving at the Hong Kong Observatory Headquarters (HKO) at a height of 500 m aloft at 8 a.m. For cases with daily number of hours of reduced visibility observed at HKO equal to 12 or above on the day of arrival, the positions are marked in black dots.

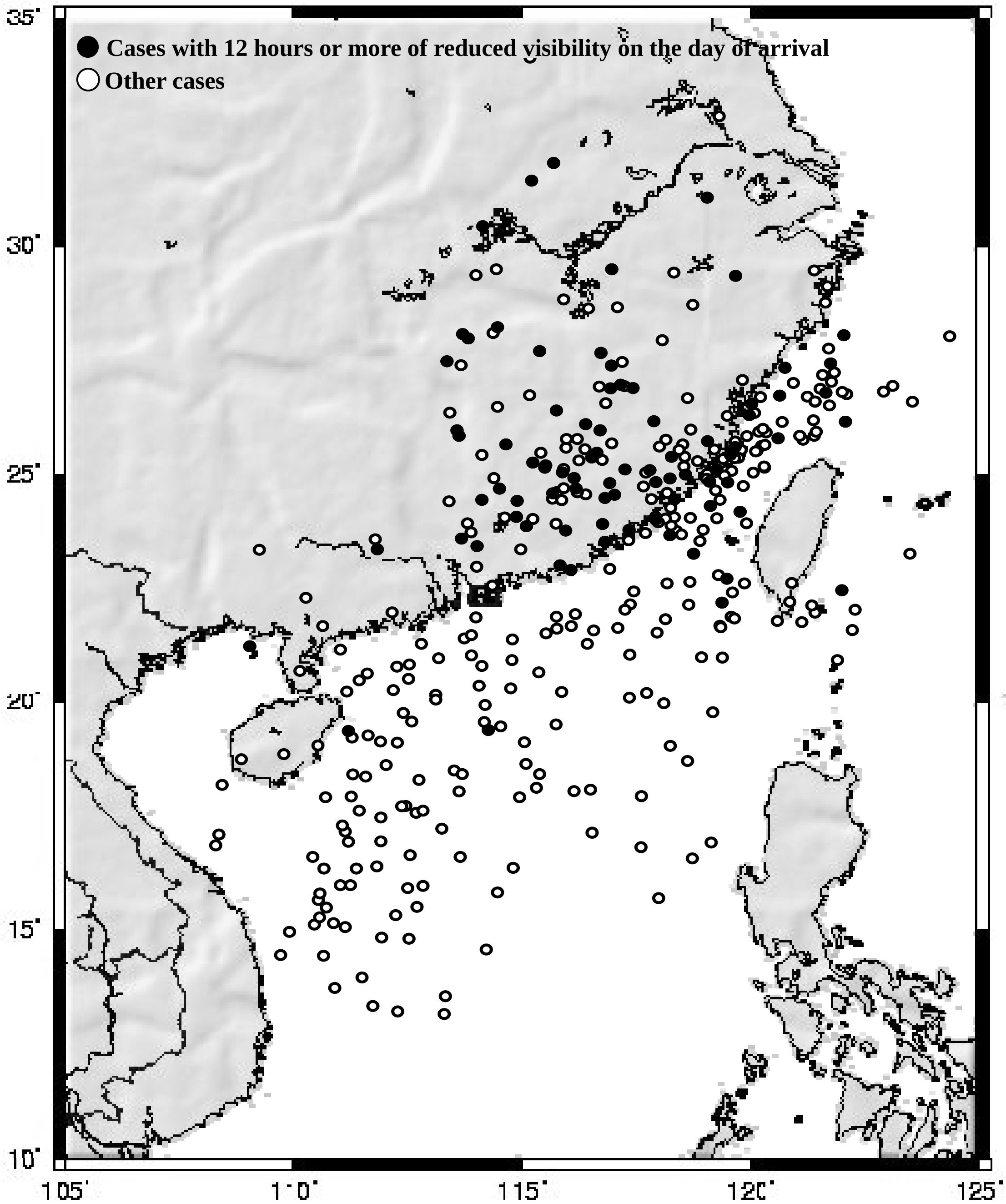


Figure 8. Positions of air mass 24 hours before arriving at the Hong Kong International Airport (HKIA) at a height of 500 m aloft at 8 a.m. For cases with daily number of hours of reduced visibility observed at HKIA equal to 12 or above on the day of arrival, the positions are marked in black dots.