Two typical weather patterns of persistent heavy pollution in Beijing - Tianjin - Hebei

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Abstract. The persistent heavy pollution weather which occured in Beijing - Tianjin - Hebei from January 26 to 31, 2013 and February 20 to 26, 2014 were compared and analysed by using meteorological elements and air quality observation data and meteorological model field re-analysis data. The results show that both the two events belong to the stagnant accumulation type. The typical configuration of weather system is zonal circulation in 500 hPa, the cold air is not active. The south branch trough is very weak, the condition of water vapor transport is quite poor, which is not conducive to precipitation. The increase of temperature in 800-850 hPa is beneficial to the formation of stable stratification near the ground. Small wind speed near the ground is not conducive to the horizontal diffusion of pollutants. High relative humidity near the ground makes for the hygroscopic growth and secondary transformation of fine particulate. But the mechanism of establishing and maintaining the static and stable situation is different between the two heavy pollution processes. It shows a dry air subsidence area in the middle and low troposphere between 700 hPa and 900 hPa in January 2013. The superposition of subsidence inversion and night radiation inversion in clear sky resulted in extremely stable atmospheric stratification, and the inversion intensity is obviously stronger than that in February 2014. The sinking motion reduces the height of the mixing layer. An extremely low boundary layer height effectively inhibits the vertical diffusion of pollutants, leads to the pollution growing rapidly. The visibility shows obvious diurnal variation with high value in the daytime and extremely low at night in January 2013. While it is a weak rising area of wet air over the polluted area between 850 hPa and near the ground in February 2014. The inversion temperature is not so strong and the height of the mixing layer is a little higher than that in January 2013. The relative humidity of the middle and lower troposphere is high and the cloud cover is more, which results in the less solar radiation received by surface during the daytime, the lower temperature and the higher atmospheric stability. The maintaining of atmospheric static stability makes the pollution gradually accumulating. The visibility always keeps low value at all times in February 2014.

1. Introduction
In recent years, with the fact that rapidly economic developing, the acceleration of urbanization process, the density of urban population has increased, the number of motor vehicles has increased, and the energy consumption has been excessively concentrated, which has led to the significant increase in air pollutant emissions and the extremely serious air pollution in urban agglomerations[1-4]. The Beijing-Tianjin-Hebei is the representative of the urban agglomerations, and the regional air pollution has become a serious problem. For example, persistent heavy pollution weather occurred in January 2013, February 2014, December 2015, and December 2016 to early 2017 in Beijing-Tianjin-Hebei, which caused serious influence to the people's production, life and physical health. High
concern have been paid to the air pollution by the government and the public. It is well known that the excessive pollutant emission is an internal factor of heavy air pollution, meteorological conditions also play a very important role on regional air pollution[5-10]. Through the analysis of the two persistent heavy pollution events in this region from January 26 to 31, 2013 and February 20 to 26, 2014, the coupled configuration structure of high and low level weather systems and the evolution characteristics of meteorological static and stable conditions are studied, and from which the indicative physical factors for forecasting heavy pollution are found, so as to improve the forecasting ability of heavy pollution weather and provide scientific basis for early warning, emergency response and emission reduction control of heavy pollution.

2. Data and method
In this paper, the characteristics of air pollution were analysed by using the data of atmospheric composition observation of China Meteorological Administration and the data of air quality monitoring of Ministry of Environmental Protection. The atmospheric circulation background and meteorological element conditions of heavy pollution weather were studied by using conventional meteorological upper-air and ground observation data combining with operational meteorological numerical models re-analysis data (EC, T639, and NCEP).

3. Heavy pollution characteristics and weather background
Figure 1 shows the variation of PM$_{2.5}$ concentration observed by China Meteorological Administration from January 26 to 31, 2013 in Shijiazhuang. It can be seen that the duration of serious pollution with PM$_{2.5}$ concentration exceeding 150 μg/m$^3$ is more than 5 days, and the peak concentration occurs in the middle of the process, the pollution is growing rapidly, reaching 588 μg/m$^3$ at 17:00 on January 28. This kind of variation is basically consistent with the change trend of PM$_{2.5}$ concentration in Beijing during this period analyzed by Wang et al. using air quality data of Ministry of Environmental Protection[5], while the peak concentration in Beijing is 530 μg/m$^3$. According to the monitoring of PM$_{2.5}$ concentration of the Ministry of Environmental Protection (Figure 2), the heavy pollution in Beijing and Shijiazhuang last for up to 6 days from February 20 to 26, 2014. The peak concentration appears at the later stage of the process. The pollution is gradually accumulating and increasing. The peak concentration of PM$_{2.5}$ appears at 12:00 on February 26 in Beijing and it reaches 634 μg/m$^3$ at 14:00 on February 26 in Shijiazhuang. The pollution in Tianjin is relatively light during this period.

![Figure 1. PM$_{2.5}$ concentration of Shijiazhuang in January 26-31, 2013.](image1)

![Figure 2. PM$_{2.5}$ concentration of Beijing, Tianjin, Shijiazhuang in February 20-26, 2014.](image2)

Figure 3 shows the comparison of visibility during the two heavy pollution events. The visibility shows an obvious diurnal variation during the heavy pollution period from January 26 to 31, 2013, which is a little higher than 2 km in the daytime and significantly lower at night. But during the heavy pollution period from February 20 to 26, 2014, the visibility diurnal variation is very small. Especially
in Beijing and Shijiazhuang, the visibility always keeps below 2 km and lasts for up to 6 days. Comparing the low visibility during the both periods of heavy pollution in January 2013 and in February 2014, the duration of low visibility in the former event is less than that in the latter, but the minimum visibility in the former event is lower than that in the latter. In the former event, the visibility in Shijiazhuang is only 100 m, Beijing and Tianjin are about 200 m.

![Visibility comparison](image)

**Figure 3. Visibility of Beijing, Tianjin, Shijiazhuang**

(left: January 26-31, 2013; right: February 20-26, 2014)

Figure 4 shows the atmospheric circulation situation of the two events. It can be seen that the 500 hPa circulation in the two events is zonal type, which means that the cold air is not active. The high altitude over Beijing - Tianjin - Hebei area is controlled by weak ridge, which maintains the northwest airflow steadily. The water vapor content is low and the amount of cloud in the upper level is less. All of the above is beneficial to the surface radiation cooling at night and to reduce the height of the boundary layer. The pollutants near the ground are not easy to diffuse upwards rather than accumulate in the lower level. Both of these effects are conducive to the accumulation of local pollutants. In January 2013, the south branch trough is relatively straight. In February 2014, it is controlled by a weak ridge near 90°E. In both processes, the southern branch system is weak, which is not conducive to water vapor transportation to north China. It leads to continuous dry and rainless weather. Pollutants is poor dilution ability and gradually accumulated. It also can be found some formation from both the 850 hPa temperature field and the relative humidity field, the two events are controlled by warm ridge over Beijing - Tianjin - Hebei, which is conducive to forming an inversion structure in the low air and inhibiting the upward transportation of pollutants. Especially in January 2013, in line with the warm ridge, it appears an obvious "dry zone" in Beijing - Tianjin - Hebei at 850 hPa. The relative humidity is generally below 50%, and the cloud amount is less. This pattern is conducive to the cooling of surface radiation at night and the formation of temperature inversion. The low-level "warm dry cover" structure over Beijing - Tianjin - Hebei area inhibits the vertical diffusion of pollutants. But in February 2014, the relative humidity at 850 hPa in Beijing - Tianjin - Hebei region is 70-80%, which indicates that more cloud cover in the sky. On the one hand, it reduces the vertical visibility, and on the other hand, the solar radiation received by the ground decreases, which reduces the surface temperature and increases the stability of the atmosphere. The cold air force is weak on the ground weather map. Beijing - Tianjin - Hebei region is in the pressure-equalizing field at the back of the cold high pressure. The horizontal wind speed is weak, which is not conducive to the horizontal diffusion of pollutants. The high ground relative humidity is beneficial to hygroscopic growth and secondary transformation of pollutants. The 2m relative humidity is mostly above 70% during the two processes, and the relative humidity reaches about 80-90% during the heavy pollution in January 2013. To sum up, these two heavy pollution events belong to the static accumulation type. Weak cold air activity, stable atmospheric stratification, low surface wind speed, high humidity and less rainfall are the static and stable weather background that lead to aggravation of pollution and sustained..
Figure 4. High and low circulation configuration during continuous heavy pollution (up: 500 hPa height field; middle: 850 hPa temperature and relative humidity; low: surface wind field, barometric field and relative humidity) (left: January 26-31, 2013; right: February 20-26, 2014, respectively).
4. Mechanisms for the formation and maintenance of atmospheric static stability

Figure 5 shows the height-time profiles of wind, temperature, relative humidity, and vertical velocity in Beijing station drawn by the NCEP re-analysis data. It can be seen that there is an obvious temperature inversion in the low altitude during the heavy pollution period from January 26 to 31, 2013. The inversion is relatively weak on February 20 to 26, 2014, which is dominant by neutral stratification in low layer. The temperature profile is basically consistent with the sketch measured by operational sounding.

From the view of humidity profile, in the near-surface layer below 900 hPa, the relative humidity is high than 70% during the two processes, which is beneficial to the hygroscopic growth and secondary transformation of near-surface fine particulate. However, there is a significant difference in the humidity stratification between 900 hPa and 700 hPa (about 1-3 km) during the two processes. There is a clear dry layer over the polluted area in January 2013, and the structure of upper dry and lower wet is conducive to the formation of nocturnal radiation fog, resulting in extremely low visibility. But the relative humidity between 900 hPa and 700 hPa is relatively larger, mostly over 70% in February 2014, which indicates that there are more clouds in the middle and low levels. The clouds lead to the reduction of the short-wave radiation received by the ground during the day, thus lowering the surface temperature, which is favorable to maintaining stable atmospheric stratification. The pollution is gradually accumulated and increased, and the low visibility lasts for a long time.

As we all know, the influence of vertical motion on pollution has two aspects. One is the velocity direction (up or down) affecting the stability of the air. During the two periods of persistent heavy pollution in January 2013 and February 2014, the downward flow or weak rising movement below 900 hPa over Beijing is observed, which means the vertical diffusion conditions of pollutants are poor. For example, the subsidence movement in the lower troposphere is strengthened continuously during January 26-28 2013, which inhibits the vertical diffusion of pollutants in the near surface layer and continuously increases the concentration of PM$_{2.5}$. At the same time, the air sinking and warming up are beneficial to the enhancement of inversion intensity and the increase of the air stability. A strong inversion near the ground occurred on January 28, the height of mixing layer is extremely low, and the concentration of pollutants arrives at its peak. From January 29 to 31, weak upward movement below 900 hPa is observed, which resulted in the upward diffusion of pollutants on the ground. The height of mixing layer increases slightly, the concentration of PM$_{2.5}$ begins to decrease. However, due to the control of downward air flow in the upper part of 900hPa, the height of upward transport of pollutants was limited, the concentration of pollutants decreases slowly and the heavy pollution weather continues. In February 2014, there is a weak updraft below 850 hPa over Beijing, the vertical transport of pollutants is weak and it can only reach a limited height. So the pollutants accumulate continuously in the boundary layer to form heavy pollution. There is a strong subsidence movement below 700 hPa over Beijing when the concentration of pollutants reaches its peak of the both events, which is instructive to predict the most serious pollution period.

In conclusion, the establishment and maintenance of the near-surface stable stratification play an important role in the persistence and development of heavy pollution weather. But the two events have different mechanisms for the establishment and maintenance of stable stratification. In January 2013, the superposition of subsidence inversion and night radiation inversion results in extremely stable inversion stratification, and the inversion intensity is obviously stronger than that in 2014. In February 2014, Beijing - Tianjin - Hebei has high humidity and more clouds in middle and low levels, which leads to the less solar radiation received by the ground during the daytime, the lower surface temperature and the higher stable atmospheric.
Figure 5. Height-time profile of wind, temperature, humidity and vertical velocity (Pa/s) in Beijing (up: wind, temperature, and humidity; down: vertical velocity) (left: January 26-31, 2013; right: February 20-26, 2014).

5. Conclusions
1) The two heavy pollution events belong to the static accumulation type. The typical configuration of the weather system is that 500 hPa circulation is zonal, the cold air is not active, the south branch trough is weak, water vapor transport conditions is quite poor, which is not conducive to precipitation. A warm ridge appears at 850 hPa is beneficial to form a stable inversion stratification. The ground is in the pressure-equalizing field. The horizontal wind speed is weak, which is not conducive to the horizontal diffusion of pollutants. The high ground relative humidity is beneficial to hygroscopic growth and secondary transformation of pollutants.

2) The establishment and maintenance of stable stratification near the ground plays an important role in the persistence and development of heavy pollution weather. But the two events have different mechanisms for the establishment and maintenance of stable stratification. It is a dry air subsidence area in the middle and low troposphere between 700 hPa and 900 hPa in January 2013. The night clear air radiation inversion temperature overlying subsidence inversion forms extremely stable inversion stratification, and the inversion intensity is obviously stronger than that in February 2014. The sinking motion reduces the height of the mixing layer. An Extremely low boundary layer height effectively inhibits the vertical diffusion of pollutants, leads to the pollution growing rapidly. The visibility shows
obvious diurnal variation with high value in the daytime and extremely low at night. While there is a weak rising area of wet air over the polluted area between 850 hPa and near the ground in February 2014. The inversion temperature is not so strong and the height of the mixing layer is a little higher than that in January 2013. The relative humidity of the middle and lower troposphere is high and the cloud cover is more, which results in the less solar radiation received by surface during the daytime, the lower temperature and the higher atmospheric stability. The maintaining of atmospheric static stability makes the pollution gradually accumulating. The visibility always keeps low value at all times in February 2014.

3) There is consistent sinking movement under 700 hPa when the PM$_{2.5}$ concentration reaches its peak during the two events, which extremely limited the vertical diffusion of pollutants. Meanwhile, atmospheric subsidence in middle and lower troposphere and temperature warming are beneficial to the strengthen of inversion temperature and the increase of the stability of the air. The sinking motion at the lower troposphere shows a certain indication for the prediction of the most serious pollution period.

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