

1 **Analyses of winter circulation types and their impacts on haze pollution in Beijing**

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13

14 Abstract: For a better understand the interannual variation of winter haze pollution, this study
15 classifies winter circulation types and investigates their impacts on local meteorology and haze
16 pollution from 1980 to 2017 in Beijing. Circulation types are classified by T-mode principal
17 component analysis combined with the K-means cluster method using European Centre for Medium-
18 range Weather Forecasts ERA-interim sea level pressure data. The results can effectively distinguish
19 the cold air-mass processes, degeneration of cold air-mass, and stagnant weather conditions. Usually,
20 cold air-mass process over Beijing is accompanied by a low temperature, high relative humidity, large
21 pressure gradient and near-surface wind speed, and deep mixing layer. The cold air-mass process
22 facilitates pollutants dispersion and transport them outside Beijing, and hence lower PM_{2.5}
23 concentration and frequencies of haze events. In contrast, the local meteorology and haze pollution
24 were almost the inverse for stagnant weather. The local meteorological conditions and haze pollution
25 for the degeneration of cold air are between the previous circulation types. Based on PM_{2.5}
26 observation during 2010-2017, the occurrence frequency of cold air was low in the recent winters of
27 2013, 2014 and 2017, and resulted in severe PM_{2.5} pollution. High frequency of stagnant weather
28 (48.4%) was one of the reasons that haze pollution reached 37% during 1980-2017 over Beijing. The
29 time series of haze frequency was negatively correlated with that of cold air frequency. During 38

30 winters from 1980 to 2017, a decreased trend of haze days was found, which was partly related to an
31 increased trend of cold air frequency. However, the trends of haze days and cold air in Beijing were
32 not significant based on regression analysis.

33
34 Keywords: circulation types, local meteorology, haze pollution, PM_{2.5}

35 **1. Introduction**

36 Haze is defined as large amounts of inactivated fine particles floating in the atmosphere that result
37 in low visibility (less than 10 km) and turbid air. It is a weather phenomenon and a natural weather
38 disaster (Zhang et al., 2013). With rapid economic development, haze pollution has occurred
39 frequently and has attracted attention from governments, the public, and researchers. Severe haze,
40 which is mainly caused by serious aerosol pollution, is not a completely natural phenomenon in China
41 (Zhang et al., 2013). And it also affects meteorological processes, such as precipitation (Guo et al.,
42 2016). The formation of haze decreases atmospheric visibility, affects the production and daily live,
43 and has an adverse impact on human health (An et al., 2015). Unfortunately, at least 30% of the area
44 and nearby 800 million people in China are affected by different degrees of haze (Che et al., 2009).
45 There were relatively few annual haze days in the 1960s, but they increased sharply in the 1970s,
46 remained stable to 1995, and then increased from 1995 to 2012 in North China Plain (Chen et al.,
47 2015). Understanding the formation mechanisms of haze is very important for haze prevention.

48 Pollutant emission and meteorological conditions are two key factors for haze pollution, and high
49 pollutant emission is the primary cause. According to the China Statistical Yearbook, the emission of
50 sulfur dioxide, nitric oxide and dust reached 1.86×10^7 , 1.85×10^7 , and 1.54×10^7 tons, respectively, in
51 2015 (<http://www.stats.gov.cn/tjsj/ndsj/2016/indexch.htm>). Meteorological condition is another
52 important factor for haze pollution. Meteorological parameters, such as temperature, relative humidity,
53 wind speed, and boundary layer height, are significantly correlated with pollutant concentrations in
54 most Chinese cities and explained more than 70% of the variance of daily average pollutant
55 concentrations (He et al., 2017a). In January 2013, a persistent severe haze event occurred over
56 eastern China. Unusual meteorological conditions were responsible for this persistent severe haze
57 event (Zhang et al., 2014). The long term trend of haze is regional and seasonal dependent. Haze
58 showed decreasing trends during 30 winters from 1981 to 2010, while summertime haze displayed

59 continuous increasing trends, and obvious regional difference of haze trends was detected in southern
60 Hebei province (Fu et al., 2014). The weakening of near-surface winds during 1985-2005 caused the
61 increase in winter haze days over eastern China (Yang et al., 2016). At different spatial scales,
62 meteorological conditions can be divided into a large-scale circulation type and local meteorological
63 conditions. The circulation type governs local meteorological conditions and is effective in the
64 identification of haze pollution (Oanh et al., 2005); it is the main factor driving the day-to-day
65 variations in pollutant concentrations (Lee et al., 2012). Although many studies have investigated the
66 relation between circulation type and haze pollution (or air quality) (Demuzere et al., 2009; He et al.,
67 2016a; He et al., 2017a; Jiang et al., 2014; Jiang et al., 2016; Lee et al., 2012; Oanh et al., 2005;
68 Pearce et al., 2011; Zhang et al., 2012), this relation can also vary with time, location and pollutants
69 (Jiang et al., 2017).

70 Beijing, as the capital of China, has frequently suffered severe haze pollution in winter. Many
71 pollutant emission sources surround Beijing, and local vehicle emissions, special terrain and
72 meteorological conditions are the main reasons for haze pollution in Beijing (He et al., 2016b).
73 Horizontal transport of pollutants, which is affected by atmospheric circulation, may be the most
74 important factor determining the air quality of Beijing (Miao et al., 2017). Some studies have focused
75 on the relation between circulation types and air pollution in Beijing and the surrounding region (Chen
76 et al., 2008; Chen et al., 2009; Li et al., 2012; Meng and Cheng, 2002; Miao et al., 2017; Zhang et al.,
77 2012). However, few studies have analysed the long-term winter circulation types by using an
78 objective method and investigated their relationships with haze pollution in Beijing and surrounding
79 regions. This article extends our previous work (He et al., 2017b) by using long-term data to
80 investigate the thermal and dynamical characteristics of circulation types and their impacts on local
81 meteorological conditions and haze pollution over Beijing. Because haze pollution is most severe in
82 winter, this paper focuses on the winter circulation type. This result can help us understand the
83 development of haze events and is useful for haze forecasting and prevention over Beijing and similar
84 areas.

85 **2. Data and method**

86 **2.1 Meteorological data**

87 The European Centre for Medium-range Weather Forecasts (ECMWF) ERA-interim reanalysis

88 data (<https://www.ecmwf.int/en/research/climate-reanalysis/era-interim>) for 38 winters (December to
89 February) from 1980 to 2017 were used in this study. The spatial and temporal resolutions of ECMWF
90 ERA-interim data are 0.25° and 6 hours (i.e., 08:00, 14:00, 20:00, 02:00 local standard time every
91 day), respectively. Sea Level Pressure (SLP) for the area of 110°E-125°E/35°N-45°N was used to
92 identify circulation type following previous studies (He et al., 2017b; Jiang et al., 2017; Zhang et al.,
93 2012). Temperature and dew point temperature at 850 hPa, 700 hPa, and 500 hPa from the ECMWF
94 ERA-interim reanalysis data were used to calculate the K index, which represents atmospheric
95 thermal unstable capacity in the middle-low troposphere (Zhang et al., 2014). The equation for the K
96 index is given in following:

$$97 \quad K = (T_{850} - T_{500}) + T_{d850} - (T_{700} - T_{d700}) \quad (1)$$

98 where K is the K index and T_{850} , T_{700} , and T_{500} are temperatures at 850 hPa, 700 hPa, and 500
99 hPa, respectively. T_{d850} and T_{d700} are the dew point temperatures at 850 hPa and 700 hPa,
100 respectively. According to the definition of the K index, a larger K index represents a more unstable
101 middle-low tropospheric atmosphere.

102 Near-surface daily climatological data (including daily average temperature, relative humidity,
103 wind speed and wind direction) during 38 winters from 1980 to 2017 at Beijing station were acquired
104 from the National Meteorological Information Center (<http://data.cma.cn/site/index.html>). These
105 datasets were used to construct a relation between circulation type and local meteorological
106 conditions. The location of Beijing station is shown in Figure 1.



107
108 Figure 1. The location of air quality monitoring stations (American Embassy) and meteorological

109 station.

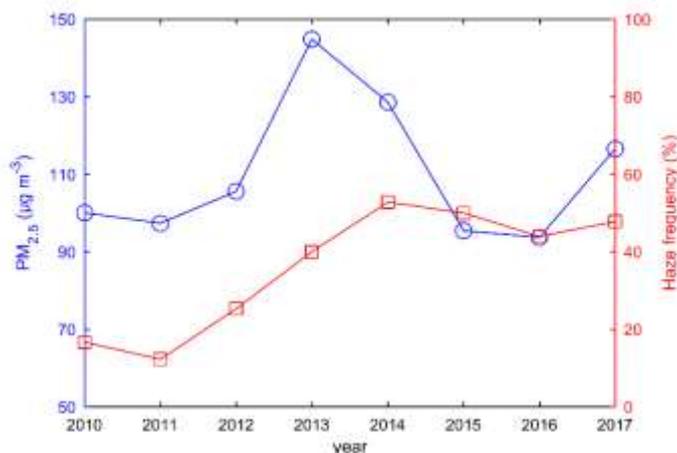
110 **2.2 Air quality data**

111 Haze is mainly caused by aerosol pollution (Zhang et al., 2013). A new ‘Ambient air quality
112 standard’ was published in 2012 by the Ministry of Environmental Protection and the General
113 Administration of Quality Supervision, Inspection and Quarantine of China. Particulate matter with
114 aerodynamic diameter less than 2.5 μm ($\text{PM}_{2.5}$) was introduced in the air quality index system for the
115 first time in China. However, long-term continuous observation of $\text{PM}_{2.5}$ is few in China. $\text{PM}_{2.5}$
116 concentration was observed and released (<http://www.stateair.net/web/post/1/1.html>) since 2008 in
117 American Embassy in Beijing (Figure 1). The monitoring station represents urban-traffic type in
118 Beijing. Considering data integrity, $\text{PM}_{2.5}$ concentrations in American Embassy during 8 winters from
119 2010 to 2017 were used to analyze the impact of circulation type on aerosol concentration. The data
120 quality control method for $\text{PM}_{2.5}$ concentration is described in our previous study (He et al., 2017a).

121 **2.3 Haze days**

122 With an increase in humidity, hygroscopic growth occurs on fine particles, which then activate as
123 cloud condensation nuclei and finally convert haze to fog. Visibility, particulate matter and relative
124 humidity are thus three important properties of haze. Because of the absence of long-term particulate
125 matter observation, only days with visibility less than 10 km and relative humidity less than 90% are
126 defined as haze days based on previous studies (Yang et al., 2016). Based on visibility and relative
127 humidity, winter haze days from 1980 to 2017 at Beijing station were obtained from the National
128 Meteorological Information Centre.

129 Aerosol scattering and absorption of visible light deteriorate atmospheric visibility. Haze pollution
130 is closely related to the loading of aerosol. Time series of average $\text{PM}_{2.5}$ concentration and occurrence
131 frequency of haze days are shown in Figure 2. Relatively low $\text{PM}_{2.5}$ concentration accompany with a
132 high occurrence frequency of haze is observed in 2015 and 2016. The possible reason maybe the
133 change of relative humidity or chemical components of $\text{PM}_{2.5}$ which affects optical characteristics of
134 aerosol.



135

136 Figure 2. Time series of average PM_{2.5} concentration and occurrence frequency of haze days during
 137 8 winters from 2010 to 2017.

138 2.4 Circulation types

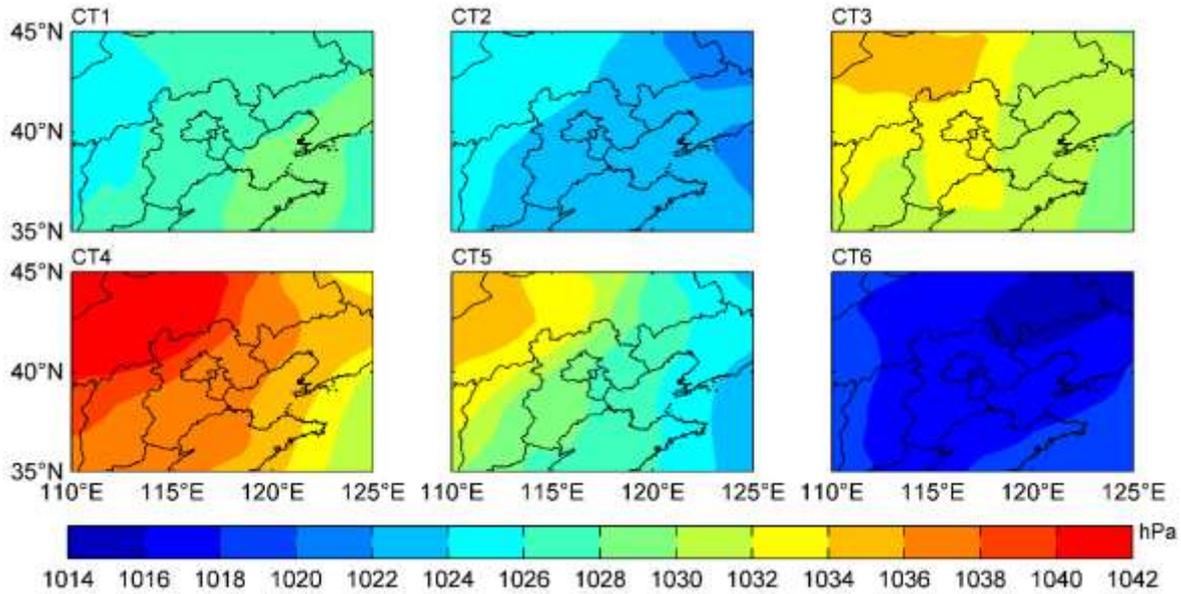
139 Five main circulation classification techniques, namely the correlation method, cluster analysis,
 140 principal component analysis (PCA), the fuzzy method, and nonlinear methods, have been frequently
 141 used to classify circulation types (Zhang et al., 2012). In this study, T-mode PCA combined with K-
 142 means cluster is used, because previous researchers have proposed this is the best approach for
 143 revealing data structures and effectively identifying circulation types (Huth, 1996). And this method
 144 has been widely used in previous studies in China (He et al., 2016a; He et al., 2017a; He et al., 2017b;
 145 Miao et al., 2017; Zhang et al., 2012). Data processing to determine circulation type included five
 146 steps. First, three-dimensional ERA SLP grid data (longitude × latitude × time) was reshaped to two-
 147 dimensional data (grid × time). Second, data was normalized using z-scores method. Third, the
 148 normalized data performed PCA. Fourth, main components were acquired according to the
 149 cumulative variance contribution of 85%. Fifth, the main components were clustered using the K-
 150 means cluster, and synoptic-scale circulations were ascertained based on cluster results. The number
 151 of clusters depends on the criterion function (Liu and Gao, 2011), and the inflection of the criterion
 152 function represents the optimal number of clusters. Finally, six circulation types were determined (i.e.,
 153 CT1 to CT6). The weather and diffusion characteristics of six circulations are discussed in the
 154 following.

155 **3. Results and Discussion**

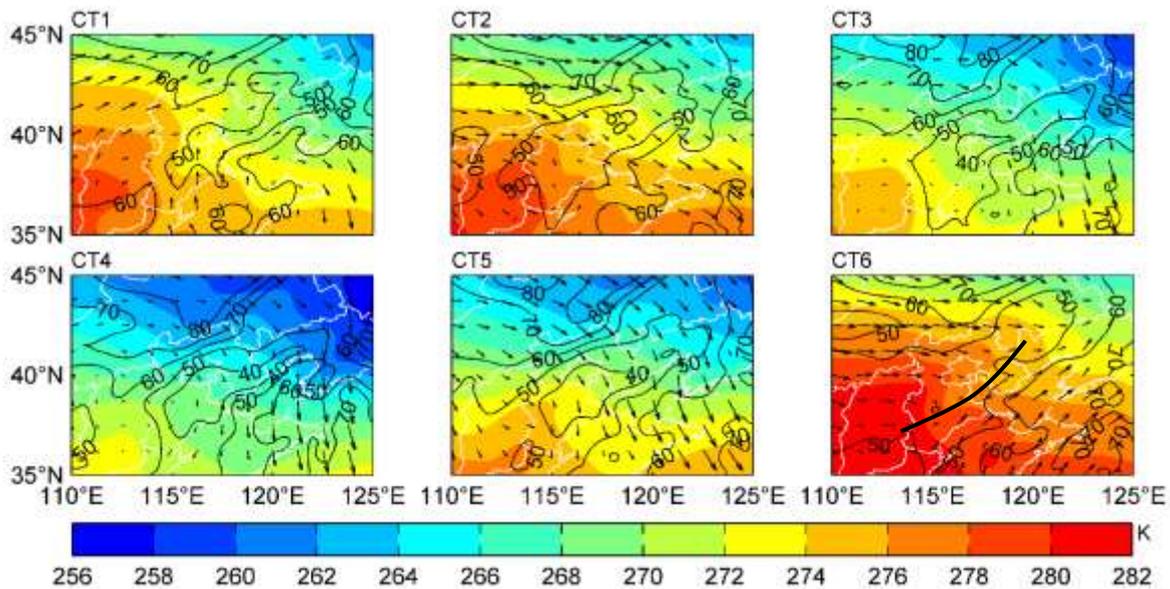
156 **3.1 Circulation types and weather characteristics**

157 Winter climate characteristics in North China are closely related to the winter monsoon. Previous
158 studies have revealed that a strong winter monsoon is beneficial to pollutant dispersion over Beijing
159 and surrounding regions (Liu et al., 2017). The change of winter circulation types is a direct indicator
160 of winter monsoon intensity. Using the T-mode PCA combined with the K-means cluster, six
161 circulation types are identified. The meteorological fields at each moment are assigned to one
162 circulation type. The mean meteorological fields for six circulation types are calculated. Figure 3
163 shows the mean SLP of six circulation types. According to the spatial distribution of SLP, CT4 showed
164 the strongest cold air synoptic process in North China, with a cold high pressure that reached 1040
165 hPa and covered Inner Mongolia. Figure 4 shows the spatial distribution of meteorological fields for
166 six circulation types at 1000 hPa. Most parts of North China were controlled by north winds for CT4.
167 The bottom of high pressure formed an obvious anti-cyclone. A southwest-northeast dry belt was
168 located in the centre of North China and the temperature gradient was large. Low temperature, low
169 relative humidity, and high wind speed were typical weather characteristics over Beijing for the CT4
170 circulation type. The cold air synoptic process of CT5 was weaker than that of CT4. Compared with
171 CT4, similar weather characteristics for CT5 were found in North China (Figure 3). CT3 was a
172 degeneration of cold air in North China. The pressure gradient of CT3 was significantly smaller than
173 that of CT4 and CT5. Although the meteorological pattern was similar to that of CT4 and CT5, the
174 wind speed (temperature) decreased (increased) remarkably over Beijing. With small pressure
175 gradients, CT1, CT2 and CT6 are typical stagnant weather. For CT1, Beijing was in the rear of a weak
176 high-pressure system. Most parts of North China were controlled by southern and southwestern wind.
177 The temperature and humidity in Beijing and surrounding regions were affected by warm advection
178 and water vapour transport were relatively high. For CT2, weak northwest wind covered most parts
179 of North China. Wind decreases significantly from northwest to southeast of North China. Spatial
180 distribution of wind was unfavourable for the ventilation capacity over Beijing. For CT6, a weak low-
181 pressure system existed in Northeast China, and the pressure gradient was very weak in North China.
182 Affected by surface pressure, the northwest region of Beijing was covered by western wind, whereas
183 the southeast region to Beijing was covered by southwest wind. The change of the wind field formed

184 a convergence zone. Atmospheric block resulted in low wind speed over Beijing. Temperatures were
 185 high over Beijing because of warm advection (Figure 4). Based on characteristics of meteorological
 186 fields over Beijing and surrounding areas, CT4 and CT5 can be defined as the cold air process, CT3
 187 is defined as weak or degenerate cold air, CT1, CT2 and CT6 are defined as stagnant weather.



188
 189 Figure 3. Mean sea level pressure of six circulation types during 38 winters from 1980 to 2017.



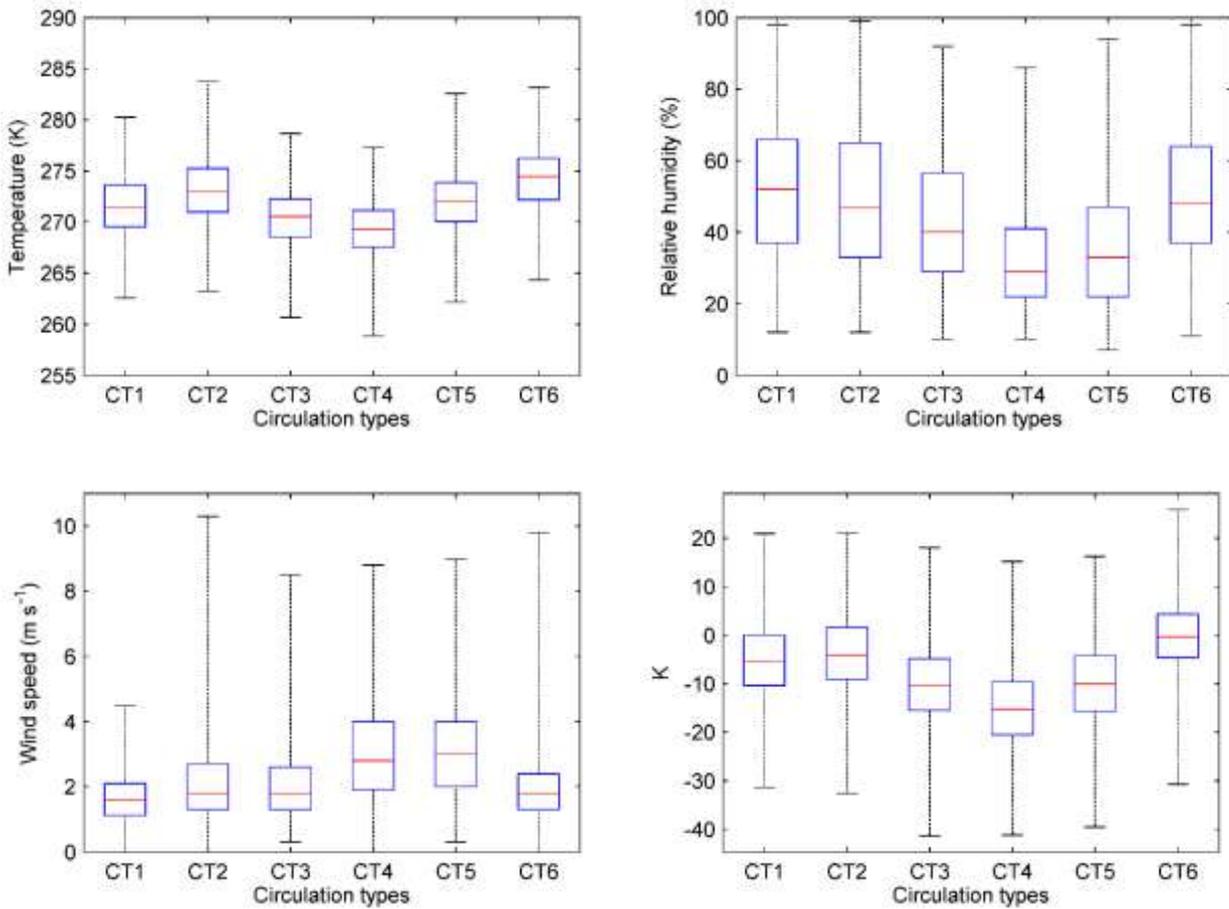
190
 191 Figure 4. Mean temperature (shade), relative humidity (contour line), and wind field (arrow) of six
 192 circulation types at 1000 hPa during 38 winters from 1980 to 2017. Black lines represent convergence
 193 lines.

194 Based on statistical analysis, the occurrence frequencies for CT1 to CT6 were 16.5%, 19.1%,

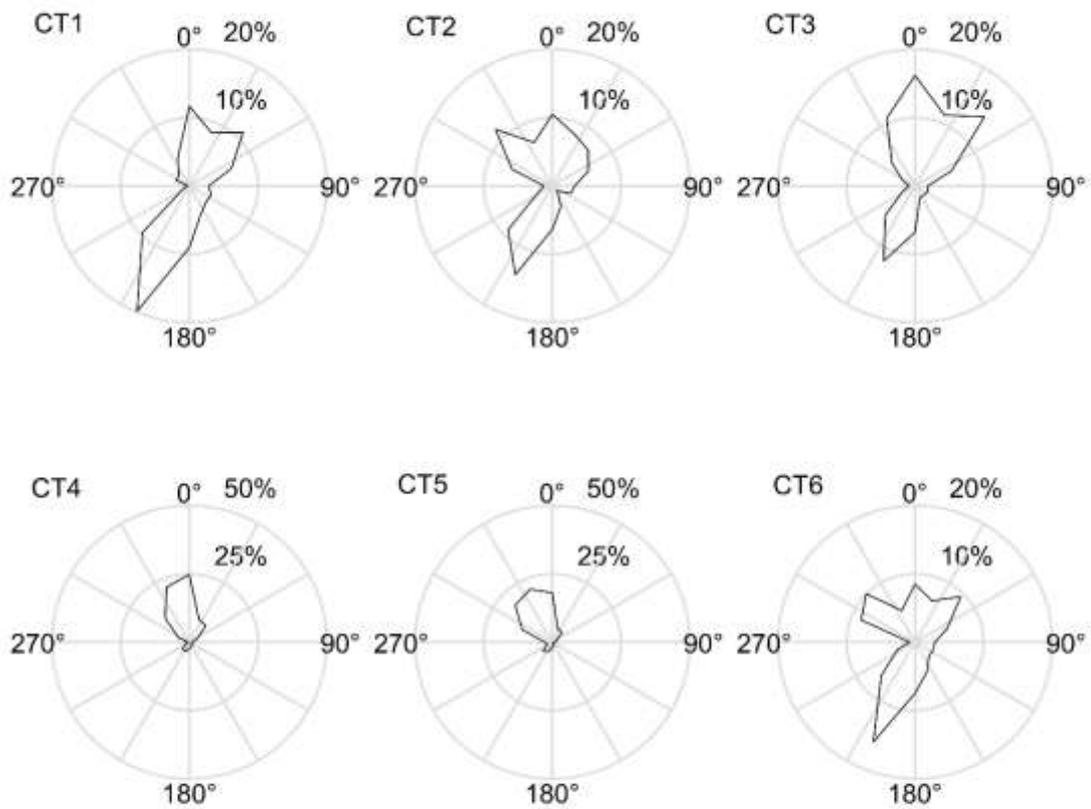
195 20.7%, 14.3%, 16.6%, and 12.8%, respectively. The occurrence frequency of stagnant weather (CT1,
196 CT2 and CT6) reached 48.4%, and 30.9% for the cold air process (CT4 and CT5), which is conducive
197 to ventilation. The cold air process often occurred in night and morning (02:00 and 08:00, Beijing
198 Time). The evolution of circulation types is an important issue, and there is an evolution between the
199 cold air process and stagnant weather in North China. When cold air breaks out, the circulation type
200 is CT4 or CT5. With the movement of cold air from the northwest to the southeast, cold air
201 degenerates and the circulation type becomes CT3, followed by CT1, and CT2. After a period of cold
202 air accumulation over Siberia and Outer Mongolia, a new cold air process breaks out, and the
203 circulation type changes from CT2 to CT4 or CT5. Another evolution between CT2 and CT6 was
204 found.

205 Local meteorological conditions were closely related to synoptic scale circulation types and
206 underlying surface condition. Figure 5 shows the box graph of surface meteorological parameters at
207 the Beijing meteorological station (Figure 1) for six circulation types during 38 winters from 1980 to
208 2017. To be consistent with daily average surface meteorological parameters, a circulation type for
209 one day is defined as a type that appears twice a day or more at four times (08:00, 14:00, 20:00, and
210 02:00) a day. Circulation types governed local surface meteorological parameters, and meteorological
211 parameters had significant differences for different circulation types based on variance analysis at the
212 95% confidence level. The source of cold high pressure was in Outer Mongolia and Siberia. The cold
213 air process brought a significant decrease of temperature and humidity over Beijing. According to
214 geostrophic wind theory, wind speed is positively correlated with the pressure gradient. The cold air
215 process resulted in a large pressure gradient and brought large winds over Beijing. The predominant
216 direction in surface was north and northwest wind for CT4 and CT5 respectively (Figure 6). Winter
217 cold high pressure in East Asia is a relatively shallow weather system, and the average thickness of
218 cold high pressure is no more than 3 km. The cold air process decreased low level temperature and
219 the K index and resulted in stable atmospheric stratification in the middle-low troposphere (upper
220 boundary layer). For stagnant weather, the local meteorological parameters were contrary to those for
221 the cold air process, i.e., 2-m temperature, 2-m relative humidity and K index were large, whereas the
222 10-m wind speed was small in Beijing. The predominant direction in surface was southwest wind
223 (Figure 6). Northwest wind was a second prevailing wind for CT2 and CT6. It is interesting that
224 atmospheric stratification in the middle-low troposphere was more stable for the cold air process than

225 for stagnant weather based on the comparison of the K index. For degeneration of cold air, the local
226 meteorological parameters were between the cold air and stagnant weather. North, northeast, and
227 southwest wind were the main wind direction in surface for CT3 (Figure 6).



229
230 Figure 5. Box graph of surface pressure (a), 2-m temperature (b), 2-m relative humidity (c) and 10-m
231 wind speed (d) in Beijing for six circulation types during 38 winters from 1980 to 2017.

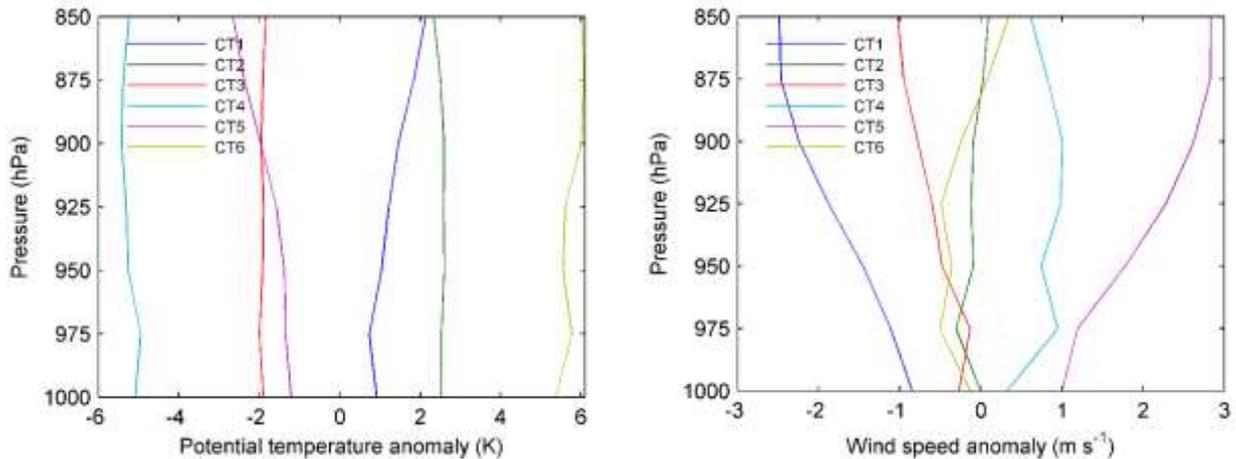


232

233 Figure 6. Wind rose map in Beijing for six circulation types during 38 winters from 1980 to 2017.

234 Boundary layer structures are also governed by atmospheric circulation (Miao et al., 2017). Figure
 235 7 shows vertical profiles of potential temperature and wind speed anomaly for six circulation types.
 236 A cold bias of potential temperature was detected for CT4 and CT5. Cold bias increased with height
 237 for CT4 and CT5, which implies that the cold air process increased the atmospheric temperature lapse
 238 rate and turbulent mixing in the boundary layer by a thermal process and formed a deep mixing layer.
 239 A positive bias of wind speed was detected for CT4 and CT5, and the positive bias increased with
 240 height in the boundary layer. This characteristic of vertical profiles of wind speed anomaly for CT4
 241 and CT5 resulted in an increase of vertical wind shear and formed a deep mixing layer by dynamical
 242 processes. For stagnant weather, i.e., CT1, CT2, and CT6, an opposite change of the vertical profiles
 243 of potential temperature and wind speed anomaly was found and formed a shallow mixing layer by
 244 thermal and dynamical processes compared with the cold air process (CT4 and CT5). For CT3,
 245 potential temperature and wind speed were smaller than the average climatological values in the
 246 boundary layer. The bias of potential temperature was constant at different heights, whereas the

247 negative bias of wind speed increased with height, which restrained the development of turbulence
248 by dynamical processes. In general, the cold air process (stagnant weather) formed a deep (shallow)
249 mixing layer by affecting local atmospheric thermal and dynamical processes. These results did not
250 contradict the K index because of different atmospheric height levels.

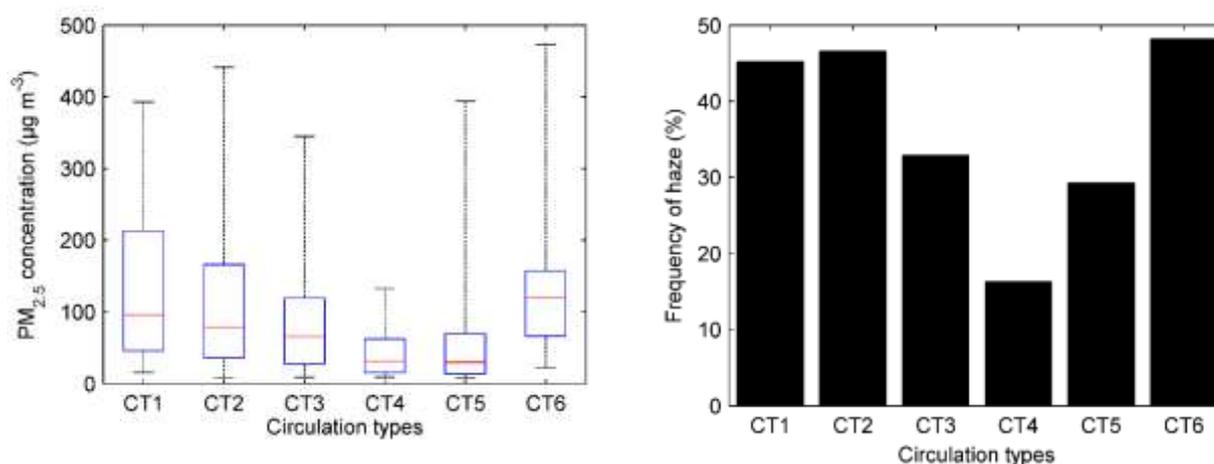


251
252 Figure 7. Vertical profiles of potential temperature anomaly (a) and wind speed anomaly (b) in Beijing
253 for six circulation types during 38 winters from 1980 to 2017.

254 3.2 Impact of weather type on PM_{2.5} and haze pollution

255 Atmospheric circulation had an obvious impact on near-surface PM_{2.5} concentration (Figure 8a).
256 Variance analysis revealed that the different circulation types had significant differences in PM_{2.5}
257 concentration at the 95% confidence level. Previous studies revealed that PM_{2.5} concentration was
258 positively correlated with 2-m temperature and 2-m relative humidity and was negatively correlated
259 with 10-m wind speed over the North China Plain; the correlation passed the t-test at a 95%
260 confidence level (He et al., 2017a; He et al., 2017b; Liu et al., 2017). With low temperature, low
261 relative humidity, and high wind speed, the cold air process (CT4 and CT5) was favourable for
262 pollutant dispersion and brought low PM_{2.5} concentration. After the cold air process (CT3), the
263 atmospheric dispersion capability weakened, and pollutant accumulation resulted in the increase of
264 PM_{2.5} concentration. Stagnant weather (CT1, CT2 and CT6) was accompanied by high temperature,
265 high humidity and low wind speed, which was unfavourable for pollutant dispersion. For CT1,
266 southwestern wind transported pollutants from south of Hebei province (He et al., 2017c; Miao et al.,
267 2017) and exacerbated atmospheric pollution over Beijing. A convergence near Beijing for CT6
268 formed pollutant accumulation. Additionally, the atmospheric stratification in the middle-low
269 troposphere was unstable for stagnant weather (i.e., large K index). Unstable atmospheric

270 stratification favours the formation of cloudy and rainy weather accompanied by high humidity and
 271 is conducive to aerosol hygroscopic growth (Zhang et al., 2014). The aerosols in the middle-low
 272 troposphere decreased near-surface shortwave radiation and then restrained turbulence development.
 273 Mixing layer height is another important factor that affects air pollution (He et al., 2017a). The cold
 274 air process (stagnant weather) formed a deep (shallow) mixing layer and enhanced (weakened) the
 275 vertical mixing of pollutants, accompanied by low (high) PM_{2.5} concentration.



276
 277 Figure 8. Box graph of daily mean PM_{2.5} concentration (a) during 4 winters from 2010 to 2017 and
 278 occurrence frequency of haze days (b) during 38 winters from 1980 to 2017 for six circulation types.

279
 280 Table 1 shows the average PM_{2.5} concentration and occurrence frequency of cold air for each winter
 281 from 2010 to 2017. The Chinese Ambient Air Quality Standards (CAAQS) Grade II standards of
 282 annual mean PM_{2.5} concentration is 35 µg m⁻³. The mean PM_{2.5} concentration in 8 winters in Beijing
 283 is 3.2 times of the Grade II value, which implies severe air pollution due to large amount of pollutant
 284 emissions. The correlation coefficients between winter average PM_{2.5} concentration and occurrence
 285 frequency of six circulation types and cold air are 0.85, 0.71, 0.14, -0.41, -0.67, -0.37, and -0.65,
 286 respectively. Based on t-test, the correlation coefficients are significant for CT1, CT2 and CT5 at 95%
 287 confidence interval. The frequency of cold air was only 25%, 21% and 23% in the winters of 2013,
 288 2014 and 2017, and a stagnant circulation of CT1 exceeded 20% in winter 2013 and 2017, which was
 289 adverse for PM_{2.5} transport and dispersion to the outside and facilitated the accumulation of pollutants.
 290 The average PM_{2.5} concentration reaches 145 µg m⁻³, 129 µg m⁻³, and 117 µg m⁻³ in winter 2013,
 291 2014 and 2017. Although the frequencies of cold air and stagnant weather in winter 2017 are close to
 292 that in winter 2013, the PM_{2.5} concentration is significant low in winter 2017 due to great emission

293 control measures. The frequency of cold air reached 41% in the winters of 2012 and 2016. Although
 294 the atmospheric circulation was favourable for pollutant dispersion, the average PM_{2.5} concentration
 295 still reached 106 µg m⁻³ and 94 µg m⁻³ in the winters of 2012 and 2016, respectively, which indicates
 296 that air pollution is very serious in Beijing. Large amounts of pollutant emissions are the main reason
 297 for serious air pollution in the studied area (He et al., 2017a).

298

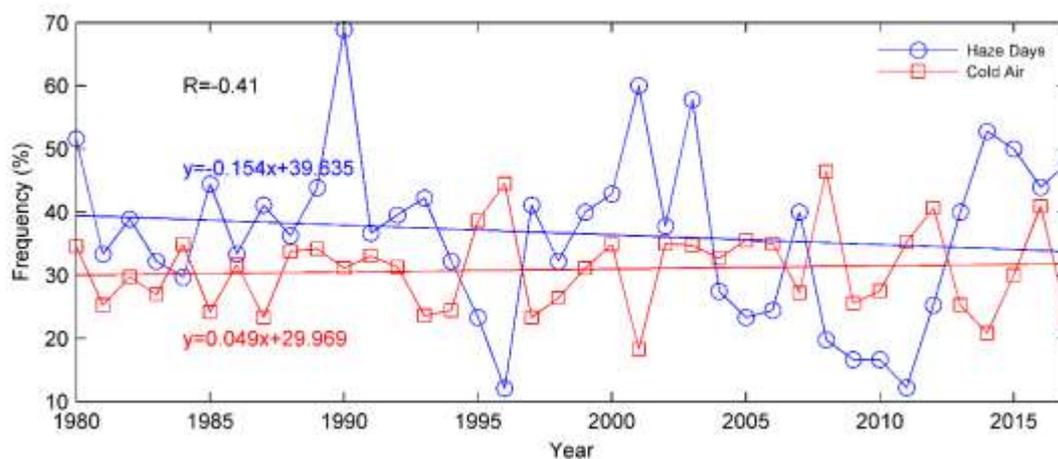
299 Table 1. PM_{2.5} concentration (mean and standard deviation, µg m⁻³) and occurrence frequency of
 300 circulation type (%) for each winter from 2010 to 2017.

	2010	2011	2012	2013	2014	2015	2016	2017
PM _{2.5} concentration	100±74	97±103	106±90	145±11	129±10	95±79	94±106	117±10
Frequency of CT1	15	10	12	29	16	14	13	22
Frequency of CT2	18	16	16	20	19	15	16	23
Frequency of CT3	20	13	27	18	27	23	20	25
Frequency of CT4	13	21	22	11	11	9	18	8
Frequency of CT5	15	14	19	14	9	21	23	15
Frequency of cold air	27	35	41	25	21	30	41	23

301

302 Correlated with aerosols and visibility, haze is disastrous weather. Similar to the PM_{2.5} analysed
 303 above, haze pollution is closely affected by atmospheric circulation (Fig. 6b). A low frequency of
 304 haze days was found under cold air processes (i.e., CT4 and CT5), and a high frequency was found

305 for stagnant weather. Figure 9 shows time series of frequency of haze days and cold air. The average
 306 occurrence frequency of haze days for the 38 winters was 37%, with a maximum value of 69% (1990)
 307 and a minimum value of 12% (1996). The correlation coefficient between the time series of frequency
 308 of haze days and cold air frequency during the 38 winters reached -0.41 ($p < 0.1$), which implies that
 309 the interannual variation of haze days was closely related to the interannual variation of cold air. In
 310 some extreme winters, such as those in 1996, 2008, and 2012, strong cold air improved air quality
 311 and decreased the frequency of haze days. Linear regression analysis revealed that frequency of
 312 winter haze decreased from 1980 to 2017, whereas the frequency of cold air slightly increased. The
 313 decreased trend of haze may have been partly caused by the increased trend of cold air. However, the
 314 trend of interannual variation of winter haze and cold air was not significant at the 95% confidence
 315 level. Artificial measurement of atmospheric visibility has been progressively replaced by automatic
 316 measurement since 2011. The bias between artificial measurement and automatic measurement of
 317 atmospheric visibility has introduced some uncertainty for haze pollution. Yang et al. (2016)
 318 investigated winter haze over eastern China from 1980 to 2014 and found that haze days increased
 319 from 21 days in 1980 to 42 days in 2014. The annual haze increased from 1995 to 2012 in North
 320 China (Chen et al., 2015). The trend of haze days in this paper is different from those in Yang et al.
 321 (2016) and Chen et al. (2015), partly because of the different study areas and seasons considered.
 322 Significant regional difference of the trends of haze days was also detected in Hebei province (Fu et
 323 al., 2014). And the trends of haze pollution was different from nearby Hebei province, which implies
 324 that haze pollution and interannual trends have obvious local characteristics due to local meteorology
 325 and local emissions.



326
 327 Figure 9. Time series of occurrence frequency of haze days and cold air during 38 winters from 1980

328 to 2017. The blue and red lines represent the liner regression trend for haze days and cold air,
329 respectively.

330 **4. Conclusion**

331 Pollutant emissions and meteorological conditions are two key factors that determine haze
332 pollution. Synoptic scale atmospheric circulation governs local meteorological values and the
333 boundary layer and thus affects local air quality. Using observations of PM_{2.5} concentrations, haze
334 days based on visibility and relative humidity, meteorological observations and reanalysis data, this
335 paper investigated winter atmospheric circulation types, and their relationship with local
336 meteorological conditions and haze pollution over Beijing.

337 Six circulation types were identified that could significantly distinguish the cold air process (a
338 degeneration of cold air) and stagnant weather. The evolution of atmospheric circulation is also
339 analysed. For the cold air process, a large pressure gradient was found in North China with cold high
340 pressure located over northwest of North China, accompanied by low temperature, high relative
341 humidity, and large winds over Beijing. Temperatures and wind speed anomalies for cold air in the
342 boundary layer implied that strong turbulence triggered by thermal and dynamical processes formed
343 a deep mixing layer. However, the analysis of the K index revealed that stable atmospheric
344 stratification in the middle-low troposphere (the upper boundary layer) was detected for the cold air
345 process. Cold air facilitated pollutant dispersion and transport to the outside, and then lower PM_{2.5}
346 concentration and frequency of haze days. The pressure gradient was very small in North China for
347 stagnant weather, resulting in a calm weather condition with relatively high temperature, low relative
348 humidity, low near-surface wind speed, and shallow mixing layer depth. Based on an analysis of the
349 K index, atmospheric stratification was unstable in the middle-low troposphere (the upper boundary
350 layer) compared with the cold air process. A convergence line was found surrounding Beijing surface
351 layer, and southerly winds brought pollutants from Hebei province. Stagnant weather was adverse for
352 pollutant dispersion and transport and facilitated the accumulation of pollution in Beijing. For the
353 degeneration of cold air, the local meteorological conditions and haze pollution were between those
354 of previous circulation types.

355 The interannual variations of PM_{2.5} concentration and haze days were significantly affected by the
356 variation of atmospheric circulation. PM_{2.5} observations revealed that PM_{2.5} pollution was severe in

357 the winters of 2013, 2014 and 2017, which was caused by low frequency of cold air and high
358 frequency of stagnant weather. The average occurrence frequency of haze days for the 38 winters
359 reached 37%. The high frequency of stagnant weather (48.4%) was one of the reason for the haze
360 pollution. The frequency of haze days was negatively correlated with the frequency of cold air, with
361 a correlation coefficient of -0.41 ($p < 0.1$). Vice versa, a decreased trend of haze days during winter
362 from 1980 to 2017 was partly related to an increased trend of cold air frequency. However, these
363 trends were not significant based on regression analysis.

364

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