Numerical simulation and cause analysis for a severe mixed pollution of smog and haze in the Pearl River Delta in Winter

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Abstract. Based on the simulation results of the Weather Research and Forecasting-Community Multiscale Air Quality (WRF-CMAQ), the meteorological elements, boundary layer characteristics and temporal and spatial distribution characteristics of particulate matter during the heavy haze-dense fog-haze pollution process from 1 to 12 January 2017 were analyzed with the aid of the data from conventional meteorological observation and environmental monitoring station. Also, the causes of this pollution have been presented considering the terrain effects. The results show that, during the first process (day 1 to day 3), the upwind transports pollutants to Shaoguan, Qingyuan and other provinces, and the local surface wind velocity is lower than 3 m·s⁻¹, which increased concentration of pollutants in the Pearl River Delta region and formed moderate smog and haze pollution. During the second process (day 4 to day 6), the average surface wind speed is lower, and the static wind is lower than 2 m·s⁻¹ with the influence of terrain effect (even lasted for 5-16 hours). Besides, the influence of the strong convergence field of small wind increases the accumulation and convergence of pollutants on the ground, and simultaneously, the thickness of the ground inversion layer is further intensified and the height of the boundary layer is as low as 100 meters. At the same time, the relative humidity increases to nearly 100%, resulting in continuous visibility of fewer than 500 meters for 10 hours. Additionally, it was found that on the day of heavy pollution in Guangzhou, the main source is coarse nuclear particles, and the corresponding actual situation is that the concentration of NO₂ was higher than that in other places, which reflects the influence of high concentration of human activities on air pollution. As the northeasterly winds continued to strengthen, pollutants across the region continued to be transported to the Pearl River Delta. Through the convergence of wind farms in Zhaoqing, Foshan, and Guangzhou, cross-regional pollutants and local pollutants emitted by the Pearl River Delta are again accumulated in the pearl river delta central area, forming a third moderate haze pollution process. It is concluded that the influence of strong convergence field of small wind under 2 m·s⁻¹ (even 5-16 hours static wind), the increase of ground temperature inversion, the height of boundary layer as low as 100 m, the increase of near-ground humidity are superposed, and the combined effect of topography are the main meteorological causes of mixed pollution of fog and haze in the Pearl River Delta in winter.
1. Introduction

Both smog and haze are particles floating in the atmosphere, which can worsen visibility and endanger human health (Kan et al. [1]; Zhang et al. [2]; Li et al. [3]). In recent years, due to the rapid economic growth and the increasing population, the visibility of the Pearl River Delta has been greatly reduced and regional smog and haze weather has frequently occurred. The composition and formation process of smog and haze weather are different (Zhang et al. [4]). By studying the characteristics of boundary layer meteorological elements and the influence of near-surface transport conditions on haze generation and elimination in the Pearl River Delta region (Fan et al. [5-6]; Wu et al. [7-8]; Li Minghua [9]), it is found that the occurrence of haze pollution in the Pearl River Delta region is related to the regional static and small wind conditions and higher temperature and humidity conditions. The conceptual model of pollution in the Pearl River Delta region is summarized (Fan et al. [10]). There are many studies on the causes of fog in the Pearl River Delta. Tan et al. [11] analyzed the chemical characteristics of smog and haze processes in summer and winter in Guangzhou. Tang et al. [12] analyzed the evolution of dense fog in Nanling Mountain by microphysical structure. Deng et al. [13] analyzed the boundary layer characteristics of a frontal fog process in Nanling Mountain. Xu et al. [14] studied the climate characteristics of fog and its mechanism. Yue et al. [15] analyzed the weather conditions and macro-micro features of near-shore fog in Zhanjiang area.

The numerical model of air pollution has been applied to the study of air pollution in the Pearl River Delta. Chen et al. [16] used the American third-generation air quality model system Model-3 (MM5/SMOKE/CMAQ) to conduct a numerical study on the main pollutants in the haze weather in the urban agglomeration of the Pearl River Delta, and concluded that the pollutants mainly accumulated in the atmospheric boundary layer and the high concentration near the ground was the direct cause of the haze weather. Fan et al. [17] used the fifth-generation mesoscale meteorological model system MM5 to conduct numerical simulation of a fogging process in the spring in Guangdong province, and the study showed that the decisive role of fog generation and elimination process was the change of 925hPa wind field. Yu et al. [18] simulated a heavy air pollution process in the Pearl River Delta region in November 2009 using CMAQ model. The results showed that the stable stratification and the static and small wind conditions formed by high-pressure ridges were the main reasons for the increase of pollutant concentration. Liu et al. [19] studied the process analysis method in CMAQ mode and showed that near-surface PM$_{10}$ mainly came from source emission and atmospheric transport, while PM$_{10}$ was mainly removed by atmospheric transport and dry and wet deposition aerosol processes. Deng et al. [20] used the air quality model system (MM5-CAMQ-SMOKE) to simulate a typical composite pollution process in the Pearl River Delta, and studied the temporal and spatial variation of O$_3$, NO$_x$ and visibility. Lan et al. [21] used the MM5/CMAQ model system to simulate the low visibility process once appeared in Hong Kong airport and its surrounding area in winter 2009. The results showed that the CMAQ model can well reflect the change of particulate concentration with time in Hong Kong airport, and the simulation effect is ideal in spatial distribution and transport of particulate concentration. Lai et al. [22] used WRF-Chem model to conduct numerical simulation study on the characteristics and formation mechanism of a combined pollution process of high concentration PM2.5 and O$_3$ in the Pearl River Delta, and found that under the influence of ground easterlies, the main pollution area was in the western part of the Pearl River Delta (including southern Zhaoqing, Foshan and northern Jiangmen).

In the Pearl River Delta, the numerical model is used to analyze the status and causes of air pollution, or individual smog or haze simulations, but there are few numerical simulations and genetic studies on mixed smog and haze pollution. Based on the observation data of ground meteorological elements in the Pearl River Delta region and the hourly concentration data of 56 national environmental air quality monitoring points in the Pearl River Delta region provided by Guangdong Provincial Department of Ecological Environment, Weather Research and Forecasting-Community Multiscale Air Quality (WRFCMAQ) is used to numerically simulate the spatial and temporal distribution characteristics of various meteorological elements and pollutants in the mixed haze pollution process in the Pearl River Delta from January 1 to 12, 2017. Additionally, the causes of particle concentration changes in
different particle modes during the heavy haze mixed pollution weather from January 4 to 6 were analyzed. Finally, preliminary analysis and discussion were conducted on the effective implementation of manual haze intervention tests and other aspects.

2. Information and methodology

2.1. Sources of information

The meteorological observation data mainly include the meteorological elements of 2.0 m temperature, 2.0 m pressure, 2.0 m relative humidity, visibility and 10.0 m horizontal wind speed of 24 meteorological observation stations in the Pearl River Delta region from January 1 to 12, 2017. The mass concentration data of PM2.5, PM10, SO2, NO2, CO, O3, and AQI is obtained from the hourly concentration data of 56 national ambient air quality monitoring points in the Pearl River Delta provided by the Guangdong Provincial Department of Ecology and Environment in the South China Regional Environmental Meteorological Service platform (EMOS). WRF-CMAQ numerical model is simulated from January 1 to 12, 2017. In this work, the hourly simulation data of meteorological elements and particulate concentration from January 1 to 12 are selected for analysis, and the causes of particle concentration changes in different particle modes during the severe haze mixed pollution weather from January 4 to January 6 are analyzed.

2.2. Model introduction

Third-Generation Air Quality Modeling System, Community Multiscale Air Quality, Model-3/CMAQ is the third generation air quality model system developed by the U.S. Environmental Protection Agency. Based on the concept of "one atmosphere", multi-module integration and multi-grid nesting are realized, and the input of meteorological field is provided by Weather Research and Forecasting (WRF). In this work, WRF (V3.6.1) mode adopted triple nested grids. The outermost layer (d01) is China and some surrounding areas, and the number of grids is 240 × 240; the second floor (d02) is south China and the grid number is 148 × 160; the third layer (d03) is the most area of the Pearl River Delta, and the number of grids is 199 × 175. The spacing of triple nested grids d01, d02 and d03 is 27 km, 9 km and 3 km respectively. There are 24 vertical layers, and the top layer of the model is 50 hPa. In WRF model, RRTMG long-short wave radiation scheme, MM5 Monin-Obukhov near-surface layer scheme, Noah land surface process scheme, YSU boundary layer scheme and KF cumulus parameterization scheme are adopted. The simulation time is from January 1 to 11, 2017, and the Final Operational Global Analysis Data (FNL) from the National Centers for Environmental Prediction (NCEP) is used as the initial field. Meanwhile, CMAQ mode (version 5.1) is used to simulate pollutants, and the first and second layer of WRF grid results are used to drive CMAQ in this work. CMAQ mode system consists of three main components (i.e. meteorological module, emission module and chemical transport module). The core module is Chemical-Transport Model (CCTM), which is mainly used to simulate pollutant transport and diffusion process, aerosol chemical process, cloud chemical process and dynamic process. Other modules include Meteorology-Chemistry Interface Processor (MCIP), Initial Conditions Processor (ICON) and Boundary Conditions Processor (BCON). CMAQ grid is divided into 24 layers vertically, and the grid system setting is the same as WRF mode, which adopts saprc07tic mechanism as the gas phase chemical reaction mechanism and uses MIX emission inventory. The MIX inventory is the 2010 Asian anthropogenic emission inventory developed for the East Asia Model Comparison Program Phase III (MICS-Asia III) and the United Nations Hemispheric Air Pollution Transfer Program (HTAP). CMAQ, the core part of Model-3, is a multi-pollutant and multi-scale air quality model system that comprehensively considers pollution problems such as photochemical oxidants, aerosols and acid deposition. Models-3 system takes full account of the physical and chemical processes that control the movement changes of various atmospheric pollutants, and has a good treatment for the transport and diffusion of pollutants.
CMAQ model system has been applied to the simulation of aerosol spatial and temporal distribution and environmental effects in the Yangtze River Delta, Pearl River Delta, North China and Northwest China (Han et al. [23]; Xiang et al. [24]; Liu et al. [25]), and the simulation results are better.

3. Analysis of numerical simulation results

3.1. Overview of air pollution in the Pearl River Delta from January 1 to 12, 2017

AQI technical requirements and standards are used to analyze the daily average AQI in the Pearl River Delta region from January 1 to 12, 2017, and the result shows that the most polluted areas are in Zhaoqing and Foshan, especially in the southeast of Zhaoqing and Duanzhou district of Zhaoqing. Taking Zhaoqing as an example, there were three air pollution processes, including moderate pollution (AQI is 101-150, and PM2.5 is 78-101 μg·m⁻³), moderate to severe pollution (AQI is 125-250, and PM2.5 is 129-229 μg·m⁻³) and moderate pollution (AQI is 101-150, and PM2.5 is 102-103 μg·m⁻³) on January 6. The worst was on January 6, when the AQI index reached 229 and PM2.5 concentrations also reached 229 μg·m⁻³. In January 2017, the three atmospheric pollution processes in Zhaoqing lasted for 2-4 days each time; the main pollutants in the three air pollution processes were fine particulate matter PM2.5, of which the AQI of the urban neutron station in Duanzhou district of Zhaoqing exceeded 250, and the mass concentration of fine particulate matter PM2.5 reached the highest value (259.00 μg·m⁻³) at 12 o’clock on the 6th, indicating severe air pollution. In addition, the number of pollution days with daily visibility below 10. 00 km is 9. The average daily visibility from 4-6 days is lower than 3 km, and the average daily minimum visibility was as low as 2.4 km. The most serious problem is the visibility ≤ 500m for two consecutive days from 0 to 9 o’clock on the 5th and from 1 to 10 o’clock on the 6th. There is also a continuous visibility ≤ 500m for 3 hours from 6 to 8 o’clock on the 4th. The relative humidity during this period is analyzed, and on the night of January 4, 5 and 6, the relative humidity is 95% to 100%, indicating that the dew point temperature basically coincides with the temperature. Therefore, the period from January 4 to 6 is dominated by heavy fog pollution. At the same time, the change of pollution concentration in Sanshui District of Foshan is analyzed, the change curve trend of PM2.5 and PM10 is basically the same as that of Zhaoqing Duanzhou District, and it is also the three air pollution processes, among which the most serious one is from January 4-6, and the peak value of PM2.5 is 390 μg·m⁻³ on January 5-6, which is 35-75 μg·m⁻³ higher than that of Zhaoqing Duanzhou District. By analyzing the data of two national control stations in Haizhu District, Guangzhou, it can be concluded that the most serious period of AQI in Guangzhou was 234-237 at 22-23 on the 5th and 175-227 at 0-9 on the 6th. Visibility is at its worst between 0-8 hours on the 5th and 6th and lasts for 9 hours with visibility ≤ 500m. It can be seen that the pollution scope expanded from 4 to 6 days, covering the Pearl River Delta region, especially Zhaoqing and Foshan.

3.2. Assessment of simulation results

The simulated values of temperature, relative humidity and wind speed from January 1 to 12,2017 in the central part of the Pearl River Delta (Zhaoqing city as an example) have a good correspondence with the observed values. As shown in Table 1, the Duanzhou District of Zhaoqing city is used as an example to analyze the temperature, relative humidity, wind speed, PM2.5 mass concentration simulation value and the correlation between the observed value, which are 0.83, 0.78, 0.23, and 0.17, respectively. The first three pass the 0.001 significance test (99.9% confidence level), while the mass concentration of PM2.5 passes the 0.01 significance test (99% confidence level). From the error values of the simulation value and the observed value, the best simulation results are temperature and relative humidity, and the average relative error is small, which are 0.11 and 0.19, respectively; and the root mean square errors are 2.48 and 18.94, respectively. The average relative error of the mass concentration of PM2.5 is 0.53, but the root mean square error is large, which is 29.7. The simulation average relative error of wind speed is large, which is 0.97, but the root mean square error is small,
which is 0.92. It may be caused by the fact that the influence of terrain is not considered in the mode setting and the roughness of urban ground buildings is higher.

Table 1. Coefficient and error analysis for meteorological elements from 1 to 12 January 2017 in Zhaoqing

|                        | Temperature (°C) | Relative Humidity (%) | Winspeed (m·s⁻¹) | Concentration of PM2.5 (μg·m⁻³) |
|------------------------|------------------|-----------------------|------------------|----------------------------------|
| Average of observations| 18.8             | 85.5                  | 1.41             | 68.1                             |
| Average of simulated   | 20.3             | 68.6                  | 2.09             | 30.4                             |
| Coefficient            | 0.83             | 0.78                  | 0.23             | 0.17                             |
| Confidence             | 99.9%            | 99.9%                 | 99.9%            | 99%                              |
| Root mean square error | 2.48             | 18.94                 | 1.15             | 29.7                             |
| Mean absolute error    | 1.98             | 16.9                  | 0.92             | 39.2                             |
| Mean relative error    | 0.11             | 0.19                  | 0.97             | 0.53                             |

The quality concentration of PM2.5 in Zhaoqing city simulated by the CMAQ model is evaluated, and the observed and simulated values of PM2.5 concentration are compared with the average values of the four national control monitoring stations. It shows the comparison between the hourly mass concentration of PM2.5 of fine particles simulated by CMAQ model and the hourly mass concentration of PM2.5 observed from January 1 to 12, 2017, the variation trend of the simulated PM2.5 concentration is in good agreement with the actual observed PM2.5 concentration trend, but it is generally low, especially in the first and middle of January 5 and 6, the concentration of PM2.5 high value zone and high value range. The simulated value is significantly lower than the observed value, which may not take into account the aggravation of cumulative pollution; while in the later stage, the pollution process simulation on January 9-10 is better. It can be seen that the three pollution processes are basically simulated well, especially the most serious pollution area on January 6 is also pointing to the southeast of Zhaoqing and the west of Foshan, that is, the Duanzhou District of Zhaoqing, Gaoyao District, Dinghu District and Foshan Sanshui District, corresponding to the most serious area of observation. As can be seen, the WRF-CMAQ model can reasonably simulate the spatial and temporal distribution characteristics of the main meteorological elements and pollutants in the Pearl River Delta region, especially in Zhaoqing, Foshan and Guangzhou.

3.3. Changes in boundary layer height

Figure 1 shows the numerical simulation of the boundary layer height time series from January 1 to January 12, 2017, in Duanzhou District, Zhaoqing city. As can be seen from Figure 3, the border levels from the night of January 1 to 6 January to the early hours of the morning are low, especially in the early hours of 5 and 6 January, the boundary layer was only about 100 meters high when it was close to the ground for 3-5 hours in a row. In the daytime, the maximum is as low as 800 meters, which is conducive to the accumulation of pollutants at night. This corresponds to the period of heavy fog pollution on January 5-6. Figure 4 shows the spatial distribution of the daily mean boundary layer height in the Pearl River Delta on January 6 and January 11, 2017. As can be seen from Figure 4, the average daily boundary layer in Zhaoqing area is as low as 200-300 meters, which is very beneficial to the accumulation of pollutants, corresponding to the heavy pollution process. The average daily boundary layer on the 11th is 500-600 meters, which is twice as high as heavy pollution, corresponding to less pollution.
Figure 1. Numerical simulation of Zhaoqing time series of boundary layer height from January 1 to 12, 2017.

Figure 2. Numerical simulation of daily mean boundary layer height distribution in Pearl River Delta Region on January 6 and 11, 2017.

3.4. Changes of near-surface wind speed and wind vector field

Figure 3 is the numerical simulation diagram of the time series of 10m wind speed on January 12, 2017, January 1, solstice in Zhaoqing city. It can be seen from Figure 9 that the wind speed of 10 m near the ground in Zhaoqing from 1 to 7 days is less than 3 m·s⁻¹, especially in the 5-6th days, the wind speed of 10m is lower than 2 m·s⁻¹. The most serious was in the early morning of June 6, when the wind speed of 10m was lower than 1 m·s⁻¹ or even calm. Figure 6 is the numerical simulation diagram of the spatial distribution of the daily mean wind field in the pearl river delta region on January 1, 2017 and January 12, 2017. As can be seen from Figure 10, when the Pearl River Delta region is mainly controlled by the northerly wind from January 1 to 12, the average wind speed in most areas of Zhaoqing area from January 1 to 7 is low (less than 2 m·s⁻¹), especially from 5th to 6th, the whole area of Zhaoqing is controlled by small wind or static risk, and there is a strong convergence area of small wind near Zhaoqing, which is very unfavorable to horizontal transport and diffusion of pollutants. On 1-3 and 9-10, the wind speed in the near-surface layer was 2-3 m·s⁻¹, and the pollution degree was relatively light.
Figure 3. Numerical Simulation Zhaoqing time series of 10 m wind speed from January 1 to 12, 2017.

Figure 4. Numerical simulation of the spatial distribution of daily mean wind fields in the Pearl River Delta (PRD) on January 6 and 11, 2017.

3.5. Vertical distribution of wind
Figure 5 is a time series diagram of vertical structure of wind field in Zhaoqing from January 1 to 12, 2017. It can be seen from the diagram that the small wind layer appears below 100 m of the pollution process, in which the small wind layer extends upward to 1500 m on the 6th. The existence of small wind layer inhibits the vertical diffusion of pollutants. On June 6, the whole atmosphere was covered with small wind layer, which aggravated the accumulation of pollutants near the ground.
3.6. Vertical distribution of temperature

Figure 6 is a numerical simulation diagram of Zhaoqing temperature vertical structure time series. It can be seen from Figure 8 that the ground inversion is easy to occur under 200m in the night of 1-7 days and 10-11 days; especially on the 5th to 6th days, the multi-layer inversion temperature appears. At the same time, the height of the boundary layer at night was low, and the height of the inversion temperature reached about 500 m; at the same time, the boundary layer at night is too low. These two conditions seriously inhibit the diffusion of pollutants in the vertical direction, which makes the pollution concentration increase rapidly near the ground.

3.7. Regional transport effect of upwind

There were three obvious pollution processes in Zhaoqing from January 1 to 7 and around 10: 1-3 days were moderate pollution, 4-7 days were heavy pollution, and 10-11 were moderate pollution. In the first process, with the strengthening of northeast winds around 3 days ago, the upwind effect of regional transport of pollutants in Shaoguan, Qingyuan and other places, as well as provinces, was obvious. The pollution in Zhaoqing three days ago was mainly affected by interregional transport. In the second process, the northeast wind shifted to easterly and southeast wind on the 4th and 6th days, and Zhaoqing was controlled by the convergence field of calm wind and small wind. At the same time, pollutants transported to the local area in the early stage and pollutants discharged from the central
part of the Pearl River Delta accumulated in Zhaoqing, causing severe pollution in Zhaoqing on 4th and 6th days. As the wind speed picked up on July 8, pollutant diffusion conditions improved, and the overall PM2.5 concentration in the Pearl River Delta fell rapidly. However, as the northeast wind continues to strengthen, cross-regional pollutants are also transported to the Pearl River Delta. Through the convergence of wind fields in Yunfu, Foshan and Guangzhou, cross-regional pollutants and local emissions from the Pearl River Delta accumulated in the center of the Pearl River Delta, forming the third pollution process. It can be seen that the regional transport effect of the upper wind direction is very obvious.

3.8. **Mass concentrations of different atmospheric particles**

Particles can be divided into three modes according to particle size distribution: Aitken nuclei (d ≤ 0.05μm), the accumulated nuclei (0.05μm < d < 2.00μm) and the coarse grain nuclei (d ≥ 2.00μm) modes, respectively. The WRF-CMAQ model was used to simulate the concentration of three kinds of particles with different particle sizes, and the time variation of the concentration of particles with different particle sizes over Zhaoqing city and Guangzhou city from January 1 to 12, 2017 was obtained. It can be seen from Figure 9 that when the air pollution occurred in Zhaoqing city in the central region of the Pearl River Delta, the mass concentration of Agen nuclei was very low, all below 10 μg·m⁻³. The main form of pollutants in the air is the coexistence of fine particulate matter (PM2.5) and coarse grain nuclei modes that accumulate in nuclear modes. The average daily mass concentration of the two is almost the same. During 5-6 days of severe pollution, particulate matter also coexisted in the accumulated nuclear mode and the coarse grain nuclei mode, in which the accumulated nuclear mode was slightly higher than the coarse grain nuclei mode by 10-15μg·m⁻³. In Guangzhou, heavy pollution occurred in 5-6 days, mainly with coarse grain particles, the mass concentration of coarse grain nuclei was about 1 times higher than that of accumulated nuclei. Studies have shown that the diurnal variation of NO₂ and SO₂ reflects the impact of motor vehicle peak and other human activities on the atmosphere[24]. In the process of urban pollution, PM₁₀ concentration is significantly correlated with NO₃ and SO₂ concentration, and gas-particle transformation is an important source of urban PM₁₀ [25]. According to the observation, the average concentration of NO₂ in downtown Guangzhou is 107.1μg·m⁻³, while the average concentration of NO₂ in downtown Zhaoqing is only 53.4μg·m⁻³, which is twice higher than that of Zhaoqing, and the mass concentration of PM₁₀ in Guangzhou is similar (97.4μg·m⁻³ and 110.5μg·m⁻³, respectively). This may be one of the reasons for the transformation of gaseous NOₓ into coarse kernel mode (d ≥ 2.00 m), which resulted in the coarse kernel mode concentration of Guangzhou city being about 1 times higher than that of the accumulated kernel mode. It may also be one of the reasons for the increase in the concentration of the accumulated kernel mode due to the high ground humidity 5-6 days ago. The mechanism of gas particle transformation and the mechanism of accumulating nuclear hygroscopicity will be further discussed in the future.

On the other hand, the occurrence of heavy pollution 5-6 days in Guangzhou was dominated by coarse grain particles, and the corresponding fact was that the concentration of NO₂ was higher than that of other places, which reflected the influence of high concentrations of human activities such as dense motor vehicles on air pollution.
4. Effects of topographic effects on air pollution

Many cities with severe pollution have successively carried out studies on the transmission and diffusion rules of air pollution under complex topographic conditions [26-28]. Liu et al. [27] and Li et al. [28] found that the presence of topographic conditions would lead to wind convergence, wind speed reduction and temperature inversion enhancement. According to the urban topography, Li et al. [28] classified the complex terrain into valley terrain, three-sided mountain and sea terrain, basin terrain, horseshoe type terrain and fjords terrain.

Based on the characteristics of multi-scale airflow movement in cities with different complex terrains, this work expounded their influence on pollutant transport and diffusion, and concluded that the pollutant transport and diffusion rule under each type of terrains is the result of the comprehensive action of weather background, topography and meteorological conditions deeply influenced by topography. Based on the special topographic structure of Zhaoqing city, this work analyzed the influence of topographic effect on air pollution.

As shown in Figure 8, Zhaoqing city is blocked by the 1000m-high Beiling Mountain range in the north and the Xijiang River in the south. There is also a large central lake in the middle, with various types of underlying surface topography, such as gateway, alluvial basin, mountainside, lake and wetland. The four state-controlled stations in the central urban area of Zhaoqing city have different topography, which are terrain topography, basin topography, lake surface topography and three-sided
mountainous terrain. These all have different effects on the transport and diffusion of pollutants. According to the hourly wind speed variation chart (skipped) of the four national control stations in Zhaoqing Central city on January 5-6, 2017, Qixinhyan Railway Station has 21 hours for the calm wind, among them, from 19 o'clock on the 5th to 11 o'clock on the 6th, the wind remained calm for 16 consecutive hours; Chengzhongzi Station (basin topography) has 5 hours of static wind, and most of the rest of the wind is between 1-2 m·s\(^{-1}\); Kengkouzi Station (three sides surrounded by mountain terrain) has 14 hours of static wind, and most of the rest of the wind is between 1-2 m·s\(^{-1}\); while the wind speed of Mugangzi Station (terrain topography) is the largest, and most is 4-8 m·s\(^{-1}\). Obviously, the terrain topography is more conducive to the diffusion of polluted air than the basin, three-sided surrounding mountains and lake surface topography.

![Topographic distribution map of the four state-controlled stations in the central city area of Zhaoqing](image)

**Figure 8.** Topographic distribution map of the four state-controlled stations in the central city area of Zhaoqing

▲ Marked as fjords Topographical Station, Mu-gang Station, ◆ Marked as basin topographical station, cheng-zhong station, ● Marked as Lake Topographical Station, Qi-xing Yan station, and ■ Marked as three-ringed mountains topographical station, Heng- Kou station).

By comparing the hourly changes of PM2.5 in the four national control stations in Figure 9, the highest concentration of PM2.5 was found in the Qixinhyan Railway Station, with an average concentration of 180.3 \(\mu g\cdot m^{-3}\); the second was Kengkouzi Station, and Mugangzi Station was the lowest, with an average concentration of 113.3 \(\mu g\cdot m^{-3}\). The Qixinhyan Railway Station was about 59.2% higher than Mugangzi Station. It can be seen that the terrain topography is conducive to the formation of wind channels, and increasing the wind speed on the ground can facilitate the horizontal diffusion of pollutants. Because of the high humidity near the surface and the high mountains in the north, the surface of the lake is very conducive to the accumulation and settlement of pollutants, accelerating the increase of pollutant concentration.
Figure 9. PM2.5 hourly variations at four state-controlled stations in central Zhaoqing city on January 6, 2017, the day of the worst pollution.

5. Conclusion and discussions
In the Pearl River Delta region, there were three obvious haze-dense smog-haze pollution processes from January 1 to 7 and around January 10: moderate pollution from 1-3 days, severe pollution from 4-7 days, and moderate pollution from 10-11 days. Based on the analysis of wind speed, boundary height, temperature and vertical distribution of wind field, humidity and topography, the cause of this mixed haze pollution process is: in the first process (1-3 days), pollutants were transported upwind in Shaoguan, Qingyuan and other places as well as inter-provincial regions. In addition, the average wind speed of local near ground wind was lower than 3m/s and the ground inversion existed, resulting in the increase of pollutant concentration in the Pearl River Delta region and the formation of moderate haze pollution. In the second process (4-6 days), the average surface wind speed was lower, coupled with the impact of topography and urban dense buildings, calm winds below 2 m·s$^{-1}$ and even lasting 5-16 hours were observed. The influence of strong convergence field caused by small wind intensifies the convergence of pollutants and the thickening of grounding inversion layer. The height of the boundary layer is as low as 100 m. With the increase of the humidity near the ground, the relative humidity increases to nearly 100%, resulting in visibility ≤ 500m for 10 consecutive hours, including fog pollution ≤ 100m for 7 consecutive hours, and PM2.5 also reaches the peak at this time. At the same time, it is found that on the day of severe pollution in Guangzhou, coarse nuclear particle is the main substance, which corresponds to the fact that the concentration of NO$_2$ is higher than that of other places, reflecting the impact of human activities such as densely populated areas of motor vehicles on air pollution. With the recovery of near ground and high wind speed on July 8, pollutant diffusion conditions improved, and the overall PM2.5 concentration in the pearl river delta fell rapidly. However, as the northeast wind continues to strengthen, cross-regional pollutants also continue to transport to the Pearl River Delta. Through the convergence of the wind fields in Zhaoqing, Foshan and Guangzhou, cross-regional pollutants and local pollutants discharged by the Pearl River Delta are re-accumulated in the central area of the Pearl River Delta, forming the third process of moderate haze pollution.

According to the simulation results of this haze-concentrated haze-haze pollution, the internal cause of haze formation is the diffusion of regional pollutants, local pollution sources and the emission of motor vehicles, while the external cause is the strong convergence of still and small winds, ground inversion, high ground humidity, continuous no precipitation, and topographic effect. By means of manual intervention such as increased construction of city air duct near the ground layer of wind speed,
humidity on the moisture absorption of catalyst to reduce the surface layer, cooling temperature and
damage grounding inversion, increasing precipitation in wet sedimentation, the impact of smog and
haze can be reduced. However, there are few experiments of manual intervention at present, so it is
necessary to carry out a large number of manual intervention experiments in multiple test sites for
scientific verification and inspection, and use factors of numerical simulation of manual intervention
to explore the effect and methods of manual intervention. At the same time, it is also necessary to
control the diffusion of trans-regional pollutants and the emission of local pollution sources and motor
vehicles through regional joint prevention.

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