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Environmental and Dynamic Conditions for the Occurrence of Persistent Haze Events in North China

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ABSTRACT

This paper presents a concise summary of recent studies on the long-term variations of haze in North China and on the environmental and dynamic conditions for severe persistent haze events. Results indicate that haze days have an obviously rising trend over the past 50 years in North China. The occurrence frequency of persistent haze events has a similar rising trend due to the continuous rise of winter temperatures, decrease of surface wind speeds, and aggravation of atmospheric stability. In North China, when severe persistent haze events occur, anomalous southwesterly winds prevail in the lower troposphere, providing sufficient moisture for the formation of haze. Moreover, North China is mainly controlled by a deep downdraft in the mid-lower troposphere, which contributes to reducing the thickness of the planetary boundary layer, obviously reducing the atmospheric capacity for pollutants. This atmospheric circulation and sinking motion provide favorable conditions for the formation and maintenance of haze in North China.

1. Introduction

In recent years, regional persistent haze pollution events have happened frequently in North China, the Pearl River Delta, and the Yangtze River Delta [1–3], with the most typical region being North China [4]. The frequent occurrence of haze events has become one of the most severe environmental problems in North China.

Regarding the reasons for frequent haze events, rapid economic development and urbanization in China have resulted in the discharge of a large amount of pollutants in recent years. In addition, it is very possible that changes in climatic conditions resulting from climate warming due to human activities are one of the reasons for haze events [3,5–7]. Pollutant dilution and diffusion capacity varies largely under different meteorological conditions. Local meteorological conditions and the planetary boundary layer (PBL) structure may change under different large-scale circulations, thus having a significant influence on the formation of atmospheric pollution [8–13]. Therefore, one of the approaches to understanding the occurrence of haze events—and persistent haze events in particular—is studying the effect of circulation conditions and related environmental and dynamic factors on haze formation. This paper summarizes the recent study results on the long-term characteristics of haze and on the environmental and dynamic conditions for severe persistent haze events in North China.

2. Spatial-temporal characteristics of haze days in North China

North China is the region with the most prevalent haze in China. From the spatial distribution of annual haze days, shown in Fig. 1(a) [3], it can be seen that haze zones mainly exist in economically developed and densely populated regions, such as Beijing, Tianjin, and southwest Hebei Province, where there are over 30 annual haze days. In particular, there are over 50 annual haze days in downtown Beijing, the north of Tianjin, Shijiazhuang, Xingtai, and Tangshan.

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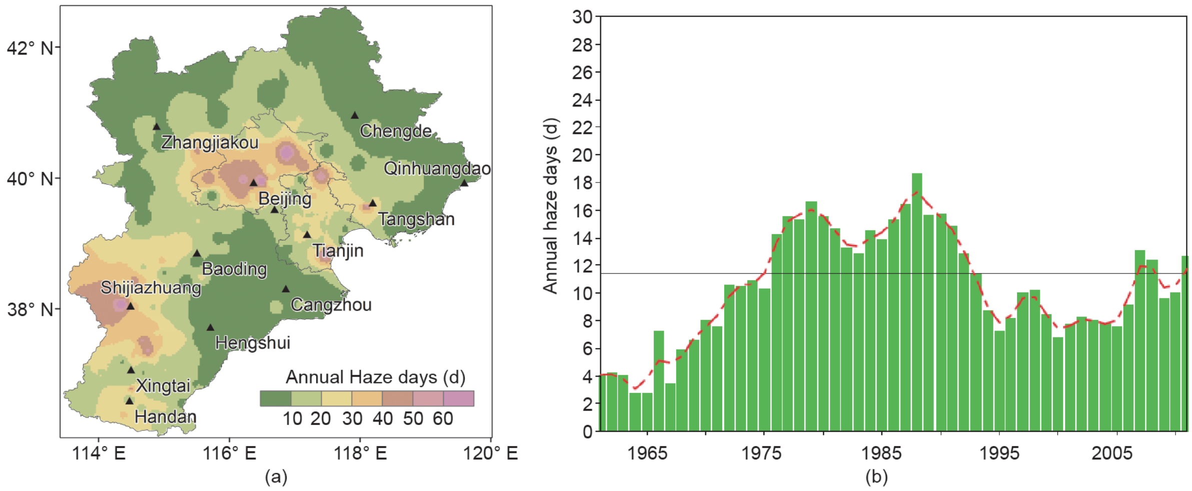

Fig. 1. (a) Spatial distribution and (b) long-term variation of annual haze days in North China. Adapted from Ref. [3].

As shown in Fig. 1(b) [3], the haze frequency in North China rose quickly before 1979 and peaked during 1976–1991, with an average of about 14–15 annual haze days. The frequency then decreased significantly; however, it has risen again since 2005 [3]. Based on the quarterly distribution, haze mainly occurs in the winter, then in the spring and autumn, and occurs at its lowest frequency in the summer [5,11].

In recent years, haze days in China have shown the significant characteristics of longer duration and larger impacted range. Once a haze occurs, it often lasts for several days or even longer, resulting in severe harm to human health. Wu et al. [14] found that most of the persistent haze events that lasted for three or more days in North China occurred in the autumn and winter. From the mid-1990s until now, the frequency of persistent haze events has clearly increased (figure not shown here). Zhang et al. [15] defined a haze event lasting for two or more days as a "persistent haze event," and found that the increase of persistent haze days is the main reason for the increase of total haze days in the past 30 years in North China. Areas with an obviously increasing trend of persistent haze days are mainly concentrated in Beijing, Tianjin, and southwest Hebei Province (Fig. 2) [15]. The range of regions with persistent haze events has an inter-decadal growth trend, with particularly significant aggravation since 2000.

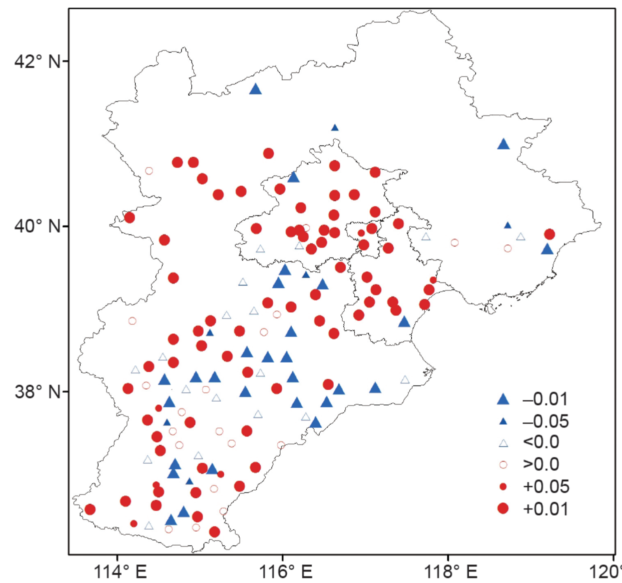

Fig. 2. Varying trends in persistent haze days in North China from 1981 to 2013. Solid/hollow circles represent increasing trends while solid/hollow triangles indicate decreasing trends; a big solid circle/triangle indicates a trend that has passed the 0.01 significance level test; a small solid circle/triangle indicates a trend that has passed the 0.05 significance level test; a hollow circle/triangle indicates a trend that has not passed the significance level. Adapted from Ref. [15].

3. Environmental conditions for haze days in North China

Generally speaking, there are two main conditions for the formation of haze weather. The first condition is a large amount of pollutants in the atmosphere, and the second is stable atmospheric stratification and low wind speed. When there is a large amount of pollutants in the air, and when the atmospheric stratification is stable, the pollutants cannot be quickly diffused, leading to the formation of haze weather. Therefore, the reasons for the increase of haze days include human activity and climatic change. Over the past 50 years, winter temperature in North China shows a rising trend, while surface wind speed has an obviously decreasing trend (Fig. 3) [7]. The increase of temperature may lead to an increase of water vapor in the atmosphere, and water vapor is an important factor for the formation of haze, due to the hygroscopic growth characteristic of haze particles. In addition, a decrease of surface wind speed can weaken the diffusion of pollutants [5]. Thus, rises in temperature and decreases in surface wind speed may cause more haze days. A haze day with a daily maximum wind speed equal to or lower than 6 $m{\cdot}s^{-1}$ is defined as a "weak wind day," and a haze day with a daily maximum wind speed of higher than 6 $m{\cdot}s^{-1}$ is defined as a "strong wind day." It is found that in North China, weak wind days are obviously increasing, while strong wind days are obviously decreasing in most cases (Table 1) [7]. These trends have a strong negative impact on the diffusion of air pollutants and a positive impact on the occurrence of haze. It is notable that the most significant influence on the increase of winter haze days in North China is the decrease of days with a daily maximum wind speed of 7–8 $m{\cdot}s^{-1}$.

A change in atmospheric stratification stability influences the vertical exchange capacity of air, with more stable atmospheric stratification enabling the formation of haze weather. The *A* index can be used to express the atmospheric thermal stability. The *A* index is calculated by the following equation:

$$A = (T_{850} - T_{500}) - [(T - T_d)_{850} + (T - T_d)_{700} + (T - T_d)_{500}] \quad (1)$$

where T is the temperature; T_d is the dew point temperature; and the numbers 500, 700, and 850 indicate different pressure levels.

The bigger the value of the *A* index, the more unstable the atmosphere will be. The variation curve of the winter *A* index

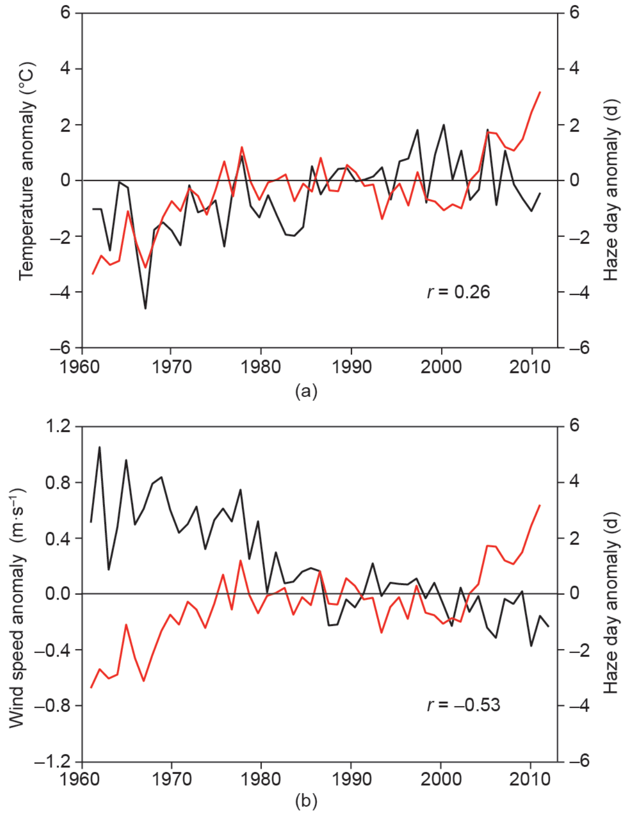

Fig. 3. (a) Time series of winter temperature anomaly (black line) and winter haze day anomaly (red line) during 1961 and 2012 in North China, where r indicates the correlation coefficient between the winter haze days anomaly and the temperature anomaly; (b) time series of winter wind speed anomaly (black line) and winter haze day anomaly (red line) during 1961 and 2012 in North China, where r indicates the correlation coefficient between the winter haze days anomaly and the winter wind speed anomaly [7].

Table 1
Correlation coefficient between winter haze days and days in different maximum wind speed classes in North China [7].

	Maximum wind speed ($v_{f,max}$) class	Correlation coefficient
Weak wind ($v_{f,max} \le 6$ m·s^{-1})	$v_{f,max} \le 2$ m·s^{-1}	**0.08**
	2 m·s^{-1} < $v_{f,max} \le 3$ m·s^{-1}	**0.32**[a]
	3 m·s^{-1} < $v_{f,max} \le 4$ m·s^{-1}	**0.32**[a]
	4 m·s^{-1} < $v_{f,max} \le 5$ m·s^{-1}	**0.29**[b]
	5 m·s^{-1} < $v_{f,max} \le 6$ m·s^{-1}	**0.06**
Strong wind ($v_{f,max} > 6$ m·s^{-1})	6 m·s^{-1} < $v_{f,max} \le 7$ m·s^{-1}	**–0.09**
	7 m·s^{-1} < $v_{f,max} \le 8$ m·s^{-1}	–0.40[a]
	8 m·s^{-1} < $v_{f,max} \le 9$ m·s^{-1}	–0.32[a]
	9 m·s^{-1} < $v_{f,max} \le 10$ m·s^{-1}	–0.34[a]
	$v_{f,max} > 10$ m·s^{-1}	–0.25[b]

Bold indicates a rising trend, while underlining indicates a decreasing trend.
[a] The correlation coefficient passes the 99% confidence level.
[b] The correlation coefficient passes the 95% confidence level.

anomaly in 1961–2012 indicates that the winter A index has a significantly negative correlation with winter haze days (Fig. 4) [7]. Before 2002, the winter index A mostly had a positive anomaly, indicating that the atmosphere had a relatively unstable status. After 2002, however, the winter A index mostly had a negative anomaly, indicating that the atmosphere had a relatively stable status. Note that winter haze days have increased rapidly since about 2002, which may have something to do with this change from a relatively unstable atmospheric stratification to a relatively stable status. Since the start of the 21st century, the discharge of pollutants has increased significantly with the increase of urban populations, acceleration of industrial development, and use of motorized vehicles. However, the relatively stable atmosphere has weakened the vertical exchange capacity of the air. Thus, many pollutants are restricted to the shallow atmosphere, creating favorable conditions for the formation of haze.

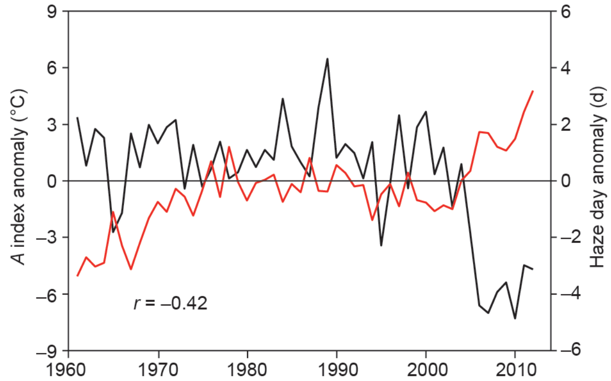

Fig. 4. Time series of winter A index anomaly (black line) and winter haze day anomaly (red line) from 1961 to 2012 in North China, where r indicates the correlation coefficient between the winter haze days anomaly and the winter A index anomaly [7].

4. Circulation and dynamic conditions for persistent haze events in North China

4.1. Circulation characteristics

An analysis of the geopotential height at 500 hPa of 13 severe persistent haze events with durations of five or more days in North China revealed that persistent haze events can be roughly divided into two types [14]. When persistent haze events of the first type occur, East Asia is mainly controlled by zonal circulation in the middle level at 500 hPa, and North China is under the influence of the zonal westerly airflow, indicating less intrusion of cold and dry air from high latitudes into this region. Such persistent haze events can be defined as the zonal westerly airflow (ZWA) type. When persistent haze events of the second type occur, the mainland of China is mainly dominated by a weak high-pressure ridge and North China is controlled by northwesterly airflow in front of the ridge. Such persistent haze events can be defined as the high-pressure ridge (HPR) type.

When severe persistent haze events occur over North China, the mainland of China is dominated by an anomalous low sea level pressure and a high anomaly over the adjacent ocean to the east of the coast, as shown in Fig. 5(a) [16], suggesting a weakness of the northerly winds from high latitudes and an increase in air temperature. Thus, westerly and southwesterly wind anomalies prevail in the region of North China and the wind velocity is weak in the lower troposphere, as shown in Fig. 5(b) [16]. Because of the westerly and southwesterly winds, pollutants from the surrounding areas are easily transported into North China. Meanwhile, due to the obstruction posed by the Yanshan Mountains to the north, the pollutants cannot easily diffuse outward; instead, they gather in this region. In addition, southwesterly winds are beneficial for transporting warm and humid airflows into North China, creating favorable moisture conditions for the hygroscopic growth of haze particles.

From another perspective, the temperature in the lower troposphere increases for severe persistent haze events, and the temperature increases more rapidly at 850 hPa than at 1000 hPa, resulting in an anomalous inversion in the lower troposphere (Fig. 6) [16]. This

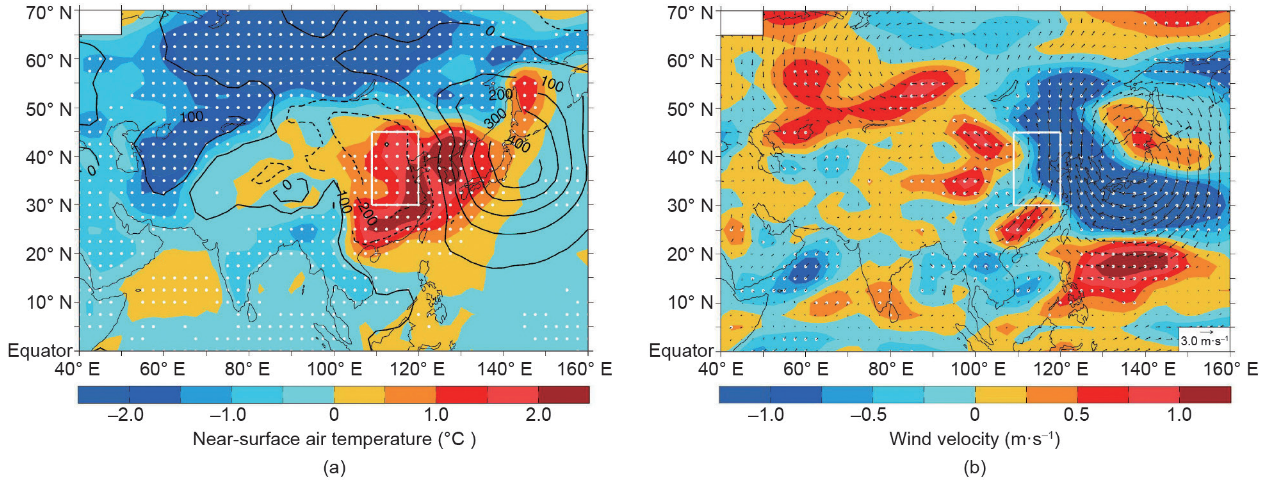

Fig. 5. Composite anomalous distributions of (a) sea level pressure (contour; units: Pa) and near-surface air temperature (shading; units: °C); (b) wind vectors (units: $m\cdot s^{-1}$) and wind velocity (shading; units: $m\cdot s^{-1}$) for severe persistent haze events. Adapted with permission from Ref. [16].

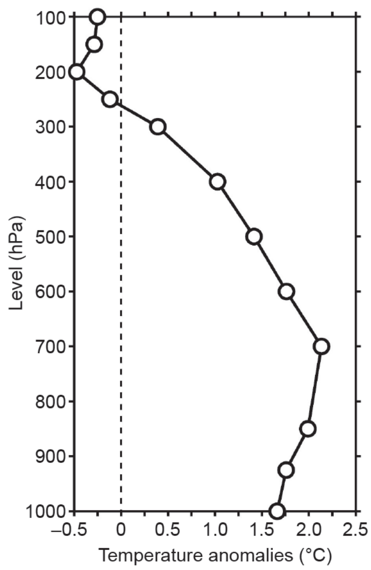

Fig. 6. Vertical distribution of air temperature anomalies over North China for severe persistent haze events. Adapted with permission from Ref. [16].

inversion can increase the stability of the atmospheric stratification at the boundary layer [16]. The anomalous inversion can weaken the vertical dispersion of pollutants, which may further lead to the long-term maintenance of a persistent haze event.

4.2. Dynamic conditions

Vertical motion is critically important for the vertical diffusion and dilution of pollutants. During the occurrence of the two types of persistent haze events described above, the wind divergence over North China has a three-layer structure of "convergence-divergence-convergence" from the surface to the middle troposphere, as shown in Fig. 7(a) and (b) [14]. Such a wind distribution of upper convergence and lower divergence is favorable for airflow making a sinking motion, as shown in Fig. 7(c) and (d) [14]. A vertical sinking motion in the mid-lower troposphere may be a very important dynamic mechanism for the formation of a persistent haze event. The shallow convergence layer below 900 hPa is favorable for the accumulation of pollutants in the regions surrounding North China. At the same time, the mid-lower troposphere is under the control of a downward flow, indicating that the atmosphere is very stable, which will inhibit the vertical diffusion of pollutants. Thus, these conditions are beneficial for the maintenance and aggravation of haze weather.

The PBL is under a direct and strong influence from the surface, and its thickness determines the effective air volume for pollutant diffusion, that is, the atmospheric environmental capacity. The vertical sinking motion in the mid-lower troposphere will squeeze the atmospheric boundary layer, thus reducing its thickness. The lower the boundary layer height is, the lower the atmospheric environmental capacity will be, which is favorable for the occurrence, expansion, and aggravation of haze weather. Furthermore, due to the effect of haze, the solar radiation reaching the ground surface decreases and the surface heat flux is decreased. This decrease tends to depress the development of the boundary layer height, while the repressed structure of the boundary layer further weakens the diffusion of pollutants, leading to heavy pollution [17]. This positive feedback mechanism of haze and boundary layer height results in a more severely polluted atmosphere over North China.

On this basis, Wu et al. [14] give a conceptual diagram for the formation mechanism of persistent haze pollution events in North China, which is shown in Fig. 8 [14]. When a severe persistent haze event occurs, North China is dominated by ZWA or by northwesterly airflow in the mid-upper troposphere. There is a prevailing weak southwesterly, southeasterly, and westerly wind in the boundary layer, with sufficient moisture condition. Regarding the dynamic conditions, due to the wind vertical distribution of a convergence layer located above a divergence layer, a deep downdraft is produced in the mid-lower troposphere over North China, which plays a critical role in the formation and maintenance of the persistent haze event. The sinking motion results in the decrease of the boundary layer thickness and the reduction of atmospheric environmental capacity. Many pollutants are prevented from upward diffusion and accumulate in the lower boundary layer, thus sustaining and aggravating the severe persistent haze event.

5. Conclusions

In recent decades, North China has suffered from severe and persistent haze pollution events. This frequently occurring air pollution has become a very serious environmental problem. This paper summarizes the climatic characteristics of haze days and the environmental and dynamic conditions for the formation of persistent haze events in North China. The following conclusions

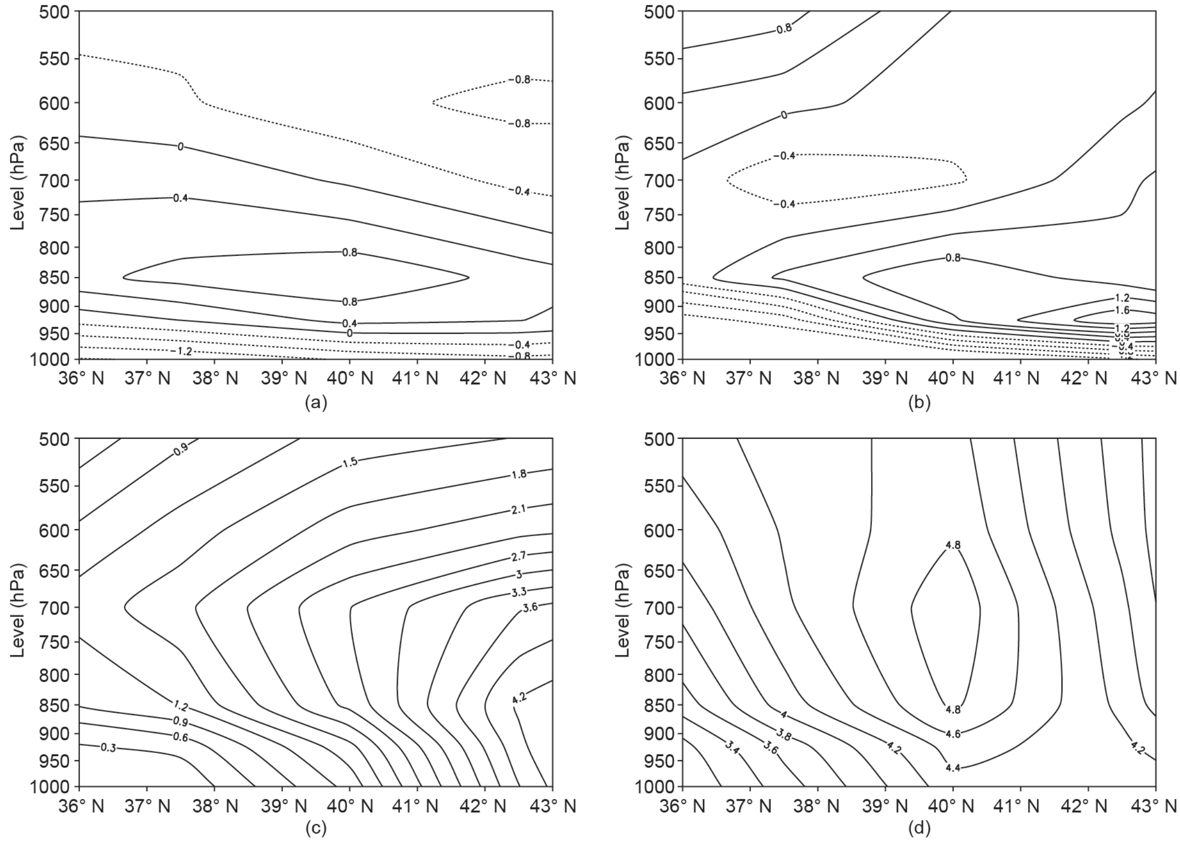

Fig. 7. Atmospheric pressure-latitude section of (a, b) wind field divergence (contour; unit: $10^{-6}\ s^{-1}$) and (c, d) vertical speed w (contour; unit: $10^{-2}\ Pa \cdot s^{-1}$), where $w = dp/dt$, $w > 0$ indicates downward motion in North China. (a) and (c) show the ZWA type of persistent haze event and (b) and (d) show the HPR type. Adapted from Ref. [14].

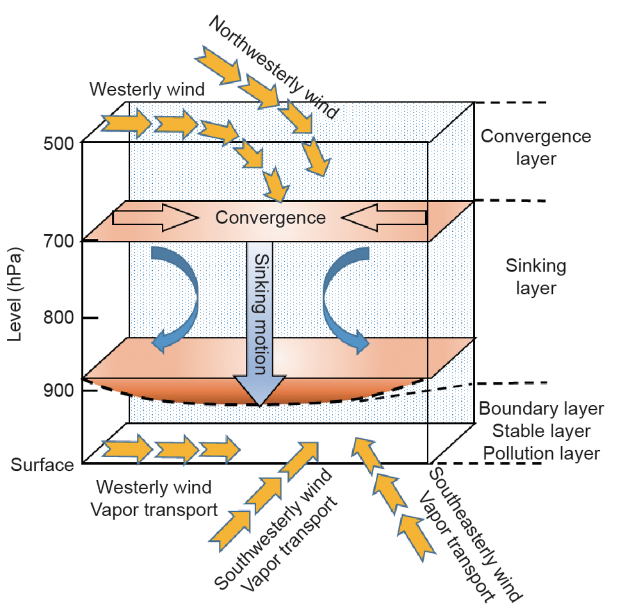

Fig. 8. A schematic of dynamic conditions for the formation of a severe persistent haze event in North China. Adapted from Ref. [14].

can be drawn:

(1) In North China, regions with frequent haze events mainly include Beijing, Tianjin, and southwest Hebei Province. Haze frequency generally shows a significantly rising trend, particularly since the start of the 21st century. Persistent haze events also show an obviously rising trend.

(2) Against the background of climate warming, a continuous rise of winter temperatures, a decrease of surface wind speeds, and a relatively stable atmosphere over North China have significant influence on the increase of haze days.

(3) Regarding large-scale circulation, the severe persistent haze events in North China often occur under ZWA circulation or HPR circulation. North China is controlled by the ZWA or by northwesterly airflow in the mid-upper troposphere. When severe persistent haze events occur, North China is mainly influenced by anomalous southwesterly winds in the PBL and the surface wind speed is weak. These conditions can transport pollutants from surrounding areas along with sufficient moisture into North China, providing the material and moisture conditions for the persistent haze events.

(4) A deep and stable downward airflow over North China in the mid-lower troposphere is favorable for reducing the PBL height and forming a temperature inversion. A lower PBL height can significantly decrease the potential atmospheric capacity for the diffusion of air pollutants, leading to high pollutant concentrations over North China.

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Compliance with ethics guidelines

Yihui Ding, Ping Wu, Yanju Liu, and Yafang Song declare that they have no conflict of interest or financial conflicts to disclose.

References

[1] Chan CK, Yao X. Air pollution in mega cities in China. Atmos Environ 2008;42(1):1–42.
[2] Wu D, Wu X, Li F, Tan H, Chen J, Cao Z, et al. Temporal and spatial variation of haze during 1951–2005 in Chinese mainland. Acta Meteorol Sinica 2010;68(5):680–8. Chinese.
[3] Ding Y, Liu Y. Analysis of long-term variations of fog and haze in China in the recent 50 years and their relations with atmospheric humidity. Sci China Earth Sci 2014;57(1):36–46.
[4] Wang Y, Zhang J, Wang L, Hu B, Tang G, Liu Z, et al. Researching significance, status and expectation of haze in Beijing-Tianjin-Hebei region. Adv Earth Sci 2014;29(3):388–96. Chinese.
[5] Hu Y. Temporal variability and spatial distribution of haze in China and its association with climate change [dissertation]. Lanzhou: Lanzhou University; 2009. Chinese.
[6] Zhang P, Guan Z, Shao P, Jiang Y, He J. Interdecadal changes in wintertime hazy days in Jiangsu Province and their association with circulation anomalies and regional warming trends. J Trop Meteorol 2015;31(1):103–11. Chinese.
[7] Wu P, Ding Y, Liu Y, Li X. Influence of the East Asia winter monsoon and atmospheric humidity on the wintertime haze frequency over central-eastern China. Acta Meteorol Sinica 2016;74(3):352–66. Chinese.
[8] Flocas H, Kelessis A, Helmis C, Petrakakis M, Zoumakis M, Pappas K. Synoptic and local scale atmospheric circulation associated with air pollution episodes in an urban Mediterranean area. Theor Appl Climatol 2009;95(3):265–77.
[9] Wang L, Zhang N, Liu Z, Sun Y, Ji D, Wang Y. The influence of climate factors, meteorological conditions, and boundary-layer structure on severe haze pollution in the Beijing-Tianjin-Hebei region during January 2013. Adv Meteorol 2014;2014(7):1–14.
[10] Zhao X, Zhao P, Xu J, Meng W, Pu W, Dong F, et al. Analysis of a winter regional haze event and its formation mechanism in the North China Plain. Atmos Chem Phys 2013;13(11):5685–96.
[11] Song L, Gao R, Li Y, Wang G. Analysis of China's haze days in the winter half-year and the climatic background during 1961–2012. Adv Climate Change Res 2014;5(1):1–6.
[12] Zhang R, Li Q, Zhang R. Meteorological conditions for the persistent severe fog and haze events over eastern China in January 2013. Sci China Earth Sci 2014;57(1):26–35.
[13] Fu G, Xu W, Yang R, Li J, Zhao C. The distribution and trends of fog and haze in the North China Plain over the past 30 years. Atmos Chem Phys 2014;14(21):11949–58.
[14] Wu P, Ding YH, Liu Y. Atmospheric circulation and dynamic mechanism for persistent haze events in the Beijing-Tianjin-Hebei region. Adv Atmos Sci 2017;34(4):429–40.
[15] Zhang Y, Zhang P, Wang J, Qu E, Liu Q, Li G. Climatic characteristics of persistent haze events over Jingjinji during 1981–2013. Meteorol Mon 2015;40(3):311–8. Chinese.
[16] Chen H, Wang H. Haze days in North China and the associated atmospheric circulations based on daily visibility data from 1960 to 2012. J Geophys Res–Atmos 2015;120(12):5895–909.
[17] Quan J, Gao Y, Zhang Q, Tie X, Cao J, Han S, et al. Evolution of planetary boundary layer under different weather conditions, and its impact on aerosol concentrations. Particuology 2013;11(1):34–40.